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Influence of environmental forcings on the seasonality of dissolved oxygen and nutrients in the Bay of Bengal

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ABSTRACT

Studies on seasonal variability of oxygen and nutrients during three seasons namely SW monsoon, fall intermonsoon and spring intermonsoon indicate influence of physical forcings on the distribution of these hydrochemical properties in the subsurface layer. In the open ocean the Minimum Oxygen Layer (MOL $\leq$10 mu Mol L^{-1}) during the southwest monsoon and fall intermonsoon is mostly confined to the north of 11N due to the penetration of high salinity water in the deeper waters of the central Bay. During spring intermonsoon MOL is mostly confined to the northern region between 14 to 20N with a narrow band of suboxic waters ($\leq$5 mu Mol L^{-1}) around 19 to 20N. Along the western margin, the MOL occupies a larger area in the intermediate and deeper waters during the SW monsoon and fall intermonsoon with a thick layer of suboxic waters during the SW monsoon which gets reduced and confined to the northern region during fall intermonsoon. The core of suboxic waters seems to disappear during the spring intermonsoon. The displacement of the water mass to shallower depths under the influence of cold core eddies is the major mechanism supplying nutrients to the surface waters whereas stratification due to the immense runoff from major rivers in the north and the associated suspended load addition seems to be inhibiting the biological production through curtailment of light penetration in the northern Bay of Bengal during the southwest monsoon. Pockets of low oxygen contents are not associated with elevation in secondary nitrite levels suggesting that circulation of the water mass under the influence of seasonal currents and gyres and the geochemical processes play a significant role in regenerative processes and regulating the intensity of the MOL in the Bay of Bengal.

1. Introduction

The Bay of Bengal is characterized by its seasonal reversal of surface currents under the influence of monsoonal wind reversal (Shetye *et al*., 1991) and the surface low salinity regions due to immense fresh water inputs through excessive precipitation over evaporation and river discharge (Yu and McCreary, 2004). This large fresh water influx from the rivers which drain into the Bay show considerable seasonal variability (Shi *et al.,* 2002) and brings along with it seasonally varying sediment load and probably contributes in terms of nutrients input to the upper layers. Accordingly, the hydrochemical properties of the Bay of Bengal are expected to respond to these factors on a seasonal scale. The

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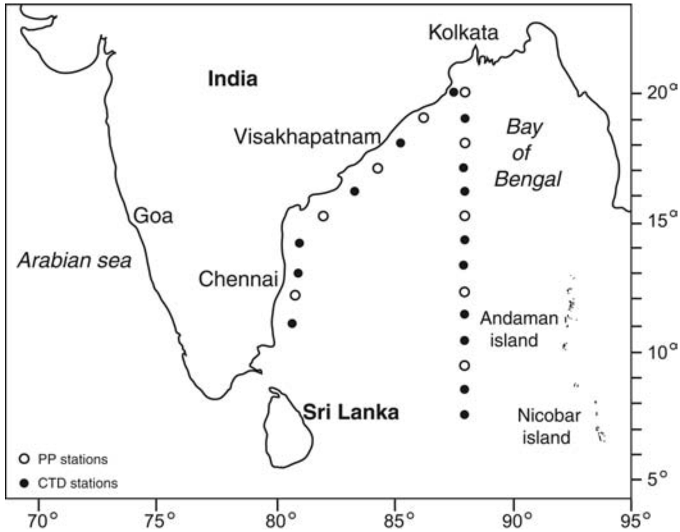

Figure 1. Map showing stations position.

seasonality of these physical forcings and the associated hydrography of this region have been studied by several researchers (Murty and Varadachari, 1968; Gopalkrishna and Sastry, 1985; Shetye *et al.,* 1993, 1996) whereas Schott and McCreary (2001) have reviewed the circulation during the monsoon and the monsoonal currents in the Bay of Bengal. Unlike the Arabian Sea which is known for its oxygen-depleted zone and denitrification (Naqvi, 1987, 2001), Oxygen Minimum Zone (OMZ) occurs at intermediate depths (60-800 m) in the Bay of Bengal. There are only few isolated reports on the water column chemistry of Bay of Bengal (Sen Gupta *et al*., 1977; de Sousa *et al*., 1981; Rao *et al*., 1994) after the International Indian Ocean Expedition (IIOE) (Wyrtki and Rochford, 1971). This paper attempts to focus on the seasonal variability of hydrochemical features of the Bay of Bengal, vis-a vis seasonal changes in physical forcings and biogeochemical processes.

2. Material and methods

As part of the Bay of Bengal Process Study (BOBPS) 24 stations along two transects were occupied on board ORV *Sagar Kanya* during the three seasons;— Southwest monsoon (July-August, 2001), fall intermonsoon (September-October, 2002) and spring intermonsoon (April-May, 2003) as shown in Figure 1. Fourteen stations were occupied between 7N to 20N in the open ocean transect along 88E and 10 stations were occupied along the western margin from 11N to 20N along ~1000 m depth contour. Samples were collected at discrete depths in the upper 1000 m water column using 10/30 liters GO-Flow bottles attached to a rosette connected to Sea Bird CTD. The temperature and salinity profiles were obtained using the CTD while samples were collected for dissolved oxygen, and nutrients in glass and plastic bottles, respectively. Dissolved oxygen was analyzed by Winkler titration. Nitrate, nitrite, phosphate and silicate were estimated by autoanalyzer (skalar) during the southwest monsoon cruise and by following the manual methods of Grasshoff *et al.* (1983) during the other two seasons. There was good agreement in the precision between the two methods. The detection limits for nitrate, phosphate and silicate were 0.1, 0.03 and 0.5 mu mol L^{-1}, respectively. Samples for Suspended Particulate Matter (SPM) were collected at five stations in the open ocean and three stations along the western margin. The samples were filtered through pre-ignited (450°C) GF/F filters. Primary production was measured in the euphotic zone at 8 depths at five stations in the open ocean and 4 stations along the western margin (Fig.1). The samples were incubated *in situ* from dawn to dusk. Primary production was measured by ^{14}C method. Chlorophyll *a* was determined fluorometrically (Turner Design Fluorometer) after calibrating the instrument with pure Chlorophyll *a* (Sigma).

3. Results and discussion

a. *Hydrographic characteristics of the study area*

The Indian monsoon current (July-September) advects warm, high salinity water mass at shallower depths (40-100 m) from the Arabian Sea into the southwestern and central Bay up to 14N during SW Monsoon (Sastry *et al.*, 1985; Murty *et al.,* 1992). The East India Coastal Current (EICC) developed during November-February carries low salinity waters from the western margin to the southern Arabian Sea (Shetye *et al.,* 1996). This EICC reverses to flow poleward during February-May along the east coast of India, carrying the Arabian Sea high salinity waters toward north. The low salinity waters formed due to the influx of fresh water brought in by several rivers in the northern region and the seasonal precipitation forms a salinity gradient in the upper 30 m of the water column. This layer is highly stratified and cannot be eroded by the weaker winds that prevail over the Bay (Shenoi *et al.*, 2002). Below this low salinity water mass, three water masses can be identified in the Bay of Bengal which include the layer between 40-100 m characterized by Arabian Sea High Salinity water mass in the Central and southern Bay. The layer between 100-300 m is the Bay of Bengal subsurface water mass ($S = 34.9$ to 35.05). Below 300 to 400 m salinity decreases gradually to lower values (35. 0) at deeper depths which is identified as the Indian Equatorial Intermediate waters (Gallagher, 1966).

In the open ocean (Fig. 2a), the salinity gradient in the upper 30 m was 7.0 at 20N which gradually decreases toward the south to 1.5 at 9N during the southwest monsoon. During fall intermonsoon, the salinity gradient in the upper 30 m was 5.5 at 20N and 0.5 at 10N. During spring intermonsoon, reduced influx of fresh water decreased the salinity gradient in the surface waters to 0.5 from north to south. The thermal structure indicated the presence of two cold core eddies around 10 and 19N (Fig. 2b). The eddies displaced the water mass by about 60 m in both the regions. Upheaval of the water mass under the influence of eddies was seen in all the three seasons.

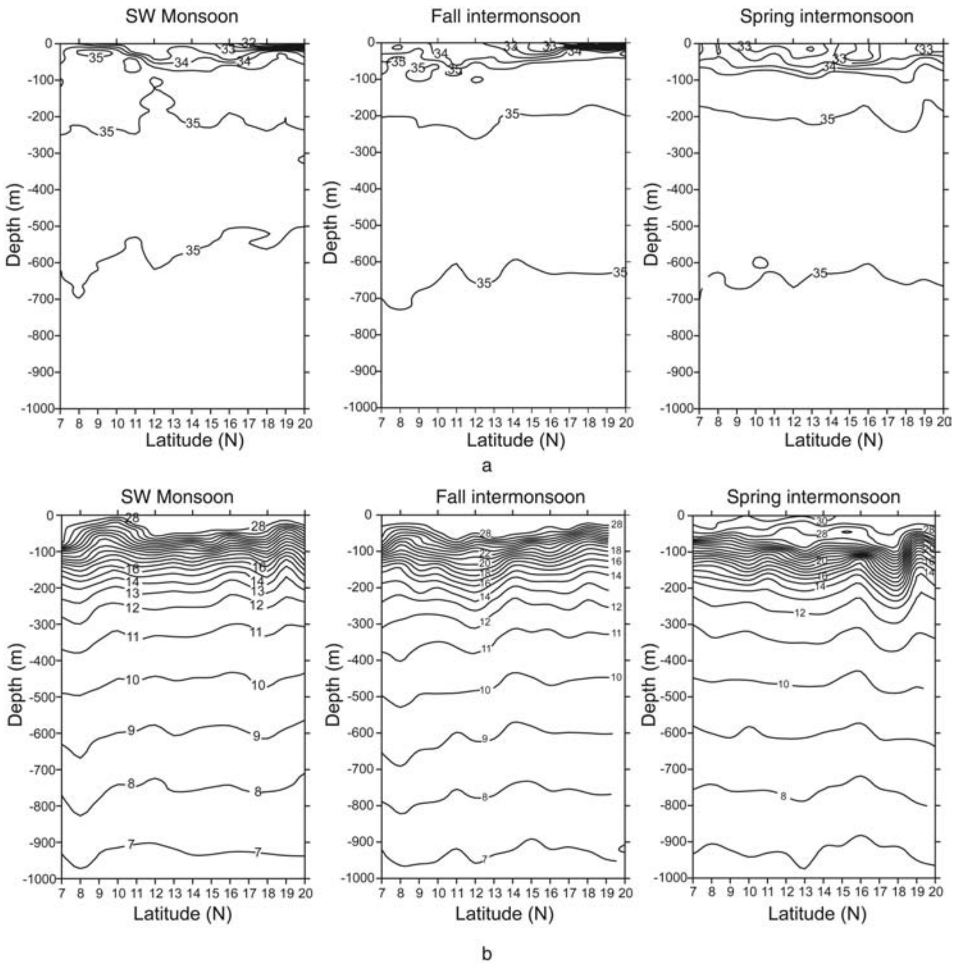

Figure 2. Distribution of salinity (a) and temperature (b) during the three seasons in the open ocean.

Along the western margin, (Fig. 3a) the salinity gradient in the upper 30 m toward the north was about 3.0, whereas toward the south it decreased to 0.3 during the SW monsoon The salinity gradient increased during fall intermonsoon to 9.0 in the northern region which was reduced to 0.5 around 11N whereas the salinity gradient was 0.5 from north to south in the upper 30 m during spring intermonsoon. The thermal structure (Fig. 3b) showed the presence of eddy at 17N in all the three seasons with the shoaling of the subsurface water mass toward shallower depths.

To further substantiate the presence of eddies we present mean anomaly maps (Fig. 4) during 10 July to 10 August 2001, 17 September to 17 October 2002 and 16 April to 16 May 2003 for summer, fall and spring respectively obtained from AVISO (http://las.aviso.oceanobs.com). This figure elucidates the spatial structure of eddies. Gopalan *et al.* (2000) detected the eddies in the Bay of Bengal from 1993 to 1996 during various

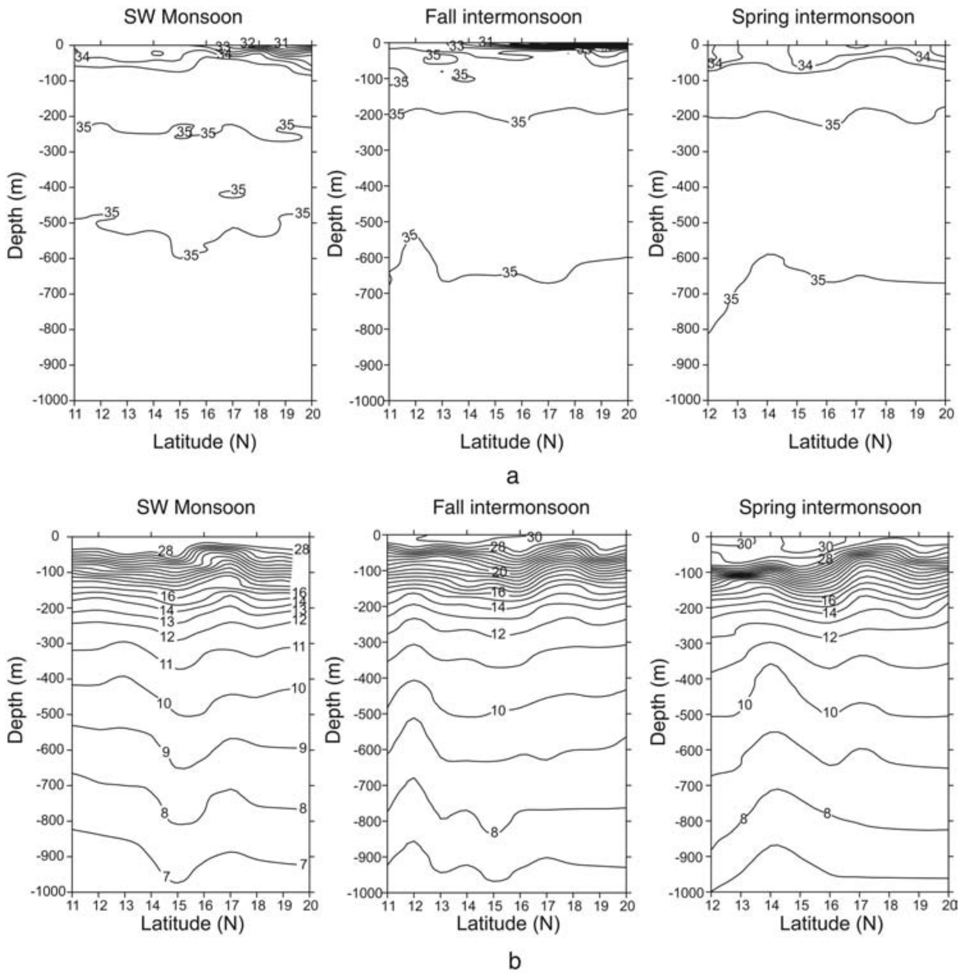

Figure 3. Distribution of salinity (a) and temperature (b) during the three seasons along the western margin.

periods of different seasons. They observed interannual variations in positions and intensities of eddies during the study period. Sharma *et al.* (1999) also observed high eddy kinentic energy toward the western side during nonmonsoon months due to the western boundary current. They also found that a large part of the Indian Ocean exhibits low eddy kinetic energy year round.

b. Dissolved oxygen

Oxygen levels showed the influence of eddies by the upward tilting of the isolines in the eddy regions (Fig. 5 a,b,c) in the open ocean in the three seasonal observations resulting in a water mass with low oxygen levels in the surface layers. During Southwest monsoon, the

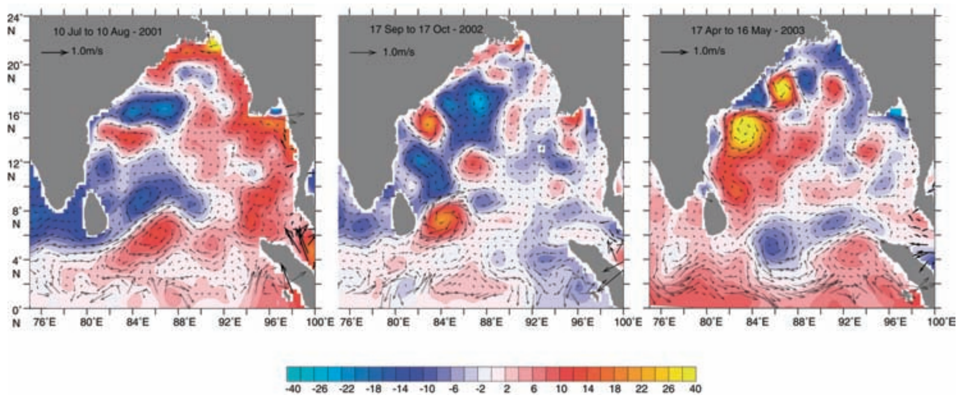

Figure 4. Spatial structure of eddies during different seasons.

upper boundary of minimum oxygen ($\leq$10 mu mol L^{-1}) extends horizontally from about 80 m at 20N to about 120 m around 11N and it extends down to about 600 m mostly confined to the north of 15N. The intermediate waters toward the south show relatively higher oxygen levels (15-35 mu mol L^{-1}) perhaps due to the penetration of Arabian Sea high salinity water into the central Bay. The deeper layer between 400 to 600 m also showed the intrusion of waters with relatively higher oxygen content which is identified as the high salinity Indian Equatorial Intermediate Waters (Gallagher, 1966). Below 600 m the oxygen levels gradually increase up to1000 m.

The eddy in the northern region appears to be well developed during fall intermonsoon season. The oxygen minimum layer is almost similar to that during the southwest monsoon and the intermediate and deeper waters are seen to be under the influence of high salinity water. During spring intermonsoon, the upper layer up to about 40 m shows relatively uniform oxygen content perhaps due to the isohaline structure of this water mass. Toward 19 to 20N however, the oxygen content is significantly lower due to the upheaval of the subsurface water mass in this region. The intense oxygen minimum is reduced during this season and mostly confined to the northern region between 15 to 20N. A narrow band of near suboxic waters ($\leq$ 5 mu mol L^{-1}) is seen around 19 to 20N between 60 to 200 m and at 15N between 100 to 120 m. The intermediate and deeper waters do not show the pattern of oxygen distribution as seen in the other two seasons perhaps due to the absence of incursion of high salinity waters at this depth during this season (Varkey *et al.*, 1996) The displacement of the water mass due to physical pumping along the western margin is seen at around 17N (Fig. 5d,e,f) in all the three seasons.. The minimum in oxygen is also heaved up from 120 m to shallower depths with pocket of suboxic waters between 60 to 100 m at 17N. The MOL with a core of suboxic waters spreads over a larger area and is uniformly distributed from south to north. The surface layer in the coastal region shows relatively higher oxygen content compared to the central Bay in the fall season (Fig. 5e). This may be due to the higher dissolution of oxygen in the less saline surface waters. There is also a core of suboxic waters between 100 to 400 m to the north of 17N. In the deeper waters minimum

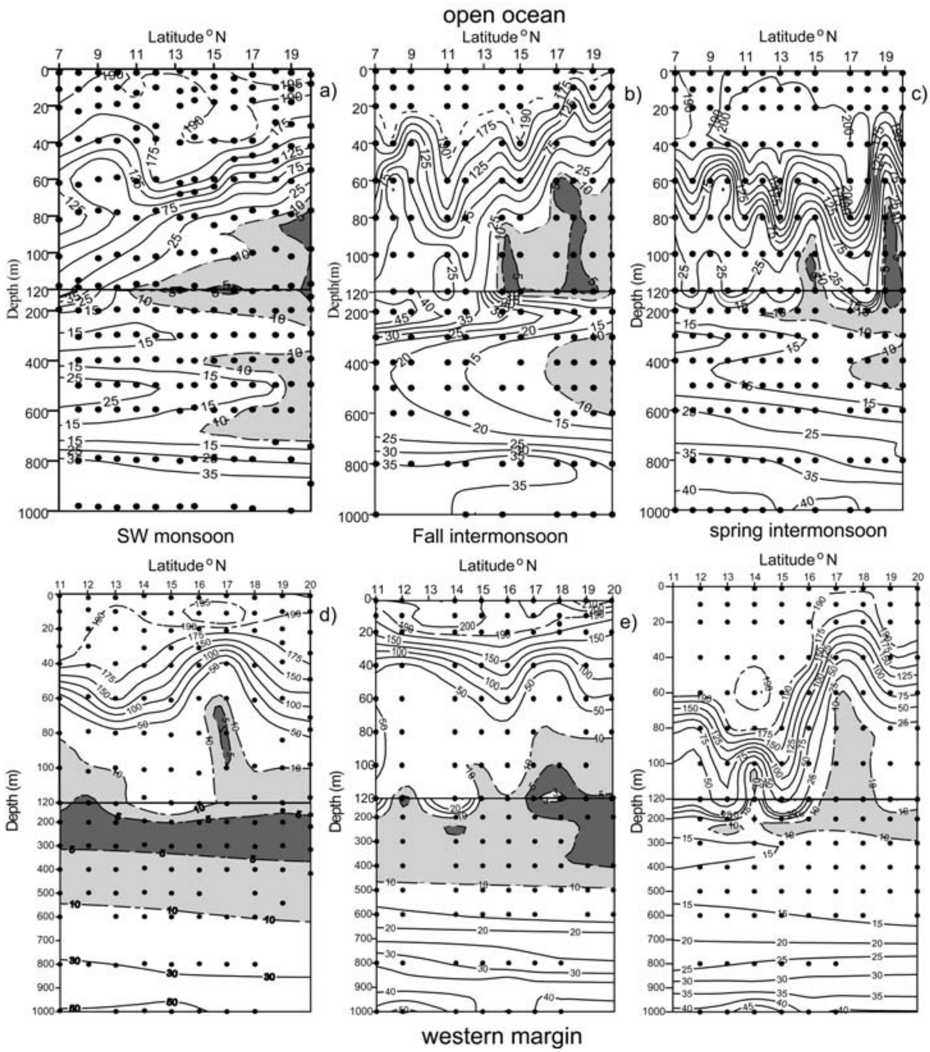

Figure 5. Distribution of dissolved oxygen (mu mol L^{-1}) during the three seasons: open ocean (a,b,c), western margin (d,e,f)

oxygen extends up to 500 m. During spring, (Fig. 5f) the minimum oxygen layer is reduced and extends from about 250 m at 13N to about 60 m at 17N. However, the core of suboxic waters prominently seen in the eddy region during the southwest and fall season is absent during spring intermoonson.

Oxygen distribution is generally governed by physical processes like atmospheric interaction, fresh water influx, upwelling, water mass transport and biological processes like photosynthesis and respiration. The seasonal variability and distribution of dissolved oxygen in the surface layer in the Bay of Bengal appears to be significantly influenced by physical processes like eddies and water circulation in the intermediate and deeper layers. Although large influx of fresh water adds biogenic matter to the Bay along with the mineral particles, the biological demand for oxygen does not lead to anoxic or oxygen depleted conditions as is prevailing in the Arabian Sea. (de Sousa *et al.*, 1996; Naqvi *et al.,* 2000). Ittekkot *et al.*, (1991) through their study of particle fluxes using sediment traps showed that forty to fifty percent of the total annual flux occurs during the SW monsoon. During other seasons particle fluxes are uniformly low. It can also be inferred from their study that organic carbon flux was decreasing from north to south and was higher in the deeper traps in the north than in the south. To verify the application of this observation to our study we plotted the depth profiles of total carbon dioxide (TCO_2) and apparent oxygen utilization (AOU) at 9N (south) and 20N (north) in the open ocean and western margin during the south west monsoon (Fig. 6). The TCO_2 levels were on an average 109 μM higher at 9N than at 20N and there was marginal difference in the AOU between the two locations from 100 to 1000 m. Along the western margin the gradient in TCO_2 between north and south was on an average 38 μM with a negligible N-S gradient in the AOU. These findings suggest lower mineralization of organic matter in the north during the southwest monsoon. Lower N-S TCO_2 gradient along the western margin indicates relatively higher remineralization of organic matter in this region. Higher biological production along the western margin as discussed in the later section and thicker minimum oxygen layer support this observation.

To verify the presence of denitrification in the suboxic cores of the MOL, nitrate deficit was calculated using 'NO' as a tracer (Naqvi and Sen Gupta, 1985). Nitrate deficit ranging from 1 to 6 mu mol L^{-1} was observed in the MOL during the three seasons. However, this nitrate deficit in the water column is not associated with secondary nitrite maximum (SNM) and is not because of active denitrification in the water column. Howell *et al.,* (1997) also observed the absence of a SNM and low ΔN values from WOCE 19N observation and relate this lack of denitrification to the large input of sediment load to the basin. These findings indicate the presence of water masses probably advected into this region from denitrification dominated areas such as the Arabian Sea.

c. Nitrate

The distribution of nitrate during different seasons in the open ocean and the western margin is shown in Figure 7. The shoaling up of the subsurface waters around 9N to 10N and around 19N helped in the pumping of nutrients to the upper layers in the euphotic zone in all the three seasons. However, during the SW monsoon, the wind forcing could not erode the stratification due to the fresh water influx in the north thereby limiting the availability of nitrate to a depth of about 20 m. The fresh water appear to be devoid of nitrate in the surface waters. Sen Gupta and Naqvi (1984) also made similar observation in the Bay. Though similar amounts of nutrients are available in the euphotic zone toward the northern as well as the southern region the integrated primary productivity at 20N was 89 mg C m^{-2} d^{-1} compared to 220 mg C m^{-2} d^{-1} at 9N. The integrated chl *a* was similar ($\sim$10 mg m^{-2}) in both the regions. The decrease in the primary productivity toward the

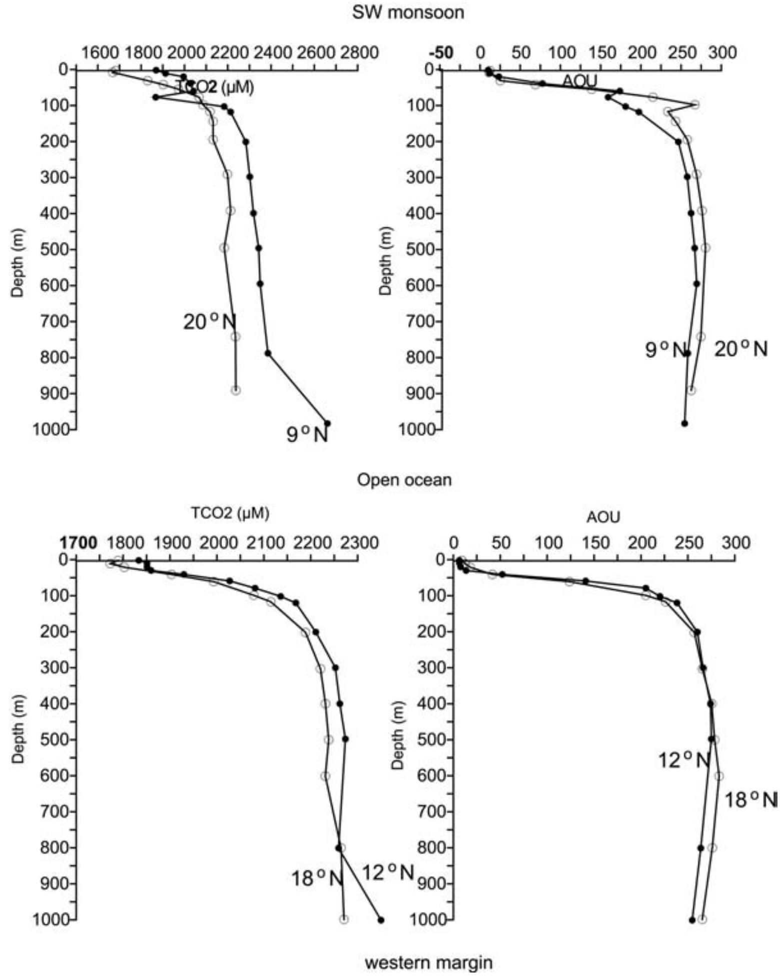

Figure 6. N-S gradient in TCO_2 (μM) and AOU in the open ocean and western margin during the southwest monsoon.

northern region may be the effect of light inhibition due to a large amount of suspended load that is added in this region from the riverine fresh water input. In the northern region (18-20N) the suspended load ranged from 0.8 –17.6 mg L^{-1} whereas in the southern region (9N) it varied from 0.2–1.1 mg L^{-1} in the euphotic zone (Bhosle, Personal communication).

There was detectable amounts of nitrate addition (0.1 mu mol L^{-1}) from the fresh water influx in the north during fall intermonsoon. Integrated productivity toward the northern region doubled (184 mg C m^{-2} d^{-1}) during this season compared to the southwest monsoon whereas it was 512 mg C m^{-2} d^{-1} toward the south. The integrated chl *a* content also showed an increasing trend from north to south with a maximum around 8N and was

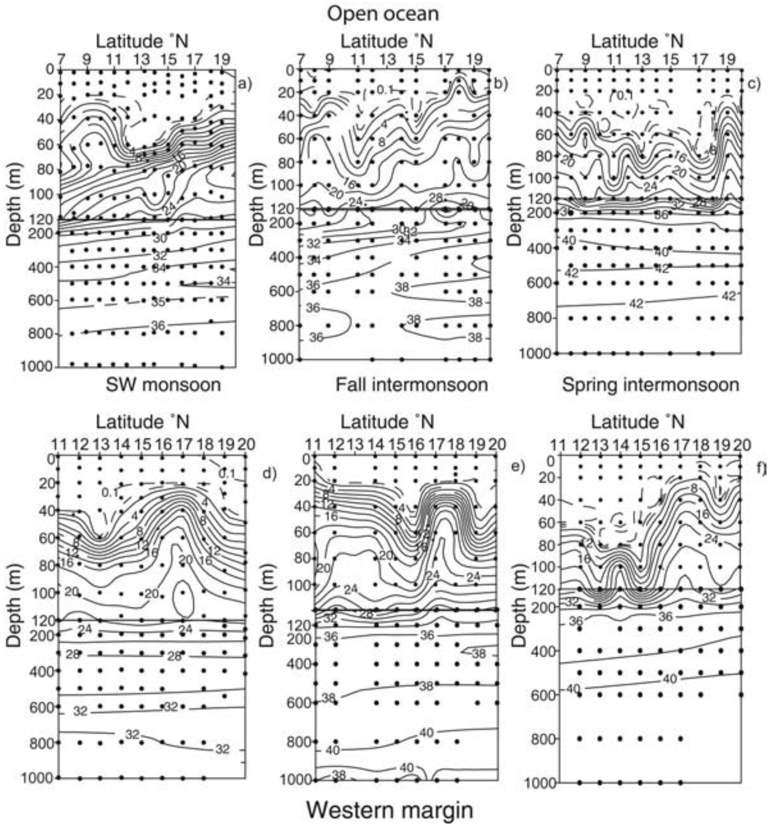

Figure 7. Distribution of nitrate (mu mol L^{-1}) during the three seasons: open ocean (a,b,c), western margin (d,e,f).

relatively higher than that observed during the southwest monsoon. The substantial increase in productivity toward the south may be due to relatively lower input of suspended matter which ranged from 0.8 to 3.4 mg L^{-1} (9N) compared to the northern area (20N) which showed a suspended load ranging from 1.4 to 6.4 mg L^{-1}. The improved light conditions might have aided in the higher production. Ittekkot *et al.* (1991) showed that the overall particle flux pattern in the Bay is controlled by the seasonally varying fresh water inputs by rivers. Further, Scheffer *et al.* (1996) and Ramaswamy *et al.* (1997) demonstrated a strong seasonality in the nature and quantity of biogenic and lithogenic fluxes in this region due to variability of fresh water and sediment inputs from rivers.

During spring intermonsoon, the oscillations in the nitrate isolines indicate weaker physical forcings compared to the other two seasons. The column production in the southern eddy region (9N) was 203 mg C m^{-2} d^{-1} associated with integrated chlorophyll content of 13.4 mg m^{-2} whereas in the northern (19N) eddy region the column productivity was 427 mg C m^{-2} d^{-1} with a chlorophyll level of 17.2 mg m^{-2} . The suspended load showed a further decrease during this season.

The western margin also showed the influence of physical forcings in providing nitrate to shallower depths with the shoaling of the isolines around 17N during the south west monsoon. Nitrate inputs from the Mahanadi and Godavari rivers were significant and the availability of nutrients in the northern region elevated the primary productivity to 434 mg C m^{-2} d^{-1} relative to the open ocean perhaps due to the availability of sufficient light and higher chl *a* for photosynthesis. A significant correlation between chl *a* and primary production rate was observed by Madhupratap *et al.* (2003) which indicated that most of the productivity was related to active chl *a* present in the water column. The productivity in the eddy region corresponding to 17N was 328 mg C m^{-2} d^{-1}. Thus, the integrated primary production in the eddy region was at least 8 times higher than that in the non eddy region (15N, 39 mg C m^{-2} d^{-1}). Toward the south surprisingly, the productivity was maximum (502 mg C m^{-2} d^{-1}) though the upper 40 m was devoid of nitrate. The integrated chl *a* was also lower (about 14 mg m^{-2}) as compared to 19 N ($\sim$ 20 mg m^{-2}). During fall intermonsoon the physical pump heaved the water mass toward 11N and 17N. The integrated chl *a* showed a decreasing trend from north to south and was associated with moderately low productivity at the sampled locations.

During the spring intermonsoon, the distribution of nitrate was similar to that in the open ocean. However, the displacement of the water mass at 17N was up to10 m and the column productivity of 438 mg C m^{-2} d^{-1} was recorded in this eddy region. Toward the south, though the nitrate deficient layer deepened to 60 m the column productivity was 305 mg C m^{-2} d^{-1}. The suspended load in general, was the lowest during this season.

d. Phosphate

The distribution of phosphate in the open ocean during the three seasons (Fig. 8) showed a trend similar to nitrate barring some major differences. There was no contribution of phosphate in the northern region through the fresh water influx during the SW monsoon. During the fall intermonsoon, phosphate concentration in the range of 0.1 to 0.4 mu mol L^{-1} was present in the surface layer from south to north whereas during the spring intermonsoon phosphate of 0.2 mu mol L^{-1} concentration was present in the surface layer toward the south between 7 to 10N. The intermediate and deeper waters showed similar trend of variations with increasing concentration with depth in all the three seasons.

Along the western margin the fresh water addition of phosphate in the northern region during SW monsoon was around 0.4 mu mol L^{-1} whereas toward the south, the upper layer up to 40 m was devoid of phosphate. During the fall intermonsoon, though, the top layer was devoid of nitrate; phosphate was present at levels ranging from 0.2 to 1.2 mu mol L^{-1} from south to north. Relatively higher levels of phosphates in the surface layer in the open ocean as well as along the western margin during this season may be the result of the contribution from fresh water due to the leaching of the soil phosphates in the north and the upheaval of the water mass from the sea. During the spring intermonsoon, unlike the open ocean the surface layer in the north showed 0.1 to 0.3 mu mol L^{-1} of phosphate which appears to be the contribution from the riverine fresh water. The intermediate and deeper waters showed gradually increasing phosphate levels up to1000 m.

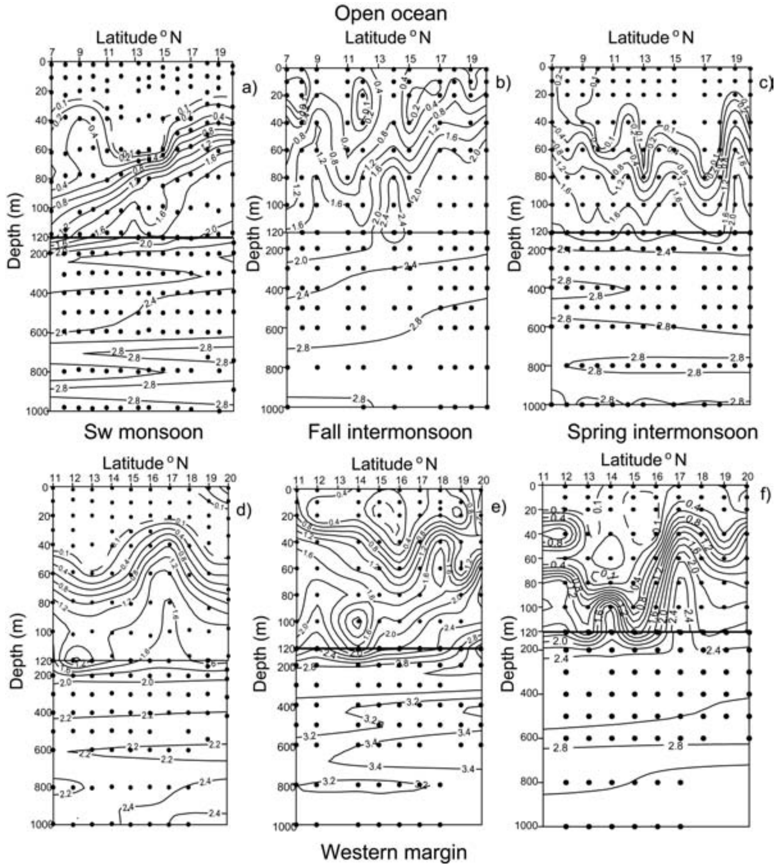

Figure 8. Distribution of phosphates (mu mol L^{-1}) during the three seasons: open ocean (a,b,c), western margin (d,e,f).

e. Silicate

Distribution of silicate follow similar pattern in the open ocean (Fig. 9) as that of nitrate with significant amounts of silicates available at shallower depths in the eddy region during the three seasons. The contribution from fresh water discharge in the northern region was up to 2 mu mol L^{-1} during the SW monsoon. The deepening of the mixed layer was also seen in the silicate distribution during the spring intermonsoon with surface silicate concentration up to 2 mu mol L^{-1}.

The influence of eddy at 17N was observed in all the three seasons along the western margin. Fresh water input at 20N resulted in the silicate concentration of about 9 mu mol L^{-1} at the surface. During the fall intermonsoon, besides the other salient features, silicate of 10 to 19 mu mol L^{-1} were added at the surface between 19 to 20N through the riverine fresh water flow whereas toward the south it was about 2 mu mol L^{-1}. During spring intermonsoon there was no significant addition of silicate in the north from the fresh water

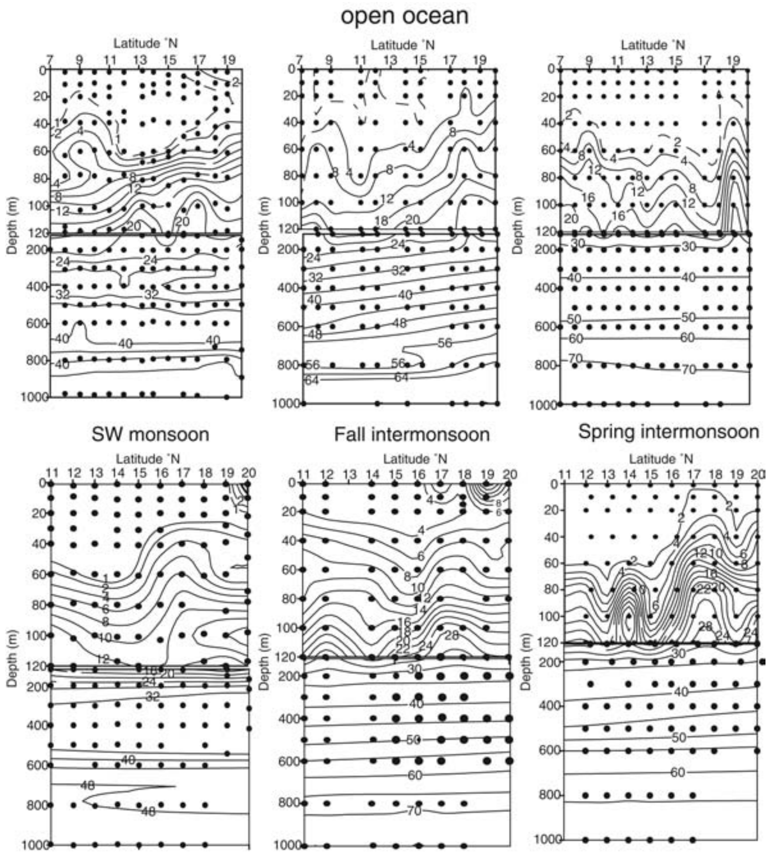

Figure 9. Distribution of silicates (mu mol L^{-1}) during the three seasons: open ocean (a,b,c), western margin (d,e,f).

addition and the 2 mu mol L^{-1} isoline was seen at the surface around 17 to 18N. The deep mixed layer of 60 m was also seen in the silicate distribution. The intermediate and deeper layers showed increasing silicate up to1000 m.

4. Conclusions

The availability of nutrients in the upper layers of the euphotic zone is governed by physical processes in the form of eddies and fresh water influx. Eddies enhance the availability of nutrients to the euphotic zone (Prasanna Kumar *et al.*, 2004) and are known to induce high new production (McGillicuddy *et al.*, 1998; Oschlies and Garcon, 1998). Consistent high new production was also observed during fall and spring intermonsoon season in the Bay (Kumar *et al.*, 2004) The biological and physico-chemical measurements over a short time scale as in this study indicate that the fresh water runoff and the climatic conditions in this part of the northern Indian Ocean do not contribute to the increase in the productivity of the bay to a large extent specially toward the north as compared to the Arabian Sea (Bhattathiri *et al.*, 1996; Prasanna Kumar *et al.,* 2000). The large influx of fresh water acts as an inhibitive factor, through strong stratification, in providing the adequate supply of nutrients to the surface layer. It also appears to hinder the penetration of light to the subsurface layer through its suspended load addition. The average annual rates of particle fluxes to the Bay of Bengal are similar to those of Arabian Sea. Relatively lower biological production in this region compared to the Arabian Sea during different seasons makes us to believe that the biogeochemical cycling in the Bay of Bengal is influenced by the addition of mineral particles from terrestrial origin. The high new production observed could also be an additional reason as new production and particle sinking are coupled over longer time scales (Eppley *et al.*, 1983) The observed weak north-south gradient in oxygen during different seasons and the marginal difference in the thickness of the minimum oxygen layer in all the three seasons toward the north lend support to the view that the particle flux in the Bay of Bengal is more of a lithogenic nature with a relatively lower proportion of biogenic material in it . Alternatively, the regeneration processes may be weaker in this region due to the rapid sinking of the biogenic particles along with the lithogenic fluxes (Ittekkot *et al.,* 1991; Kumar *et al.*,1998). Though pockets of suboxic waters are observed in the intermediate and deeper waters, no evidence of denitrification through the presence of secondary nitrite at these depths was observed in the area under investigation. The processes like upwelling which have a large impact on the productivity of the Arabian sea are encountered only in a small region off the coast of Bay of Bengal (Shetye *et al.*, 1991). The vertical diffusion which would supply nutrients to the upper thermocline are also weaker in the Bay of Bengal than in the Arabian Sea (Narvekar *et al.*, 1998). The Arabian sea and Bay of Bengal though situated at similar latitudes, have different climatic settings and are influenced by physical forcings, circulation patterns and chemical processes of dissimilar intensity. The consequences of weaker winds like lack of strong coastal upwelling which would supply nutrients to the coastal waters and to the open ocean by lateral advection and lack of vertical mixing of the surface layers due to the presence of strong stratification makes the Bay of Bengal less productive than its counterpart in the west.

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