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Strong CO_2 emissions from the Arabian Sea during South-West Monsoon

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Abstract. The partial pressure of CO_2 (pCO_2) was measured during the 1995 South-West Monsoon in the Arabian Sea. The Arabian Sea was characterized throughout by a moderate supersaturation of 12-30 µatm. The stable atmospheric pCO_2 level was around 345 µatm. An extreme supersaturation was found in areas of coastal upwelling off the Omani coast with pCO_2 peak values in surface waters of 750 µatm. Such two-fold saturation (218%) is rarely found elsewhere in open ocean environments. We also encountered cold upwelled water 300 nm off the Omani coast in the region of Ekman pumping, which was also characterized by a strongly elevated seawater pCO_2 of up to 525 µatm. Due to the strong monsoonal wind forcing the Arabian Sea as a whole and the areas of upwelling in particular represent a significant source of atmospheric CO_2 with flux densities from around 2 mmol m^{-2} d^{-1} in the open ocean to 119 mmol m^{-2} d^{-1} in coastal upwelling. Local air masses passing the area of coastal upwelling showed increasing CO_2 concentrations, which are consistent with such strong emissions.

Introduction

The Arabian Sea is known for its marked seasonality, which is among the most pronounced to be found in the world ocean [*Banse and English*, 1994]. The monsoonal forcing is the key in the understanding of the strong seasonal oscillations, which are most obvious in the complete semi-annual reversal of the Somali Current [*Schott et al.*, 1990]. A characteristic feature of the South-West Monsoon period (June-September) is the occurrence of intense coastal upwelling off the coasts of Somalia and Oman [*Smith and Bottero*, 1977; *Swallow*, 1984; *Elliott and Savidge*, 1990]. The existence of open-ocean upwelling through Ekman pumping caused by the low-level Findlater Jet [*Findlater*, 1969] in an area off the Omani coast has also been postulated [*Smith and Bottero*, 1977].

The man-made perturbation of the global carbon cycle and its oceanic components have been receiving special attention among scientists in recent years [*Siegenthaler and Sarmiento*, 1993]. A key parameter in this context is the partial pressure of CO_2 (pCO_2) as it provides insight in the saturation state of seawater. Any partial pressure difference (ΔpCO_2) between surface seawater and overlying air is the thermodynamic driving force for net CO_2 exchange. Few measurements of the pCO_2 have been made in the Arabian Sea, especially during the period of the South-West Monsoon [e.g. *Miyake and Sugimura*, 1969; *Poisson et al.* 1993]. In spite of the limited data base the Arabian Sea appears to serve as a significant source of CO_2 to the atmosphere [*Somasundar et al.*, 1990; *George et al.*, 1994]. Three reasons support the assumption of strong CO_2 emissions during the South-West Monsoon: First, upwelling caused by the monsoon exposes water with higher pCO_2 to the atmosphere as this parameter generally shows an increase with depth. Secondly, this effect is enhanced by the prevailance of an oxygen minimum zone at depths of 100-1200 m [*Olson et al.*, 1993; *Warren*, 1994]. This suboxic layer of accumulated respiratory CO_2, resulting in very high pCO_2 values, is most pronounced in the Northwest Arabian Sea, where it coincides with the typical source depth and area of the upwelling. Finally, any supersaturated waters exposed to the atmosphere are subject to the strong monsoonal wind forcing, which translates to high transfer coefficents driving large sea-to-air fluxes of CO_2.

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Methods

This work was carried out on board the German R/V *Meteor* (leg 32-5) during the South-West Monsoon in July/August 1995 under the framework of the German JGOFS - Arabian Sea Process Study. The pCO_2 in surface seawater and air was measured continuously during the entire cruise from Mahé (Seychelles) to Muscat (Oman). The location of the pCO_2 sections discussed below is shown by the letters "A" to "F" in Fig. 1. The newly designed underway pCO_2 system has shown excellent agreement with another system during a short at-sea intercomparison [*Körtzinger et al.*, 1996b]. It also took part in the first large international at-sea intercomparison of underway pCO_2 systems during a recent *Meteor* cruise [*Körtzinger et al.*, 1996a].

Seawater pCO_2 was logged as 1-min averages; atmospheric pCO_2 was measured every hour. The infrared gas analyzer was calibrated every six hours using a zero gas (CO_2-free air) and two standard gases containing CO_2 in natural air (340.7 and 389.9 ppmv). The accuracy of CO_2 measurements deteriorates from better than ±1 ppmv (at 300-450 ppmv) to about ±5 ppmv (at 750 ppmv) due to the restricted concentration range of the calibration gases. Bubble-free seawater was pumped from the "moon pool" of the vessel with a submersible pump. About 2 dm^3 min^{-1} were teed-off close to the equilibrator from the total flow of 40 dm^3 min^{-1}. Clean air was sampled above the bridge and pumped to the system at a flow rate of 1 dm^3 min^{-1}. All pCO_2 data are calculated for 100% humidity at the air-sea interface. Seawater pCO_2 was corrected back to *in-situ* (bulk) seawater temperature accounting for the slight warming

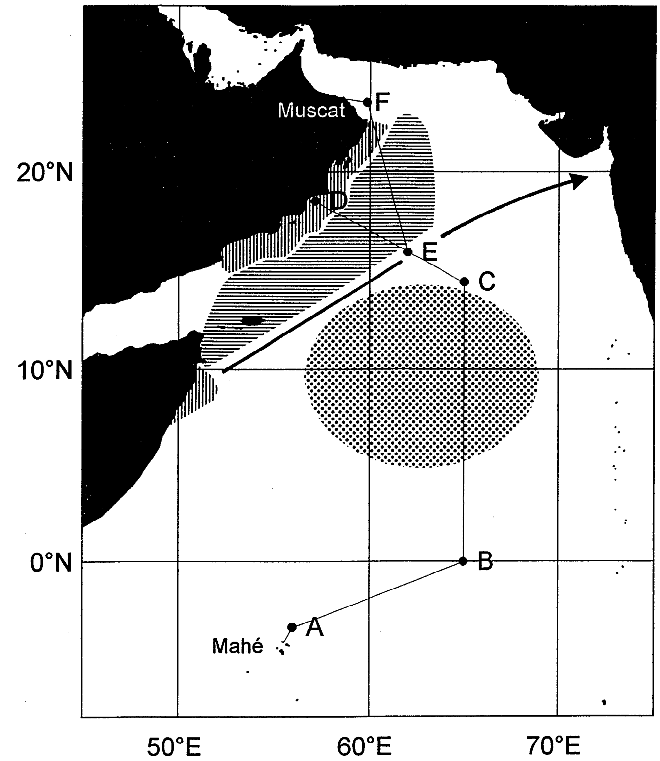

Figure 1. Cruise track of R/V *Meteor* cruise 32-5 in July/August 1995. The location of surface profiles discussed here is indicated by letters "A" to "F". Also shown are the prominent features of the South-West Monsoon: areas of coastal upwelling off the coasts of Somalia and Oman (vertical hatching), area of Ekman pumping (horizontal hatching), and area of mixed layer deepening (shaded). The arrow delineates the axis of the Findlater Jet.

of about 0.4±0.1°C between the intake and the equilibrator. *In-situ* temperature and salinity of surface water were measured continuously with the shipborne thermosalinograph. All corrections and equations involved in the calculation of final pCO_2 data are more fully described in *Körtzinger et al.* [1996b]. The oscillations of about ±0.6 µatm due to the semi-diurnal atmospheric tide in low latitudes (amplitude 1.5-2 mbar) where removed from the atmospheric pCO_2 profiles using a sine function fitted to the pCO_2 anomalies (measured values minus daily means) based on local time.

Results and Discussion

Surface pCO_2 profiles were classified into two groups. The first (Fig. 2) includes profiles A-B and B-C representing a mainly oligotrophic tropical ocean situation. Surface waters are moderately supersaturated by 12-30 µatm mainly as a result of the general warming. No typical North-East Trade Wind regime is active in the Indian Ocean. Therefore no equatorial upwelling occurs, which could drive the exposure of waters more strongly supersaturated than those found here. Profile A-B can be regarded as being composed of two different patterns separated by a frontal system at 61°E. Higher temperatures of 28.5-29°C to the east of the front are associated with the lowest supersaturation encountered during the entire cruise (ΔpCO_2 = 12-15 µatm). To the west seawater temperatures gradually decrease towards 26.5°C with stronger supersaturation (ΔpCO_2 = 20-30 µatm). The front is probably part of the monsoonal convergence zone between the anti-cyclonic gyre with the South-West Monsoon Current to the north and the South Equatorial Current to the south. Another interesting feature can be seen close to the equator at 64°15'E (0°20'S), where the two hemispheres are separated by an atmospheric front across which the CO_2 mole fraction in air increases by about 3 ppmv from S to N, while it is comparatively stable in other areas (except the area of coastal upwelling, see below). Along profile B-C seawater temperature decreases northward, reflecting the deepening of the mixed layer as driven by negative curl wind stress. Although a small parallel trend of about 5 µatm increase in pCO_2 (S to N) was observed, the effect of the mixed layer deepening on the degree of CO_2 saturation of surface water is weak. However, along section B-C the pCO_2 picture generally shows higher small-scale variability, probably as an effect of the prevailing stronger wind stress [*Rao et al.*, 1991] as compared to profile A-B.

The second group of profiles in Fig. 3 shows a drastically different situation. The overall variability of both, pCO_2 and temperature is roughly one order of magnitude higher than in Fig. 2 (note extended scales). In profile C-D two prominent features arise from the otherwise moderately supersaturated background situation. The most obvious one is caused by strong coastal upwelling west of 58°E with water temperature falling from >26°C to <20°C within 30 nm. Seawater pCO_2 rises concurrently to 600-715 µatm. Such two-fold saturation can be a normal feature in enclosed coastal or estuarine environments [*Frankignoulle*, 1988], but it is rarely found under oceanic conditions. The second prominent feature is a peak-like cold water structure at 61°15'E roughly 300 nm off the Omani coast, which coincided with a dome-like feature in satellite SST images. The temperature decreases by about 2-3°C towards the center of the peak, pCO_2 increased by 100-150 µatm. While this feature is situated well in the area of (postulated) Ekman pumping, hydrographical data and its

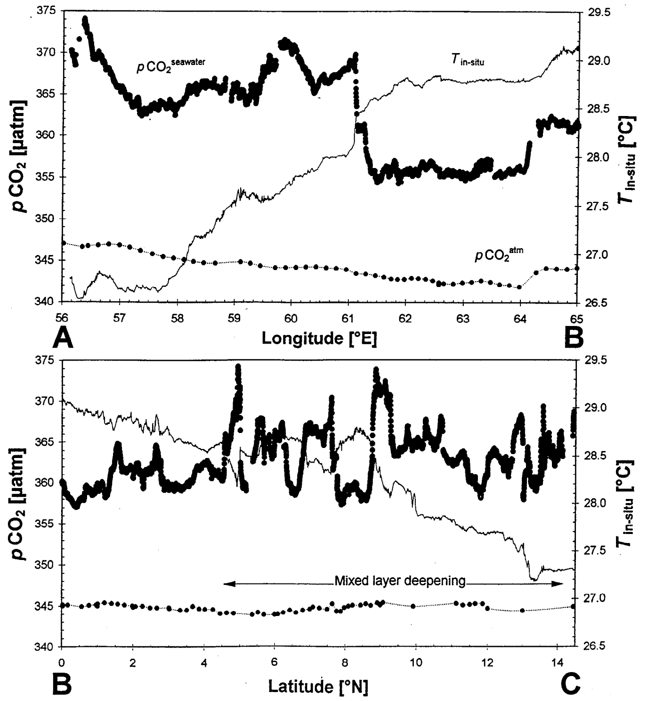

Figure 2. Surface data along sections A-B (top) and B-C (bottom) of R/V *Meteor* cruise 32-5: the partial pressure of CO_2 (pCO_2) in surface seawater (bold line) and air (dots on dashed line) and the *in-situ* seawater temperature $T_{in\text{-}situ}$ (thin line). The location of the sections is shown in Fig. 1.

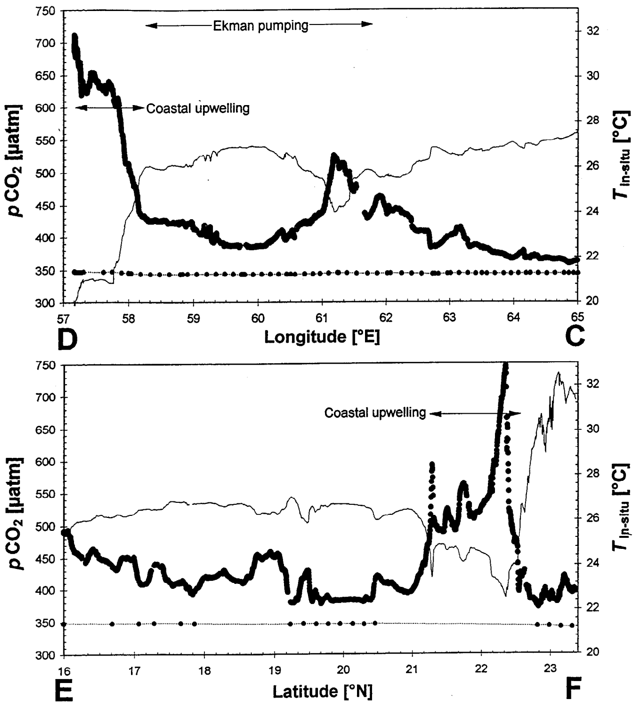

Figure 3. Surface data along sections C-D (top) and E-F (bottom) of R/V *Meteor* cruise 32-5: the partial pressure of CO_2 (pCO_2) in surface seawater (bold line) and air (dots on dashed line) and the *in-situ* seawater temperature $T_{in\text{-}situ}$ (thin line). The location of the sections is shown in Fig. 1.

dynamic nature do not suggest an origin from the open-ocean upwelling. The feature more likely represents an upwelling filament derived from coastal upwelling off the Omani coast (pers. comm., J. Waniek, Kiel).

Profile E-F crossed the northernmost extension of the coastal upwelling area between 21° and 22°30'N. Although the pCO_2 and temperature profiles show much stronger small-scale variability than the previous ones, they exhibit similar behaviour. Temperature falls well below 24°C in the coastal upwelling region and the pCO_2 values are even higher (750 µatm) with marked peak-like patterns at the flanks. Outside the proper coastal upwelling regime (i.e. 16° to 21°N) the seawater pCO_2 level remains markedly elevated as compared to the situation along sections A-B and B-C, yielding ΔpCO_2 values of 30-140 µatm. This underlines the important role of the area of Ekman pumping as a CO_2 source. Finally, in the Gulf of Oman temperatures exceed 32°C and the seawater is supersaturated on the average by about 55 µatm. This reflects the enhanced warming of surface waters in the gulf. The more pronounced supersaturation in this non-upwelling area is much less subject to strong monsoonal wind forcing and therefore does not generate such extreme emissions.

Air-Sea Exchange of CO_2

The air-sea exchange flux density (F, mmol m^{-2} d^{-1}) of CO_2 can be expressed as $F = k\ K^0\ (pCO_2^{sw}\text{-}pCO_2^{air})$, or $F = k\ K^0\ (\Delta pCO_2)$, where k is the transfer velocity and K^0 is the solubility coefficient of CO_2 in seawater calculated after *Weiss* [1974]; pCO_2^{sw} and pCO_2^{air} are the partial pressures of CO_2 in seawater and air, respectively. Their difference is expressed as ΔpCO_2. The valid parametrization of the wind speed dependance of k is still a matter of debate [*Watson et al.*, 1995]. We have used three parametrizations of k which are in common use: the tri-linear relationship after *Liss and Merlivat* [1986] (hereafter referred to as LM86), the quadratic relationship for climatological winds after *Wanninkhof* [1992] (hereafter referred to as W92) and the linear relationship of *Tans et al.* [1990] for $k\ K^0$ (hereafter referred to as T90). The transfer velocities were adjusted to seawater temperatures assuming that k is proportional to $(Sc/600)^{-1/2}$ (LM86) or $(Sc/660)^{-1/2}$ (W92) at the given wind speeds, where the Schmidt number Sc of CO_2 was calculated after *Wanninkhof* [1992].

Based on our results the Arabian Sea serves as a source for atmospheric CO_2 throughout. In order to provide a rough estimate of CO_2 emissions during the 1995 South-West Monsoon the Arabian Sea was divided into three regimes (Fig. 1): (1) coastal upwelling, (2) Ekman pumping, and (3) open ocean, the areas of which are given in Table 1. These estimates are based on a synopsis made by J. Brock in *SCOR* [1995]. Emissions of CO_2 were calculated for three months representing the period of the South-West Monsoon using mean observed values of ΔpCO_2, temperature and salinity as well as climatological winds estimated after *Rao et al.* [1991]. The results are summarized in Table 1. It should be emphasized that (in contrast to W92 and T90) calculations after LM86 using climatological winds yield too low transfer velocities [*Wanninkhof*, 1992] and may therefore serve as lower limits.

Flux densities range from 1.6-2.9 mmol m^{-2} d^{-1} in the open ocean to 52-119 mmol m^{-2} d^{-1} in the area of coastal upwelling. Combined emissions from areas of coastal upwelling and Ekman pumping (18.5-42.5 Tg C) are of the same order as open ocean emissions (11.2-33.5 Tg C). Total emissions during the 1995 South-West Monsoon (29.6-76.0 Tg C) account for a significant portion of the annual emissions estimated to be 74 Tg C yr^{-1} [*Somasundar et al.*, 1990] and 69-79 Tg C yr^{-1} [*George et al.*, 1994]. This proves the importance of the South-West Monsoon which implies that estimates of

Table 1. Estimates of CO_2 Emissions from the Arabian Sea during the 1995 South-West Monsoon.

Regime	Surface Area[a]	Temperature	Wind Speed[b]	ΔpCO_2[c]	Emissions (LM86)[d]	Emissions (W92)[d,e]	Emissions (T90)[d]
	10^6 km^2	°C	m s^{-1}	µatm	Tg C	Tg C	Tg C
Coastal upwelling	0.20	22	13	250	11.2	25.7	23.7
Ekman pumping	0.50	26	13	80	7.3	16.7	18.8
Open ocean	6.28	28	7.5	25	11.2	19.9	33.5
total	6.98				29.6	62.2	76.0

a Areas are calculated from an equal-area projection of the Arabian Sea with boundaries of the different regimes after J. Brock in *SCOR* [1995]. As southern and eastern boundary we have chosen the equator and the southern tip of India. The Gulf of Aden and the Gulf of Oman are included in the calculation. The Persian Gulf and the Red Sea are not .

b Climatological wind speed estimated after *Rao et al.* [1991].

c Estimates based on measurements during cruise no. 32-5 of R/V *Meteor* in July/August 1995.

d Emissions (1 Tg = 10^{12} g) are calculated for three months, representing the period of the South-West Monsoon.

e Based on the parametrization for climatological winds.

annual emissions based on premonsoon data tend to be underestimating as already pointed out by *George et al.* [1994].

A significant increase of atmospheric CO_2 concentrations from a mean background value around 359.6 ppmv north of the equator to a mean value of 361.8 ppmv at the northeastern tip of the area of coastal upwelling was observed. This is attributed to strong CO_2 emissions into these local air masses during their 24-hour passage across this area. A simple box model calculation was made to check this hypothesis. The box was located on top of the coastal upwelling area with an estimated length $d = 1000$ km, which is consistent with the area of coastal upwelling as shown in Fig. 1. We assumed a height of the tropospheric boundary layer $H_m = 1000$ m (low-level Findlater Jet centered at about 1500 m) and used a constant wind speed $v = 12.5$ m s^{-1}. The measured background CO_2 concentration (C_{in}) was assigned to the air entering the box from southeast. Measurements at the northeastern tip of the box provided the CO_2 concentration of the air leaving the box (C_{out}). Vertical exchange through the upper boundary and horizontal exchange by lateral transport were considered to be negligible (i.e. the box was surrounded by background air CO_2 concentrations). The flux density F of CO_2 from the ocean into the box is then given by $F = (C_{out}-C_{in})\, v\, H_m\, d^{-1} = 85$ mmol m^{-2} d^{-1}. This flux density is equivalent to a ΔpCO_2 of 244 µatm (W92 for spot winds) to 433 µatm (LM86) at the observed wind speed. These upper and lower estimates nicely bracket the observed partial pressure difference of 300-400 µatm. This admittedly rather crude approximation yields results fully consistent with the presence of an unusual situation, where strong ocean emissions of CO_2 directly influence local atmospheric CO_2 concentrations.

Summary

We observed a general moderate supersaturation (ΔpCO_2 = 12-30 µatm) of surface waters with respect to atmospheric CO_2 concentrations in the Arabian Sea. This situation reflects the tropical characteristics with high water temperatures and is comparable to low latitude areas in the Atlantic and Pacific Oceans. The areas of coastal upwelling and (postulated) Ekman pumping in the northwestern part of the Arabian Sea show a contrasting situation with extreme supersaturation during the period of the South-West Monsoon. The most pronounced supersaturation was found in the area of vigorous coastal upwelling (ΔpCO_2 up to 405 µatm). This effect is still important in the area of Ekman pumping (ΔpCO_2 up to 185 µatm). Emissions during the three month period of the South-West Monsoon are of comparable size in the upwelling regimes and the open ocean although very different surface areas are involved. Total estimated emissions during the 1995 South-West Monsoon (29.6-76.0 Tg C) account for a significant portion of literature values of the annual emissions from the Arabian Sea thus underlining the importance of this season. While the calculated CO_2 flux density (up to 119 mmol m^{-2} d^{-1}) is certainly on the high end for oceanic environments the total emissions remain of low significance on the global scale due to the small portion of the world ocean's area involved.

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References

Banse, K., and D.C. English, Seasonality of coastal zone colour scanner phytoplankton pigment in the offshore oceans, *J. Geophys. Res., 99,* 7323-7345, 1994.

Elliott, A.J., and G. Savidge, Some features of the upwelling off Oman, *J. Mar. Res., 48,* 319-333, 1990.

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

Frankignoulle, M., Field measurements of air-sea CO_2 exchange, *Limnol. Oceanogr., 33,* 313-322, 1988.

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

Körtzinger, A., L. Mintrop, and J.C. Duinker, The floating dripstone cave - CO_2 teams compare underway systems, *U.S. JGOFS News, 7,* 14-15, 1996a.

Körtzinger, A., H. Thomas, B. Schneider, N. Gronau, L. Mintrop, and J.C. Duinker, At-sea intercomparison of two newly designed underway pCO_2 systems - Encouraging results. *Mar. Chem., 52,* 133-145, 1996b.

Liss, P.S., and L. Merlivat, Air-sea exchange rates: Introduction and synthesis, in *The Role of Air-Sea Exchange in Geochemical Cycling,* edited by P. Buat-Ménard, pp. 113-127, D. Reidel Publishing Company, Dordrecht, 1986.

Miyake, Y., and Y. Sugimura, Carbon dioxide in the surface waters and the atmosphere in the Pacific, Indian and the Antarctic Ocean areas, *Rec. Oceanogr. Works Japan, 10,* 28-33, 1969.

Olson, D.B., G.L. Hitchcock, R.A. Fine, and B.A. Warren, Maintenance of the low-oxygen layer in the central Arabian Sea, *Deep-Sea Res., 40,* 673-685, 1993.

Poisson, A., N. Metzl, C. Brunet, B. Schauer, B. Bres, D. Ruiz-Pino, and F. Louanchi, Variability of sources and sinks of CO_2 in the Western Indian and Southern Oceans during the year 1991, *J. Geophys. Res., C12,* 22,759-22,778, 1993.

Rao, R.R., R.L. Molinari, and J. Festa, Surface Meteorological and Near Surface Oceanographic Atlas of the Tropical Indian Ocean, *NOAA Technical Memorandum ERL AOML-69,* 1991.

Schott, F., J.C. Swallow, and M. Fieux, The Somali Current at the Equator: annual cycle of currents and transports in the upper 1,000 m and connection with neighbouring latitudes, *Deep-Sea Res., 37,* 1825-1848, 1990.

SCOR, The Joint Global Ocean FluxStudy - Arabian Sea Process Study, *JGOFS Report No. 17,* 64 pp., Baltimore, 1995.

Siegenthaler, U., and J.L. Sarmiento, Atmospheric carbon dioxide and the ocean, *Nature, 365,* 119-125, 1993.

Smith, R.L., and J.S. Bottero, On upwelling in the Arabian Sea, in *A Voyage of Discovery,* edited by M.V. Angel, pp. 291-304, Pergamon Press, New York, 1977.

Somasundar, K., A. Rajendran, M. Dileep Kumar, and R. Sen Gupta, Carbon and nitrogen budgets of the Arabian Sea, *Mar. Chem., 30,* 363-377, 1990.

Swallow, J.C., Some aspects of the physical oceanography of the Indian Ocean, *Deep-Sea. Res., 31,* 639-650, 1984.

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

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

Warren, B.A., Context of the suboxic layer in the Arabian Sea, in *Biogeochemistry of the Arabian Sea,* edited by D. Lal, pp. 203-216, Indian Academy of Sciences, Bangalore, 1994.

Watson, A.J., P.D. Nightingale, and D.J. Cooper, Modelling atmosphere-ocean CO_2 transfer, *Phil. Trans. R. Soc. Lond., B, 348,* 125-132, 1995.

Weiss, R.F., Carbon dioxide in water and seawater: the solubility of a non-ideal gas, *Mar. Chem., 2,* 203-215, 1974.

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