Signature of terrestrial influence on nitrogen isotopic composition of suspended particulate matter in the Bay of Bengal

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Nitrogen concentration and its isotopic composition in surface suspended matter have been measured at 24 different locations during the post-monsoon season in the Bay of Bengal. In general, the stable nitrogen isotopic composition of surface particulate organic nitrogen (PON) in the Bay of Bengal appears to be a mixture of particulate matter from the continent and marine phytoplankton, the latter having inherited the isotopic composition of deeper nitrate. Higher δ^{15}N values of surface PON in open ocean locations could be due to the supply of nitrate with higher δ^{15}N values. However, offshore locations have been diluted by the continental influence leading to low δ^{15}N values in PON.

PARTICULATE organic matter (POM), which mainly consists of phytoplankton, micro zooplankton and bacteria in the marine environment, plays an important role in cycling of bioavailable elements[1]. Due to its significant vertical transport, it enables the ocean to remove carbon dioxide from the surface layer and, in turn, from the lower atmosphere, to the deeper parts of the ocean or settle permanently as sediment on the ocean floor. The study of the nitrogen isotopic composition (δ^{15}N) of particulate organic nitrogen (PON) in suspended particulate matter provides an insight into the availability and utilization of nutrients such as nitrate, ammonia and urea in the euphotic zone. Several studies in this regard have been done in different parts of the world ocean[1–5]. Similar studies in the ocean sediments have been used for the reconstruction of past changes in surface ocean nutrient utilization[6–8]. In addition, sediment trap material has also been analysed in some cases[9]. To better understand the nitrogen isotope systematics in ocean sediments and sediment trap material, it is essential to measure directly the nitrogen isotopes in surface POM to either verify whether surface δ^{15}N is faithfully transmitted down to the sediment column[10] or to quantify the isotopic modification, if any[11]. For a general discussion on nitrogen isotope variations in marine particulate matter, reference is made to Sanjeev Kumar[12] and Kumar *et al.*[13].

We report the ^{15}N content of surface PON from the Bay of Bengal, collected during the fall intermonsoon (September–October) period, 2002. Earlier, Saino and Hattori[1] have reported a few values from this region (mainly from eastern Indian Ocean). We also investigate the observed relationship between PON and δ^{15}N, the processes responsible for variation in δ^{15}N and the possible role of riverine inputs in modifying the isotopic composition of PON.

Sampling was performed onboard *ORV Sagar Kanya* (SK-182), as a part of Bay of Bengal process study (BOBPS, Figure 1). Water samples were collected with a clean plastic bucket from sea surface. Two litres of sea surface water were filtered through a precombusted (400°C for 4 h) Whatman GF/F glass fibre filter of 47 mm diameter. After filtration, the samples were dried at 50°C and stored for isotopic analysis.

Nitrogen isotope ratio and PON were measured in the laboratory using a Carlo Erba elemental analyser interfaced via ConfloIII to a Finnigan Delta Plus mass spectrometer. For precise analysis, the method of Owens and Rees[14] with a modification in oxygen injection time was used. In this method, integration of ion beam areas (m/z 28 + 29 + 30) after the calibration against standard material (IAEA-NO-3, KNO_3) provided the measurement of PON. Since the 47 mm GF/F filter paper was used for the sample filtration, it was difficult to accommodate the whole filter paper in the inlet of the Elemental Analyser. Therefore, the filter paper was cut into two/four approximately equal parts for the analysis. The variability in PON measurement for the same sample was found to be around 10%. The reproducibility for isotopic measurements was 0.3‰ (standard IAEA-NO-3, KNO_3 yielded 4.91 ± 0.3‰ (1σ) for $n = 19$; IAEA quoted value 4.7‰). However, the variability in δ^{15}N and PON due to repeated analysis of the same samples was found to be more than the 0.3‰ (Table 1). This variation in isotopic composition may be either due to the small amounts of sample measured or to heterogeneity in the sample itself as seen earlier[1]. The ambient nitrate concentration (limit of detection 0.1 μM) was measured using column reduction technique[15].

Table 2 gives an account of PON concentrations and the δ^{15}N values along with the locations of 24 different samples. These locations fall in two transects: one parallel to

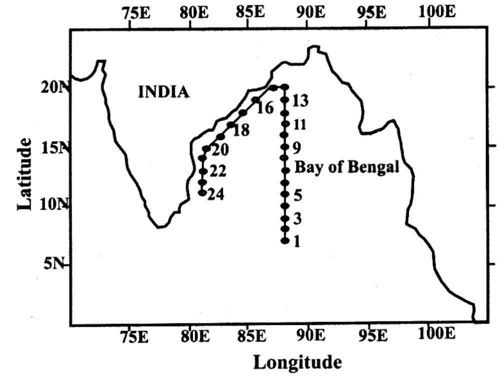

Figure 1. Cruise track of SK-182 showing sample locations.

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Table 1. Low reproducibility of δ^{15}N (average ~0.3‰) for some samples indicating the sample heterogeneity

CTD station	Sample depth (m)	Fraction of filter paper used for analysis	PON (μM)	Mean PON (μM)	δ^{15}N (‰)	Mean δ^{15}N (‰)
3	20	0.25	0.95	0.92 ± 0.08	7.0	5.8 ± 0.9
		0.25	1.02		4.9	
		0.25	0.89		5.6	
		0.25	0.83		5.7	
	40	0.5	0.55	0.53 ± 0.02	5.9	7.9 ± 0.2
		0.5	0.51		9.8	
	60	0.25	0.54	0.54 ± 0.03	4.8	3.4 ± 1.0
		0.25	0.55		3.0	
		0.25	0.58		3.0	
		0.25	0.51		2.7	
9	Surface	0.25	0.89	0.89	1.5	2.1 ± 0.6
		0.25	0.89		2.7	
12	Surface	0.25	0.79	0.92 ± 0.13	1.1	1.8 ± 0.7
		0.25	1.04		2.5	
20	40	0.25	1.63	1.44 ± 0.17	0.1	–0.2 ± 1.5
		0.25	1.39		1.1	
		0.5	1.31		–1.9	

Table 2. PON and δ^{15}N values of the samples along with locations

CTD station	Latitude (°N)	Longitude (°E)	PON (μM)	δ^{15}N (‰)
1	7	88	1.6	6.6
2	8	88	1.91	5.3
3	9	88	2.01	7.6
4	10	88	1.0	2.1
5	11	88	0.92	3.8
6	12	88	0.79	3.9
7	13	88	1.78	6.5
8	14	88	1.9	7.0
9	15	88	0.88	2.6
10	16	88	2.08	6.2
11	17	88	1.84	3.0
12	18	88	1.03	2.5
13	19	88	1.63	4.5
14	20	88	1.21	3.0
15	20	87	2.51	4.9
16	19	85.3	1.35	3.0
17	18	84.5	1.44	3.0
18	17	83.5	1.51	2.0
19	16	82.5	1.11	4.9
20	15	81.5	0.89	2.3
21	14	81	1.08	2.0
22	13	81	1.15	3.1
23	12	81	0.87	3.5
24	11	81	1.25	4.4

the Indian coast (CTD14 to CTD24), called the off-shore transect, and the other, along 88°E longitude (CTD1-CTD13), called the open ocean transect. Overall, PON ranges from 0.89 to 2.51 μM. δ^{15}N values range from 2‰ to a maximum of 7.6‰ and lie between the known oceanic δ^{15}N ranges for PON.

The variability in the data set listed in Table 2 may be viewed from two different aspects. One in terms of variability from south to north in general, and the other as off-shore and open ocean transects. Figure 2 *a* shows variability in PON with latitude. There seems to be no systematic relationship between the two ($r^2 = 0.01$). PON values of open ocean stations, in general, are higher than those for the corresponding off-shore locations at the same latitude except at two locations (11°N and 18°N). However, the maximum PON of 2.51 μM was observed at CTD15, which is a off-shore station and the closest to the coast with the shallowest station depth of 620 m.

The observed latitudinal variation in δ^{15}N (Figure 2 *b*) also does not follow any significant trend ($r^2 = 0.14$), although it shows a general decrease in δ^{15}N for higher latitudes. As observed in the case of PON, for δ^{15}N also the values of open ocean locations are higher than those of off-shore stations except at 11°N and 18°N, where off-shore values are higher than those of open ocean.

Figure 3 shows a positive linear correlation between PON and δ^{15}N ($r^2 = 0.41$). Off-shore stations show less variability and the data points lie in the lower regime, i.e. low δ^{15}N and low PON. On the other hand, the open ocean transect shows two clusters with low PON–low δ^{15}N (average ~3‰) and with high PON–high δ^{15}N (average ~6‰).

In general, the following observations for the PON–δ^{15}N relationships can be made in this study: (i) there exists a positive relationship between PON and δ^{15}N, (ii) low PON–low δ^{15}N for off-shore transect locations, and (iii) two-cluster relationship between the two in the open ocean transect.

δ^{15}N data (Table 2) overrules the possibility of N_2 fixation as such in the region. N_2 fixers, such as cyanobacteria *trichodesmium*, exhibit low δ^{15}N value around[16,17] –2 to 0‰. All the values found in this region are far above the required value for an area dominated by N_2 fixers. Also, preferential removal of ^{15}N enriched nitrogen by sinking matter[18] does not seem to occur in this region, as the $\delta^{15}N$ values of sinking particles are in the range[9] of 2.2–6.2‰, which is comparable to the observed values in the suspended particles during this study.

The Bay of Bengal (BOB) is a region where surface nitrate is depleted (around ~0.2 μM during study period) and often falls below the detection limit (0.1 μM). Higher $\delta^{15}N$ values in such regions may be attributed to two different reasons: first, uptake of regenerated ammonia without fractionation[3]; and second, supply of nitrate from deeper waters due to presence of shallow nitracline, which is between[19] 50 and 100 m. Nitracline at these depths may be considered shallower compared to the Atlantic Ocean where it varies[20] from 30 to 170 m. In the first case, due to nutrient-poor conditions, as soon as regeneration of ammonia takes place, it is rapidly taken up by the algae present. In such a case, there is little time left for isotopic fractionation to take place and the nitrogen isotopic composition of NH_4^+ is imprinted in PON without much modification. Rise in $\delta^{15}N$ due to this process may be observed by assessing the *f*-ratios (ratio of new to total production)[21]. If the *f*-ratios are smaller, there could be a possible effect of the regenerated ammonia on the $\delta^{15}N$ of PON. In fact, *f*-ratio more than 0.5 has not been frequently observed in mesotrophic conditions[22,23]. Therefore, there is a possibility of both nitrate and ammonia signatures on PON in such waters. But in BOB during September–October 2002, higher new production has been observed during our study[24]. Therefore, regenerated ammonia seems to have played a limited role in higher $\delta^{15}N$ of PON.

The values reported here are in agreement with the $\delta^{15}N$ values reported for nitrate in deeper waters (~3–7‰)[25], implying that there could be supply of nitrate from waters below the nitracline because of it being shallow[20]. This supply may be one of the causes of higher productivity and biomass observed in the region during the same cruise[24]. Absence of measurable nitrate in the surface water indicates that as soon as it upwells to the surface, it is consumed quickly by the algae. The consumption is fast enough to leave no time for isotopic fractionation to take place and the original ^{15}N signal of nitrate is mirrored in the ^{15}N of PON[16,26]. The exact mechanism by which these nutrients reach the surface is a subject of speculation. In the case of BOB, this phenomenon may not be a steady state process, it may have strong influence of season and continental inputs. BOB is the northeastern part of Indian Ocean and its uniqueness lies in the amount of freshwater it receives (1.6×10^{12} m^3 y^{-1}) from the six major rivers draining

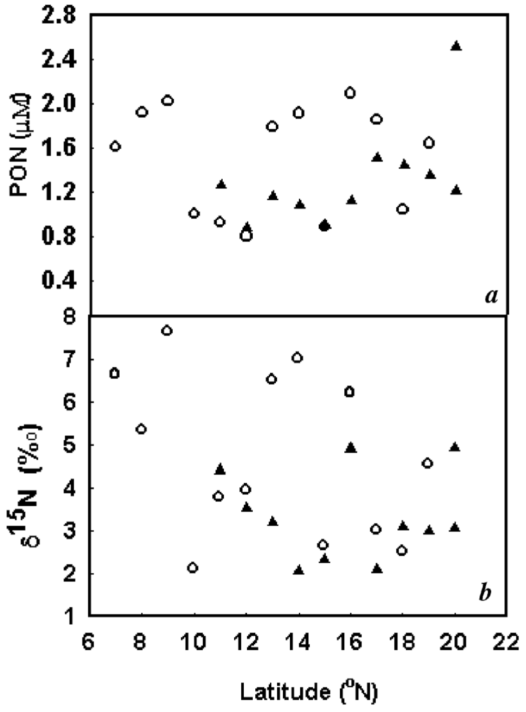

Figure 2. Variation of (*a*) PON concentration and (*b*) $\delta^{15}N$ values of surface PON with latitude (O: open ocean stations and ▲: off-shore stations).

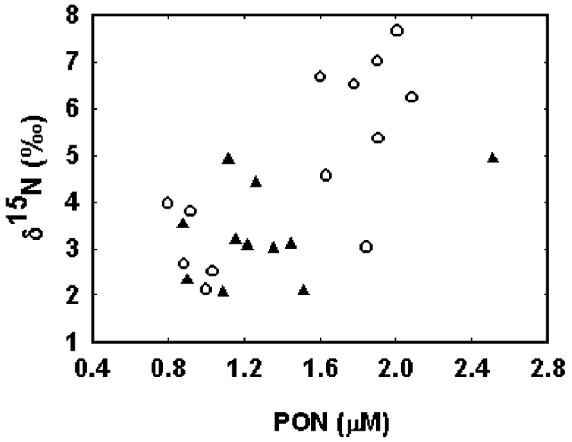

Figure 3. Relationship between PON and $\delta^{15}N$ (O: open ocean stations and ▲: off-shore stations).

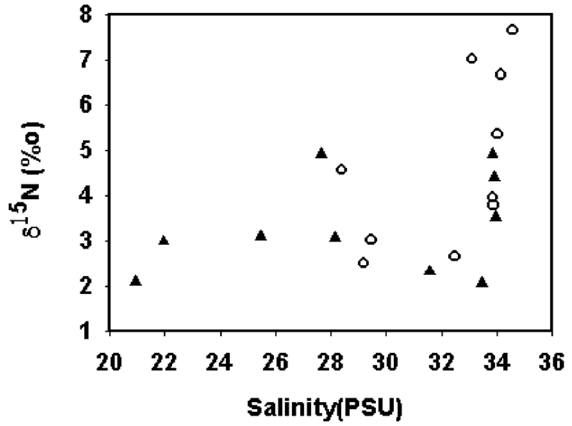

Figure 4. Relationship between $\delta^{15}N$ and salinity (O: open ocean stations and ▲: off-shore stations).

into it. This causes the surface BOB to be strongly stratified. Under normal circumstances, winds over BOB are not able to evade the stratified layer, thus inhibiting nutrient-rich lower waters from coming up[19]. But this scenario may not be true for the year 2002 when southwest monsoon over India failed (~20% less rainfall than the normal according to India Meteorological Department) leading to reduced discharge of freshwater from major rivers to the Bay. This reduced discharge might have caused the stratification to be less intense enabling the strong winds (cyclone in some cases) to break the barrier and bring nutrients to the surface. It is quite possible that the kind of $\delta^{15}N$ signal observed in the years of failed monsoon may not be true for the years that have received normal or excess rainfall. In the former case, supply of nitrate from the waters below thermocline appears to play a more vital role than that of ammonia.

In general, the off-shore locations have relatively lower $\delta^{15}N$ (<4.5‰) except at two stations (CTD15 and CTD19) where the values are 4.9‰. These lower values may be attributed to the contribution of terrestrial sources to the PON. The terrestrial particulate matter, brought by major rivers, due to its lower $\delta^{15}N$ values might have diluted the overall $\delta^{15}N$ signal of PON, although there exists no literature regarding the $\delta^{15}N$ of particulate matter draining into the Bay of Bengal. Overall, the $\delta^{15}N$ values of PON observed in the Bay may be explained in terms of mixing of terrestrial particulate matter with low $\delta^{15}N$ (which has more influence on off-shore locations), and the marine phytoplankton (which has inherited the higher $\delta^{15}N$ of nitrate from deeper waters). This is seen clearly in Figure 4, where $\delta^{15}N$ is plotted against salinity.

To investigate the $\delta^{15}N$ as proxy of productivity[20] we plotted our productivity data[24] with $\delta^{15}N$ values of PON observed during the same study. There seems to be a significant positive correlation with $r^2 = 0.59$ (Figure 5) excluding two out of nine data points, in agreement with the relationship observed by Mino *et al.*[20] for oligotrophic waters. The excluded data are for the southernmost stations with highest surface nitrate values and moderate $\delta^{15}N$ value (3.5‰). It is difficult to assess whether the moderate $\delta^{15}N$ value at these two stations is due to the partial utilization of nitrate or due to terrestrial influence. The goodness of fit (r^2) falls drastically down (0.23) with the inclusion of excluded (two) data points. Based on this study we infer that for stations north of 12°N, nitrate has contributed significantly in biological productivity and to the $\delta^{15}N$ values of PON.

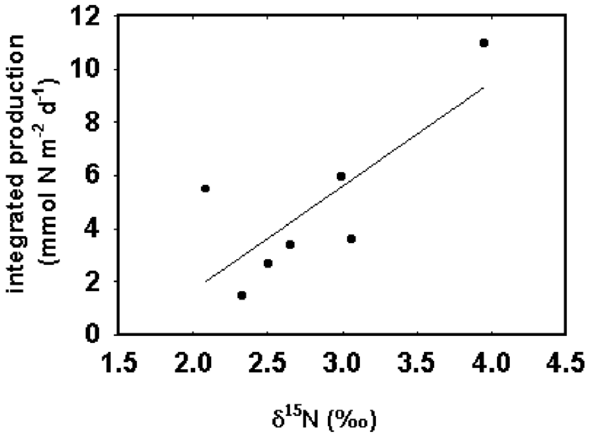

Figure 5. Relationship between integrated production and $\delta^{15}N$.

The measurements of nitrogen isotopic composition of PON in BOB during post-monsoon reveals the mixing between continental input and marine phytoplankton, the latter having inherited the isotopic composition of the deeper nitrate without fractionation. The off-shore locations appear to have been diluted by the continental influence, leading to low $\delta^{15}N$ values to surface PON. In order to assess the degree of terrestrial influence on oceanic PON, the study of nitrogen isotopic composition in PON of river waters draining into the Bay is recommended.

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Meteorite falls over India during 2003: Petrographic and chemical characterization and cosmogenic records

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Two meteorite falls observed over India in 2003 led to the recovery of surviving fragments. The Kasauli meteorite that fell in northern India is a single fall, while Kendrapara meteorite is a multiple fall that covered a large coastal region of Orissa. Data for petrographic characteristics and chemical composition suggest that the two meteorites belong to the H group of chondrites, with Kasuali suffering a lesser degree of thermal metamorphism than Kendrapara during their residence in their parent bodies. Cosmogenic records indicate a large size (≥ 1 m) for the Kendrapara meteoroid that has spent ~5 million years in interplanetary space following its ejection from its parent body until its fall on the Earth. On the other hand, the Kasauli meteoroid spent an unusually long time (~37 Ma) in interplanetary space before its fall and lost ~80% of its original mass during atmospheric ablation.

METEORITES are some of the oldest remnants of the solar system available for laboratory studies. Primitive meteorites contain in them microscopic refractory objects that are considered to be some of the first solids to form in the solar system. Studies of these objects provide us insight into the processes governing the very early evolution of the solar system and also the mode of its probable origin[1]. Meteorite studies in general provide clues to understand the evolution of their parent bodies, primarily the asteroids and occasionally Mars and the Moon. They also provide information about the energetic environment in the interplanetary space where they spend a considerable period of time, ranging from less than a million years to a few tens of million years after being ejected from their parent bodies until their eventual fall on the Earth[2]. Thus any new fall of meteorite is an important opportunity for planetary scientists to further our understanding of some or all of the above aspects related to solar-system studies. The global meteorite collection has increased several folds during the past 35 years, due mainly to collections of a large number of meteorites from cold and hot deserts, where they are accumulating over thousands of years[3]. However, fresh falls of meteorites that are unaffected by terrestrial weathering processes are often better for a variety of investigations.

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