

Productivity measurements in the Bay of Bengal using the ^{15}N tracer: Implications to the global carbon cycle

Sanjeev Kumar* & R.Ramesh

Physical Research Laboratory, Ahmedabad - 380 009, India

*[E-mail: sanjeev@prl.ernet.in]

Received 5 May 2004, revised 4 February 2005

During September-October 2002 (Fall intermonsoon), a cruise was undertaken in the shelf and offshore Bay of Bengal onboard ORV Sagar Kanya as a part of the Bay of Bengal Process Study, when physical, chemical and biological parameters were measured in the Bay. This paper describes the first ^{15}N based productivity measurements made in the Bay, which are comparable to the ^{14}C based measurements made concurrently. Results show that the productivity to Chl *a* ratios have a mean of 2.6 ± 3.3 / hr. Offshore stations have an average productivity of $\sim 360 \text{ mgC /m}^2/\text{d}$, whereas shelf stations have $\sim 280 \text{ mgC /m}^2/\text{d}$. The highest value of $875 \text{ mgC /m}^2/\text{d}$ was found at a station where the mixed layer depth was the maximum ($\sim 55\text{m}$, approximately equal to the average photic depth during the cruise). Both offshore and shelf stations have an average *f*-ratio (ratio of new to total production, conservative estimate) of ~ 0.5 . The *f* ratios in the Bay of Bengal, higher relative to its western counterpart, the highly productive Arabian Sea ($f \sim 0.3$), implies that the Bay is capable of removing the anthropogenic excess CO_2 from the atmosphere at least as efficiently as the Arabian Sea, if not more, at least during the fall intermonsoon season. Nitrate from depth could be brought up during this season by frequent cyclonic activity. Present study provides the first direct confirmation of high new production in the Bay, earlier suggested based on pCO_2 measurements.

[Key words: New production, *f*-ratio, nitrate, carbon cycle, Bay of Bengal]

Introduction

The increasing atmospheric CO_2 , which has risen already by more than 30% from its pre-industrial level is a matter of global concern¹, mainly because of its “greenhouse” property that causes global warming by trapping the outgoing long wave radiation emitted by the earth. This has led to an increase of $0.6 \pm 0.2^\circ\text{C}$ in the earth’s surface temperature during the last century² and further warming is predicted by climate models. The observed growth rate of CO_2 in the atmosphere is less than the rate at which it is being injected into the atmosphere by the burning of fossil fuels. Obviously a significant part of the injected CO_2 is being taken up by the terrestrial and marine biospheres. To quantify this uptake, a good number of major international scientific programmes, such as the JGOFS (Joint Global Ocean Fluxes Study, aimed at assessing the role of the global ocean as source/sink of CO_2), concentrated mainly on highly productive areas of the ocean such as the Arabian Sea³. Its eastern counterpart, the Bay of Bengal (BOB) is less sampled and studied⁴. BOB is of special interest to oceanographers due to its characteristics in terms of

the seasonally reverting atmospheric forcing, limited northern extent and a large and seasonal freshwater pulse. Recent measurement programmes such as the BOBMEX (Bay of Bengal Monsoon Experiment)⁵, MLR (Marine Living Resources) and BOBPS (Bay of Bengal Process Studies)⁶ are beginning to offer some new insights into the various oceanographic processes that operate within the Bay. This paper reports a part of BOBPS work: the first measurements of ^{15}N based production in BOB during the 2002 fall intermonsoon period. The objective was to quantify the fraction of the biologically fixed carbon that is exported downwards (called the export or new production) in the Bay of Bengal using ^{15}N tracer technique.

New production⁷⁻⁹ is defined as the part of the primary production supported by external nitrogenous inputs of upwelled, riverine or eolian origin introduced into the photic zone (this may be any nitrogenous component: atmospheric N_2 fixed by *Trichodesmium*, nitrite, nitrate, urea, ammonia or dissolved organic nitrogen). Regenerated production is a part of the primary production that sustains on recycled nutrients such as ammonium or urea in the

photic zone itself. Nitrate could also be a part of the regenerated production if there is a significant nitrification in the photic zone. The sum of the new and regenerated production gives the total production while the ratio of the new to total production⁹ yields the 'f-ratio'. We have made the following conventional assumptions: (i) the extraneous nitrogen that causes new production in BOB is only nitrate and (ii) as the NO_3 was quite low in the top 40 m at most locations during the study period, the regenerated production in BOB is only due to ammonium and urea, and dissolved organic nitrogen other than urea does not play a significant role. These assumptions can be tested when the ^{15}N based method is routinely applied in future along with other methods.

Materials and Methods

Bay of Bengal (BOB), located in the northeastern part of the Indian Ocean, occupies an area of $\sim 2.2 \times 10^6 \text{ km}^2$ and is significantly influenced by both south-west (summer) and the north-east (winter) monsoons; the surface circulation in BOB reverses seasonally with the monsoon winds¹⁰. During summer, the Summer Monsoon current brings Arabian Sea waters to the southern BOB while during winter, the low salinity waters of the Bay¹⁰ enter the southern Arabian Sea through the Winter Monsoon current. The East India Coastal Current (EICC) flows clockwise along the western margin of BOB during summer, while in winter, it flows anti-clockwise. The major processes that lead to this circulation pattern in the Bay are Ekman pumping and remote forcing from the equatorial Indian Ocean¹⁰. TOPEX/Poseidon altimeter data also reveal the presence of large scale eddies. BOB has a positive water balance and receives $\sim 2 \text{ m}$ of rainfall. In addition, during the summer monsoon, fresh water discharge from the rivers draining into it (from Ganga, Brahmaputra, Irrawady, Godavari, Krishna and a number of smaller rivers from peninsular India) reaches its maximum¹¹. The annual fresh water discharge¹² is $\sim 1.5 \times 10^{12} \text{ m}^3/\text{yr}$. This is accompanied by a sediment discharge of $1.4 \times 10^9 \text{ tonnes/yr}$. There is also an influx of nutrients such as Si ($\sim 130 \times 10^9 \text{ mol/yr}$)¹³, P ($\sim 3 \times 10^9 \text{ mol/yr}$)¹³ and N ($\sim 10^{11} \text{ mol/yr}$)¹⁴. Usually nitrate is the limiting nutrient for plankton in BOB¹⁴.

As part of the BOBPS (Bay of Bengal Process Studies), a cruise was undertaken during September-October 2002 onboard *ORV Sagar Kanya* (SK-182, Fall Intermonsoon). The cruise track followed is

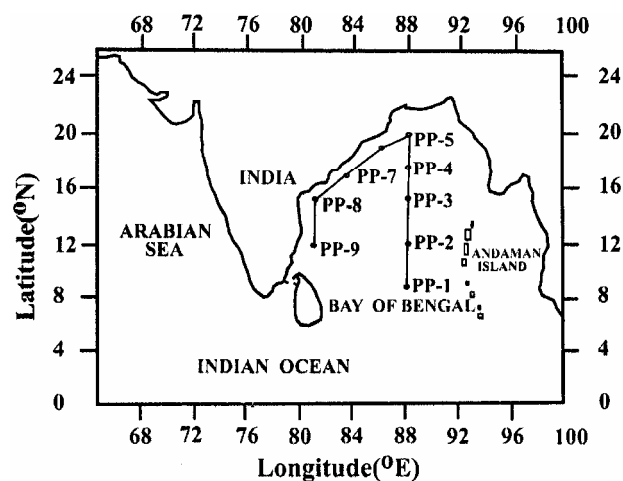


Fig. 1—The sampling locations during fall intermonsoon 2002 in the Bay of Bengal. PP denotes the stations where ^{15}N experiments have been carried out.

shown in Fig.1. Twenty four CTD stations were occupied and primary productivity was measured at nine of these stations (named PP1, PP2PP9). The first four, located along the 88°E were offshore stations and the rest were along the western margin of BOB (shelf stations). Table 1 gives the details such as dates of occupation, SST, water depth, mixed layer depth (MLD), column nitrate along with the ^{15}N based column productivity (in units of $\text{mgC}/\text{m}^2/\text{d}$) over the photic zone, and conservative estimates of f-ratios. While we measured the new and total production based on ^{15}N tracer, scientists from National Institute of Oceanography (NIO, Goa) measured the total production based on the traditional ^{14}C tracer. Several physical (temperature, salinity, wind speed, currents), chemical (dissolved nitrate, nitrite, phosphate, silica, oxygen) and biological (Chlorophyll *a*, phytoplankton, zooplankton, bacterial biomass) parameters were measured by NIO scientists and these details will be published elsewhere by them (for experimental details, see ref. 6).

Photic depth was estimated at each station during noon using a Secchi disc. In general, the photic depth was found to be $\sim 60 \text{ m}$, except at PP6, where it was $\sim 40 \text{ m}$. We followed the method of Dugdale & Goering⁷, detailed in the JGOFS protocol⁸ for measuring the total and new production. Water samples were collected before dawn around 4 A.M. IST in 30 L Go-Flo bottles. The depths chosen were - surface, 20, 40 and 60 m except at PP6, where the chosen depths were -surface, 15, 25 and 40 m. For experiments with nitrate and ammonium tracers,

Table 1—Environmental parameters, productivity and f ratios during fall intermonsoon 2002 (SK-182) in the Bay of Bengal. *denotes shelf stations, others are offshore stations. The last three columns pertain to the photic zone (~60 m, except for PP6 where it was ~40 m).

Station	Latitude (°N)	Longitude (°E)	Date (2002)	SST (°C)	Water depth (m)	MLD (m)	Col. NO ₃ (mmol m ⁻²)	f- ratio	Column Productivity based on ¹⁵ N measurements (mgC/m ² /d)
PP1	8° 59' 58.9"	87° 58' 43.1"	18/9	28.2	3500	37	336	0.34	100
PP2	11° 58' 57.9"	87° 57' 58.2"	21/9	28.7	3220	55	79	0.8	875
PP3	15° 0' 9.3"	87° 58' 24"	23/9	28.3	2900	26	60	0.42	265
PP4	17° 56' 33.1"	87° 54' 38.6"	26/0	29.0	2200	3	572	0.57	210
PP5*	20° 0' 0.4"	88° 0' 1.8"	29/9	28.9	990	6	525	0.6	280
PP6*	18° 59' 44.8"	85° 30' 4.8"	1/10	29.9	680	7	145	0.75	470
PP7*	16° 59' 29.7"	83° 30' 3"	3/10	30.0	2500	5	566	0.71	430
PP8*	15° 0' 20"	81° 29' 47"	6/10	29.4	2695	6	252	0.11	120
PP9*	11° 59' 37.3"	81° 0' 9.8"	10/10	30.0	3300	30	626	0.54	90

waters were collected in 2 L polycarbonate Nalgene® bottles whereas for urea experiments 1 L polycarbonate bottles were used in duplicate. In all, more than 10 L of seawater was collected from each depth. After collection of the samples the bottles were covered with neutral density filters with light cut-off corresponding to the depth from which they were collected. All bottles were kept wrapped under a thick black blanket in a dark room till 10.00 A.M. IST. Prior to incubation at 10.00 A.M., tracers containing 99 atom % ¹⁵N (sodium nitrate, ammonium chloride and urea, obtained from SIGMA-ALDRICH, USA) were added to the bottles. For the nitrate tracer, efforts were made to add not more than 10% of the ambient concentration, based on the nitrate measurements made either at that particular or the previous CTD station, separated by ~1° latitude. Typical nitrate concentration ranged from below detection limit (< 0.1 µM) to 0.2 µM at surface and increased to 5–20 µM at 60 m. Ambient ammonium and urea measurements could not be made due to logistic problems and therefore constant concentrations of 0.01 and 0.03 µM respectively, were added. Thus the uptake rates obtained for ammonium and urea are conservative estimates. The bottles were kept in a big plastic tub, and seawater from 5 m depth was circulated to keep the temperature constant, and incubated till 2 P.M. At the end of the incubation, bottles were transferred to the ship-board laboratory and were kept wrapped in a thick black blanket in a dark cabin. All samples were filtered sequentially, through precombusted (4 hr at 400°C) 47 mm diameter and 0.7 µm pore size Whatman GF/F filters, washed with filtered seawater, dried in an oven at

50°C overnight and brought to the shore laboratory for further analysis. The incubation bottles were thoroughly cleaned with 0.5 N HCl, and thrice with milliQ water and rinsed with the sample seawater prior to collection. Quite often additional samples were collected from different depths, tracers added and filtered immediately. These were termed as “zero-time enrichment” or blanks. In addition, from each CTD station, 2 L of surface seawater were filtered to determine the natural ¹⁵N abundance in suspended matter. When the above experiments were going on, independent samples were collected to carry out *in-situ* incubation for 12 hours using the ¹⁴C method. The ¹⁴C based experiments were carried out at 8 different depths (surface, 10, 20, 40, 60, 80, 100, and 120 m) at all stations irrespective of photic depth (These results will be published elsewhere by the BOBPS group). For comparing the total productivity estimated by the ¹⁴C method with that from ¹⁵N based experiment, we chose ¹⁴C based productivity values corresponding to our choice of depths (¹⁵N based), viz., surface, 20, 40 and 60 m only, so that there is no additional variability introduced due to the different choices of depths.

For the present study, an Elemental Analyzer (Flash EA 1112 Series, CE Instruments, Italy) interfaced with Finnigan Delta Plus continuous flow mass spectrometer (Thermo Quest Finnigan, Germany) via Conflo III was used. For isotopic analysis, one quarter of the filter was wrapped in a silver foil and dropped into the combustion furnace of the elemental analyzer, where the sample was combusted with 5 grade oxygen (99.999 %). Due to oxidation, oxides of all major elements were formed,

and were passed through a reduction chamber containing reduced copper, where oxides of nitrogen were reduced to N_2 . The gaseous mixture then passed through a dry H_2O -absorbant and a gas chromatographic column and pure N_2 gas was admitted into the mass spectrometer. In the whole process, dry helium (99.999 %) acted as the carrier gas. Thus for each sample, the ^{15}N abundance was determined in atom percent units. Blanks were 0.368 ± 0.001 , 0.397 ± 0.011 and 0.411 ± 0.036 atom % respectively for nitrate, ammonium and urea. All results presented here are blank corrected. The precision of isotope measurements was less than 1% for nitrate and urea experiments, while it was around 3% for ammonium experiments. Two standards, IAEA – NO – 3 (KNO_3 , No. 213) and IAEA – N – 2 ($[NH_4]_2 SO_4$, No. 342) gave values of 0.3674 ± 0.0009 ($n = 37$) and 0.3727 ± 0.00008 ($n = 6$) respectively. The values quoted by IAEA are 0.3681 and 0.3738 respectively.

The mass spectrometer was calibrated by combusting known amounts of atropine (also KNO_3 and $[NH_4]_2 SO_4$) standard so that the total area under the peak of masses 28, 29 and 30 could be used as a measure of the particulate organic nitrogen (PON) in the sample. One such calibration is shown in Fig. 2. The precision of measurement of PON is less than 10 % based on duplicate analyses. Once the PON and atom % excess in the sample, $^{15}N_{sample}$, were measured, the uptake rate was calculated using the equation of Dugdale & Wilkerson¹⁵:

$$\text{Uptake rate} = [\text{PON} * ^{15}N_{sample}] / [t * ^{15}N_d]$$

where $^{15}N_d$ was the atom % excess in the dissolved phase (tracer added + natural abundance in the measured proportions) and t the total time of

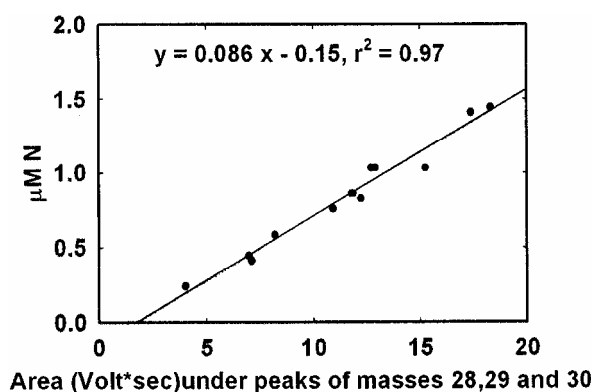


Fig. 2—Calibration of the mass spectrometer with atropine standard to calculate PON content.

incubation (constantly 4 hours). This form of the equation takes care of the presence of detrital material in the filter.

The total production was calculated as the sum of nitrate, ammonium and urea uptake rates. New production, by convention, is taken as the nitrate uptake rate and regenerated production is taken as the sum of ammonium and urea uptakes. For converting the hourly production to daily production, multiplication by 12 was made except for ammonium uptake rates, which were multiplied by 18 to account for dark uptake. The units used are $mmol N/m^3/hr$ for each depth and $mmol N/m^2/d$ for the integrated column (i.e., photic zone) production. Using the Redfield ratio of C:N = 106:16 in marine organic matter, multiplication of the above by 6.625 yields values in units of $mmol C/m^3/hr$, which, when further multiplied by 12, yields values in units of $mgC/m^2/d$. Eventhough, C/N ratio is somewhat variable¹⁶, we use the most accepted statistical average value of ~6.6. The f ratios have been calculated as integrated nitrate uptake/integrated (nitrate+ ammonium + urea) uptake. Since this uses conservative estimates of ammonium and urea uptakes, the f ratios thus calculated provide the upper bounds.

Results and Discussion

The depth profiles of ^{15}N based production (in units of $mg C/m^3/d$) at all PP stations are shown in Fig. 3, and those of measured nitrate concentrations in Fig. 4. The integrated (photic zone) column production and f-ratios are shown in Table 1. Most depth profiles in Fig. 3 do not show a sub-surface maximum. This is expected in BOB⁴, because of lower incident light levels relative to the Arabian Sea, due to increased cloudiness.

One possible check on the measured productivity is the 'productivity normalized to chlorophyll' obtained by dividing the productivity ($mgC/m^3/hr$) by the measured Chl *a* (mg/m^3). These values averaged around $2.6 \pm 3.3/hr$ for our measurements, with a maximum of 15.4/hr at surface of PP7. Likewise the ^{14}C based estimate made concurrently (see section on methods) had a mean of $2.2 \pm 2.3/hr$, quite similar to present results. The maximum in this case was 11.8, again at surface of PP7. The ^{14}C (denoted by $\times$) and ^{15}N based productivity (denoted by y) values are well correlated: $y = 0.85x + 0.82$, with a linear correlation coefficient of 0.80, significant at 0.005 level ($n = 34$). The slope of 0.85 implies that the ^{15}N based

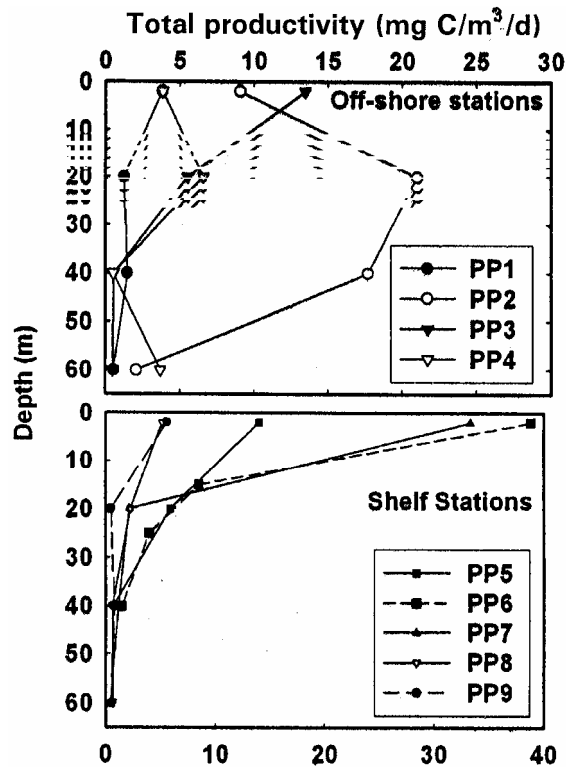


Fig. 3—Depth profiles of ^{15}N -based productivity at all the PP stations.

productivity is on the average less than that based on ^{14}C by $\sim 15\%$. However, this could be the result of analytical uncertainties associated with both the methods ($\sim 10\%$), and therefore we conclude that in general there is a good agreement between the two methods.

Table 1 presents the total productivity in terms of carbon. The total productivity ranged from 90 to 875 $\text{mgC/m}^2/\text{d}$ with an average value of 316 $\text{mgC/m}^2/\text{d}$. The total production based on ^{14}C during the same cruise had a similar average value of $\sim 330 \text{ mgC/m}^2/\text{d}$ (and ranged from 182 to 504 $\text{mgC/m}^2/\text{d}$). The production along 88°E ranged from 182 to 504 $\text{mgC/m}^2/\text{d}$ whereas the range along the western margin was 193 to 418 $\text{mgC/m}^2/\text{d}$. The average value during present study was greater than the average value ($\sim 210 \text{ mgC/m}^2/\text{d}$) reported⁶ for the summer monsoon 2001. The reason could be increased availability of nutrients during the fall intermonsoon due to the churning up of the ocean by cyclonic activity, and reduced average cloudiness relative to June–August. For example, the productivity is the highest in the second station (PP2), where the mixed layer depth is also the deepest (Table 1).

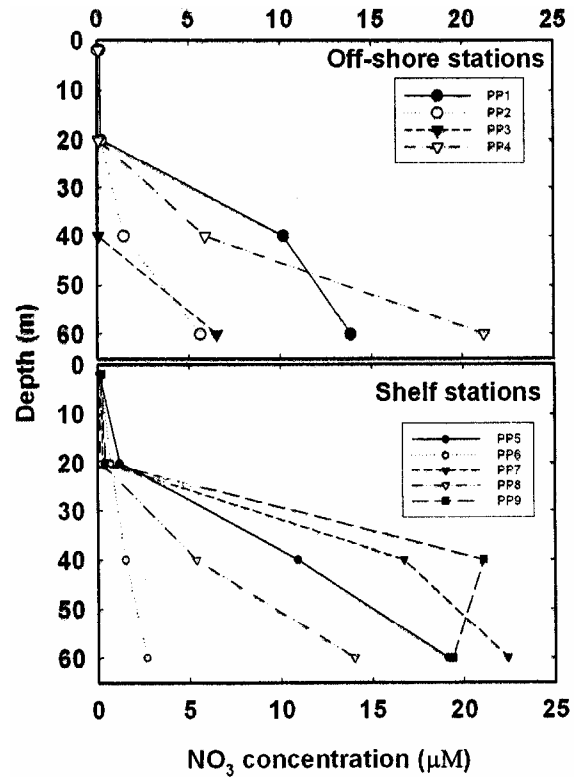


Fig. 4—Depth profiles of nitrate⁴⁹ at all the PP stations.

Earlier measurements of productivity from BOB by the ^{14}C method show higher values^{17–19} than the recent ^{14}C based measurements, which is being attributed to the clean technique being followed during recent measurements⁶. However, the average productivity values for BOB (300 $\text{mgC/m}^2/\text{d}$) are lower than values reported for the Arabian Sea²⁰, which is around $\sim 800 \text{ mgC/m}^2/\text{d}$. The reason for this difference between the two adjacent basins is the relatively lower concentration of nitrate (the limiting nutrient) in the surface waters of BOB due to stratification⁶.

First four stations (PP1 to PP4) are offshore stations which show an average productivity of $\sim 360 \text{ mgC/m}^2/\text{d}$ with an f-ratio of ~ 0.5 . PP4 to PP9 are shelf stations. The productivity for these stations averages $\sim 280 \text{ mgC/m}^2/\text{d}$ with an f-ratio of ~ 0.5 . Although the f-ratios for offshore and shelf stations are similar, the source of nitrate seems to be different. The source for the offshore is nitrate from deeper waters, which is evident from observed natural $\delta^{15}\text{N}$ values ($\sim 5\%$) of suspended matter comprised mainly of phytoplanktons in the surface waters of the open Bay²¹. Most of these values are closer to the $\delta^{15}\text{N}$ values of reported deeper nitrates²². There is no

measurable nitrate present in the surface water; whatever nitrate comes to the surface is apparently consumed quickly by the algae, thus showing virtually no nitrate. The consumption is probably so fast that there is no time for isotopic fractionation and the original ^{15}N signal of nitrate is mirrored in the ^{15}N of $\text{PON}^{23,24}$. The exact mechanism by which these nutrients reach the surface BOB is a subject of speculation; this phenomenon may not be a steady state process because a strong seasonality exists. It may be strongly influenced by the highly seasonal continental inputs. However, using the same argument of natural $\delta^{15}\text{N}$ of suspended matter in surface waters, the source of nitrate (or also other nitrogenous nutrients) in the shelf region seems to be influenced by terrestrial inputs, as the average $\delta^{15}\text{N}$ values of suspended matter here ($\sim 2.5\text{‰}$) is less than that at offshore²¹.

Figure 5A shows the relationship between total productivity and f-ratios, which indicates higher f-ratio for higher total productivity, emphasizing the substantial role that nitrate plays in the total production. A curve (rectangular hyperbola chosen to

mimic the saturation behaviour) representing:

$$f\text{-ratio} = (1.02 \pm 0.25) \text{ Total production} / [(213 \pm 126) + \text{Total production}]$$

fits the observed data best with a correlation coefficient of 0.87, significant at 0.05 level. However, column nitrate integrated over the photic depth and f-ratio (Fig. 5B) does not show any particular relationship with the f ratio. There is no significant variation in the photic depth (~ 60 m) except at PP 6, where it was 40 m. Thus integrated nitrate may not be a good parameter for detecting new or total production in BOB. Based on the present study, it appears that new production is more significant in BOB compared to other ocean basins (such as the adjacent Arabian Sea). As the time averaged new production (annual time scales) is approximately equal to the export production, it appears from our study that BOB can remove atmospheric carbon dioxide from the atmosphere at least as effectively as the Arabian Sea. This is the first direct verification of high new production in BOB, predicted earlier based on pCO_2 measurements²⁵.

Potential nutrient sources

The uniqueness of BOB lies in the tremendous freshwater influx it receives from rivers draining the subcontinent²⁶. This high influx of freshwater brings a lot of nutrients, such as nitrate¹⁴ from the hinterland. However, measurements reported²⁷ in both the dry (Jan-May) and the cyclonic seasons (Oct-Dec., when the sea is churned more often by cyclones) do not indicate a significant presence of nitrate in the surface layer. This absence persists during the summer monsoon^{28,29}. This has led to the speculation that rivers draining into BOB do not provide nitrate for the phytoplankton uptake. Probably, the nitrate brought by rivers apparently gets consumed in the estuary itself.

Another mechanism that brings nutrients to the surface is upwelling, known to cause high biological productivity in the Arabian Sea. The nutrient rich waters upwelled off Somalia and Arabia are advected laterally out of the upwelling region and contribute to productivity in the Central Arabian Sea³⁰. However, BOB lacks such intense upwelling except a 40 km wide band along the western margin (east coast of India) that has been found to be the result of local longshore wind stress³¹. This upwelling has been observed during the southwest monsoon and disappears northward, overwhelmed by the enormous freshwater influx from Ganga -Brahmaputra rivers.

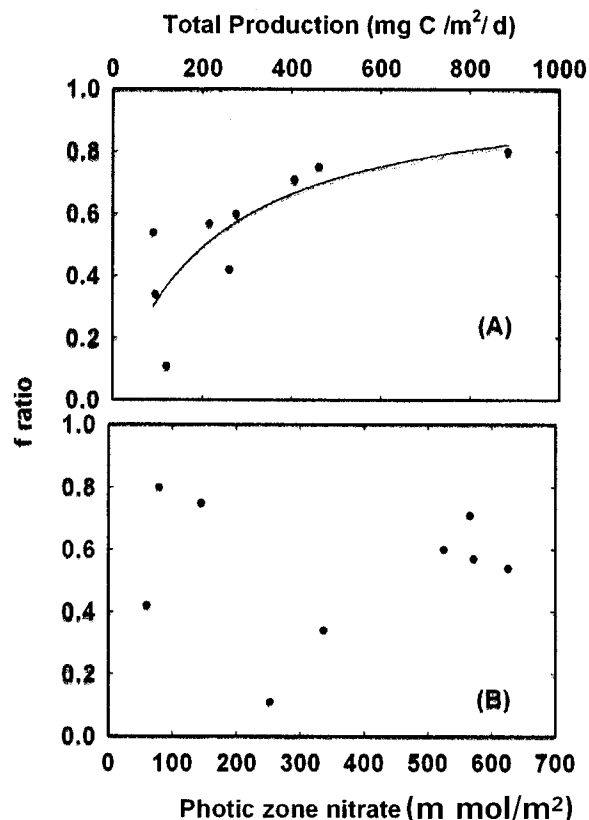


Fig. 5—(A) f ratio as a function of total production; (B) f ratio as a function of photic zone column nitrate.

Wind driven turbulent mixing is another phenomenon that can inject nutrients in the upper layer of the ocean. During the southwest monsoon this mixing is stronger in Arabian Sea than in BOB. This is due to the weak winds and stable and strong stratification of the surface layer in BOB³². The huge influx of freshwater leads to a significant decrease in salinity and increase in SST during summer causing a strong stratification. The weak winds over BOB are insufficient to erode the stratified layer³² and hence wind-driven vertical mixing may play a limited role, except during cyclones.

Cooling of surface waters by the northeasterly winds during the northeast monsoon has been suggested³³. Winter cooling of surface water in the month of January has also been reported³⁴. However, this winter cooling does not lead to convective mixing as in the case of Arabian Sea³⁵. Mixing is again prevented due to the presence of low salinity water in the upper layer.

Presence of thermocline oscillations and cold-core eddy signatures during summer 2001 has been reported⁶. These eddies could pump cold water and nutrients from below to upper subsurface waters. But such eddies are usually capped by surface freshwater layer and are unable to surface, thus not contributing significantly to the surface nitrate pool.

Another potential nutrient supply to the BOB may be from submarine groundwater discharge. An annual subsurface discharge from Bengal Basin to the BOB of $1.5 \pm 0.5 \times 10^{11} \text{ m}^3/\text{yr}$, which is $\sim 10\%$ of Ganga-Brahmaputra riverine flux to the Bay, has been reported³⁶. The depth of discharge is more than 30m. However, the nitrate in groundwater sampled from domestic wells in Bangladesh shows large variations ranging from 1 to 191 $\mu\text{mol/kg}$, with most of the wells showing nitrate less than detection limit. Taking a conservative 10 $\mu\text{mol/kg}$ as the mean concentration, this would lead to a total annual nitrogen flux of $1.5 \times 10^9 \text{ mol N}$, $\sim 1\%$ of the surface flux of nitrogen²⁵ from rivers. Thus, available data do not clearly advocate the submarine discharge to be the substantial source of nutrient in the surface BOB. Further studies are required for better quantification.

An examination of the nutrient pool availability and requirement of nutrient to sustain the observed average new production suggests that the nutrients brought in by rivers or atmospheric input can at best support 20 % of total requirement whereas rest 80 % has to be supplied from the deeper waters³⁷.

Table 2—Time-averaged fluxes of organic carbon^{11, 39, 46-48} ($\text{gC/m}^2/\text{y}$) in sediment traps, 1000 m above sea floor (values in parentheses are from shallow trap, 1000 m below sea surface).

Trap	Latitude (°N)	Longitude (°E)	Flux ($\text{gC/m}^2/\text{y}$)	Duration of sampling (yr)
ARABIAN SEA				
WAST	16° 20'	60° 30'	3.2	4
CAST	14° 31'	64° 46'	1.9	3
EAST	15° 31'	68° 43'	2.1	4
MS-1	17° 41'	58° 51'	3.8	1
MS-2	17° 24'	58° 48'	5.6	1
MS-3	17° 12'	59° 36'	5.3	1
MS-4	15° 20'	61° 30'	3.7	1
MS-5	10° 00'	65° 00'	1.3	1
BAY OF BENGAL				
NBBT-N	17° 27'	89° 36'	2.86(3.11)	10
NBBT-S	15° 32'	89° 13'	2.38(2.38)	10
CBBT	13° 09'	84° 22'	2.7(2.6)	10
SBBT	4° 28'	87° 19'	2.27(2.5)	10

Paradoxes of the Bay

Overall, the existing literature points towards the stratification of surface layer to be one of the major causes for BOB's low productivity. However, the following facts are in stark contradiction to the reported low productivity in BOB:

- Numerical abundance of phytoplankton (0.41×10^8 - $7.1 \times 10^8/\text{m}^2$) in the BOB³⁸ is comparable to that of Central and eastern Arabian Sea (0.3×10^8 - $10 \times 10^8/\text{m}^2$).
- The sediment trap data show comparable downward average annual flux of organic carbon for both BOB and Arabian Sea^{11,39} (Table 2, barring the highly productive western Arabian Sea), despite the lower euphotic layer productivity in BOB. One explanation of this paradox is that in the Bay, organic carbon is ballasted into the deep by the high lithogenic flux from rivers, which form aggregates with the former⁴⁰. However independent estimates of new production based on nitrogen uptake could help in resolving this paradox, because, under steady state, new production is considered theoretically equal to the export production⁹, the part of primary production which goes out of surface layer. Regions with high new production have high export production, leading to increased downward flux of organic matter, and hence, organic carbon. Present measurements during

Table 3—Comparison of f-ratios and total production of the Arabian Sea and the BOB (asterisk denotes that urea uptake rates were not considered for calculating the f ratios)

	f-ratios	Productivity (mgC/m ² /d)
Arabian Sea		
Intermonsoon ⁴¹ (Nov-Dec 1994)	0.07-0.52	87-1876
Intermonsoon ⁴² (Mar-Apr 1995)	0.11-0.30*	1378-2385*
Southwest monsoon ⁴² (Jul-Aug 1995)	0.10-0.22*	1733-3538*
Northeast monsoon ⁴³ (Jan-Feb 1995)	0.01-0.31*	127-3180*
(Oct-Nov 1995)	0.04-0.29*	310-1908*
Bay of Bengal		
Fall Intermonsoon (this work) (Sep-Oct 2002)	0.11-0.80	90-875

September-October 2002 shows f-ratios to be very high, ranging from 0.1 to 0.8 (mean ~0.5), regardless of the proximity to the coast. This is significantly higher than the values (mean < 0.3) reported for the highly productive northwestern Arabian Sea⁴¹⁻⁴³. The reason could be that the phytoplankton ecosystem in the Bay probably remains in a short supply of nitrate and can readily assimilate whatever nitrate becomes available, thus capable of potentially high new production. At most locations, the nitrate uptake during the present study was maximum at the surface than at the typical subsurface chlorophyll maxima. Similar pattern was observed for the ¹⁴C uptake also. The reason could be the optimum light level at surface during the study period.

(iii) Table 3 compares the f-ratio of Arabian Sea and Bay of Bengal, which shows that even if the total production in the Arabian Sea is high, the part of the total production that leaves the photic zone may be comparable. Hence, BOB and similar traditionally considered to be low productive may be playing a more significant role in global carbon cycle than hitherto unrecognized.

(iv) The presence of Oxygen Minimum Zone (OMZ)⁴⁴ between 100-500 m in the BOB. Its presence in ocean is usually explained by the utilization of oxygen due to decomposition of organic matter brought into the deeper water from surface. This explanation holds good for Arabian

Sea where overhead productivity is high and the degradation of organic matter settling down consumes the oxygen leading to OMZ and denitrification zones⁴⁵. But the existence of OMZ (though not as intense as Arabian Sea) in BOB, where the overhead productivity is less⁴, is indeed puzzling. One possible reason for this might be that high new production as the fraction of organic matter going to deeper waters is more than that previously believed.

Conclusion

The first detailed measurements of ¹⁵N-based productivity carried out in the Bay of Bengal during September- October 2002 reveal that the values obtained are comparable to the traditional ¹⁴C based *in situ* method. Offshore stations have an average productivity of ~360 mgC/m²/d, whereas shelf stations have ~280 mgC/m²/d. Both have an average f-ratio of ~0.5. This high f ratio implies that the Bay of Bengal is capable of removing the anthropogenic excess CO₂ from the atmosphere as efficiently as the highly productive Arabian Sea, at least during the fall intermonsoon. Nitrate from the deep could be brought up during this season by frequent cyclonic activity. Present study provides the first direct confirmation of high production in the Bay, earlier suggested based on pCO₂ measurements²⁵.

Acknowledgement

Authors thank Dr. M. Madhupratap (deceased), coordinator, BOBPS, and Dr. S. Prasanna Kumar, Chief Scientist, SK-182, for the opportunity to participate in the cruise, Dr. N. Ramaiah, Dr. S. Sardesai, Dr. N. B. Bhosle, and other NIO, PRL colleagues who participated in the SK-182 cruise. We also thank Dr. M. Sudhakar of NCAOR, Goa, and the Department of Ocean Development, Government of India for providing the ship time to conduct this study, funded by ISRO-GBP, Department of Space, Government of India. Thanks are also due to Dr. M. S. Sheshshayee of University of Agricultural Sciences, Bangalore for his help in mass spectrometric measurements and our PRL colleagues Lokesh Sahu and A.K. Sudhir for help during onboard experiment.

References

- 1 Keeling, C D & Whorf T P, *Trends: A compendium of data on global change*, (Carbon dioxide Information Analysis Center, Oak Ridge National Laboratory, Tennessee, USA) 2000.
- 2 Houghton J, *Global warming: the complete briefing*, (Cambridge University Press, Cambridge, UK) 1997, pp. 261.

- 3 Smith S L, Understanding the Arabian Sea: Reflections on the 1994-1996 Arabian Sea Expedition, *Deep-Sea Res- II*, 48 (2001) 1385-1402.
- 4 Radhakrishna K, Primary productivity of the Bay of Bengal during March-April, 1975, *Indian J Mar Sci*, 7 (1978) 58-60.
- 5 Bhat G S, Gadgil S, Harish Kumar P V, Kalsi S R, Madhusudanan P, Murthy V S N, Prasada Rao C V K, Ramesh Babu V, Rao L V G, Ravichandran M, Reddy K G, Sanjeeva Rao P, Sengupta D, Sikka D, R Swain & Vinaychandran P N, BOBMEX-the Bay of Bengal Monsoon Experiment, *Bull Am Met Soc*, 82 (2001) 2217-2243.
- 6 Madhupratap M, Gauns M, Ramaiah N, Prasanna Kumar S, Muraleedharan P M, DeSouza S N, Sardesai S & Muraleedharan U, Biogeochemistry of the Bay of Bengal: physical, chemical and primary productivity characteristics of the central and western Bay of Bengal during summer monsoon 2001, *Deep-Sea Res-II*, 50 (2003) 881-896.
- 7 Dugdale R C & Goering J J, Uptake of new and regenerated forms of nitrogen in primary productivity, *Limnol Oceanogr*, 12 (1967) 196-206.
- 8 JGOFS Report, *Protocol for the Joint Global Ocean Fluxes Study (JGOFS) core measurements*, (SCOR, Bergen, Norway) 1996, pp. 145.
- 9 Eppley R W & Peterson B J, Particulate organic matter flux and planktonic new production in the deep ocean, *Nature*, 282 (1979) 677-680.
- 10 Shankar D, Vinaychandran P N & Unnikrishnan A S, The monsoon currents in the north Indian Ocean, *Progr Oceanogr*, 52 (2002) 63-120.
- 11 Unger D, Ittekkot V, Schafer P, Tiemann J & Reschke S, Seasonality and interannual variability of particle fluxes to the deep Bay of Bengal: influence of riverine input and oceanographic processes, *Deep- Sea Res-II*, 50 (2003) 897-923.
- 12 Subramanian V, Sediment load of Indian rivers, *Curr Sci*, 64 (1993) 928-930.
- 13 Sen Gupta, R, DeSouza, S N & Joseph T, On nitrogen and phosphorus in the western Bay of Bengal, *Indian J Mar Sci*, 6 (1977) 107-110.
- 14 Qasim S Z, Primary production in some tropical environments, in *Marine production mechanisms, and international biological programme 20*, edited by Dunbar M J, (Cambridge University Press, Cambridge), 1979, pp. 31-69.
- 15 Dugdale, R C & Wilkerson, F P, The use of ^{15}N to measure nitrogen uptake in eutrophic oceans, experimental considerations, *Limnol Oceanogr*, 31 (1986) 673-689.
- 16 Hedges J I, Baldock J A, Gelin Y, Lee C, Peterson M & Wakeham S G, Evidence for non-selective preservation of organic matter in sinking marine particles, *Nature*, 409 (2001) 801-804.
- 17 Gomes H R, Goes J I & Saino T, Influence of physical processes and freshwater discharge on seasonality of phytoplankton regime in the Bay of Bengal, *Cont Shelf Res*, 20 (2000) 313-330.
- 18 Bhattathiri P M A, Devassy V P, & Radhakrishna K, Primary production in the Bay of Bengal during southwest monsoon of 1978, *Mahasagar- Bull Natn Inst Oceanogr*, 13 (1980) 315-323.
- 19 Devassy V P, Bhattathiri, P M A & Radhakrishna K, Primary production in the Bay of Bengal during August 1977, *Mahasagar- Bull Natn Inst Oceanogr*, 16 (1983) 443-447.
- 20 Bhattathiri P M A, Pant A, Sawant S, Gauns M, Matondakar S G P & Mohanraju R, Phytoplankton production and chlorophyll distribution in eastern and central Arabian Sea in 1994-1995, *Curr Sci*, 71 (1996) 857-862.
- 21 Kumar S, Ramesh R, Bhosle N B, Sardesai S & Sheshshayee M S, Natural isotopic composition of nitrogen in suspended particulate matter in the Bay of Bengal, *Biogeosciences*, 1 (2004) 63-70.
- 22 Tanaka T & Saino T, Modified method for the analysis of nitrogen isotopic composition of oceanic nitrate at low concentration, *J Oceanogr*, 58 (2002) 539-546.
- 23 Altabet M A & McCarthy J J, Temporal and spatial variations in the natural abundance of ^{15}N PON from warm core ring, *Deep-Sea Res*, Part A, 32 (1985) 755-772.
- 24 Wada E & Hattori A, *Nitrogen in the sea: forms, abundances, and rate processes*, (CRC Press, Boca Raton, Fla.) 1991, pp. 208.
- 25 Dileep Kumar M, Naqvi S W A, George M D & Jayakumar D A, A sink for atmospheric carbon dioxide in the northeast Indian Ocean, *J Geophys Res*, 101 (C8) (1996) 18121-18125.
- 26 UNESCO, River inputs in the ocean systems: status and recommendations for research, *UNESCO Tech Pap Mar Sci* No. 55, (1998).
- 27 Rao C K, Naqvi S W A, Dileep Kumar M, Varaprasad S J D, Jayakumar D A, George M D & Singbal S Y S, Hydrochemistry of the Bay of Bengal: possible reasons for a different water column cycling of carbon and nitrogen from Arabian Sea, *Mar Chem*, 47 (1994) 279-290.
- 28 De Sousa S N, Naqvi S W A & Reddy C V G, Distribution of nutrients in the western Bay of Bengal, *Indian J Mar Sci*, 10 (1981) 327-331.
- 29 Rajendran A, Rajagopal M D, Reddy C V G, Distribution of dissolved silicate in the Arabian Sea and Bay of Bengal, *Indian J Mar Sci*, 9 (1980) 172-178.
- 30 Prasanna Kumar S, Madhupratap M, Dileep Kumar M, Muraleedharan P M, De Souza S N, Gauns M & Sarma V V S, High biological productivity in the Arabia Sea during summer monsoon driven by Ekman pumping and lateral advection, *Curr Sci*, 81 (2001) 1633-1638.
- 31 Shetye S R, Shenoi S S C, Gouveia A D, Michael G S, Sundar D & Nampoothiri G, Wind driven coastal upwelling along the western boundary of the Bay of Bengal during southwest monsoon, *Cont Shelf Res*, 11 (1991) 1397-1408.
- 32 Prasanna Kumar S, Muraleedharan P M, Prasad T G, Gauns M, Ramaiah N, De Souza S N, Sardesai S & Madhupratap M, Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea? *Geophys Res Lett*, 29 (2002) 2235, [doi: 10.1029/2002GL016013].
- 33 Shetye S R, Gouveia A D, Shankar D, Shenoi S S C, Vinayachandran P N, Sundar D, Michael G S & Nampoothiri G, Hydrography and circulation in the western Bay of Bengal during northeast monsoon, *J Geophys Res*, 101(C6) (1996) 14,011-14,025.
- 34 Murty V S N, Subramanian B, Gangadhara Rao L V, Reddy G V, Seasonal variation of sea surface temperature in the Bay of Bengal during 1992 as derived from NOAA-AVHRR SST data, *Int J Rem Sens*, 19 (1998) 2361-2371.

- 35 Madhupratap M, Prasanna Kumar S, Bhattachiri P M A, Dileep Kumar M, Raghukumar S, Nair K K C & Ramaiah N, Mechanism of the biological response to winter cooling in the northeastern Arabian Sea, *Nature*, 384 (1996) 549-552.
- 36 Dowling C B, Poreda R J & Basu A R, The ground water geochemistry of Bengal Basin: Weathering, chemisorption, and trace metal flux to the oceans, *Geochim Cosmochim Acta*, 67 (2003) 2117-2136.
- 37 Kumar S, Ramesh R, Sardesai S & Sheshshayee M S, High new production in the Bay of Bengal: possible causes and implications, *Geophys Res Lett*, 31 (2004) L18304 [doi: 10.1029/2004GL021005].
- 38 Sawant S & Madhupratap M, Seasonality and composition of phytoplankton in the Arabian Sea, *Curr Sci*, 71 (1996) 869-873.
- 39 Ittekkot V, Nair R R, Honjo S, Ramaswami V, Bartsch M, Manganini S, & Desai B N, Enhanced particle fluxes in the Bay of Bengal induced by injection of freshwater, *Nature*, 351 (1991) 385-387.
- 40 Ittekkot V, Particle flux studies in the Indian Ocean, *EOS Transactions*, 72 (1991) 527-530.
- 41 Watts L J & Owens N J P, Nitrogen assimilation and f-ratio in the Indian Ocean during an intermonsoon period, *Deep-Sea Res-II*, 46 (1999) 725-743.
- 42 Sambrotto R N, Nitrogen Production in the northern Arabian Sea during the spring intermonsoon and southwest monsoon seasons, *Deep-Sea Res II*, 48 (2001) 1173-1198.
- 43 McCarthy J J, Garside C & Nevis J, Nitrogen dynamics during the Arabian Sea northeast monsoon, *Deep-Sea Res II*, 46 (1999) 1623-1664.
- 44 Olson D B, Hitchcock G L, Fine R A & Warren B A, Maintenance of low-oxygen layer in the Central Arabian Sea, *Deep-Sea Res II*, 40 (1993) 697-709.
- 45 Naqvi S W A, Geographical extent of denitrification in the Arabian Sea, *Oceanol Acta*, 14 (1991) 281-290.
- 46 Haake B, Ittekkot V, Rixen T, Ramaswami V, Nair, R R & Curry W B, Seasonality and interannual variability of particle fluxes to the deep Arabian Sea, *Deep-Sea Res I*, 40 (1993) 1323-1344.
- 47 Honjo S, Dymond J, Prell W & Ittekkot V, Monsoon-controlled export fluxes to the interior of the Arabian Sea, *Deep-Sea Res II*, 46 (1999) 1859-1902.
- 48 Lee C, Murray D W, Barber R T, Buesseler K O, Dymond J, Hedges J I, Honjo S, Manganini, S J, Marra J, Moser C, Peterson M L, Prell W L & Wakeham S G, Particulate organic carbon fluxes: compilation of results from the 1995 US JGOFS Arabian Sea Process study, *Deep-Sea Res II*, 45 (1999) 2489-2501.
- 49 Strickland J D H & Parson T R, *A practical handbook of seawater analysis*, (Fish Res Board, Ottawa, Canada) 1972, pp. 127-130.