

Sources and sinks of CO₂ in the west coast of Bay of Bengal

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ABSTRACT

Observations at high spatial resolution (100 × 50 km²) in the western continental shelf of Bay of Bengal during southwest monsoon, when peak discharge occurs into the Bay through major rivers of the Indian subcontinent, revealed that freshwater discharge exerts dominant control on the inorganic carbon components in surface waters. Lower than present atmospheric pCO₂ levels were found in the northwestern (NW) than southwestern (SW) coastal Bay of Bengal. The pCO₂ levels in the peninsular rivers were an order of magnitude higher (5000–17000 μatm) than that of atmospheric levels and glacial river Ganges (~500 μatm). The discharge from the peninsular rivers has a stronger influence in the SW region, whereas the Ganges river discharge has a stronger influence in the NW region. Source or sink of CO₂ in the shelf region depends on the discharged river characteristics and the East India Coastal Current that distributes discharged water along the coast. Although during northeast monsoon, the situation is briefly reversed and the region acts as a sink, and on annual scale, the western Bay of Bengal acts as a source for atmospheric CO₂ than hitherto hypothesised.

Keywords: CO₂ fluxes, river discharge, monsoon, coastal processes, carbon cycle

1. Introduction

Continental shelf zones are usually active in biological production (IGBP, 1993). Although they comprise only 7.6% of the surface area of the world oceans (Sverdrup et al., 1942), they play a significant role in the net absorption of atmospheric CO₂. Tsunogai et al. (1999), backed by observation of removal of a significant amount of pCO₂ from the atmosphere (~55 μatm) in the shelf region of the East China Sea, hypothesised that if the world continental shelf zone absorbs atmospheric CO₂ at the same rate as the East China Sea, the uptake from atmosphere by this mechanism would translate to ~1 GtC yr⁻¹.

On the other hand, it is well known that waters in the inner estuary of many coastal regions (e.g. Green et al., 2006; Dai et al., 2008; Sarma et al., 2009) are net heterotrophic because of the large input of terrestrial particulate organic carbon (POC). In these systems, the surface water is generally supersaturated with respect to

pCO₂ and frequently exceeds 2000 μatm (Borges et al., 2005; Chen and Borges, 2009; Laruelle et al., 2010). Recently Sarma et al. (2011) observed high pCO₂ levels (>30 000 μatm) in the Godavari estuary, India during peak discharge period as a result of high heterotrophic activities. On the shelf off river mouth, water is relatively less heterotrophic than in the estuary because of a reduced amount of available terrestrial POC for decomposition due to dilution, and increased biological productivity due to better light conditions, as the suspended particles settle quickly across the photic depth (Breed et al., 2004). Furthermore, there is mixing with ambient seawater that has a lower pCO₂, and the pCO₂ of surface water quickly drops to near or slightly below saturation (Dai et al., 2008).

Takahashi et al. (2009), based on the gridded measured data in the world ocean, found that the Bay of Bengal is a perennial sink for atmospheric CO₂. Kumar et al. (1996) measured surface pCO₂ levels in the western Bay of Bengal during pre-southwest (March–April) and northeast monsoon (NEM) (December, 1991) periods and found that pCO₂ levels were always less than the atmospheric values, supporting the study by Takahashi et al. In the absence of

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data during southwest monsoon (SWM) period in the Bay of Bengal, Kumar et al. (1996) hypothesised that discharge of higher rates of freshwater, that is, nutrient-rich inputs to the coastal region, the Bay of Bengal may become a more significant sink for atmospheric CO₂ than other seasons.

On the other hand, most of the Indian estuaries, namely, Mandovi-Zuari (Sarma et al., 2001), Chilika lake (Gupta et al., 2008), Cochin estuary (Gupta et al., 2009) and Godavari estuary (Sarma et al., 2011) are strong sources of CO₂ to the atmosphere during the entire year and maximum during the high discharge period, whereas Hoogly estuary of river Ganges is a mild source (Mukhopadhyay et al., 2002). Therefore, the discharge of either acidic/basic water from these estuaries to the coastal region might have significant impact on spatial gradients in fluxes of CO₂ to the atmosphere. No observations have been carried out so far along the east coast of India during peak discharge period to understand how discharges from different rivers influence coastal CO₂ fluxes. The aim of this article is to understand the influence of major peninsular rivers along the east coast of India on pCO₂ levels and fluxes at the air–water interface in the coastal Bay of Bengal during SWM.

2. Study region

The north Indian Ocean is a unique region in terms of its geographical setting, as it is semi-enclosed and connected to the Indian Ocean in the south, and its circulation pattern is driven by monsoons. The Bay of Bengal is a region of positive water balance where precipitation and river runoff far exceeds evaporation, which leads to low surface salinities and strong stratification (Varkey et al., 1996). The extreme meteorological forcing, known as monsoon, manifests strong seasonality. Typically, the two components of annual cycles are referred to as the SWM (June–October) and NEM (November–February). Winds change their directions; they are from the NE during the NEM and from the SW during the SWM. The East India Coastal Current (EICC) reverses their direction twice a year. It flows northeastward from February to September with a strong peak in March–April, and flows southwestward from October to January, with the strongest flow in November (Schott and McCreary, 2001). The seasonal change in circulation and winds led to supply of nutrients to the surface by different mechanisms (Marra and Barber, 2005; Wiggert et al., 2005; Lévy et al., 2007).

The Bay of Bengal receives an enormous amount of freshwater from major rivers, such as the Ganges, Brahmaputra, Godavari, Mahanadi, Cauvery, Irrawady and Krishna ($1.6 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$; UNESCO, 1979), and high precipitation ($\sim 2 \text{ m yr}^{-1}$; Prasad, 1997). The river system delivers the major parts of its annual average sediment

($1.1 \times 10^9 \text{ t}$) during June to October (Milliman and Meade, 1983; Milliman and Syvitski, 1992). The fluvial inputs are major sources of nutrients to the Bay of Bengal. The annual supply of nutrients by the Ganges and Brahmaputra rivers to the Bay of Bengal is $133 \times 10^9 \text{ mol yr}^{-1}$ which is $\sim 2\%$ of the riverine input to the world ocean (Sarin et al., 1989). Both river runoff and precipitation are more intense during the SWM (Unger et al., 2003). As a result, salinity of the surface waters is 3 to 7 units lower in the Bay of Bengal than in the adjacent basin, the Arabian Sea (LaViolette, 1967; Varkey et al., 1996), which leads to strong stratification throughout the year (Shetye et al., 1991, 1996; Shetye, 1993).

The Bay of Bengal is traditionally considered to be a region of low biological productivity because of light inhibition resulting from turbidity and cloud cover (Madhupratap et al., 2003, and references therein). Unlike in the west coast of the Arabian Sea, upwelling in the Bay of Bengal is confined very close to the coast during the SWM (Murty and Varadachari, 1968; Shetye et al., 1991), and offshore Ekman transport of upwelled waters is hindered by equatorward flow of the freshwater plume (Gopalakrishna and Sastry, 1985). Therefore, Prasanna Kumar et al. (2002) suggested that the primary production in the Bay of Bengal is strongly controlled by the availability of nutrients. Studies have been conducted on understanding nutrients (Rao et al., 1994) and inorganic carbon system (George et al., 1994; Kumar et al., 1996) in the Bay of Bengal during pre-SWM and NEM. They noticed that surface waters are completely devoid of nutrients due to strong vertical stratification, whereas surface pCO₂ levels were mostly less than atmospheric values during both pre-SWM and NEM seasons.

3. Material and methods

Surface samples were collected on board ORV Sagar Nidhi (#SN 42) during 23 July to 10 August 2010, representing peak SWM, in the coastal waters off major rivers, namely, Krishna (KN–north of Krishna estuary and KS–south of Krishna estuary, respectively), Godavari (GN, GS) and Mahanadi (MN, MS) and minor rivers, Vamsadara (VD) and Hyadri (HD) (Fig. 1). Seventy-three stations were occupied in nine transects (eight stations in each transect, except off Godavari estuary where it is nine stations) off riverine outflow. The transects were perpendicular to the coastline from close to coast ($< 0.5 \text{ km}$) to the continental slope. Transect V (off Visakhapatnam) was chosen to represent no discharge location (Fig. 1).

Water sampling was carried out using a Seabird Conductivity-Temperature-Depth-rosette system fitted with 10 L Niskin bottles. Samples were collected at different stations containing water column depth of 25, 50, 75,

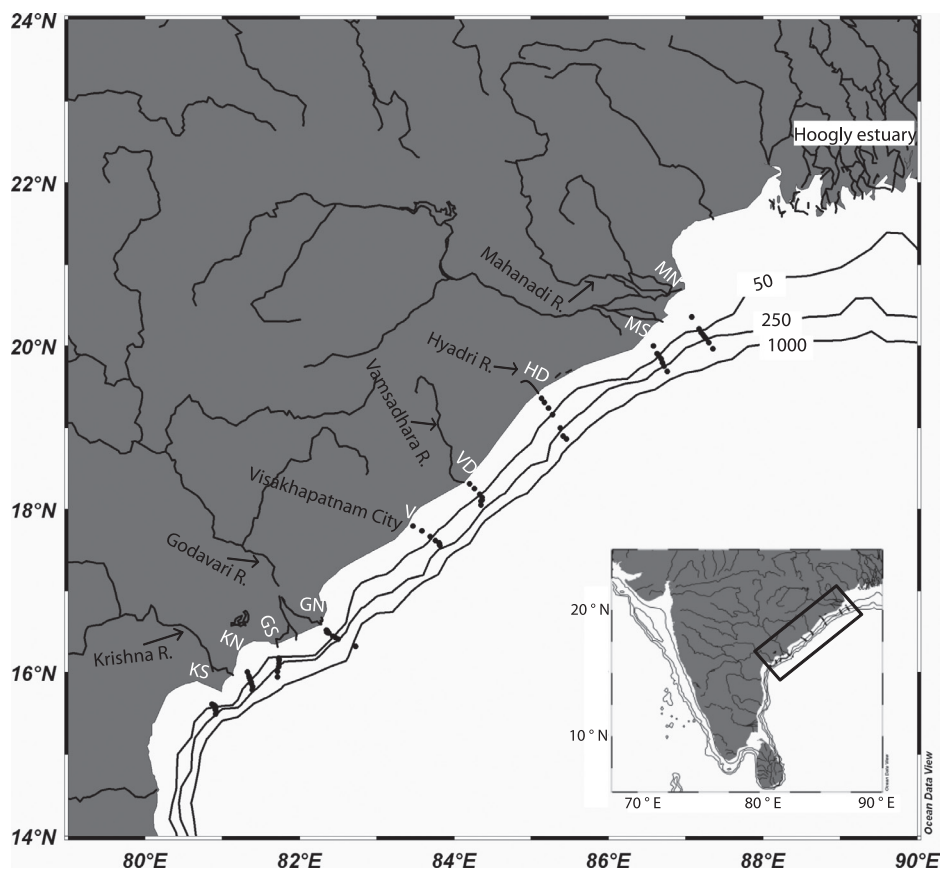


Fig. 1. Sampling locations in the western coastal Bay of Bengal. Isobaths of 50, 250 and 1000 m were also shown. Acronyms K, G, VD, HD, M stands for rivers Krishna, Godavari, Vamsadhara, Hyadri and Mahanadi, whereas N and S attached to the river name represent north and south of the mouth of the river, respectively. Transect names are given in white, whereas river names are given in black.

100, 250, 500, 750 and 1000 m from the coast to offshore. At each station, samples were collected from the surface to bottom at standard depths. Analysis for nutrients (nitrate, nitrite, phosphate and silicate) and oxygen were completed shortly after collection of the samples. Dissolved oxygen (DO) was estimated using Winkler's method following automated potentiometric end point detection (Carritt and Carpenter, 1966). Nutrients were analysed following standard colorimetric procedures (Grashoff et al., 1992). The analytical precision, expressed as standard deviation, was $\pm 0.07\%$ for DO, whereas for nitrate + nitrite, ammonium, phosphate and silicate were ± 0.02 , 0.02 , 0.01 and $0.02 \mu\text{mol l}^{-1}$, respectively. A 2 to 5 L of water sample was filtered through GF/F filter (Whatman), and Chlorophyll-*a* (Chl-*a*) on the filter was first extracted with N, N-dimethylformamide at 4°C in dark for 12 h and then analysed spectrofluorometrically (Varian Eclipse Fluorescence Spectrophotometer, Agilent Technologies, Santa Clara, California, USA) following Suzuki and Ishimaru (1990). The analytical precision for Chl-*a* analysis was $\pm 4\%$. The pH and total alkalinity (TA) were measured by

potentiometric (Metrohm, Zofingen, Switzerland) Gran titration method following standard operating procedures suggested by the Department of Energy (DOE) (1998). Dissolved inorganic carbon (DIC) was measured using a Coulometer (UIC Inc., Joliet, Illinois, USA) attached to an automated subsampling system (Sarma, 1998). The precisions for pH, TA and DIC were ± 0.002 , ± 2.0 and $\pm 1.8 \mu\text{mol l}^{-1}$, respectively. The pCO_2 was computed using measured salinity, temperature, nutrients (phosphate and silicate), pH and DIC using CO₂ SYS program (Lewis and Wallace, 1998). The CO₂ dissociation constants given by Millero et al. (2006) for 0 to 40 salinity range were utilised. Air-water flux of CO₂ was estimated using formulations given by Wanninkhof (1992) using surface pCO_2 levels and measured wind speed at 10 m above the sea levels.

The suspended particulate matter (SPM) was measured based on weight difference of the matter retained on $0.22 \mu\text{m}$ pore size polycarbonate filters after passing 1 L of sample. Particulate organic carbon was measured by filtering about 1 L of water samples through pre-combusted GF/F filter, at 300°C for 6 h, at low vacuum and

dried at 60° C for at least 24 h. Filters were acid (hydrochloric acid) fumigated for 12 h in the desiccators to remove inorganic carbon. The content and isotopic ratios of organic carbon in the particulate matter was measured on elemental analyser coupled with Isotope Ratio Mass Spectrometer (EA-IRMS-Delta V, Finnigan, Germany), and results are expressed relative to conventional standards, that is, pee dee belamnite (PDB) limestone for carbon (Coplen, 1996) as δ values, defined as:

$$\delta R = [(X_{\text{sample}} - X_{\text{standard}}) / X_{\text{standard}}] \times 10^3 [\text{‰}]$$

where $R = {}^{13}\text{C}$ and $X = {}^{13}\text{C}/{}^{12}\text{C}$. The high-purity tank CO_2 was used as working standard for carbon. These gases were calibrated with internal reference materials. Standard deviation on 20 aliquots of the same samples was lower than 0.2‰ for $\delta^{13}\text{C}$. River discharge data were obtained from dam authorities of the respective river.

4. Results

Sea surface temperature (SST) ranged from 26.79 to 29.98 °C (Fig. 2a), whereas sea surface salinity varied between 20.58 and 34.1 psu (Fig. 2b). Relatively warmer and low saline waters were observed in the northwestern (NW) than SW coastal region of Bay of Bengal. Suspended particulate matter showed contrasting distribution pattern to that of salinity with higher concentration in the SW ($26.9 \pm 12 \text{ mg l}^{-1}$) than NW region ($12.1 \pm 6 \text{ mg l}^{-1}$) (Fig. 2c). Dissolved oxygen concentrations varied from 155 to 215 $\mu\text{mol kg}^{-1}$, and lower concentrations were found close to the coast and increased towards offshore (Fig. 2d). Surface nitrate concentration ranged between near detection limits to 13.2 $\mu\text{mol kg}^{-1}$ and high concentrations were observed off Godavari estuary (Fig. 2e). High Chl-*a* concentrations were

noticed in the NW (4.8 to 7.0 mg l^{-1}) than in the SW region (0.3–5 mg l^{-1}) (Fig. 2f).

Dissolved inorganic components also showed similar distribution pattern of salinity and temperature. Both DIC and TA were lower in the NW (1621 ± 57 and $1967 \pm 53 \mu\text{mol kg}^{-1}$, respectively) and increased rapidly towards SW region (2020 ± 38 and $2222 \pm 17 \mu\text{mol kg}^{-1}$, respectively) (Fig. 3a, b). In contrast, pH increased towards NW (8.45 ± 0.03) than SW region (8.12 ± 0.03) (Fig. 3c). Below atmospheric pCO_2 levels were found in the NW ($205 \pm 24 \mu\text{atm}$), whereas supersaturation was observed in the SW region ($505 \pm 77 \mu\text{atm}$) (Fig. 3d). The $\delta^{13}\text{C}$ of POC ($\delta^{13}\text{C}_{\text{POC}}$) was heavier ($-22.8 \pm 0.5\text{‰}$) in the NW than SW coastal Bay of Bengal ($-25.4 \pm 0.8\text{‰}$).

5. Discussion

Surface temperature was lower in the SW coast of the Bay of Bengal ($\sim 26.7\text{--}28.5^\circ \text{C}$; KS, KN, GS, GN and V transects) and higher ($\sim 28.7\text{--}30^\circ \text{C}$; Fig. 2a) in the NW (VD, HD, MS and MN transects). This pattern contrasts with that of salinity which was lower in the NW (~ 22 psu) than in the SW region (~ 33 psu; Fig. 2b). A sharp gradient in surface temperature and salinity was noticed around 18°N . The difference in the salinity distribution arises from seasonally reversing coastal circulation. During the SWM, a well-developed western boundary current, a part of the seasonal subtropical gyre, transports high-salinity waters northward (Shetye, 1993). The EICC flow towards north up to $\sim 19^\circ \text{N}$ and turns eastward. Similarly southward flowing EICC from the north turns eastward at $\sim 19^\circ \text{N}$. The front develops in this region where these two currents merge (Varkey et al., 1996). The occurrence of low salinity (~ 29 psu) waters over a large area of the northern bay was

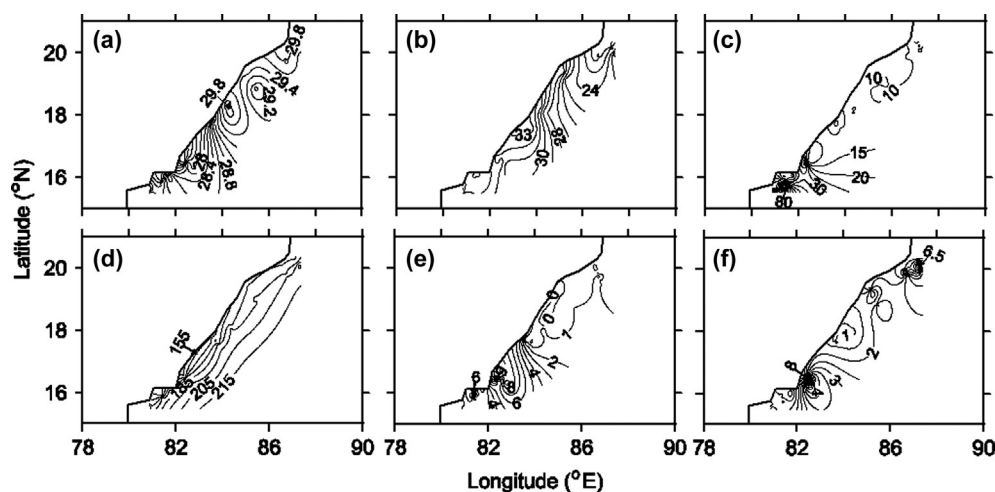


Fig. 2. Distribution of (a) temperature ($^\circ\text{C}$), (b) salinity (psu), (c) suspended particulate matter (mg L^{-1}), (d) dissolved oxygen ($\mu\text{mol kg}^{-1}$), (e) dissolved nitrate ($\mu\text{mol kg}^{-1}$) and (f) Chlorophyll-*a* (mg L^{-1}) during southwest monsoon.

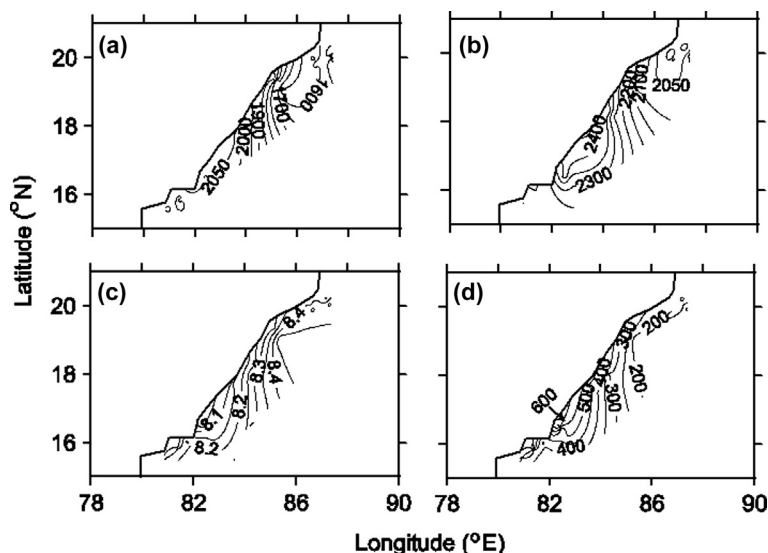


Fig. 3. Distribution of (a) dissolved inorganic carbon ($\mu\text{mol kg}^{-1}$), (b) total alkalinity ($\mu\text{mol kg}^{-1}$), (c) pH and (d) pCO_2 (μatm) in the west coast of the Bay of Bengal.

reported by Conkright et al. (1994) due to huge discharge of major rivers such as the Ganges, Brahmaputra and Irrawady-Salween system ($>14\,000\text{ m}^3\text{ s}^{-1}$ by each river system). Although discharge from the Mahanadi river is less ($\sim 683\text{ m}^3\text{ s}^{-1}$) compared to the Godavari river ($1050\text{ m}^3\text{ s}^{-1}$) and Krishna river ($823\text{ m}^3\text{ s}^{-1}$), the low salinity in the north was more influenced by discharges from the Ganges river ($\sim 15\,000\text{ m}^3\text{ s}^{-1}$) that join equatorward flowing EICC in the NW region. South of Vamsadara river, the influence of Ganges river progressively decreases due to mixing with local water. As such, the waters of the SW region are characterised by low SST and high salinity. An attendant mild upwelling reinforces this physical structure, and the vertical salinity gradient between surface (0 m) and 50 m deep is small ($<0.5\text{ psu}$) in the SW region. Occurrence of mild upwelling along the east coast of India was noticed and it was found that it was mostly confined close to the coast (Murty and Varadachari, 1968; Shetye et al., 1991). The transport of upwelled waters to the surface is hindered by freshwater plume (Gopalakrishna and Sastry, 1985). The upwelling in the NW region is hindered by low saline water at surface that led to strong salinity gradient ($\sim 13\text{ psu}$) between surface and 50 m deep (Sarma et al., 2011). This suggests that vertical stratification is stronger in the NW than SW region that might control nutrients inputs to the surface in the former region (Fig. 2a, b). At a time of meagre river discharge during pre-SWM, Kumar et al. (1996) observed high salinity (32 to 32.5 psu) in the NW region. Intermediate ranges of salinity were observed cf., ~ 26 to 30 psu and 28 to 33 psu for the two regions of NW and SW coastal Bay of Bengal, respectively, in the present study (Fig. 2b).

The SPM was low in the NW (9.2 – 12.4 mg l^{-1}) compared to the SW region (30 – 34 mg l^{-1}) (Fig. 2c). Based on the clay mineral distribution, Rao et al. (1988) suggested that the Ganges river derived sediment does not reach up to the shelf off the peninsular rivers as the major outflow of the Ganges river is eastward (Varkey et al., 1996). Due to low SPM in the NW region, light availability increases phytoplankton growth (Fig. 2f). Madhupratap et al. (2003) and references therein) also suggested that light availability controls the phytoplankton growth in the Bay of Bengal during SWM. The Chl-*a* along the east coast of India increased from SW (0.79 to 1.17 mg m^{-3}) to NW (3.6 to 5.1 mg m^{-3}) with sharp increase associated with salinity front (Fig. 2b and f). However, high Chl-*a* was also observed off Godavari estuary ($3.2 \pm 1\text{ mg m}^{-3}$), where relatively low saline water was observed ($31.9 \pm 0.8\text{ psu}$) compared to nearby locations ($>33 \pm 0.5\text{ psu}$). Nitrate concentrations were low in the NW region ($<1\text{ }\mu\text{mol kg}^{-1}$) compared to SW (2 to $13\text{ }\mu\text{mol kg}^{-1}$) region (Fig. 2e) suggesting that efficient utilisation of nutrients in the former region due to availability of more light facilitated by low SPM (Fig. 2c). The distribution of DO followed Chl-*a* (Fig. 2d, f) and DO values were higher in the NW compared to SW region suggesting more biological production in the NW region.

Low dissolved inorganic carbon components, DIC and TA, were observed in the NW and increased towards SW, while pH experiences high values in the NW compared to SW region. The highest DIC, TA and lowest pH were observed off Godavari estuary (2086.8 ± 54 , $2388.9 \pm 39\text{ }\mu\text{mol kg}^{-1}$ and 8.07 ± 0.05 respectively) while reverse trend was noticed off Mahanadi estuary (1684.6 ± 91 , 2009 ± 95

Table 1. Mean \pm SD of different parameters along the transect lines

Transect	Salinity	Chl- <i>a</i> (mg m ⁻³)	DIC (μ mol kg ⁻¹)	TA (μ mol kg ⁻¹)	pH	pCO ₂ (μ atm)
KS ^a	33.22 \pm 0.98	1.17 \pm 0.4	1995 \pm 27	2227 \pm 20	8.13 \pm 0.03	489 \pm 68
KN	33.86 \pm 0.24	1.07 \pm 0.3	2052 \pm 21	2223 \pm 17	8.11 \pm 0.04	520 \pm 83
GS	33.56 \pm 0.79	0.79 \pm 0.4	2062 \pm 27	2235 \pm 56	8.15 \pm 0.05	456 \pm 77
GN ^a	31.96 \pm 0.88	3.19 \pm 2.5	2087 \pm 54	2389 \pm 39	8.07 \pm 0.05	576 \pm 87
V	33.14 \pm 0.65	1.29 \pm 0.3	2022 \pm 37	2432 \pm 26	8.17 \pm 0.03	432 \pm 50
VD ^a	29.13 \pm 1.11	1.27 \pm 0.7	1909 \pm 38	2275 \pm 47	8.27 \pm 0.03	331 \pm 36
Had	26.00 \pm 1.76	1.55 \pm 0.9	1698 \pm 25	2105 \pm 92	8.39 \pm 0.08	226 \pm 57
MS ^a	23.24 \pm 1.84	5.08 \pm 1.7	1644 \pm 64	1969 \pm 46	8.41 \pm 0.03	216 \pm 26
MN ^a	21.68 \pm 0.78	3.60 \pm 1.6	1590 \pm 40	1951 \pm 54	8.44 \pm 0.02	198 \pm 12

TA, total alkalinity.

^aTransects that are directly affected by the river discharge from the respective river.

μ mol kg⁻¹, 8.41 \pm 0.005, respectively) (Table 1 and Fig. 3). Nevertheless, sharp gradients in inorganic carbon components were associated with the salinity gradient (Fig. 2b). The concentrations of inorganic carbon components were different off the mouth of rivers in the coastal region due to different discharge conditions. For instance, DIC off Krishna estuary (KS; 1995 \pm 27 μ mol kg⁻¹) was much lower than that off Godavari estuary (GN; 2087 \pm 54 μ mol kg⁻¹) but higher than that off Hyadri estuary (HD; 1698 \pm 25 μ mol kg⁻¹) suggesting that the chemical composition of the estuarine waters may be influencing (Table 1). To examine this, samples were collected at three stations from mouths of the estuary to about 10 km towards inner estuary during the same day of sampling in the coastal transects of KS, GS and MN, except for Ganges estuary (Hoogly estuary). The highest DIC value was observed in the Krishna estuary (3078 \pm 76 μ mol kg⁻¹) followed by values reported for the Ganges estuary (1680 \pm 54 μ mol kg⁻¹; computed from TA and pH given by Mukhopadhyay et al., 2002), and the lowest was found in the Mahanadi estuary (1082 \pm 64 μ mol kg⁻¹) (Table 2). Similarly, the lowest pH was noticed in the Mahanadi estuary (7.02 \pm 0.1) and the highest in the Ganges estuary (8.13 \pm 0.24; Mukhopadhyay et al., 2002). Interestingly, DIC in the Krishna estuary (3078 μ mol kg⁻¹) was twice

that of Godavari estuary (1591 μ mol kg⁻¹; 1228–1723 μ mol kg⁻¹), the shelf values are not far apart, cf., 2087 \pm 54 μ mol kg⁻¹ off Godavari estuary and 1995 \pm 27 μ mol kg⁻¹ off Krishna estuary (Tables 1 and 2). On the other hand, the mean DIC in the NW region (1650 \pm 50 μ mol kg⁻¹) is close to that of DIC in the Ganges estuary (1680 \pm 54 μ mol kg⁻¹). DIC distribution pattern in NW region clearly revealed that high discharges from the Ganges estuary (\sim 15 000 m³ s⁻¹) preserve their estuarine signal in their adjacent coastal region while lose their estuarine impact in other regions due to faster dilution and low discharge volumes (Krishna river; 823 m³ s⁻¹ and Godavari river; 1050 m³ s⁻¹). In addition to this, upwelling of subsurface waters in the SW region enriches DIC further. Hence, the observed DIC is net effect of dilution of estuarine and upwelled waters.

Most significantly, pCO₂ followed a conservative pattern with salinity (Fig. 2b) and decreased towards NW region similar to the pattern observed during other seasons (Kumar et al., 1996). The highest pCO₂ level off Godavari estuary (576 \pm 87 μ atm) and lowest off Mahanadi estuary (198 \pm 12 μ atm) were recorded in the present study. An interesting feature is that a large area of the coastal Bay of Bengal was characterised by pCO₂ levels far above the atmospheric levels with the air–sea gradient exceeding 100

Table 2. Mean \pm SD of inorganic carbon components of surface waters in the inner estuaries

Estuary	Discharge (m ³ s ⁻¹)	DIC (μ mol kg ⁻¹)	pH	TA (μ mol kg ⁻¹)	pCO ₂ (μ atm)
Krishna (KS)	823 ^a	3078 \pm 76	7.219 \pm 0.09	3614 \pm 109	17 205 \pm 3500
Godavari (GN)	1050 ^b	1591 \pm 53	7.470 \pm 0.07	1760 \pm 75	4981 \pm 1042
Mahanadi (MN)	683 ^c	1082 \pm 64	7.020 \pm 0.10	1382 \pm 63	9585 \pm 2234
Ganges	15000 ^d	1680 \pm 54	8.130 \pm 0.24	1678 \pm 330	502 \pm 100

TA, total alkalinity.

^aCollected from Krishna Barrage, Vijayawada.

^bCollected from Cotton Barrage, Dowleiswaram.

^cCollected from Dam authorities, Cuttack.

^dCollected from Indira Gandhi Dam authorities, Farakka.

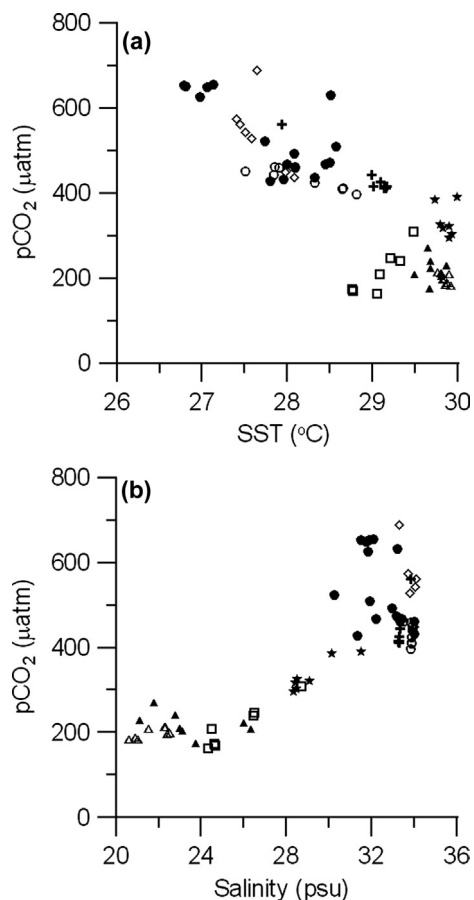


Fig. 4. Relationship of pCO₂ with (a) sea surface temperature and (b) salinity. The data collected off Godavari estuary north (GN–closed circles), Godavari estuary south (GS–open circles), Krishna estuary south (KS–open diamonds), Krishna estuary north (KN–closed diamonds), Visakhapatnam (V–plus), Vamsadhara estuary (VD–star), Hyadri estuary (HD–open square), Mahanadi estuary north (MN–closed triangle) and Mahanadi estuary south (MS–open triangle).

µatm. The pCO₂ showed negative relation with SST (Fig. 4a). Low SST and high pCO₂ were observed off Godavari and Krishna estuaries, whereas the opposite was observed off Mahanadi estuary suggesting that mild upwelling associated with less discharge contributed to high pCO₂ levels in the SW region whereas high discharge and low riverine pCO₂ in the NW region (Fig. 4a). Salinity showed strong positive relationship with pCO₂ suggesting that high river runoff and the subsequent spreading of freshwaters from the Ganges estuary by the prevailing surface circulation led to low pCO₂ in the NW region (Fig. 4b). In addition, high Chl-*a* in the NW region further decreased pCO₂ levels through primary production. The isotopic ratios of POC is lighter ($d^{13}C_{POC} = 22.8 \pm 0.5\%$) in the NW which is close to marine plankton signal of -23.2%

(Thornton and McManus, 1994) than in the SW region ($d^{13}C_{POC} = 25.4 \pm 0.6\%$) suggesting POC in the former region was mainly contributed through in situ primary production. Thus, low pCO₂ levels in the NW coastal region were influenced by both physical and biological processes.

The Bay of Bengal is considered to be low productive region as most of the riverine nutrients are removed within the estuary itself (Prasanna Kumar et al., 2002; Sarma et al., 2009) and strong stratification resulting in decreased supply of nutrients through vertical mixing. Schafer et al. (1993) suggested that a substantial fraction of the new production should be supported by the atmospheric deposition of combined nitrogen. However, it has been observed that increase in nutrients concentration in the coastal waters (SW region: 5.96 ± 2 , 0.4 ± 0.3 and 4.6 ± 2 $\mu\text{mol kg}^{-1}$ and NW region: 0.55 ± 0.3 , 0.43 ± 0.2 and 11.6 ± 5 $\mu\text{mol kg}^{-1}$ for nitrate, phosphate and silicate, respectively) suggests that river discharge supports phytoplankton blooms (0.8 to 5.1 mg m^{-3} of Chl-*a*) in the coastal regions of Bay of Bengal during SWM (Fig. 2f). Other high productive regions in the northern Indian Ocean are associated with both high nutrients and pCO₂ due to vertical mixing, such as upwelling zones (Goyet et al., 1998; Barber et al., 2001). In contrast, fluvial inputs of nutrients decrease pCO₂ levels on one hand and high pCO₂ driven by heterotrophy in the inner estuary enhances pCO₂ levels on other hand along the west coast of Bay of Bengal.

The calculated air–sea fluxes of CO₂ suggested that SW region is significant source for atmospheric CO₂ (7.8 $\text{mmolC m}^{-2} \text{d}^{-1}$; range: 1.0 – 18.8 $\text{mmolC m}^{-2} \text{d}^{-1}$) whereas sink from the NW region (-10.9 $\text{mmolC m}^{-2} \text{d}^{-1}$; -13.8 to -4.4 $\text{mmolC m}^{-2} \text{d}^{-1}$) with mean flux from the entire coast amounts to 0.2 $\text{mmolC m}^{-2} \text{d}^{-1}$. George et al. (1994) found that Bay of Bengal is a net source of CO₂ to atmosphere during pre-SWM (0.66 $\text{mmolC m}^{-2} \text{d}^{-1}$). The Bay of Bengal is concluded as a net sink (-0.61 $\text{mmolC m}^{-2} \text{d}^{-1}$; -4.87 to 11.1 $\text{mmolC m}^{-2} \text{d}^{-1}$) during NEM (Kumar et al., 1996). Our results for the peak SWM can be taken as typical of the whole season, and because SWM remains active in the region for a major part of the year (5 months: June–October), together with the result of George et al. (1994), suggest that except during the brief NEM, the coastal Bay of Bengal acts as a net source for CO₂ to the atmosphere.

The peninsular rivers mostly supersaturated with reference to atmospheric CO₂ and the regions influenced by such rivers act as a source. Accordingly, Tsunogai et al. (1999) hypothesised that entire shelf region of the world act as a sink for atmospheric CO₂ and it is not acceptable from the present study. A source or sink for atmospheric CO₂ in

the continental shelf is mainly determined by the characteristics of discharged waters.

6. Summary and conclusions

Observations in the western continental shelf region of Bay of Bengal and its major estuaries during peak river discharge period revealed that freshwater discharge from different peninsular rivers exerts a decisive control over the inorganic carbon components in surface waters of the coast. Lower pCO₂ levels in the NW and higher pCO₂ levels in the SW region were noticed when compared to that of the atmospheric levels. Coastal Bay of Bengal acts as a source or sink depending on coastal surface circulation led majorly by riverine influx and the EICC. The polewards flowing EICC, although ameliorated by the pCO₂ richer river inputs, does not effectively enrich the pCO₂ of surface water during a major part of the year. Our results together with the earlier reports (George et al., 1994; Kumar et al., 1996) suggest that the coastal Bay of Bengal acts as a net source for CO₂ to the atmosphere throughout the year except for a brief NEM.

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