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# Environmental controls on the seasonal carbon dioxide fluxes in the northeastern Indian Ocean

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Total carbon dioxide ($TCO_2$) and computations of partial pressure of carbon dioxide ($pCO_2$) had been examined in Northerneastern region of Indian Ocean. It exhibit seasonal and spatial variability. North-south gradients in the $pCO_2$ levels were closely related to gradients in salinity caused by fresh water discharge received from rivers. Eddies observed in this region helped to elevate the nutrients availability and the biological controls by increasing the productivity. These phenomena elevated the carbon dioxide draw down during the fair seasons. Seasonal fluxes estimated from local wind speed and air-sea carbon dioxide difference indicate that during southwest monsoon, the northeastern Indian Ocean acts as a strong sink of carbon dioxide (-20.04 mmol $m^{-2}$ $d^{-1}$ ). Also during fall intermonsoon the area acts as a weak sink of carbon dioxide (-4.69 mmol $m^{-2}$ $d^{-1}$ ). During winter monsoon, this region behaves as a weak carbon dioxide source with an average sea to air flux of 4.77 mmol $m^{-2}$ $d^{-1}$. In the northern region, salinity levels in the surface level are high during winter compared to the other two seasons. Northeastern Indian Ocean shows significant intraseasonal variability in carbon dioxide fluxes that are mediated by eddies which provide carbon dioxide and nutrients from the subsurface waters to the mixed layer.

**[Keywords:** Carbon dioxide fluxes, Salinity, Temperature, Primary productivity, Wind speed, Eddies, Seasonal variability, Northeastern Indian Ocean

## Introduction

The northwestern Indian Ocean is known for its large upwelling system and winter convection phenomenon[1,2,3] resulting high primary production[4] associated with blooms. This region is a perennial source of carbon dioxide[3,5] Based on the observations carried out during the presouthwest monsoon and northeast monsoon, Kumar *et al*.[6] reported a sink for carbon dioxide in the northeastern Indian Ocean. However, $CO_2$ flux of 0.33 mmol $m^{-2}$ $d^{-1}$ has been recorded[7] from this region during premonsoon indicating the seasonal variability in $CO_2$ fluxes. Significant seasonal asymmetry and interannual variability in the uptake of carbon dioxide has also been observed on a decadal scale as a result of climate changes affecting physical and biological features in the North Atlantic Ocean[8,9]. Northeastern Indian Ocean is characterized by low salinity surface waters due to the immense discharge of river water from the Ganges, Brahmaputra, Mahanadi, Godavari, Krishna, Kaveri and Irrawadi rivers. The less saline water forms a strong stratification in the surface layer resulting in shallow mixed layer. These physical features associated with weaker winds which cannot erode the stratification influence the carbon dioxide system. Observations carried out in the northeastern Indian ocean under the Bay of Bengal Process Studies (BOBPS) programme during 2001-2005 indicate the presence of several eddies and their role in enhancing the availability of nutrients and biological production in the surface waters in the eddie regions[10,11]. Present study is aimed to determine the spatiotemporal distribution of pCO2 and its seasonal air-sea fluxes in relation to physical, biological and environmental processes.

## Materials and Methods

Samples were collected at 24 stations in the northeastern region of the Indian Ocean (Fig. 1) on board ORV Sagar Kanya during the three seasons;- Southwest monsoon (July-August, 2001), fall intermonsoon (September-October, 2002) and winter monsoon (December-January 2005). Fourteen stations were occupied between 7°N to 20°N in the open ocean transect along 88°E and 10 stations were occupied along the western margin from 11° N to 20°N. along ~1000 m depth contour. Samples were collected at discrete depths in the upper 1000 m water

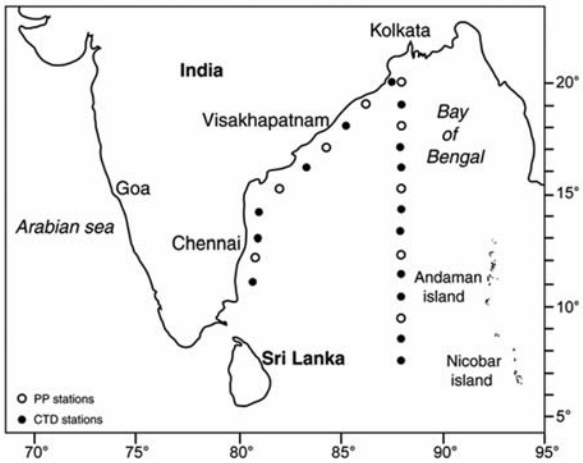


Fig. 1—Map showing stations positions in the Northeastern Indian Ocean

column using 10/30 litres GO-Flow bottles attached to a rosette connected to Sea Bird CTD. The temperature and salinity profiles were obtained using the CTD while samples were collected for *p*H and carbon dioxide following the JGOFS protocol. Total carbon dioxide was determined by Coulometry using UIC Inc. instruments coulometer. *p*H on free ion ($pH_f$) and total scale ($pH_T$) was estimated by cresol red spectrophotometry[12]. Precision of analyses for carbon dioxide was determined by running replicates of the same sample and was found to be ± 4.4 µM. $pCO_2$ was computed from the $pH_f$ on sea water scale (mol $kg^{-1}$) and $TCO_2$ using the carbonic acid dissociation constants by Mehrbach *et al*[13] and refit by Dickson & Millero[14] using the CO2SYS programme[15]. Solubility of carbon dioxide determined by Weiss[16] as a function of temperature and salinity is used. Uncertainty in the estimation of $pCO_2$ computed from the TCO2 replicates was ± 0.7 µatm. $CO_2$ flux was calculated using the gas transfer coefficients of Wanninkhof[17]. Primary production was measured by $^{14}C$ method at 8 depths in the euphotic zone at five stations in the open ocean and 4 stations along the western margin (Fig. 1). Samples were incubated in situ from dawn to dusk. The wind speed was measured by using the hand held anemometer (portable net kit, dyna lab, Pune).

## Results and Discussion

### Open ocean

The thermal structure (Fig. 2a) shows the eddie pumping of the subsurface water mass to shallower depths at 9°N and 19°N during southwest monsoon and fall intermonsoon. Presence of eddies during the southwest monsoon and fall intermonsoon has been substantiated by mean anomaly maps obtained from AVISO (http://las.aviso.oceanobs.com) to elucidate the spatial structure of eddies and are presented in Sardessai *et al*[11]. The eddie upheaval at 19°N was masked by low salinity waters of 28.54 and 28.40 psu during southwest monsoon and fall intermonsoon and formed a salinity gradient of about 7 and 5.5 psu respectively in the upper 30 m layer (). In the southern eddie region (9°N), the fresh water influence was much lower with surface salinity of 33.05 psu and 34.58 psu during southwest monsoon and fall intermonsoon respectively causing a salinity gradient of about 0.5 psu in the upper 30 m. Winter monsoon was characterised by 40 m deep mixed layer from 7°N to13°N which gradually deepened to 80 m towards 20°N with upheaval of the water mass at 10°N and elevation of the 28°C isotherm up to the surface in the north (Fig. 2a). Reduced influx of fresh water increased the surface salinity to 32.84 psu in the north and 33.74 psu in the south (Fig. 3a). The influence of these physical characteristics on the $TCO_2$ distribution is shown in figure 4(a). The vertical distribution and the seasonal variability of biogeochemical properties under the influence of physical forcings have been described in detail elsewhere[10,11,18,19]. However, we incorporate the important features relevant to this study in the discussion of total carbon dioxide ($TCO_2$) and partial pressure of carbon dioxide ($pCO_2$) during the three seasons. During the southwest monsoon, the surface waters in the eddy region (19°N) showed lower $TCO_2$ ranging from 1650-1700 µmol $kg^{-1}$. Physical dilution of sea water caused by high river water influx from major rivers such as Ganges, Brahmaputra, Mahanadi and Godavari, dominated salinity as well as curtailed nutrients upheaval under the influence of eddie from reaching the surface waters. High suspended load (0.8-17.6 mg/l) brought in by the fresh water which was also devoid of nutrients inhibited the light penetration resulting in lower primary production of 89-168 $mgCm^{-2}d^{-1}$ in the northern region[11]. In the southern eddy region (9°N), elevation in the salinity levels and eddie pumping of the colder higher $TCO_2$ subsurface water mass to shallower depths and lower biological production of 220 $mgCm^{-2}d^{-1}$ increased the $TCO_2$ levels to 1900 µmol $kg^{-1}$. Thus the $TCO_2$ concentration in the fresh water diluted low salinity regions were 190-210 µmol $kg^{-1}$ lower than the $TCO_2$

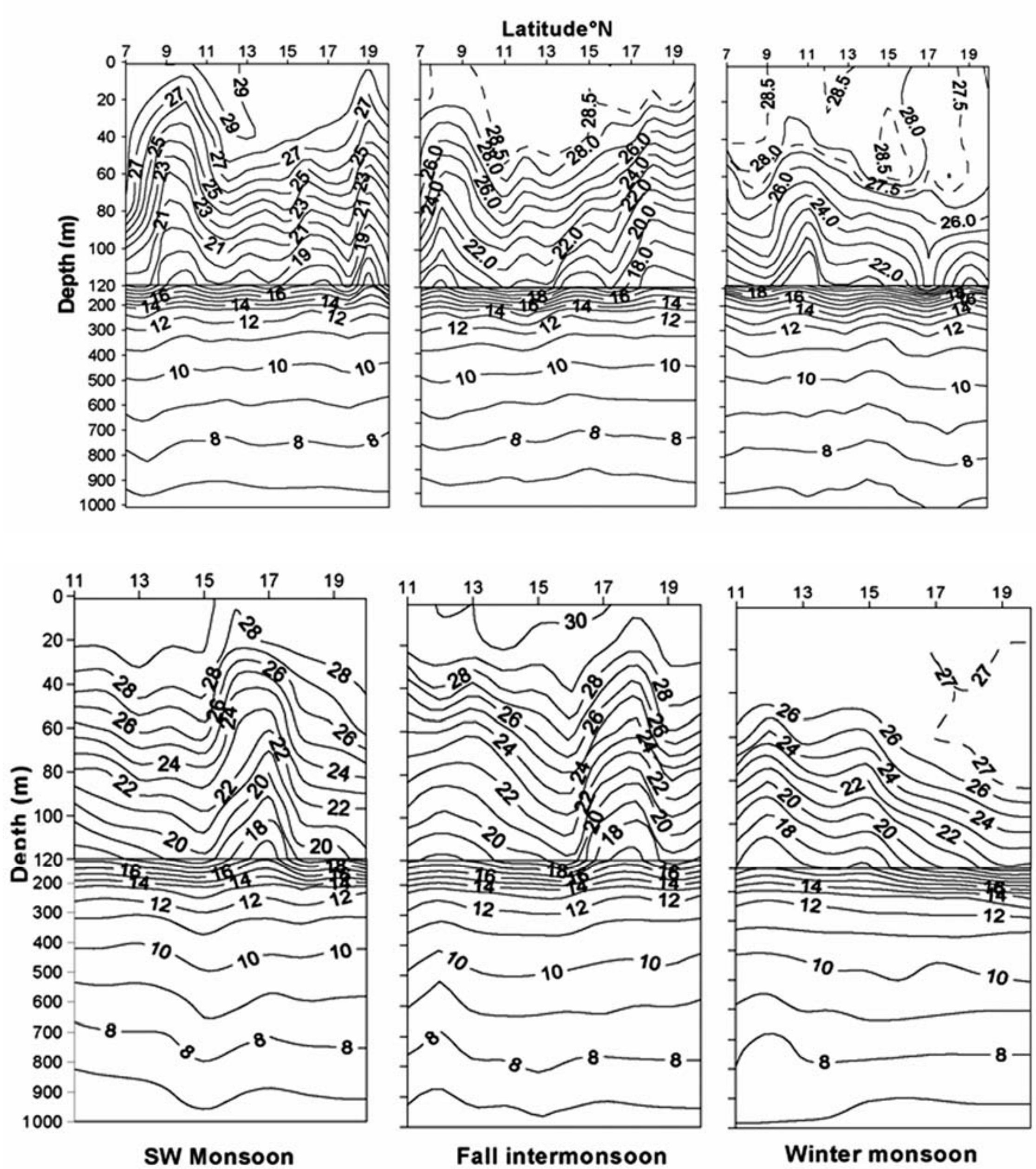


Fig. 2—Distribution of temperature (°C) in the open ocean (a) and along the western margin (b) during the three seasons

levels of southern region. Similarly, during the fall intermonsoon, low $TCO_2$ levels of 1500-1650 µmol $kg^{-1}$ towards the north were associated with fresh water discharge whereas in the south (9°N) though the eddy pumping of the water mass elevated the $TCO_2$ levels to shallower depths the higher draw down of carbon dioxide as indicated by enhanced primary production (512 $mgCm^{-2}d^{-1}$) reduced the $TCO_2$ levels to 1550-1700 µmol $kg^{-1}$ in the surface waters. During winter the low influx of fresh water, moderately lower production ranging from 260 to 603 $mgCm^{-2}d^{-1}$ as well as colder surface waters in the north (<27.5°C) showed the $TCO_2$ levels of 1800 µmol $kg^{-1}$ in the upper layer from north to south. Goyet *et al*.[20] observed large spatial variations in surface sea water $TCO_2$ in the northern Indian Ocean and attributed this variability mainly to physical processes characterized by water masses of different temperature and salinity.

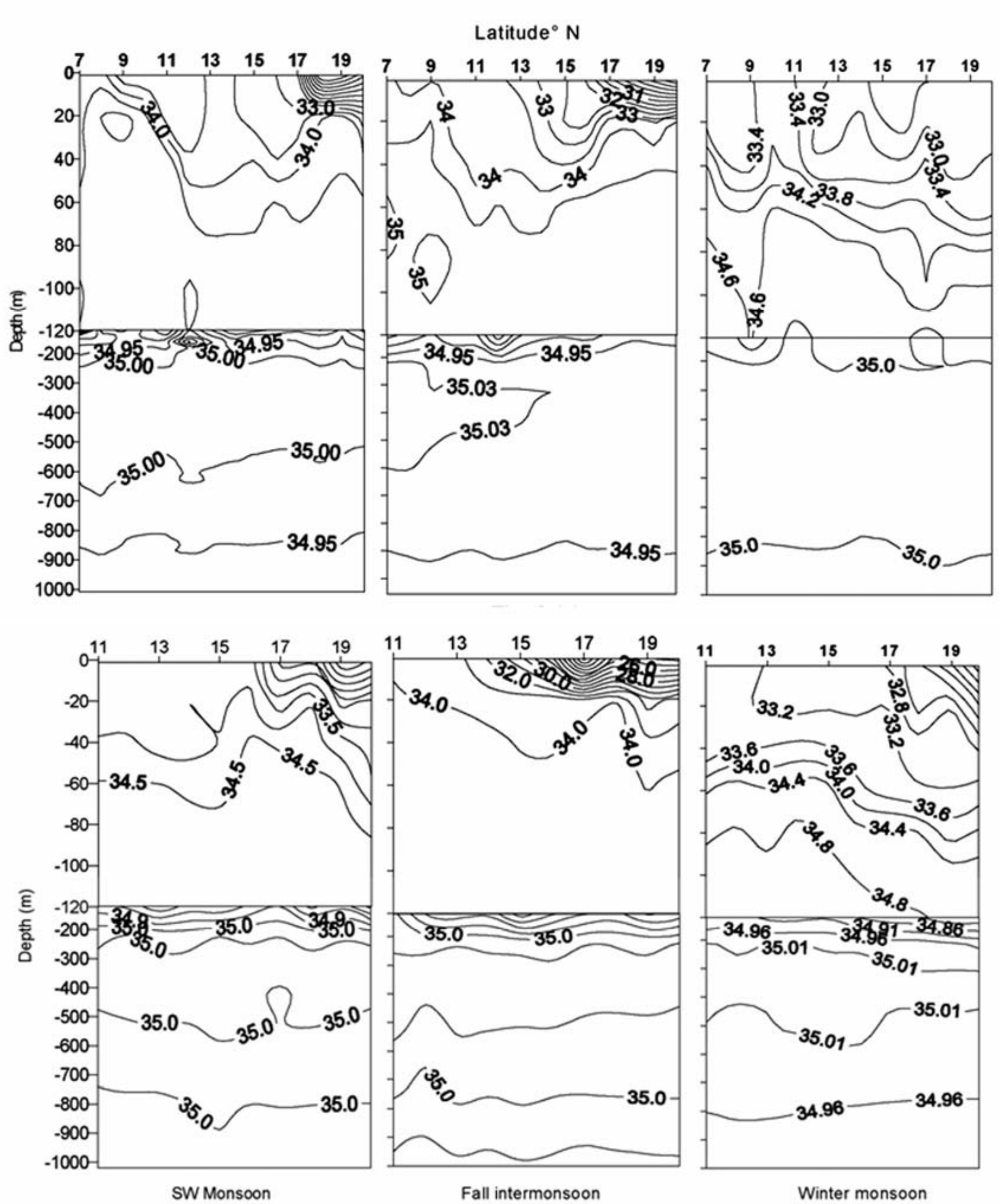


Fig. 3—Distribution of salinity in the open ocean (a) and along the western margin (b) during the three seasons

Physical and biological controls in the northern and southern region are reflected in the distribution of $pCO_2$ during the three seasons (Fig. 4b) During southwest monsoon, $pCO_2$ level of 206 µatm was computed in the northern eddie region whereas $pCO_2$ level of 300 µatm was computed at 10 m in the southern eddie region and at 40 m in the non eddie region (13-15°N). Upheaval of the water mass at 19°N elevated the $pCO_2$ levels of 250 µatm to 20 m. Fall intermonsoon was characterized by higher surface $pCO_2$ levels compared to the southwest monsoon. $pCO_2$ concentration of >350 µatm was observed at the surface at some locations in the south, at 10 m at 19° N, 20°N and >400 µatm at 10 m at 9°N. Thermohaline structure with colder waters (~28°C) and higher salinities (32.51-34.58 psu) towards the south was associated with deep mixed layer (24-64 m) whereas

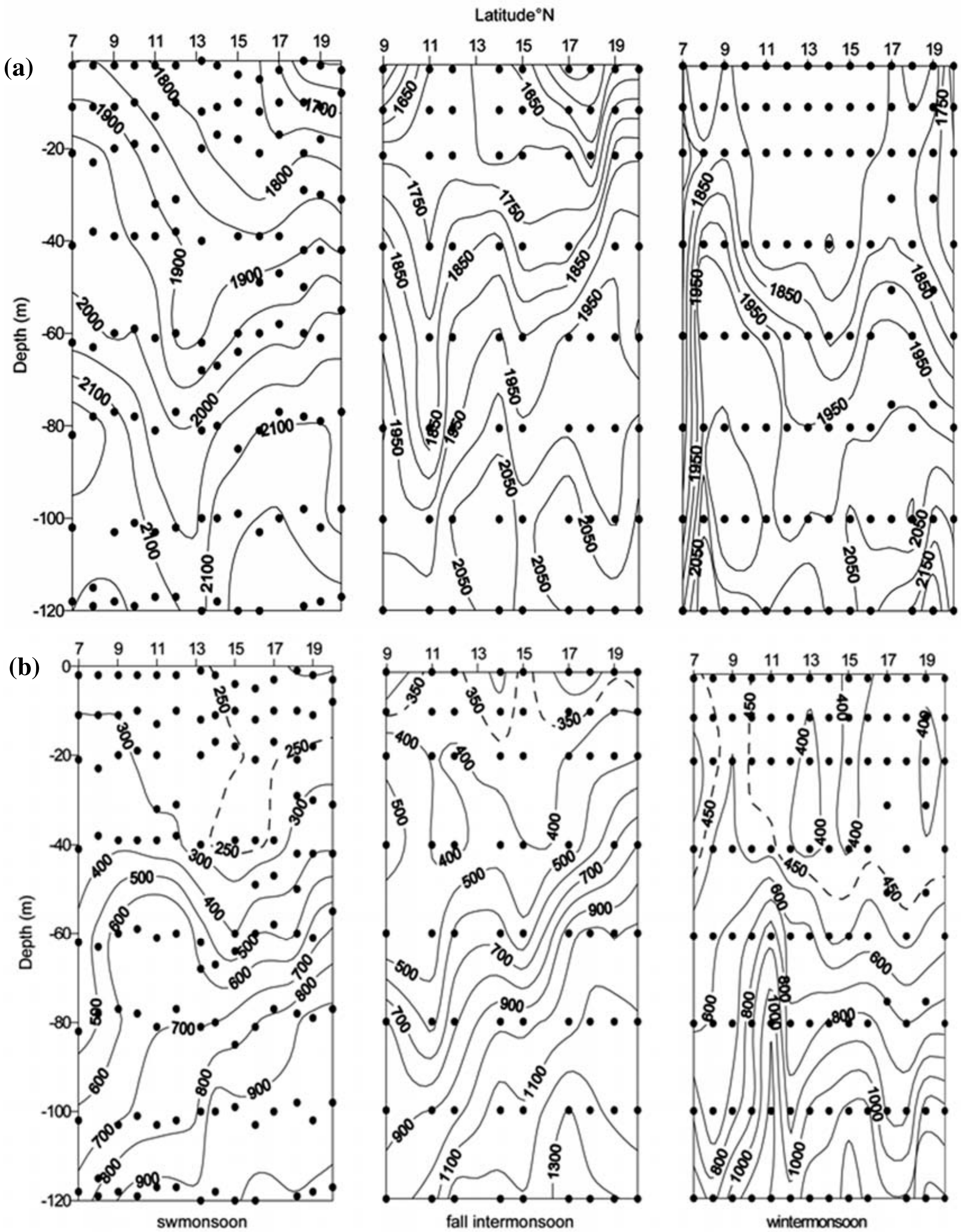


Fig. 4—Distribution of $TCO_2$ (μM/kg) (a) and $pCO_2$ (μatm) (b) in the open ocean during the three seasons

towards the north though waters were warmer (~29°C) the dominant low salinity (28.41-29.46 psu) and shallow isothermal layer (6-16 m) resulted in pockets of low surface $pCO_2$ levels. During the winter monsoon $pCO_2$ levels varied from 400 to 450 μatm in the upper 40 m mixed layer from north to south. Sea Surface Temperature (SST) showed an overall decrease of 1°C from SW monsoon to winter monsoon and a salinity increase of 4-5 psu in the north suggesting the dominance of thermohaline properties on the $pCO_2$ levels during this season.

**Western Margin**

Temperature variability along the western margin (Fig. 2b) during the three seasons indicate the presence of eddie around 17°N during the southwest and fall intermonsoon seasons and around 12 and 15°N in winter season. Surface salinity (Fig. 3b) minimum was 29.61, 21.95 and 32.53 psu during southwest monsoon, fall intermonsoon and winter season respectively in the north (19°N). Physical controls in the form of eddies, fresh water influence and the biological controls influence the $TCO_2$ distribution (Fig. 5a). During southwest monsoon and fall intermonsoon, the fresh water dominance in the north could be seen from the reduced surface $TCO_2$ levels of 1680 and 1450 µmol/kg respectively whereas $TCO_2$ levels of >1800 and 1900 µmol/kg

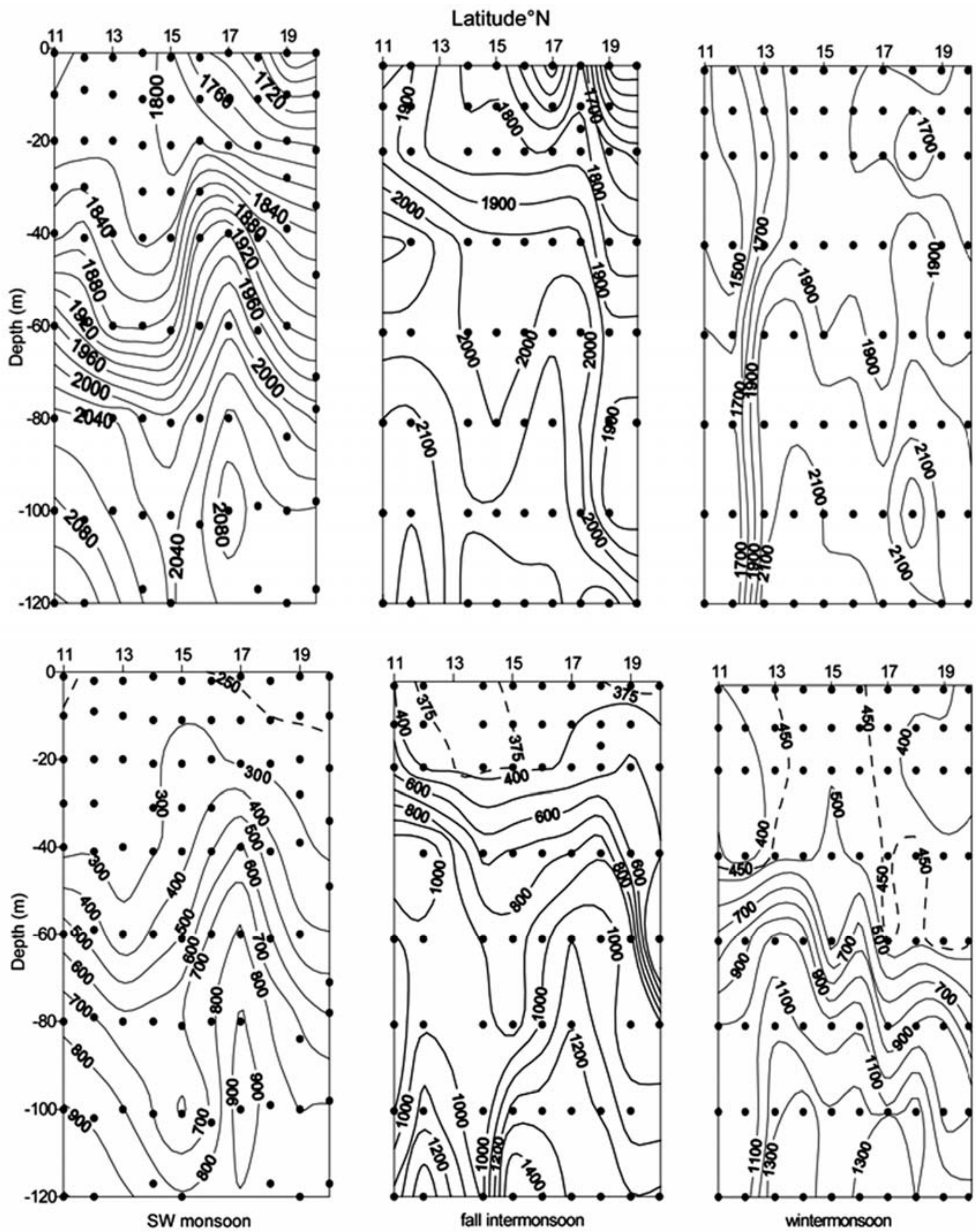


Fig. 5—Distribution of $TCO_2$ (µM/kg) (a) and $pCO_2$ (µatm) (b) along the western margin during the three seasons

respectively were found in the upper 10 m of the water column in the southern region. High/low biological controls (502/244 $mgCm^{-2}d^{-1}$) in southwest monsoon/ (fall intermonsoon) also influenced the carbon dioxide levels in this region (12°N). During winter season $TCO_2$ concentration of 1550 µmol/kg associated with low temperature of 26.51°C and low productivity (331 $mgCm^{-2}d^{-1}$) was observed towards south at 12°N. Impact of physical and biological controls on TCO2 distribution results in surface $pCO_2$ levels ranging from 217-264 µatm in the southwest monsoon which increased to about 338 to 406 µatm during the fall intermonsoon (Fig. 5b). Highest $pCO_2$ levels ranging from 375 to 400 µatm associated with the northward western boundary current during the presouthwest monsoon and lowest $pCO_2$ values ranging from 225 to 300 µatm have been reported by Kumar *et al.*[6] within the southward coastal current during northeast monsoon. Higher $pCO_2$ is sustained by low rate of biological production and shallow mixed layer (<10 m) except in the south and north where the isothermal layer was thicker (>20 m) and colder (~29°C) (Fig. 2b). Based on the one dimensional model to reproduce the seasonal cycle of SST and $pCO_2$, Lefevre and Taylor[21] confirmed that the seasonal cycle of $pCO_2$ is mainly governed by the temperature changes in the north and south Atlantic gyres. In winter monsoon $pCO_2$ ranged from 400 to 450 µatm in the ~40 m mixed layer towards the south and ~80 m in the north. Reduced temperature appears to be the measure mechanism regulating the distribution of $pCO_2$ in the surface layer during the winter season along the western margin with an average temperature decrease of 3.5°C compared to the fall intermonsoon. Increase in $pCO_2$ with a decrease in SST may be the result of deep convective mixing in the mixed layer induced by surface cooling in winter. Thus the seasonal changes in the surface water $pCO_2$ were greater than 200 µatm across the northeastern Indian Ocean.

**Air-sea gas transfer**

Spatial distribution of $pCO_2$ in the surface waters in the open ocean and along the western margin are compared to that of the atmospheric $pCO_2$ levels of 377 ppm and is shown in (Fig. 6a,b). Globally averaged atmospheric carbon dioxide levels of 377 ppm in 2004 has been reported by World Meteorological Organisation (WMO) green house gas bulletin, APA 2006[22]. It is observed that the $pCO_2$ (µatm) is considerably lower than the atmospheric $pCO_2$ during the southwest monsoon in the open ocean as well as western margin from north to south. The fall intermonsoon showed $pCO_2$ levels lower than the atmosphere in both the areas of observation but was higher than the southwest monsoon. This variability could be attributed to the differing physical properties like temperature and salinity, higher draw down of carbon dioxide by the photosynthetic activity as well as low inorganic carbon levels in the fresh water influx towards the north. Winter monsoon was found to be having higher $pCO_2$ levels compared to air among the three seasons which may be attributed to relatively higher salinity, colder surface waters and deeper mixed layer during this season.

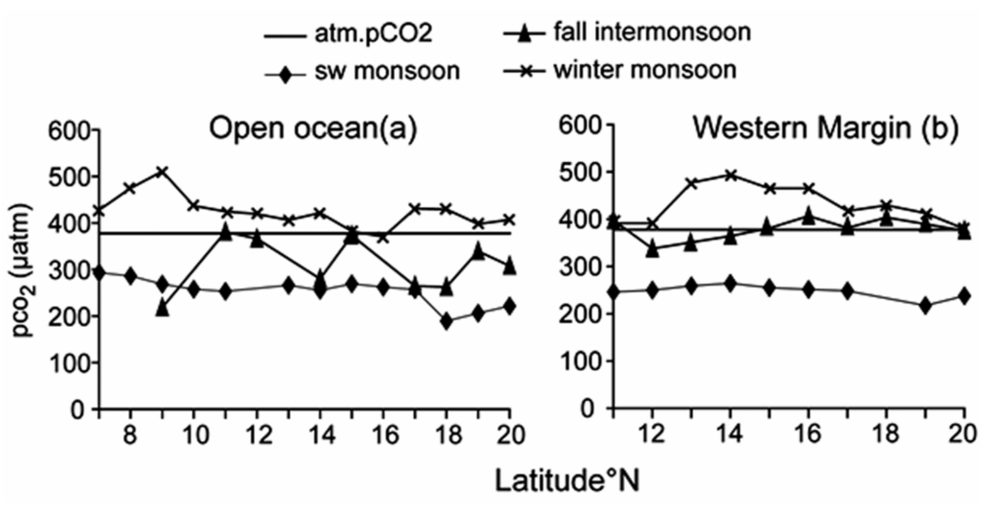


Fig. 6—Latitudinal variations of surface water $pCO_2$ (µatm) compared to the atmospheric $pCO_2$ (µatm) concentration

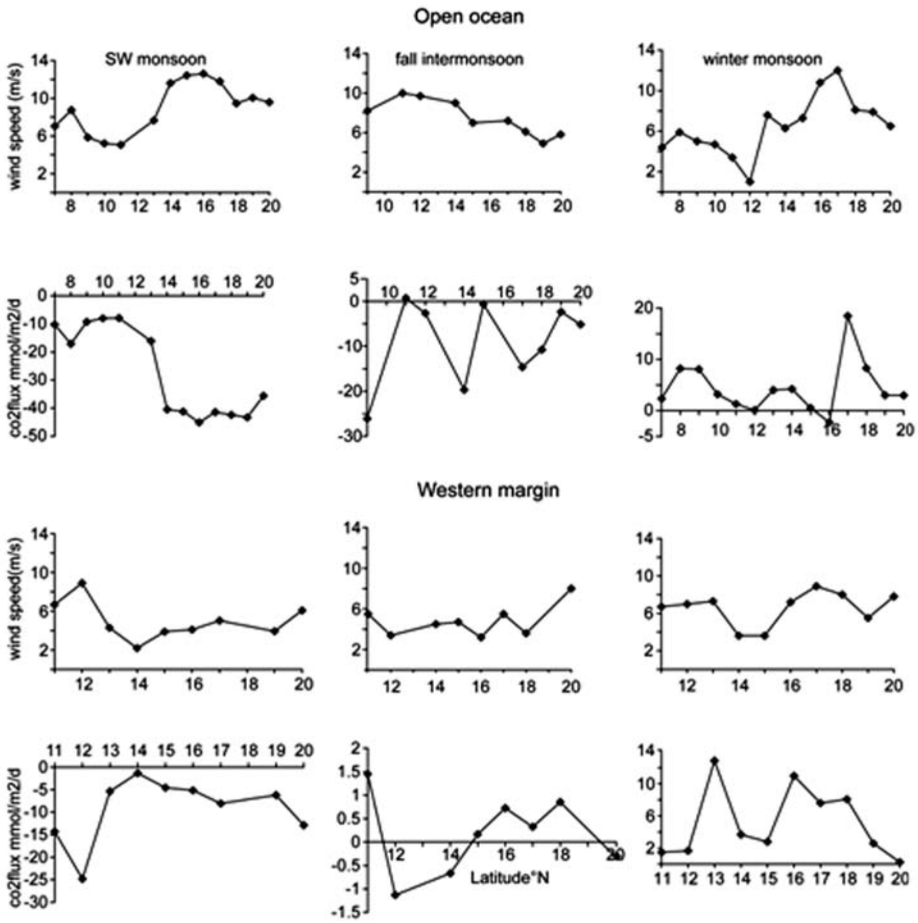


Fig. 7—Latitudinal variations of carbon dioxide fluxes along with the wind speed during different seasons in the open ocean and western margin

**$CO_2$ flux**

Figure 6 shows the temporal and spatial variability of carbon dioxide flux along with the wind speed in the open ocean and western margin. Draw down of carbon dioxide from air to sea showed an inverse relationship with the wind speed during the southwest monsoon and fall intermonsoon Fig. 7. There was sea to air flux during winter monsoon and the amplitude of variation of $CO_2$ flux in general varied with the amplitude of the wind speed. Maximum gas transfer was observed during the winter season at 17°N in the open ocean when the wind speed was the maximum. whereas the lowest gas transfer was associated with the lowest temperature at 20°N along the western margin. Evaluation of seasonal fluxes of carbon dioxide from the Bay of Bengal indicate an average flux of -20.0 mmol $m^{-2}$ $d^{-1}$ during the southwest monsoon. During the fall intermonsoon an average flux of -4.7 mmol $m^{-2}$ $d^{-1}$ is observed. Changes in thermohaline properties and lower wind speed result in significantly lower air sea $CO_2$ flux in this season. The winter monsoon shows average sea to air flux of 4.77 mmol $m^{-2}$ $d^{-1}$ among the three seasons.

Surface water $pCO_2$ levels are regulated by biological, chemical and physical processes[23]. The solubility of carbon dioxide changes with temperature and due to the partitioning of carbon dioxide species[24]. The present study recorded the highest SST during fall intermonsoon (30.60°C) and lowest SST during winter season (25.73°C). Biological controls were substantial towards the south during southwest and fall intermonsoon seasons and the stratification due to fresh water influx dominated the $pCO_2$ distribution in the north. The northeastern Indian Ocean which was hitherto known to be a sink of carbon dioxide from the limited observations carried out so far is found to exhibit significant intraseasonal variability and reduction in sink strength and also found to switch from sink status to a weakly emitting source of carbon dioxide. Earlier studies on the spatio-temporal variability and air sea $CO_2$ gas exchange carried out in the Indian Ocean as part of the World Ocean Circulation Experiment (WOCE) by Bates *et al* [25] observed that the northern Indian Ocean and the equatorial Zone were perennial sources of carbon dioxide to the atmosphere. These findings support significant interannual variability in carbon dioxide fluxes from these regions.

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