

2.3 Air-Sea Interactions and Exchanges

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Introduction

At the time of planning JGOFS Process Studies, it was recognised that the Arabian Sea makes a significant contribution to biogeochemical ocean-atmosphere transfer processes. However, the magnitudes of these exchanges were not well quantified even for constituents such as carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄), for which some data were available. For others like ammonia (NH₃) and dimethylsulphide (DMS), which had not been measured previously, new measurements were planned. The work carried out during the JGOFS and related cruises on these climatically important atmospheric constituents, has greatly expanded the database, allowing for improved estimates of their air-sea exchange rates.

Carbon Dioxide (CO₂)

At the time of JGOFS planning, the Indian Ocean north of the Hydrochemical Front at ~10°S was believed to serve as a source of CO₂ to the atmosphere. In this respect there were several crucial questions concerning carbon cycling in the region that the JGOFS programme aimed to address. It was thought that since the upwelled water at the surface had very high pCO₂, upwelling in conjunction with a wind-induced enhancement of the air-sea gas exchange coefficient would result in a large efflux of CO₂ to the atmosphere from the northwestern Indian Ocean. This effect would be aided by the secretion of CaCO₃ by organisms (which raises pCO₂), but opposed by the high rate of photosynthetic production (which lowers pCO₂), sustained by copious nutrients in the mixed-layer. The relative importance of these processes was not known. Also, as the physical forcings associated with the NE and SW Monsoons are highly variable in space and time, large changes in the air-sea exchange of CO₂ were expected.

Extensive surveys made under the JGOFS, WOCE (World Ocean Circulation Experiment) and, to a smaller extent, OACES (Ocean-Atmosphere Carbon Exchange Study) programmes have greatly increased the existing carbon database for the Indian Ocean. This has enabled a much more reliable quantification of the air-sea CO₂ exchange and an evaluation of its spatial and temporal variations in the Indian Ocean, particularly in the Arabian Sea. These data were generated through both continuous underway pCO₂ measurements and discrete water sampling. Results of these studies have conclusively established that the Arabian Sea is indeed a source of CO₂ to the atmosphere at almost all places and during all seasons, but with very large seasonal and geographical variability. The surface-water pCO₂ levels are the highest in coastal upwelling zones: values reaching up to 700 µatm being observed off Oman (**Figure 1**) during the Southwest (SW) Monsoon season (Körtzinger *et al.*, 1997; Goyet *et al.*, 1998; Mintrop *et al.*, 1999). In the northern Arabian Sea, convective mixing during the NE Monsoon can elevate the pCO₂ level to 500 µatm even in offshore areas (Sarma *et al.*, submitted). pCO₂ approaching 700 µatm was also recorded in the SW Monsoon upwelling zone off western India; however, as the upwelled water in this region is often overlain by a low-salinity layer formed as a result of intense rainfall in the coastal zone, the surface water pCO₂ (minimum 266 µatm) may sometimes be below saturation (Sarma *et al.*, 2000). Ignoring these rare instances of pCO₂ undersaturation caused by a combination of physical and biological processes (a similar phenomenon has also

been reported from the Bay of Bengal; see Kumar *et al.*, 1996), it would appear that the increases in $p\text{CO}_2$, through upwelling and vertical mixing of subsurface waters greatly overwhelm its biological removal in the northwestern Indian Ocean. Interestingly, the atmospheric $p\text{CO}_2$, which also exhibits considerable seasonal variability, is the lowest ($\sim 340 \mu\text{atm}$) during or just after the SW Monsoon (Goyet *et al.*, 1998) accentuating the sea-air CO_2 gradient ($\Delta p\text{CO}_2 = p\text{CO}_2^{\text{sea}} - p\text{CO}_2^{\text{air}}$), while the exchange coefficient is the highest due to strong monsoon winds. The combination of these effects leads to some of the most intense emissions of CO_2 (up to $119 \text{ mmol m}^{-2} \text{ d}^{-1}$, Körtzinger *et al.*, 1997) from the sea surface.

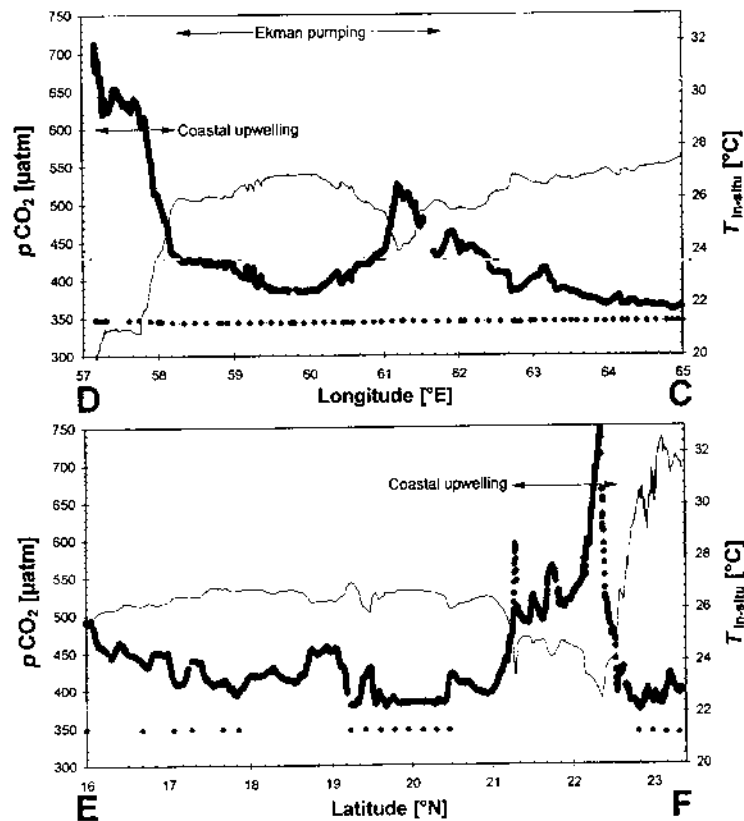


Figure 1. Partial pressure of CO_2 in surface water (bold curves) and in the atmosphere (dots on dashed curves) and water temperature (thin curve) along two transects of the upwelling zone off Oman during July-August, 1995 (from Körtzinger *et al.*, 1997).

In the Arabian Sea, seasonal contrasts in $p\text{CO}_2$ and in the air-sea flux are best marked in coastal waters, but large seasonality in the open ocean is also observed in the Southern Indian Ocean (Figure 2; Louanchi *et al.*, 1996; Sabine *et al.*, 2000). The amplitude of seasonal changes in the open Arabian Sea is somewhat uncertain. The U.S. JGOFS observations in the central and western Arabian Sea over a complete annual cycle, involving continuous, automated measurements, revealed substantial seasonal changes in the offshore region, with the lowest $\Delta p\text{CO}_2$ ($< 32 \mu\text{atm}$) occurring during the non-Southwest Monsoon periods (Goyet *et al.*, 1998).

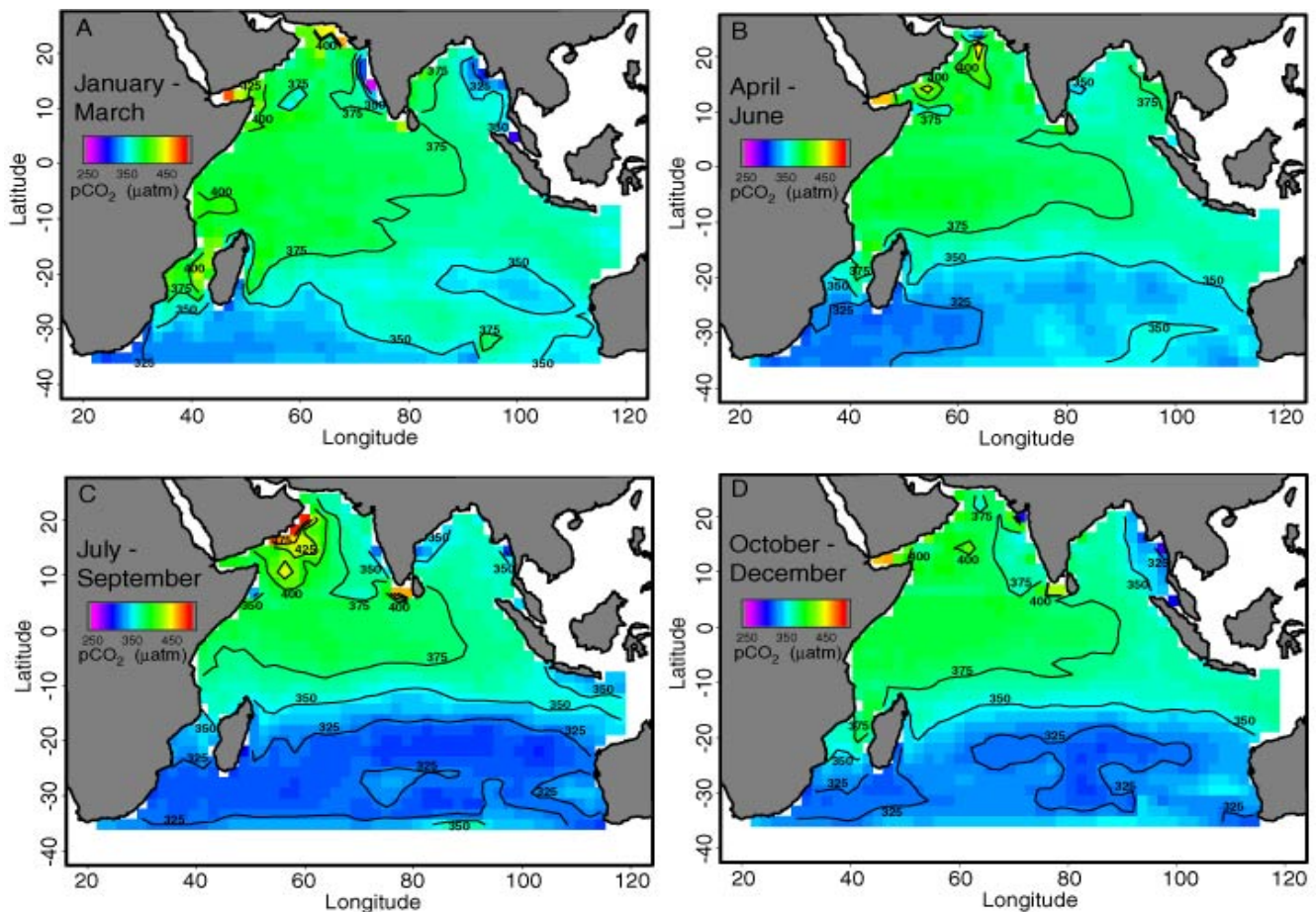


Fig. 2 Maps of surface water pCO₂ broken down by season. Color and contours in µatm. Taken from Sabine *et al.*, *Mar. Chem.*, 72, 33-53, 2000.

Figure 2. Season-wise distribution of surface water pCO₂ (µatm) in the Indian Ocean (from Sabine *et al.*, 2000).

In comparison, the Indian JGOFS data, mostly based on pH-TCO₂ or pH-alkalinity measurements (Sarma *et al.*, 1998), indicated smaller variability and higher ΔpCO₂ (up to 124 µatm). Accordingly, estimates of annual CO₂ flux to the atmosphere from the Arabian Sea also differ significantly (7 TgC by Goyet *et al.*, 1998, and 79 TgC by Sarma *et al.*, 1998). The latter estimate is close to that [30-76 TgC (3 months)⁻¹] based on observations during the SW Monsoon season as a part of the German JGOFS programme (Körtzinger *et al.*, 1997). While some of these differences may arise from different techniques used for measurements, data interpolation and computations, they probably reflect the large temporal (both seasonal and interannual) and spatial variations that characterize air-sea CO₂ exchange in this region.

The WOCE-JGOFS data combined with earlier measurements made during the GEOSECS and INDIGO expeditions have been used to evaluate the extent of anthropogenic CO₂ penetration in the Indian Ocean (Sabine *et al.*, 1999). The highest concentrations and the deepest penetrations (>1 km) were found to occur in the region of the subtropical convergence (30-40°S) evidently through the formation of intermediate waters, while these were the least in the Antarctic region. The northwestern Indian Ocean, which receives outflows from the Persian Gulf and the Red Sea, appears to hold more anthropogenic CO₂ than the equatorial Indian Ocean (Sabine *et al.*, 199; **Figure 3A**). The total inventory of anthropogenic CO₂ in the Indian Ocean north of 35°S has been estimated to be 13.6 PgC (1 Pg = 10¹⁵ g) while the increase over the 18-year interval between the GEOSECS and WOCE-JGOFS expeditions works out to be 4.1 Pg C. An interesting aspect of these results is that the observed trends of anthropogenic CO₂ distribution (Sabine *et al.*, 199; **Figure 3A**) show some important differences from those predicted by the Princeton

ocean biogeochemistry model (Sabine *et al.*, 1999; **Figure 3B**) with the databased penetration estimate being higher in the northern Indian Ocean and lower in the Antarctic sector.

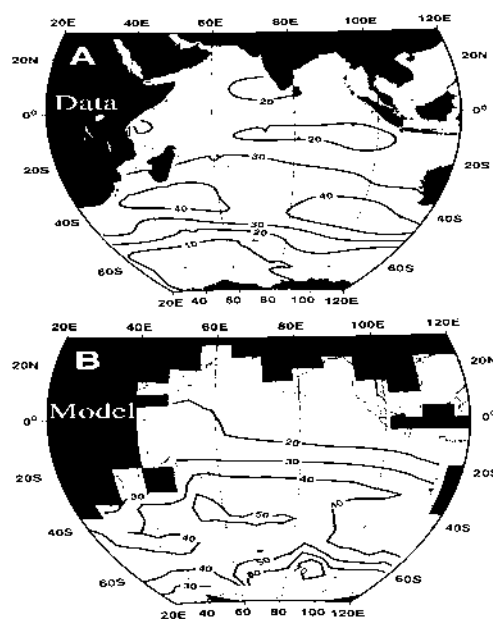


Figure 3. Distribution of vertically integrated anthropogenic CO₂ (mol m⁻²) based on (A) data and (B) model estimates (from Sabine *et al.*, 1999).

Evaluation of anthropogenic CO₂ penetration in the northern Indian Ocean has also been made following another approach that takes into account contributions from various source water masses. This work is documented in Goyet *et al.* (1999). The WOCE data used for this study were collected along three transects, the first in the Gulf of Aden parallel to the Yemeni coast, the second across the Arabian Sea along 9°N latitude, and the third across the Bay of Bengal (including the Andaman Sea) along 10°N latitude. Surface waters in these regions were computed to contain over 40 μmol kg⁻¹ of anthropogenic CO₂. The depth of penetration of the anthropogenic signal was noticed to decrease from ~1500 m in the Gulf of Aden (which receives freshly-formed intermediate waters from the Red Sea) to <1000 m in the Bay of Bengal. Underway pCO₂ analysis carried out during the same expedition (**Figure 4**) revealed fairly large supersaturations in the Gulf of Aden and in the western and central parts of the Arabian Sea. This was presumably due to the aforementioned upwelling and warming of CO₂-rich deeper waters. Lower pCO₂ values in the easternmost portion of the Arabian Sea transect and along most of the Bay of Bengal transect were associated with low-salinity surface water masses. It may be noted that the ΔpCO₂ reached a minimum of ~-30 μatm in the Andaman Sea that receives large runoff from the Irrawaddy and Salween rivers. This further reinforces the view that freshwater discharge in the northeastern Indian Ocean makes this region a net sink for atmospheric CO₂ unlike the northwestern Indian Ocean (Kumar *et al.*, 1996).

Regional variability of pCO₂ in surface waters and of the causative processes (thermodynamics, vertical mixing, biological activity and air-sea exchange) has also been demonstrated through modelling by Louanchi *et al.* (1996). The one-dimensional model employed by these authors in different provinces of the Indian Ocean north of 50°S latitude, yielded a spatio-temporal distribution that closely matched with the observations. However, some discrepancies between the model results and observations were noticed. For example, the model-predicted distribution for the Arabian Sea showed two peaks separated by a minimum during the SW Monsoon (July-August) that is not consistent with the data as described above.

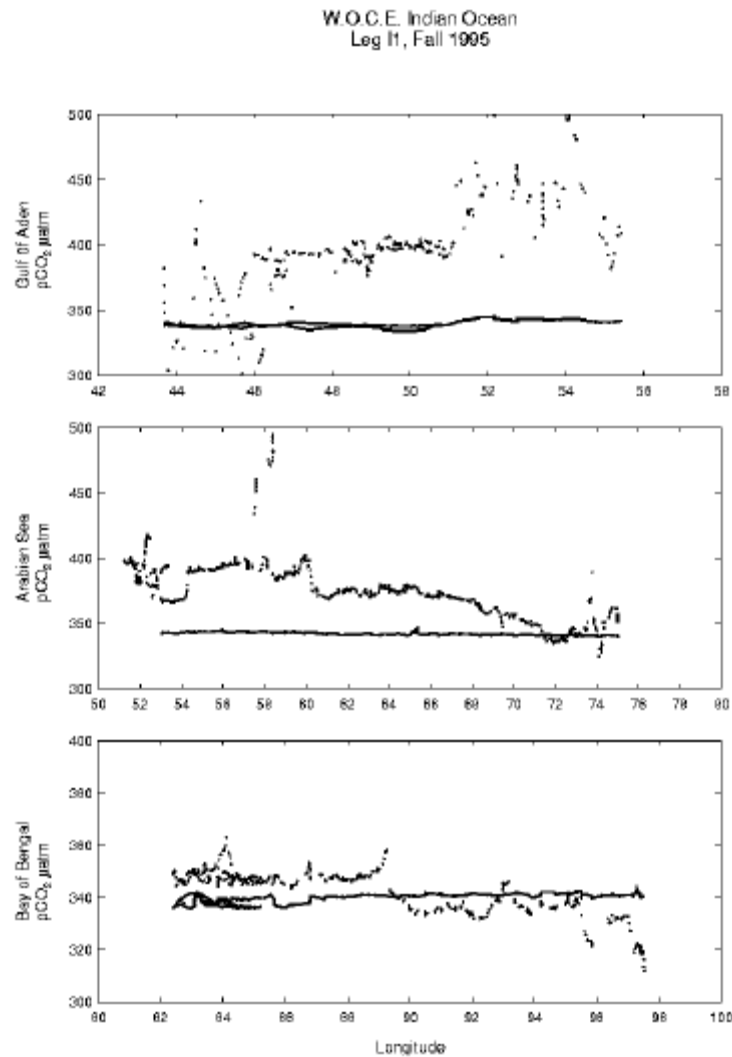


Figure 4. Distributions of $p\text{CO}_2$ in surface water (circles) and in the atmosphere (triangles) during August-October, 1995, along three WOCE transects: (a) from Gulf of Aden to the Arabian Sea; (b) along Lat. 9°N in the Arabian Sea; and (c) along Lat. 10°N in the Bay of Bengal and the Andaman Sea (from Goyet *et al.*, 1999).

This indicates a possible overestimation of the loss (through the biological pump and air-sea exchange) or an underestimation of supply (entrapment from deeper water). Also, the seasonal contrast in surface $p\text{CO}_2$ was generally greater in the eastern equatorial Indian Ocean than in the northwest Indian Ocean. The model results enabled the identification of four different provinces based on their characteristic surface $p\text{CO}_2$ fields. While the region south of 35°S latitude appears to be a net sink ($\sim 500 \text{ TgC y}^{-1}$) for atmospheric CO_2 during all months (with a maximum during the Austral winter), that north of 10°S latitude is a net source ($\sim 150 \text{ TgC y}^{-1}$ with maximal emission during the SW Monsoon). Between these two extremes lie the southern subtropical region and the transition zone bounded by the latitudes 20°S and 10°S ; the former serves as a moderate sink ($\sim 170 \text{ TgC y}^{-1}$) whereas the latter is neither a sink nor a source on an annual basis.

Sabine *et al.* (2000) have recently utilized 240,000 surface $p\text{CO}_2$ measurements made during 1995-96 under JGOFS, WOCE and OACES to establish its relationships with other parameters such as the sea surface temperature (SST), salinity and location. These relationships are then used with the NCEP/NCAR reanalysis, SSTs, winds and atmospheric pressures and the salinity values derived from Levitus *et al.*, (1994) to compute basin-wide $p\text{CO}_2$ and air-sea fluxes for

each month. Their results show a larger seasonal cycle for the tropical and subtropical Indian Ocean than simulated by Louanchi *et al.* (1996). Also, unlike the Pacific and the Atlantic Oceans, the equatorial Indian Ocean appears to be a relatively small source of CO₂ to the atmosphere. The net annual flux of CO₂ for the region lying north of 36°S latitude was 150 TgC, and it was directed from the atmosphere to the ocean. This is at variance with the results of Louanchi *et al.* (1996) who concluded that the Indian Ocean north of 35°S latitude serves as a weak source of atmospheric CO₂ (22 TgC y⁻¹). The estimate of Sabine *et al.* (2000) is in agreement with that of Takahashi *et al.* (1999), although the regional breakdowns of the estimates are different because of different techniques used for data processing. As expected, the air-sea fluxes exhibit large geographical and seasonal changes. The Indian Ocean as a whole (north of 36°N) oscillates between a weak net source (22 Tg) during January-March and a net sink (87 Tg) during July-September. Interestingly the period of maximal net absorption is the same as that of maximal SW Monsoon-forced emissions from the Arabian Sea reflecting the dominance of removal by CO₂-undersaturated waters, largely due to biological processes, in determining the net CO₂ uptake/emission balance in the region. The study of Sabine *et al.* (2000) did not cover the frontal zone, which is an even stronger sink of atmospheric CO₂. For example, Metzl *et al.* (1997) estimated that the sub-Antarctic waters (40-50°S) in the Indian sector absorb 420 TgC annually; this compares favourably with the model-derived estimate of Louanchi *et al.* (1996) for the region south of 35°S. Thus, it may be concluded that the Indian Ocean, including the sub-Antarctic Zone, on balance absorbs a minimum of 0.5 Pg CO₂-C from the atmosphere annually, a quarter of the total oceanic CO₂ uptake (Houghton *et al.*, 1996). It may be noted that the average annual increase ($4.1/18 = 0.23 \text{ Pg C y}^{-1}$) in anthropogenic CO₂ inventory north of 35°S estimated by Sabine *et al.* (1999) is of the same order.

Molecular Nitrogen and Nitrous Oxide

The Arabian Sea is one of three major oceanic water-column denitrification sites. Current estimates of denitrification rates in this region vary from 12 TgN y⁻¹ (Mantoura *et al.*, 1993) to 33 TgN y⁻¹ (Naqvi and Shailaja, 1993). The high-quality nutrient data collected during the JGOFS cruises were expected to narrow this gap. Howell *et al.* (1997) combined the nitrate and chlorofluorocarbon (CFC-11) data collected during the WOCE programme to arrive at a denitrification rate of 21 TgN y⁻¹. This is slightly lower than most other estimates (the most recent one being 33 TgN y⁻¹ by Bange *et al.*, 2000). Thus, it would appear that the Arabian Sea accounts for at least one-third of the global oceanic water column denitrification (Naqvi, 1987). This high rate of molecular nitrogen (N₂) production is countered by substantial N-fixation in the region as evident from recent measurements of natural abundance of nitrogen isotopes in dissolved nitrate (NO₃⁻) (Brandes *et al.*, 1998). Brandes *et al.* (1998) observed that near-surface NO₃⁻ in the Arabian Sea suboxic zone has a nitrogen isotopic composition close to the oceanic average ($\delta^{15}\text{N} \approx 6 \text{ per mil}$) in spite of the huge denitrification-related enrichment of ¹⁵N ($\delta^{15}\text{N} > 11 \text{ per mil}$) in subsurface waters (>200 m). This has been attributed to the fixation of light nitrogen at an estimated basin-wide rate of 6 Tg y⁻¹. This implies a net loss of combined nitrogen and production of N₂ at a rate of ~15-27 TgN y⁻¹.

Apart from denitrification and nitrogen fixation, the other important term in the nitrogen budget to which the Arabian Sea makes a significant contribution, is the efflux of N₂O from the sea surface. Of the total inputs of N₂O to the atmosphere from all natural sources (~12 TgN-N₂O y⁻¹), at least one-third seems to come from the oceans (Nevison *et al.*, 1995). However, emissions of N₂O are not uniformly distributed over the oceanic surface with the eastern-boundary upwelling zones underlain by O₂-deficient waters making disproportionately large contributions (Codispoti and Christensen, 1985; Suntharalingam *et al.*, 2000). Studies carried out under JGOFS have led to a better quantification of this efflux. These studies (*e.g.*, **Figure 5**) revealed

very high surface saturations (>300%) in the upwelling zones off Oman, Somalia and southwestern India (Bange *et al.*, 1996; de Wilde and Helder, 1997; Patra *et al.*, 1999).

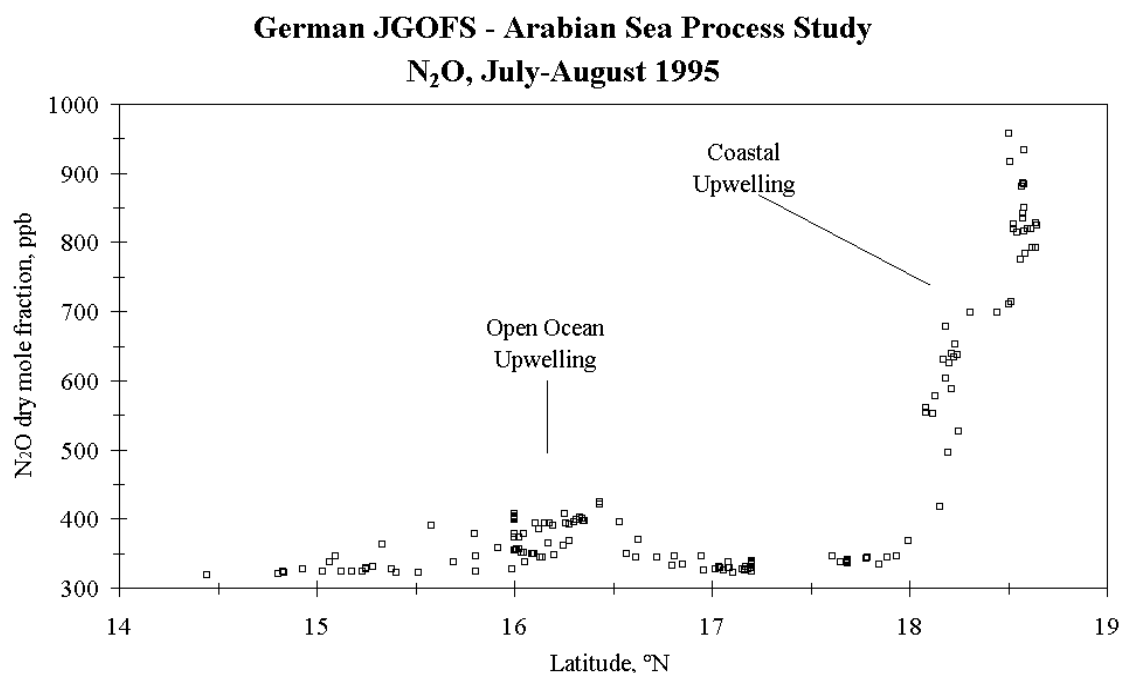


Figure 5. N₂O of equilibrated seawater along the same transect as in **Figure 1** (lower panel) (from Bange *et al.*, 1996).

The sea-to-air fluxes of N₂O from these regions are also similarly high (maximum of ~500 μmol m⁻² d⁻¹). In the open ocean, surface N₂O saturations and its fluxes to the atmosphere are generally lower (**Figure 5**) than those reported previously (Law and Owens, 1990; Naqvi and Noronha, 1991). These also show smaller temporal variability except for the zones of offshore upwelling and winter mixing (Bange *et al.*, 1996; de Wilde and Helder, 1997; Lal and Patra, 1998). However, even in coastal upwelling zones, seasonal changes in the mixed layer N₂O saturations may sometimes be small, as observed by Upstill-Goddard *et al.* (1999) in the western Arabian Sea, indicating a balance between the processes of gas exchange, net production and supply/removal by advection and vertical mixing. Nevertheless, large changes in air-sea exchange can still occur due to variations in the wind speed (Upstill-Goddard *et al.*, 1999). However, the highest globally recorded N₂O concentrations in surface water (up to 436 nM or 8,250% saturation) were measured within the seasonally-suboxic zone off western India during a three-year (1997-99) study. This study was conducted as part of the Indian LOICZ (Land-Ocean Interactions in the Coastal Zone) programme (Naqvi *et al.*, 2000). These extreme concentrations are higher than those observed (62.5 nM or 953% saturation) during a more limited survey made during the SW Monsoon of 1995 (Naqvi *et al.*, 1998). Interestingly, the highest concentrations were found in waters that were apparently affected by denitrification, as suggested by high nitrite concentrations (see **Figure 6**), a process that generally results in a net consumption of N₂O (Codispoti and Christensen, 1985).

This is consistent with the results of incubation experiments (Naqvi *et al.*, 2000), which indicated that in shallow, denitrifying systems with high rates of denitrification and experiencing frequent aeration due to turbulence, the N₂O-reductase activity may be suppressed to such a degree that a large fraction of the nitrogen undergoing bacterial reduction ends up as N₂O (Naqvi *et al.*, 2000).

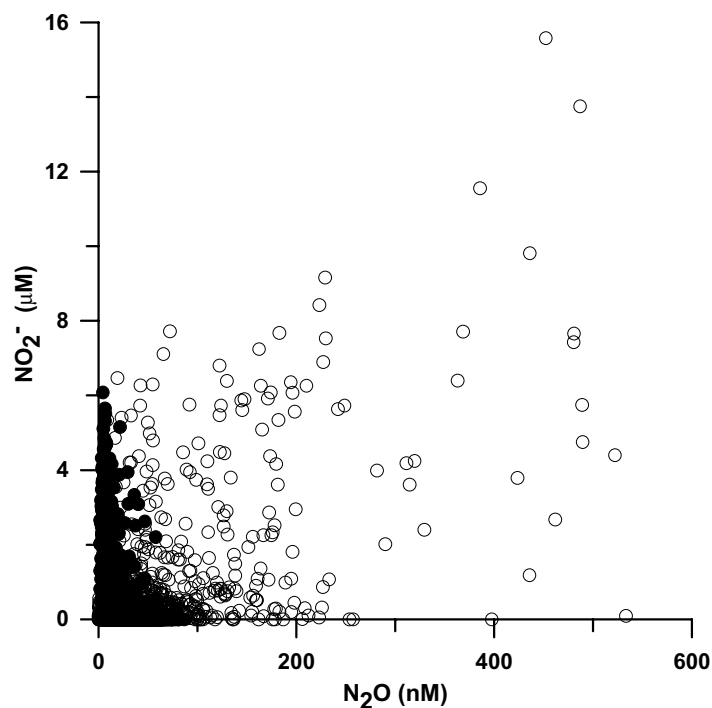


Figure 6. Plot of nitrite (NO_2^-) versus nitrous oxide (N_2O) in the shallow (open circles) and deep (closed circles) suboxic zones of the Arabian Sea (from Naqvi *et al.*, 2000).

Estimates of the annually integrated N_2O -flux from the Arabian Sea, based on the JGOFS data, range between 0.16 and 1.5 Tg N_2O y^{-1} . These estimates are strongly dependent on the choice of model used to compute the air-sea exchange coefficient and the interpolation scheme. Recently, Bange *et al.* (submitted) have pooled all the data generated between 1977 and 1997 to compute high resolution ($1^\circ \times 1^\circ$) seasonal and annual N_2O concentration fields in the surface layer. The annual emission rate, estimated to range between 0.33 and 0.70 Tg N_2O , seems to be dominated by fluxes from coastal regions during the SW Monsoon. However, this data set does not include the anomalously high N_2O concentrations in the inner shelf off the Indian west coast. In this region high oxygen demand coupled with strong stratification causes severe oxygen depletion below the shallow pycnocline. But while the causative processes (upwelling of nutrient-rich waters and the outflow of freshwater from land resulting from intense rainfall in the coastal zone) are primarily natural, it is quite likely that the coastal hypoxic system has further intensified in recent years. Such intensification, evident from the previously unreported occurrence of hydrogen sulphide, might arise from an increase in productivity fuelled by a higher flux of nutrients from land. This could have contributed to the enormous N_2O accumulation observed in the region. But if the N_2O concentrations in the region were high even before this intensification, then the above estimate of “natural” N_2O emissions from this region would be too low. In any case, if we take into account the seasonal flux of N_2O from the shelf (0.06-0.39 Tg N_2O ; Naqvi *et al.*, 2000), the current sea-to-air flux of N_2O from this region could be as much as 1 Tg N_2O y^{-1} , about one quarter of the total global oceanic emissions (Houghton *et al.*, 1996).

Ammonia and Methylamines

Under the UK JGOFS programme, measurements of ammonia/ammonium ($\text{NH}_3/\text{NH}_4^+$) and methylamines (MAs) [monomethylamine (MMA), dimethylamine (DMA) and trimethylamine (TMA)] were made in seawater, atmosphere and rainwater in the central and western Arabian Sea during two seasons (August-October and November-December, 1994) (Gibb *et al.*, 1999).

Concentrations of all species were generally elevated in the coastal upwelling zone off Oman relative to those measured in the central Arabian Sea, with $\text{NH}_3/\text{NH}_4^+$ levels being up to two orders of magnitude higher than those of the MAs. MMA was the most abundant MA, being present in concentrations reaching up to 66 nM, while TMA levels did not exceed 4 nM (see also Burkill, this volume). Both the coastal and offshore waters of the Arabian Sea appeared to emit NH_3 to the atmosphere with large temporal variations. However, the air-sea exchange probably represented a small proportion of the aquatic turnover of NH_3 and MAs, which seem to be controlled mainly by the structure, activity and seasonality of the microbiological cycle. Most of the removal of NH_3 and MAs appeared to occur through wet deposition (**Figure 7**), contributing little (<1%) to the new production. However, by virtue of being the dominant atmospheric bases, NH_3 and MAs may play an important role in tropospheric chemistry and climatic modification.

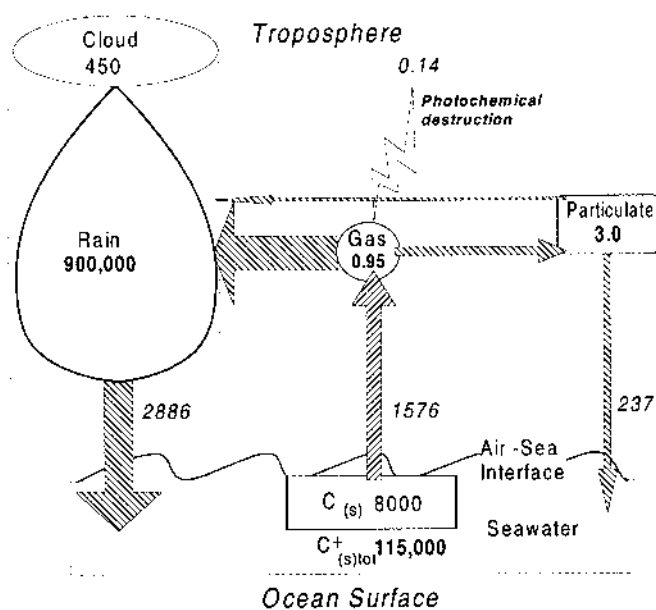


Figure 7. Schematic diagram of the cycling of $\text{NH}_3+\text{NH}_4^+$ in the remote Arabian Sea in which pools (boxes, nmol m^{-3}) and processes (arrows, $\text{nmol m}^{-3} \text{d}^{-1}$) are represented in broad approximation to their relative magnitudes (from Gibb *et al.*, 1999).

Nitrate and Lead-210

As a part of the Indian JGOFS programme, seasonal distributions of NO_3^- and lead-210 (^{210}Pb) have been studied in the aerosols over the central-eastern Arabian Sea for investigating the sources of NO_3^- and quantifying its deposition flux (Sarin *et al.*, 1999). Higher NO_3^- concentrations (0.4 to $4.1 \mu\text{g m}^{-3}$) were observed during the Spring Intermonsoon and NE Monsoon as compared to the SW Monsoon (0.2 - $0.8 \mu\text{g m}^{-3}$). Using a $\text{NO}_3^-/^{210}\text{Pb}$ ratio of $43 \mu\text{g dpm}^{-1}$ and the measured ^{210}Pb deposition flux of $20 \text{dpm m}^{-2} \text{d}^{-1}$, the atmospheric deposition of NO_3^- was estimated to be $1 \text{mg m}^{-2} \text{d}^{-1}$. These results suggest that that the atmospheric NO_3^- deposition plays an insignificant role in fuelling new production in the region.

Methane

Prior to the JGOFS programme, there had been only one report on CH_4 distribution in the Arabian Sea (Owens *et al.*, 1991). High surface-water concentrations and consequently larger-than-the-oceanic-average CH_4 fluxes observed in this study prompted additional investigations on CH_4 by several groups, the results of which have been published recently (Patra *et al.*, 1998;

Bange *et al.*, 1998; Upstill-Goddard *et al.*, 1999; Jayakumar *et al.*, 2001). In agreement with the findings of Owens *et al.* (1991), Patra *et al.* (1998) reported high surface saturations, averaging 140, 173 and 200% during the Northeast Monsoon, Spring Intermonsoon and SW Monsoon periods in the central and eastern Arabian Sea. Upstill-Goddard *et al.* (1999) observed moderate saturations in the Omani upwelling zone both during the late SW Monsoon ($170\pm 55\%$) and Spring Intermonsoon ($179\pm 15\%$) seasons; the corresponding open ocean values were $130\pm 5\%$ and $115\pm 2\%$. In contrast to these data, Bange *et al.* (1998) showed near-saturation (103-107%) in the central Arabian Sea, rising to a maximum of 156% in the upwelled water near the coast of Oman (**Figure 8**). The annual emission rate of CH₄ from the Arabian Sea was estimated at 0.032-0.053 Tg CH₄ y⁻¹ by Patra *et al.* (1998), 0.011-0.020 Tg CH₄ y⁻¹ by Bange *et al.* (1998) and 0.1-0.18 Tg CH₄ y⁻¹ by Upstill-Goddard *et al.* (1999). Whether the order-of-magnitude differences in the published estimates of CH₄ emissions from the Arabian Sea represent natural variations or they arise, at least in part, from systematic measurement errors is still not clear. However, even the highest of these estimates is probably still <2% of the estimated emission rate from the oceans as a whole (Upstill-Goddard *et al.*, 1999), which itself is at the most 4% of the atmospheric flux of CH₄ from all natural and anthropogenic sources (Crutzen, 1991). Evidently, unlike N₂O, CH₄ emissions from the Arabian Sea are not globally significant.

It should be noted that most of the CH₄ data collected in the Arabian Sea have come from offshore areas. As pointed out by Bange *et al.* (1994), the contribution of the coastal zone to the oceanic CH₄ budget may be disproportionately large. This is also supported by the results of a recent study (Jayakumar *et al.*, 2001), which yielded CH₄ saturations comparable to those observed by other workers in the open ocean, but very large supersaturations (up to ~2500%) in the coastal waters affected by monsoonal runoff from land. Still higher supersaturations (up to ~13,000%) were recorded in the estuarine surface water pointing to a source of CH₄ in coastal wetlands. Elevated (CH₄) concentrations (~50 nM) have also been found in the seasonal oxygen-depleted zone, when the sub-pycnocline waters turned fully anoxic (D.A. Jayakumar, unpublished data). However, the impact of these processes on the CH₄ budget of the Arabian Sea still remains to be evaluated fully (see also Burkill, this volume).

Dimethylsulphide

As part of the UK and German JGOFS cruises and a related programme in India, measurements of dimethylsulphide (DMS) have been made for the first time in the Arabian Sea. Although the complete data sets generated during these studies have not yet been made available, large spatial and temporal changes in the concentrations of DMS, and its precursor and oxidation product, dimethylsulphoniopropionate (DMSP) and dimethylsulphoxide (DMSO), respectively, appear to occur in this region. For example, in the productive surface waters of the Omani upwelling zone, sampled by Hatton *et al.* (1999), marked increases in the concentrations of DMSP (on average from 21.5 to 37.5 nM), DMSO (from 2.9 to 7.7 nM), and DMS (from 1.3 to 3.3 nM) were observed over an interval of three weeks during the transition from SW Monsoon to Fall Intermonsoon, presumably caused by a shift in the dominant phytoplankton groups (from diatoms to prymnesiophytes). The concentrations were relatively low (21.0, 4.3 and 2.1 nM, respectively) in the oligotrophic surface waters of the central Arabian Sea. DMSO occurred in fairly high and rather uniform concentrations throughout the water column, and although its production through photo-oxidation in the surface layer probably represented an important sink of DMS, significant amounts of the latter should be emitted to the atmosphere from this region. This flux remains to be quantified, and for this purpose representative data from different biogeochemical provinces (particularly those which support the growth of the DMS-producing organisms such as coccolithophores and *Phaeocystis*) are needed.

German JGOFS - Arabian Sea Process Study CH₄, June-July 1997

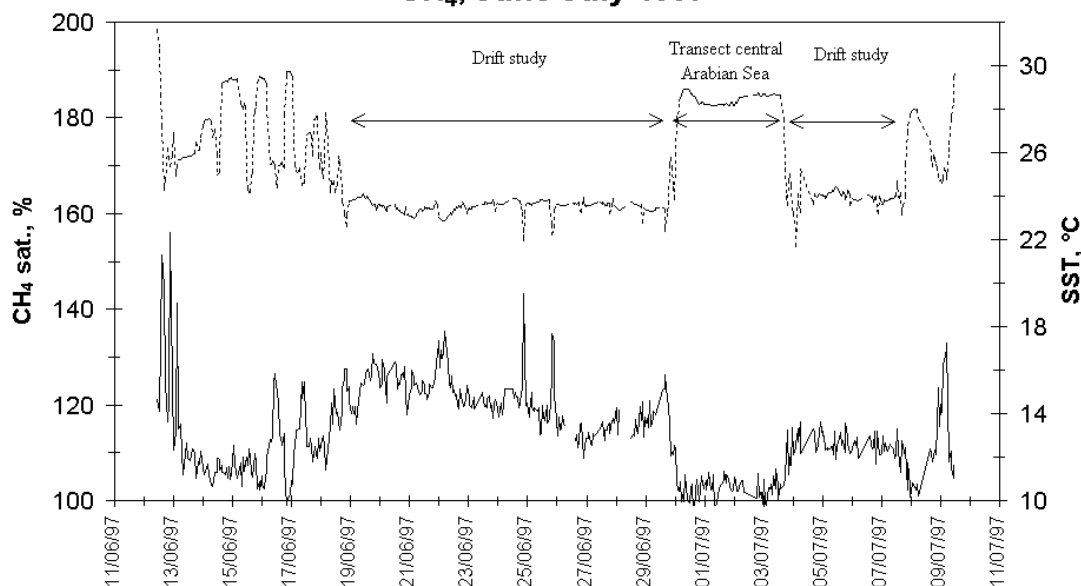


Figure 8. CH₄ saturations (solid curves) and sea surface temperature (dashed curves) in the western Arabian Sea during June-July 1997. The transect ABC was located offshore outside the upwelling zone while the drift stations experienced upwelling (from Bange *et al.*, 1998).

Recommendations

Due to the delicate biogeochemical balance that exists in the Arabian Sea, minor climatic/environmental perturbations can have potentially large impacts on chemical fluxes, especially of greenhouse gases in the region. It is for this reason that the Arabian Sea is regarded as a sensitive ocean scale barometer of global climate change (Mantoura *et al.*, 1993). Recent results suggest that the human activities may already be modifying such fluxes, even though it cannot be established whether the effects observed are due to local processes (eutrophication) alone or caused by slight modifications of physical forcing functions (circulation and freshwater runoff) (Naqvi *et al.*, 2000). Nonetheless, since these fluxes are globally significant, we must keep a close watch on both the coastal and open ocean oxygen-deficient zones, fully understand the mechanisms of biogeochemical transformations using modern tools (for example, stable isotopes and molecular probes), identify the emerging trends and develop capability to predict future changes. In spite of the recent focus on this region under several international programmes, there still exist some serious deficiencies in the geographical and temporal coverage that need to be remedied. For example, the Bay of Bengal still remains to be adequately sampled (especially along the Burmese and Bangladeshi coasts). Also, the contribution of benthic cycling to greenhouse gas fluxes is still largely unknown. As another major international programme is unlikely to be launched in this region in near future, serious efforts should be made towards capacity building such that the less-developed coastal states can initiate studies in their coastal zones.