Seasonal controls on surface pCO_2 in the central and eastern Arabian Sea

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The variability in partial pressure of carbon dioxide (pCO_2) and its control by biological and physical processes in the mixed layer (ML) of the central and eastern Arabian Sea during inter-monsoon, northeast monsoon, and southwest monsoon seasons were studied. The ML varied from 80–120 m during NE monsoon, 60–80 m and 20–30 m during SW- and inter-monsoon seasons, respectively, and the variability resulted from different physical processes. Significant seasonal variability was found in pCO_2 levels. During SW monsoon, coastal waters contain two contrasting regimes; **(a)** pCO_2 levels of 520–685 μatm were observed in the SW coast of India, the highest found so far from this region, driven by intense upwelling and **(b)** low levels of pCO_2 (266 μatm) were found associated with monsoonal fresh water influx. It varied in ranges of 416–527 μatm and 375–446 μatm during inter- and NE monsoon, respectively, in coastal waters with higher values occurring in the north. The central Arabian Sea pCO_2 levels were 351–433, 379–475 and 385–432 μatm during NE- inter and SW monsoon seasons, respectively. The mixed layer pCO_2 relations with temperature, oxygen, chlorophyll *a* and primary production revealed that the former is largely regulated by physical processes during SW- and NE monsoon whereas both physical and biological processes are important in inter-monsoon. Application of Louanchi *et al* (1996) model revealed that the mixing effect is the dominant during monsoons, however, the biological effect is equally significant during SW monsoon whereas thermodynamics and fluxes influence during inter-monsoons.

1. Introduction

The Arabian Sea is characterised by diverse biogeochemical provinces with pronounced seasonal variations (Zeitzschel 1973). The semi-annual reversal of surface circulation, between southwest (summer, SW) and northeast (winter, NE) monsoons (Wyrtki 1973; Brock *et al* 1992; Shetye *et al* 1994), together with the occurrence of sub-oxic intermediate waters in the Arabian Sea (Sen Gupta *et al* 1976; Naqvi 1991) makes this a unique region in the world oceans. The central Arabian Sea is more productive than the subtropical gyre while the area north of 20°N is even more productive than the former (Banse 1987). The changing variability and intensities of wind also make this region important in regard to air-sea exchange of biogenic gases. The SW monsoonal upwelling and winter convection (overturning) processes bring nutrient rich subsurface waters into the photic zone leading to enhanced biological production (Banse 1987; De Souza *et al* 1996; Madhupratap *et al* 1996). In addition to the temporal variations, considerable spatial variations do occur. Strong gradients in biogeochemical processes in the pelagic zone are created by the asymmetric effects of the monsoon within the basin. Upwelling is the most pronounced off the coasts of Oman and Somalia (Swallow 1984) while comparatively weaker upwelling has been noticed off the Southwest coast of India (Wyrtki 1973). This is driven by offshore Ekman transport of surface water under the influence of winds parallel to the coast (Smith and Bottero 1977). During the SW monsoon, a narrow, low-level atmospheric Findlater Jet (Findlater 1969, 1974) generates strong gradients in the wind stress over the Arabian Sea. To the northwest of the jet axis, a positive wind stress curl drives divergence (open-ocean upwelling) through

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Ekman pumping whereas to the southeast of the jet, the curl is negative causing convergence (sinking) of surface waters. The upwelling off the southwest coast of India increases carbon dioxide levels in surface waters (Sarma *et al* 1996; Sarma 1999).

Surface pCO_2 levels are found to be higher than that in the atmosphere, throughout the year, but with variable fluxes across the air-sea interface (Sarma *et al* 1998). The Arabian Sea is found to serve as a significant source of carbon dioxide to the atmosphere (Somasundar *et al* 1990; Kumar *et al* 1992; George *et al* 1994; Sarma *et al* 1998; Goyet *et al* 1998). Kortzinger *et al* (1997) recorded high pCO_2 of ~ 700 μatm in the Omani upwelling region during the same period. Louanchi *et al* (1996) have developed a one-dimensional model to quantify the influence of different processes on surface pCO_2 and found the mixing process to be dominant in regulating factors in the tropical zone that acts as a net sink. The purpose of the present investigation is to understand the seasonal variability in the surface pCO_2 abundance and its control by physical and biological factors in the central and eastern Arabian Sea.

2. Methods

Five cruises (figure 1) were undertaken on board ORV *Sagar Kanya* during April – May 1994 (inter-monsoon), February 1995 (NE monsoon), June – July 1995 (southwest monsoon), July – August 1995 (southwest monsoon) and August 1996 (southwest monsoon). Except the third one (June – July 1995) all the other cruises were carried out under the JGOFS (India) Programme. Water samples were collected using a Sea-Bird CTD system fitted with 1.8/5/30 litres Niskin/Go-Flo bottles. Samples were analysed for dissolved oxygen, Total carbon dioxide (TCO_2) and pH following colorimetric (Pai *et al* 1993), coulometric ((UIC Inc., USA) George *et al* 1994; Sarma *et al* 1996) and spectrophotometric techniques (Byrne and Breland 1989), respectively. During inter-monsoon and June – July 1995 (SW monsoon) cruises dissolved oxygen was measured by the Winkler procedure. Comparison of both titrimetry and colorimetry techniques were made, to examine the sensitivity of the latter technique, which showed that Winkler method underestimates in the oxic zone whereas it overestimates in the sub-oxic zones due to loss of iodine and excess addition of thiosulphate for the detection of endpoint, respectively (Sarma 1999). The coulometric technique to measure TCO_2 consisted of a semi-automated sampling system to eliminate atmospheric carbon dioxide contamination during the subsampling and stripping before measurement. The accuracy of the TCO_2 was checked with Certified Reference Materials, supplied by Dr. A.G. Dickson of Scripps Institution of Oceanography, USA, and found to be within 0.2–0.3%. Spectrophotometric pH method yielded hydrogen ion on the free scale pH°_{25} at 25°C and atmospheric pressure. This pH°_{25} was first converted to $pH_{in\ situ}$, according to Millero (1979). pH as a function of temperature, pressure and salinity was computed using the constants given by Hansson (1973) and Mehrbach *et al* (1973). Bisulphate effect was calculated based on the formulations that were given by Hansson (1973) for the conversion of $pH_{in\ situ}$ to pH_T (on total scale) since the effect of fluoride ion shall not be significant (Dickson 1993). Total sulphate was calculated from the salinity based on the principle of constancy of ionic composition. The pCO_2 was computed based on TCO_2 and pH_T using the apparent dissociation constants of carbonic acid determined by Goyet and Poisson (1989) at atmospheric pressure. The precisions of TCO_2, pH_T and pCO_2 were ± 2 μM, ± 0.002 and ± 4 μatm, respectively. Chlorophyll *a* and primary production were determined as per JGOFS Protocols (UNESCO 1994; Bhattathiri *et al* 1996).

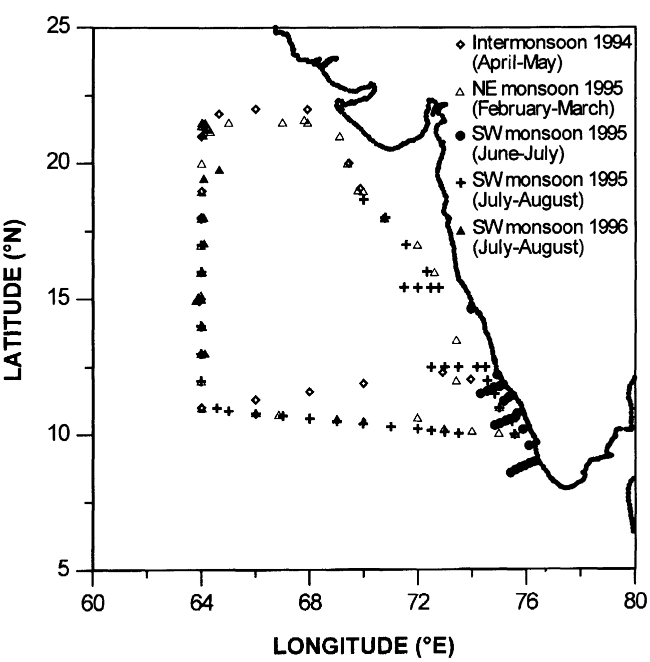

Figure 1. Station locations occupied in the JGOFS (India) cruises.

3. Results and discussion

The vertical distribution of carbon and nitrogen components during different seasons in the study region were discussed elsewhere (Sarma *et al* 1996; De Souza *et al* 1996; Sarma *et al* 1998). However, we discuss here, in brief, the important features relevant to the present study. Surface waters were completely devoid of nitrate during the inter-monsoon period whereas it was about 2 μM in the northern Arabian Sea during NE monsoon. This was attributed to injection of subsurface waters by winter convective mixing (De

Souza *et al* 1996). Nitrate was found to be relatively higher around 16°N during SW monsoon ($\sim 4\ \mu$M; de Souza *et al* 1996) that was driven by open sea upwelling or advected waters from the Arabia coast or due to gyral circulation (Waniek *et al* 1996 and Morrison *et al* 1998) and the availability of nitrate has triggered primary production (770 mgC m^{-2} d^{-1}; Bhattathiri *et al* 1996). The TCO$_2$ distribution in the upper layers of the Arabian Sea exhibited lowest during inter-monsoon and the high in the NE and SW monsoon was attributed to winter overturning and open sea upwelling respectively (Sarma *et al* 1996; 1998). The higher biological production at the surface results in higher respiration rates in the subsurface layers. The intense regeneration of organic matter leads to prevalence of sub-oxic conditions and also enhances pCO$_2$ levels in waters to $> 1000\ \mu$atm in the lower thermocline (Sarma *et al* 1996; 1998). As a result of these physical processes carbon dioxide and nutrient enriched subsurface waters enter the surface that lead to flux of CO$_2$ to the atmosphere. Sarma *et al* (1996, 1998) observed that surface pCO$_2$ is higher than atmospheric value of 355 μatm throughout the year.

The north-south variations in sea surface temperature (SST) and mixed layer depth (MLD), along 64°E, are shown in figure 2 for different seasons. The SST decreased from $\sim$ 28°C in the south to $<$ 25°C in the north in NE monsoon and from $\sim$ 30°C to 28°C during inter-monsoon while it varied between 26 and 27.5°C during SW monsoon with no significant latitudinal differences. The MLD was 70 m at 12°N that deepened to 120 m at 17°N and again shoaled to $\sim$ 75 m at 20°N during NE monsoon. Comparatively, the MLD was very shallow and was largely around 30 m in intermonsoon whereas during SW monsoon it was deeper ($\sim$ 100 m) to the south of 14°N that decreased northward. This northward decrease in SW-monsoonal MLD is a manifestation of the influence of Findlater

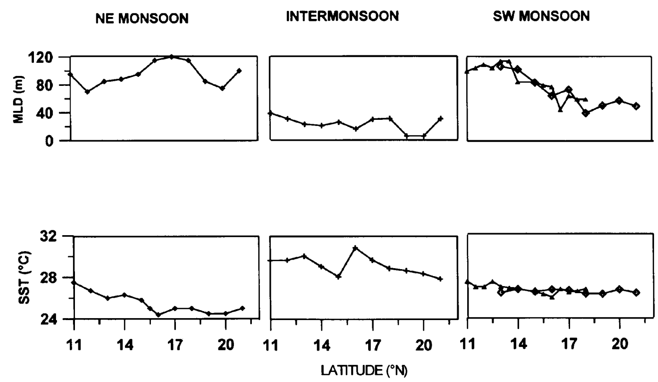

Figure 2. Seasonal variations in SST and MLD in the Arabian Sea along 64°E. In the right panel, triangles are for SW monsoon 1995 and diamonds for the same season of 1996.

jet that leads to divergence to the north of its southwest-northeast axis (Findlater 1969).

The seasonal mixed layer dissolved oxygen and pCO$_2$ distributions along the 64°E and west coast of India are depicted in figures 3 and 4, respectively. Along 64°E oxygen ranged between 190 and 270 μM in all seasons whereas in coastal waters it varied from $\sim$ 90 to 245 μM. Despite the conspicuous seasonal variability in the levels of oxygen, the gradients were not significant between the south and the north. While the SW monsoonal upwelling signature of low oxygen was obvious along the southwest Indian coast (figure 3) its abundance was the highest in NE monsoon in coastal as well as in the central Arabian Sea. Oxygen levels during inter- and SW monsoon along 64°E were nearly the same. Higher values in NE monsoon could have been due to convection driven by higher biological production. Less turbulence at the interface, due to the lowest wind speeds in this season (Madhupratap *et al* 1996; Sarma *et al* 1998) may have restricted the oxygen ejection to the atmosphere. In June – July 1995, the pCO$_2$ values were between 520

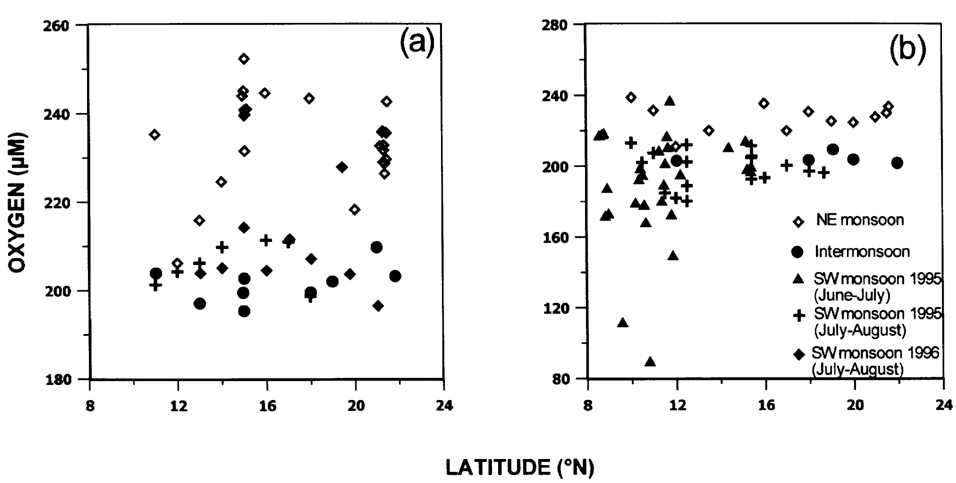

Figure 3. Variations in near surface dissolved oxygen (a) along 64°E and (b) along the west coast of India.

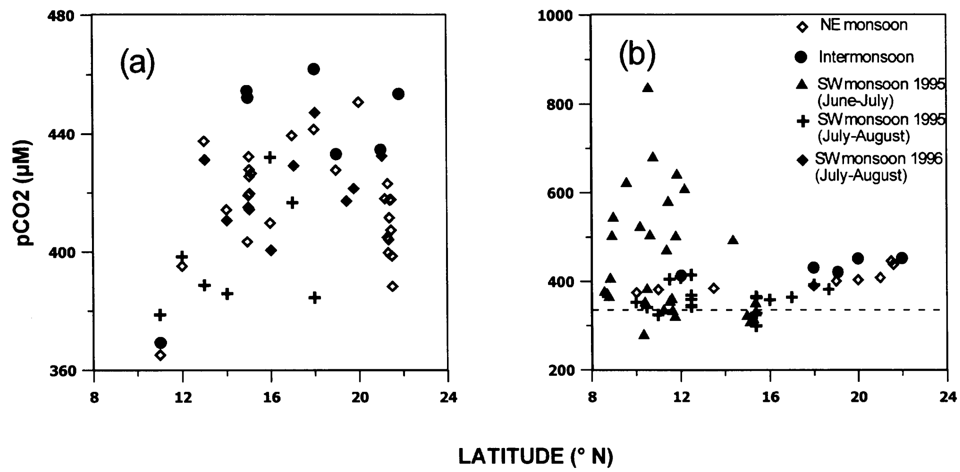

Figure 4. Variations in near surface pCO_2 **(a)** along 64E and (b) along the west coast of India. Dashed line in the right panel indicates atmospheric value.

and 685 μatm along the southwest coast of India where the upwelling was intense (figure 4). During July – August 1995, low values (266 μatm) occurred along Goa-Mangalore ($\sim$ 15°N) coast due to higher fresh water influence, as indicated by a salinity of 31.500. Coastal waters contained a pCO_2 of 416–427 μatm in inter-monsoon and 375–446 μatm in NE monsoon with higher values occurring in the north. Along the 64°E, the pCO_2 ranges were 351–433 μatm in NE monsoon, 379–478 μatm in inter-monsoon and 385–432 μatm in SW monsoon. This differs from the oxygen distribution (higher in NE monsoon) in general since the pCO_2 during inter-monsoon was generally higher than in other seasons. Bacteria are found to be more abundant during inter-monsoon that was not entirely supported by primary production (Ramaiah *et al* 1996) and hence the higher bacterial respiration would have resulted in higher pCO_2. As a matter of fact, organic carbon produced during monsoon seasons is expected to be oxidised in the non-monsoon seasons, as there will be a time lag for bacteria to respond (Ducklow 1993). For instance, the bacterial densities have been reported to be $0.24 - 0.96 \times 10^9 l^{-1}$ in inter-monsoon, $0.13 - 0.64 \times 10^9 l^{-1}$ in SW monsoon and $0.05 - 0.09 \times 10^9 l^{-1}$ in NE monsoon (Ramaiah *et al* 1996). Interestingly, surface pCO_2 values appear to be higher between 16 and 20°N in the central Arabian Sea in all seasons (figure 4). This region houses the most intense denitrifying intermediate waters of the Arabian Sea (Naqvi 1991). Hence, higher pCO_2 between these latitudes could have arisen from the relative increase in upward pumping of the comparatively enhanced pCO_2 waters due to increased remineralization at mid-depths of this region, as suggested by Kumar *et al* (1992).

In order to examine the controlling factors to sustain low pCO_2 levels (266 μatm) in the coastal regions during SW monsoon, the relation between salinity and pCO_2 in the mixed layer was evaluated. It exhibited a strong correlation with low pCO_2 levels coinciding with low salinity in the coastal regions (figure 5). The river waters contain low TCO_2 of $\sim$750 μM (Meybeck 1982). This together with high productivity in coastal waters results in low pCO_2 levels. This region, therefore, is expected to act as a sink for atmospheric carbon dioxide.

The chlorophyll *a* in the mixed layer varied in ranges of 0.05–0.111, 0.05–0.458 and 0.09–1.343 mg m^{-3} during inter-, NE- and SW- monsoon seasons, respectively. The surface primary production ranges, respectively, were 0.8–8.76, 0.2–43.8 and 0.2–71.4 mgC m^{-3} d^{-1}. Higher values were generally found in coastal waters (Bhattathiri *et al* 1996). High chlorophyll *a* values in SW monsoon were in response to upwelling whereas those in NE monsoon were due to convective mixing.

The near surface pCO_2 levels in the study area were almost always higher than in the atmosphere throughout the year (Sarma *et al* 1998). pCO_2 exhibited

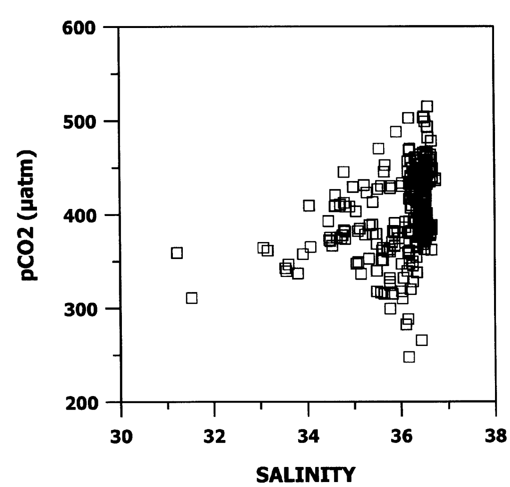

Figure 5. Relation between pCO_2 and salinity in the mixed layer in all seasons in the Arabian Sea.

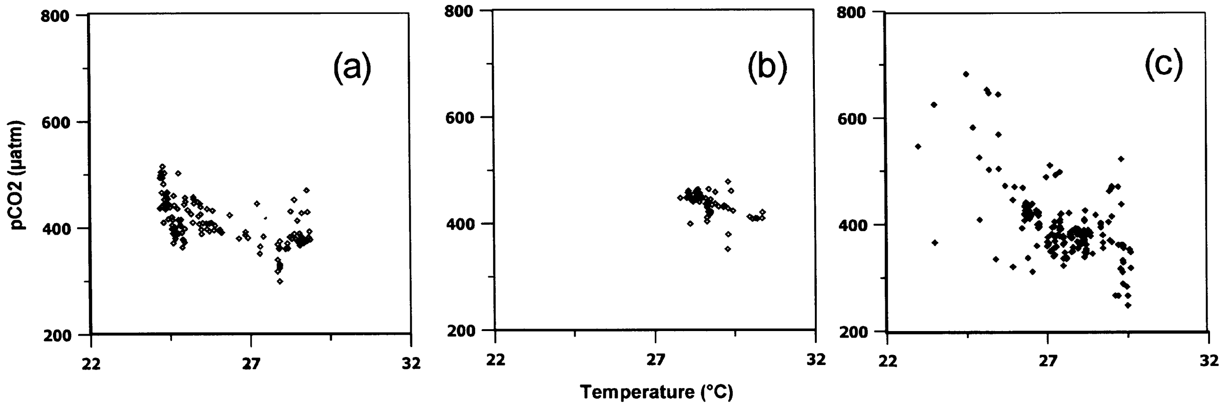

Figure 6. Relations for temperature with pCO_2 in the mixed layer in **(a)** NE- (b) inter and **(c)** southwest monsoon seasons.

strong to weak negative relations with temperature (figure 6) and oxygen (figure 7) that resulted from NE monsoon cooling and SW monsoonal upwelling, which bring cold and carbon dioxide enriched subsurface waters to the surface. Such processes do not occur during inter-monsoon. The biological properties, however, did not show any specific trends in relation to changes in pCO_2 (figures 8 and 9). Inter-monsoon experienced the most oligotrophic conditions that resulted in low chlorophyll *a* and primary productivity. The surface layer is relatively well stratified from north to south in inter-monsoon compared to other seasons. During inter-monsoon, the pCO_2 is fixed by photosynthesis at surface and is not rapidly replenished by upward pumping due to stratification. Moreover, the continued release of CO_2 through decomposition of organic matter within the surface layer by the bacteria becomes dominant which would have led to the poor correlation (table 1) in inter-monsoon. Increase in bacterial abundance in inter-monsoon has been related to the decay of phytoplankton blooms of NE monsoon (Ramaiah *et al* 1996) and the exudates resulting from such blooms (Ducklow 1993). In addition to this, increased surface temperatures (figure 2) would affect the solubility of the carbon dioxide in the seawater as it is a function of temperature and salinity (Weiss 1974).

Strong to weak negative correlations were observed between chlorophyll and surface pCO_2 in the North Atlantic (between 47°N and 60°N) during spring (Watson *et al* 1991) that show a possible biological control. Our results, however, indicate weak relations for pCO_2 with biological parameters (figures 8 and 9) than with physicochemical parameters (figures 6 and 7; table 1) strongly suggesting that pCO_2 in the central and eastern Arabian Sea is largely controlled by physical processes than biological ones. Besides, a slope of -31.8 and strong correlation (table 1) reveal that physical processes led to a large change in pCO_2 (figure 6) during the SW-monsoon than in any other season. The lesser slope (-14.6) with large scatter ($r^2 = 0.33$) in NE monsoon suggests an increased role for biological processes in regulating surface pCO_2, than in SW monsoon. For instance, the minimal pCO_2 values at temperatures < 25°C might have resulted from higher biological fixation (figure 6). This enhanced biological control of pCO_2 is augmented by the negative relation between pCO_2 and oxygen

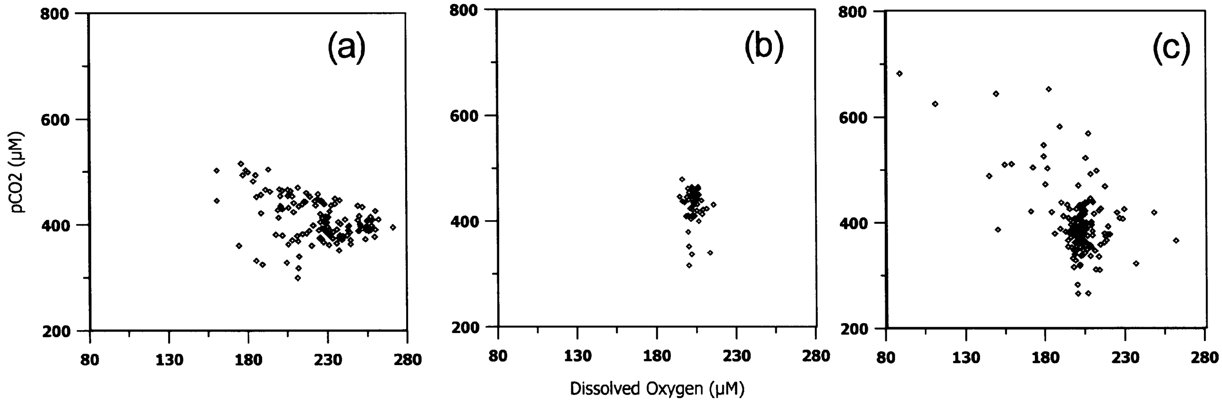

Figure 7. Relations for dissolved oxygen with pCO_2 in the mixed layers in **(a)** NE-, **(b)** inter and **(c)** southwest monsoon seasons.

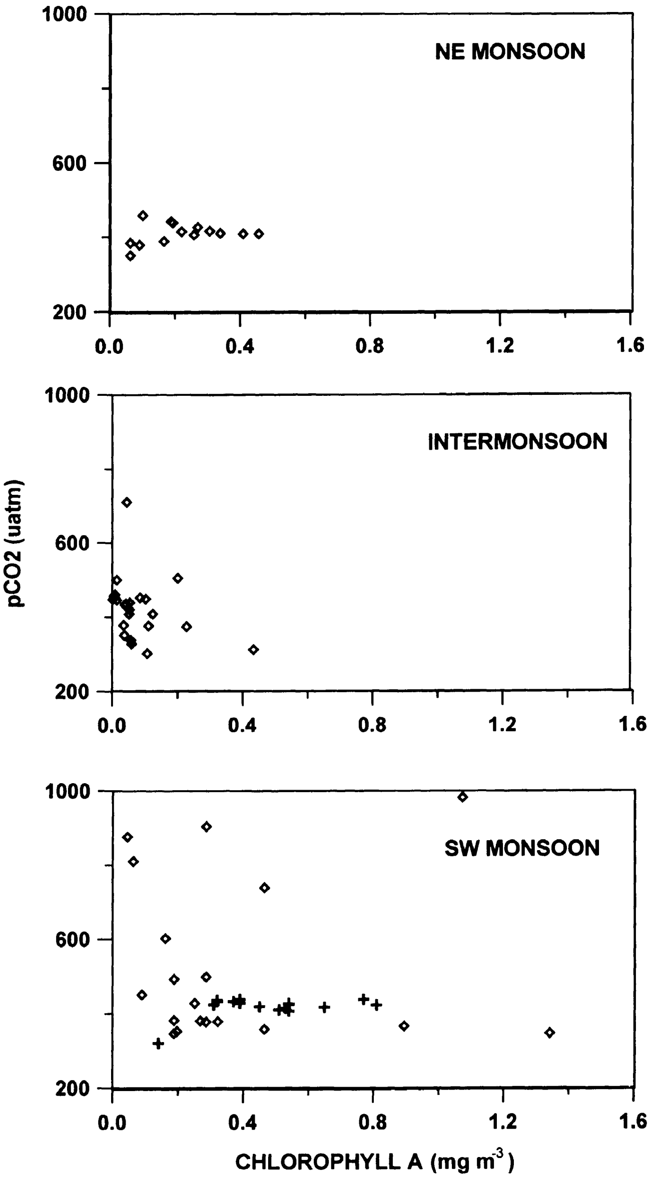

Figure 8. Relations for pCO_2 with chlorophyll *a* in mixed layer during different seasons.

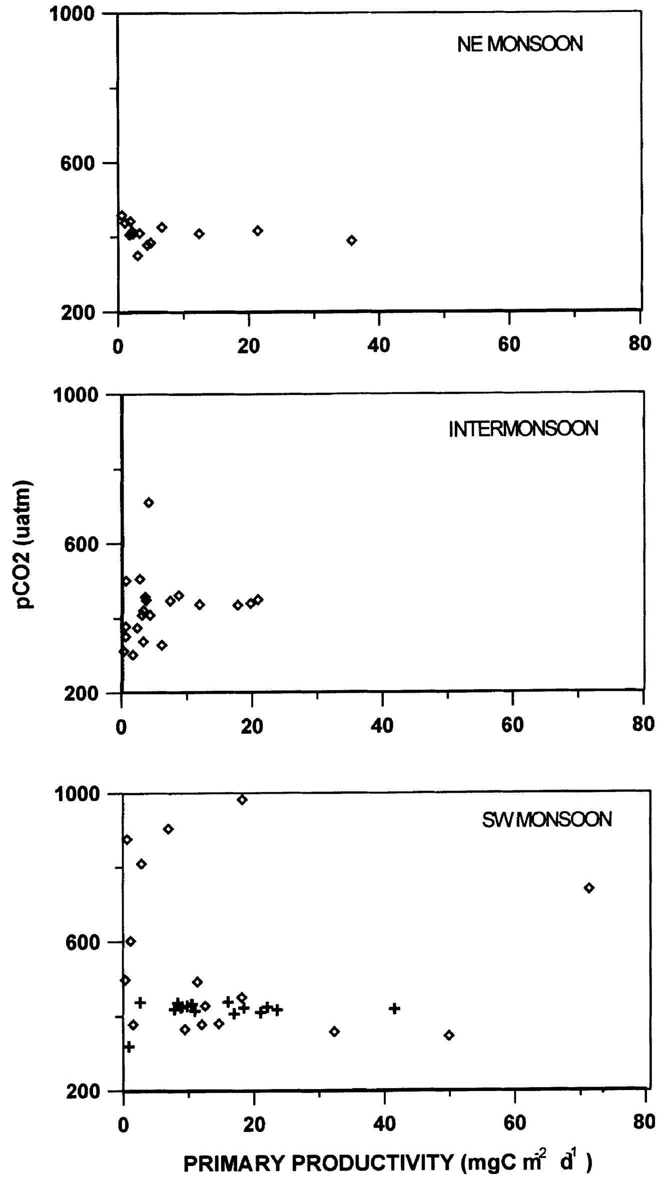

Figure 9. Relations for mixed layer pCO_2 with primary production in mixed layer during different seasons.

caused by the linkage: winter overturning - nutrient pumping - photosynthetically produced oxygen. The higher slope (-0.72) and significant correlation ($r^2 = 0.20$) during NE monsoon than in SW monsoon (slope $= -1.91$ and $r^2 = 0.30$) reveal that comparatively higher biological influence on pCO_2 during NE monsoon. On the other hand, poor correlations of pCO_2 with temperature and oxygen (figures 6 and 7; table 1) together with the higher surface abundance of pCO_2, than in NE monsoon (figure 4), and unclear relations for pCO_2 with chlorophyll *a* (figure 8) and primary production (figure 9) strongly suggest the biological (microbial) dominance over the physical processes in controlling the pCO_2 distribution during inter-monsoon.

The controlling factors responsible to sustain high pCO_2 levels in the surface throughout the year were also examined through the use of Louanchi *et al* (1996) model. This model quantifies the influence of different processes on surface pCO_2. Although, this model may have some limitations in identifying the role of biological pump in the Arabian Sea, especially during inter-monsoon season when the euphotic zone is deeper than mixed layer, it is expected to find major processes responsible in controlling the surface pCO_2.

The Louanchi *et al* (1996) model consists of two boxes, a surface mixed layer box in which the physical and biogeochemical processes control the pCO_2 variations and a subsurface box in which dissolved inorganic carbon system is considered invariant with definite boundary conditions. Four processes are defined to control surface pCO_2 distribution; air-sea exchange, biological pump, exchange between two boxes and thermodynamic effects on the CO_2 system

Table 1. *Coefficients of linear relations for oxygen and temperature with pCO_2 in the Arabian Sea mixed layer (r = correlation coefficient).*

Season	Slope	r^2
(a) Temperature *vs.* pCO_2		
Intermonsoon	−17.9	0.26
NE-monsoon	−14.6	0.33
SW-monsoon	−31.8	0.38
(b) DO *vs.* pCO_2		
Intermonsoon	−0.92	0.01
NE-monsoon	−0.72	0.20
SW-monsoon	−1.91	0.30

in the surface box. The variations in pCO_2 are expressed by:

$$\partial f/\partial t = (\partial f/\partial t)_B + (\partial f/\partial t)_M + (\partial f/\partial t)_F + (\partial f/\partial t)_{T,S}$$

where $\partial f/\partial t$ is the total pCO_2 variation within a time period of ∂t; $(\partial f/\partial t)_B$ is the biological contribution to pCO_2 change; $(\partial f/\partial t)_M$ is the contribution from mixing processes; $(\partial f/\partial t)_F$ is the air-sea exchange contribution; and $(\partial f/\partial t)_{T,S}$ is the thermodynamical contribution. The biological effect on pCO_2 is calculated from the variations in total inorganic carbon (TC) and total alkalinity (TA) as those are linked to biomass production and calcite formation in the surface waters, respectively. This effect is computed based on the availability of inorganic nitrogen (IN) and changes in chlorophyll in the mixed layer. The mixing effect is calculated based on the gradient between the dissolved element (TC, TA and IN) in the mixed layer and below it. The air-sea fluxes of carbon dioxide is calculated according to the formulation given below:

$$F = K^* S^* (pCO_{2\,\mathrm{sea}} - pCO_{2\,\mathrm{air}}).$$

Piston velocity (K) is calculated using SST and wind speed according to Wanninkhof (1992). The solubility of carbon dioxide (S) is a function of temperature and salinity (Weiss 1974). Atmospheric pCO_2 ($pCO_{2\,\mathrm{air}}$) value was considered as 355 μatm during all the seasons. The thermodynamics effect on surface pCO_2 is estimated using the relations proposed by Goyet *et al* (1993).

This model was used at 2 stations in the central Arabian Sea at 21°N and 11°N along 64°E during three seasons. Results of this model are given in table 2. These results show that pCO_2 seasonal cycle is marked by the monsoon cycle. During NE monsoon water cools, by 2–5°C than inter-monsoon, that leads to absorption of atmospheric carbon dioxide as solubility increases with decrease in temperature. Moreover, convective mixing pumps carbon dioxide rich subsurface waters into the surface resulting in oversaturation in the surface waters. During NE monsoon, the mixing effect at the two locations was observed to be high 53.5 and 21.7 μatm per season (4 months; 121.66 days), respectively, at 21°N and 11°N. On the other hand, thermodynamics effect is more at 21°N (29.25 μatm) than at 11°N (6.28 μatm) due to intense convective mixing in the north (figure 2). Moreover, the biological effect is also significant at 21°N (12.46 μatm) than at the 11°N (6.82 μatm) that resulted in injection of nutrient rich waters into the surface by convective mixing which enhances primary production (Madhupratap *et al* 1996). Flux effect is very less (0.82 and 2.04 μatm respectively at 21°N and 11°N) during this season at both the stations due to weak winds.

The impact of monsoonal mixing is the major contributor to high surface pCO_2 during SW monsoon in the Arabian Sea. Open ocean upwelling driven by Findlater Jet (Findlater 1969) brings subsurface waters to the surface that increases surface pCO_2. This amounted to 70.3 and 36.3 μatm, respectively, at 21°N and 11°N. As a result of open ocean upwelling, nutrient availability enhances primary production. Hence, biological effect, in fact, follows mixing effect to account for surface pCO_2 levels. This is observed to be 14.78 and 10.15 μatm, respectively, at 21°N and 11°N. Flux effect seems to be somewhat important at 21°N (21.45 μatm) due to high winds compared to 11°N (1.13 μatm). The effect of surface water temperature is minimal (7.03 and 5.38 at 21°N and 11°N, respectively).

Table 2. *Coefficients of controlling factors obtained by using the model of Louanchi et al (1996) for the central and eastern Arabian Sea.*

Season	Biology	Mixing	Flux	Thermodynamics	pCO_2 (model)	pCO_2 (observed)
21°N, 64°E						
Intermonsoon	−0.010	0.00	118.8	−32.1	441.7	437.4
SW monsoon	−14.78	70.33	21.45	7.03	439.0	432.5
NE monsoon	−12.46	53.5	0.82	29.25	426.1	442.0
11°N, 64°E						
Intermonsoon	−0.005	0.00	12.6	64.63	432.2	365.3
SW monsoon	−10.15	36.37	1.13	5.38	387.7	381.0
NE monsoon	−6.82	21.70	2.04	6.28	378.2	377.1

During inter-monsoon, the major influencing factors on surface pCO_2 appear to be thermodynamics and fluxes. Higher solar radiation (30 Wm^{-2} than in NE monsoon; Prasanna Kumar and Prasad 1996) increases surface water temperature that results in a decrease in the solubility. This contributes to increase in pCO_2 by 32.1 and 64.63 μatm at 21°N and 11°N, respectively. Besides, the winds were higher in the north that led to higher sea-to-air fluxes. The effect of flux amounted to 118.8 and 12.6 μatm at the 21°N and 11°N, respectively. However, biological and mixing effects are very less during this season due to stratification. Stratification hinders vertical mixing that results in development of oligotrophic conditions with undetectable levels of nutrients in surface waters.

Overall, the model results were in good agreement with our observations (depicted in figures 6–9 and table 1) revealing that mixing processes during the monsoons and thermodynamics and fluxes effects during inter-monsoon largely regulate pCO_2 levels in surface water of the Arabian Sea. However, this model suffers from some limitations especially, in regard to biological influence. During inter-monsoon, subsurface chlorophyll maximum develops below the mixed layer but within the euphotic zone (Bhattathiri *et al* 1996). This model does not facilitate its inclusion. Secondly role of regeneration could have been underestimated since it is considered as a constant, i.e., 50% of the produced organic matter is regenerated in the surface layers.

4. Conclusions

pCO_2 in the Arabian Sea is always oversaturated with respect to that in the atmosphere, almost throughout the year. During SW monsoon two contrasting regimes were observed; high pCO_2 (520–685 μatm) along in the SW coast of India because of intense upwelling and low pCO_2 levels ($\sim$266 μatm) as a result of fresh water influx from the rivers. Otherwise, it varied from 416 to 527 μatm and from 375 to 446 μatm during inter- and NE monsoon in the coastal waters with higher values occurring in the north. The central Arabian Sea pCO_2 ranges were 385–432, 351–433 and 379–475 μatm during SW-, NE- and inter-monsoon seasons, respectively. The observed pCO_2 relations with temperature, oxygen, chlorophyll *a* and primary production revealed that its distribution is largely regulated by physical processes during SW- and NE monsoon whereas both physical and biological processes, especially microbiological processes, are important in inter-monsoon. These observations were augmented by the Louanchi *et al* (1996) model that showed the mixing effect to be dominant during monsoons whereas thermodynamics and flux effects are important during inter-monsoon.

Acknowledgements

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