Carbon dioxide and nitrous oxide in the North Indian Ocean

M. Dileep Kumar, S. W. A. Naqvi, D. A. Jayakumar, M. D. George, P. V. Narvekar and S. N. de Sousa

National Institute of Oceanography, Dona Paula, Goa 403 004, India

The understanding of biogeochemical cycling of carbon dioxide and nitrous oxide in the oceans is essential for predicting the fate of anthropogenically emitted components. The North Indian Ocean, with its diverse regimes, provides us with a natural laboratory that can unravel the mechanisms controlling these gases with implications for the global aquatic bodies. In this review we discuss the anthropogenically impinged global budgets for these gases, summarize our results, largely collected under the Global Change Programme from the North Indian Ocean and evaluate the contributions from this region to the global sea-to-air fluxes.

OVER the geological times the earth system has been at its steady course towards attaining a steady state with respect to quantities and fluxes of materials in and among various reservoirs (i.e. land, ocean and atmosphere). Man's efforts for the betterment of his living standards have led to an unprecedented interference in the natural processes of this system in recent times. The localized pollution on land or in water bodies affects the biogeochemical processes largely locally, whereas the pollutants released to the atmosphere would be of global significance.

The rising levels of gases such as carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and freons (chlorofluorocarbons) in the atmosphere have been recognized not only to change the natural balances of carbon and nitrogen but also affect climate and human health[1]. The accumulation of these gases in the atmosphere enhances the greenhouse effect by absorbing the infrared radiation and leads to stratospheric ozone depletion. Nitrous oxide is 200 times more effective as a greenhouse gas, on per mole basis, compared to CO_2, but, due to a much lower concentration, it accounts for only about 5% of the total warming effect[2]. Under the International Geosphere–Biosphere Programme (IGBP) 'A study of global change', a lot of studies are being carried out globally on biogeochemical processes involving the greenhouse gases. We provide here a synthesis of the available data on CO_2 and N_2O cycling in the North Indian Ocean, largely generated as a result of our participation in the IGBP, in the context of global biogeochemical cycles.

Global balance of impinged CO_2 and N_2O

The atmospheric CO_2 and N_2O concentrations are increasing at annual rates[2] of 0.5% and 0.2%, respectively. The major anthropogenic activities contributing to the observed increases are fossil fuel combustion, use of fertilizers and deforestation. Of the total CO_2 released (7.3×10^3 Mt C yr^{-1}), 3.4×10^3 Mt C yr^{-1} is accumulating in the atmosphere whereas 2×10^3 Mt C yr^{-1} is being removed by the oceans[3] (Figure 1 *a*). However, there is considerable controversy regarding the amount associated with deforestation (1.9×10^3 Mt C yr^{-1}), which at present is attributed to an unknown sink or unaccounted recycled carbon accumulation in soils[3]. The increase in carbon fixation on land, due to the use of nitrogen fertilizers, has not so far been included in the carbon budget. It may account for the missing carbon to some extent. For instance, the agricultural nitrogen fixation in 1974 is estimated[4] to be about 39 Mt N yr^{-1}; this accounts for 0.65×10^3 Mt C yr^{-1}, with a C:N ratio of 19:1 for terrestrial plant material. Thus, this increased carbon fixation could roughly account for at least 34% of the presently missing carbon.

The land-to-air fluxes of N_2O (Figure 1 *b*) are essentially closer to the lower ranges given by Yoshinari[5] (cultivated soils, fertilized soils, unfertilized soils, tropical forests and temperate forests account for 2.0, 3.0, 4.5, 5.8 and 3.0 Mt N yr^{-1}, respectively), to which the flux (0.03 Mt N yr^{-1}) from watershed regions[6] was added in this attempt. The fossil fuel combustion and

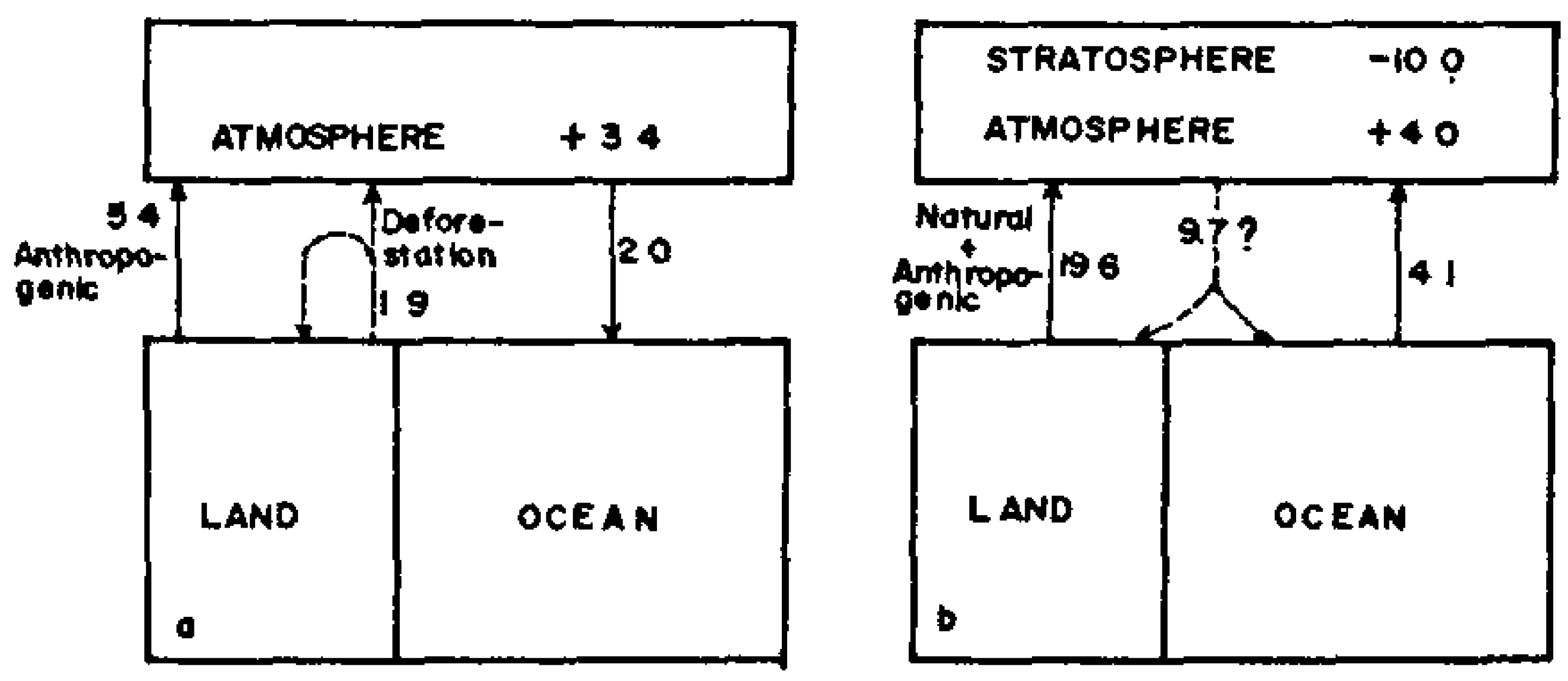


Figure 1. Global budgets for *a*, anthropogenic component (only) of CO_2; and *b*, human-influenced total N_2O. CO_2 figures are in Gt C yr^{-1} (10^{15} g C yr^{-1}) and those of N_2O are in Mt N yr^{-1} (10^{12} g N yr^{-1}).

biomass burning contribute[7] 0.5 and 0.3 Mt N yr^{-1}, respectively, wherein nylon production results in an emission[8] of 0.42 Mt N yr^{-1}. We evaluated the fluxes from coastal wetlands and marshes to be 0.1 Mt N yr^{-1} based on the data of de Angelis and Gordon[9]. The upwelling zones gives a flux[10] of 1.0 Mt N yr^{-1} while the open ocean gives at least 3.0 Mt N yr^{-1}, which is closer to that given by Yoshinari[5], though the values in the literature vary over a wide range (1–44.5 Mt N yr^{-1}). The only known sink for N_2O is its photolytic decomposition in the stratosphere (Figure 1 *b*). After accounting for its stratospheric loss and atmospheric accumulation, we find that about 9.7 Mt N yr^{-1} is not balanced (Figure 1 *b*). This reveals that either the fluxes, especially from land, are overestimated or there could be an unknown sink, as in the case of carbon, but which is unlikely.

The unique North Indian Ocean

The presence of the Asian landmass, which bounds the Indian Ocean at relatively low latitudes, makes the North Indian Ocean geographically distinct. The Indian peninsula bifurcates the North Indian Ocean into two hydrographically and climatologically different water bodies – the Arabian Sea and the Bay of Bengal. The Arabia Sea occupies an area of 6.225×10^6 km^2 while the Bay of Bengal covers 4.087×10^6 km^2, excluding the Laccadive and Andaman seas. Seven major rivers flow into the Bay of Bengal (Brahmaputra, Ganges, Irrawady, Godavari, Mahanadi, Krishna and Kaveri) whereas three pour into the Arabian Sea (Indus, Narmada and Tapti). These rivers carry 1625×10^9 and 301×10^9 m^3 yr^{-1} of fresh water and 1387×10^6 and 195×10^6 tons yr^{-1} of suspended solids, respectively, into the Bay of Bengal and the Arabian Sea[11]. In addition to the smaller run-off, excess evaporation in the Arabian Sea leads to a negative water balance[12].

The North Indian Ocean is among the more productive parts of the oceans with a surface production (upper 1 m layer) amounting to 112 Mt C yr^{-1} (ref. 13). The productivity is particularly high in the Gulf of Oman and off the coasts of Arabia, Somalia and Southwest India in the Arabian Sea and off the Southeast Indian Coast, Visakhapatnam, Sri Lanka and Burmese coasts in the Bay of Bengal. An anomalous feature of the oceanography of the Indian Ocean is that the zones of intense upwelling occur not along the eastern boundary, as happens in the Pacific and the Atlantic Oceans, but in the northwestern parts off the Somali and the Arabia coasts. Consequently, the column productivity in the Arabian Sea is much higher compared to that in the Bay of Bengal. The high productivity causes intense oxygen demand in the subsurface layers. Due to this, the water column in the Arabian Sea experiences severe oxygen depletion, resulting in the onset of reducing conditions, thus making the North Indian Ocean one of the most important denitrification sites[14–18] in the world.

Carbon dioxide in the North Indian Ocean

A higher rate of biological production in the Arabian Sea compared to that in the Bay of Bengal coupled with the different hydrographies of the two regions causes vast differences in the biogeochemical cycling in subsurface waters. Although the entire North Indian Ocean experiences a severe oxygen depletion at mid-depths, the oxygen minimum layer is not only much more thicker in the Arabian Sea but is also far more intense. Consequently, while the Arabian Sea experiences denitrification within a large volume of intermediate waters, the Bay of Bengal is not an active water column denitrification site[18]. Denitrification is the most intense in the northeastern and central parts of the Arabian Sea. An intermediate particle maximum (as inferred from the vertical profiles of the beam attenuation coefficient,

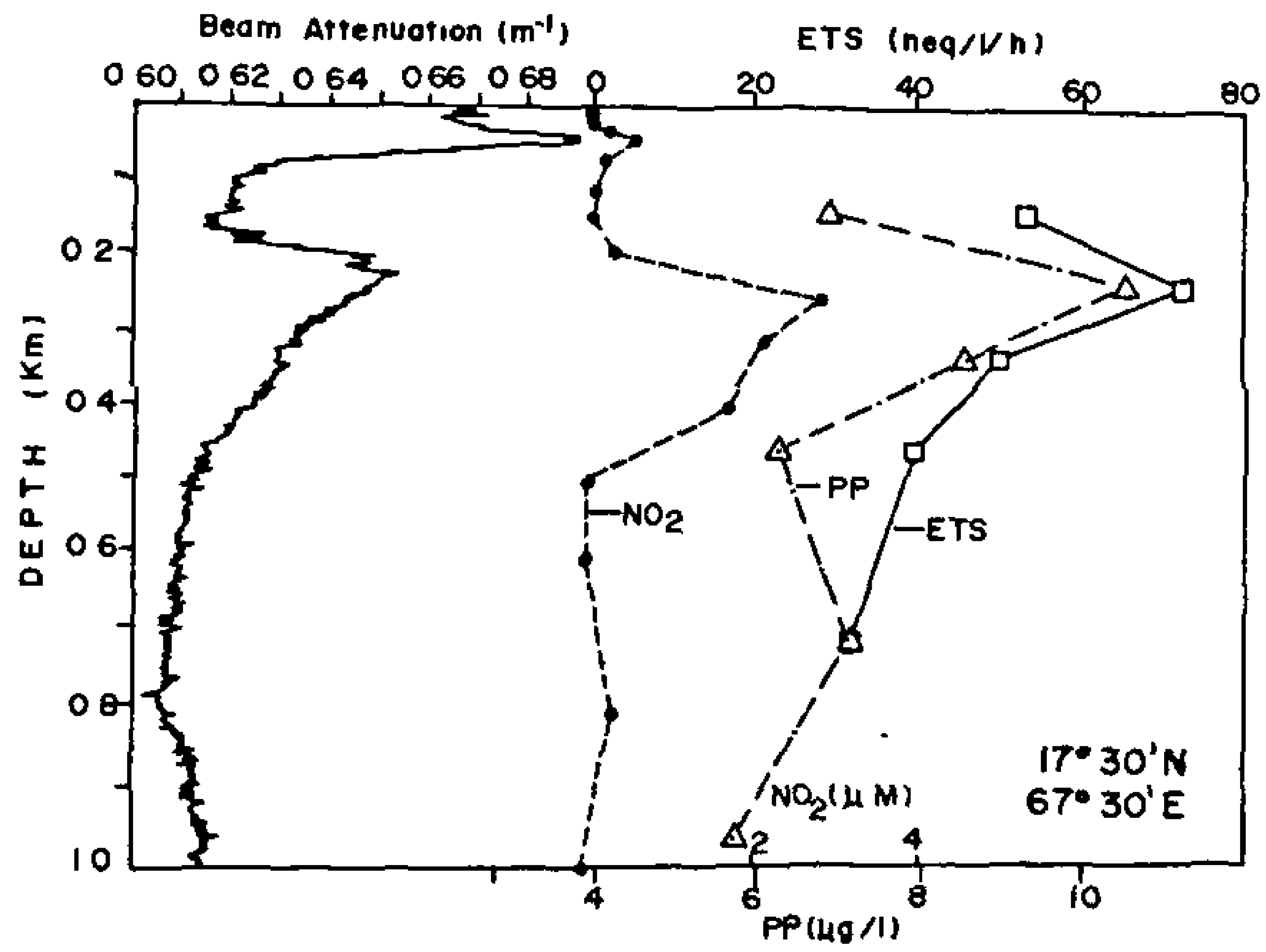


Figure 2 Profiles of beam attenuation coefficient (BAC), nitrite (NO_2^-), particulate protein (PP) and electron transport system (ETS) activities at a station in the central Arabian Sea

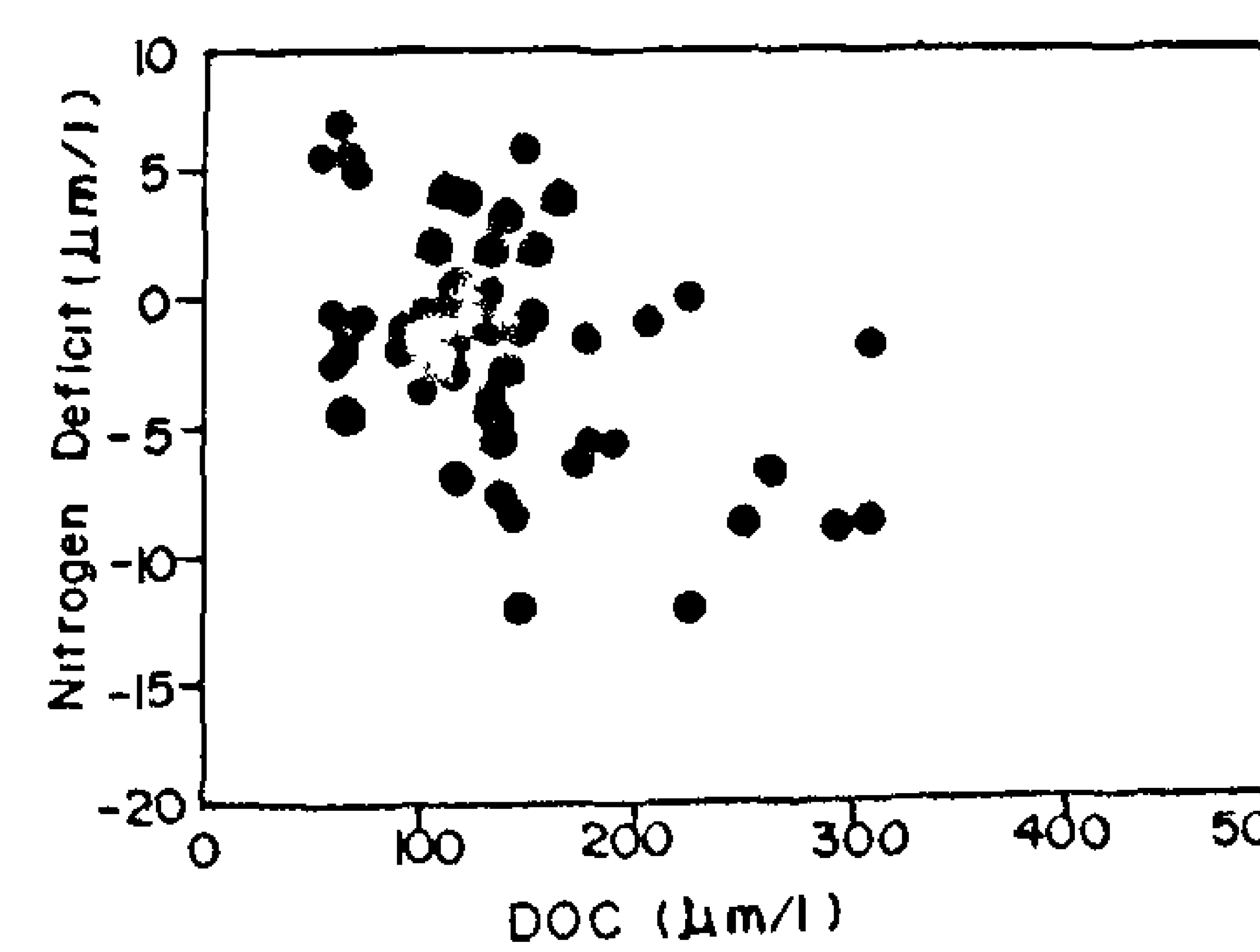


Figure 3. Relation between dissolved organic carbon (DOC) and nitrate deficit in the Arabian Sea

BAC) has been found[19] to be associated with denitrification in the Arabian sea; particulate protein (PP) and activity of the respiratory electron transport system (ETS) also showed maxima (Figure 2; data collected during February 1992 on FORV Sagar Sampada Cruise 98) within the denitrifying layer. The raining particulate organic carbon from the overlying waters seems to be insufficient to support the measured metabolic rates, thus underscoring the role of organic carbon supplied through lateral processes in fuelling subsurface respiration within the oligotrophic central regions of the Arabian Sea[19]. This view is augmented by the observed negative relation[20] between DOC and inorganic nitrate deficits (Figure 3). The DOC levels are lower in the north than in southern Arabian Sea probably owing to the faster utilization and turnover of this form of carbon. Consequently, the total carbon dioxide (TCO_2) is also found to be inversely related to the DOC in the Arabian Sea[20].

In the subsurface layers the TCO_2 is higher in the North than in the South Arabian Sea because of the increased respiration rates in the northern region and also due to the aging of waters as they move northward. In the Bay of Bengal, on the other hand, there occur negligible north–south gradients in TCO_2 and O_2, presumably due to a much lower rate of organic decomposition within the water column from a combination of lower biological productivity and rapid settlement of organic matter through the water column, consequent to its incorporation into rapidly sinking terrigenous material. The increase in TCO_2 with depth is due to the decomposition of organic and inorganic materials. Surprisingly, in spite of the differences in productivity between the Arabian Sea and the Bay of Bengal and the rapid settlement of organic matter in the latter region, the levels of TCO_2 are almost the same (Figure 4 *a*,*b*). Sinking fluxes of organic matter ranged between 2.04 and 3.59 $g\ C\ m^{-2}\ yr^{-1}$ in the Bay of Bengal[21], while they varied from 1.53 to 1.80 $g\ C\ m^{-2}\ yr^{-1}$ in the Arabian Sea[22]. These differences, due to organic matter decomposition, could be balanced by increased contribution of skeletal dissolution to TCO_2 in the Bay of Bengal deep waters. Approximately 40–50% of the TCO_2 difference (at depths >1 km) between latitudes 10° and ~20°N in the Arabian Sea is accounted for by skeletal dissolution, but this mechanism is responsible for ~85% of TCO_2 increase between latitudes 11° and 18°N in the Bay of Bengal[23]. The prevailing reducing conditions lower the pH levels in the Arabian Sea as compared to those in the Bay of Bengal. As a result, the intermediate waters in the former region are more corrosive to skeletal carbonate materials than those in the latter[23]. Interestingly, skeletal dissolution is relatively more in the north and eastern parts than in the south and western regions of the Arabian Sea[24].

The pH within the oxygen minimum zone is generally lower than in other layers and hence the carbonate equilibrium tends to shift relatively more towards the formation of carbonic acid. This increases the partial pressure of CO_2 (pCO_2) in this zone, although the TCO_2 concentrations are higher in the deep and bottom waters than in the oxygen-minimum zones (Figure 5 *a*,*b*). As the pH is considerably lower in the Arabian Sea than in the Bay of Bengal, the computed pCO_2, based on pH and TCO_2, is relatively higher in the former region[23]. A maximum pCO_2 of 1200 µatm occurs in the oxygen-minimum zone of the central Arabian Sea while it is 1100 µatm in the central Bay of Bengal. The pCO_2 is higher by about 100 µatm at any depth in the Arabian Sea than in the Bay of Bengal.

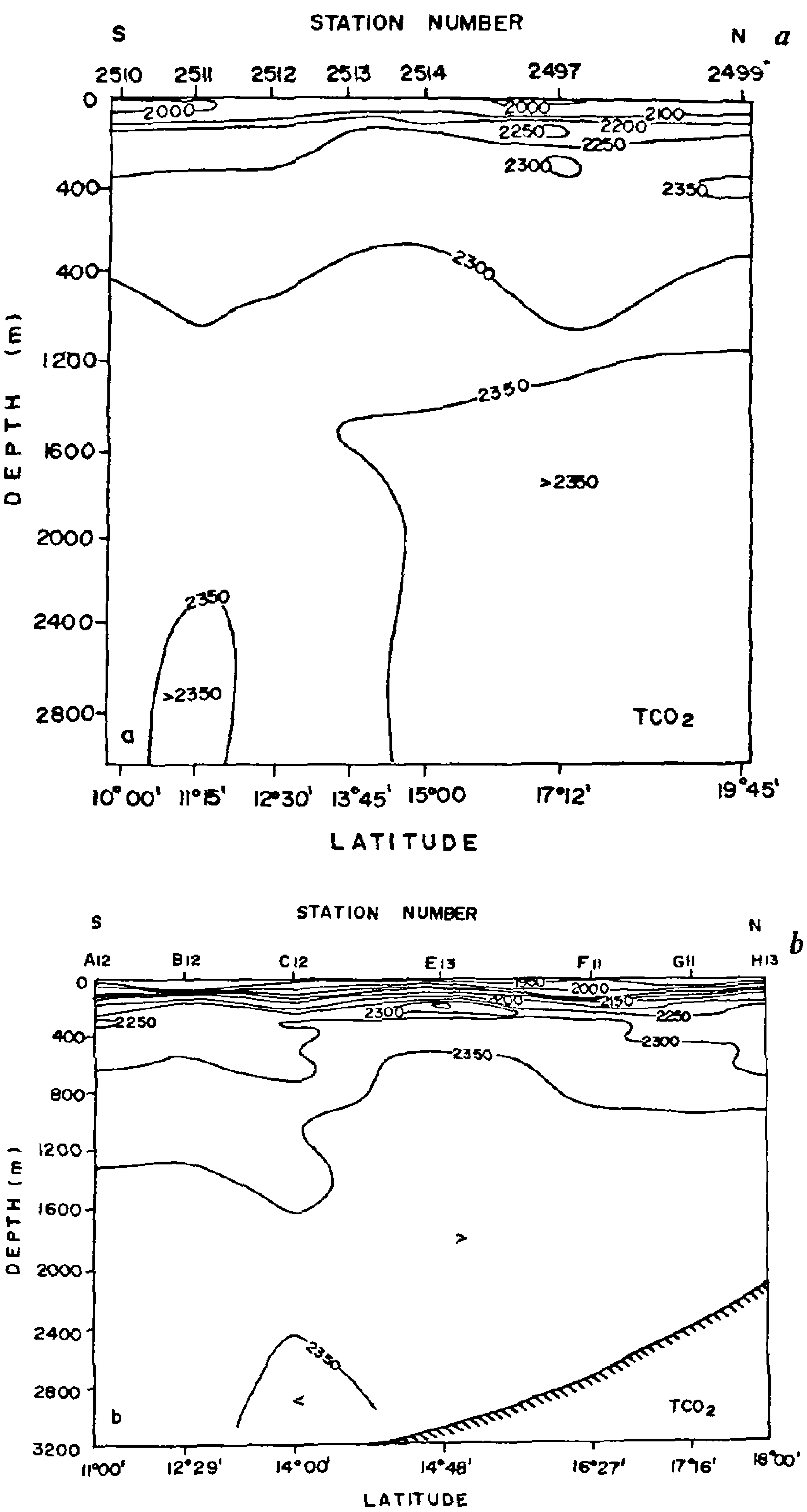


Figure 4. Distribution of total CO_2 (µM) in *a*, Arabian Sea; *b*, Bay of Bengal.

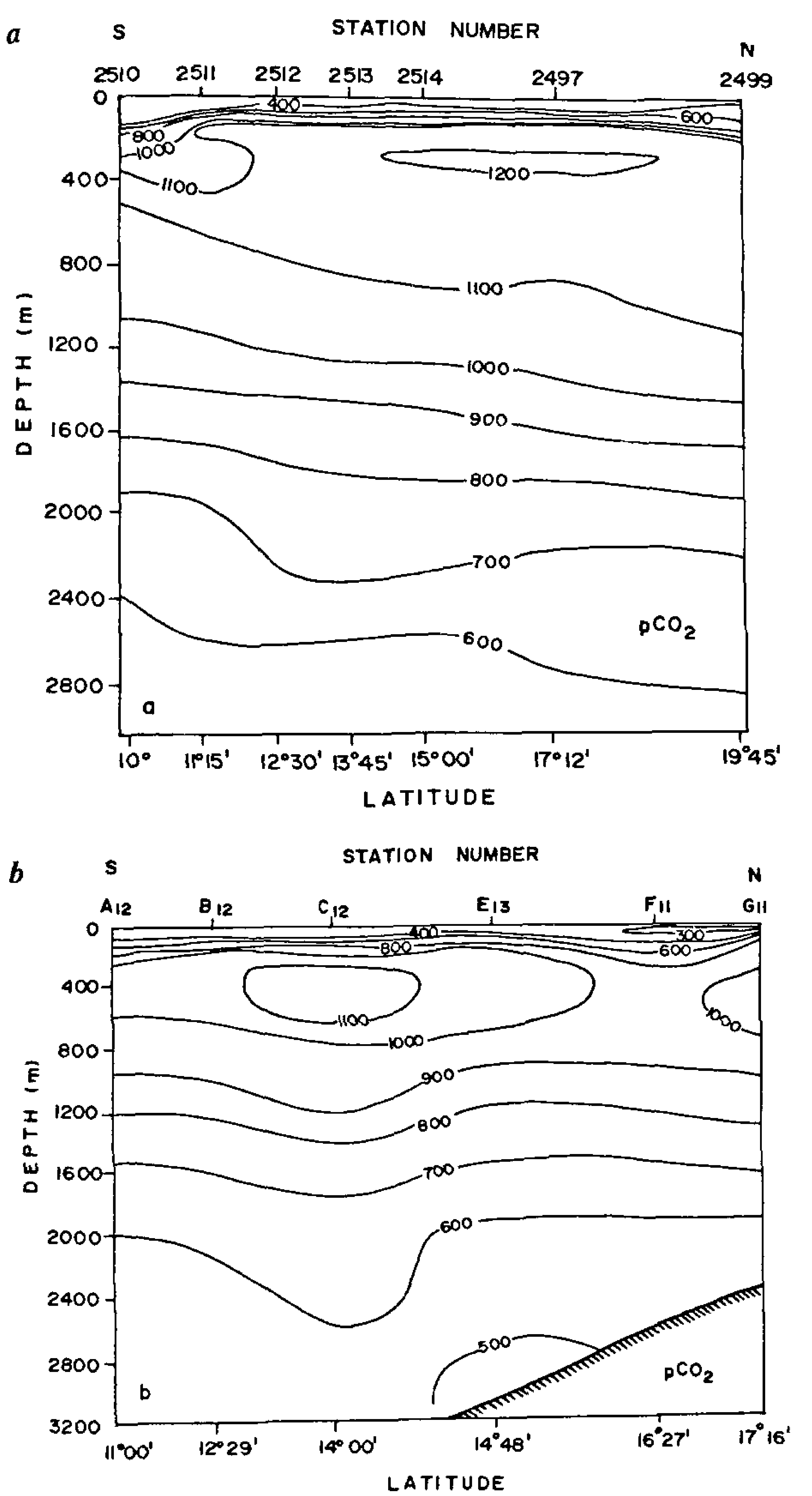


Figure 5. Distribution of pCO_2 (µatm) in *a*, The Arabian Sea; *b*, Bay of Bengal.

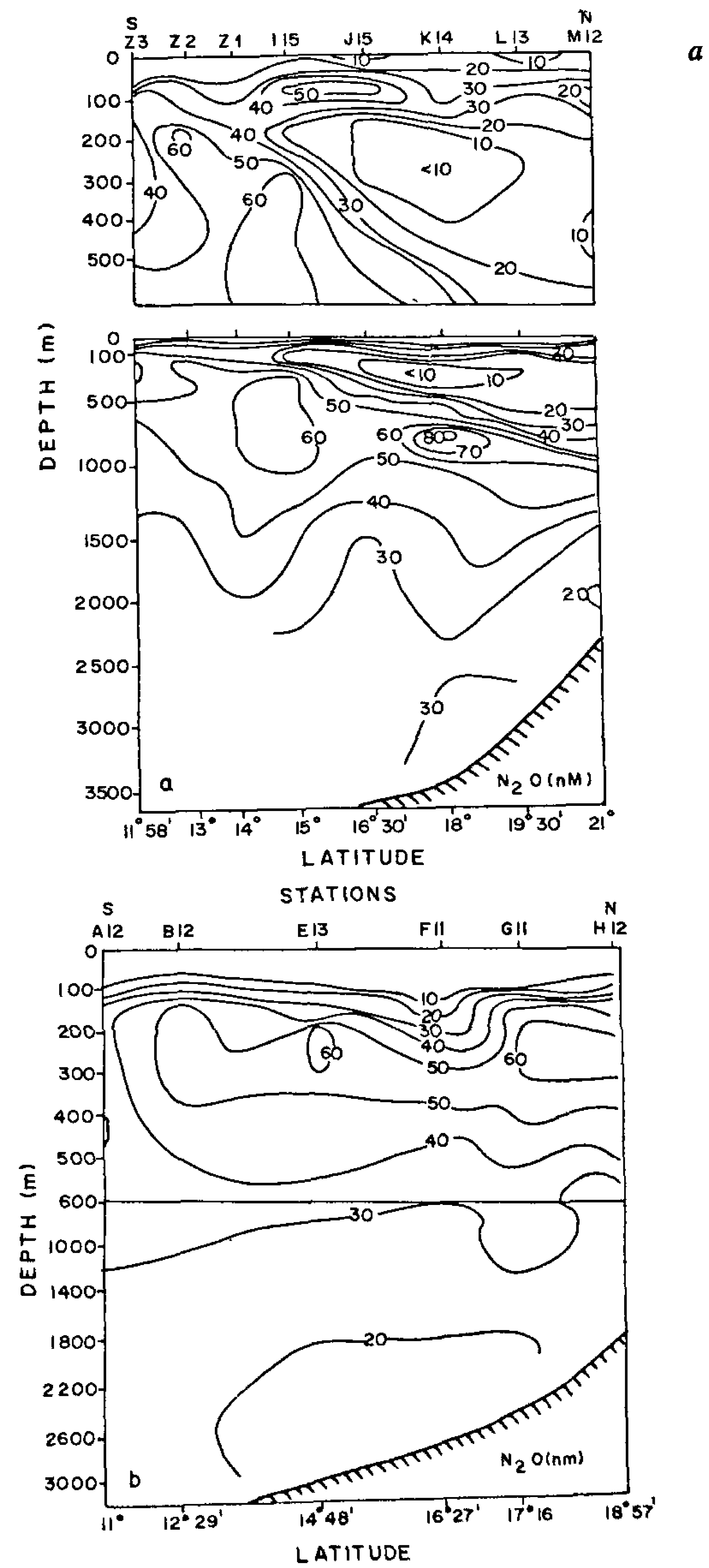


Figure 6. Nitrous oxide (nM) distribution in. *a*, The Arabian Sea, *b*, Bay of Bengal

Nitrous oxide in the North Indian Ocean

Vertical profiles of N_2O generally exhibit maxima within the oxygen-minimum zones. The most significant point revealed by Figure 6 (data from ref. 25) is the occurrence of double maxima in N_2O with a minimum in the intensely reducing intermediate waters of the north-eastern Arabian Sea[25,26]. Outside the denitrification zone, N_2O exhibits a single peak coinciding with the oxygen minimum[25,27]. Consumption of N_2O within the strongly reducing zones appears to produce the minimum in N_2O within the denitrifying zone of the north-eastern Arabian Sea, while the maxima in N_2O occur at the boundaries of this zone, particularly at the lower boundary with concentrations as high as 80 nM (Figure 6 *a*). The N_2O concentrations increase in the northward direction (Figure 6 *b*) in the Bay of Bengal, with a maximum of 80 nM (occurring to the west of the transect shown in the figure). Maximum in the north corresponds to oxygen minimum. Although very low levels of oxygen are observed in subsurface layers of the northernmost Bay of Bengal, the absence of a secondary nitrite shows that denitrification may not occur within the water column in this region. The occurrence of strong sources and sinks of N_2O in close proximity to each other is expected to lead to a very rapid turnover of N_2O in this region, which may have important implications for the residence time and isotopic composition of oceanic N_2O. The relations between apparent N_2O production and the apparent oxygen utilization are positively linear in different depth ranges in the Arabian Sea[25] and the Bay of Bengal[27]. The slopes estimated for the Arabian Sea are higher than those for the other oceanic regions, implying that the rate of N_2O production in this region is much higher[25]. Based on the horizontal gradients and that expected from oxygen utilized, significant quantities of N_2O are expected to be consumed within the sediments[25,27].

The enhanced production of N_2O in the subsurface layers leads to large vertical gradients within the upper thermocline and the consequent large fluxes into the surface layers through eddy diffusion. The Arabian Sea surface waters are relatively more supersaturated (average of 186%; refs 25, 26) as compared to those in the Bay of Bengal (125%; ref. 27). This higher saturation is related to higher vertical diffusion coefficients in the Arabian Sea (0.55 $cm^2 s^{-1}$; ref. 25) than in the Bay of Bengal (0.16 $cm^2 s^{-1}$; ref. 27), in the thermocline region. The suppressed vertical mixing in the Bay of Bengal is caused by strong thermohaline stratification caused by river run-off.

Sea-to-air fluxes in the North Indian Ocean

The differences between the concentrations observed at sea surface and those expected from the solubility calculations, based on the abundance of these gases in the atmosphere, determine the magnitude and direction of gas fluxes between the atmosphere and the sea. The abundance of N_2O and pCO_2 in surface layers will be governed by the gradients in these properties below the surface mixed layer and the rate of vertical mixing. The levels of pCO_2 (Figure 5) and N_2O (Figure 6) are higher within the oxygen-minimum zones in the North Indian Ocean sustaining large upward fluxes of these gases across the thermocline.

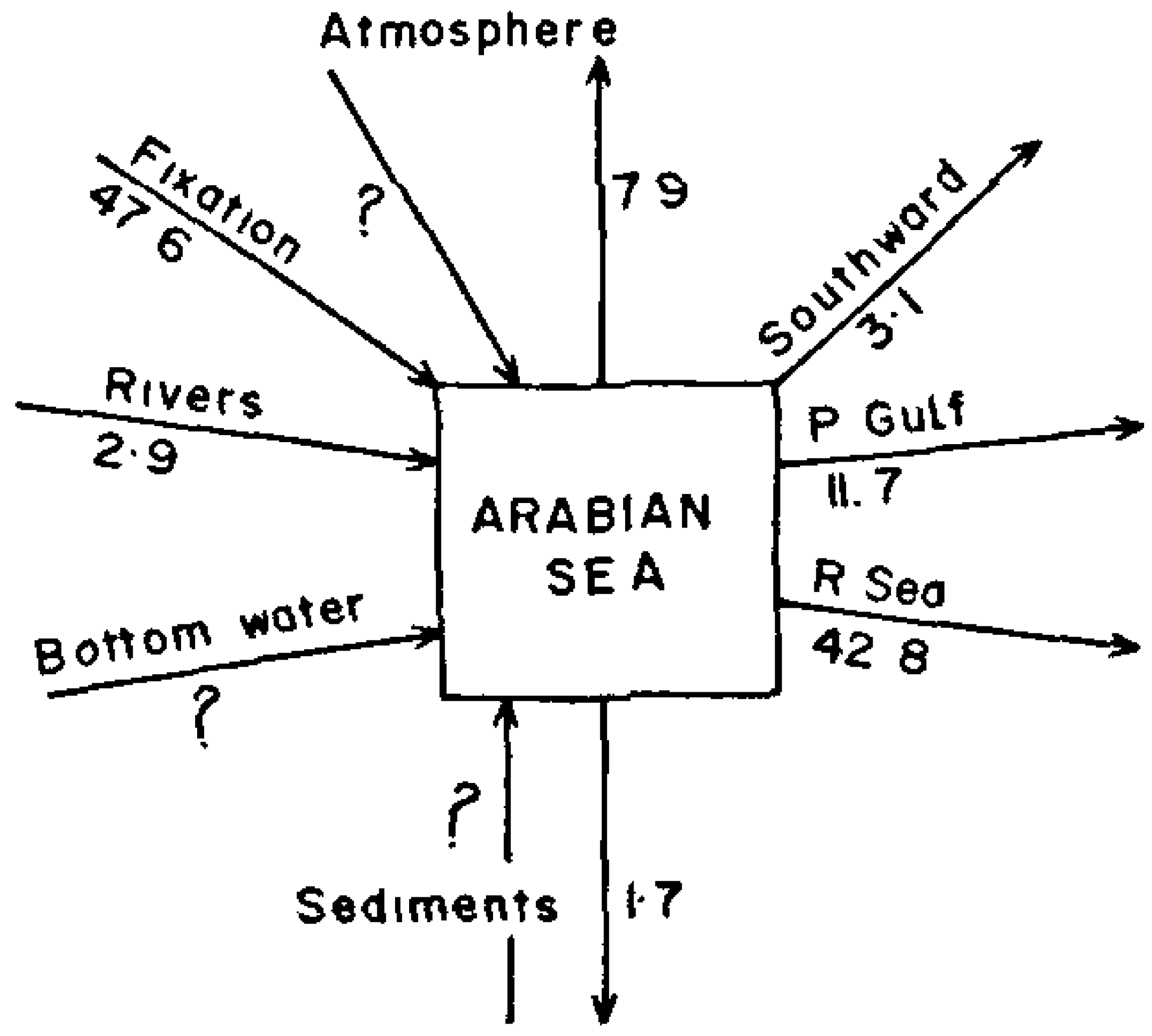
The fraction of CO_2 in air, in equilibrium with surface waters, over the Arabian Sea is calculated to be >0.6, which increases northward[24]. This also indicates that the Arabian Sea acts as a source of CO_2 to the atmosphere, in accordance with the earlier predictions[28–30]. The higher pCO_2 gradient between the deep and surface layers in the Arabian Sea than that in the Bay of Bengal (Figure 5) results in higher average exchange rates in the former region (2.0 mmol $m^{-2} d^{-1}$) than in the latter (0.17 mmol $m^{-2} d^{-1}$); here an atmospheric CO_2 of 350 µatm was used. Within the Arabian Sea the fluxes are higher in the north than in the south. The overall atmospheric fluxes of CO_2 are much larger from the Arabian Sea (55 Mt C yr^{-1}) compared to those from the Bay of Bengal (3 Mt C yr^{-1}). This difference arises from a combination of lower pCO_2 gradient, lesser vertical diffusion coefficients and smaller area of the Bay of Bengal.

A high degree of supersaturation of N_2O in the surface waters of the North Indian Ocean results in significant evasion of this gas to the atmosphere. As in the case of CO_2, the N_2O in surface layers is also controlled by upward diffusion from the subsurface layers. The average emission rates for this gas are 4.46 µmol $m^{-2} d^{-1}$ in the Arabian Sea and 0.65 µmol $m^{-2} d^{-1}$ in the Bay of Bengal. These rates amount to N_2O fluxes of 0.28 and 0.03 Mt N yr^{-1} from the Arabian Sea and the Bay of Bengal, respectively[25,27]. Hence, relatively large amounts of these greenhouse gases are emitted from the former region than from the latter.

Budgets for CO_2 and N_2O in the North Indian Ocean

In order to understand the biogeochemical cycling of an element it is essential to quantify its fluxes between various major reservoirs as well as between various compartments within a reservoir. The situation in the

a



b

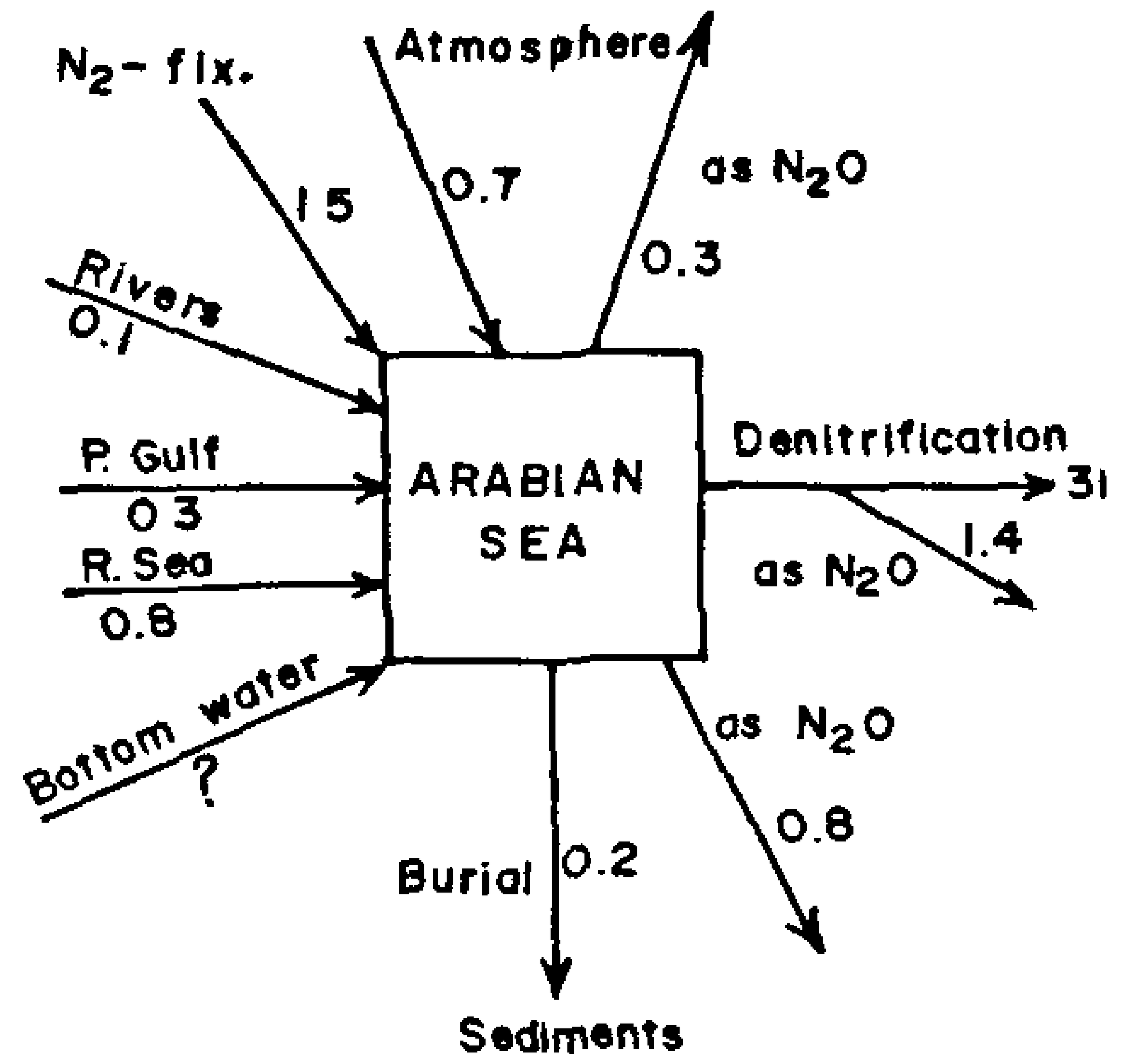


Figure 7. Budgets for *a*, carbon, *b*, nitrogen (including N_2O) in the Arabian Sea

Indian Ocean is complicated by the presence of marginal water bodies that continuously exchange water and solutes with the Arabian Sea and with river run-off that brings in enormous amounts of inorganic and organic substances into the Bay of Bengal. Recently, attempts have been made to quantify the fluxes between various reservoirs in the Arabian Sea[30,31]. Figure 7 depicts the estimated net carbon and nitrogen fluxes into and out of the Arabian Sea. The flow of carbon into the Arabian Sea from the rivers is the only estimated external input (using an annual discharge rate of 238 km^3 and an average HCO_3^- concentration[32] of 12 mg C l^{-1}), which is close to that (2.3 Mt C yr^{-1}) evaluated earlier[30]. The unknowns are its influx from the atmosphere, inflow from the south of equator and upward diffusion of regenerated CO_2 from the sediments. The biologically fixed carbon transported to subsurface Arabian Sea layers, through sinking of particulate organic material, is estimated[31,33] to be about 47.6 Mt C yr^{-1}. The estimated fluxes (Figure 7) reveal that the Arabian Sea serves as a source of CO_2 to the atmosphere and the surrounding bodies, the Persian Gulf and the Red Sea. Carbon is also supplied to the underlying sediments and to some extent to the South Indian Ocean. These estimates indicate that the Arabian Sea is constrained by a CO_2 deficit of ~88 Mt C yr^{-1}. In order to maintain the CO_2 in the Arabian Sea at steady state, this amount must be supplied from the south, through the inflowing bottom water, and from the atmosphere.

As our state of understanding of the processes regulating N_2O in the Arabian Sea is still rudimentary, it is difficult to work out the budget for this gas. Figure 7 shows the net fluxes of N_2O together with those of nitrogen[25,30,31,33]. In contrast to their negative contribution to CO_2, the Persian Gulf and the Red Sea act as net sources of nitrogen to the Arabian Sea. The losses of nitrous oxide from the Arabian Sea amount to 2.5 Mt N yr^{-1}. Hence, the Arabian Sea should produce an equal amount annually.

The estimated carbon fluxes into the confluence zones of the rivers Ganges and Brahmaputra are 14.6 Mt C yr^{-1} and 17.1 Mt C yr^{-1}, respectively[34]. The carbon input through dissolved and particulate organic forms from the Ganges amounts[34,35] to 1.5–2.0 Mt C yr^{-1}. The Bay of Bengal serves as a mild source of atmospheric N_2O and CO_2 during the southwest premonsoon[23,27] but as a sink for CO_2 during the northeast monsoon[36].

Contribution of the North Indian Ocean to global air–sea fluxes

The contribution of the North Indian Ocean to the global sea-to-air flux[2] of CO_2 of 90 Gt C yr^{-1} appears to be small (0.06 Gt C yr^{-1}). However, it amounts to about 5% of the efflux from global equatorial oceans. On the contrary, the N_2O emission from this region is globally significant as it is about 8% of the estimated atmospheric input from the oceans. However, the region under study is significantly influenced by the highly variable monsoonal winds and intermittent cyclones. The transfer velocities of gases across the air–sea interface increases with increase in wind velocity. These transfer velocities have been computed to be enhanced seven times during the monsoon season compared to those during the non-monsoon seasons[37]. However, all the estimates made so far, including those for global fluxes, are derived from observations made during the calm seasons and do not consider the stability of sea surface as well as contributions from bubbles, and, hence, should be considered as underestimates. Further, the Arabian Sea experiences strong upwelling seasonally associated with the monsoons. Hence, the dynamics of these gases need to be studied in detail in order to make more accurate estimates of sea-to-air fluxes from this most dynamic region of the world oceans.

1 IGBP, Report No 1, ICSU, Stockholm, 1986.
2 Rodhe, H , *Science*, 1990, **248**. 1217–1219
3. Siegenthaler, U and Sarmiento, J L., *Nature*, 1993, **365**, 119–125.
4 Pratt, P. F., Barber, J. C., Corrin, M. L., Goering, J , Hauck, R. D , Johnston, H. S., Klute, A , Knowless, R., Nelson, D W , Pickett, R C. and Stephens, E. R , *Clim Change*, 1977, **1**, 109–135.
5. Yoshinari, T , in *Denitrification in Soil and Sediment* (eds Revsbech, N P and Sorensen, J), Plenum Press, New York, 1990, pp 129–150
6 Bowden, W B and Bermann, F. H., *Science*, 1986, **233**, 867–869.
7 Codispoti, L. A , Elkins, J W , Yoshinari, T , Friederich, G E., Sakamoto, C. M and Packard, T. T , in *Oceanography of the Indian Ocean* (ed. Desai, B N), Oxford & IBH, New Delhi, 1992, pp. 271–284.
8 Thiemens, M. H and Trogler, W C., *Science*, 1991, **251**, 932–934
9. de Angelis, M. A. and Gordon, L. I , *Estuarine Coastal Shelf Sci* , 1985, **20**, 375–386
10 Codispoti, L. A and Christensen, J P., *Mar Chem* , 1985, **16**, 277–300.
11. Subramanian, V , *Curr Sci* , 1993, **64**, 928–930
12. Ramanathan, K R. and Pisharoty, P R , in *World Water Balance*, IASH–UNESCO–WMO, Gentbrugge, 1972, vol I, pp. 39–41.
13 Qasim, S Z., *Indian J Mar. Sci.*, 1977, **6**, 122–137
14 Sen Gupta, R , Rajagopal, M D and Qasim, S. Z., *Indian J Mar Sci* , 1976, **5**, 201–211.
15 Sen Gupta, R. and Naqvi, S. W. A , *Deep-Sea Res* , 1984, **31**, 671–706
16. Naqvi, S. W. A., *J. Mar. Res.*, 1987, **45**, 1049–1072.
17. Naqvi, S. W. A , *Oceanol Acta*, 1991, **14**, 281–290.
18. Rao, C. K., Naqvi, S W A , Kumar, M D , Varaprasad, S J D , Jayakumar, D A , George, M D. and Singbal, S Y S , *Mar Chem.*, 1994, **47**, 279–290.
19 Naqvi, S. W. A., Kumar, M D , Narvekar, P V , de Souza, S N., George, M. D and D'Silva, C., *J Geophys Res* , 1993, **98**, 16469–16479
20 Kumar, M D , Rajendran, A., Somasundar, K , Haake, B , Jenisch, A , Shuo, Z , Ittekkot, V. and Desai, B N , *Mar Chem* , 1990, **31**, 299–316.
21. Ittekkot, V , Nair, R R , Honjo, S , Ramaswamy, V , Bartsch, M , Manganini, S and Desai, B N , *Nature*, **351**, 385–387

22 Nair, R R, Ittekkot, V, Manganini, S, Ramaswamy, V., Haake, B, Degens, E T, Desai, B N and Honjo, S, *Nature*, 1989, 338, 749–751.
23 George, M D, Kumar, M D, Naqvi, S. W A, Banerjce, S, Narvekar, P V, de Souza, S. N and Jayakumar, D A., *Mar. Chem*, 1994, 47, 243–254.
24 Kumar, M D, Rajendran, A, Somasundar, K, Ittekkot, V. and Desai, B N, in *Oceanography of the Indian Ocean* (ed. Desai, B N). Oxford & IBH, New Delhi, 1992, pp 313–325.
25 Naqvi, S W A and Noronha, R. J, *Deep-Sea Res.*, 1991, 38, 871–890
26 Law, C S and Owens, N. J P., *Nature*, 1990, 346, 826–828.
27 Naqvi, S W. A, Jayakumar, D A, Nair, M., Kumar, M. D. and George, M D, *Mar Chem*, 1994, 47, 279–290
28 Takahashi, T, *Oceanus*, 1989, 32, 22–29
29 Tans, P P, Fung, I Y and Takahashi, T, *Science*, 1990, 247, 1431–1438
30 Somasundar, K Rajendran, A, Kumar, M. D and Sen Gupta, R, *Mar Chem*, 1990, 30, 363–377
31 Naqvi, S W A, Sen Gupta, R and Kumar, M. D, in *Interactions between Global Climate Subsystems, The Legacy of Hann*, Geophysical Monograph No. 75, IUGG Volume 15, American Geophysical Union, 1992, pp 85–92.
32. Pande, K., Sarin, M. M, Trivedi, J R, Krishnaswami, S and Sharma K. K, *Chem Geol*, 116, 245–259.
33 Naqvi, S. W. A., Noronha, R J., Shailaja, M S, Somasundar, K. and Sen Gupta, R., in *Oceanography of the Indian Ocean* (ed. Desai, B. N), Oxford & IBH, New Delhi, 1992, pp 285–311
34. Safiullah, S., Mofizuddin, M., Ali, S. M. I and Kabir, S. E., in *Transport of Carbon and Minerals in Major World Rivers*, SCOPE/UNEP Sonderband Heft 64, 1987, Part 4, pp 435–442.
35. Kumar, M. D., George, M. D. and Sen Gupta, R, in *Oceanography of the Indian Ocean* (ed. Desai, B. N), Oxford & IBH, New Delhi, 1992, pp. 347–358
36. Kumar, M D, Naqvi, S. W. A, George, M. D and Jayakumar, D. A., submitted to *J Geophys. Res.*
37. Etcheto, J, Boutin, J. and Merlivat, M., *Tellus*, 1991, 43, 247–255

ACKNOWLEDGEMENTS. We thank the Director, NIO, Dr A. P. Mitra and Dr R. Sen Gupta for their encouragement and support.

Received 2 September 1994, revised accepted 8 September 1995

Internal waves – A novel measurement technique

Rao Tatavarti, P. N. Ananth, K. Rajasree*, V. Vidyalal*, P. Radhakrishnan*, V. P. N. Nampoori* and C. P. G. Vallabhan*

N P O L., Defence Research and Development Organization, Thrikkakara, Cochin 682 021, India
*Laser Division, International School of Photonics, Cochin University of Science and Technology, Cochin 682 022, India

We present here a novel opto-electronic technique to directly measure the internal wave oscillations, created by systematically disturbing a density stratified water column with a rotating propeller in a laboratory wave tank. The technique, based on the principle of laser beam deflection (LBD), apart from being noninvasive and highly sensitive, does not have the customary constraints on the sampling frequency and the duration of data sampling, as is the case with conventional experimental procedures. The noninvasive nature of this technique has good potential in future studies of diffusion and mixing processes in different disciplines.

INTERNAL waves in the ocean are ubiquitous, being associated with wind and air pressure fluctuations, changes in ocean floor topography, wakes of moving bodies and instabilities in the water body. Studies on internal waves enable a better understanding of the various mixing processes in the ocean, which result in the redistribution of momentum, temperature (heat) and salinity, responsible for climatic changes and, nutrients responsible for biological productivity. The oceanic internal waves occupy a vast continuum of spatial and temporal scales[1]. Available data on oceanic motions suggest horizontal scales ranging from a few tens of meters to a few kilometers and temporal scales ranging from the inertial period f^{-1} (order of magnitude in days), to the Brunt Vaisala period N^{-1} (order of magnitude in minutes).

Internal wave measurements

To the best of our knowledge, only indirect eulerian field of internal waves were measured by monitoring a closely related physical parameter like temperature or current velocity. Lagrangian field measurements of internal waves involve neutrally buoyant floats that are tracked, or sensor arrays towed horizontally through water. The literature[2–6] points out the limitations of the indirect eulerian measurements, whereas the established Lagrangian techniques are constrained by the uncertainties in understanding the underlying physics[7].

The electrical conductivity of salt water in the ocean was earlier considered to provide a convenient way of