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The central and eastern Arabian Sea as a perennial source of atmospheric carbon dioxide

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ABSTRACT

Seasonal (winter monsoon, intermonsoon and southwest monsoon) and interannual (between southwest monsoon seasons of 1995 and 1996) variations in total carbon dioxide (TCO_2) and partial pressure of CO_2 (pCO_2) were studied in the central and eastern Arabian Sea as a part of the JGOFS (India) Programme. The pCO_2 values were computed from the results of coulometric TCO_2 and spectrophotometric pH measurements. Seasonal variability in TCO_2 is evident with the changing circulation and biological production. In all seasons, the pCO_2 is higher in surface waters of the Arabian Sea, except along the Indian coast in the southwest monsoon, than that in atmosphere, and thus this region appears to be a perennial source of atmospheric CO_2. Significantly, an average of $\sim 45\ Tg\ y^{-1}$ could be ejected to atmosphere from the study region, that seems to far exceed the earlier estimations. The estimated fluxes, however, are in agreement with those from the eastern equatorial Pacific Ocean.

1. Introduction

The oceans are expected to buffer a significant proportion of anthropogenically emanated CO_2. The Indian Ocean has been shown to be a net sink of atmospheric CO_2 (Takahashi, 1989; Louanchi et al., 1996). However, surface waters of the North Indian Ocean are found to be richer in CO_2 than the atmosphere (Takahashi, 1989; Tans et al., 1990). This agrees with our results from the Arabian Sea (Kumar et al., 1992; George et al., 1994; Sarma et al., 1996) but does not with those from the Bay of Bengal which could be a seasonal sink (Kumar et al., 1996). However, observational evidence on the natural variability of CO_2 and its air-sea fluxes in space and time in the oceans, in the Indian Ocean in particular, is generally lacking.

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The Joint Global Ocean Flux Study programme of India (JGOFS-India) has concentrated its efforts on the central and eastern parts of the Arabian Sea, to study the variability in air-sea fluxes and cycling of CO_2. The study area (Fig. 1) is a dynamic region experiencing convection in winter (Banse, 1984; Madhupratap et al., 1996) and upwelling in the southwest (SW) monsoon (Shetye et al., 1990; Muraleedharan and Prasanna Kumar, 1996). The seasonal variability in oxygen, nutrients and carbon components was conspicuous down to a few hundred meters (de Sousa et al., 1996; Sarma et al., 1996). The present attempt is to study the temporal, including the interannual SW monsoonal changes between 1995 and 1996, and spatial variations in air-sea fluxes of CO_2 in the Arabian Sea.

2. Methods

Four cruises (Fig. 1) were undertaken on board ORV Sagar Kanya during April-May 1994 (SK91;

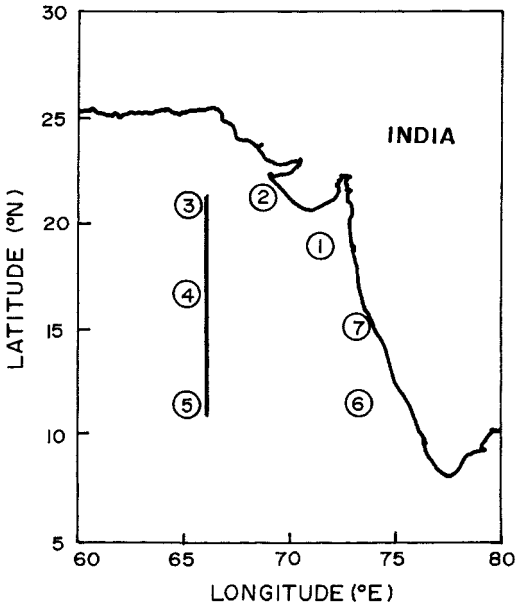

Fig. 1. North-South transect in the central Arabian Sea and areas identified by numbered circles for which the flux calculations were made.

intermonsoon), February 1995 (SK 99; winter monsoon), July-August 1995 (SK 104; SW monsoon) and August 1996 (SK 115; SW monsoon). Water samples were usually collected using a rosette attached to a Sea-Bird CTD system from surface, 10, 25, 50, 75, 100, 150 and 200 m, but with some necessary alterations based on the physico-chemical structure of the upper water column. Samples were analysed for total CO_2 (TCO_2) and pH by coulometry and spectrophotometry, respectively (George et al., 1994). The TCO_2 was measured through a semi-automated sample extraction system that avoids atmospheric CO_2 contamination (Sarma et al., 1996). The accuracy of TCO_2 analysis was found, using Certified Reference Materials supplied by Dr. A. G. Dickson of the Scripps Institution of Oceanography, to be 0.2–0.3%. Our pH measurements between spectrophotometry (free ion scale) and potentiometry (NBS scale), for a seawater sample of 34.574, agreed to ± 0.007. The precisions of TCO_2 and pH were $\pm 2\,\mu M$ and ± 0.002, respectively. The pCO_2 was calculated (through TCO_2 and pH) using the carbonic acid ionization constants derived by Goyet and Poisson (1989) based also on Hansson (1973). The computed pCO_2 had a precision of ± 4 µatm. The relations given by Wanninkhof (1992) were used in estimating the CO_2 transfer coefficients based on observed wind speeds, and then used to calculate air-sea fluxes. The errors in flux calculations, at a surface pCO_2 of 398 ± 4 µatm and wind speeds of 5 and 20 m s^{-1}, were ± 0.2 and ± 3.9 mmol m^{-2} d^{-1}, respectively.

3. Results and discussion

The concentrations of dissolved substances in surface layers of oceans are largely controlled by mixing and biological processes. The TCO_2 distribution in upper layers of the Arabian Sea (Fig. 2) exhibited lowest values in the 1995 SW-monsoon and highest in the winter seasons. Nitrate was found to be relatively higher around 16°N during the 1995 SW-monsoon ($\sim 4\,\mu M$; de Sousa et al., 1996), whereas it was $\sim 1\,\mu M$ in the same season in 1996. Availability of high nitrate might have resulted in the lower TCO_2 in 1995 through biological fixation. Primary production is found to be the highest in the SW monsoon (770 mgC m^{-2} d^{-1}) followed by the winter (337–643 mgC m^{-2} d^{-1}) and intermonsoon (193–199 mgC m^{-2} d^{-1}) seasons (Bhattathiri et al., 1996). The northern subsurface TCO_2 decrease during the 1995 SW monsoon (Fig. 2) is characterised by a concomitant decrease in alkalinity only by ~ 15 µeqv l^{-1}. This is perhaps due to minority carbonaceous populations where the diatoms dominated the phytoplankton composition (Sawant and Madhupratap, 1996). The elevated TCO_2 levels in 1996, on the other hand, could have been due to lateral advection of Arabia upwelled water (Waniek et al., 1996) in addition to that regenerated, in situ. The Findlater Jet (Findlater, 1969) is expected to drive upwelling to the north of its axis in the Arabian Sea (Muraleedharan and Prasanna Kumar, 1996) that may have led to the observed patterns in nitrate (de Sousa et al., 1996) and TCO_2 (Sarma et al., 1996) particularly to the north of 15°N. The highest TCO_2 in winter (Fig. 2), particularly in the north, is due to convection that also resulted in relatively high surface nitrate ($\sim 2\,\mu M$), but, surprisingly, the primary production has remained lower than that in the SW-monsoon (Madhupratap et al., 1996).

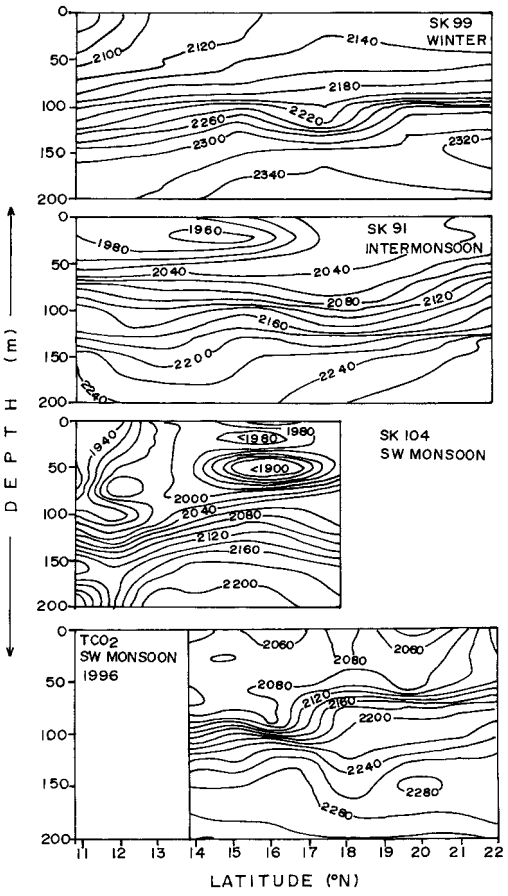

Fig. 2. Distribution of total carbon dioxide (μM) in the central Arabian Sea in different seasons.

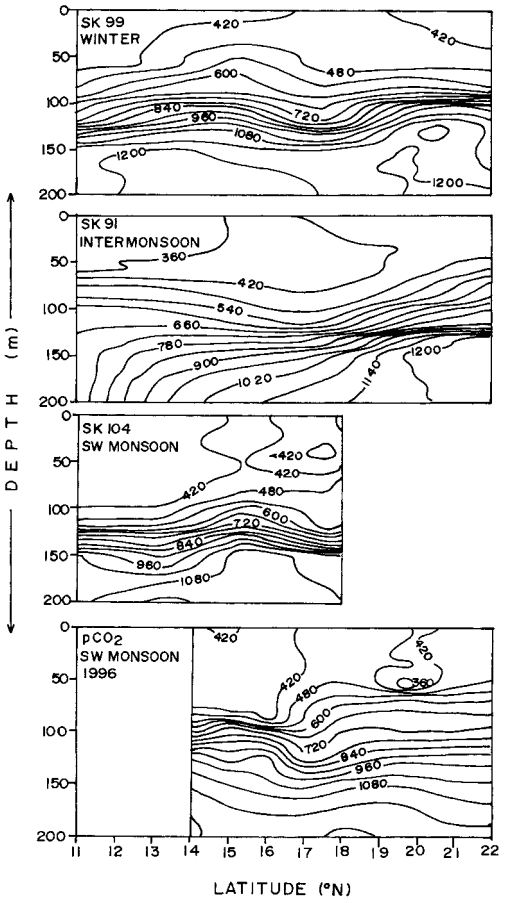

Fig. 3. Distribution of partial pressure of carbon dioxide (μatm) in the central Arabian Sea in different seasons.

The higher biological production at the surface results in higher respiration rates in subsurface layers. The intense regeneration of organic matter leads to sub-oxic conditions and also to relatively lower pH values in the Arabian Sea compared to those in the Bay of Bengal (George et al., 1994). Regeneration of organic material enhances pCO_2 contents in water to >1000 μatm in the lower thermocline (Fig. 3). The surface pCO_2 levels were nearly the same except in intermonsoon when it was <360 μatm in the south. At 200 m, the values were higher in winter and the 1996 SW-monsoon compared to those in the intermonsoon (except north of 20°N) and the 1995 SW-monsoon. The surface waters of the central Arabian Sea are supersaturated with respect to pCO_2 in the atmosphere. We also considered data from the eastern Arabian Sea regions marked with encircled numbers in Fig. 1, for better understanding of the spatial variations in fluxes. The distributions of TCO_2 and pCO_2 along the eastern Arabian Sea were found to be almost similar to those in Figs. 2, 3, respectively. The calculated average fluxes are given in Table 1, with reference to areas shown in Fig. 1. The number of measurements made within $2^\circ \times 2^\circ$ square boxes (latitude by longitude) in each area are given in parentheses in Table 1. These are more than 3 in some areas since we undertook time-series measurements. An atmospheric CO_2 value of 355 μatm was used in sea-to-air flux computation. Positive values indicate fluxes from sea to air. The Arabian Sea appears to act as a source to atmospheric CO_2 in

Table 1. *Seasonal and temporal variability in sea-to-air fluxes (mmol m^{-2} d^{-1}) of carbon dioxide in the Arabian Sea*

Season\Area	1	2	3	4	5	6	7
northeast monsoon	7.2	3.6	1.0	1.9	0.3	1.7	1.4
	(2)	(5)	(12)	(12)	(20)	(3)	(2)
	[8]	[5]	[4]	[3]	[4]	[4]	[6]
intermonsoon	4.1	18.5	13.2	0.9	0.1	3.5	1.1
	(2)	(3)	(4)	(3)	(3)	(2)	(1)
	[2]	[9]	[8]	[2]	[3]	[3]	[3]
southwest monsoon 1995	—	—	41.5	24.4	6.9	1.0	−10.2
			(1)	(2)	(3)	(5)	(2)
			[17]	[12]	[10]	[4]	[10]
southwest monsoon 1996	—	—	14.3	13.9	6.2	—	—
			(4)	(4)	(1)		
			[14]	[14]	[6]		

Areas are as shown in Fig. 1. Numbers in parentheses denote the measurements made in the respective areas. Numbers in square brackets indicate average wind speeds ($m\,s^{-1}$) in $2^\circ \times 2^o$ grids considered.

almost all seasons and regions in the central and eastern Arabian Sea. An exception is area 7 in the SW-monsoon. This is mainly because of the river run-off that contained low TCO_2 and more nutrients. During this season, Muraleedharan and Prasanna Kumar (1996) have found salinities <34.000 in near coastal regions. These low salinities are because of run-off from several small rivers in Goa and Kerala (central and southern states along the west coast) that are active only during the SW monsoon, and are also due to southward-moving coastal currents (Shetye et al., 1990). Thus the observed low TCO_2 values could arise from biological fixation triggered by terrigenous nutrient inputs, as has been found in the Bay of Bengal (Kumar et al., 1996). Despite the occurrence of higher pCO_2 below the mixed layer, the same cannot be pumped up because of the prevailing lens of low salinity surface water that causes physico-chemical hindrance. This facilitates the biological draw-down of atmospheric CO_2.

The fluxes (Table 1) may not necessarily reflect pCO_2 trends in Fig. 3 since the flux is strongly dependant on the prevailing wind speed. Formulations of Wanninkhof (1992) were used here in transfer velocity and flux evaluations since his equations are based on natural and bomb-produced ^{14}C invasion rates in oceans, whereas the Liss and Merlivat (1986) equations, limited to winds of $8\,m\,s^{-1}$, are based on tracer experiments in a lake. For higher wind speeds, the latter workers extrapolated wind-wave tank results. Hence, while at a wind speed of $5\,m\,s^{-1}$, the transfer velocities obtained using Wanninkhof (1992) are twice higher (8.7 and 4.3 cm hr^{-1}, respectively), than those based on Liss and Merlivat (1986), and thrice higher at $13\,m\,s^{-1}$ (60.4 and 23.2 cm hr^{-1}, respectively). Since winds in the Arabian Sea are in excess of $8\,m\,s^{-1}$, particularly in pre- and SW-monsoon seasons, we preferred to use the equations of Wanninkhof (1992). Fluxes are significantly higher during the SW monsoon season, specifically in the North. Fluxes (Table 1) agree with those from the eastern equatorial Pacific Ocean, of 1–2 mmol $m^{-2}\,d^{-1}$ in spring and 17 mmol $m^{-2}\,d^{-1}$ in fall (Feely et al., 1995). The average fluxes obtained from those in Table 1 together with a study area of 1.6×10^{12} m^2 (area to the east of 64°E and to the north of 10°N that amounts to $\sim 1/4$ of the total Arabian Sea area of 6.225×10^{12} m^2) yield 4, 10, 22 and 20 Tg $season^{-1}$, respectively, for northeast monsoon, intermonsoon and SW monsoons of 1995 and 1996. Assuming the flux in post-southwest monsoon to be nearly equivalent to that in intermonsoon, an annual flux from the study area is ~ 45 Tg (~ 6.4 mmol $m^{-2}\,d^{-1}$). Although in confirmity with the direction, these fluxes seem to far exceed

the estimations for the North Indian Ocean of 60 Tg y^{-1} (Takahashi, 1989) and for the total Arabian Sea of 79 Tg y^{-1} (George et al. (1994), the latter of whom also evaluated fluxes using Wanninkhof (1992)), including a recent estimate for the western Arabian Sea of 8.4 Tg y^{-1} (C. Goyet, personal communication, 1997). The latter used an interpolation of surface temperatures for pCO_2 evaluations, without biological considerations, and hence the flux may have been an underestimate. Present fluxes also seem to be higher, since Fig. 8 of Louanchi et al. (1996) indicates an average flux of 10 Tg $month^{-1}$ (120 Tg y^{-1}) for the region between 10°S and 20°N in the Indian Ocean. Hence, the Arabian Sea is significant and perennial, because the sea as a whole acts as a chimney except in coastal pockets influenced by run-off, source of atmospheric CO_2. It should, however, be noted that these data do not represent the most intense upwelling regions in the Arabian Sea from where even higher fluxes, subject to wind speeds, may be expected.

4. Conclusions

The TCO_2 and pCO_2 are seasonally variable in surface layers of the central and eastern Arabian Sea. The surface layers are supersaturated with respect to the atmospheric CO_2, and hence the study region emanates significant quantities (45 Tg y^{-1}) round the year. The fluxes are in agreement with those reported for the eastern equatorial Pacific, but are much higher than earlier evaluations for the Arabian Sea.

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REFERENCES

Banse, K. 1984. Over view of the hydrography and associated biological phenomena in the Arabian Sea, off Pakistan. In: *Marine geology and oceanography of Arabian Sea and coastal Pakistan* (eds. B. U. Haq and J. D. Milliman). Von Nostrand Reinhold, New York, pp. 271–303.

Bhattathiri, P. M. A., Pant, A., Sawant, S., Gauns, M., Matondkar, S. G. P. and Mohanraju, R. 1996. Phytoplankton production and chlorophyll distribution in the eastern and central Arabian Sea in 1994–1995. *Curr. Sci.* **71**, 857–862.

De Sousa, S. N., Kumar, M. D., Sardessai, S., Sarma, V. V. S. S. and Shirodkar, P. V. 1996. Seasonal variability in oxygen and nutrients in the central and eastern Arabian Sea. *Curr. Sci.* **71**, 847–851.

Feely, R. A., Wanninkhof, R., Cosca, C. E., Chen, H., Steckley, M. and Murphy, P. P. 1995. fCO2 distributions in the Eastern Equatorial Pacific during and after the 1992–93 El Nino. In: *Global fluxes of carbon and its related substances in the coastal sea-ocean-atmosphere system* (eds. S. Tsunogai, K. Iseki, I. Koike and T. Oba). M&J International, Yokohama, pp. 360–367.

Findlater, J. 1969. A major low-level air current near the Indian Ocean during the northern summer. *Quart. J. R. Meteor. Soc.* **95**, 362–380.

George, M. D., Kumar, M. D., Naqvi, S. W. A., Banerjee, S., Narvekar, P. V., de Sousa, S. N. and Jayakumar, D. A. 1994. A study of the carbon dioxide system in the northern Indian Ocean during premonsoon. *Mar. Chem.* **47**, 243–254.

Goyet, C. and Poisson, A. 1989. New determination of carbonic acid constants in seawater as a function of temperature and salinity. *Deep-Sea Res.* **36A**, 1635–1654.

Hansson, I. 1973. A new set of acidity constants for carbonic acid and boric acid in seawater. *Deep-Sea Res.* **20**, 461–478.

Kumar, M. D., Rajendran, A., Somasundar, K., Ittekkot, V. and Desai, B. N. 1992. Processes controlling carbon components in the Arabian Sea. In: *Oceanography of the Indian Ocean* (ed. B. N. Desai). Oxford-IBH, New Delhi, pp. 313–325.

Kumar, M. D., Naqvi, S. W. A., George, M. D. and Jayakumar, D. A. 1996. A sink for atmospheric carbon dioxide in the northeast Indian Ocean. *J. Geophys. Res.* **101**, 18,121–18,125.

Liss, P. S. and Merlivat, L. 1986. Air-sea gas exchange rates: Introduction and synthesis. In: *The rôle of air-sea exchange in geochemical cycling* (ed. P. Buat-Menard). D. Reidel, Norwell, Mass., pp. 113–129.

Louanchi, F., Metzl, N. and Poisson, A. 1996. Modelling the monthly sea surface fCO2 fields in the Indian Ocean. *Mar. Chem.* **55**, 265–279.

Madhupratap, M., Prasanna Kumar, S., Bhattathiri, P. M. A., Kumar, M. D., Raghukumar, S., Nair,

K. K. C. and Ramaiah, N. 1996. Mechanism of the biological response to winter cooling in the north-eastern Arabian Sea. *Nature (London)* **384**, 549–552.

Muraleedharan, P. M. and Prasanna Kumar, S. 1996. Arabian Sea upwelling — a comparison between coastal and open ocean regions. *Curr. Sci.* **71**, 842–846.

Sarma, V. V. S. S., Kumar, M. D., George, M. D. and Rajendran, A. 1996. Seasonal variations in inorganic carbon components in the central and eastern Arabian Sea. *Curr. Sci.* **71**, 852–856.

Sawant, S. and Madhupratap, M. 1996. Seasonality and composition of phytoplankton in the Arabian Sea. *Curr. Sci.* **71**, 869–873.

Shetye, S. R., Gouveia, A. D., Shenoi, S. S. C., Sundar, D., Michael, G. S., Almeida, A. M. and Santhanam, K. 1990. Hydrography and circulation off the west coast of India during the South-west monsoon 1987. *J. Mar. Res.* **48**, 359–378.

Takahashi, T. 1989. The carbon dioxide puzzle. *Oceanus* **32**, 22–29.

Tans, P. P., Fung, I. Y. and Takahashi, T. 1990. Observational constraints on the global atmospheric CO_2 budget. *Science* **247**, 1431–1438.

Waniek, J., Waniek, J. and Zeitzschel, B. 1996. The cold water structure at 17°N, 65°E: Hydrography and nutrients. *EOS* **76**, OS4 (OS11B-10).

Wanninkhof, R. 1992. Relationship between wind speed and gas exchange over the ocean. *J. Geophys. Res*, **97**, 7373–7382.