

Sources of organic matter and tracing of nutrient pollution in the coastal Bay of Bengal

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Abstract

Stable isotopic composition of carbon ($\delta^{13}\text{C}_{\text{POM}}$) and nitrogen ($\delta^{15}\text{N}_{\text{POM}}$) in the particulate organic matter (POM) is used to identify sources of organic carbon and nutrients using monthly time-series observation in the coastal Bay of Bengal (BoB). The hydrographic structure indicates that the coastal BoB is influenced by coastal upwelling during March-May, advection of peninsular river discharge during June to September and glacial (Ganges) river discharge during October to December due to reversing of East India Coastal Currents (EICC). C/N ratios in POM were mostly higher values than Redfield ratio in the study region indicating possible contribution of terrestrial origin. Enriched $\delta^{13}\text{C}_{\text{POM}}$ were found during March-May associated with coastal upwelling indicating major contribution of POM from the *in situ* production while lower values were noticed during June to September followed by October to December indicating influence of terrestrial sources. $\delta^{15}\text{N}_{\text{POM}}$ displayed strong inverse relation with salinity and linear relation with Chl-a suggesting that anthropogenic nutrients from the land increased coastal phytoplankton biomass. $\delta^{15}\text{N}_{\text{POM}}$ linearly decreased with increase in distance from the coast and reached to the typical offshore value of 6-6.5‰ indicating that terrestrial nutrients influence was spread up to a distance of 15 to 20 km from the coast in the study region. Our study suggested that coastal waters are influenced by terrestrial/anthropogenic nutrients and its impact can be noticed up to 15 to 20 km from the coast and its impact on Biodiversity Beyond National Jurisdiction may be negligible than hitherto hypothesized.

1. Introduction

Stable isotopic composition of carbon ($\delta^{13}\text{C}_{\text{POM}}$) and nitrogen ($\delta^{15}\text{N}_{\text{POM}}$) in suspended particulate organic matter (POM) is used to understand the sources and transformation pathways of organic matter in the aquatic environment (eg: Middelburg and Nieuwenhuize, 1998; Wada et al., 1987). Due to wide variability in $\delta^{13}\text{C}_{\text{POM}}$ and $\delta^{15}\text{N}_{\text{POM}}$, it is possible to distinguish the source of organic matter from terrestrial or marine origin (eg. Boutton, 1991; Fry and Scherr, 1984; Riera et al., 1999). This technique also suffers from several problems mainly associated with degradation of organic matter that modifies isotopic composition due to fractionation during this process (eg: Middelburg and Nieuwenhuize, 1998). In addition to this, $\delta^{13}\text{C}_{\text{POM}}$ is also influenced by the source of dissolved inorganic carbon (DIC) and its isotopic composition ($\delta^{13}\text{C}_{\text{DIC}}$) as it is taken up by the phytoplankton during photosynthesis and its signatures are reflected in the POM (eg: Popp et al., 1998; Keller and Morel, 1999). Similarly, $\delta^{15}\text{N}_{\text{POM}}$ displays wide variations mainly caused by varied sources of nutrients and internal cycling including nitrification, denitrification, N_2 fixation (Altabet et al., 1994; Brandes et al., 1998). For example, $\delta^{15}\text{N}_{\text{POM}}$ produced in the denitrification zone is high due to enrichment of $\delta^{15}\text{N}_{\text{NO}_3}$ during denitrification processes (Schafer and Ittekkot, 1995; Naqvi et al., 1998; Montoya and Voss, 2006).

Increased anthropogenic activities, resulting in pumping of sewage (domestic, agricultural and industrial) to the coastal waters, have severe impact on coastal ecosystem (Lotze et al., 2006; Reopanichkul et al., 2009; Nixon and Buckley, 2002; Diaz and Rosenberg, 2008; Oczkowski et al., 2009). One of the major sources of nitrogenous nutrient to the coastal waters comes from sewage (Costanzo et al., 2001; McClelland et al., 1997; Schlacher et al., 2005). $\delta^{15}\text{N}_{\text{POM}}$ can identify the source of nutrient, as it reflects the source of nutrient taken up, and it is significantly enriched ($>10\%$) for sewage and depleted for fertilizers ($0\pm 1\%$) (Cole et al., 2004; Heaton, 1986; Dailer et al., 2010; Fernandes et al., 2012). Based on the $\delta^{15}\text{N}$ signals in multiple taxa, Connolly et al. (2013) noticed that the impact of sewage can be noticed from coast to 15 kms offshore in the Adelaide coast (Southern Australia).

Several major rivers drain in to the Bay of Bengal (BoB), such as Ganges, Brahmaputra, Godavari, Mahanadi etc, and transport annually $1.6 \times 10^{12} \text{ m}^3$ of freshwater (UNESCO, 1979) and 1.1×10^9 tonnes of sediment (Milliman and Meade, 1983; Milliman and Syvitski, 1992). Significant agricultural activities undergo along the bank of these rivers due to availability of freshwater (Sarma et al., 2014) and therefore it is hypothesized that river waters may be contaminated with nutrients from the agricultural and sewage sources. The Central Ground Water Board (CGWB, 2012) reported that most districts in each Indian state where the concentration of nitrate in ground waters exceeded 45 mg/l,

above the permissible levels for drinking, and it is attributed in several place to use of agricultural fertilizers. Sarma et al. (2014) measured $\delta^{15}\text{N}_{\text{POM}}$ in the Indian estuaries during the discharge period and noticed enriched values in the highly polluted estuaries ($>10\text{‰}$) than unpolluted estuaries ($<6\text{‰}$). Nevertheless, estuaries are expected to bring pollutants to the coastal BoB, especially during monsoon period (June-September). BoBLME (2014) reported that major rivers, such as Ganges, Brahmaputra, Irrawady, Godavari etc, discharge freshwater along with untreated sewage into the BoB that lead to strong pressure on fisheries abundance in the BoB resulting in its depletion. Recently Bristow et al. (2017) hypothesized that nutrients come from the riverine sources may make BoB a dead zone due to increase in primary production and sinking carbon fluxes. United Nations released a report stating that the pollutants released by the neighbouring countries of BoB may be damaging Biodiversity Beyond National Jurisdiction (BBNJ) and studies are needed to prove their influence on ecosystem (www.un.org).

On the other hand, Naqvi et al. (2000) reported the formation of intense seasonal oxygen minimum zone (OMZ) along the west coast of India due to seasonal coastal upwelling and it is intensified due to release of fertilizers nitrogen to the coastal ocean leading eutrophication. In contrast, Gupta et al. (2016) observed at Kochi, in the southwest coast of India, that despite unprecedented urbanization in India, unchanged oxygen levels were reported in the west coast of India for the last 5 decades indicating little effect of human activities on formation of coastal OMZ. Gomes et al. (2014) noticed massive out-break of green *Noctiluca scintillans* in the northeastern Arabian Sea and suggested one of the possible causes to be release of untreated sewage from India and Pakistan. In contrast, Sarma et al. (2018a) noticed no tracers of sewage in the green *Noctiluca* bloom region in the northeastern Arabian Sea based on $\delta^{13}\text{C}_{\text{POM}}$ and $\delta^{15}\text{N}_{\text{POM}}$ and explained that change in direction of West India Coastal Currents (WICC), led to weak vertical mixing and less silicate supply, is responsible for formation of dinoflagellate blooms for a period of 10 days to two weeks. Therefore, it is hypothesized that released pollutants may confine close to the coast and its spread to the offshore region may be limited. The main aim of this study is to identify the sources of organic matter and nutrients using $\delta^{13}\text{C}_{\text{POM}}$ and $\delta^{15}\text{N}_{\text{POM}}$ in the POM in the coastal waters and evaluate how far from the coast these pollutants influence ecosystem.

2. Material and methods

Monthly seawater sampling was conducted on board a mechanized boat at 6 stations, from close to coast and 30 km offshore, in the coastal BoB, central east coast of India (Fig. 1). Surface water samples were collected for the period of 12 months (January to December 2018). Samples were also collected

from the major sewage channels in the Visakhapatnam city region, where discharge occurs to the coastal BoB, to examine the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ POM of sewage endmember. Pressure, temperature and salinity in the surface water was measured using a portable conductivity, temperature and depth (CTD) profiler (SBE 19 plus; Sea Bird Electronics, USA). Water samples were collected using 10 L Niskin bottles attached to a rosette (ECO rosette sampler, SBE, USA).

About 2-L of surface seawater sample was filtered through a GF/F filter (0.7 μm pore size; Advantec) and Chl-*a* retained on the filter was quantified following Suzuki and Ishimaru (1990) with the analytical precision of 0.04 mg m^{-3} . Total suspended particulate matter (SPM) was estimated by filtering 1 L of sample through 0.22 μm polycarbonate filter (Millipore) and dried at 60°C for 24 h and weight difference between before and after filtration is taken as the content of SPM. The concentration of nitrate was measured using colorimetric technique following Grashoff et al. (1985).

For measurement of content and isotopic composition of carbon and nitrogen of POM, about 1 L of water is filtered through pre-combusted (at 450°C for 12 h) GF/F filter (0.7 μm pore size, Whatman) under a gentle vacuum and dried at 60°C for 24 h. An aliquot of the filter was exposed to hydrochloric acid fumes for 12 h to remove traces of inorganic carbon and such treatment is not given for nitrogen analysis as it would significantly alter N isotopic composition (Goering et al., 1990; Bunn et al., 1995; Pinnegar and Polunin, 1999). The concentration and stable isotopic composition of carbon and nitrogen were measured using an isotope ratio mass spectrometer (IRMS; Delta V plus; Thermo Electron, Germany) coupled to elemental analyzer (Flash EA, Thermo) via a ConFlo IV interface. The concentration of carbon and nitrogen is reported as $\mu\text{g/l}$ and isotopic composition in δ notation calculated as follows.

$$\delta R = \left(\frac{X_{sam}}{X_{std}} - 1 \right) \times 1000 \text{ ‰}$$

where, ^{13}C for carbon (C) and ^{15}N for nitrogen are represented by R. X_{sam} is $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$ of sample for C and N respectively. Similarly, X_{std} denotes $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$ of standard for C and N respectively. For calibration, IAEA standards and internal standards, such as glutamic acid, alanine, and Organic Analytical Standard (OAS), were used for calibration. The long-term precision of the instrument is about $\pm 0.2\%$ for both C and N.

3. Results

3.1. Hydrographic features in the coastal Bay of Bengal

The temperature variability in the surface water showed classical seasonal feature with lower during winter (November to February) and higher during summer (June to October). Seasonal upwelling

occurs between March and May when cooler temperatures by 2 to 2.5°C was observed compared to summer (Fig. 2a). The mean temperature during March-May was $28.04 \pm 0.6^\circ\text{C}$ and it was $29.4 \pm 0.8^\circ\text{C}$ and $26.8 \pm 0.8^\circ\text{C}$ during summer (June to September) and winter (November to February) respectively. The waters are gradually warmed up from close to coast to the offshore during all seasons. The surface salinity displayed temporal variability with high salinity during March to June and decreased towards December with mean salinity of 33.4 ± 0.2 during former and $\sim 23.5 \pm 3$ during latter period (Fig. 2b). The high SPM concentration was observed during March to June (32 ± 2 mg/l) and it was decreased to 12 ± 4 mg/l during September to December (Fig. 2c). The SPM concentrations decreased from coast to offshore during entire study period. The concentration of nitrate was low during winter (< 1 μM) and it was increased to > 1 μM during March to September and decreased during October to December (Fig. 2d). The concentration of Chl-a was high from close to coast to 5 kms offshore and decreased gradually towards offshore. Higher concentrations of Chl-a were observed during March to June and October to November than other months (Fig. 2e).

3.2. Temporal and spatial variability in concentrations and isotopic composition of carbon and nitrogen in POM

The concentration of POC and PON varied between 18 to 85 $\mu\text{g/l}$ and 2.5 to 16 $\mu\text{g/l}$ respectively with higher concentrations during March to August compared to other periods (Fig. 3a,b). No clear gradient in concentration of POC and PON were observed between close to coast and offshore. The contribution of organic carbon and nitrogen to total SPM was ranged between 0.08 to 0.95% and 0.01 to 0.12% respectively with higher contribution was observed during October to December followed by March to April (Fig. 3c,d). The C/N ratio varied between 5.5 and 10.9 and close to Redfield (6.6) values were observed during January to March (5.5 to 7.7; mean 6.7 ± 0.6) and higher values were observed during other period (5.7 to 10.9; mean 8.4 ± 1.2). Increase in C/N ratio from coast to offshore was observed during January to October (Fig. 3e). The POC/Chl-a ratio varied between 22 and 128 and lower values were observed close to coast (up to 5-10 km) and increased towards offshore (Fig. 3f). The higher values (> 60) were observed during June to September and also in December.

The isotopic composition of carbon ($\delta^{13}\text{C}_{\text{POM}}$) varied between -27.4 and -20.7‰ and depleted values were observed during June to December compared to January to May with the lowest during July and August (Fig. 4a). Depleted $\delta^{13}\text{C}_{\text{POM}}$ values were observed close to the coast and increased towards offshore. $\delta^{15}\text{N}_{\text{POM}}$ varied from 5.2 to 9.6‰ and depleted values were observed between May and August. Enriched $\delta^{15}\text{N}_{\text{POM}}$ values were found close to the coast than offshore (Fig. 4b). Salinity displayed significant inverse relation with contribution of organic nitrogen ($r^2=0.64$; $p<0.001$) and

carbon ($r^2=0.62$; $p<0.01$) to the SPM during June to December and relation during other periods was not significant (Fig. 5a,b). Similarly salinity showed significant inverse relationship with $\delta^{15}\text{N}_{\text{POM}}$ ($r^2=0.60$; $p<0.001$) and $\delta^{13}\text{C}_{\text{POM}}$ ($r^2=0.55$; $p<0.001$) during June to December and this relationship was insignificant during other periods (Fig. 5c,d). The $\delta^{15}\text{N}_{\text{POM}}$ displayed inverse relation with distance from the coast but the slope of the relation was slightly higher for the data during January to June (slope=-0.04 and $r^2=0.86$; $p<0.001$) than July to December (slope=-0.03 and $r^2=0.88$; $p<0.001$) (Fig. 6). Though $\delta^{13}\text{C}_{\text{POM}}$ was decrease from coast to offshore, however this relation is statistically insignificant.

4. Discussion

The EICC flows from pole to equatorward between January and August and opposite direction during September to December (Varkey et al., 1996; Shetye et al., 1991; 1996) leading to significant impact on hydrographic structure of coastal BoB. The water column is weakly stratified during January to May, moderately stratified during June to September and highly stratified during October to December due to change in direction of coastal currents (Sarma et al., 2013; 2018b). This results in occurrence of coastal upwelling during March to May, influence of advection of freshwater discharge by peninsular rivers during June to September and major river Ganges during October to December (Sarma et al., 2018b). These events have variable impact on hydrographic structure, source of nutrients, organic carbon and phytoplankton biomass. Recently Sarma et al. (2018b) noticed that variations in the hydrographic features and dissolved inorganic carbon components are governed by the direction of EICC. Hence, the variability in content and isotopic composition of POM is discussed with reference major physical features.

4.1. Coastal upwelling

The occurrence of coastal upwelling associated with high phytoplankton biomass was reported earlier during March to May (Sasmal et al., 2005; Sasmal, 2007). However, the intensity of upwelling is weak and confined close to the coast due to stratification driven by fresh water inputs (Murty and Varadachari, 1968; Gopalakrishna and Sastry, 1985; Shetye et al., 1991). Existence of cool and high saline waters were observed during January to May from coast to the 30 km offshore, compared to other months. The waters were cool from coast to offshore during January and February due to blowing of cool winds from the northeast direction (Varkey et al., 1996), in contrast, water gradually warmed from coast to offshore during March to May indicating occurrence of coastal upwelling during this period. Increase in concentration of SPM was observed associating with coastal upwelling indicating that vertical mixing of water brought upper sediments to the water column. The concentration of SPM

was more than 3 times higher during March-May than October-November, when minimum in SPM was observed (Fig. 2c). The enhanced SPM during March-May indicates that upwelling of subsurface waters mixed surface sediments into the water column due to shallow shelf leading to increase in SPM. Upwelling brought nutrient rich waters from the subsurface resulting in increase in dissolved inorganic nitrate to 0.75 to $\sim 2 \mu\text{M}$ and it was higher close to coast and decreased towards offshore due to reduced influence of upwelling away from the coast (Fig. 2d). Significant increase in phytoplankton biomass (in terms of Chl-a) was observed associating with upwelling (Fig. 2e). Sasmal (2007) noticed a plume of high phytoplankton biomass in the central east coast of India associated with coastal upwelling during March-May. Increase in nutrients concentrations and Chl-a was also observed earlier in the study region during March-May (Sarma et al., 2013; 2018b). Though higher nitrate concentrations were observed up to 25 km from the coast, increase in SPM was noticed up to 30 km from the coast. This resulted in decrease in phytoplankton biomass from coast to offshore. The concentration of POC and PON were significantly higher during March to April than other periods. However, the contribution of organic carbon and nitrogen to the SPM was also double during March-May compared to that of January. This suggest that either enhanced *in situ* primary production or sedimentary organic carbon may be contributed to the POM pool during this period. The mean C/N ratio (7.5 ± 0.5) during March to May is slightly higher than that of Redfield ratio of 6.6 indicating that contribution of some fraction of sedimentary organic matter to the POM pool may be possible. Krishna et al. (2013) noticed higher C/N ratios (11 to 23) in the sediments in the study region suggesting that contribution of sediments possibly increased C/N ratios in the water column. The POC/Chl-*a* (wt:wt) ratio is used to identify source of organic matter in the aquatic environment (Cifuentes et al., 1988; Richard et al., 1997; Bentaleb et al., 1998). Low POC/Chl-*a* ratios are observed in the POM pool if the freshly produced organic matter contributed and vice versa in case of terrestrial organic matter. POC/Chl-*a* ratios of 40 to 50 (Montagnes et al., 1994) is expected if the entire POC is produced through *in situ* processes. The POC/Chl-*a* ratios during March to May varied between 15 and 85 (mean of 44 ± 20) indicating that significant fraction of POM pool is contributed by *in situ* production. The spatial variations in POC/Chl-*a* ratio, low close to coast to high in offshore, is caused by availability of nutrients, and phytoplankton groups contributing to the Chl-*a* (Fig. 3f). The higher POC/Chl-*a* ratio of 74 to 126 is reported in the cyanobacteria-dominated communities (eg: Lorenzoni et al., 2015; Satyendranath et al., 2009). Bharati et al. (2018) reported perennial dominance of microplankton (diatoms) in the study region due to availability of silicate. Therefore, the higher POC/Chl-*a* ratio indicates contribution of terrestrial organic matter in the study region. $\delta^{15}\text{N}_{\text{POM}}$ and $\delta^{13}\text{C}_{\text{POM}}$ varied between 5.8 to 8.2‰ (mean of 7.1 ± 0.9 ‰) and -24.6 to -21.4‰ (mean of -22.0 ± 1.3 ‰) respectively

during March-May and the mean values are close to that of marine isotopic signature of carbon (-23.2 ± 1) and nitrogen (5.9 ± 0.5) (Thornton and McManus, 1994; Galvan et al., 2008; Bristow et al., 2017) indicating that *in situ* production seems to be major contributor to the POM pool and enriched $\delta^{15}\text{N}_{\text{POM}}$ indicate some fraction of terrestrial nutrients input. The spatial distribution of $\delta^{13}\text{C}_{\text{POM}}$ indicate that it is depleted close to the coast and enriched towards offshore and vice versa for $\delta^{15}\text{N}_{\text{POM}}$ and this gradient is also consistent with the phytoplankton biomass suggesting enhanced variable phytoplankton uptake, sources of nutrients and organic matter might have caused the spatial difference. The higher Chl-*a* close to the coast indicate enhanced primary production that result in fixation of more ^{12}C resulting in depletion in $\delta^{13}\text{C}_{\text{POM}}$ close to coast. The linear relationship between Chl-*a* and $\delta^{15}\text{N}_{\text{POM}}$ ($r^2=0.47$; $p<0.001$) indicates that nutrients brought by river (terrestrial nutrients, which contains enriched isotopic value; Sarma et al., 2014) support phytoplankton biomass in the coastal BoB. The depletion in $\delta^{15}\text{N}_{\text{POM}}$ with distance from the coast indicates that the influence of terrestrial nutrients decreased from close to coast to the offshore (Fig. 6).

4.2. Advection river discharge from peninsular rivers

The EICC continued to flow from equator to poleward during June to September that bring water from southeast coast of India where several peninsular rivers, such as Godavari, Krishna, Penna and Cauvery, opened to the BoB and their discharge peaks during June to September (Ittekkot et al., 1994; Sarma et al., 2014). Enhanced SPM concentrations associated with river discharge was reported at off Mahanadi, Godavari and Krishna river mouths in the coastal BoB (Sarma et al, 2012; 2015). Krishna et al. (2015) reported that the flux of dissolved inorganic nitrogen to the coastal waters of $254 \text{ kgN km}^{-2} \text{ y}^{-1}$ from Godavari river whereas it was $8\text{-}36 \text{ kgN km}^{-2} \text{ y}^{-1}$ from other rivers in the southwestern India. Increase in concentration of nitrate was observed up to 10 km from the coast during June-August associated with increase in Chl-*a*, which is more prominent up to 3-5 kms from the coast (Fig. 2d,f). Enhanced Chl-*a* in the coastal waters, off river mouths, were reported during peak discharge period (July-August; Sarma et al., 2012; 2013) and attributed to discharge of nutrients by rivers. Though the increase in Chl-*a* during June to August was smaller compared to October-December that could possibly due to enhanced grazing pressure in response to upwelling during earlier months. Sarma et al. (2015) found enhanced concentrations of SPM associated with river discharge, at off Godavari river mouth, but significant fraction of SPM might have been deposited on to the shelf before it reaches to the study region. The sources of organic matter to the Godavari and Krishna estuaries were studied during different discharge periods and noticed that dominant terrestrial sources contribute to the POM during peak discharge period whereas *in situ* processes contribute significantly during moderate and

no discharge periods (Gawade et al., 2018; Babu et al., 2020). Therefore, discharge of riverine POM to the coastal waters is expected to contain significant contribution of terrestrial sources.

Like March-April, higher concentration of POC and PON were observed during June to August and the contribution of organic matter to SPM was also close to that of found during March (0.2 and 0.03% respectively) (Fig. 3a-d). The C/N ratios were slightly higher during June to September (8.5 ± 0.4) than March to May (7.5 ± 0.5) indicating that enhanced contribution from the terrestrial origin. The POC/Chl-*a* ratio was low (<50) close to the coast (up to 10 km) and increased to ~ 95 indicating that some fraction of the organic matter is contributed by terrestrial/riverine origin (Fig. 3f).

$\delta^{13}\text{C}_{\text{POM}}$ ranged between -26.5 and -25.0‰ during June to September with relatively lighter values close to the coast and heavier towards offshore by $\sim 0.5\text{‰}$ (Fig. 4a). Depleted $\delta^{13}\text{C}_{\text{POM}}$ is associated with decrease in salinity by 0.5 to 2.5 indicating that significant fraction of river-borne terrestrial organic matter brought to the study region by EICC (Fig. 4a). However, no significant relation was observed between salinity and $\delta^{13}\text{C}_{\text{POM}}$ during June to September. The $\delta^{15}\text{N}_{\text{POM}}$ varied in narrow range between 5.6 and 7.1‰ with enriched close to the coast and depleted towards offshore. The $\delta^{15}\text{N}_{\text{POM}}$ of the peninsular estuaries varied between 5 and 14.2‰ and relatively enriched values ($>10\text{‰}$) were observed in the heavily polluted estuaries during peak discharge period (Sarma et al., 2014) resulting in increase in the $\delta^{15}\text{N}$ close to the coast. Chl-*a* showed significant linear relation with $\delta^{15}\text{N}$ ($r^2=0.52$; $p<0.001$) suggesting that land derived nutrients seem to support coastal phytoplankton biomass during this period. Nevertheless, this study suggests that coastal BoB received significant fraction of terrestrial organic matter, mainly through peninsular rivers, during June to September.

4.3. Advection river discharge from Ganges river

The EICC reverses its direction and flows from pole to equatorward during September to December resulting in bringing of Ganges discharge waters from the northwestern BoB to the study region (Varkey et al., 1996; Shetye et al., 1991; 1996). Sarma et al. (2018b) noticed that low saline water advected from the northwestern coastal Bay to the study region associated with decrease in dissolved inorganic carbon and high Chl-*a* and suggesting that seasonal reversal in EICC controls dissolved inorganic carbon distribution in the coastal BoB. During the present study, low salinity of 21.5-25 is observed during October to December associated with low SPM and nitrate (Fig. 2). However, Chl-*a* concentration was high during October-December (Fig. 2e) due to existence of favourable conditions, such as low SPM, and stable water column, for phytoplankton growth (Sarma et al., 2012; Bandopadhyay et al., 2017). Rao et al. (1988) reported, based on distribution of clay mineralogy, that sediments from Ganges river does not reach to the Indian shelf as the major outflow of the Ganges is

eastward. Due to less SPM concentration in the waters, photic zone deepens resulting in increase in phytoplankton biomass. Sarma et al. (2012) noticed higher Chl-*a* associated with low nutrients and SPM during peak discharge period in the northwestern BoB. Despite high Chl-*a*, the concentration of POC and PON were not high (Fig. 3a,b) compared to other months (mainly March to August) however the contribution of organic carbon and nitrogen to SPM was the highest during this period (Fig. 3c,d). The C/N ratios were ranged between 7.2 and 10.2 and they are higher than traditional Redfield value of 6.6 indicating possible contribution from terrestrial origin (Fig. 3e). The POC/Chl-*a* ratio was varied between 25 and 120 and higher ratio was observed during December further indicate possible terrestrial sources (Fig. 3f).

$\delta^{13}\text{C}_{\text{POM}}$ showed weak spatial variability during October to December and it was $\sim -24.0\text{‰}$ during this period (Fig. 4a), which is slightly depleted than typical marine signatures of -23.2‰ (Thornton and McManus, 1994; Galvan et al., 2008), indicating possible sources from terrestrial origin, apart from *in situ* production, and it is consistent with the high phytoplankton biomass. $\delta^{15}\text{N}_{\text{POM}}$ relatively enriched by 1‰ in the coast than offshore indicating that possible sources of organic matter from the anthropogenic origin at close to coast (Fig. 4b). Ganges river is known to be highly polluted with reference to domestic and industrial pollution (O'Donnell and Talbot-Jones, 2018) and $\delta^{15}\text{N}_{\text{POM}}$ in the Ganges was reported to be 2.5 during wet period (Sarma et al., 2014). Despite dominant Ganges input during October-December due to change in direction of EICC, the enriched $\delta^{15}\text{N}_{\text{POM}}$ values may be either due to addition of pollutants in the enroute or enrichment of inorganic nitrogen and subsequent uptake of the enriched nitrate by phytoplankton enhanced $\delta^{15}\text{N}_{\text{POM}}$. The concentration of nitrate was low during October to December and fractionation of $\delta^{15}\text{N}$ would be more at lower nitrate concentrations. Ganges export significant amount of nitrate to the coastal BoB (Krishna et al., 2015) and its consumption by phytoplankton in the en route from northern BoB to the study region may enrich its isotopic composition. The uptake of such enriched nitrate by phytoplankton enhances $\delta^{15}\text{N}_{\text{POM}}$ during October to December. The salinity showed inverse relation with $\delta^{15}\text{N}$ ($r^2=0.38$; $p<0.05$), and linear relation with Chl-*a* ($r^2=0.48$; $p<0.001$) suggesting that river-borne nutrients, which are sourced from pollutants (O'Donnell and Talbot-Jones, 2018) seems to be supported phytoplankton biomass during this period.

4.4. Influence of input of pollutants to the coastal waters

Coastal regions are highly stressed with pollution from various sources such as pollutants (including domestic and agricultural) carried by rivers, direct discharge of pollutants from domestic and industrial sources. The anthropogenic nitrogen can seriously damage biodiversity, food web dynamics and

quality of habitat (Cloern, 2001; Deegan et al., 2012; Conley et al., 2009; Canfield et al., 2010). Krishna et al. (2015) reported that $254 \text{ kgN km}^{-2} \text{ y}^{-1}$ of inorganic nitrogen is exported to the coastal BoB through Indian rivers. Increase in phytoplankton biomass at off rivers mouths have been identified along the east coast of India (Sarma et al., 2012; 2013). However, offshore extent of anthropogenic nitrogen inputs is unknown along the Indian coast. The inverse relationship of %OC, %ON, $\delta^{13}\text{C}_{\text{POM}}$ and $\delta^{15}\text{N}_{\text{POM}}$ with salinity during June to December indicate that river discharge brings significant amount of terrestrial organic carbon and nitrogen to the study region (Fig. 5c,d). The isotopic composition of nitrogen is widely used to identify presence of sewage-nitrogen as its uptake by phytoplankton records its signatures in the PON. $\delta^{13}\text{C}_{\text{POM}}$ and $\delta^{15}\text{N}_{\text{POM}}$ suggests that major fraction of the POM pool is produced within the water column, therefore it is possible to identify possible utilization of anthropogenic nitrogen by the plankton. $\delta^{15}\text{N}_{\text{POM}}$ in sewage is heavier ($\sim 14 \pm 4\%$) close to the study region and similar enriched value was reported in the west coast as well ($15.8 \pm 1.6\%$; Sarma et al., 2018a) resulting in increase in $\delta^{15}\text{N}_{\text{POM}}$ due to uptake of sewage nitrogen by the phytoplankton and transferred to the other parts of the ecosystem through food web. The municipal sewage in the study region is collected to the tank and released to the coastal ocean after partial treatment resulting in enrichment in $\delta^{15}\text{N}_{\text{POM}}$ (Savage, 2005). $\delta^{15}\text{N}_{\text{POM}}$ was enriched close to the coast and depleted with distance from the coast. In order to examine the spatial variability in $\delta^{15}\text{N}_{\text{POM}}$, the data are plotted with reference to distance (Fig. 5). The mean $\delta^{15}\text{N}_{\text{POM}}$ during February to May (dry/no discharge period) were 7.3% and depleted to $\sim 5.9\%$ at a distance of 10-12 km with higher slope (-0.04 ; Fig. 5). Similarly, $\delta^{15}\text{N}$ during June to December (wet/discharge period) was 7.6% and depleted to 6.3% at 20-22 kms with lower slope (-0.03 ; Fig. 5) compared to dry period. The mean $\delta^{15}\text{N}_{\text{POM}}$ in the open ocean region (~ 200 km from the coast) was 6 to 6.2% (Sarma et al., 2019) suggesting that the impact of pollutant-based nitrogen impact can be noticed up to 10 to 20 kms from the coast in the study region. This study suggested that coastal waters are influenced by pollutants from the rivers, or direct inputs from domestic and industrial sources, however, this impact can be noticed up to 10-20 kms from the coast in the study region. Its impact may go further to the offshore in the region whereas large rivers, such as Ganges, Godavari, Mahanadi etc, rivers discharge to the coastal region and it may be possible to evaluate the extent of pollution impact towards offshore using similar technique in the entire east coast of India.

5. Summary and Conclusions

In order to examine the variability in sources of organic matter and nutrients with reference to discharge from different rivers, time-series observations were conducted in the coastal Bay of Bengal

(BoB) at monthly time-scale over a period of 12 months (January to December 2018). The hydrographic structure indicated that the direction of East India Coastal Current (EICC) controlled the water column stratification, nutrients inputs and phytoplankton biomass. Occurrence of coastal upwelling was noticed during March-May, when POM pool was mainly contributed by *in situ* production and sedimentary sources. During June to September, when EICC flows from equator to poleward, the study region is influenced by discharged from peninsular rivers. The EICC reverses its direction from pole to equatorward during October to December, and brings water from northwestern BoB, where Ganges river discharges. The C/N, POC/Chl-*a* ratios, $\delta^{13}\text{C}_{\text{POM}}$ and $\delta^{15}\text{N}_{\text{POM}}$ confirm that significant amount of terrestrial carbon and nutrients were brought to the study region from peninsular rivers during June to September and the Ganges river during October to December. Strong inverse relation of $\delta^{15}\text{N}_{\text{POM}}$ with salinity and linear relation with Chl-*a* indicating that anthropogenic nutrients from the land increased coastal phytoplankton biomass. $\delta^{15}\text{N}_{\text{POM}}$ linearly decreased with distance from the coast and reached to the typical open ocean value of 6-6.5‰ in the BoB indicating that terrestrial nutrients influence can be observed up a distance of 15 to 20 km from the coast. Our study reveals that coastal waters are contaminated by terrestrial/ anthropogenic organic carbon and nutrients up to 15-20 km from the coast, however, its impact on Biodiversity Beyond National Jurisdiction may be negligible than hitherto hypothesized.

Acknowledgement: We would like to thank Director, National Institute of Oceanography for encouragement and support. We appreciate the support given by project staff and boat personnel during sampling and filtration. The Ministry of Earth Science is thanked for funding this program through GEOTRACES program. We would like to appreciate the comments and suggestions given by three anonymous reviewers that improved the presentation of our results. This has NIO contribution number.....

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Legend to Figures

1. Map showing the station locations. The freshwater discharge by different rivers are also shown.
2. Temporal and spatial variability in a) temperature ($^{\circ}\text{C}$), b) salinity (psu), c) SPM (mg/l), d) Nitrate (μM) and e) Chl-a (mg m^{-3}) in the surface waters
3. Temporal and spatial variability in a) POC ($\mu\text{g/l}$), b) PON ($\mu\text{g/l}$), c) OC%, d) ON%, e) C:N ratio (dimensionless) and f) POC:Chl-a ratio (dimensionless) in the surface waters
4. Temporal and spatial variability in a) $\delta^{13}\text{C}_{\text{POM}}$ (‰) and b) $\delta^{15}\text{N}_{\text{POM}}$ (‰) in the surface water in the coastal BoB.
5. Relationship of salinity with a) contribution of organic nitrogen (%ON), b) organic carbon (%C), c) $\delta^{15}\text{N}_{\text{POM}}$ (‰) and d) $\delta^{13}\text{C}_{\text{POM}}$ (‰) in the study region during January to May (red closed circles) and June to December (black closed circles) in the surface waters. The regression equation was constructed based on June to December data (black closed circles).
6. Mean variations in $\delta^{15}\text{N}_{\text{POM}}$ (‰) with distance from coast during January to May (Blue) and June to December (Red) in the coastal BoB in the surface waters.

Figure 1:

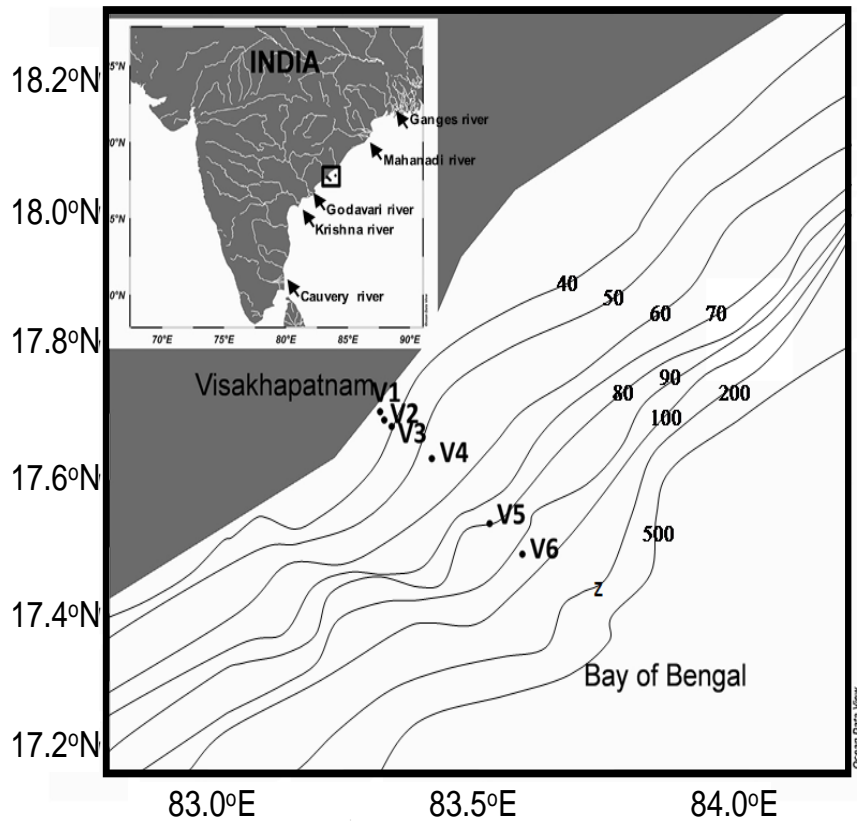


Figure 2:

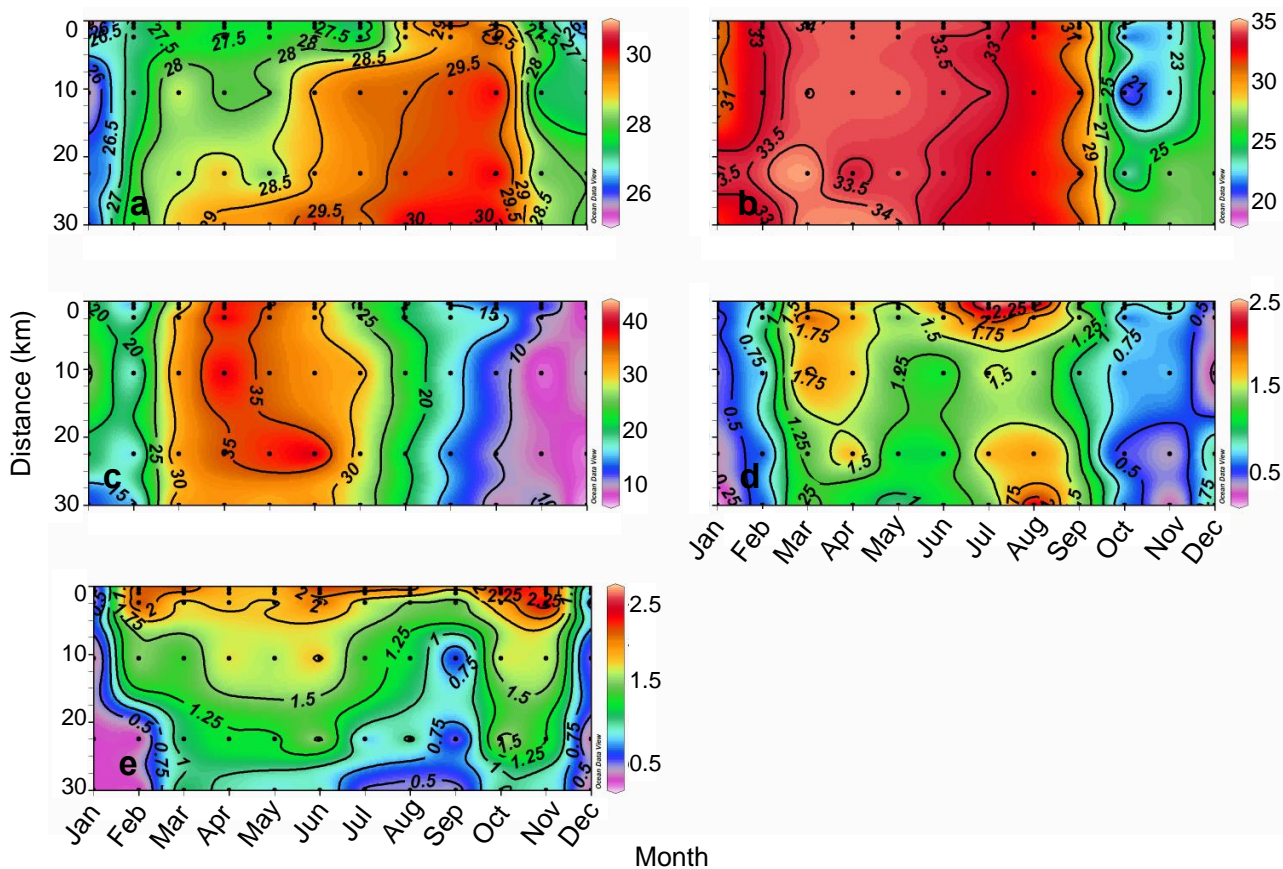
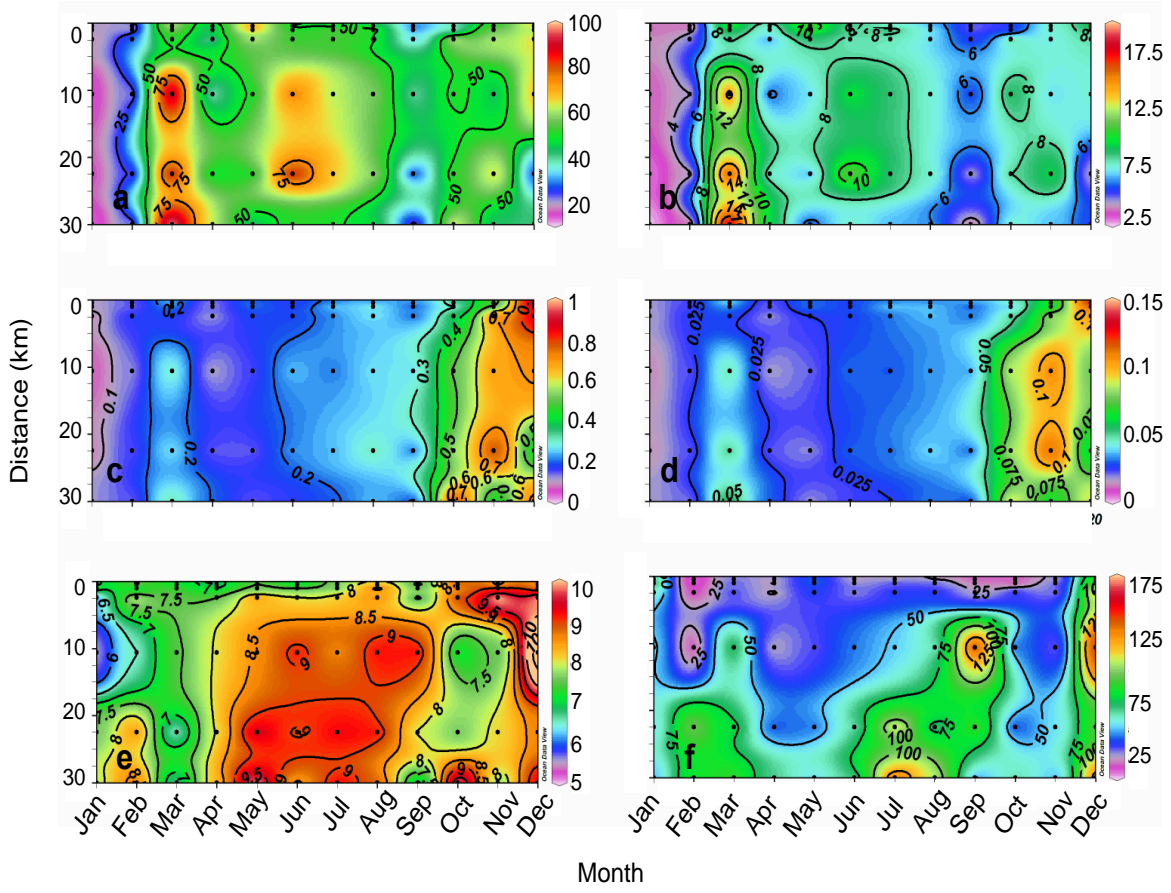


Figure 3:



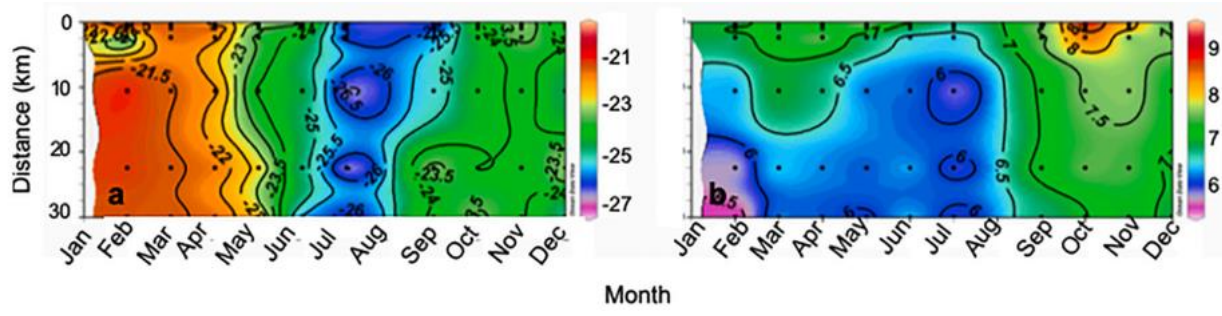


Figure 4:

Figure 5:

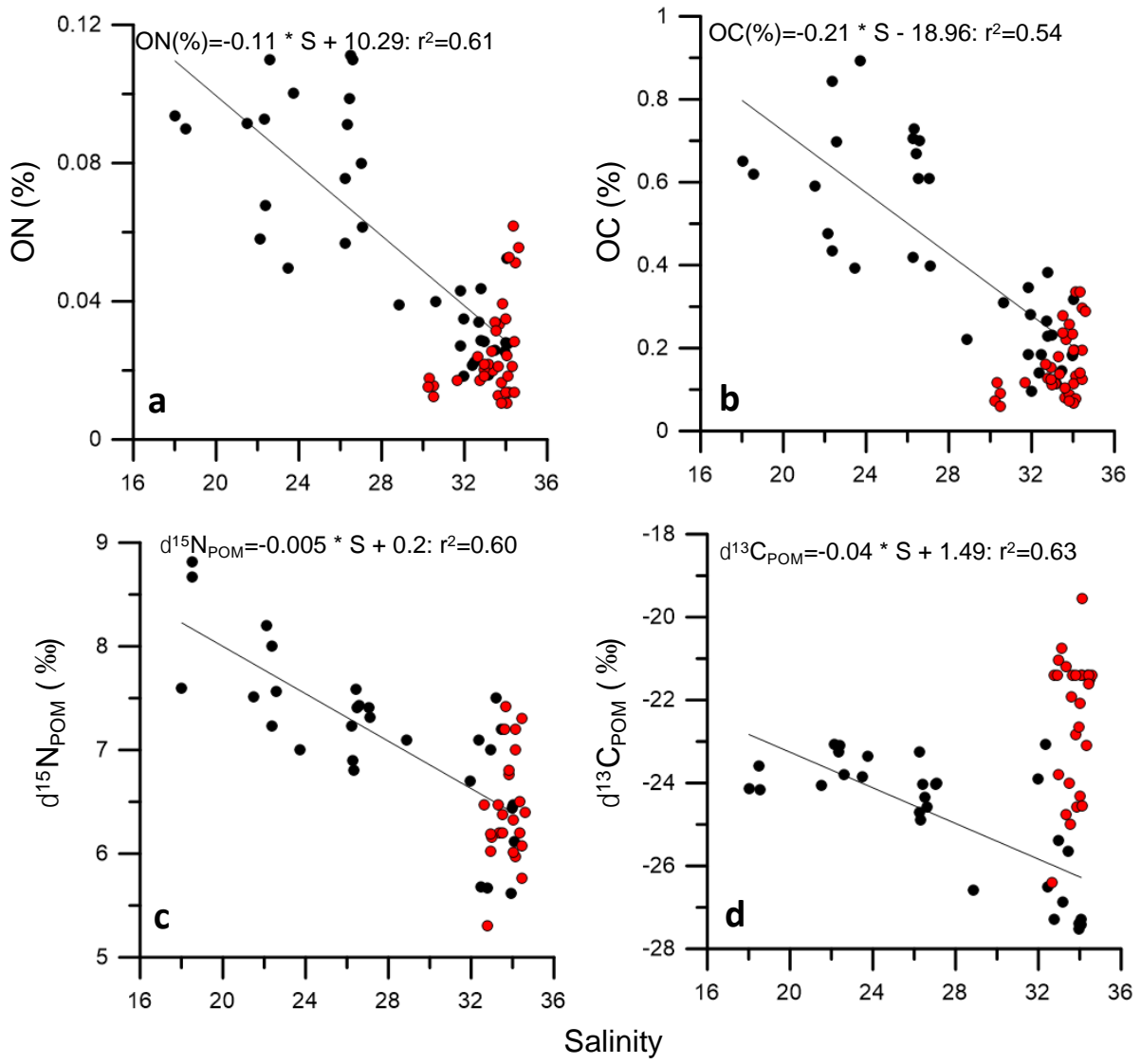


Figure 6:

