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ARTICLE

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Full Length Research Paper

Evidence for enhanced chlorophyll-a levels in the Bay of Bengal during early north-east monsoon

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To understand the chlorophyll-a distribution in the neritic waters of the northern Indian Ocean, which comprises the Arabian Sea on the west and the Bay of Bengal on the east, seawater samples were collected during early north-east monsoon season (November, 2008). The column integrated chlorophyll-a over the Arabian Sea and the North Bay of Bengal exhibit high concentrations. However, the southernmost station (0806) shows enhanced chlorophyll-a concentration compared to other stations in the south Bay (0807, 0808 and 0809). This is attributed to eddy pumping of nutrients from subsurface to surface waters of the Bay during the study period due to cyclonic conditions. This observation is further supported by the lack of nutrients in the surface waters at the other stations from the south Bay compared to the station 0806, which has high nutrient concentrations. The observed salinity in the Bay of Bengal shows a strong north-south gradient with higher salinity in the southern part of the Bay. The supply of nutrients through fluvial input (that is, dominantly from the northern region) is insignificant. The enhanced chlorophyll-a concentration over the farthest station (0806) can be either due to Eddy mediated biological production or lateral advective transport of nutrients.

Key words: Chlorophyll-a, Arabian Sea, Bay of Bengal, GEOTRACES, Eddies.

INTRODUCTION

The northern Indian Ocean (NIO) is a unique geographical location, comprising the Arabian Sea on its western side and the Bay of Bengal on the east, with

seasonal reversal of winds (North-East and South-West). These two basins distinctly differ in their physical and chemical properties. The Arabian Sea is a negative water

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body where evaporation exceeds precipitation and river runoff, thereby responsible for its high salinity (av. > 35), whereas the Bay of Bengal is a positive water balance region with precipitation and river runoff ($1.625 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$) (Subramanian, 1993) exceeding evaporation, making it less saline (av. > 35). The Arabian Sea is known as one of the most productive zones of the world oceans. This region accounts for a significant portion of global marine productivity. The high productivity zones in the Arabian Sea, are off Oman and Somalia (Morrison et al., 1998) along its west coast (that is, mostly due to the intense upwelling of nutrients during the south-west monsoon, June-September) and off Goa and Mangalore (Shetye et al., 1990) along the east coast of the Arabian Sea. The strong upwelling during the south-west monsoon season (June-September) and subsequent convective mixing (Kumar et al., 1996; Kumar and Prasad, 1996; Madhupratap et al., 1996; Kumar and Prasad, 1999; Barber et al., 2001) during the north-east monsoon (November-February) results in bringing the nutrient rich water from subsurface to surface (De Souza et al., 1981), thereby making this region more productive (Gauns et al., 2005) compared to its eastern counterpart, the Bay of Bengal.

On the other hand, the northern Bay of Bengal (BoB) is characterized by relatively low productivity during the south-west monsoon season compared to the Arabian Sea (AS), due to enormous freshwater discharge from the Ganga-Brahmaputra river system resulting in strong density stratification in the surface layers. Earlier studies on the air-sea exchange of CO_2 in the northern Indian Ocean also highlighted that the northwestern part of the Bay can act as a sink for atmospheric CO_2 (Kumar et al., 1996; Bhushan et al., 2000, 2003; Dutta and Bhushan, 2012). In addition, several other factors such as turbidity, intense cloud cover and narrow shelf region of the Bay makes this region low in productivity (Qasim, 1977; SenGupta et al., 1977; Radhakrishna et al., 1978; Gauns et al., 2005). However, evidence for the localized source of upwelling close to the southwestern boundary of the BoB during summer had been reported (Shetye et al., 1991). The stratification and low solar radiation during the monsoon periods result in low chlorophyll-a and primary productivity in the western BoB (Jyothibabu et al., 2008a) and the microzooplankton play an important role in transferring primary organic carbon from smaller phytoplankton to mesozooplankton (Jyothibabu et al., 2008b). During the south-west (SW) monsoon, the integrated chlorophyll-a is about a factor of 4-5 less in the Bay compared to that in the Arabian Sea (Prasanna Kumar et al., 2002). It has also been observed that primary productivity during the SW-monsoon season in the Arabian Sea is about a factor of 8 more compared to that in the BoB (Prasanna Kumar et al., 2002). In contrast, during North-East monsoon season, the Bay is typically characterized by high productivity compared to that in summer owing to thin freshwater lens at the

surface, which can be churned by the relatively weaker monsoonal winds ($\sim 5 \text{ m/s}$). The role of Eddies in enhancing the productivity over the Bay has been highlighted in several studies (Narvekar and Prasanna Kumar, 2006; Kumar et al., 2007; Vidya and Kumar, 2013). Albeit, there exist a difference in terms of the abundance of chlorophyll-a and fixation of carbon during primary production. The sediment trap measurement has shown that both basins have a comparable rate of export fluxes for organic carbon (Ramaswamy and Nair, 1994). The Bay of Bengal does not exhibit large-scale seasonal and spatial variability in phytoplankton standing stock and production (Madhu et al., 2006). Further, a recent study has observed that the redox-sensitive elements in the Arabian Sea and the Bay of Bengal region behave conservatively and the distribution of these elements is governed by physical processes of advection and mixing between water masses and evaporation and not by biogeochemical processes operating in the water column (Singh et al., 2011; Goswami et al., 2012).

The present study is a part of the international GEOTRACES initiative for the measurement of trace elements and their isotopes in the northern Indian Ocean, a cruise (SS-259) onboard FORV Sagar Sampada. This research aims to study here the distribution of chlorophyll-a (representative of plankton biomass) and nutrients during the early north-east monsoon season (November, 2008). This is in order to understand or at least identify the governing factors responsible for the observed chlorophyll-a distributions in the neritic waters of the Arabian Sea (AS) and the Bay of Bengal (BoB) during NE-monsoon season. Figure 1 depicts the cruise track of the research expedition (that is, SS-259) during 8-30th November 2008 along with the stations occupied for the hydrographic parameters that include dissolved oxygen, pH, salinity, and nutrient depth profiles. The whole data set is divided into two groups (A and B), with A referring to samples collected over the Arabian Sea leg during the cruise, which includes stations 0802, 0803 and 0805, whereas the remaining stations, named as B region, seawater samples were collected from the Bay (Figure 1). During the study period, the surface level winds were predominantly from north-easterly in direction and the average surface level wind vectors are depicted in Figure 2.

MATERIALS AND METHODS

All hydrographic measurements were made onboard FORV Sagar Sampada during the study period. Water samples were collected for the dissolved oxygen, chlorophyll-a, nutrients (such as NO_3^- , NO_2^- , PO_4^{3-} and SiO_4^{4-}), salinity, pH and alkalinity using a Sea-Bird Electronics CTD rosette system, equipped with 12-L Niskin bottles. The analytical protocol followed for measuring these parameters are discussed in the subsequent sections. The deep (depths up to 50 m above the maximum water depth) and shallow (depth less than 200 m) cast samples were analyzed for salinity on Autosol (Guildline 8400B Autosol). Seawater temperature data were

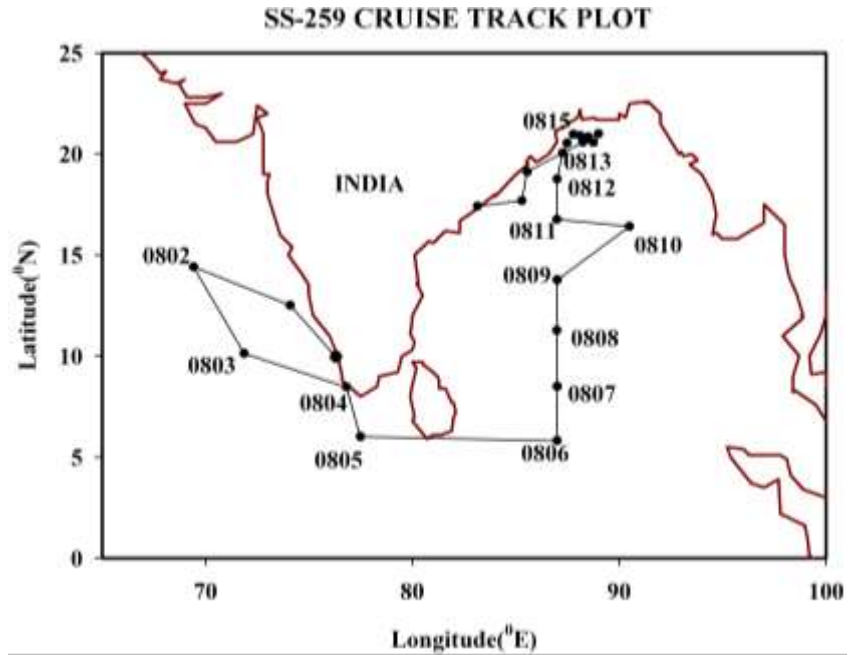


Figure 1. Cruise track of SS-259 (November 2008) along with the sampled stations for hydrographic parameters.

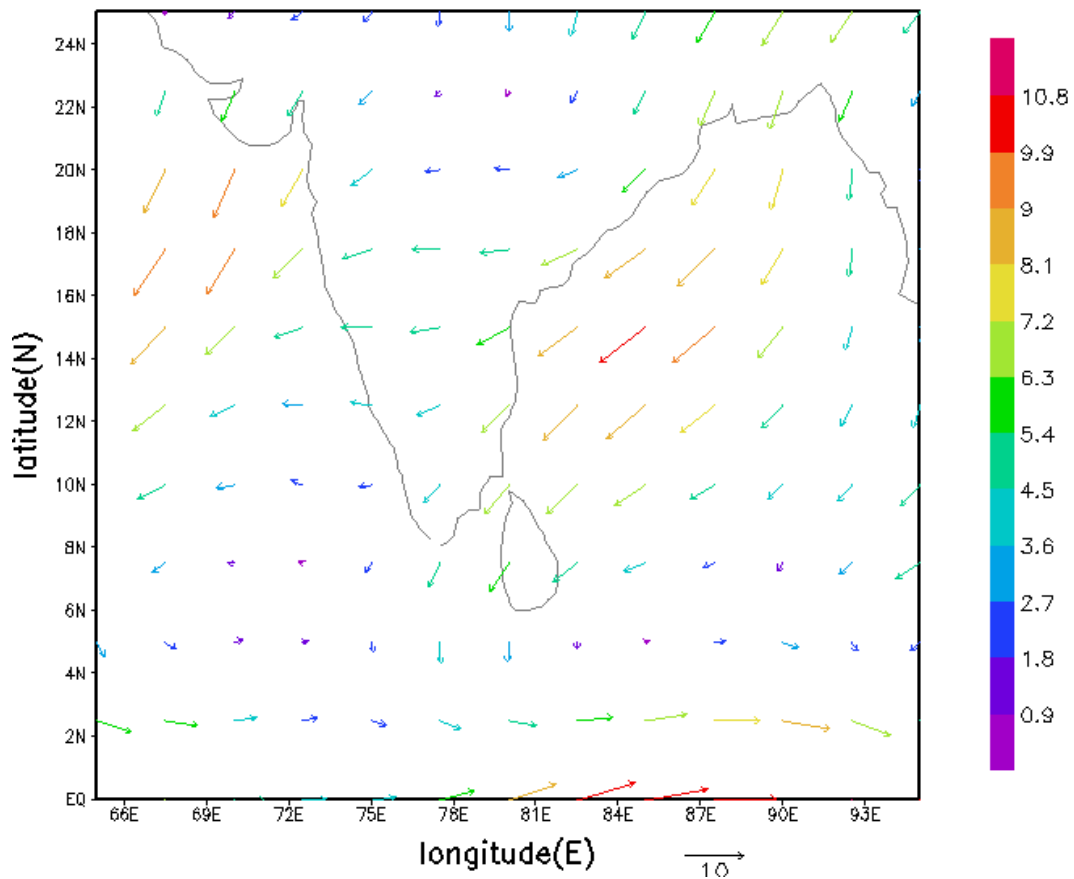


Figure 2. Monthly surface level wind vectors during November 2008 over the northern Indian Ocean.

obtained from the CTD after the hydrocast. Samples were subsequently analyzed for pH with a pH meter. The periodic calibration of pH meter (WT-W series Lab-pH720) was done using known standards of pH 4.2, 7.0 and 9.0. However, for alkalinity measurement, pH meter is combined with Dosimat auto-titrator (Metrohm) and titrated with 0.01 N HCl to pH 4.3 (HCO_3^- endpoint).

Chlorophyll measurements

For chlorophyll-a measurement, water samples were collected from 8 discrete depths (0, 10, 20, 30, 50, 75, 100 and 120 m). These depths were selected to cover the euphotic zone (that is, a well-ventilated zone for primary production or plankton biomass). An aliquot of 2 L of seawater is filtered through 0.7 μm pore size Whatman GF/F filters. Prior to filtration of the water sample, 1 ml of 1% MgCO_3 suspension is added to the filters as it could prevent acidification of extract and, thereby, prevent the formation of pheophytin. After the filtration, filter papers are dried under suction for 1 to 2 min and carefully transferred to (pre-soaked 90% acetone washed) a screw cap test tubes; thereafter, 10 ml of 90% acetone was added to it. These test tubes are vigorously shaken and covered with aluminium foil to prevent light penetration and kept in the refrigerator for 15 to 20 h. Further, the extract is transferred into pre-cleaned 90% acetone soaked centrifuge tubes and centrifuged at 2400 rpm. The supernatant solution is transferred to another test tube and the solutions made up to 10 ml with 90% acetone and analyzed for the determination of chlorophyll-a on a spectrophotometer (Shimadzu, Model-UV 1650PC) following the standard procedures for measurement and calibrations (Parsons et al., 1984).

Nutrients measurements

Seawater samples were analyzed for nutrients (NO_3^- , NO_2^- , PO_4^{3-} and SiO_4^{4-}) using SKALAR Autoanalyzer. All the primary stock standard solutions were prepared by carefully weighing the suitable amount of purified salts (obtained from Merck) and dissolved in ultrapure deionized water (Millipore Co., specific resistivity > 18.2 $\text{M}\Omega\text{-cm}$). These stock solutions were used to prepare the calibration standards in nutrient analysis during the study period. The analytical protocols followed for the analysis of nutrients are similar to the standard methods (Grasshoff et al., 1999).

Dissolved oxygen measurements

To determine the dissolved oxygen (DO) concentration in seawater, samples were collected in 60-ml glass bottles (with stopper) through a glass nozzle with PVC tubing to minimize air contamination. While sampling, care was taken to ensure negligible contact of the sample with air and no air bubbles were trapped in the glass bottle. Prior to the sampling, the sampling glass bottles were calibrated to ascertain its exact volume gravimetrically before the cruise. The dissolved oxygen in the water samples was measured using the classical Winkler's method. The method involves the addition of Winkler A and Winkler B reagents immediately after collection for the precipitation of oxygen (that is, brown coloured precipitate as $\text{MnO}(\text{OH})_2$) from the sample. After vigorous shaking, the bottles were kept in dark in order to avoid light penetration until measurement. The measurement of DO is performed after 8 to 15 h. Prior to the measurement, DO bottles were acidified with approximately 1 ml of 50% H_2SO_4 solution to dissolve the precipitate. The liberated oxygen oxidizes the excess iodide ions in the acidic medium into iodine, which subsequently complexes with

iodide ions to form I_3^- complex. This I_3^- in solution is decomposed to iodine while titrating with 0.001 N thiosulphate solution. The amount of thiosulphate consumed corresponds to amount of iodine liberated, which in turn will depend on the amount of dissolved oxygen concentration present in the solution. The detailed description of reagent preparations and analytical method is adopted from JGOFS (Knap et al., 1996).

RESULTS AND DISCUSSION

At all stations, near zero concentrations of nutrients were observed at the surface and increased with depth. Typical vertical profiles of nutrients and dissolved oxygen at 0802, 0806 and 0809 were given in Figure 3. The dissolved oxygen concentrations (Singh et al., 2011) in the surface seawater during this cruise ranges from 201 – 254 $\mu\text{mol L}^{-1}$ (or 4.5 - 5.7 ml L^{-1}). The oxygen minimum zone (OMZ) is characteristic of a typical depth range where oxygen concentrations are substantially low due to biological degradation of organic matter in the water column. In the present study, the oxygen minimum zone (OMZ) is at a depth range of 200 - 1000 m in the Arabian Sea, whereas it is observed in between 200 m and 800 m in the Bay of Bengal. Numerous studies have suggested that the columnar primary productivity in the Arabian Sea is higher compared to that in the Bay of Bengal (Gauns et al., 2006). Consequently, remineralization of sinking organic matter in the Arabian Sea might have contributed to not only the relative increase in consumption of dissolved oxygen during bacterial respiration in the intermediate waters but also expanding the extent of OMZ. Therefore, relative increase in depth range of OMZ in the Arabian Sea compared to the Bay of Bengal could be due to differences in the water-column primary productivity, which is also reflected in the column-integrated chlorophyll-a levels during the study period.

At station 0802, severe suboxic conditions were observed (Dissolved oxygen concentration < 10 $\mu\text{mol/Kg}$, Figure 1). Below the OMZ, dissolved oxygen concentrations increased significantly. The high dissolved oxygen concentrations in the surface waters are mainly due to its contact with atmosphere whereas degradation of sinking organic matter in the intermediate water column is responsible for the low oxygen concentrations in the OMZ. As observed during this cruise, the chlorophyll-a concentrations in the surface waters of the Arabian Sea varies from 0.06 to 0.43 mg m^{-3} (Group A region), whereas it was found to be 0.01 to 0.23 mg m^{-3} (Group B region) over the Bay of Bengal during the early north-east monsoon (November 2008). The column integrated chlorophyll-a concentrations over these two adjacent marine regions (BoB and AS) are comparable in magnitude during the study period. The column integrated chlorophyll-a concentrations range from 2.2 to 22.8 mg m^{-2} in the Arabian Sea and 2.0 to 26.3 mg m^{-2} in the Bay of Bengal as shown in Figure 4. It is evident from Figure 4 that the column integrated chlorophyll-a levels

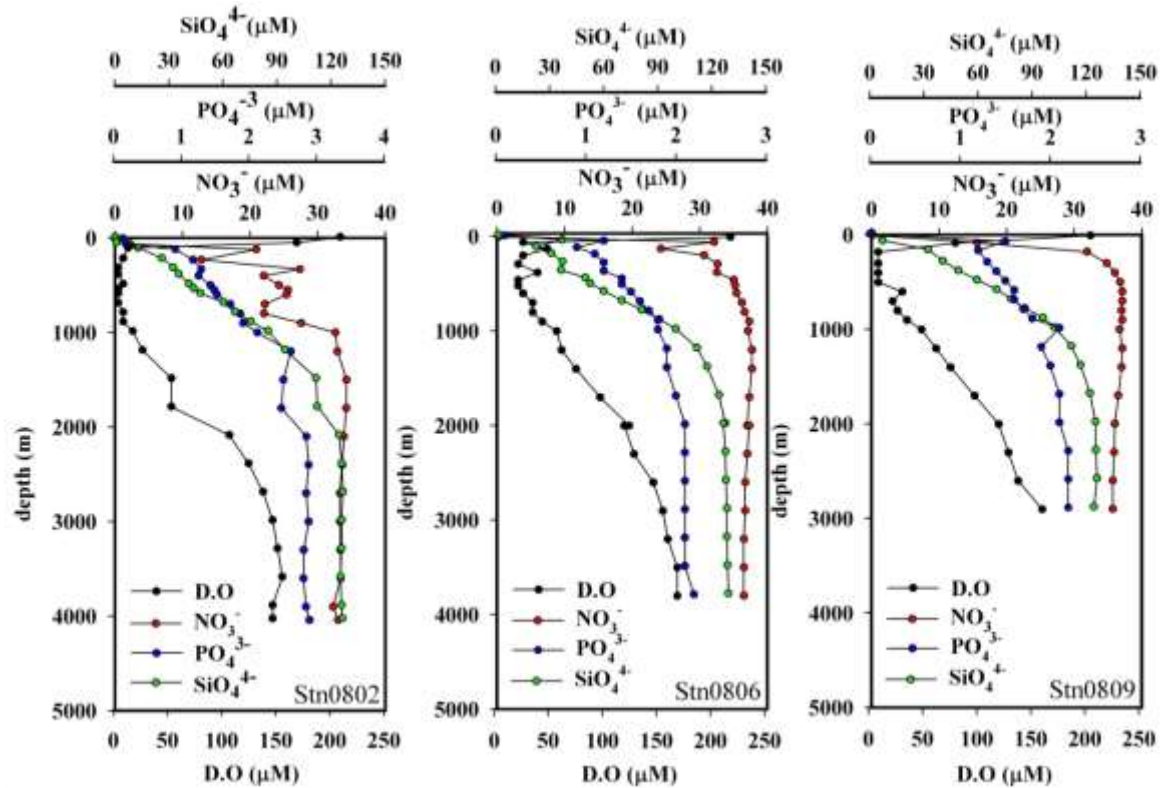


Figure 3. Vertical profile nutrients (NO_3^- , PO_4^{3-} , SiO_4^{4-}) and Dissolved Oxygen at 0802 (from the Arabian Sea) and 0806, 0809 (from the Bay of Bengal) during November 2008.

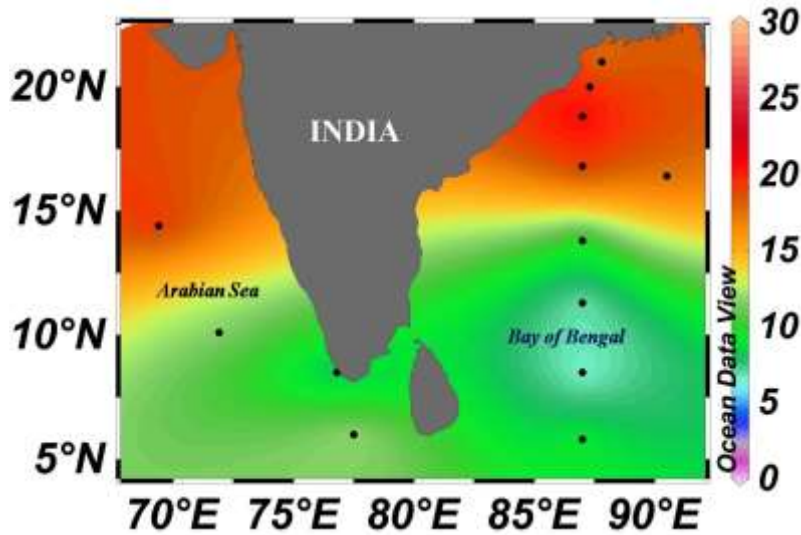


Figure 4. Column integrated chlorophyll-a (mg/m^2) levels in the northern Indian Ocean during November 2008.

are significantly higher in the Arabian Sea (AS) and the northern Bay of Bengal (N-BoB). It has been suggested that convective mixing in the winter facilitates the upwelling of the nutrient-rich deep water to the surface in

the Arabian Sea, and thus, can account for the observed high column integrated chlorophyll-a concentrations (Figure 5a). In contrast, the surface chlorophyll-levels were low over the Arabian Sea and the Bay of Bengal

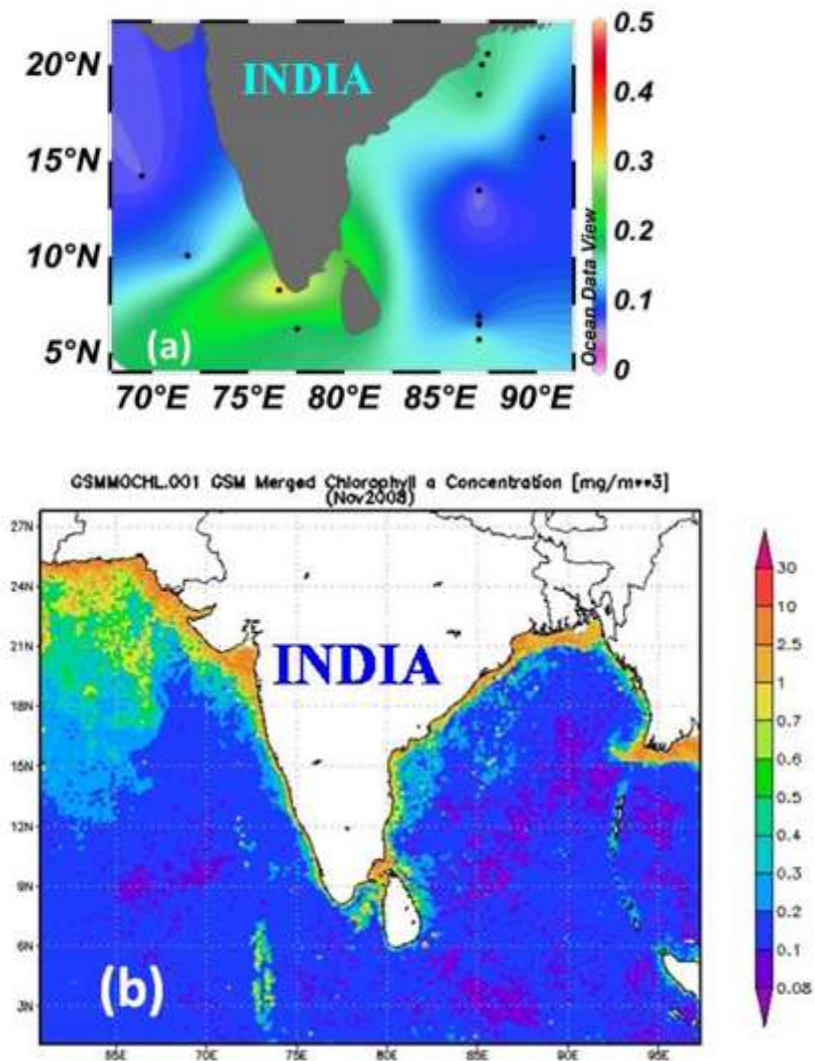


Figure 5. (a) Surface level chlorophyll-a concentration (mg/m^3) along the cruise track during the study period (b) monthly composite image of chlorophyll-a (mg/m^3) derived from SEAWIFS (data, during November 2008).

except for the 0804 and 0805 (Figure 5a). The measured chlorophyll-a concentrations were further supported by the satellite data during the study period (Figure 5b). Overall, there is a good agreement between the observed *in situ* mass concentrations and the satellite-derived chlorophyll-a concentration obtained from SeaWiFS. A satellite-based study of chlorophyll-a distribution during the NE-monsoon (November to February) highlighted the role of Eddies and cyclones in the south-western part of the Bay of Bengal towards enhancing the chlorophyll-a levels (up to 2 mg m^{-3} (Vinayachandran and Mathew, 2003).

The occurrence of subsurface chlorophyll maxima (SCM) is a well-known water column feature that apparently describes the physiological conditions of the

plankton biomass. At all stations in the Arabian Sea and the Bay of Bengal, except for the northern station (0815, where the water depth is ca. 50 m), subsurface chlorophyll maxima (SCM) is observed during the study period along the cruise track (Figure 6). In the Arabian Sea, the SCM varied from 0.14 to 0.43 mg m^{-3} , generally found at the depths of 30 to 75 m with its maximum chlorophyll-a concentration observed at 50 m. Similarly, in the Bay of Bengal, the presence of subsurface chlorophyll maxima was found between 30 to 100 m, while SCM concentration varied from 0.29 to 0.42 mg m^{-3} . In contrast, the stations 0807, 0808 and 0809 sampled from the southern part of the Bay, do not show significant chlorophyll concentrations ($< 0.05 \text{ mg m}^{-3}$) in any samples.

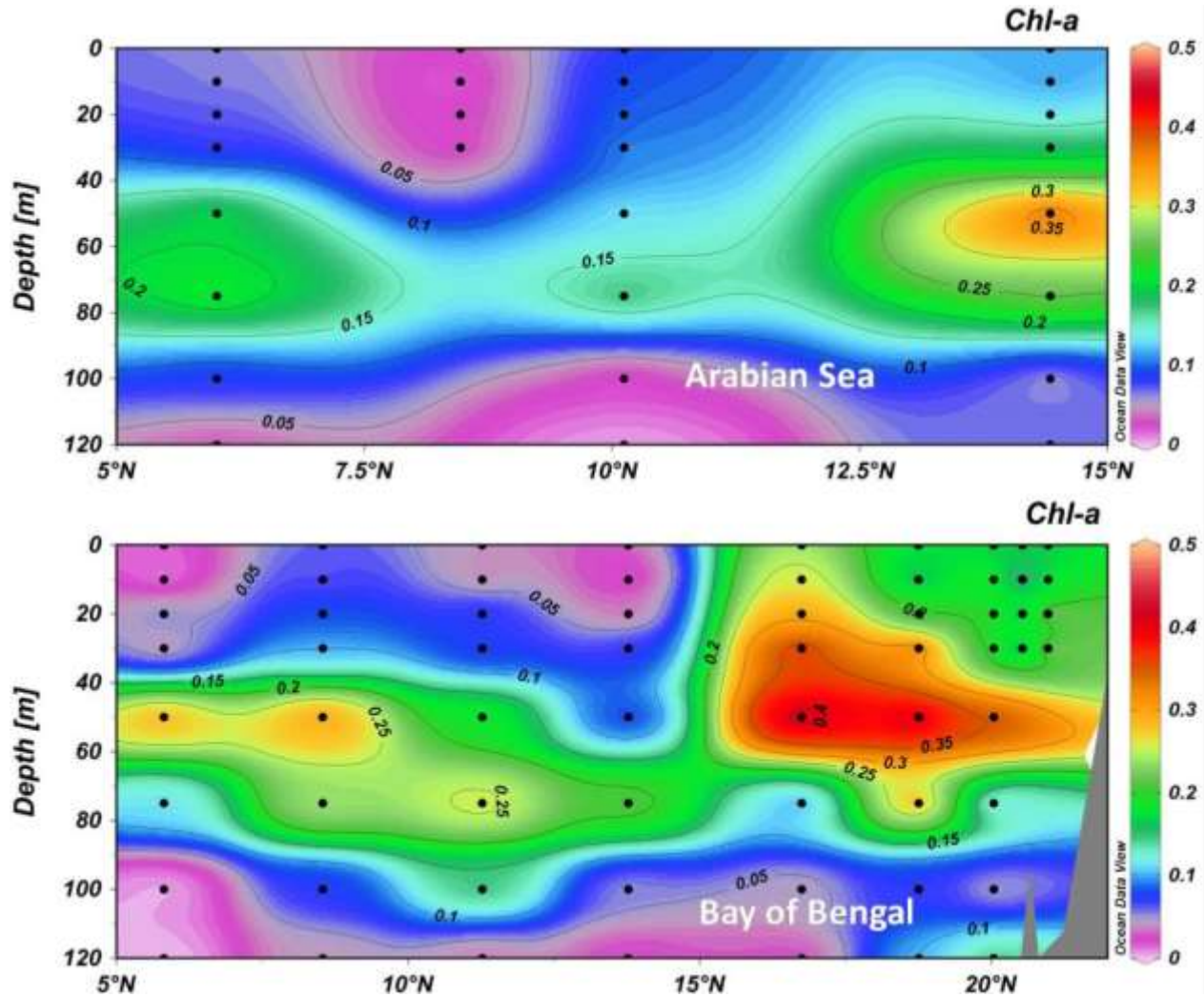


Figure 6. Latitudinal depth profiles of chlorophyll-a (in mg/m^3) in the Arabian Sea (top panel) and the Bay of Bengal during the cruise undertaken between 8 to 30th November'08.

Although surface chlorophyll-a concentration is relatively lower over the Bay, these levels are comparable to those in the Arabian Sea. Among the Arabian Sea stations (0802, 0803, 0804 and 0805), the surface chlorophyll-a concentrations were high in the off Mangalore station (0802), a region that is typically characterized by high productivity due to coastal upwelling. In the Bay of Bengal, a strong gradient of chlorophyll-a distributions in the surface waters was observed along the entire cruise track with systematically high concentrations over the northern part of the Bay of Bengal (that is, stations 0810, 0811, 0812, 0813, and 0815) in comparison to the southern stations (0807, 0808, and 0809). Because the Bay receives a large amount of nutrient input from the Ganga and other rivers, it thus explains the high chlorophyll-a concentrations at the northernmost stations compared to those from the

southernmost stations. Surprisingly, among the stations (0806, 0807, 0808, 0809) sampled in the south Bay, high chlorophyll-a concentrations were found at the farthest south station in Figure 1 (0806). This is probably due to Eddy pumping of nutrients from subsurface waters or from the advective transport of nutrients at this station due to cyclonic disturbance as recorded during this cruise.

To investigate this in detail, the surface salinity distribution over the Bay along the cruise track was analyzed. Due to the freshwater influx, the salinity level of surface seawater in stations sampled from the northern part of Bay of Bengal are relatively less (salinity as low as 29 at the northernmost station, 0814 (Table 1) compared to the southern Bay. In addition, the salinity gradient in the surface waters shows an increasing trend from the northern Bay of Bengal to the southern Bay with a salinity of 28.6 at 0814 to 33.7 at 0806. From these observations,

Table 1. Surface salinity, surface chlorophyll-a (mg/m^3) and integrated chlorophyll-a concentration (mg/m^2) for all the stations sampled for hydrographic parameter in the Arabian Sea and the Bay of Bengal.

Region	Station	Surface Salinity (psu)	Surface chlorophyll-a (mg m^{-3})	Column Integrated Chlorophyll-a (mg m^{-2})
AS	0802	36.7	0.06	22.8
AS	0803	35.5	0.07	12.4
AS	0804	-	0.41	2.2
AS	0805	34.4	0.13	15.9
S-BOB	0806	33.5	0.23	11.4
S-BOB	0807	33.3	0.01	3.6
S-BOB	0808	33.3	0.01	3.4
S-BOB	0809	33.2	0.02	2.0
N-BOB	0810	32.1	0.06	18.8
N-BOB	0811	33.8	0.22	25.4
N-BOB	0812	32.1	0.20	26.3
N-BOB	0813	32.7	0.20	22.3
N-BOB	0815	29.6	0.15	11.4

it is discernible that the nutrient input through river discharge may not have a significant influence on the stations sampled from the southern part of Bay of Bengal (as evident from low chlorophyll concentrations (Table 1). Therefore, increase in concentrations of chlorophyll-a at farthest sampling station in the south Bay (0806) could either be due to Eddy pumping of nutrients from deep waters to the surface or due to the lateral advective transport of nutrients from surrounding coastal regions (Nuncio and Kumar, 2012). This hypothesis is further supported by the absence of nutrients (NO_3^- , PO_4^{3-} , SiO_4^{4-}) at the stations 0807 to 0809, whereas significant concentrations were observed in the surface waters at station 0806 (farthest station in the south Bay).

A cyclonic storm was recorded prior to the occupation of this station over the South Bay during the sampling period. Therefore, the observed chlorophyll-a concentration (representative of plankton biomass) at this station over the Bay could be due to Eddy mediated biological production. This observation further corroborates the hypothesis that Eddies or lateral advective transport may have a significant role in enhancing the biological productivity. Earlier studies highlighted the role of Eddies in enhancing the biological productivity by supplying nutrients from subsurface waters to the surface (Kumar et al., 2007; Nuncio and Kumar, 2012). Although light limitation, turbidity, cloud cover and freshwater stratification have a strong influence on the biological productivity over the Bay, it seems that eddies play a significant role in regulating biological productivity in the Bay of Bengal.

Conclusions

This study measured the hydrographic parameters

(nutrients, dissolved oxygen, pH, salinity, and Chlorophyll-a) in the waters of the Arabian Sea and the Bay of Bengal during NE-monsoon. The observed chlorophyll-a levels in both basins are somewhat comparable, that is, at least for the Arabian Sea stations and northernmost stations of the Bay of Bengal. Additionally, the chlorophyll-a levels from the SeaWiFS satellite data are consistent with those observed during the present study. Notable differences in the depth range at which subsurface chlorophyll maxima (SCM) was observed between Arabian Sea (30 to 80 m) and the Bay of Bengal (30 to 100 m). The relative increase in freshwater influx and suspended load to the later marine basin (that is, Bay of Bengal) might have an influence on the vertical standing stocks of phytoplankton biomass in the surface waters. A conspicuous increase in abundance of Chlorophyll-a and high nutrients was observed at an offshore station in the Bay of Bengal, which is attributed here to Eddy pumping or later advection of nutrients. A cyclonic storm was observed prior to the water-sampling at station 0806, perhaps corroborating the role of Eddy pumping. However, further investigation is needed regarding the variations in the phytoplankton composition (that is, small vs. large plankton) to understand how and what extent Eddies can affect the physiological conditions of marine phytoplankton, and thereby, linked to carbon sequestration.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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