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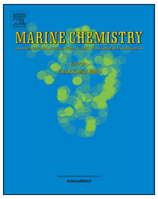

East India Coastal Current controls the dissolved inorganic carbon in the coastal Bay of Bengal

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ABSTRACT

Monthly variations in dissolved inorganic components (DIC) were measured in the coastal waters off Visakhapatnam in the western Bay of Bengal (BoB) to examine the controlling factors on their distribution and fluxes to the atmosphere. The seasonal variations in the direction of East India Coastal Current (EICC) bring significant variations in the hydrographic properties in the coastal western Bay. Poleward moving EICC from February to May brings in high saline waters to the study region resulting in weak stratification and the coastally trapped upwelling Kelvin Waves aid coastal upwelling. On the other hand, equatorward flowing EICC from October to December brings in low saline, warm waters to the study region resulting in strong stratification, and contributes to lower concentrations of DIC and partial pressure of carbon dioxide (pCO_2) and higher pH. During March–August period, higher concentrations of DIC and pCO_2 and lower pH were observed due to upwelling of subsurface waters under the influence of an shoreward approaching cyclonic eddy. The DIC, pH and pCO_2 displayed significant relations with temperature, salinity and chlorophyll-a in the both inshore and offshore region. Biological processes are dominant over mixing effect during March–August in both inshore and offshore regions, while their impact decreases towards offshore. Similarly thermal effect is higher during March–August and salinity effect is significantly higher during October–December when the EICC brings in freshwaters from the northern Bay. It is also noticed that the impact of fluxes variations is significantly low. This study suggests that the physical processes modulate the biological processes significantly to influence the DIC system in the coastal BoB and makes it as a strong source for atmospheric CO_2 than hitherto hypothesized to be a sink.

1. Introduction

The coastal ocean is usually an important sink for atmospheric carbon dioxide (CO_2) (IGBP, 1993), but the changing environmental conditions due to anthropogenic activities would alter the strength of sink (Bauer et al., 2013; Regnier et al., 2013). Tsunogai et al. (1999) estimated that global coastal ocean absorb about ~1 PgC y^{-1} of CO_2, based on the extrapolation of CO_2 absorption found in the East China Sea to global coastal ocean. In contrast, the coastal oceans in the subtropics, such as northern South China Sea, was found to be a weak source to the atmospheric CO_2 (Zhai et al., 2005, 2013; Dai et al., 2013). These observations revealed that coastal oceans are not always sink for the atmospheric CO_2. Recent addition of more CO_2 data, and data synthesis activities resulted in decrease in net sink of atmospheric CO_2 by the global coastal ocean to ~0.2 PgC y^{-1} (Chen et al., 2013; Laruelle et al., 2014). Despite several efforts to improve realistic estimation of CO_2 absorption (sink) in the global coastal ocean, significant uncertainty still remains due to paucity of data (Borges, 2005; Laruelle et al., 2018).

The Bay of Bengal (BoB), the northeastern part of the Indian Ocean, is a unique region with reference to regional settings (closed on three sides and open to the Indian Ocean in the south), freshwater discharge of variable magnitudes and characteristics (Sarma et al., 2012a) from different rivers such as the Ganges, Godavari, Krishna, Mahanadi (UNESCO, 1979), seasonally reversing coastal currents (Murty et al., 1993; Shetye et al., 1996) and occurrence of seasonal coastal upwelling (Gopalakrishna and Sastry, 1985). Kumar et al. (1996) suggested that coastal BoB acts as a strong sink for atmospheric CO_2 during March/April 1991 and attributed to high biological production driven by nutrients from rivers and a subsequent increase in scavenging of this organic matter to depth by river-borne mineral particles (Ittekkot et al., 1991). In contrast, estuaries are known to be net heterotrophic due to the large inputs of terrestrial organic matter (Green et al., 2006; Dai et al., 2008; Sarma et al., 2009) with supersaturated levels of partial pressure of CO_2 (pCO_2) by several folds compared to the atmospheric CO_2 (Borges et al., 2005; Chen and Borges, 2009; Laruelle et al., 2010, 2018). Sarma et al. (2012a) report that pCO_2 levels vary between 293 and 15,210 µatm in the Indian estuaries opened to the BoB and would in turn enhance pCO_2 levels in the coastal BoB. In contrast, Chen et al. (2012), based on > 100 estuaries, noticed that super saturation of CO_2 in the upper estuaries, however, the river plumes are significant sink for the atmospheric CO_2.

Sarma et al. (2012a) measured DIC system for the first time during southwest monsoon (peak discharge period) along the western coastal BoB and observed that northwestern coastal BoB acts as a sink for atmospheric CO_2 due to discharge of relatively alkaline waters by the

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Ganges river while southwestern coastal Bay is a source due to discharge of acidic and high pCO_2 waters by peninsular rivers viz., Godavari, Krishna. Therefore, it is suggested that either source or sink of CO_2 in the shelf region depends on the discharged river characteristics. Seasonal reversal of East India Coastal Current (EICC) towards equator during October – December distributes the river-discharge along the coast and brings in large seasonal variations in the water column characteristics along the coastal BoB (Rao et al., 1994; Naqvi et al., 1994; Kumar et al., 1996; Sarma et al., 2013a,b).

The coastal circulation in the western BoB is dominated by the seasonally reversing currents and multiple meso-scale cyclonic and anticyclonic eddies. The seasonal currents constitute a poleward flowing East India Coastal Current (EICC) – also known as the Western Boundary Current (WBC; Shetye et al., 1993; Sanilkumar et al., 1997; Babu et al., 2003; Gangopadhyay et al., 2013). The WBC forms during January and develops best during March–April, and decays by June (Shetye et al., 1993). Sarma et al. (2016) showed that the EICC is dominantly equatorward south of 17°N during November–December 2013, and a poleward coastal current associated with an anticyclonic eddy north of 17°N. Sarma et al. (2015) showed that interannual variability in the observed coastal currents during southwest monsoon (August–September) season is associated with the dynamics of Indian Ocean Dipole (IOD) events of negative IOD in 2010 and positive IOD in 2011. Recent studies based on ADCP current observations and HF (High Frequency) radar surface currents along the east coast of India, the authors (Mukherjee et al., 2014; Mukhopadhyay et al., 2017) report seasonal and intraseasonal variability of EICC. This has motivated us to examine the influence of seasonal EICC on the shelf and nearshore regions off east coast of India on the hydrographic and biogeochemical parameters off Visakhapatnam.

The aim of this study is to examine the factors controlling the DIC system and fluxes of CO_2 to the atmosphere in the coastal BoB through time-series observations of sea water sampling along a transect off Visakhapatnam and also the time series observations of currents at a coastal station north of the above transect using a moored Acoustic Doppler Current Profiler (ADCP) at the depth of 180 m.

2. Material and methods

2.1. Study site characteristics

The continental shelf of east coast of India is relatively narrow, compared to west coast, and it is quite steep in the study region of Visakhapatnam where water column depth of 100 m occurs at ~30 km from the coast (Fig. 1). In the BoB, being a tropical basin, the biological production is modulated to a large extent by physical processes bringing nutrients to the photic layer by seasonal upwelling, cyclones and heavy rainfall (Maneesha et al., 2011; Sarma et al., 2013a). Though the study region (Fig. 1) does not receive freshwater discharge directly as no rivers are opened within 100 km from north/south of the region, it gets seasonally the low salinity waters of the riverine freshwater discharge from the northern Bay through the equatorward flowing EICC during post-monsoon season (October–December). This results in strong salinity stratification during this period (Shetye et al., 1996) and changes the water column characteristics in the study region. In contrast, weak salinity gradient occurs during pre-monsoon season (February–May) due to poleward flowing EICC advecting high-saline waters from south. The mean salinity of the surface waters of the BoB are 2 to 6 lesser due to large freshwater discharge from rivers (Rao et al., 1994) than that of its adjacent basin Arabian Sea.

2.2. Sample collection and analysis

Monthly sea water sampling was conducted on board mechanized boat from 0.5 km from the coast to ~30 km offshore in the coastal BoB, off Visakhapatnam, at six fixed stations along a transect (Fig. 1) at standard depths from January to December 2015. In this study the stations (V1, V2 and V3), occupied within 15 km distance from the coast, are considered as inshore region and the stations (V4, V5 and V6), occupied between 15 and 30 km distance, are considered as offshore region. This classification is done based on the nutrients and Chlorophyll-a (Chl-a) variability between these two regions as per the study of Sarma et al. (2013a,b). The mean of each parameter for each month at the stations V1-V3 and that of stations V4-V6 are represented as inshore and offshore regions respectively, and are used to construct the annual cycle for inshore and offshore regions. Vertical profiles of pressure, temperature and salinity were measured using a portable conductivity, temperature and depth (CTD) profiler (SBE 19 plus; SeaBird Electronics, US). The water sampling was done at standard depths using 10 L Niskin bottle attached to rosette with pressure triggered closing mechanism (ECO rosette sampler, SBE, US). Bubble-free water samples were first collected for dissolved oxygen (DO) followed by dissolved inorganic carbon (DIC), and pH. The DO was measured using Winkler titration method following potentiometric detection (Carpenter, 1966) using potentiometer (Titrando Metrohm, Zofingen, Switzerland). A 2-L water sample was filtered through a GF/F filter (0.7 μm pore size, Whatman) and Chl-a retained on the filter was first extracted with *N,N*-dimethylformamide (DMF), at 4^{o} C in the dark for 12 h and then spectrofluorometrically analyzed (Varian Eclipse fluorophotometer) following Suzuki and Ishimaru (1990). The analytical precision for Chl-a analysis was ± 0.04 $mg\,m^{-3}$. The concentrations of nutrients were measured following standard spectrophotometric procedures using an autoanalyzer (Technicon; Taacs, Australia) (Grasshoff et al., 1983). The detection limits for nitrate, ammonia, phosphate, and silicate were ± 0.05, ± 0.05, ± 0.02, and ± 0.03 μM, respectively. The pH was measured using glass electrodes (Metrohm, Zofingen, Switzerland) following standard operating procedures suggested by the Department of Energy (DOE, 1998). pH was measured in the NBS scale and then converted to total scale using CO2sys program (Lewis and Wallace, 1998). DIC was measured using a coulometer (model CM 5014; UIC Inc., Joliet, Il, USA) attached to an automated subsampling system (Sarma, 1998; Sarma et al., 2012a; Sarma et al., 2015). The precisions for pH, and DIC were ± 0.002, and ± 1.8 μM, respectively. The accuracy of the pH and DIC was estimated using Certified Reference Material supply by Dr. A.G. Dickson of Scripps Institute of Oceanography, USA as 0.015 and 4 μM respectively. The pCO_2, calcite and aragonite saturation was computed using the measured salinity, temperature, nutrients (phosphate and silicate), pH and DIC using the CO_2 SYS programme (Lewis and Wallace, 1998) using the CO_2 dissociation constants given by Millero et al. (2006) in the 0–40 salinity range. The accuracy of the estimated pCO_2 is ~7 μatm. The air-water flux of CO_2 was estimated using formulations given by Wanninkhof (2014) based on surface pCO_2 levels and monthly mean wind speeds measured close to the study region using automated weather station at 10 m above sea level and atmospheric pCO_2 values obtained from CDIAC (http://cdiac.esd.ornl.gov/pns/current_ ghg. html).

2.3. Time-series observations of coastal currents off Visakhapatnam in 2015

One year long time-series of coastal current measurements were carried out off Visakhapatnam by deploying a mooring fitted with Acoustic Doppler Current Profiler (ADCP, #300 kHz; Make: Teledyne RD Instruments, USA) at 180 m at a coastal station (BOVS6: 17°48′N, 83°58′E marked in Fig. 1) from 5 March 2015 to 6 March 2016. The ADCP recorded the currents at 4 m depth bins and 30 min interval. Following Mukherjee et al. (2014) and Sarma et al. (2015), quality control measures were applied to the ADCP data processing and time-series of currents data were obtained in the depth range of 20–180 m. The processed time-series of zonal (U, east–west flow) and meridional (V, north–south flow) velocity data were 36 h low-pass filtered to remove the tidal and local inertial oscillations (39 h period) and daily