

Impact of river discharge on the coastal water pH and pCO₂ levels during the Indian Ocean Dipole (IOD) years in the western Bay of Bengal

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Abstract

Monthly variations in inorganic carbon components during January 2010-December 2011 in the coastal Bay of Bengal (BoB) were studied in relation to the variations in Godavari River (GR) discharge using ship board measurements, buoy data and satellite remote sensing data. Higher GR discharge was observed during the 2010 monsoon ($1133 \text{ m}^3 \text{ s}^{-1}$) resulting in low salinity and strong stratification in the coastal region. During 2011 monsoon season, low GR discharge ($403 \text{ m}^3 \text{ s}^{-1}$) resulted in weaker stratification in the coastal waters. Contrasting atmospheric and oceanic conditions prevailed in the north Indian Ocean during 2010-2011 in association with the negative Indian Ocean Dipole (nIOD) event in 2010 and positive IOD (pIOD) event in 2011. Consequently, anomalous onshore easterly surface winds and warmer Sea Surface Temperature (SST) anomalies occurred in the BoB during nIOD event and an anomalous strong alongshore northeastward surface winds and colder SST anomalies occurred during pIOD event in the coastal western BoB. The observed weaker stratification due to low GR discharge and the anomalous alongshore surface winds favoured coastal upwelling during pIOD event in the 2011 monsoon, and consequently lowered the SST and the pH (pCO₂) levels by 0.01 units (higher by 60 μatm) than those observed during the nIOD event. This study thus reveals that reduced GR discharge together with pIOD event contributed to enhanced acidification and pCO₂ levels in the coastal western BoB. It could be envisioned that the enhanced acidity in the coastal waters due to variations in river discharge and phases of IOD may significantly modify the coastal ecosystem that requires careful evaluation.

Introduction

The fossil fuels burning, cement manufacturing and land-use changes are some of the important processes responsible for increase in atmospheric CO₂ (Forster et al., 2007). The increase in CO₂ at the ocean surface is larger in the coastal region (Wootton et al., 2008) than in the open ocean (Bates, 2007). The uptake of ~50% of the anthropogenic CO₂ emissions from atmosphere (Sabine et al., 2004) leads to increase in acidity of the ocean by 30% resulting in a decrease of the average surface ocean pH by more than 0.1 unit since the start of the industrial revolution (Haugan and Drange, 1996). Perennial increase in anthropogenic CO₂ to atmosphere would result in continued surface ocean acidification and it is predicted that the average ocean pH may decrease by 0.4 units by 2100 (Turley, 2008). On the other hand, both the fresh water discharge by rivers and upwelling significantly enhance acidification in the coastal waters at the rates far beyond the open ocean regions (Hauri et al., 2009).

Continental shelf zones are the most biological productive zones in the aquatic ecosystem as they receive significant amount of nutrients from various sources through land-ocean interaction (IGBP, 1993). It is estimated that continental shelves absorb ~0.22 to 1.0 GtC y⁻¹ from atmosphere (Borges, 2005; Borges et al., 2005; Cai et al., 2006; Chen and Borges, 2009), in contrast, it is estimated that estuaries emit about 0.27 GtC y⁻¹ of CO₂ to atmosphere (Laruelle et al., 2010) with large uncertainties due to lack of data. Sarma et al. (2011; 2012a) reported that Indian monsoonal estuaries harbour acidic and high pCO₂ waters during discharge period compared to dry period due to significant modification of terrestrial organic matter through microbial decomposition. The input of such acidic waters to the coastal BoB may have significant impact on the inorganic carbon system. Recently, Sarma et al. (2015) reported coastal water acidification due to increased anthropogenic aerosol loading in the northern BoB in winter and spring during recent decades, and the pH of the coastal waters decreased at the rate of 0.007 units y⁻¹, which was 2 to 3 times higher than that of elsewhere in the world.

Sarma et al. (2012b) reported that the direction of CO₂ flux (source or sink) from the coastal western BoB was dependent on the characteristics of the discharged water from the rivers. They further noted that the coastal regions influenced by the peninsular rivers were the strong net source while glacial river, the Ganges, was a net sink for atmospheric CO₂. It was hypothesized that decreased river discharge, either due to weak intensity of the monsoon or dam regulation of freshwater release, would decrease pCO₂ levels and acidification in the coastal BoB and therefore decreases the CO₂ flux to atmosphere (Sarma et al., 2012b). On the contrary, weakening of stratification would promote upwelling and in turn would increase the pCO₂ levels and acidification in the coastal BoB.

The coastal western BoB receives huge freshwater discharge of $1.6 \times 10^{12} \text{ m}^3 \text{ y}^{-1}$ from various rivers, such as the Ganges, Mahanadi, Godavari, Krishna and Cauvery (UNESCO, 1979), and sediment load of 1.1×10^9 tonnes (Milliman and Meade, 1983; Milliman and Syvitski, 1992) during southwest monsoon (June to September) period when Indian subcontinent receives maximum rainfall. During the same period, winds blow from southwest over the coastal western BoB and favours coastal upwelling (Shetye et al., 1996). But, the intensity of upwelling is weak and confined close to the coast due to strong stratification driven by freshwater discharge (Murty and Varadachari, 1968; Gopalakrishna and Sastry, 1985; Shetye et al., 1991). The net impact of these two processes on the coastal western BoB, however, is hitherto unclear, due to lack of time-series measurements. In this study, we present the results of the systematic studies made over two years (January 2010-December 2011) to examine how reduced river discharge influences acidification and surface pCO_2 levels in the coastal western BoB using extensive water sampling, current measurements and satellite remote sensing sensor data. Coincidentally, our study period covered two important climatic events of the north Indian Ocean known as the negative Indian Ocean Dipole (nIOD) in 2010 and positive Indian Ocean Dipole (pIOD) event in 2011. Hence, these data helped us to examine the impacts of the anomalous atmospheric and oceanic conditions associated with these climatic events on coastal acidification and pCO_2 levels off the mouth of the Godavari River in the coastal western BoB.

2. Sampling and Methods

2.1. Shipboard measurements

Surface water samples were collected at 4 stations at standard depths covering the water column from surface to bottom using a mechanized boat from the coast to the distance of ~ 22 km offshore at monthly intervals from January 2010 to December 2011 (Fig. 1). Profiles of temperature and salinity were measured using the Conductivity, Temperature and Depth Probe (CTD; Sea Bird Electronics, *19 Plus*, USA). Salinity sensor was calibrated using Autosal (Guildline 8400, USA) with international standard and the accuracy was found to be ± 0.002 . Samples were collected using 5/10L Niskin bottles for dissolved oxygen (DO), suspended particulate matter (SPM), nutrients, dissolved inorganic carbon (DIC), total alkalinity (TA) and pH. Care was taken to avoid bubbles entering the water samples. All samples were poisoned, sealed and analyzed within 2 days from the sampling date. DO was estimated using Winkler's method following automated potentiometric end point detection (Carritt and Carpenter, 1966) and the analytical precision, expressed as standard deviation, was $\pm 0.07\%$. About 1 L of water sample was filtered through pre-weighed $0.22 \mu\text{m}$ pore size polycarbonate filter and SPM on the filter was estimated as a weight of the matter retained on the

filter. Nutrients were measured following standard spectrophotometric procedures (Grashoff et al., 1992). The pH and TA were measured by potentiometric (Metrohm, Zofingen, Switzerland) Gran titration method following standard operating procedures suggested by the Department of Energy (DOE, US, 1998). Dissolved Inorganic Carbon (DIC) was measured using a Coulometer (UIC Inc, Joliet, Illinois, USA) attached to an automated sub-sampling system (Sarma, 1998). The precisions for pH, TA and DIC were ± 0.002 , ± 2.0 and ± 1.8 μM respectively. The pCO_2 was computed using measured salinity, temperature, nutrients (phosphate and silicate), pH and DIC using CO_2SYS program (Lewis and Wallace, 1998). The CO_2 dissociation constant given by Millero et al. (2006) for 0 to 40 salinity range was utilized. Air-water flux of CO_2 was estimated using formulations given by Wanninkhof (1992) and measured wind speed at the coast using Automated Weather Station (AWS). The GR discharge data were obtained from the Andhra Pradesh State Government Irrigation Department, Godavari dam authorities, Dowleiswaram, India.

2.2. Coastal current measurements off Visakhapatnam using Moorings

A shallow mooring fitted with an Acoustic Doppler Current Profiler (ADCP, #300 kHz; Make: Teledyne RD Instruments, USA) at 100 m below surface and an Acoustic Release (AR, IXSEA, USA) at 2 m below the ADCP was deployed on 18 May 2010 at the water depth of 108 m at the BOVS1 location ($17^\circ 48.889'\text{N}$, $83^\circ 58.674'\text{E}$) for measuring the coastal currents (Fig.1). This mooring was recovered on 20 March 2011 during a cruise onboard the Research Vessel *Sindhu Sankalp*. Soon after the data were transferred to the desktop computer onboard the vessel, the mooring was redeployed at the BOVS2 location, closely located to BOVS1 on 20 March 2011 and recovered on 14 February 2012. However, currents data were obtained only till 10 September 2011 at BOVS2. The ADCPs were set for data recording at 4 m depth bins and 15 minute time intervals. Owing to the reflection of the acoustic pulses at sea surface, the top few meters data below sea surface were contaminated, and removed in the quality control procedures. From these moorings, time-series currents data were obtained over the depth range of 10-100 m at the 4 m depth and 15 minute time intervals. Thus obtained zonal (U, east-west flow) and meridional (V, north-south flow) velocity time-series data were subjected to quality control measures while processing the data and the data-gaps over smaller time and depth intervals were filled in using the interpolation techniques. This U and V data were further subjected to 36 hours low-pass filtering, by which all the tidal and the local inertial oscillations were removed, and daily averaged. The daily averaged U and V data were used in the present study. Following the standard physical oceanographic data processing methods (Pond and Pickard, 1978), the daily averaged U and V time-series data were used to

estimate the depth-integrated volume transport (m^2/s or equivalently Sverdrups/m) for each day and fortnightly and monthly mean transports were estimated for both BOVS1 and BOVS2 data sets.

2.3. Satellite Remote sensing data for surface winds and sea surface heights

The Advanced Scatterometer (ASCAT) derived wind products of surface wind vectors data at $0.25^\circ \times 0.25^\circ$ grids for the study period were downloaded from the website (<http://las.incois.gov.in/las>) of Indian National Centre for Ocean Information and Services (INCOIS). The ASCAT ocean surface winds are a 10 meter neutral stability wind, and these winds are processed by National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NESDIS). Sea surface Height (SSH) and the SSH derived geostrophic currents data were downloaded from the website <http://oceanwatch.pifsc.noaa.gov/las/servlets/dataset>. The SSH data is the AVISO Delayed-Time Reference Mean Sea-Level Anomaly (MSLA) product (<http://www.aviso.altimetry.fr/en/data.html>) that combines the data from TOPEX/Poseidon/ERS/Jason-1/Envisat and Jason-2/Envisat. SSH data contains MSLA data in addition to sea surface height climatology. Sea Surface Height Anomalies (SSHA) and geostrophic current (vectors) anomalies are calculated after subtracting the respective seasonal cycle generated using the respective data base for 16 years (1993-2008) period in the north Indian Ocean study area.

2.4 Climatological monthly data of SST and wind speed

The TropFlux monthly data set (Praveenkumar et al., 2011) and ERA-Interim reanalysis monthly wind products (Dee et al., 2011) were used to estimate the monthly SST anomalies and surface wind speed anomalies for the study period after subtracting the respective seasonal cycle generated using the respective base data for 31 years from January 1979 to December 2009.

Results

The southwest monsoon fed Godavari river discharge, downstream of the river, into coastal western BoB generally occurs with a peak in July – August (Sarma et al., 2011; Acharyya et al., 2012). The observed daily GR discharge varied between 0 and $16547 \text{ m}^3 \text{ s}^{-1}$ with an annual means of 1133 and $403 \text{ m}^3 \text{ s}^{-1}$ during 2010 and 2011 respectively (Fig. 2a). The variations in GR discharge were associated with the ~20% less monsoonal precipitation over south Indian Peninsula during the 2011 monsoon from that of long term mean of all over India over the past 25 years (Anonymous, 2012; <http://www.imd.gov.in>). Relatively cooler ($27.6 \pm 0.5^\circ\text{C}$) and more saline (29.8 ± 1.3) waters were noticed during August-October 2011 than those in 2011 ($28.7 \pm 0.6^\circ\text{C}$ and 26.6 ± 2 respectively) (Figs. 2b-c). The surface salinity of coastal western BoB was around 32-33 during non-discharge period (January-June and November-December) and decreased significantly to 26-30 during discharge

period (July to October) (Fig. 2c). These variations suggest that possible occurrence of coastal upwelling during the 2011 monsoon augmented by the lower GR discharge. Discharge of freshwater from the monsoonal estuaries brings significant amount of SPM to the coastal region (Sarma et al., 2009; 2012b). Lower concentrations of SPM were observed during non-discharge period ($\sim 20 \text{ mg l}^{-1}$) compared to discharge period ($>50 \text{ mg l}^{-1}$) (Fig. 2d). Since the GR discharge was relatively less during the 2011 monsoon, the observed SPM concentrations were also relatively less ($28 \pm 5 \text{ mg l}^{-1}$), compared to those during the 2010 monsoon ($48 \pm 5 \text{ mg l}^{-1}$). In addition to this, under-saturation of oxygen was noticed during the higher discharge period of the 2010 monsoon (75-80%) compared to the less-discharge period of the 2011 monsoon (85-99%) (Fig. 2e).

Surface water pH of the coastal BoB was relatively higher (8.14 ± 0.02) during less-discharge period of the 2011 monsoon compared to higher discharge period of the 2010 monsoon (8.05 ± 0.04) (Fig. 2f). Contrastingly, concentrations of DIC and TA were higher during the less-discharge period (2054 ± 68 and $2342 \pm 92 \text{ } \mu\text{M}$) than the high discharge period (1790 ± 19 and $2088 \pm 17 \text{ } \mu\text{M}$) respectively suggesting that higher discharge brought acidic and low inorganic carbon waters to the coastal western BoB (Figs. 2g-h) leading to inhibition of up-sloping of contours to surface during the 2010 monsoon (Fig. 3). DIC showed significant linear relation with salinity ($r^2=0.78$; $p<0.001$) and weak inverse relation with Chl-a ($r^2=0.32$; $p<0.05$) (figures not shown) indicating that influence of biological and mixing processes to DIC variations. TA displayed significant linear relation with salinity ($r^2=0.52$; $p<0.001$) suggesting that mixing of freshwater is the major influencing factor (Figure not shown). The pCO_2 levels during the 2 year (2010-2011) study period ranged from 377 to 681 μatm . Relatively lower mean pCO_2 levels were observed during the less-discharge period ($474 \pm 42 \text{ } \mu\text{atm}$) of the 2011 monsoon than the higher discharge period ($603 \pm 44 \text{ } \mu\text{atm}$) of the 2010 monsoon (Fig. 2i). The entire surface pCO_2 data (2010-2011) were correlated with salinity which displayed two different relationships, i.e., (1) inverse relation with salinity at <28 ($-23.2 \times S + 995.7$; $r^2=0.68$; $p<0.001$) and (2) linear relation at salinity >28 ($24.1 \times S + 306.6$; $r^2=0.72$; $p<0.001$) indicating that two mechanisms may be responsible for their variability during the entire study period (Fig. 4). The former relationship suggests the influence of river water whereas the latter relationship indicates influence of vertical mixing. Sarma et al. (2013) noticed similar relationship with nutrients in the coastal BoB at a time-series station off Visakhapatnam. The flux of CO_2 at the sea-to-air interface ranged from 0.2 to 4.8 $\text{mmol C m}^{-2} \text{ d}^{-1}$ during study period and relatively higher fluxes were observed during the 2011 monsoon than those in the 2010 monsoon.

Discussion

Year-to-year variations in Indian monsoon rain fall, GR discharge and coastal upwelling

The variations in rainfall during southwest monsoon (June – September) over Indian subcontinent are influenced by El Niño and IOD (Ashok et al., 2001, 2004). It was noticed that no depressions were formed in the northern Indian Ocean during the 2010 southwest monsoon period in association with the development of negative phase IOD (nIOD). Ashok et al. (2001, 2004) showed that the pIOD causes more rainfall to the Indian sub-continent and Bay of Bengal and less rainfall during nIOD. In the year 2010 strong La Niña and the nIOD conditions dominated and augmented towards excess Indian Summer Monsoon Rainfall (ISMR). In the year 2011 both neutral El Niño Southern Oscillation (ENSO) and pIOD conditions emerged and became stronger by the end of August 2011. Further, the southern peninsula region, covering the coastal districts of Andhra Pradesh where study region is located, received less rainfall over the study region during 13 June – 17 August 2011 (Anonymous, 2012) leading to lower river discharge into the coastal study region (Fig. 2a). The monthly mean ASCAT surface winds (vectors) during August 2010 and August 2011 along the coastal western BoB at the locations of observations show that the wind speeds were weak in August 2010 in association with the large scale nIOD event over the North Indian Ocean and the surface winds strengthened during August 2011 under the influence of the pIOD event in 2011 and also clear from the colour code of the magnitude of wind speed (ms^{-1}) from Figs. 5a-b.

In association with the strong La Niña and nIOD conditions over the North Indian Ocean, anomalous surface winds were easterly in the open BoB north of 5°N in July-August 2010 (Figs. 6a-b). By September 2010, the anomalous wind conditions were different over the BoB under the influence of weakening of nIOD event (Fig. 6c). In contrast, in July-August 2011, anomalous surface winds were south-westerly and extended towards east coast of India and became alongshore winds after crossing 10°N and continued till September 2011 (Figs. 6d-f). Behera et al. (1999) proposed that the anomalous alongshore wind anomalies off the east coast of India during the pIOD event were resulted from the large scale vertical subsidence of lower tropospheric winds over the South Equatorial Tropical Indian Ocean (SETIO) and ascending motions over the warmer monsoon region of India. Further, the monthly rainfall dataset for the homogeneous region of the Southern Indian Peninsular (<http://www.tropmet.res.in>) show that both 2010 and 2011 years were normal monsoon years, but received excess rainfall in the year 2010 monsoon (<http://www.imd.gov.in>) whereas in the year 2011 received normal or less rainfall (<http://www.imd.gov.in>). From the above information, it could be inferred that GR discharge rate was higher during the 2010 monsoon (Fig. 2a) compared to

that in 2011 monsoon (Fig. 2a) due to relatively higher (lower) rainfall associated with nIOD (pIOD) in the former (latter) year. This resulted in weaker stratification in the coastal region off Godavari River mouth during the 2011 monsoon. Saji and Yamagata (2003) reported negative partial correlation between SST anomalies (SSTA) and Dipole Mode Index (DMI) (Saji et al., 1999), independent of Niño3, in the central Pacific, off Sumatra coast and off east coast of India (see their Figure 21). This suggests that anomalous SSTs in these regions are associated with the IOD events. Maximum positive SSTA up to 0.5 °C occurred in August 2010 at the time of peak discharge into the coastal BoB (Fig. 6b). In contrast, maximum negative SSTA up to -0.4°C occurred in the coastal BoB during August-September 2011, the weaker discharge period (Figs. 6d-f). In addition to this, the anomalous alongshore northeastward surface winds off the central east coast of India favour coastal upwelling in August 2011 (Fig. 3 lower panel). Whereas during the nIOD event the anomalous onshore surface winds from the east suppress coastal upwelling as noticed in August 2010 (Fig. 3 top panel) coinciding with the anomalous warmer SSTA (Fig. 6). Inhibition of coastal upwelling due to strong stratification along the east coast of India was reported earlier using mathematical modelling (Johns et al., 1993).

The observed currents on the continental shelf off Visakhapatnam (Fig. 1) suggest the existence of intra-seasonal variability in the coastal currents during the southwest monsoon period (Figs. 7a-b). More particularly, the coastal currents at 20 m depth were stronger and flow equatorward during mid-July to mid-August 2010 (Fig. 7a), in contrast to that for the same period of 2011 (Fig. 7b), when the currents at 22 m were weaker and opposite. This observed variation in the coastal current pattern is consistent with the strength of surface wind speed vectors (Figs. 5a-b) and the pattern of anomalous wind speed vectors (Fig. 6). The estimated depth-integrated meridional volume transport of the observed coastal currents in the upper 100 m (figure not shown) also supported the strong equatorward flow with a maximum equatorward transport of 4.5 Sv (1 Sverdrup (Sv)= $10^6 \text{ m}^3 \text{ s}^{-1}$) from mid-August to mid-September 2010 (not shown here). This is more consistent with the sea surface height anomaly (SSHA) and the derived geostrophic currents pattern in the coastal western BoB (Figs. 8a-f). It is to mention that the pattern of variations of SSHA and the surface geostrophic currents anomalies off Sumatra coast in the SETIO reflect clearly the dominant influences of the nIOD event in 2010 (positive SSHA and cyclonic circulation cell) and pIOD event in 2011 (negative SSHA and anticyclonic circulation cell). The nIOD event weakened from July to September 2010 both in the SETIO and also in the BoB. Whereas the pIOD event strengthened from July to September 2011 (Figs. 8a-f). In the study region, off Visakhapatnam, the prevailing anomalous anticyclonic circulation cell or meso-scale anticyclonic eddy (positive and higher SSHA) weakened

with the weakening of nIOD event from July to September (Figs. 8a-c). On the other hand, the anticyclonic circulation cell or the meso-scale anticyclonic eddy off Visakhapatnam strengthened and anomalous poleward coastal current developed along the east coast of India. This is in agreement with the weakening of observed currents in August-September in 2011 (Fig. 7b) in comparison with those in 2010 for the same period (Fig. 7a). In association with the anomalous poleward flow extending up to the mooring locations (BOVS1 and BOVS2) the depth-integrated meridional volume transport in the upper 100 m in August-September 2011 was very weak (~ 1 Sv) (not shown here), which is far less than that noticed in August-September 2010. This strengthened anomalous coastal current in August 2011 and the anomalous alongshore northeastward surface winds under the influence of the large scale pIOD event have led support to the coastal upwelling process and under its influence up-sloping of isopleths in the observed parameters is noticed (Fig. 3 lower panel). The observed variations in the meridional volume transport along the coast highly contributes to the suppression of the coastal upwelling during the 2010 monsoon when the coastal region received heavy GR discharge and anomalous surface winds were from the east towards the shore. In contrast, the anomalously strong alongshore northeastward winds during the 2011 monsoon weakened the equatorward volume transport, when the coastal region received lower GR discharge, and supported overall contribution to the upwelling process due to anomalous offshore Ekman transport in August 2011. Subrahmanyam et al. (2011) also noticed that the anomalous coastal circulation is equatorward during the nIOD event in 2005 and poleward during the pIOD event of 2006 indicating that upwelling is favoured during latter period. This is well supported from the studies of Behera et al. (1999) and Saji and Yamagata (2003).

Year-to-year variations in inorganic carbon components in the coastal western BoB

Since the pH of Godavari river water is relatively acidic (6.5 ± 0.4) during peak discharge period (Sarma et al., 2011), it is expected that the pH of coastal BoB may also be low due to discharge. It has been hypothesized that decreased discharge from the Godavari river may increase pH of coastal waters leading to sink for atmospheric CO_2 (Kumar et al., 1996; Sarma et al., 2012b). In contrast to this, decrease in pH was noticed by 0.01 units in association with the intensified coastal upwelling during the 2011 monsoon when discharge was three times lower than that of the 2010 monsoon. The vertical structures of temperature, salinity, pH and pCO_2 indicated inhibition of upwelling by strong surface stratification due to river discharge during the 2010 monsoon and upsloping of contours from ~ 40 m deep during the 2011 monsoon due to weak stratification. The salinity gradient in the upper 50 m was very high (>3) during the 2010 monsoon and very low (<0.5) during the 2011 monsoon leading to upwelling of acidic and pCO_2 rich waters to the surface. The pH of coastal waters was

lower by 0.01 units during the 2011 monsoon than the 2010 monsoon. Similarly the pCO₂ levels were relatively higher during the less-discharge period of 2011 (603±44 μatm) than the high discharge period of 2010 (547±31 μatm). Though pCO₂ levels during less-discharge period were more or less uniform during both 2010 (458±26 μatm) and 2011 (446±18 μatm) monsoons, their concentrations were significantly higher during the 2011 discharge period than that of 2010 by 60 μatm suggesting that coastal upwelling enhanced acidification and hence the pCO₂ levels in the surface waters of the coastal BoB. The annual mean sea-to-air flux of CO₂ was almost 40% higher during the 2011 monsoon (1.17 mmol C m⁻² d⁻¹) than during the 2010 monsoon (0.76 mmol C m⁻² d⁻¹). Such increase in flux was almost double during the 2011 monsoon (3.04 mmol C m⁻² d⁻¹) than during the 2010 monsoon (1.55 mmol C m⁻² d⁻¹) suggesting that intensified coastal upwelling increased flux of CO₂ to the atmosphere. Nevertheless, this study suggests that the coastal western BoB acidifies during southwest monsoon period due to injection of acidic river water, and it intensifies during weak monsoon year and large-scale wind field associated with the pIOD year that triggers coastal upwelling.

Acharyya et al. (2012) noticed that reduced river discharge into the Godavari estuary enhanced the phytoplankton biomass and further attributed that the reduced river discharge, either natural (monsoon variability related) or artificial through construction of more dams on the river, leading to turning the hitherto healthy Indian estuaries into eutrophication. On the other hand, this study provides the evidence that the decreased river discharge and the large-scale wind field variability due to the pIOD event lead to setting up of favourable conditions for the occurrence of coastal upwelling resulting in enhanced acidification, as the deeper waters are relatively more acidic than river waters, and increases pCO₂ levels and flux to the atmosphere from the coastal BoB. Besides the impact of the climatic events on the monsoon rainfall and the associated river discharge variations in the region (either enhanced or decreased), the construction of more dams across the rivers to conserve freshwater for the ever growing needs on the land would also reduce the river discharge into the coastal region. The increased acidification (or CO₂ enrichment) seems to have significant impact on calcification and marine primary production (Riebesell et al., 2000; Riebesell, 2004 and references there in). Recent microcosm experiments conducted in the coastal BoB revealed enhancement in the abundance of *tintinnids* under elevated CO₂ levels (Biswas et al., 2012). Therefore, changes in the acidity of coastal waters would have significant impact on the ecosystem functioning in this sensitive region and requires more careful evaluation in the future studies. Similar process may be happening along the east coast of India off other river mouths and it can be hypothesized that weakening of monsoon may lead to decrease in river discharge and intensify coastal upwelling and acidify the

coastal waters. This hypothesis must be tested in further using observations, remote sensing sensor data and modelling.

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Legend to figures

Figure 1: Map showing the transect with stations where sampling was conducted off Godavari River mouth region in the coastal western Bay of Bengal. The mooring locations at BOVS1 and BOVS2 for current measurements off Visakhapatnam are also shown.

Figure 2. Monthly variations of (a) Godavari River discharge during January 2010-December 2011 and various observed parameters along the transect in the coastal western Bay of Bengal (b) sea surface temperature ($^{\circ}\text{C}$), (c) sea surface salinity, (d) suspended particulate matter (SPM; mg l^{-1}), (e) dissolved oxygen saturation (%), (f) pH, (g) dissolved inorganic carbon (μM), (h) total alkalinity (μM) and (i) pCO_2 (μatm). Figure (a) is repeated on top of the right side panel for examining the variability in the other parameters on the right side panel.

Figure 3: Vertical distributions of observed parameters (a-b) temperature ($^{\circ}\text{C}$), (c-d) salinity, (e-f) pH and (g-h) pCO_2 (μatm) during August 2010 (upper panel) and (2011 (lower panel) along the transect in the coastal western Bay of Bengal.

Figure 4: Scatter plot between the observed sea surface salinity and pCO_2 (μatm) in the coastal western Bay of Bengal showing the linear relationships when the salinity is less than 28 units and more than 28 units. The regression equations are also shown in the figure.

Figure 5: Advanced Scatterometer (ASCAT) derived surface winds (vectors) over the western Bay of Bengal during (a) August 2010 and (b) August 2011. The colour code bar denotes the magnitude of the wind speed in ms^{-1} . The transect stations and the mooring stations are also depicted.

Figure 6: Monthly variations of TropFlux sea surface temperature anomalies (colour shading) overlaid on the surface wind speed vector anomalies during (a-c) July, August and September in 2010 and (d-f) July, August and September in 2011 when the negative (positive) Indian Ocean Dipole (IOD) event conditions prevailed in 2010 (2011). Colour code scale for SSTA is given on the right side and the wind vector scale is given on the top right corner.

Figure 7: Time variations of the 36 hours low-pass filtered and daily averaged observed currents vectors during June-October (a) at 20m depth at station BOVS1 in 2010 and (b) at 22m depth at station BOVS2 in 2011 off Visakhapatnam.

Figure 8: Satellite altimeter derived Sea Surface Height Anomaly (SSHA) superimposed with the surface geostrophic currents anomalies (vectors) in the North Indian Ocean region during (a-c) July-September 2010 (upper panel) and (d-f) July-September 2011 (lower panel). The SSHA and geostrophic current (vectors) anomalies are calculated after subtracting the respective seasonal cycle generated using the respective data base for 16 years (1993-2008) period in the north Indian Ocean study area.

Figure 1:

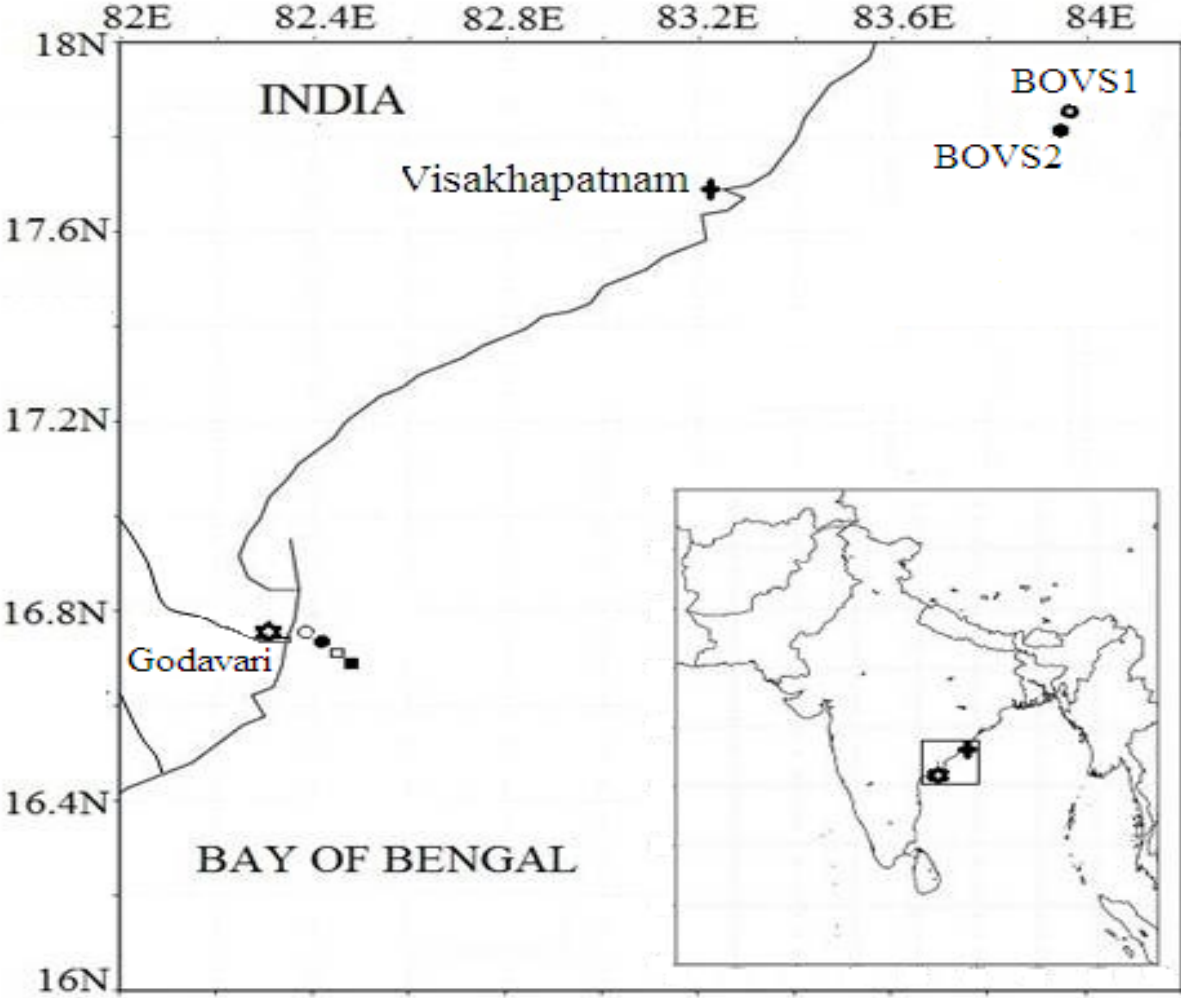


Figure 2:

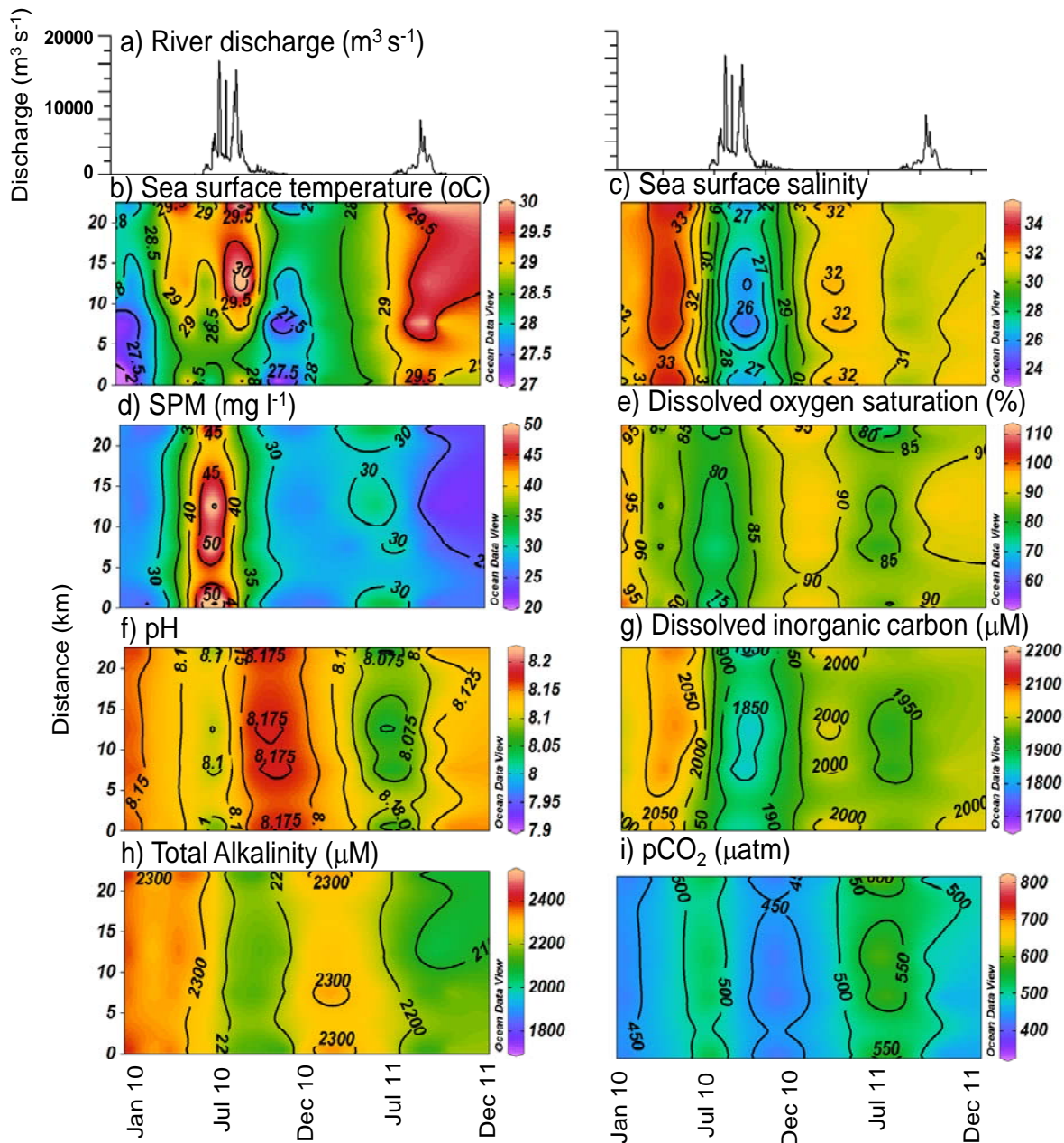


Figure 3:

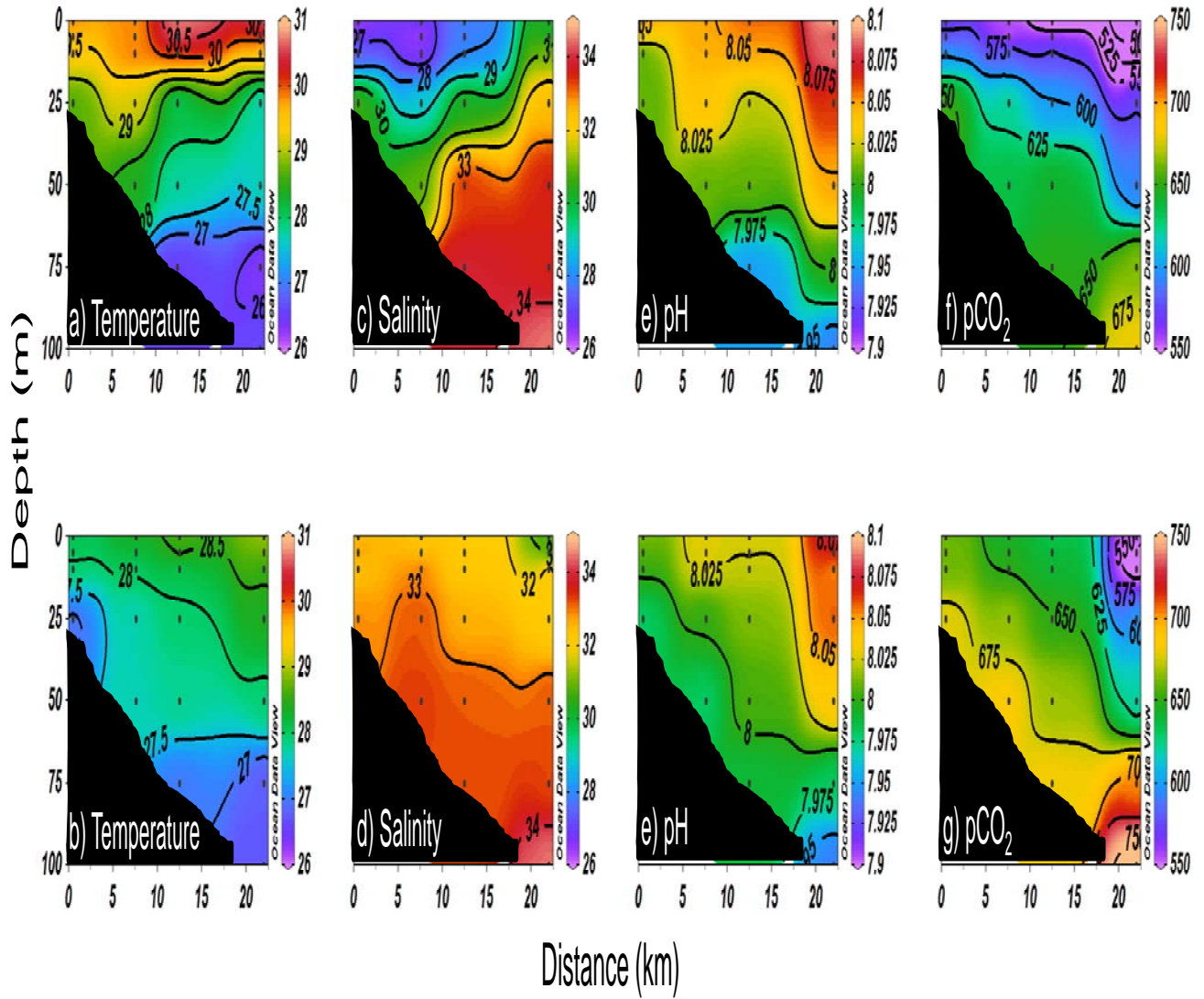


Figure:4

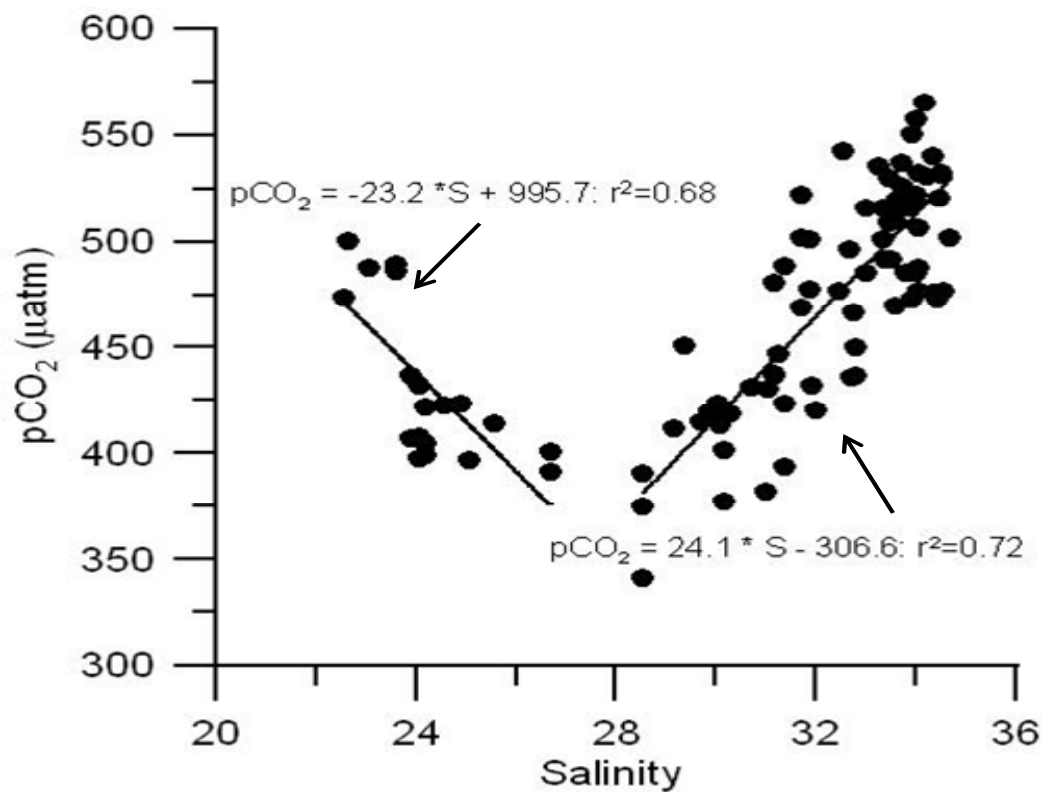


Figure 5:

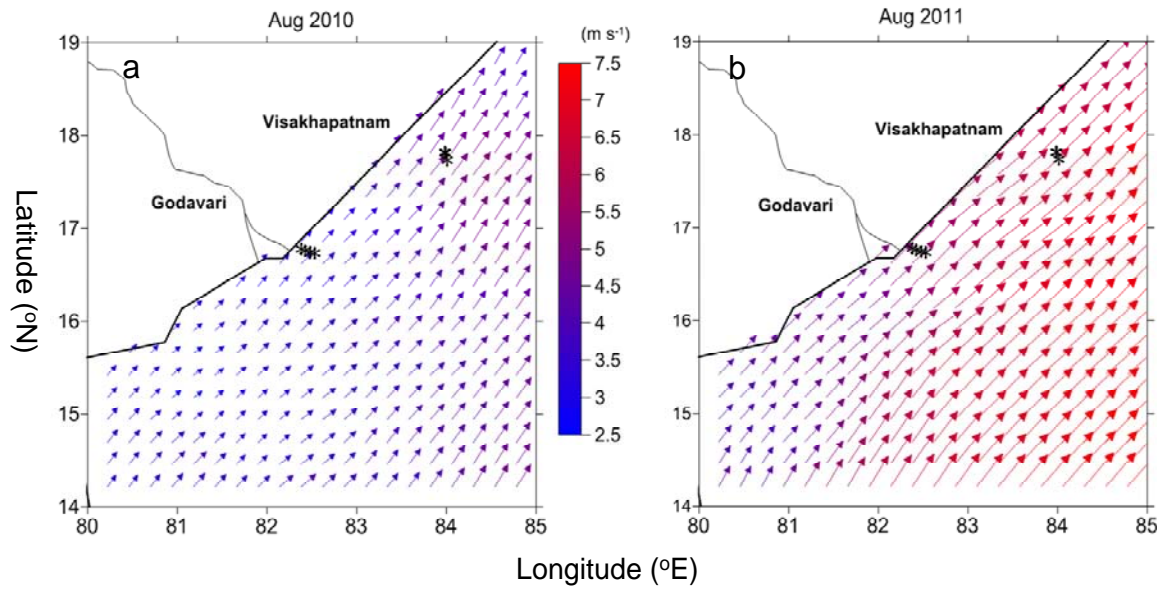


Figure 6

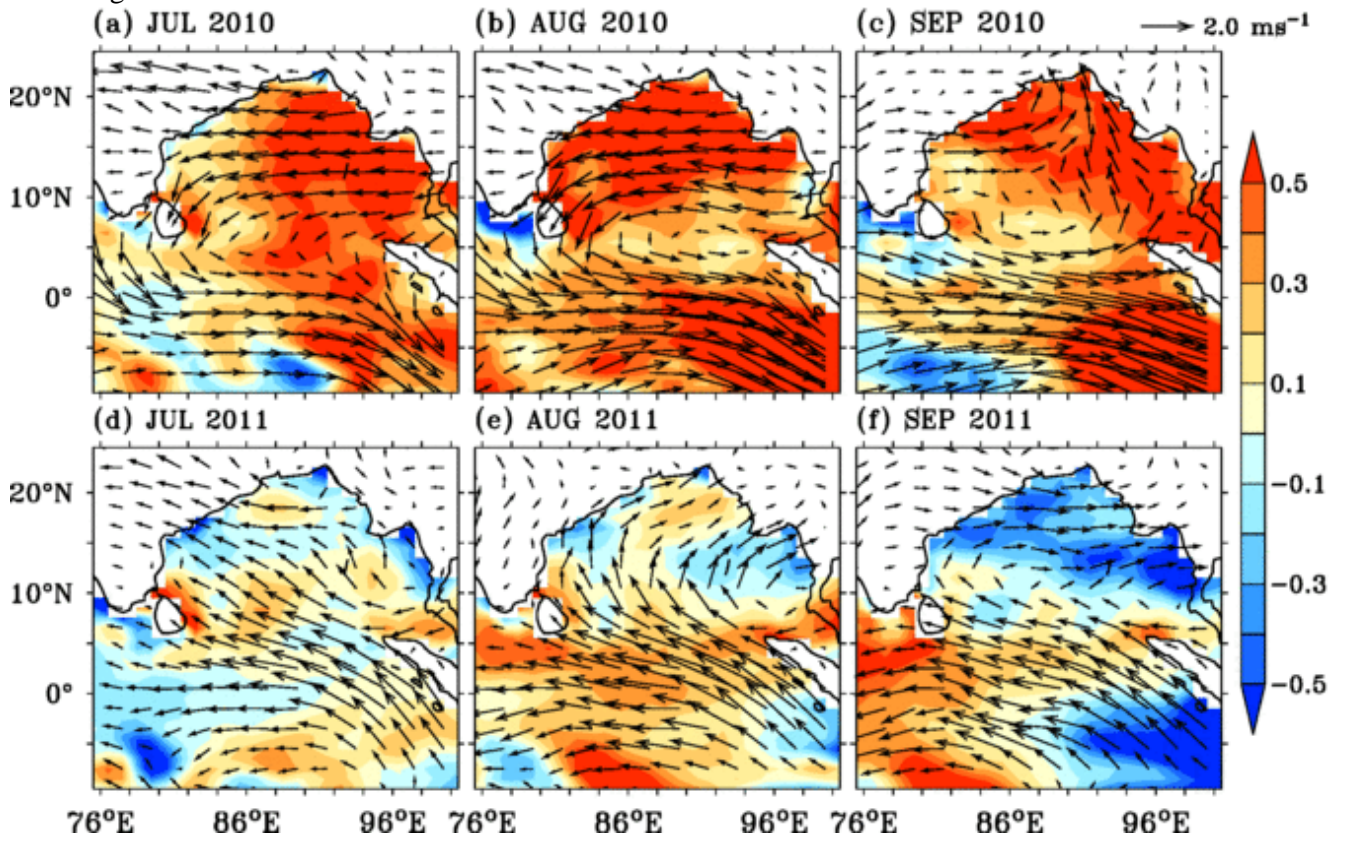


Figure 7:

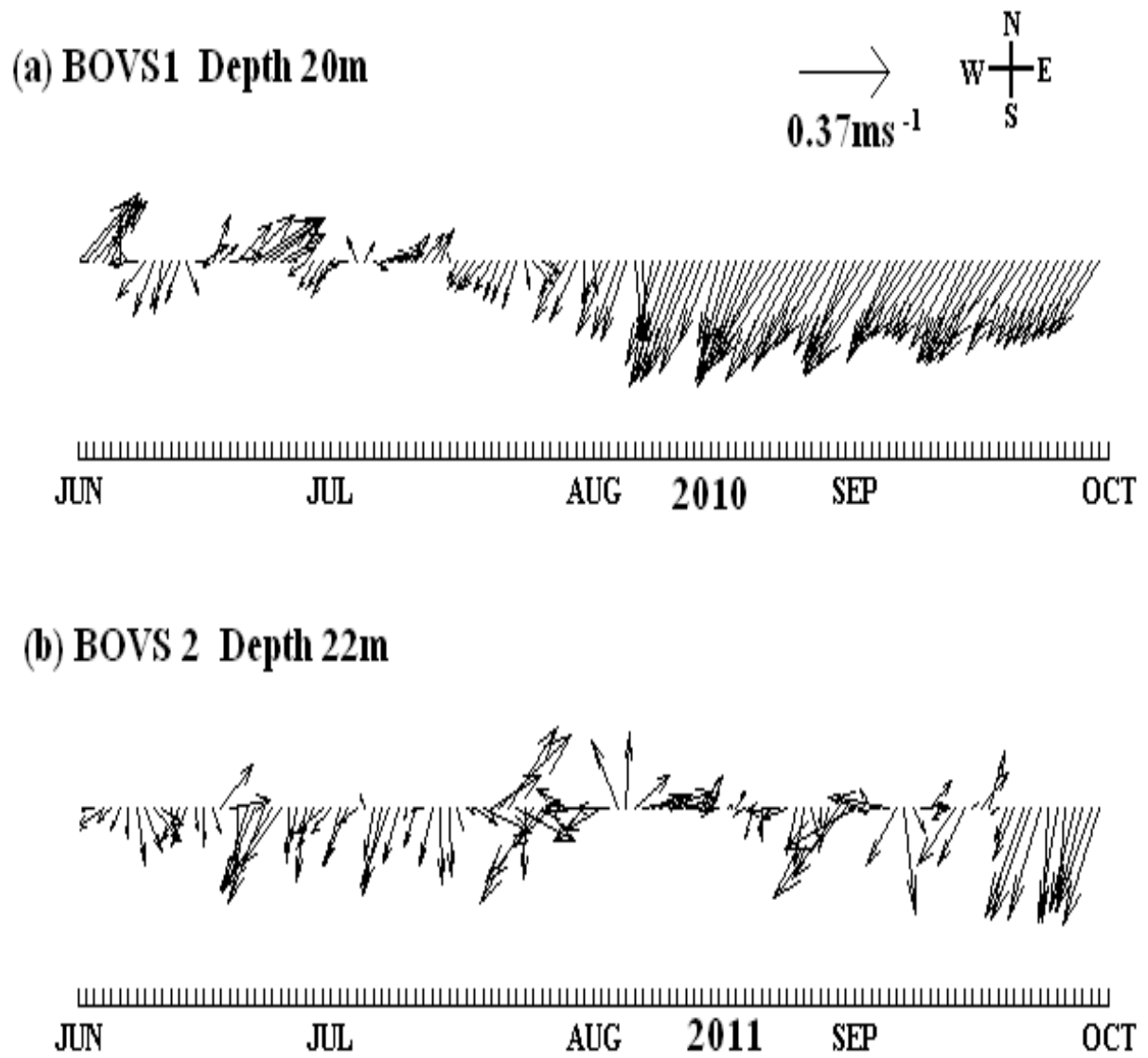


Figure 8

