

## **Impact of atmospheric and physical forcings on biogeochemical cycling of dissolved oxygen and nutrients in the coastal Bay of Bengal**

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### Abstract

Time-series observations were conducted off Visakhapatnam, central west coast of Bay of Bengal, from October 2007 to April 2009 to examine the influence of physical and atmospheric processes on water column nutrients biogeochemistry. The thermal structure displayed inversions of 0.5 to 1.0° C during winter and were weaker in summer. Water column was vertically stratified during the entire study period and was stronger during October-November 2007 and August to December 2008 compared to other study period. High concentrations of chlorophyll-a and nutrients were associated with the extreme atmospheric events. The strong relation of nutrients with salinity indicates physical processes, such as circulation, mixing and river discharge, have a significant control on phytoplankton blooms in the coastal Bay of Bengal. Phosphate seems to be a controlling nutrient during winter whereas availability of light and suspended matter limits production in summer. Formation of low oxygen conditions were observed in the bottom waters due to enhanced primary production by extreme atmospheric events, however, re-oxygenation of bottom waters through sinking of oxygen rich surface waters by warm core (anticyclonic) eddy led to its near recovery. This study reveals that atmospheric and physical processes have significant impact on the water column biogeochemistry in the coastal Bay of Bengal.

## 1. Introduction

The northeastern Indian Ocean (Bay of Bengal) is a unique and dynamic area with reference to seasonal change in wind direction, immense river discharge ( $1.6 \times 10^{12} \text{ m}^3 \text{ y}^{-1}$ ; UNESCO, 1979), heavy precipitation (2 m; Prasad, 1997), excess precipitation over evaporation (Varkey et al., 1996), frequent depressions and cyclones (Vinayachandran and Mathew, 2003). The river discharge together with the monsoon exerts a strong influence on the surface water circulation and stratification. Wind force is not enough to disrupt surface stratification in the Bay of Bengal (Patra et al., 2007). Therefore, supply of nutrients through vertical mixing is rather scarce. In contrast, strong winds, associated with depressions and cyclones, churn up upper ocean, erode density layer and inject nutrients to photic layer (Nayak et al., 2001; Vinayachandran and Mathew, 2003; Smitha et al., 2006). Tropical cyclones occur over Bay of Bengal during summer and winter that result in formation of phytoplankton blooms (Gomes et al., 2000; Vinayachandran, 2009). For instance, enhanced Chl-a concentration from 1 to  $10 \text{ mg m}^{-3}$  was observed off east coast of India due to flux of terrestrial nutrient to coastal ocean by super cyclone 1999 (Nayak et al., 2001; Madhu et al., 2002). Strong upwelling occurs along the east coast of India during summer (March-September) and its intensity decreases from south to north due to heavy river runoff in the northern Bay (Shetye et al., 1991). Upwelling promotes phytoplankton blooms along the west coast of Bay of Bengal (Gomes et al., 2000). In addition to this, occurrence of phytoplankton blooms during winter (November-February) was attributed to offshore Ekman pumping (Vinayachandran and Mathew, 2003). The primary production is higher during winter ( $0.2$  to  $0.56 \text{ gC m}^{-2} \text{ d}^{-1}$ ) than summer monsoon ( $0.1$  to  $0.2 \text{ gC m}^{-2} \text{ d}^{-1}$ ) due to thick cloud cover over Bay of Bengal during latter season (Gomes et al., 2000). Though primary productivity in the Bay of Bengal is low, compared to its adjacent basin Arabian Sea (Madhupratap et al., 1996; 2003), however higher rates were observed near the river mouth (Radhakrishna, 1978) and along the certain parts of western boundary due to the availability of high nutrients (Madhu et al., 2006; Kumar et al., 2010). Influence of atmospheric disturbances on phytoplankton biomass was recently reported in the coastal Bay of Bengal (Maneesha et al., 2011). Based on the remote sensing sensors data, Maneesha et al (2011) observed that each episodic atmospheric event enhances phytoplankton biomass and sustains for up to 2-3 weeks.

Prasanna Kumar et al. (2002) reported that the cold core eddies are important source of nutrients to promote phytoplankton blooms in the Bay of Bengal. However, the influence of atmospheric processes on surface biogeochemistry, such as nutrients and Chl-a, have not been well understood in the Bay of

Bengal and their impact on subsurface processes are unclear. For instance, like other regions of the northern Indian Ocean, oxygen depleted layer exists in the Bay of Bengal at the intermediate depths (Wyrski and Rochford, 1971; Rao et al., 1994; Sarma, 2002). Dissolved oxygen (DO) concentration in the intermediate layer (100-1000 m) is lower in the Arabian Sea ( $<5 \mu\text{M}$ ) compared to the Bay of Bengal ( $>10 \mu\text{M}$ ) and was attributed to faster scavenging of organic matter in the latter basin (Ittekkot et al., 1991; Rao et al., 1994). Naqvi et al. (2000) reported seasonal occurrence of suboxic to hypoxic conditions along the shelf of west coast of India that was attributed to coastal upwelling and anthropogenic inputs (such as fertilizers) through river runoff. Bay of Bengal indeed harbors conducive environment for the formation of suboxic conditions due to different sources of nutrients, as discussed above, and formation of phytoplankton blooms. However, there have been no reports of formation of suboxic conditions in the coastal Bay of Bengal. This could be also due to lack of systematic observations along the west coast of Bay of Bengal. In order to examine this, first ever time-series observations were conducted at 6 stations off Visakhapatnam, central east coast of India, to understand how physical and atmospheric forcing influence the biogeochemical processes of the water column in the coastal Bay of Bengal under the Surface Ocean Lower Atmosphere Study (SOLAS) program. The questions addressed in this study are: (i) what controls variations in nutrients and phytoplankton biomass in the coastal Bay of Bengal? and (ii) What are the potential causes for the development of suboxic or hypoxic conditions in the coastal Bay of Bengal?

## **2. Material and methods**

*Study site:* The continental shelf in the study site is quite steep as water column depth of 100m contour occurs at  $\sim 30$  km from the coast (Fig. 1). Bay of Bengal being a tropical basin, the biological production to a large extent must be modulated by the physical processes bringing nutrients to the photic layer. The study region receives enormous amount of freshwater by river discharge that peaks during monsoon (June to September; Fig. 2; Ittekkot et al., 1991; Varkey et al., 1996; Unger et al., 2003). In addition to this study site also affected by episodic events such as heavy precipitation associated with land drainage, cyclones, and seasonal coastal upwelling that brings significant quantities of nutrients to the photic layer (Maneesha et al., 2011). The depth of photic layer depends on the suspended load, which is again proportional to the amount of discharge. The primary production in the study region is also depended on the availability of solar radiation, which is relatively lower during summer due to large cloud cover than winter (Goes et al., 2000; Madhupratap et al., 2003).

## 2.1. Sample collection and analysis

The sampling was conducted in the coastal Bay of Bengal at six fixed stations (Fig. 1) at standard depths at monthly interval from October 2007 to April 2009. However sampling could not be done for three months (June, July and September 2008) due to logistical reasons. Vertical profiles of pressure, temperature and salinity were measured using portable Conductivity, Temperature and Depth (CTD) profiler (SBE 19 plus, SeaBird Electronics Inc., USA) and water samples were collected from surface, 5, 10, 15, 25, 50, 75 and 100 m using 5/10-litre Niskin bottle. The depth of the photic layer was measured using photosynthetic Active Radiation (PAR) sensor (Biospherical Instruments Inc., USA). Photic depth was calculated as drop in PAR by 1% from that of surface. Bubble free water samples were first taken for dissolved oxygen (DO) measurements following Winkler titration method of Carritt and Carpenter (1966). The analytical precision, expressed as standard deviation, was 0.07% for oxygen. The concentrations of nutrients were measured following standard spectrophotometric procedures using Autoanalyzer (Technicon, Tacs Private Limited, Australia) (Grasshoff et al., 1983). The detection limits for nitrate, ammonia, phosphate and silicate were  $\pm 0.05$ ,  $\pm 0.05$ ,  $\pm 0.02$  and  $\pm 0.03$   $\mu\text{M}$  respectively. A 2 L of water sample was filtered through GF/F filter (0.7  $\mu\text{m}$  pore size; Whatman). Chl-a on the filter was first extracted with *N,N*-dimethylformamide (DMF), at 4° C in dark for 12 h and then spectrofluorometrically analysed (Varian Eclipse fluorescence photometer) following Suzuki and Ishimaru (1990). The analytical precision for Chl-a analysis was  $\pm 4\%$ .

## 2.2. Experimental approach

In order to examine the biological response to nutrient enrichment, *in vitro* natural nutrient enrichment experiments were conducted. Nearly 20L of surface and 100 m deep water was collected in the transparent polypropylene Nalgene containers from V6 station on 22<sup>nd</sup> September 2009. Deep water was filtered through GF/F filter (0.7  $\mu\text{m}$ ; Whatman) to remove plankton whereas surface samples were sieved through a 200  $\mu\text{m}$  mesh to remove large zooplankton. The concentration of nutrients in the deep water was 15.2 and 2.4  $\mu\text{M}$  of nitrate and phosphate respectively. In one container, both surface and filtered deep water were mixed 1:1 ratio to enrich nutrients levels in the surface water. In another container, only surface sample was taken (control) and both were incubated on deck by continuously flowing surface seawater to maintain temperature of the sample close to *in situ*. The variations in nutrients and Chl-a were monitored for 4 days.

### 2.3. Other data source and statistics

The atmospheric data, such as rainfall, cyclone *Sidr*, were obtained from Indian Meteorological Department (IMD; [www.imd.gov.in](http://www.imd.gov.in)). The time-series Sea Surface Height Anomaly (SSHA) data was obtained from AVISO (<http://www.aviso.oceanobs.com/en/data/products/>). Sea surface currents data were obtained from altimetry ([www.aoml.noaa.gov](http://www.aoml.noaa.gov)). Downward solar radiation data was obtained from NOAA-NCEP reanalysis (<http://irid.ldeo.columbia.edu/SOURCES/NOAA/NCEP-DOE/reanalysis/>). Apparent Oxygen Utilization (AOU) was computed using formulations given by Garcia and Gordon (1992). Statistical analysis was performed using STATISTICA software to obtain linear correlation of nutrients with physical (salinity and temperature) and biological (Chl-a) properties and one way ANOVA was performed to examine the significance of variations of DO with reference to time. The contour figures were drawn using Ocean Data View while two dimensional (X-Y) figures were drawn with the help of Grapher (version 6.0).

## 3. Results and Discussion

### 3.1. Variability in water column temperature and salinity: Influence of physical and atmospheric events

Surface temperature structure followed classical solar radiation pattern which was cooler during winter (November to May) and warmer during summer (June to October). Water temperatures in the upper 10-15 m were cooler close to the coast (station V1) and increased towards offshore (Station V6) by 0.5 to 2.0° C (Fig. 3). For instance the mean water temperature in the upper 15m during October to December 2007 was ~27° C at station V1 whereas it was ~28° C at station V6 during same period. Stations V1, V2 and V3 (water column depth of 10, 20, and 30 m respectively; Fig. 1) displayed vertically uniform temperature whereas clear thermocline can be observed at stations V4 to V6 (Fig. 3 d-f). Hereafter the former three stations are called coastal and the latter three are called offshore stations.

Temperature structure during study period displayed presence of inversions of 0.5 to 1.0° C at all stations (Fig. 3a-f) and is consistent with previous reports (Shetye et al., 1996; Thadathil et al., 2002 and Thompson et al., 2006). Several mechanisms contribute to the temperature inversions in the Bay of Bengal, such as wind-forced advection of cold waters over warm waters, net heat loss at the surface and advection of cold, less saline over warm saline waters (Thadathil et al., 2002; Thompson et al., 2006). Significant temperature inversions were found especially during November 2007 to February 2008 and

November 2008 to February 2009 at all stations except at V1. Shetye et al. (1996) observed the freshest and coolest mixed layer during winter (northeast (NE) monsoon) that was attributed to cooling of surface water by northeasterly winds, resulting in temperature inversions. Thompson et al. (2006) noticed presence of temperature inversions in the Bay of Bengal throughout the year and were relatively strong during November to mid of March and weak during April and August which is consistent with our observations.

The vertical salinity structure showed strong stratification during the entire study period with vertical gradient in salinity between surface and 20 m by 2 to 10 during October-November 2007 and August to December 2008 whereas 0.5 to 1 during other period (Fig. 4). Less saline water was observed in the upper 15 m at all stations during October 2007 that was caused by heavy local precipitation of 238 mm on 4-5<sup>th</sup> October 2007 (Venkateswarlu and Sudhavalli, 2010). Gradual increase in salinity by 6 to 14 was observed from October 2007 to May 2008 at all stations. Again less saline waters were observed between August 2008 and January 2009 (25.5). These events were associated with local rainfall. The strong temperature inversions observed during winter were mainly caused by low saline water brought by equatorward moving East India Coastal Current (EICC). The weak salinity gradient during latter period (summer) was caused by change in the direction of EICC from equatorward to poleward resulting in advection of high saline Arabian Sea coastal waters to north along east coast of India (Shetye et al., 1996) that resulting in weakening of inversions (seasonal change in EICC direction is given in supplementary figure S1).

### *3.2. Variations in Chl-a and nutrients in the coastal Bay of Bengal*

The surface Chl-a concentration ranged between 0.31 to 3.31 and 0.11 to 3.44 mg m<sup>-3</sup> in the coastal and offshore regions respectively (Fig. 5). Relatively higher Chl-a was observed in the coastal region and was associated with high nutrient concentrations. For instance surface nitrate concentrations were ranged from 0.95 to 7.04 and 0.28 to 2.81  $\mu$ M in the coastal and offshore regions respectively (Fig. 6) whereas phosphate varied from 0.99-5.06 and 0.21-1.14  $\mu$ M respectively (Fig. 7). On the other hand, silicate concentrations ranged from 0.7-27.2 and 1.1-10.1  $\mu$ M respectively in the coastal and offshore regions (Fig. 8). Similarly the variations in DO concentration in the coastal (184.1-234.2 $\mu$ M) and offshore (170.9-226.7  $\mu$ M; Fig. 9) were broadly consistent with Chl-a (Fig. 5;  $r^2=0.3$ ;  $p<0.05$ ) suggesting biological process have dominant control. Intra-annual variations in Chl-a and nutrients were

caused by physical (vertical mixing, river discharge), and biogeochemical processes. Vertical mixing enhances nutrients concentration due to increase in its concentrations with depth. Such source of nutrients is normally associated with increase in salinity and decrease in temperature. On the other hand, association of nutrient increase with low salinity and warm waters denotes river driven sources. Based on the increase in Chl-a and associated changes in nutrients, temperature and salinity, it is possible to evaluate potential mechanisms controlling phytoplankton biomass in a given region. In our study region, both Chl-a and nutrients displayed significant monthly variability and were mainly associated with physical and atmospheric processes such as heavy rainfall, cyclone, offshore Ekman pumping, upwelling and circulation and are discussed below.

High Chl-a concentrations were observed ( $2.5$  to  $3.5$   $\text{mg m}^{-3}$ ; Fig. 5) in the coastal region during October 2007, which was 5 to 7 times higher than that of same period in 2006 ( $0.5$ - $0.8$   $\text{mg m}^{-3}$ ; Sarma et al., 2006). The patch of high Chl-a was (Fig. 5) associated with low saline (Fig. 4) and high concentrations of nitrate (Fig. 6), phosphate (Fig. 7) and silicate (Fig. 8; Table 1). High dissolved oxygen concentrations and oversaturation (106%) were observed, associated with high Chl-a in the low salinity patch indicating enhanced phytoplankton biomass was fueled by terregeneous nutrients. High silicate concentrations further indicates that nutrients were mainly brought by the land drainage (Fig. 8). Recently Maneesha et al. (2011) observed occurrence of high Chl-a patch of 100 x 200 kms off Visakhapatnam (our time-series region) due to heavy local precipitation. About 3 times higher primary production was observed during October 2007 than in the previous month ( $5$ - $18$   $\text{mgC m}^{-3} \text{d}^{-1}$  in September to  $18$ - $69$   $\text{mgC m}^{-3} \text{d}^{-1}$  in October 2007; Maneesha et al., 2011) suggesting episodic heavy rainfall event promoted phytoplankton bloom and sustained for about 2 weeks.

Similar observations were also noticed during October-November 2008 when increased silicate concentrations ( $13.7 \pm 2.6$   $\mu\text{M}$ ; Table 1; Fig. 8) were associated with freshwater input (salinity  $\sim 26.0$ ) in the upper 10 m (Fig. 4) in response to 124 mm of rainfall. However low Chl-a ( $0.23 \pm 0.11$   $\text{mg m}^{-3}$ ) was found during October 2008 and was increased to  $1.38 \pm 0.61$   $\text{mg m}^{-3}$  by November 2008. Since sampling was carried out immediate after rainfall event during October 2008, its influence on phytoplankton biomass was not noticed. Furthermore, satellite altimetry data suggests that EICC was relatively weak ( $\sim 0.3$   $\text{m s}^{-1}$ ) during October-November 2008 than 2007 ( $\sim 1.1$   $\text{m s}^{-1}$ ) that led to less spread of nutrients brought by land drainage. Hence enhanced Chl-a concentrations were found during November 2008

( $1.38 \pm 0.61 \text{ mg m}^{-3}$ ). Due to cloud cover, satellite Chl-a imageries could not be retrieved to examine the spread and length of the bloom period.

Enhanced Chl-a were observed during November 2007 (Table 1) associated with cooler temperature (Fig. 3) in the upper 20 m from the coast to about 20 km offshore (Fig. 3b) and high nutrients (nitrate and phosphate; Fig. 6,7). The potential source of nutrients could be land-derived material brought either by local precipitation or advected from elsewhere by coastal currents. No significant precipitation was recorded surrounding to the study site during November (27 mm); therefore, the latter mechanism may be possible. The EICC flows from north to south (equatorward flow) along the east coast of India during November (Shetye et al., 1996; Varkey et al, 1996). Therefore, nutrients might have been brought from the northwestern coastal Bay of Bengal to the study region.

It has been observed that cyclone *Sidr* that was formed in the southeast Andaman Sea and intensified to a very severe cyclone and crossed Bangladesh coast on 15<sup>th</sup> November 2007. As a result of cyclone *Sidr*, massive landfall occurred that led to injection of terrogenous nutrients to the coast off Bangladesh (Maneesha et al., 2011). The near surface currents by altimeter suggest that the EICC was strong during this period ( $1.5 \text{ to } 2 \text{ m s}^{-1}$ ) along the west coast of Bay of Bengal. Hence, nutrient rich cold waters from the Bangladesh coast can reach the study region by EICC within 2 to 3 days. This resulted in enhanced nutrients and phytoplankton biomass at the study site during November 2007.

Enhanced dissolved oxygen concentrations in the upper 30-40m (by  $10\text{-}20 \text{ }\mu\text{M}$ ; Fig. 9) was observed during December than November 2007 associating with high Chl-a indicating increased primary production. Upslopping of cooler waters from the subsurface depth can be noticed during December to February (Fig. 3). Vinayachandran and Mathew (2003) reported occurrence of openocean upwelling by ekman pumping led to formation of phytoplankton blooms in the southwest coast of Bay of Bengal. They further noticed that these blooms intensify due to cyclones. Due to occurrence of cyclone *Sidr* during previous month (November 2007), the phytoplankton blooms were intensified during December 2007. It was further observed that phosphate levels quickly stripped off from the surface layer in the offshore and decreased from December 2007 to February 2008 from  $1.12 \pm 0.3$  to  $0.15 \pm 0.1 \text{ }\mu\text{M}$ , when nitrate was relatively high ( $1.06 \text{ to } 2.89 \text{ }\mu\text{M}$ ; Table 1b), suggesting that phosphate seems to be a controlling nutrient during this period. Low Chl-a and DO in February resulted from the decrease in nutrient inputs. In contrast to this, Chl-a concentrations remained high with high nitrate ( $1.74 \pm 4.5 \text{ }\mu\text{M}$ )



and phosphate ( $1.19 \pm 1 \mu\text{M}$ ; Table 1a) in the coastal waters. It is possible that coastal water receive nutrients through vertical mixing as the vertical salinity gradient was relatively weak (Fig. 4).

The temperatures in the upper 50-70 m were further cooled with increased salinity and upsloping of isoline from March to June 2008 indicating occurrence of coastal upwelling (Fig. 3, 4). Occurrence of localized upwelling along east coast was observed and normally found to be restricted to ~40 km wide band along the western Bay of Bengal (Murty and Varadachari, 1968; de Sousa et al., 1981; Shetye et al., 1991). In contrast, penetration of high DO (Fig. 9f) and low nitrate (Fig. 6f) contours to the deeper depth was observed at station V6 during March 2008 suggesting sinking of waters towards offshore region. Based on the altimeter data, existence of warm core (anticyclonic) eddy was observed at station V6 suggesting sinking was led by warm core eddy. As a result of enhanced nutrients due to upwelling, Chl-a concentration increased to  $2.60 \pm 0.24 \text{ mg m}^{-3}$  in the coastal region whereas it was less in the offshore ( $0.69 \pm 0.52 \text{ mg m}^{-3}$ ). Despite injection of nutrients by upwelling, the increase in Chl-a during March 2008 was not dramatic compared to other periods that was caused by thick cloud cover. It was observed that downward solar radiation was lower by  $50\text{-}65 \text{ W m}^{-2}$  during summer than winter.

#### 3.4. Mechanisms controlling nutrients distribution in the photic zone

The relationship between nutrients and salinity indicates the source of nutrients to the system. For instance, the nutrients increase associates with increase in salinity indicates vertical mixing while decrease in salinity denotes riverine sources. In order to examine the impact of physical processes on nutrients distribution in the study region, the relationship between nutrients and salinity was derived. Temperature-salinity relationship in the photic layer displays two pools of waters, i.e., warmer low saline ( $\leq 30$ ) and colder high saline waters ( $> 30$ ) that were mainly contributed by river discharge and vertical mixing respectively (Fig 10a). The relationship of nutrients and Chl-a with salinity indicates two mechanisms are responsible for their variability during entire study period. When salinity was  $\leq 30$ , inverse relationships of Chl-a ( $r^2=0.38$ ;  $n=30$ ;  $p<0.05$ ), nitrate ( $r^2=0.62$ ;  $n=29$ ;  $p<0.001$ ) and silicate ( $r^2=0.49$ ;  $n=26$ ;  $p<0.001$ ) with salinity suggest that river water is a significant source of nitrate and silicate to the coastal region to support high Chl-a (Fig. 10). High concentrations of nutrients, and Chl-a were associated with high salinity and were caused by upwelling, ekman pumping and cyclone driven vertical mixing. In contrast to this, phosphate, and ammonium showed no significant relationship with salinity and their concentration rather increased slightly with salinity.

Variability in Chl-a and nutrients concentrations were also caused non-cyclicly of physical and atmospheric forcing. For instance, variability in Chl-a concentration during summer to winter (August to December) in 2007 and 2008 were probably due to different source of water mass. Close to the coast, warmer and saltier waters were found than offshore (V4-V6) by  $0.5^{\circ}\text{C}$  and  $2^{\circ}\text{C}$  respectively during August to December 2008 than 2007. Salinity during November to December was lower during 2008 than 2007 suggesting that more influence of river discharge during former year. Nutrients concentrations were relatively higher during 2008 than 2007 during August to December suggesting that more nutrients were brought by high river discharge during former year. This was further observed that mean suspended load during 2008 was higher by  $8\pm 3\text{ mg l}^{-1}$  than 2007 ( $4\pm 2\text{ mg l}^{-1}$ ) and was associated with high discharge (Irrigation Department, personnel communication, 2011). This led to a decrease in photic depth during 2008 that might have influenced phytoplankton biomass. Increase in nutrient (nitrate, phosphate and silicate; Fig. 6-8) concentration in the coastal stations can be noticed in April 2009, which was relatively higher than that of 2008. The increase in coastal nutrients during April 2009 was associated with coastal upwelling. Both temperature and salinity data suggest that relatively more cool and saline waters were noticed during April 2009 than 2008 suggesting upwelling was more intense during former than latter period that resulting in injection of more nutrients to the surface. In addition to this, both N:P and Si:N ratios were significantly different during winter 2007-2008 (N:P= $12.4\pm 0.8$ : Si:N= $3.3\pm 0.4$ ) than 2008-2009 (N:P= $9.8\pm 2.5$ : Si:N= $2.0\pm 0.2$ ). This variability was mainly driven by source of nutrients. During 2007-2008 winter, nutrients were received by different extreme atmospheric events that brought nutrients rich waters from the land-runoff. In contrast to this, such extreme events were absent during 2008-2009 winter when nutrients source were solely due to river runoff where nitrate is relatively depleted as most of it is normally consumed within the estuary itself (Sarma et al., 2010).

### 3.5. Phytoplankton response to enhanced nutrients levels

Time-series observations indicate that phytoplankton in the surface waters were starving for nutrients. To examine this *in vitro* natural nutrient enrichment experiment was conducted during September 2009. In the control, Chl-a was  $\sim 0.64\text{ mg m}^{-3}$  and has been rapidly increased to  $1.68\text{ mg m}^{-3}$  on day 2 and then decreased to  $0.38\text{ mg m}^{-3}$  on the day 4 (Table 2). The increase in Chl-a in the control could possibly due to increase in the bottle temperature by about  $1$  to  $2^{\circ}\text{C}$  from that of *in situ* temperature and also availability of nutrients. The rapid decrease in Chl-a was associated with depletion of nutrients, especially nitrate. The nitrate concentrations were close to the threshold level to control the

phytoplankton biomass in the control bottle (Justic et al., 1995). The nitrate concentrations decreased rapidly from 0.98 to 0.11  $\mu\text{M}$  whereas phosphate at the end of the experiment was  $\sim 0.49 \mu\text{M}$  suggesting that rapid removal of nitrate in the sample resulting in decrease in Chl-a. The mean low N:P ratio ( $<2$ ) than Redfield ratio of 16 (Redfield et al., 1963; Brzezinski, 1985; Brzezinski and Nelson, 1995) in the control bottle further suggest that nitrogen is the limited nutrient for phytoplankton biomass. On the other hand, Chl-a was relatively lower in the nutrients enriched sample ( $\sim 0.27 \text{ mg m}^{-3}$ ) due to dilution of filtered deep water. The increase in Chl-a in the nutrients enriched water was seen at the end of day 2 ( $0.43 \text{ mg m}^{-3}$ ) and then increased sharply to  $3.74 \text{ mg m}^{-3}$  on day 4. In the nutrient enriched sample, N:P ratios increased to  $>4$  and both phosphate and nitrate exhausted to almost half by the end of day 4. As a result, the response of phytoplankton biomass was seen associated with extreme atmospheric or physical events brought nutrients to the sunlit zone. It is further evidenced from Nayak *et al* (2001) observations that enhanced Chl-a levels of  $\sim 5\text{-}10 \text{ mg m}^{-3}$  were found along the central west coast of the Bay of Bengal after the landfall driven by super cyclone on 29<sup>th</sup> October 1999, at Paradip, Orissa. Madhu et al. (2002) also noted enhanced nutrients concentrations (nitrate by  $1 \mu\text{M}$ ) and the consequent increase in primary production (by 21 to  $955 \text{ mgC m}^{-2} \text{ d}^{-1}$ ) in the south western Bay of Bengal, driven by the super cyclone. Similar observations were recently reported by Maneesha et al (2011) in response to cyclone *Sidr*.

### 3.5. Influence of physical processes on subsurface waters

In addition to the extremely atmospheric events, the coastal Bay of Bengal receives huge amount of fertilizers through the rivers as the use of fertilizers in the east coast is several folds higher than that of west coast (Indian Agriculture department, <http://indiastat.com/agriculture/2/stats.aspx>). Due to nutrients enrichment in the surface, it is obvious that subsurface oxygen levels are expected to be low in the coastal Bay of Bengal than Arabian Sea where hypoxic conditions were noticed (Naqvi et al., 2000). The DO concentrations at 100 m depth at station V6 were found to be decreased from  $73.5 \mu\text{M}$  during October 2007 to  $\sim 5 \mu\text{M}$  in February 2008 and increased sharply to  $57.5 \mu\text{M}$  in March 2008 at the same depth (Fig. 11). The variations in DO levels at 100 m depth with reference to time were statistically significant (one way ANOVA,  $f=25.1$ ;  $p<0.001$ ;  $n=15$ ). DO concentrations decreased gradually after April 2008, albeit with fluctuations, to April 2009 with the lowest concentrations of  $\sim 20 \mu\text{M}$  in December 2008. Apparent oxygen utilization (AOU) increased from  $125 \mu\text{M}$  in October 2007 to  $220 \mu\text{M}$  in February 2008 and then decreased to  $100 \mu\text{M}$  in March 2008 (Figure not shown). The decrease in

subsurface oxygen levels were caused by either increase in stratification that lead to decrease in vertical mixing of oxygen or increase biomass in the water column resulting in enhanced organic matter decomposition at depth.. The density difference between surface and 100 m is a proxy for strength of the stratification as the more difference indicates stronger stratification and vice versa. The density difference between surface and 100m layer varied between 0.9 and 11.4 g m<sup>-3</sup> during study period with the highest during October-November 2007 while the lowest was found during December 2007 and 2008. (Fig 11) and showed significant positive correlation with bottom DO ( $r^2=0.58$ ;  $p<0.001$ ). Though strong stratification decreases DO levels in the subsurface waters due to decreased supply from the upper layers, however, the positive relation between surface to bottom density difference and bottom DO suggests that stratification alone is not responsible for development of low DO levels at the bottom in our study region (Fig. 11). On the other hand water column integrated Chl-a showed negative correlation with DO levels at 100m ( $r^2=0.59$ ;  $p<0.001$ ), except during October and November 2007, strongly suggesting that enhanced phytoplankton biomass due to physical processes are responsible for variations in DO levels at bottom. (Fig. 11). Interestingly, DO concentration increased sharply from ~5  $\mu\text{M}$  in February 2008 to 57.5  $\mu\text{M}$  in March 2008. What was the potential mechanism for the decrease in DO concentration to such low levels in February 2008 and sharp increase in March 2008 at 100 m depth? Several recent works suggested that water column nutrients and oxygen concentrations in the Bay of Bengal, both onshore and offshore, were mainly driven by physical process alone through advection of water masses and faster scavenging of organic matter through mineral particles (Madhu et al., 2006; Sardesai et al., 2007). In order to examine the advection of low oxygen waters from the offshore region to the station V6, the vertical profile of DO was observed at about 10 km towards offshore from station V6 during February 2008. DO at these two stations are almost equal at 100 m. Therefore, horizontal advection may not be possible reason for oxygen decrease at station V6. On the other hand, DO at 200 m was ~7  $\mu\text{M}$  in February, where temperature was lower by 5° C and salinity was higher by ~0.5 from that of 100 m depth. If vertical mixing is responsible for the decrease of DO at 100 m, this should result in decrease in appreciable degree of temperature at 100 m. Interestingly, the temperature variations at 100 m at station V6 from December to February was <0.5° C strongly suggesting that low DO was not due to vertical mixing. Low concentration of DO in winter does not seem to be a regular phenomenon as ~20  $\mu\text{M}$  was found in 2008-2009 winter, suggesting it may be a unique feature in 2007-2008 winter. Chl-a and nutrient, between October and December 2007, were significantly higher than that of 2008 due to occurrence of extreme atmospheric events during former

year. This led to enhanced organic carbon fluxes to deep and decrease in DO levels through decomposition by resident heterotrophs. Interestingly sharp increase in DO levels during March 2008 from that of former month was associated with deepening of isotherms (Fig. 3f) and nitracline (Fig. 6f) suggesting sinking of water mass from surface. The surface currents data by altimeter images on the day of sampling suggest that no eddies were found close to our time-series locations (Fig. 6) during the sampling dates from October 2007 to February 2008, however, westward moving anticyclonic eddy (warm core) was observed close to the station V6 in March 2008. Sinking takes place in the anticyclonic eddy resulting in injection of oxygen rich and nutrient poor waters to the deep (Sandra et al., 2005). The variations in sea surface height anomaly (SSHA) indicate upwelling and sinking of waters as the negative anomaly suggests upwelling while positive indicates sinking of waters. The SSHA varied between  $-9.2$  and  $14.8$  cm during the study period and sharp increase of  $14.8$  cm was observed in March 2008 confirming sinking of waters. The bottom water oxygen concentrations showed weak positive relation with SSHA ( $r^2=0.26$ ;  $n=15$ ;  $p=0.1$ ) suggesting that warm core eddies may play significant role on maintenance of suboxic waters in the coastal Bay of Bengal. This study suggests that not only enhanced biomass regeneration, but also eddies play significant role on controlling oxygen levels in the bottom waters of the coastal Bay of Bengal.

#### 4. *Summary and Conclusions*

Time-series observations in physical and biogeochemical processes in the west coast of Bay of Bengal reveal that physical processes, such as circulation and river discharge, have significant impact on nutrients cycling and phytoplankton biomass. Despite high river discharge associated with nutrients in summer, phytoplankton biomass was higher during winter than summer due to thick cloud cover and suspended load controlling phytoplankton biomass during latter season. The subsurface DO levels decreased from  $\sim 73.5$   $\mu\text{M}$  during October 2007 to  $\sim 5$   $\mu\text{M}$  in February 2008 indicating the possible formation of sub-oxic condition due to enhanced surface production and their eventual sinking. The sharp increase in DO concentrations to  $57.5$   $\mu\text{M}$  in March 2008 was associated with sinking of surface waters driven by anticyclonic eddy. Unlike in the west coast of India, where suboxic to anoxic conditions form during summer, the formation of such conditions in the east coast of India were hindered by re-oxygenation of deep waters by anticyclonic (warm core) eddies. This study reveals that significant impact of the atmospheric forcing on the water column biogeochemistry in the coastal Bay of Bengal.

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## Legend to figures

Figure 1: Locations of the time-series station, off Visakhapatnam, in the east coast of India. The lines in the insert denotes river network in India.

Figure 2: Schematic diagram showing the sources of nutrients to the photic layer in the study region and influence of different physical process in the a) coastal and b) offshore region.

Figure 3: Time-series variations in temperature ( $^{\circ}\text{C}$ ) at different stations. a-f are stations V1 to V6 respectively. The boxes indicates where temperature inversions can be noticed.

Figure 4: Time-series variations in salinity at different stations. a-f are stations V1 to V6 respectively.

Figure 5: Time-series variations in Chl-a ( $\text{mg m}^{-3}$ ) at different stations. a-f are stations V1 to V6 respectively.

Figure 6: Time-series variations in nitrate ( $\mu\text{M}$ ) at different stations. a-f are stations V1 to V6 respectively.

Figure 7: Same as in Figure 6 for phosphate ( $\mu\text{M}$ ).

Figure 8: Same as in Figure 6 for silicate ( $\mu\text{M}$ ).

Figure 9: Time-series variations in dissolved oxygen ( $\mu\text{M}$ ) at different stations. a-f are stations V1 to V6 respectively.

Figure 10: Relationships of salinity with a) temperature, b) Chl-a, c) Nitrate, d) Phosphate, e) ammonium and f) silicate in the photic layer. The open circles represent salinity  $<30$  and solid circles for salinity  $>30$ . The solid line denotes the correlation line.

Figure 11: Monthly variations in bottom water dissolved oxygen at 100 m (red), difference in density between surface and 100 m (purple) and water column integrated Chl-a (green) at station V6. The figure in insert show relation of DO concentration at 100 m with density gradient from surface to 100m and water column integrated Chl-a. In the latter relationship, the data points during October and November 2007 were excluded.

Table 1a: Mean ( $\pm$ SD) of photic zone Chl-a ( $\text{mg m}^{-3}$ ), DO ( $\mu\text{M}$ ), nutrients ( $\mu\text{M}$ ) and their ratios in the coastal (V1-V3) stations in the coastal Bay of Bengal.

Month/year	Chl-a	DO	$\text{NO}_3$	$\text{NH}_4$	$\text{PO}_4$	$\text{Si(OH)}_4$	N:P	Si:N
Oct 2007	3.31 $\pm$ 1.1	202.5 $\pm$ 10	1.28 $\pm$ 0.5	0.66 $\pm$ 0.4	0.84 $\pm$ 0.7	13.41 $\pm$ 7.8	3.6 $\pm$ 2	18.2 $\pm$ 7
Nov 2007	1.91 $\pm$ 0.2	2223.1 $\pm$ 12	7.46 $\pm$ 1.8	3.76 $\pm$ 3	0.60 $\pm$ 0.1	0.71 $\pm$ 0.2	19.5 $\pm$ 9	1.2 $\pm$ 0.6
Dec 2007	2.47 $\pm$ 0.8	236.7 $\pm$ 14	1.19 $\pm$ 0.9	0.83 $\pm$ 0.5	0.30 $\pm$ 1.7	3.39 $\pm$ 1.2	12.5 $\pm$ 0.5	2.0 $\pm$ 2.0
Jan 2008	1.54 $\pm$ 0.4	2221.0 $\pm$ 11	2.30 $\pm$ 3.1	2.09 $\pm$ 0.8	0.52 $\pm$ 0.5	2.80 $\pm$ 1.8	14.8 $\pm$ 44	0.9 $\pm$ 0.3
Feb 2008	1.81 $\pm$ 0.4	195.8 $\pm$ 9	1.74 $\pm$ 4.5	1.68 $\pm$ 1.3	1.19 $\pm$ 1.0	1.45 $\pm$ 1.6	11.2 $\pm$ 21	0.8 $\pm$ 0.5
Mar 2008	2.60 $\pm$ 0.2	180.0 $\pm$ 16	4.16 $\pm$ 1.3	1.69 $\pm$ 0.5	1.37 $\pm$ 0.6	2.48 $\pm$ 0.6	14.5 $\pm$ 1	1.0 $\pm$ 0.6
Apr 2008	3.00 $\pm$ 2.2	243.9 $\pm$ 16	3.87 $\pm$ 2.6	1.30 $\pm$ 0.2	0.30 $\pm$ 1.0	3.37 $\pm$ 0.6	13.7 $\pm$ 2	5.2 $\pm$ 5
May 2008	1.98 $\pm$ 0.6	202.2 $\pm$ 18	3.27 $\pm$ 1.5	1.82 $\pm$ 0.3	0.32 $\pm$ 0.1	2.07 $\pm$ 0.4	15.8 $\pm$ 6	6.9 $\pm$ 2
Aug 2008	0.69 $\pm$ 0.5	212.4 $\pm$ 21	4.88 $\pm$ 3.2	0.80 $\pm$ 0.2	2.17 $\pm$ 2.6	2.94 $\pm$ 2.2	2.6 $\pm$ 0.3	0.5 $\pm$ 0.1
Oct 2008	0.23 $\pm$ 0.1	222.5 $\pm$ 13	2.54 $\pm$ 0.9	0.66 $\pm$ 0.1	0.79 $\pm$ 0.1	14.08 $\pm$ 2.6	4.0 $\pm$ 0.5	4.4 $\pm$ 1.2
Nov 2008	1.38 $\pm$ 0.6	209.8 $\pm$ 16	2.05 $\pm$ 4.2	5.36 $\pm$ 1.9	1.13 $\pm$ 0.3	17.83 $\pm$ 4.5	15.8 $\pm$ 4	2.4 $\pm$ 0.9
Dec 2008	0.31 $\pm$ 0.2	198.6 $\pm$ 9	2.76 $\pm$ 1.0	0.86 $\pm$ 0.3	0.32 $\pm$ 0.1	1.58 $\pm$ 0.6	11.5 $\pm$ 4	5.0 $\pm$ 2
Jan 2009	0.53 $\pm$ 0.2	218.7 $\pm$ 22	0.96 $\pm$ 0.9	1.31 $\pm$ 0.4	0.38 $\pm$ 0.3	2.90 $\pm$ 1.1	10.2 $\pm$ 1	1.3 $\pm$ 0.3
Feb 2009	0.40 $\pm$ 0.2	209.8 $\pm$ 22	1.07 $\pm$ 3.0	1.84 $\pm$ 0.5	0.47 $\pm$ 0.1	2.10 $\pm$ 1.0	11.4 $\pm$ 4	0.8 $\pm$ 0.1
Mar 2009	1.27 $\pm$ 0.8	215.8 $\pm$ 19	4.00 $\pm$ 0.7	0.96 $\pm$ 0.3	2.87 $\pm$ 1.0	2.51 $\pm$ 2.1	12.4 $\pm$ 2	0.3 $\pm$ 3
Apr 2009	1.52 $\pm$ 0.4	236.3 $\pm$ 55	2.03 $\pm$ 2.4	3.14 $\pm$ 1.2	1.61 $\pm$ 1.5	25.25 $\pm$ 12	15.9 $\pm$ 14	5.1 $\pm$ 2

Table 1b: Mean ( $\pm$ SD) of photic zone Chl-a ( $\text{mg m}^{-3}$ ), DO ( $\mu\text{M}$ ), nutrients ( $\mu\text{M}$ ) and their ratios in the offshore (V4-V6) stations in the coastal Bay of Bengal.

Month/year	Chl-a	DO	NO <sub>3</sub>	NH <sub>4</sub>	PO <sub>4</sub>	Si(OH) <sub>4</sub>	N:P	Si:N
Oct 2007	3.44 $\pm$ 1.0	181.2 $\pm$ 23	1.02 $\pm$ 0.3	1.27 $\pm$ 0.8	0.66 $\pm$ 0.4	10.07 $\pm$ 2.4	4.7 $\pm$ 2	4.8 $\pm$ 7
Nov 2007	1.32 $\pm$ 0.6	209.4 $\pm$ 7	5.36 $\pm$ 2.7	2.51 $\pm$ 1.1	0.74 $\pm$ 0.1	1.40 $\pm$ 1.0	11.4 $\pm$ 6	0.2 $\pm$ 0.1
Dec 2007	0.68 $\pm$ 0.3	207.2 $\pm$ 8	1.06 $\pm$ 0.8	1.85 $\pm$ 1.8	1.12 $\pm$ 0.3	1.95 $\pm$ 1.6	16.5 $\pm$ 8	0.7 $\pm$ 0.1
Jan 2008	0.38 $\pm$ 0.1	197.6 $\pm$ 4	2.89 $\pm$ 2.7	0.65 $\pm$ 0.6	0.16 $\pm$ 0.1	2.48 $\pm$ 1.3	22.4 $\pm$ 15	0.7 $\pm$ 0.1
Feb 2008	0.29 $\pm$ 0.1	186.5 $\pm$ 5	1.35 $\pm$ 1.3	1.20 $\pm$ 0.6	0.15 $\pm$ 0.1	2.83 $\pm$ 0.7	18.6 $\pm$ 10	1.1 $\pm$ 0.2
Mar 2008	0.69 $\pm$ 0.5	178.0 $\pm$ 31	1.53 $\pm$ 0.4	1.06 $\pm$ 0.2	0.32 $\pm$ 0.1	2.45 $\pm$ 0.4	7.7 $\pm$ 1	0.9 $\pm$ 0.1
Apr 2008	0.16 $\pm$ 0.1	240.4 $\pm$ 5	5.34 $\pm$ 1.8	1.06 $\pm$ 0.1	0.90 $\pm$ 0.3	2.50 $\pm$ 0.8	8.7 $\pm$ 2	0.4 $\pm$ 0.1
May 2008	0.29 $\pm$ 0.1	205.6 $\pm$ 2	2.12 $\pm$ 1.2	0.92 $\pm$ 0.2	0.29 $\pm$ 0.1	3.73 $\pm$ 0.3	12.2 $\pm$ 4	1.4 $\pm$ 0.2
Aug 2008	0.19 $\pm$ 0.1	205.1 $\pm$ 11	1.98 $\pm$ 0.5	0.63 $\pm$ 0.2	0.21 $\pm$ 0.2	4.19 $\pm$ 3.4	9.6 $\pm$ 1	1.6 $\pm$ 0.2
Oct 2008	0.60 $\pm$ 0.6	216.7 $\pm$ 19	1.80 $\pm$ 0.4	0.56 $\pm$ 0.1	0.85 $\pm$ 0.1	6.69 $\pm$ 2.1	5.1 $\pm$ 0.5	2.8 $\pm$ 0.3
Nov 2008	0.55 $\pm$ 0.6	201.8 $\pm$ 46	1.17 $\pm$ 3.2	4.61 $\pm$ 3.4	0.72 $\pm$ 0.4	2.37 $\pm$ 1.8	7.0 $\pm$ 0.8	1.2 $\pm$ 0.1
Dec 2008	0.13 $\pm$ 0.1	181.2 $\pm$ 9	1.38 $\pm$ 0.8	0.91 $\pm$ 0.2	0.35 $\pm$ 0.1	4.90 $\pm$ 2.8	7.1 $\pm$ 3	2.1 $\pm$ 0.3
Jan 2009	0.12 $\pm$ 0.1	205.3 $\pm$ 7	1.00 $\pm$ 1.0	1.76 $\pm$ 1.6	0.37 $\pm$ 0.6	2.19 $\pm$ 1.1	12.3 $\pm$ 2	0.8 $\pm$ 0.3
Feb 2009	0.11 $\pm$ 0.1	195.9 $\pm$ 7	1.19 $\pm$ 1.0	1.64 $\pm$ 0.5	0.25 $\pm$ 0.1	1.64 $\pm$ 1.0	12.4 $\pm$ 1	0.4 $\pm$ 0.1
Mar 2009	0.16 $\pm$ 0.1	187.6 $\pm$ 9	2.21 $\pm$ 0.9	0.72 $\pm$ 0.3	0.26 $\pm$ 0.1	3.89 $\pm$ 0.7	13.0 $\pm$ 2	2.3 $\pm$ 0.1
Apr 2009	1.35 $\pm$ 0.6	221.1 $\pm$ 6	1.54 $\pm$ 0.8	1.65 $\pm$ 2.4	0.30 $\pm$ 0.2	1.16 $\pm$ 1.0	14.4 $\pm$ 4	1.4 $\pm$ 0.4

Table 2: Initial and final conditions of nutrients and Chl-a in the incubation experiment. BD=below detection limits

Days	Surface (Control)					Surface+deep water				
	NO <sub>3</sub> (μM)	NH <sub>4</sub> (μM)	PO <sub>4</sub> (μM)	SiO <sub>4</sub> (μM)	Chl-a (mg m <sup>-3</sup> )	NO <sub>3</sub> (μM)	NH <sub>4</sub> (μM)	PO <sub>4</sub> (μM)	SiO <sub>4</sub> (μM)	Chl-a (mg m <sup>-3</sup> )
0	1.00	0.25	0.82	3.27	0.64	7.97	0.12	1.84	13.27	0.27
1	0.84	0.20	0.78	3.17	1.27	7.36	0.11	1.64	13.10	0.23
2	0.67	0.11	0.83	3.05	1.68	7.26	BD	1.61	13.07	0.43
3	0.23	0.08	0.62	3.01	1.29	5.93	BD	1.47	13.16	2.09
4	0.11	0.15	0.49	2.87	0.38	4.91	BD	1.23	13.14	3.74

Figure 1

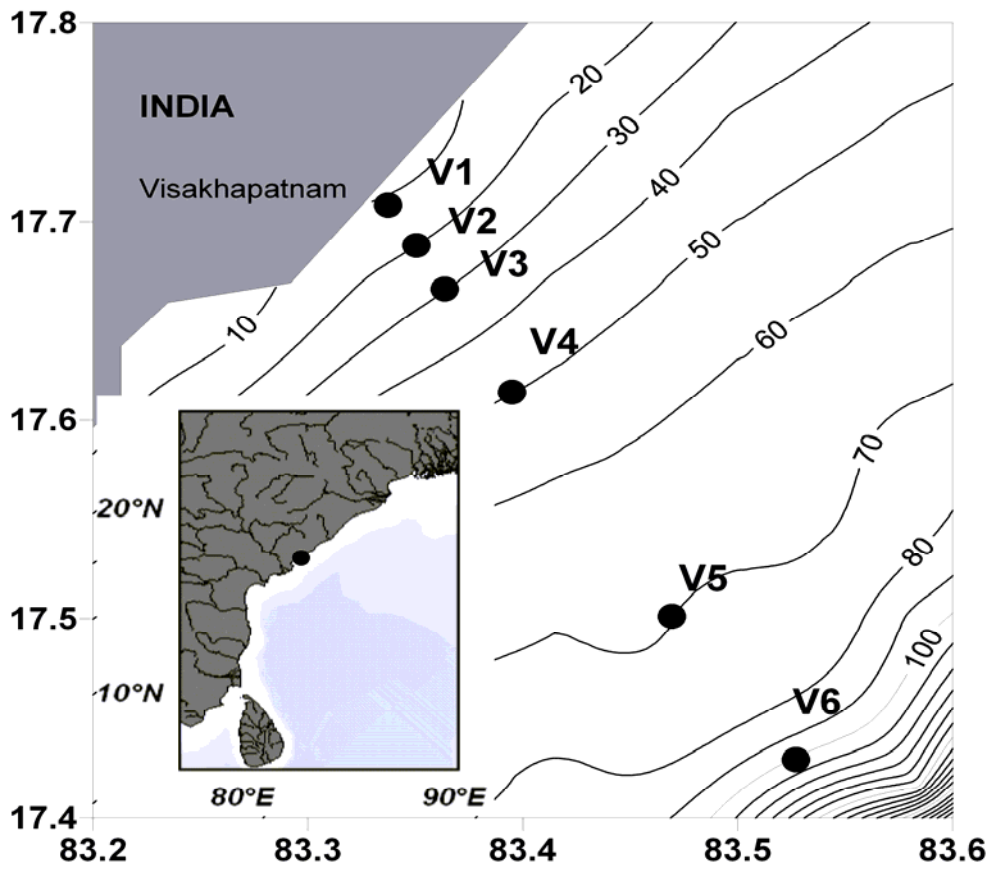


Figure 2

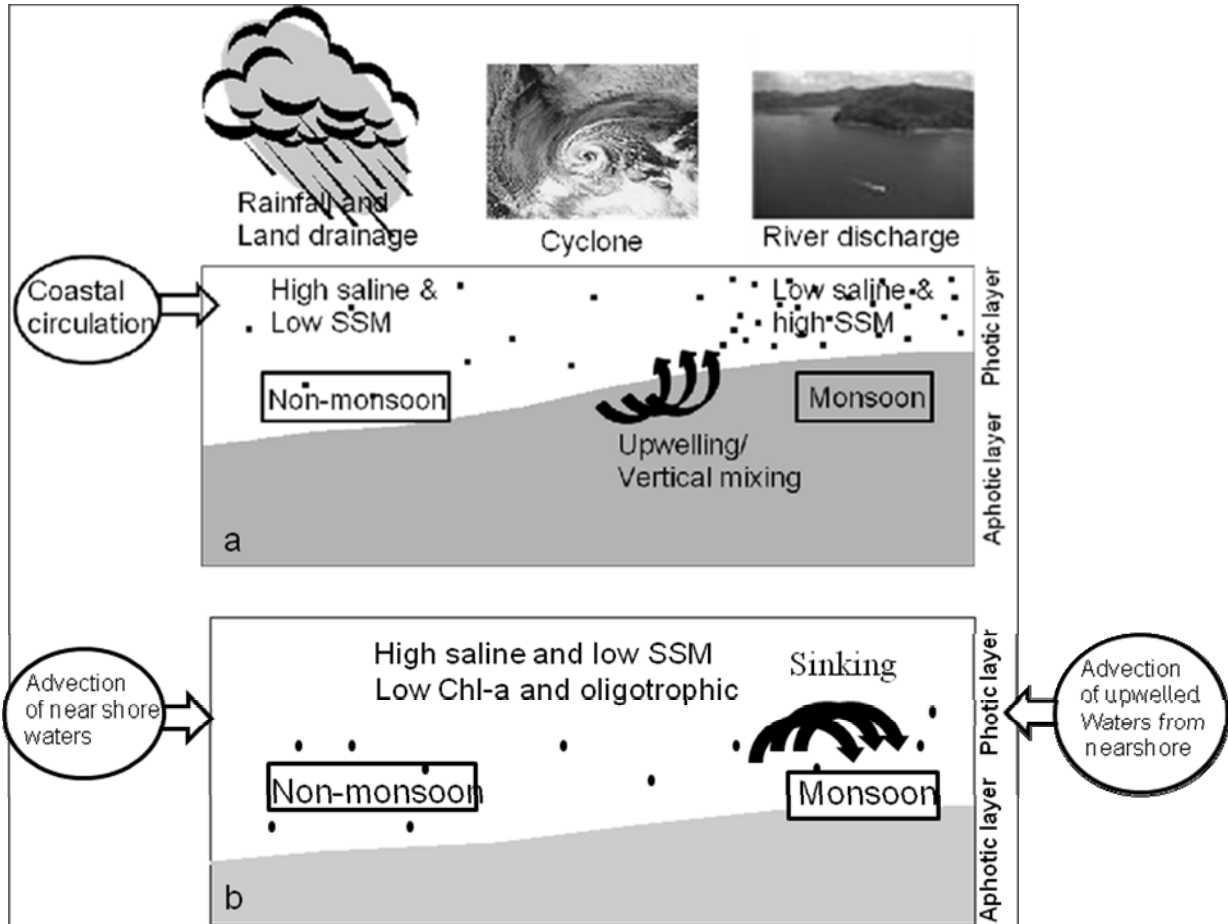


Figure 3

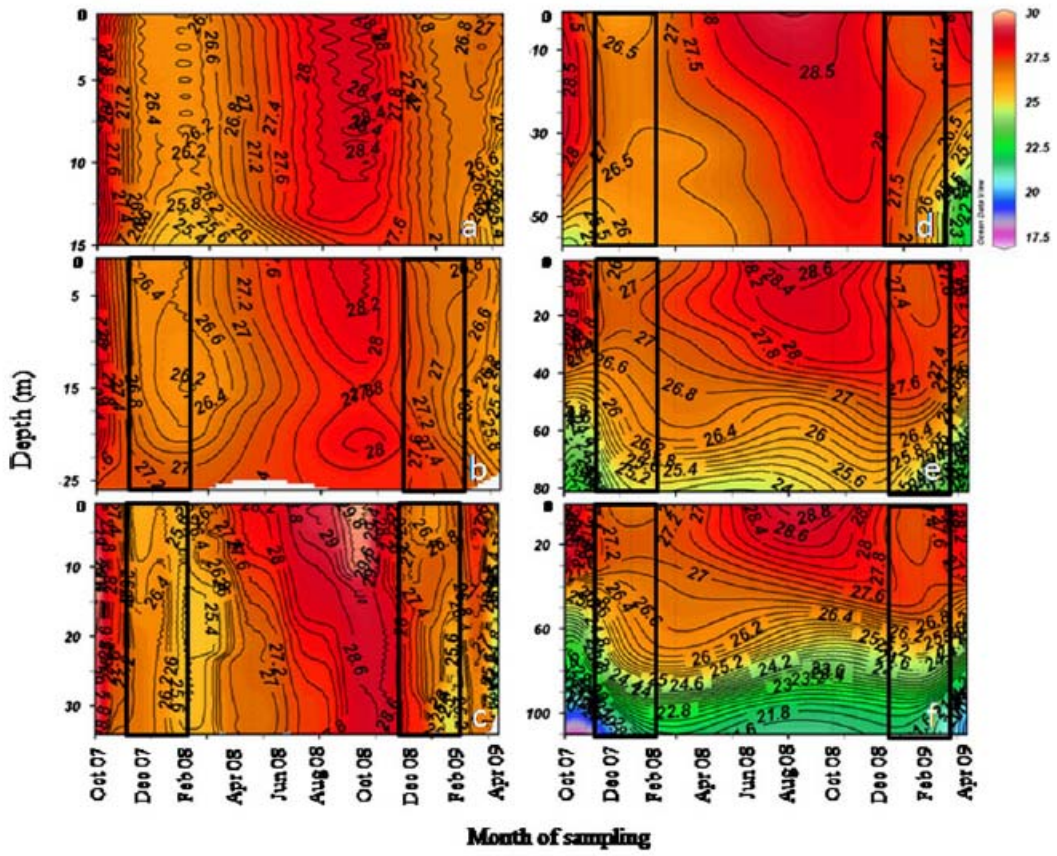


Figure 4

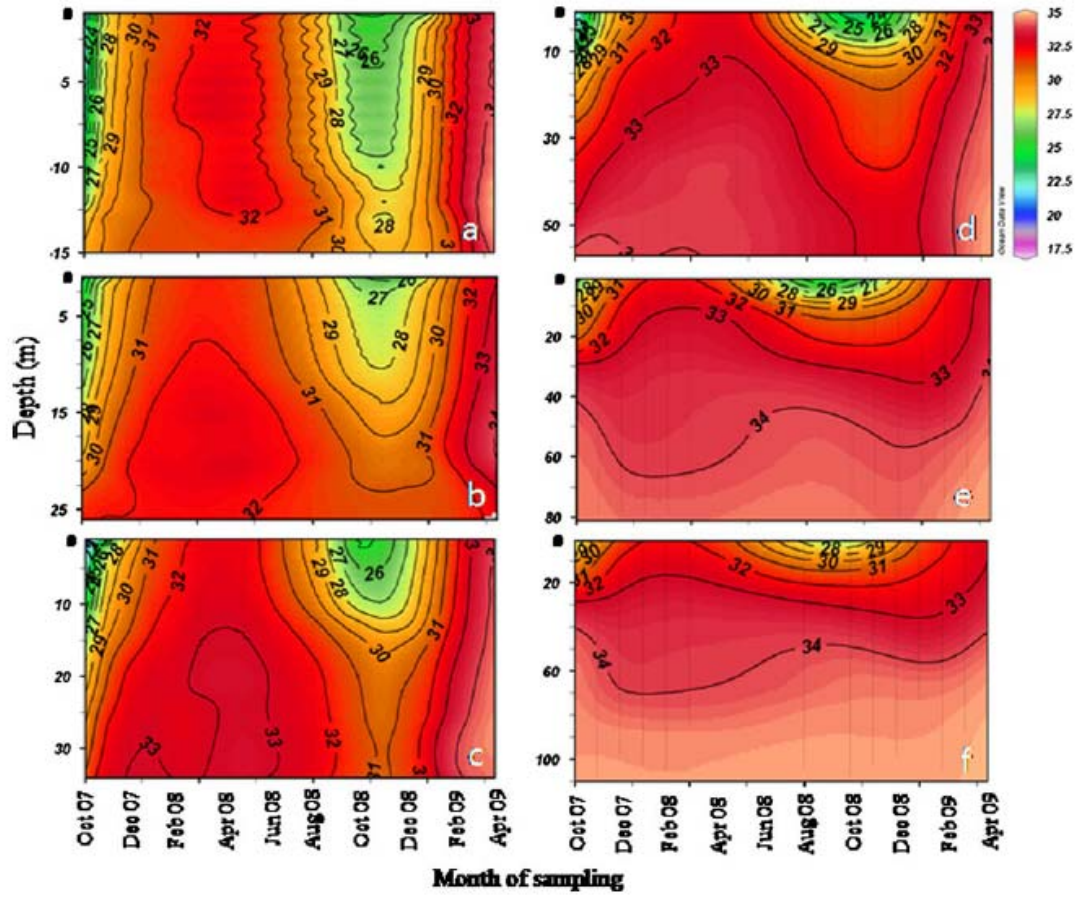




Figure 5

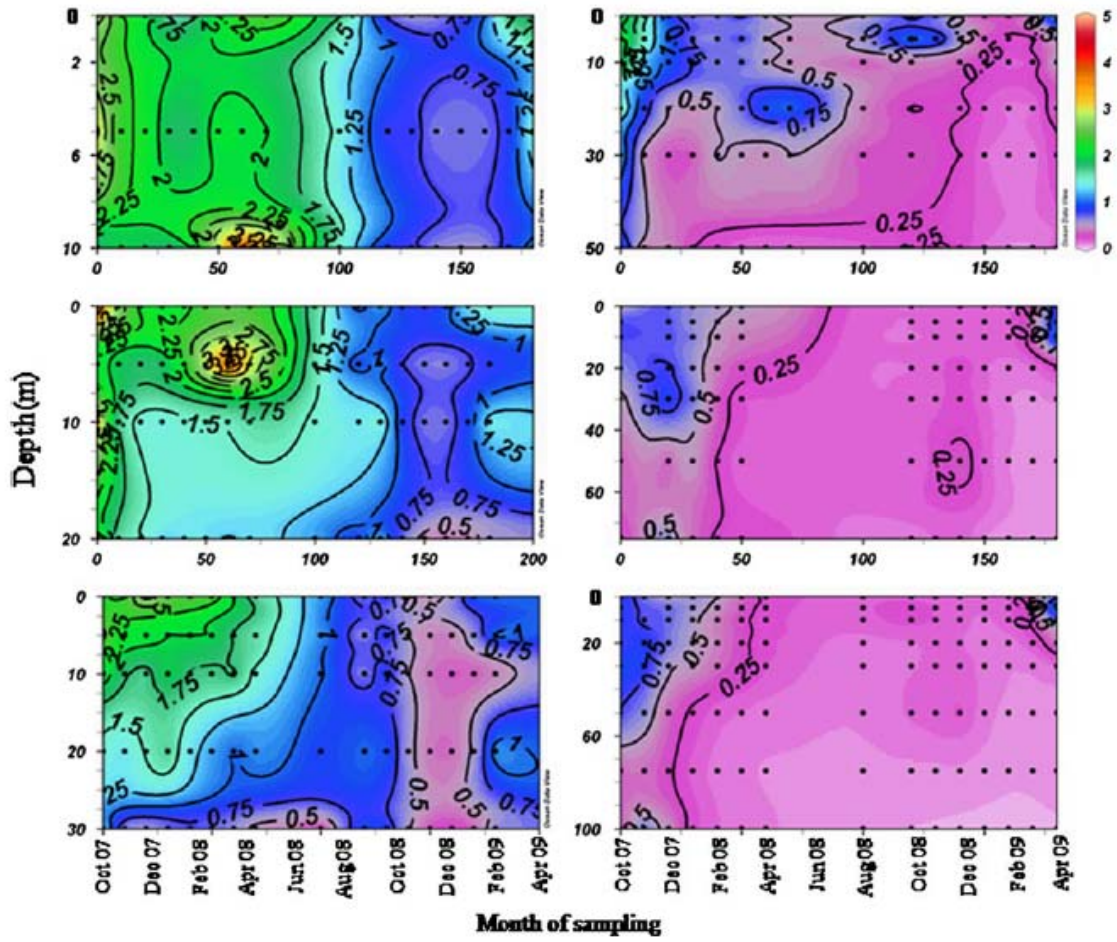


Figure 6

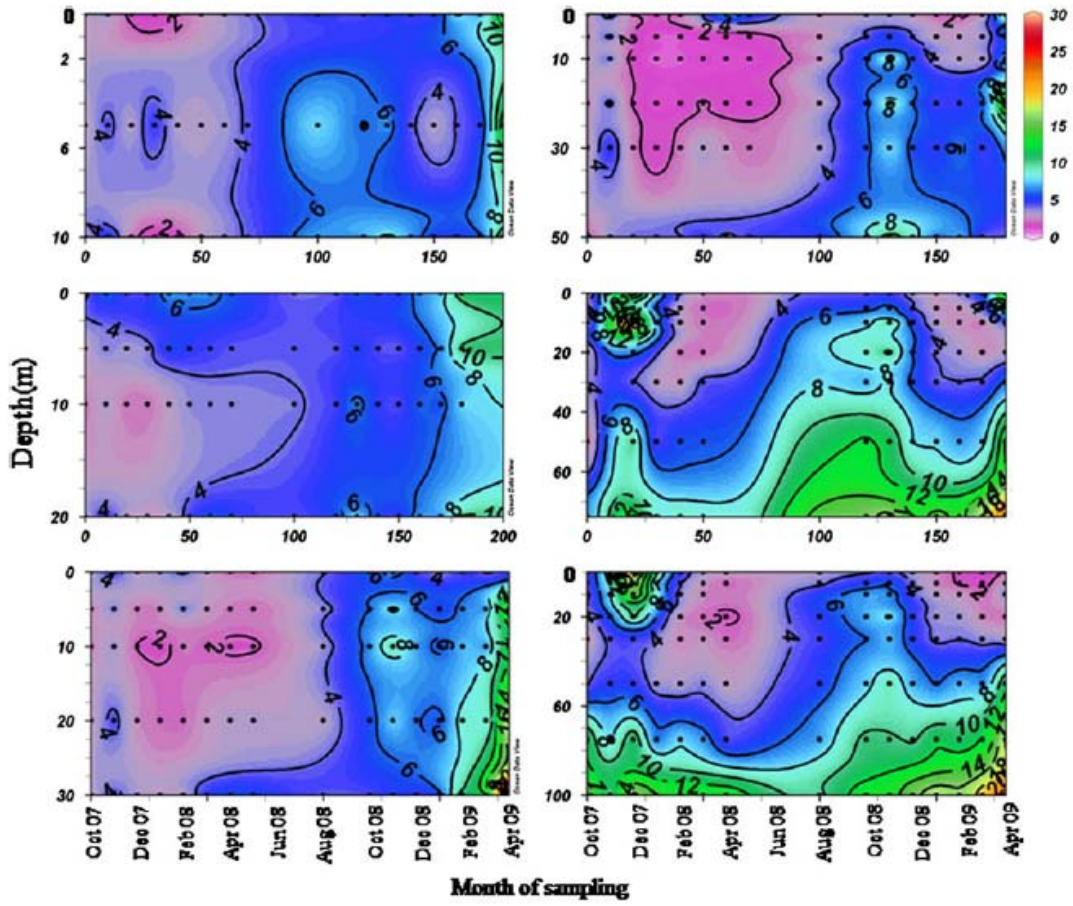


Figure 7

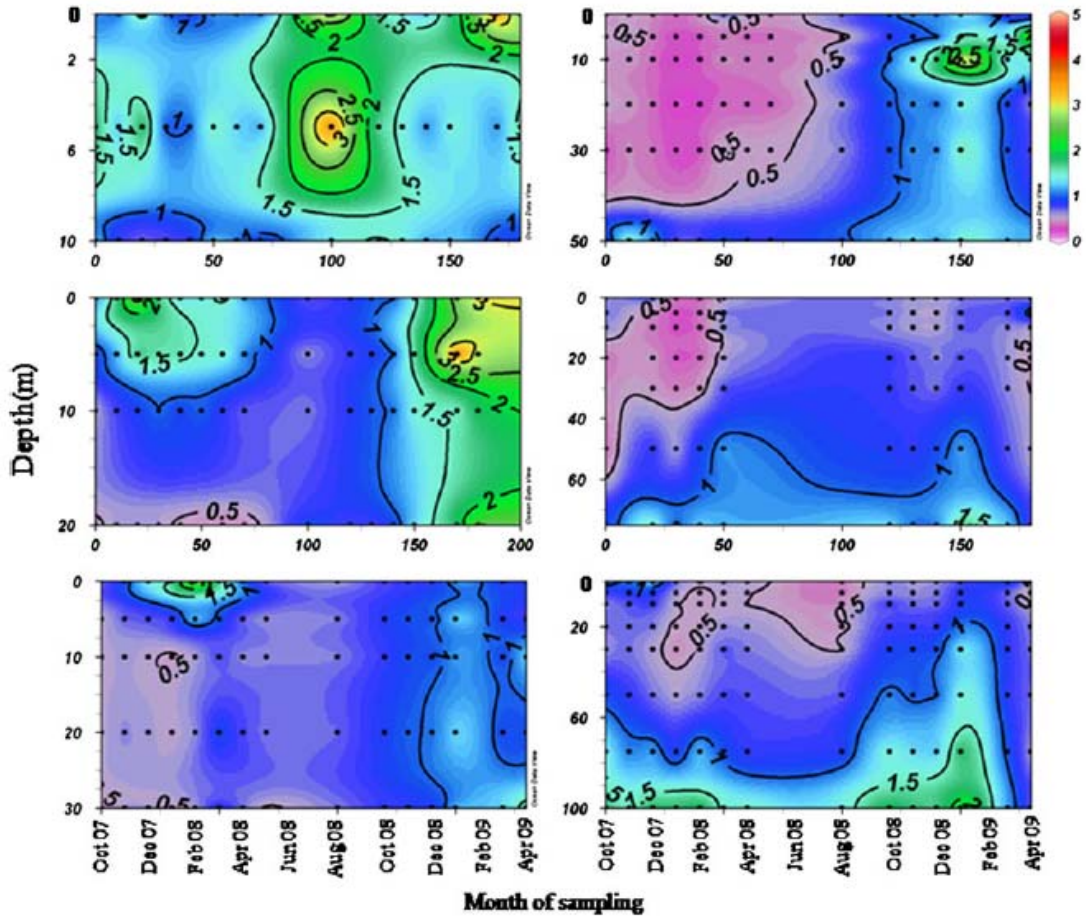




Figure 8:

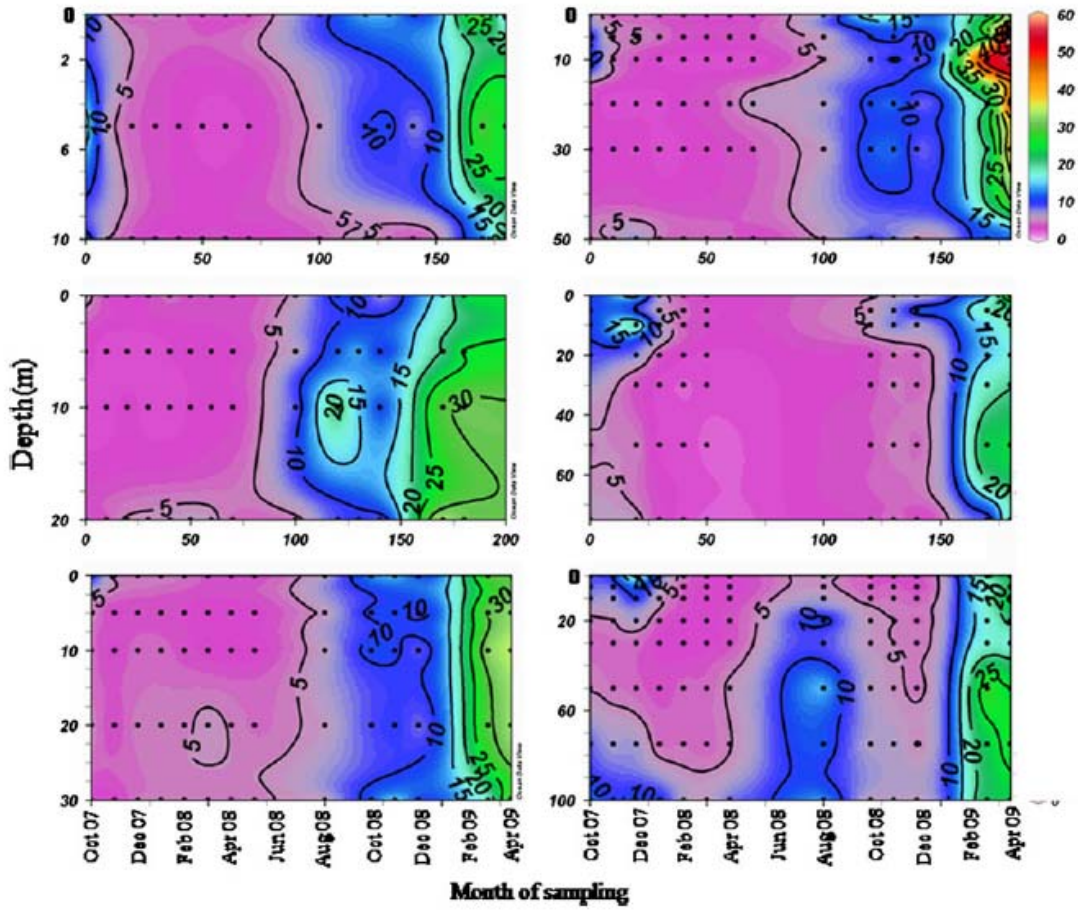


Figure 9

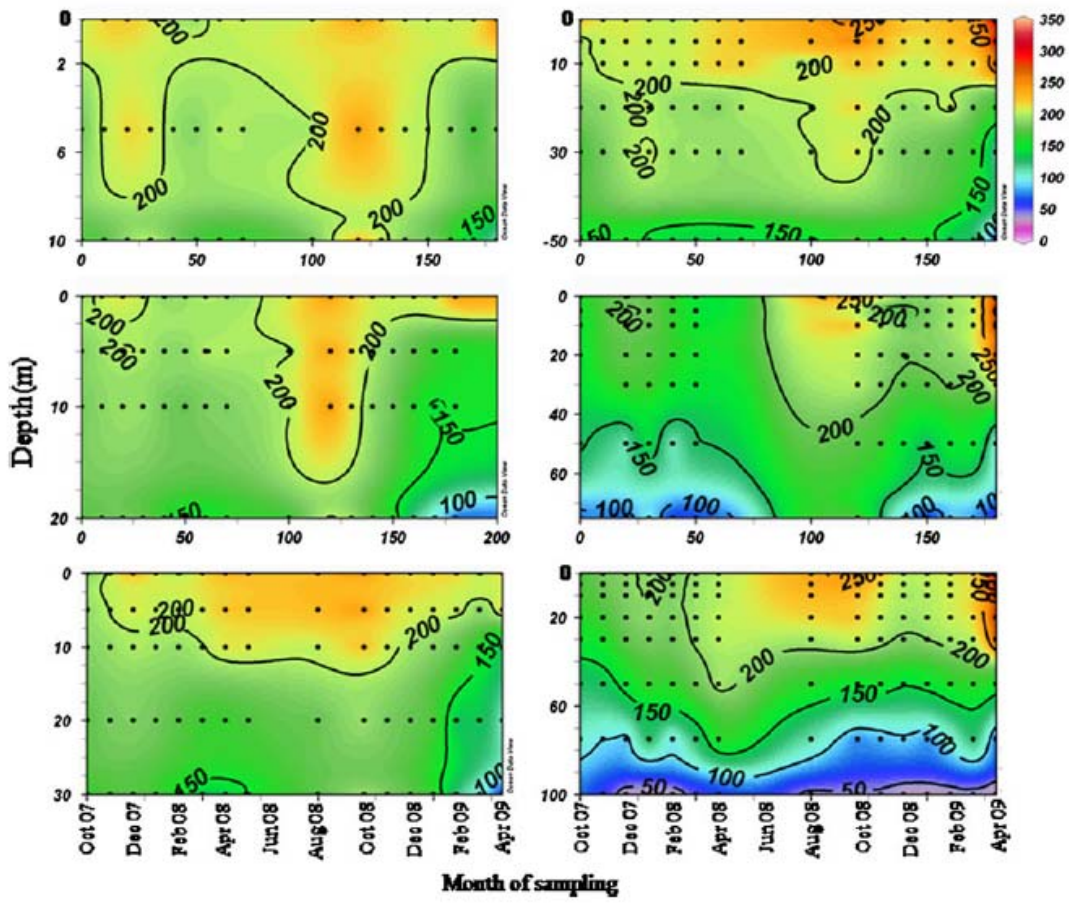


Figure 10

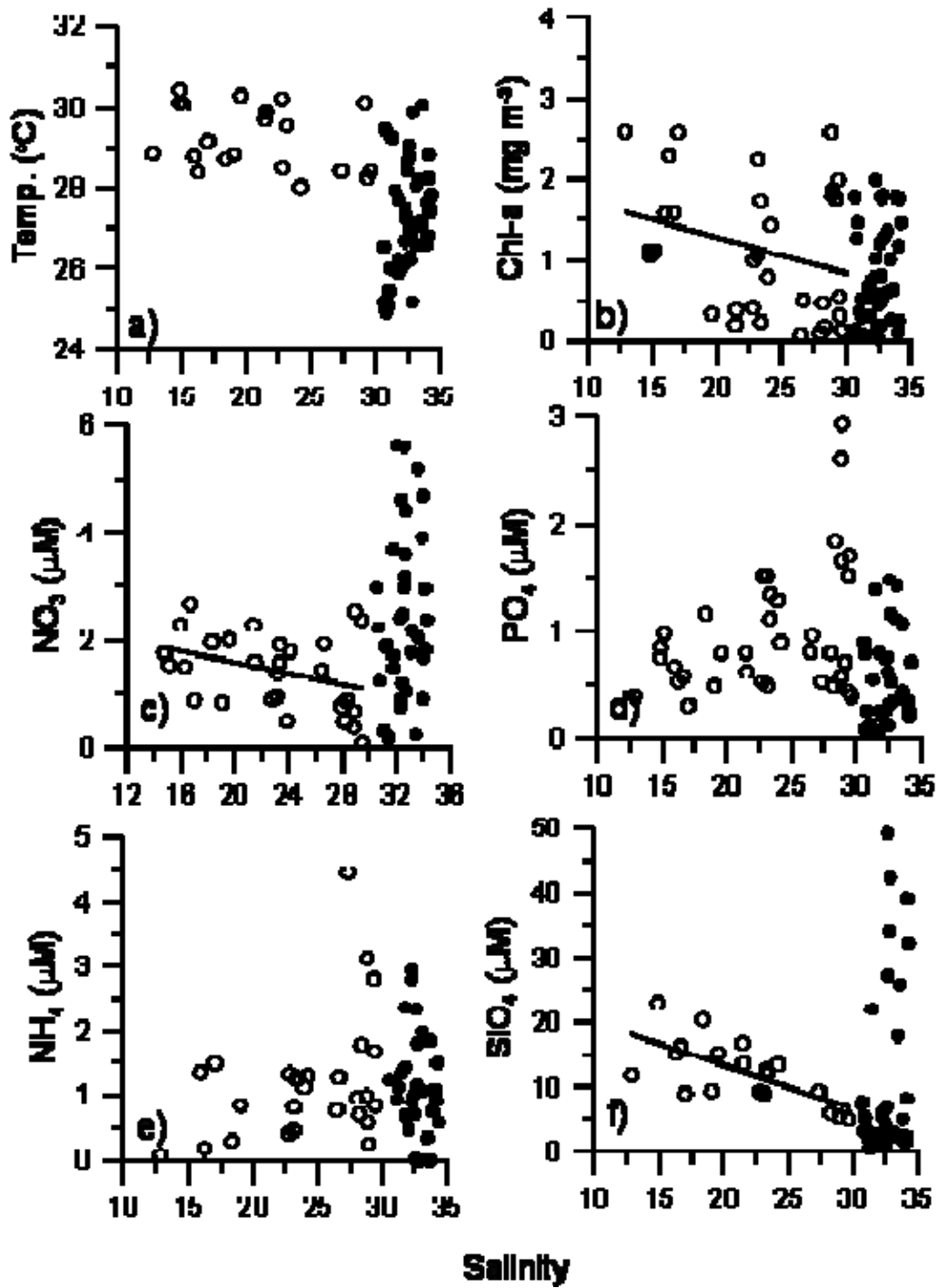
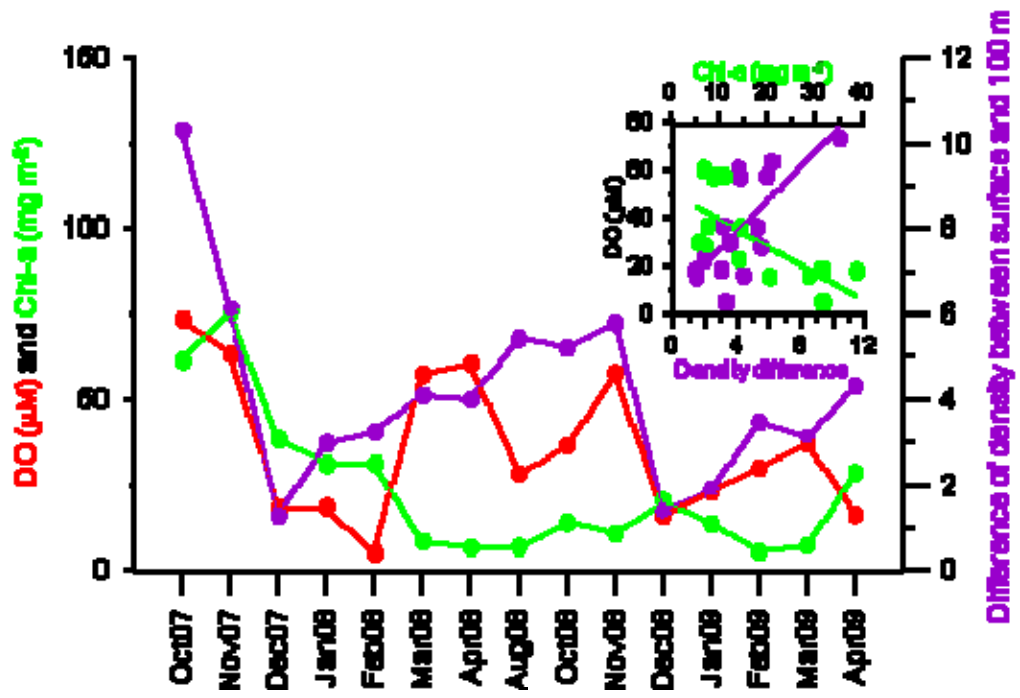


Figure 11



Supplimentary Figure S1: The speed and direction of East India Coastal Currents, which were obtained from [www.aoml.noaa.gov](http://www.aoml.noaa.gov) (merged product of JASON 1-2, TOPEX, ERS-2, ENVISAT and GFO), along the west coast of Bay of Bengal. The black circle denotes study region.

