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

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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 ~360 mgC /m$^2$/d, whereas shelf stations have ~280 mgC /m$^2$/d. The highest value of $875$ mgC /m$^2$/d was found at a station where the mixed layer depth was the maximum (~55m, 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 ~ 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 concern, 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 ± 0.2°C in the earth’s surface temperature during the last century 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 Sea. Its eastern counterpart, the Bay of Bengal (BOB) is less sampled and studied. 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), MLR (Marine Living Resources) and BOBPS (Bay of Bengal Process Studies) 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 production 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 production 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 ~ $2.2 \times 10^6$ km$^2$ and is significantly influenced by both southwest (summer) and the north-east (winter) monsoons; the surface circulation in BOB reverses seasonally with the monsoon winds$^{10}$. During summer, the Summer Monsoon current brings Arabian Sea waters to the southern BOB while during winter, the low salinity waters of the Bay$^{10}$ 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 Ocean$^{10}$. TOPEX/Poseidon altimeter data also reveal the presence of large scale eddies. BOB has a positive water balance and receives ~ 2 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 maximum$^{11}$. The annual fresh water discharge$^{12}$ is ~ $1.5 \times 10^{12}$ m$^3$/yr. This is accompanied by a sediment discharge of $1.4 \times 10^9$ tonnes/yr. There is also an influx of nutrients such as Si ($\sim 130 \times 10^9$ mol/yr)$^{13}$, P ($\sim 3 \times 10^9$ mol/yr)$^{13}$ and N ($\sim 10^{11}$ mol/yr)$^{14}$. Usually nitrate is the limiting nutrient for plankton in BOB$^{14}$.

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 shown in Fig.1. Twenty four CTD stations were occupied and primary productivity was measured at nine of these stations (named PP1, PP2 ......PP9). The first four, located along the 88$^\circ$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 mgC/m$^2$/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 ~ 60 m, except at PP6, where it was ~40 m. We followed the method of Dugdale & Goering$^7$, detailed in the JGOFS protocol$^8$ 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,
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 black blanket in a dark room till 10.00 A.M. IST. Collected. All bottles were kept wrapped under 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 Finngan 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 N₂. The gaseous mixture then passed through a dry H₂O-absorbant and a gas chromatographic column and pure N₂ 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 ¹⁵N 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 (KNO₃, No. 213) and IAEA – N – 2 ([NH₄]₂SO₄, 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 KNO₃ and [NH₄]₂SO₄) 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, ¹⁵N sample, were measured, the uptake rate was calculated using the equation of Dugdale & Wilkerson¹⁵:

\[
\text{Uptake rate} = \frac{\text{PON} \times ¹⁵N_{\text{sample}}}{t \times ¹⁵N_d}
\]

where ¹⁵N_d was the atom % excess in the dissolved phase (tracer added + natural abundance in the measured proportions) and t the total time of 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/m³/hr for each depth and mmol N/m²/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/m³/hr, which, when further multiplied by 12, yields values in units of mgC/m²/d. Eventhough, C/N ratio is somewhat variable,¹⁶ 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 ¹⁵N based production (in units of mg C/m³/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 BOB, 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/m³/hr) by the measured Chl a (mg/m³). These values averaged around 2.6 ± 3.3/hr for our measurements, with a maximum of 15.4/hr at surface of PP7. Likewise the ¹⁴C based estimate made concurrently (see section on methods) had a mean of 2.2±2.3/hr, quite similar to present results. The maximum in this case was 11.8, again at surface of PP7. The ¹⁴C (denoted by ×) and ¹⁵N based productivity (denoted by y) values are well correlated: y = 0.85 x + 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 ¹⁵N based productivities are ~85% of the ¹⁴C based productivities.
productivity is on the average less than that based on $^{14}$C by ~15%. However, this could be the result of analytical uncertainties associated with both the methods (~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 mgC/m$^2$/d with an average value of 316 mgC/m$^2$/d. The production based on $^{14}$C during the same cruise had a similar average value of ~330 mgC/m$^2$/d (and ranged from 182 to 504 mgC/m$^2$/d). The production along 88°E ranged from 182 to 504 mgC/m$^2$/d whereas the range along the western margin was 193 to 418 mgC/m$^2$/d. The average value during present study was greater than the average value (~210 mgC/m$^2$/d) reported 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).

Earlier measurements of productivity from BOB by the $^{14}$C method show higher values than the recent $^{14}$C based measurements, which is being attributed to the clean technique being followed during recent measurements. However, the average productivity values for BOB (300 mgC/m$^2$/d) are lower than values reported for the Arabian Sea, which is around ~800 mgC/m$^2$/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 stratification.

First four stations (PP1 to PP4) are offshore stations which show an average productivity of ~360 mgC/m$^2$/d with an f-ratio of ~0.5. PP4 to PP9 are shelf stations. The productivity for these stations averages ~280 mgC/m$^2$/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 $\delta^{15}$N values (~5‰) of suspended matter comprised mainly of phytoplanktons in the surface waters of the open Bay. Most of these values are closer to the $\delta^{15}$N values of reported deeper nitrate. 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 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 \(\delta^{15}\)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 \(\delta^{15}\)N values of suspended matter here (~2.5‰) is less than that at offshore\(^{21}\).

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:

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

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 \(p\text{CO}_2\) measurements\(^{25}\).

**Potential nutrient sources**

The uniqueness of BOB lies in the tremendous freshwater influx it receives from rivers draining the subcontinent\(^{26}\). This high influx of freshwater brings a lot of nutrients, such as nitrate\(^{14}\) from the hinterland. However, measurements reported\(^{27}\) 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 Sea\(^{30}\). 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 stress\(^{31}\). This upwelling has been observed during the southwest monsoon and disappears northward, overwhelmed by the enormous freshwater influx from Ganga-Brahmaputra rivers.
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 BOB. 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 layer 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 suggested. Winter cooling of surface water in the month of January has also been reported. However, this winter cooling does not lead to convective mixing as in the case of Arabian Sea. 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 reported. 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 ± 0.5 × 10^{11} m^3/yr, which is ~10% of Ganga-Brahmaputra riverine flux to the Bay, has been reported. 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 µmol/kg, with most of the wells showing nitrate less than detection limit. Taking a conservative 10 µmol/kg as the mean concentration, this would lead to a total annual nitrogen flux of 1.5 × 10^9 mol N, ~1% of the surface flux of nitrogen 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 waters.

<table>
<thead>
<tr>
<th>Trap</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Flux (gC/m²/y)</th>
<th>Duration of sampling (yr)</th>
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<tbody>
<tr>
<td>WAST</td>
<td>16° 20'</td>
<td>60° 30'</td>
<td>3.2</td>
<td>4</td>
</tr>
<tr>
<td>CAST</td>
<td>14° 31'</td>
<td>64° 46'</td>
<td>1.9</td>
<td>3</td>
</tr>
<tr>
<td>EAST</td>
<td>15° 31'</td>
<td>68° 43'</td>
<td>2.1</td>
<td>4</td>
</tr>
<tr>
<td>MS-1</td>
<td>17° 41'</td>
<td>58° 51'</td>
<td>3.8</td>
<td>1</td>
</tr>
<tr>
<td>MS-2</td>
<td>17° 24'</td>
<td>58° 48'</td>
<td>5.6</td>
<td>1</td>
</tr>
<tr>
<td>MS-3</td>
<td>17° 12'</td>
<td>59° 36'</td>
<td>5.3</td>
<td>1</td>
</tr>
<tr>
<td>MS-4</td>
<td>15° 20'</td>
<td>61° 30'</td>
<td>3.7</td>
<td>1</td>
</tr>
<tr>
<td>MS-5</td>
<td>10° 00'</td>
<td>65° 00'</td>
<td>1.3</td>
<td>1</td>
</tr>
<tr>
<td>NBBT-N</td>
<td>17° 27'</td>
<td>89° 36'</td>
<td>2.86(3.11)</td>
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<tr>
<td>NBBT-S</td>
<td>15° 32'</td>
<td>89° 13'</td>
<td>2.38(2.38)</td>
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<tr>
<td>CBBT</td>
<td>13° 09'</td>
<td>84° 22'</td>
<td>2.7(2.6)</td>
<td>10</td>
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<tr>
<td>SBBT</td>
<td>4° 28'</td>
<td>87° 19'</td>
<td>2.27(2.5)</td>
<td>10</td>
</tr>
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</table>

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:

(i) Numerical abundance of phytoplankton (0.41*10^8 -7.1*10^8/m³) in the BOB is comparable to that of Central and eastern Arabian Sea (0.3 10^8-10^9/m³).

(ii) The sediment trap data show comparable downward average annual flux of organic carbon for both BOB and Arabian Sea (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 former. 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 production, 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...
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 Sea. 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.

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)

<table>
<thead>
<tr>
<th></th>
<th>f-ratios</th>
<th>Productivity (mgC/m²/d)</th>
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</thead>
<tbody>
<tr>
<td>Arabian Sea</td>
<td></td>
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<tr>
<td>Intermonsoon 41</td>
<td>0.07-0.52</td>
<td>87-1876</td>
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<tr>
<td>(Nov-Dec 1994)</td>
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<tr>
<td>Intermonsoon 42</td>
<td>0.11-0.30*</td>
<td>1378-2385*</td>
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<tr>
<td>(Mar-Apr 1995)</td>
<td></td>
<td></td>
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<tr>
<td>Southwest monsoon 42</td>
<td>0.10-0.22*</td>
<td>1733-3538*</td>
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<tr>
<td>(Jul-Aug 1995)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northeast monsoon 43</td>
<td>0.01-0.31*</td>
<td>127-3180*</td>
</tr>
<tr>
<td>(Jan-Feb 1995)</td>
<td></td>
<td></td>
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<tr>
<td>(Oct Nov 1995)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bay of Bengal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall Intermonsoon 43</td>
<td>0.11-0.80</td>
<td>90-875</td>
</tr>
<tr>
<td>(this work)</td>
<td></td>
<td></td>
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<tr>
<td>(Sep-Oct 2002)</td>
<td></td>
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</table>

Sea where overhead productivity is high and the degradation of organic matter settling down consumes the oxygen leading to OMZ and denitrification zones. But the existence of OMZ (though not as intense as Arabian Sea) in BOB, where the overhead productivity is less, 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 measurements.

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**References**

SANJEEV KUMAR & RAMESH: PRODUCTIVITY MEASUREMENTS


