

Carbon dioxide and nitrous oxide in the North Indian Ocean

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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 health¹. 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 effect². 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 rates² 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 ($7.3 \times 10^3 \text{ Mt C yr}^{-1}$), $3.4 \times 10^3 \text{ Mt C yr}^{-1}$ is accumulating in the atmosphere whereas $2 \times 10^3 \text{ Mt C yr}^{-1}$ is being removed by the oceans³ (Figure 1 a). However, there is considerable controversy regarding the amount associated with deforestation ($1.9 \times 10^3 \text{ Mt C yr}^{-1}$), which at present is attributed to an unknown sink or unaccounted recycled carbon accumulation in soils³. 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 estimated⁴ to be about 39 Mt N yr^{-1} ; this accounts for $0.65 \times 10^3 \text{ Mt C yr}^{-1}$, 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 Yoshinari⁵ (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 ($0.03 \text{ Mt N yr}^{-1}$) from watershed regions⁶ was added in this attempt. The fossil fuel combustion and

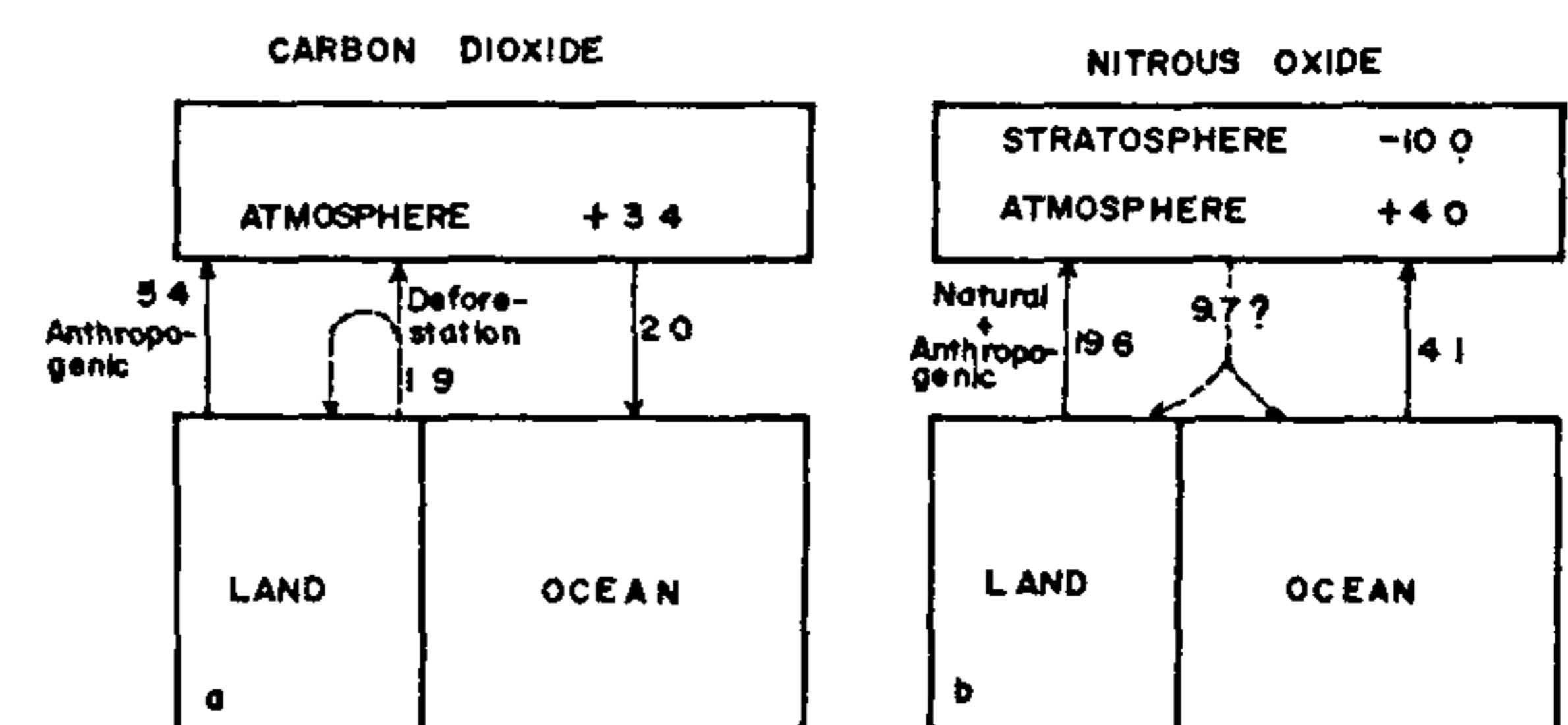


Figure 1. Global budgets for *a*, anthropogenic component (only) of CO_2 ; and *b*, human-influenced total N_2O . CO_2 figures are in Gt C yr^{-1} ($10^{15} \text{ g C yr}^{-1}$) and those of N_2O are in Mt N yr^{-1} ($10^{12} \text{ g N yr}^{-1}$).

biomass burning contribute⁷ 0.5 and 0.3 Mt N yr⁻¹, respectively, wherein nylon production results in an emission⁸ 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 Gordon⁹. The upwelling zones gives a flux¹⁰ 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 Yoshinari⁵, though the values in the literature vary over a wide range (1–44.5 Mt N yr⁻¹). The only known sink for N₂O 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 $6.225 \times 10^6 \text{ km}^2$ while the Bay of Bengal covers $4.087 \times 10^6 \text{ km}^2$, 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 $301 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ of fresh water and 1387×10^6 and $195 \times 10^6 \text{ tons yr}^{-1}$ of suspended solids, respectively, into the Bay of Bengal and the Arabian Sea¹¹. In addition to the smaller run-off, excess evaporation in the Arabian Sea leads to a negative water balance¹².

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 hydroographies 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 site¹⁸. 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,

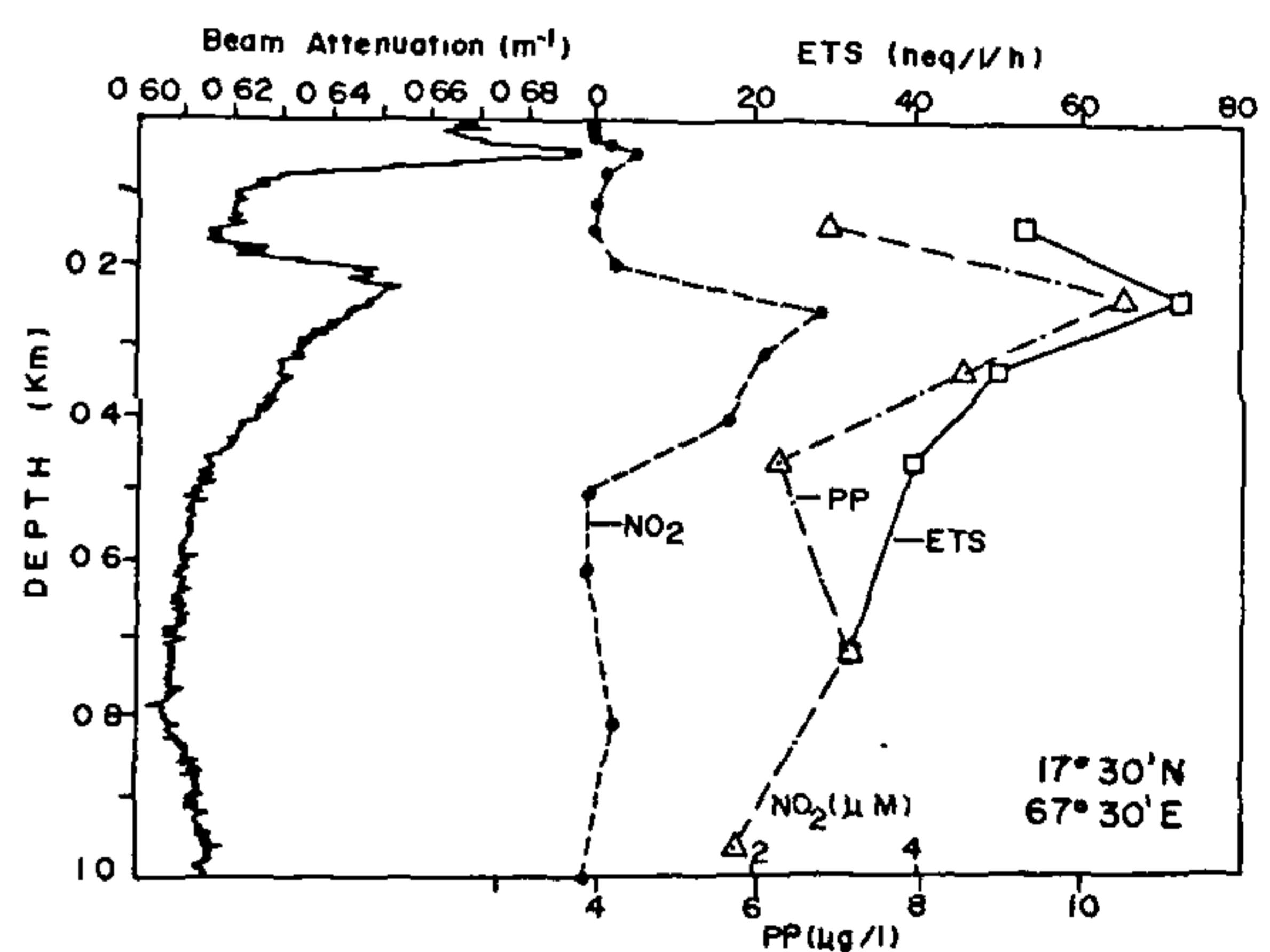


Figure 2 Profiles of beam attenuation coefficient (BAC), nitrite (NO₂), particulate protein (PP) and electron transport system (ETS) activities at a station in the central Arabian Sea

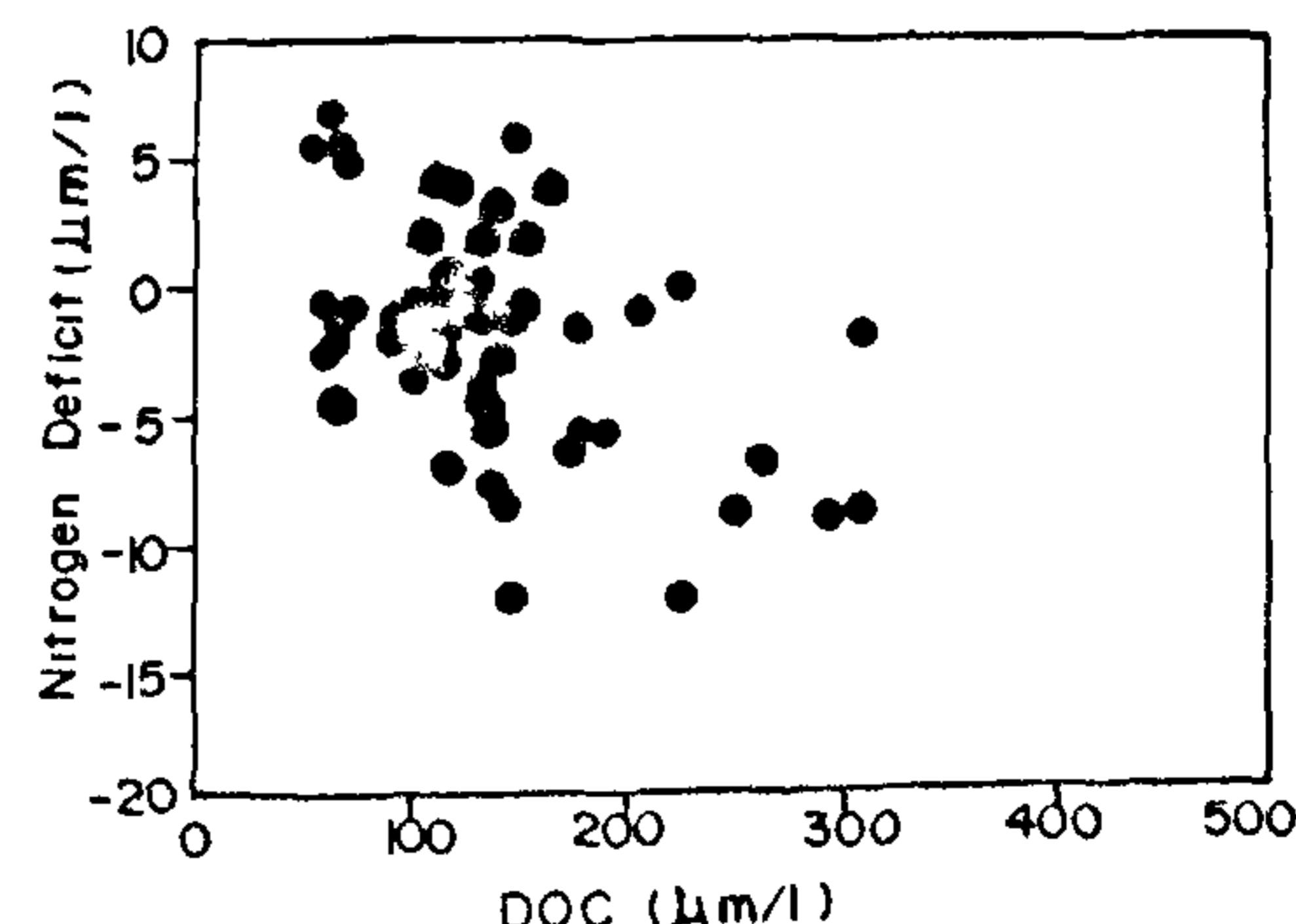


Figure 3. Relation between dissolved organic carbon (DOC) and nitrogen deficit in the Arabian Sea

BAC) has been found¹⁹ 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 Sea¹⁹. This view is augmented by the observed negative relation²⁰ 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 Sea²⁰.

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 $3.59 \text{ g C m}^{-2} \text{ yr}^{-1}$ in the Bay of Bengal²¹, while they varied from 1.53 to $1.80 \text{ g C m}^{-2} \text{ yr}^{-1}$ in the Arabian Sea²². 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 $>1 \text{ km}$) between latitudes 10° and $\sim 20^\circ\text{N}$ in the Arabian Sea is accounted for by skeletal dissolution, but this mechanism is responsible for $\sim 85\%$ of TCO_2 increase between latitudes 11° and 18°N in the Bay of Bengal²³. 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 latter²³. Interestingly, skeletal dissolution is relatively more in the north and eastern parts than in the south and western regions of the Arabian Sea²⁴.

The pH within the oxygen minimum zone is generally lower than in other layers and hence the carbonate

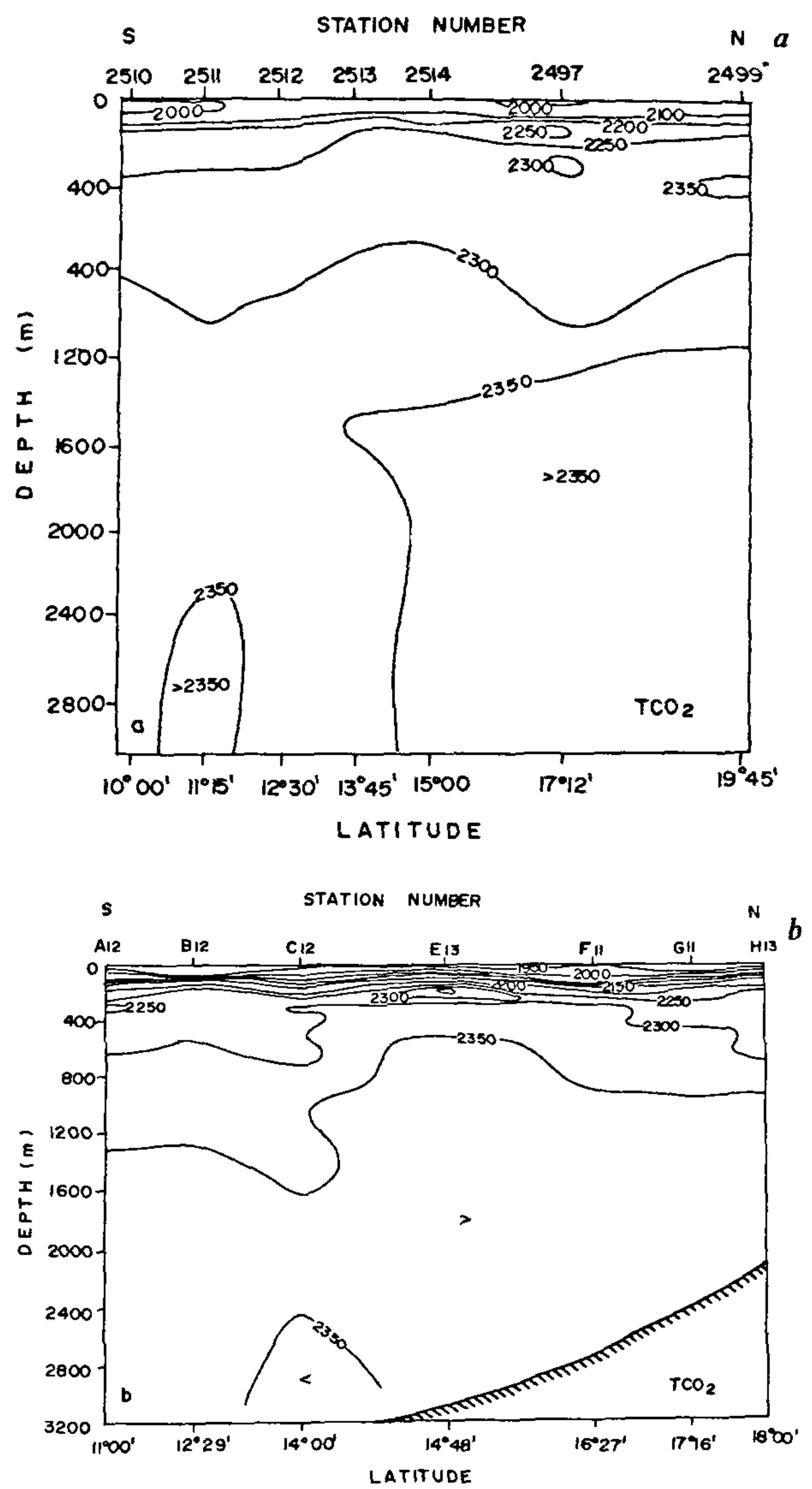


Figure 4. Distribution of total CO_2 (μM) in a, Arabian Sea; b, Bay of Bengal.

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 region²³. A maximum pCO_2 of $1200 \mu\text{atm}$ occurs in the oxygen-minimum zone of the central Arabian Sea while it is $1100 \mu\text{atm}$ in the central Bay of Bengal. The pCO_2 is higher by about $100 \mu\text{atm}$ at any depth in the Arabian Sea than in the Bay of Bengal.

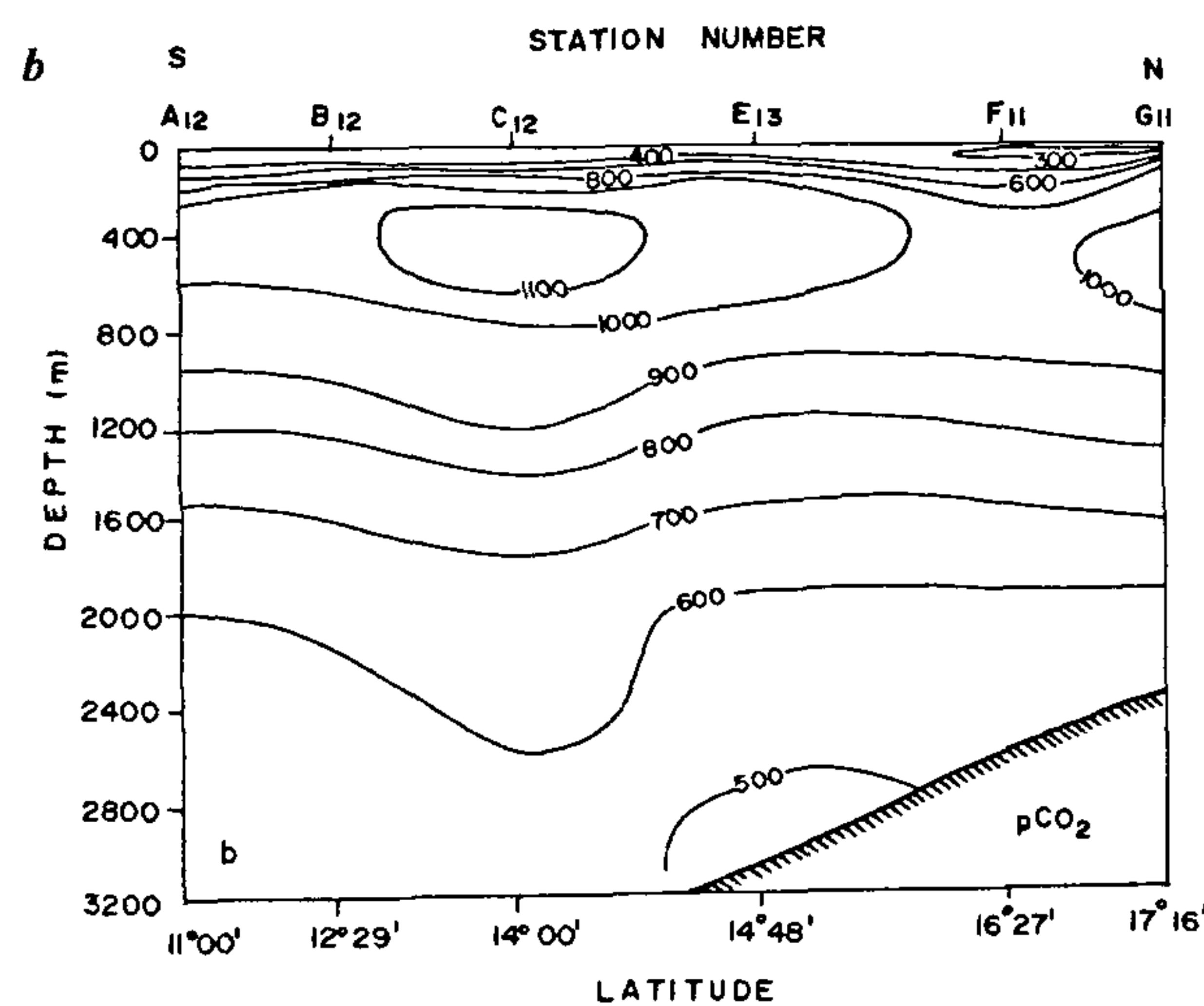
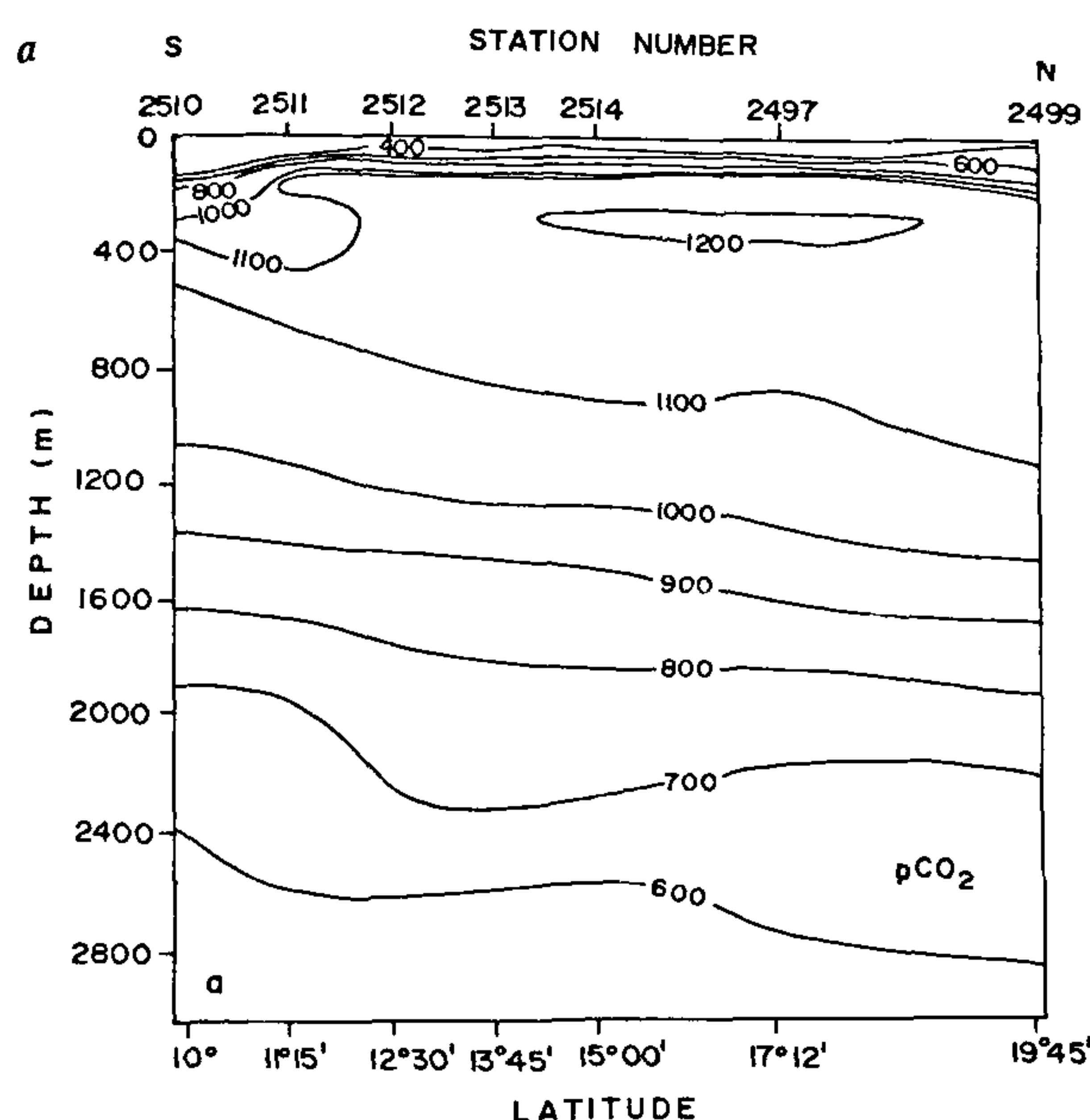


Figure 5. Distribution of $p\text{CO}_2$ (μatm) in *a*, The Arabian Sea; *b*, Bay of Bengal.

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

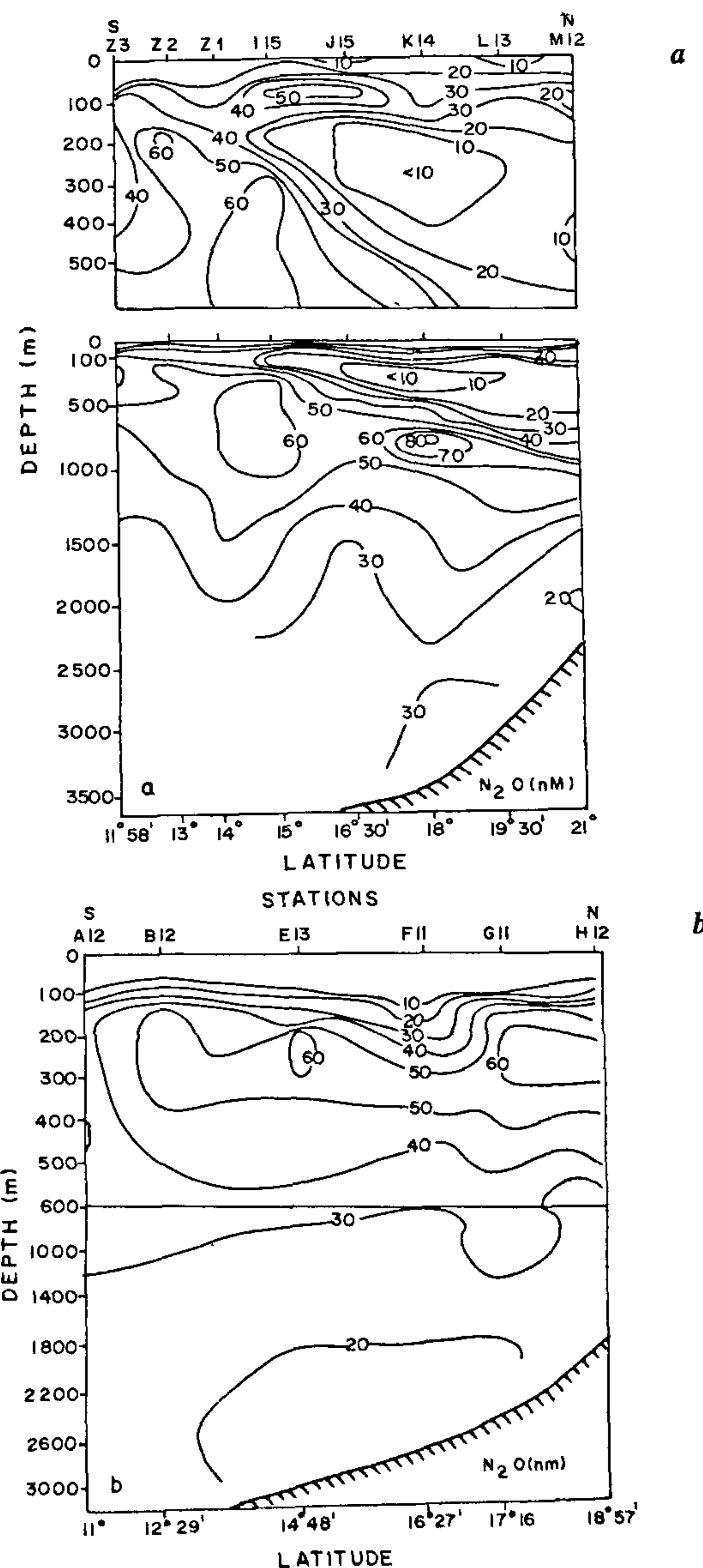


Figure 6. Nitrous oxide (nM) distribution in *a*, The Arabian Sea, *b*, Bay of Bengal.

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 Sea²⁵ and the Bay of Bengal²⁷. 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 higher²⁵. 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 ($0.55 \text{ cm}^2 \text{ s}^{-1}$; ref. 25) than in the Bay of Bengal ($0.16 \text{ cm}^2 \text{ s}^{-1}$; 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 northward²⁴. This also indicates that the Arabian Sea acts as a source of CO_2 to the atmosphere, in accordance with the earlier predictions²⁸⁻³⁰. 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 ($2.0 \text{ mmol m}^{-2} \text{ d}^{-1}$) than in the latter ($0.17 \text{ mmol m}^{-2} \text{ d}^{-1}$); here an atmospheric CO_2 of $350 \mu\text{atm}$ 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 $4.46 \mu\text{mol m}^{-2} \text{ d}^{-1}$ in the Arabian Sea and $0.65 \mu\text{mol m}^{-2} \text{ d}^{-1}$ in the Bay of Bengal. These rates amount to N_2O fluxes of 0.28 and $0.03 \text{ Mt N yr}^{-1}$ 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

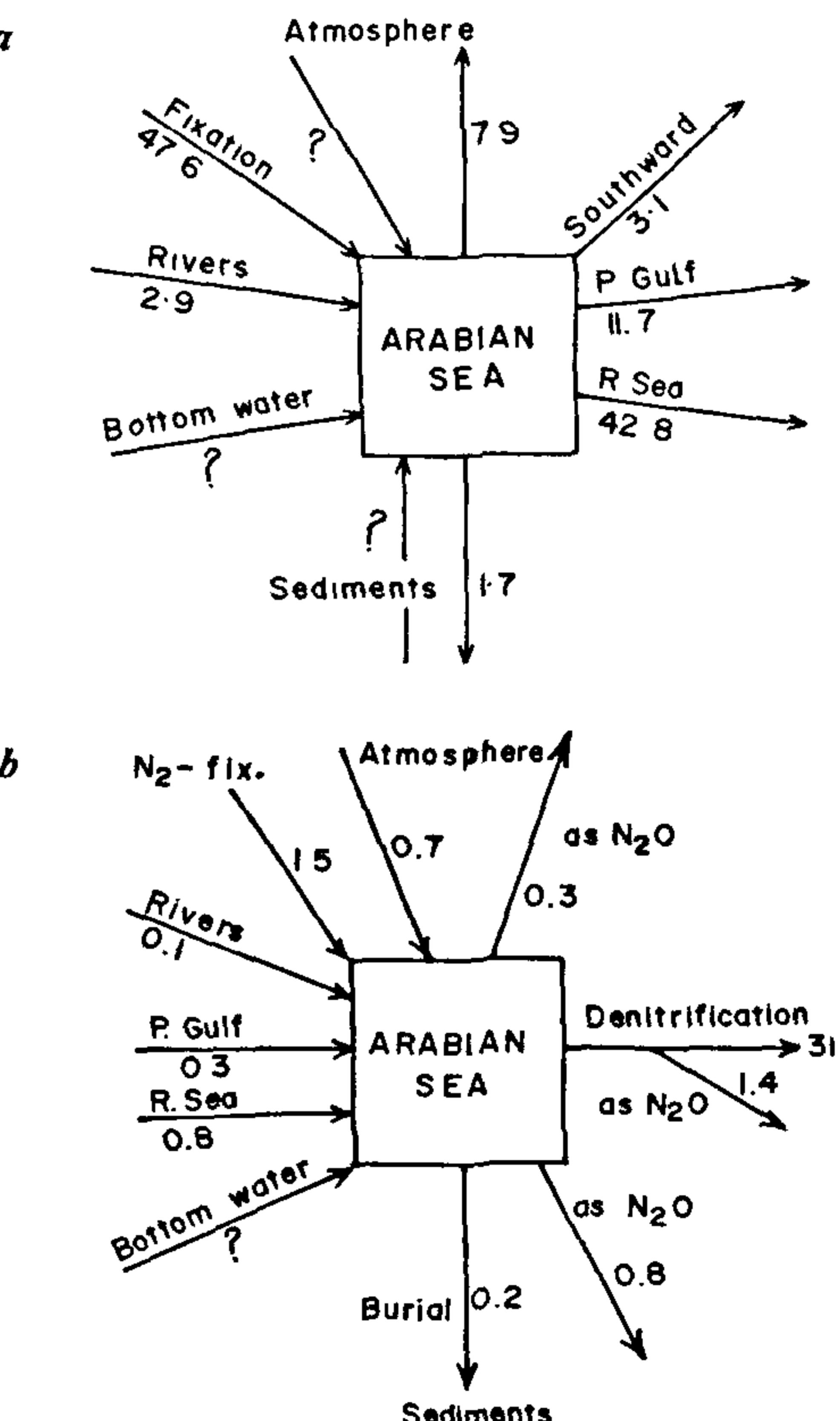


Figure 7. Budgets for *a*, carbon, *b*, nitrogen (including N_2O) in the Arabian Sea

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 km³ and an average HCO₃⁻ concentration³² of 12 mg C l⁻¹), which is close to that (2.3 Mt C yr⁻¹) evaluated earlier³⁰. The unknowns are its influx from the atmosphere, inflow from the south of equator and upward diffusion of regenerated CO₂ 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 CO₂ 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 CO₂ deficit of ~88 Mt C yr⁻¹. In order to maintain the CO₂ 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 N₂O 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 N₂O together with those of nitrogen^{25,30,31,33}. In contrast to their negative contribution to CO₂, 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, respectively³⁴. 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 N₂O and CO₂ during the southwest premonsoon^{23,27} but as a sink for CO₂ during the northeast monsoon³⁶.

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

The contribution of the North Indian Ocean to the global sea-to-air flux² of CO₂ 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 con-

trary, the N₂O 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 seasons³⁷. 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.

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