

## Hydrochemistry of the Bay of Bengal: possible reasons for a different water-column cycling of carbon and nitrogen from the Arabian Sea

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### Abstract

A study on biogeochemical cycling in the western Bay of Bengal was undertaken during two seasons (pre-southwest monsoon and northeast monsoon of 1991). Relationships of the conservative tracers NO and PO with potential temperature ( $\Theta$ ) are used to identify three end-member water masses in the Bay: the low-salinity surface water, the high-salinity intermediate water advecting from the Arabian Sea, and the deep water of circumpolar origin. A hydrochemical discontinuity at  $\sim 12^\circ\text{C}$  appears to define the boundary of zones of linear mixing among these waters. The shallower occurrence of the discontinuity in the Bay as compared to the Arabian Sea appears to restrict the thickness of the oxygen minimum layer in the former region. Marked seasonal changes appear to occur in intermediate waters, presumably reflecting changes in the coastal circulation off India. A secondary nitrite maximum is not observed in the Bay, and the NO– $\Theta$  relationships are indistinguishable from those observed in the oxic parts of the Arabian Sea, firmly indicating that the Bay of Bengal is not an active denitrification site. The absence of denitrification in the Bay appears to be incompatible with a slower renewal of intermediate waters and a higher sinking flux of particulate organic matter in comparison with the Arabian Sea. It is proposed that the lower respiration rates in the Bay might result from a rapid sinking of organic matter with relatively little decomposition within the water column caused by the large inputs of terrigenous material. Small N–S gradients in oxygen and carbon dioxide support this view.

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### 1. Introduction

The immense river runoff into the northeastern Indian Ocean is expected to influence the biogeochemical cycles to a great extent. In addition to supplying large amounts of dissolved and suspended matter, the runoff may also affect the chemistry through controls on circulation and mix-

ing. The rivers from this region are known to make disproportionately large contributions to the global transport of suspended load by rivers to the ocean (Milliman and Meade, 1983). The lithogenic substances may strongly influence the sedimentation of biogenic matter (Ittekkot et al., 1992). This is expected to significantly alter the water-column regeneration processes, the extent of which remains unknown.

Like other parts of the northern Indian Ocean,

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the Bay of Bengal also experiences an intense depletion of dissolved oxygen at intermediate depths (Wyrski, 1971). The suboxic conditions may lead to important transformation in redox elements of which nitrogen is perhaps the most important. Biochemical reduction of nitrate ions with the terminal production of molecular nitrogen (denitrification) is an important respiratory process in such environments (Richards, 1965). However, unlike the Arabian Sea (Naqvi et al., 1992; Mantoura et al., 1993), the effect of the oxygen-poor conditions on nitrogen cycling in the Bay is not yet fully understood. The data collected during the International Indian Ocean Expedition (IIOE) were inadequate to evaluate these effects. Unfortunately, not much has been added to the chemical data base from the Bay of Bengal since the IIOE and confusion still prevails in the literature as to whether or not the Bay of Bengal is a water-column denitrification site. It has been considered to be potentially reducing in two major reviews on marine denitrification provided by Deuser (1975) and Hattori (1983). Deuser's map delineating the geographical extent of the oxygen-deficient ( $< 10 \mu\text{M}$ ) intermediate and deep waters shows the northeastern Bay as oxygen-deficient. He also raised the possibility of the occurrence of reducing conditions in some parts of the Indian Ocean other than the Arabian Sea. Being more specific, Hattori stated (p. 202) "The Bay of Bengal in the Indian Ocean may contribute to oceanic denitrification, as oxygen concentrations of less than 0.2 ml/l and high nitrite concentrations have been observed (Wyrski, 1971). The volume of low-oxygen waters in this bay has not been computed, and no estimates of its yearly denitrification activity have been made". However, we know of no instance when a secondary nitrite maximum has been observed in the Bay of Bengal. Similarly, an earlier report on the occurrence of hydrogen sulphide in intermediate waters of the Bay (Ivanenkov and Rozanov, 1961) also appears to be questionable (Sen Gupta and Naqvi, 1984). Nonetheless, deficiencies in nitrate, with reference to the values expected from the apparent oxygen utilization (AOU), have been observed in the Bay, prompting suggestions that sizable denitrification might occur

in this area (Sen Gupta et al., 1977; Naqvi et al., 1978).

It has been shown previously that appreciable changes in the composition of subsurface waters in the Arabian Sea may be caused by the seasonal reversals of water circulation which may extend to considerable depths (Naqvi et al., 1990). Surface circulation in the Bay of Bengal also undergoes large seasonal changes (Shetye, 1993; Shetye et al., 1993). It is not known to what extent these changes affect the composition of subsurface waters. This issue is important since it may be related to the possible differences in the biogeochemistry of the two areas.

A multi-disciplinary observational programme undertaken recently in the Bay of Bengal provided us with an opportunity to generate reliable data sets on nutrients and dissolved oxygen during two seasons. These data enable us to address some of the issues outlined above.

## 2. Material and methods

The two cruises of the research vessel *Sagar Kanya* (63rd and 70th) during which the data were obtained, were undertaken during March–April and December 1991, corresponding to pre-southwest monsoon and northeast monsoon seasons, respectively.

Water sampling at standard depths at the locations shown in Fig. 1 was done using a Seabird Conductivity–Temperature–Depth (CTD)-rosette system fitted with Niskin bottles. Analyses for nutrients (nitrate, nitrite and phosphate) and oxygen were completed shortly after collection of the samples. Dissolved oxygen was estimated by the Winkler titrimetric technique. Nutrients were estimated with SKALAR 6-channel Analyzer 5100/1 following standard procedures (Grasshoff et al., 1983). Phosphate analysis was also performed manually at several stations using the method of Murphy and Riley (1962); an excellent agreement was found between the manual and autoanalyzer data. In order to ensure consistency between the data sets we used the same nutrient standards during both the cruises. These standards, prepared in

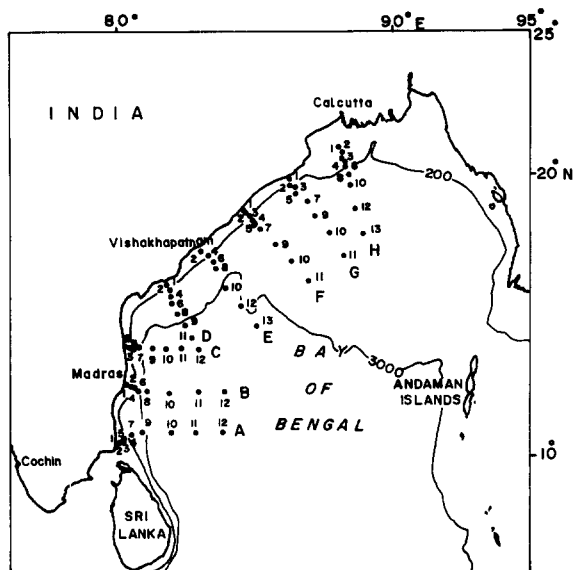


Fig. 1. Station locations.

bulk and stored in sealed sterilized ampoules, have been used by us during all surveys conducted since 1987, and so the results from the Bay of Bengal could be compared with those from the Arabian Sea (Naqvi et al., 1990). Depth profiles of nitrous oxide were also generated at selected stations, as described in detail elsewhere (Naqvi et al., 1994—this issue).

Potential temperature ( $\Theta$ ) was calculated following Fofonoff and Millard (1983). The nutrient tracers NO and PO (Broecker, 1974) were computed as follows:

$$\text{NO} = 9.1 \text{NO}_3 + \text{O}_2$$

$$\text{PO} = 138 \text{PO}_4 + \text{O}_2$$

where all properties have the units of  $\mu\text{M}$ . The factors 9.1 and 138 represent the oxidative ratios,  $\Delta\text{O}_2/\Delta\text{NO}_3$  and  $\Delta\text{O}_2/\Delta\text{PO}_4$ , respectively (Redfield et al., 1963; Takahashi et al., 1985; Minster and Boulaheid, 1987). It may be noted that while the phosphate oxidative ratio is subject to some uncertainty (Takahashi et al., 1985), any other reasonable choice of the ratio will not alter the conclusions reached in this study.

### 3. Results and discussion

#### 3.1. Surface circulation

Our two observation periods are characterized by vastly different circulation regimes in the Bay of Bengal, the understanding of which was a major objective of the overall observational programme. Based on the physical oceanographic data collected during the same cruises, the coastal circulation in the western Bay of Bengal has been described by Shetye (1993) and Shetye et al. (1993). The salient features are as follows.

The major circulation feature in the western Bay of Bengal during the pre-southwest monsoon was a poleward western boundary current (WBC) carrying warmer waters of southern origin. The inshore side of the current was marked by cooler, more saline waters brought to the surface due to the presence of the current which transported approximately  $10 \times 10^6 \text{ m}^3/\text{s}$ . The hydrography was suggestive of many features associated with the WBCs of the sub-tropical gyres of the world oceans such as a recirculation zone, waves and eddies. The seasonal sub-tropical gyre in the Bay of Bengal may form during January. It may be best developed during March–April and decay with the onset of the southwest monsoon in June. The thermohaline structure suggests that the WBC may extend down to the depths of the oxygen minimum.

Observations during the northeast monsoon showed the presence of a  $\sim 40 \text{ km}$  wide coastal plume which was best marked by the low-salinity waters it carried towards the equator all along the east coast of India (Shetye, 1993). The plume had characteristics similar to currents and transported  $1\text{--}2 \times 10^6 \text{ m}^3/\text{s}$ . The current provides an excellent example of how the influx of freshwater could affect the circulation in the Bay. The southward movement of the low density water was probably caused by the presence of equatorward alongshore winds.

#### 3.2. Water masses: property–property relations

Unlike the Arabian Sea, the thermohaline structure of subsurface waters of the Bay of Bengal is

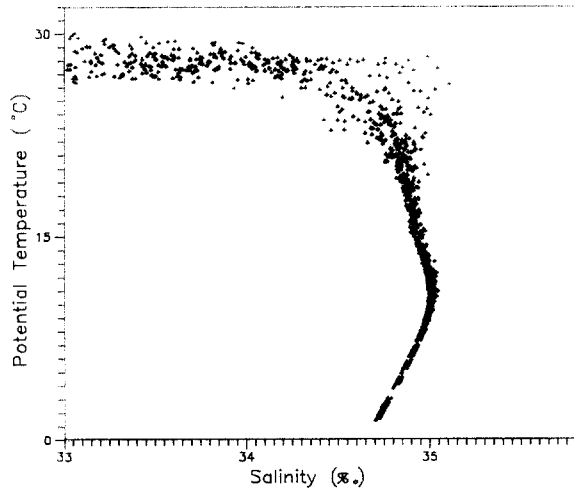


Fig. 2. Plot of potential temperature vs. salinity in the Bay of Bengal.

almost featureless. A rather broad salinity maximum is found at intermediate depths (Fig. 2). It has been attributed to the advection of high salinity water [the North Indian high-salinity intermediate water of Wyrski (1973)] from the Arabian Sea by the monsoon current (Sastry et al., 1985; Murthy et al., 1992). This maximum is similar to

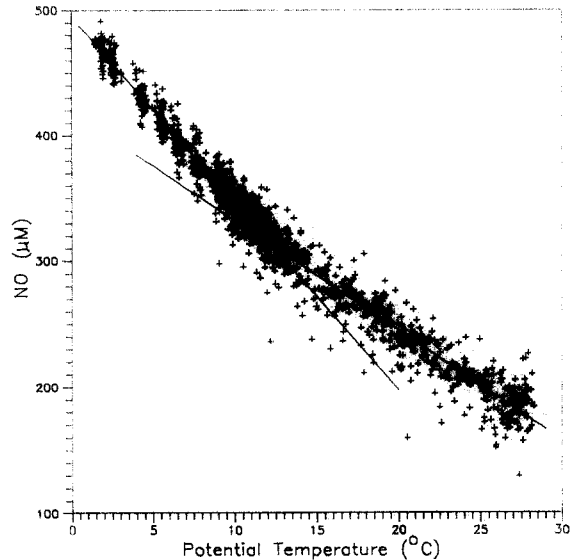


Fig. 3. Plot of nitrate tracer (NO) vs. potential temperature; straight lines give linear regressions at  $\Theta \leq 12$  and  $\Theta > 12^\circ\text{C}$ .

the Red Sea salinity maximum in the Arabian Sea in that it represents the upper boundary of the zone where the potential temperature–salinity ( $\Theta$ – $S$ ) relationship is linear (Fig. 2). In the Arabian Sea a discontinuity in the hydrochemical structure occurs at about this level (9–10°C) (Somasundar et al., 1987; Naqvi et al., 1990). In the following we shall show that a similar discontinuity exists in the Bay of Bengal as well.

Combining the data collected during both the cruises, plots of the conservative tracers NO and PO vs.  $\Theta$  are presented in Figs. 3 and 4. Both NO and PO appear to be linearly related with  $\Theta$  in two ranges. The NO– $\Theta$  and PO– $\Theta$  regression lines for appropriate depth intervals intersected at 12.28 and 12.07°C, respectively. The significant changes in slopes imply increases in the preformed nutrient contents below these levels, probably representing a transition from the intermediate to deep waters. Located close to this “chemical” discontinuity, a “physical” discontinuity is also discernible from the  $\Theta$ – $S$  plot at 10.85°C (Fig. 2). The depth range where these discontinuities occur is 300–400 m. Thus, based on the property distribution, we propose that the water masses of the Bay of Bengal could simply be regarded as mixtures of three end-members:

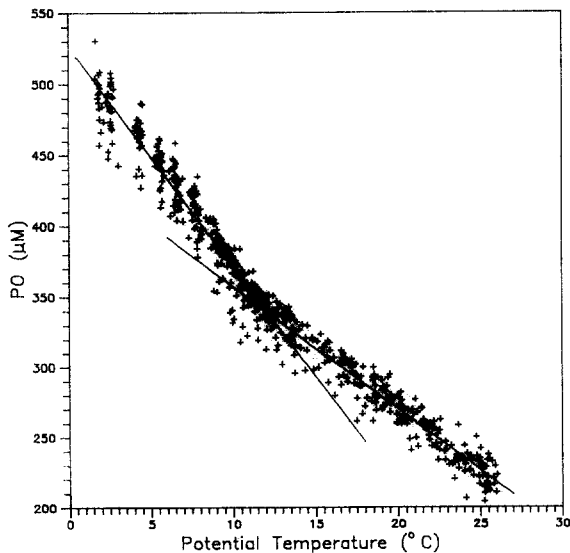


Fig. 4. Plot of phosphate tracer (PO) vs. potential temperature; straight lines give linear regressions at  $\Theta \leq 12$  and  $\Theta > 12^\circ\text{C}$ .

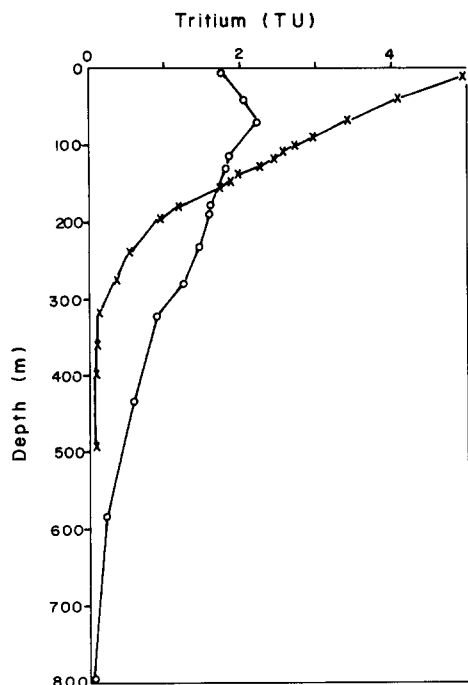


Fig. 5. Vertical profiles of tritium at GEOSECS stations 416 (Arabian Sea, O) and 446 (Bay of Bengal, x) (Ostlund et al., 1980).

- (1) the low-salinity surface water formed due to the excessive river runoff;
- (2) the North Indian high-salinity intermediate water entering the Bay after flowing around Sri Lanka; and
- (3) the deep waters advecting into the region either along the eastern flank of the Ninety-east Ridge or northward from the Central Indian Basin (Warren, 1981).

The 12-degree discontinuity appears to define the boundary of the linear mixing regimes of (1) with (2) and (2) with (3).

The shallower occurrence of the hydrochemical discontinuity in the Bay of Bengal as compared to the Arabian Sea is supported by tritium data generated during the GEOSECS expedition (Ostlund et al., 1980). These data clearly show a much greater vertical penetration of tritium in the Arabian Sea than in the Bay of Bengal (Fig. 5). This is ostensibly related to the fact that, while the Arabian Sea directly receives nutrient-depleted dense waters from the two marginal seas (the

contribution from the Red Sea is especially important as it reaches greater depths than the outflow from the Gulf), the Bay of Bengal does not. The shallower location of the discontinuity is of considerable biogeochemical significance as it may account for the smaller thickness of the oxygen-minimum layer in the Bay. These observations underscore the importance of the watermass composition in determining the depth range of the oxygen-depleted waters in the northern Indian Ocean. An implication of these results is that the variability of the outflows from the two marginal seas in response to the changes in sea level and/or climate could potentially modify the mid-depth redox environment in the northern Indian Ocean on geological time scale.

### 3.3. Property distributions and seasonal changes

A measure of the extent of temporal changes in chemical composition of subsurface waters in the western Bay of Bengal could be obtained by comparing the vertical sections of oxygen and nitrate along a longshore transect (comprising the most offshore stations of all legs) and two transects oriented normal to the coast (Legs B and G) (Figs. 6–11).

The oxygen concentrations within the broad minimum (defined by the 20  $\mu\text{M}$  contour) showed slight decreases northward, particularly during the northeast monsoon (Fig. 6). But these could well be within the errors associated with the Winkler titrations at very low oxygen concentrations (Broenkow and Cline, 1969). It is noteworthy that the N–S (Fig. 6) and the E–W (Figs. 7 and 8) gradients in oxygen at any depth are much weaker and the thickness of the oxygen-minimum layer is remarkably more uniform in the Bay of Bengal as compared to the Arabian Sea.

Nitrate distribution during the two seasons was comparable in the southwestern Bay (Figs. 9 and 10). By contrast, striking seasonal changes were recorded in the northeastern Bay (Figs. 9 and 11). Nitrate profiles at several stations located in this region contained minima as exemplified by the data at Sta. G-11 depicted in Fig. 12. Confirmed by repeated runs of the samples, the nitrate minima occurred in the same general area but not at the

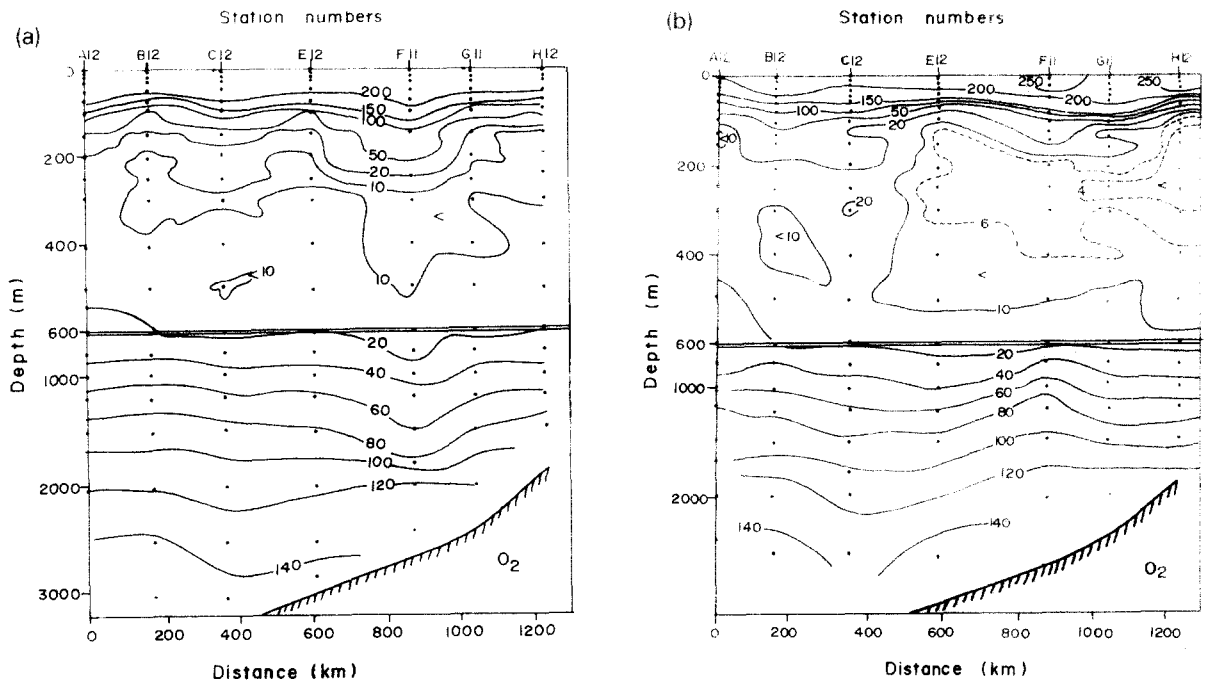


Fig. 6. Distribution of dissolved oxygen ( $\mu\text{M}$ ) in the longshore section during (a) pre-southwest monsoon, and (b) northeast monsoon.

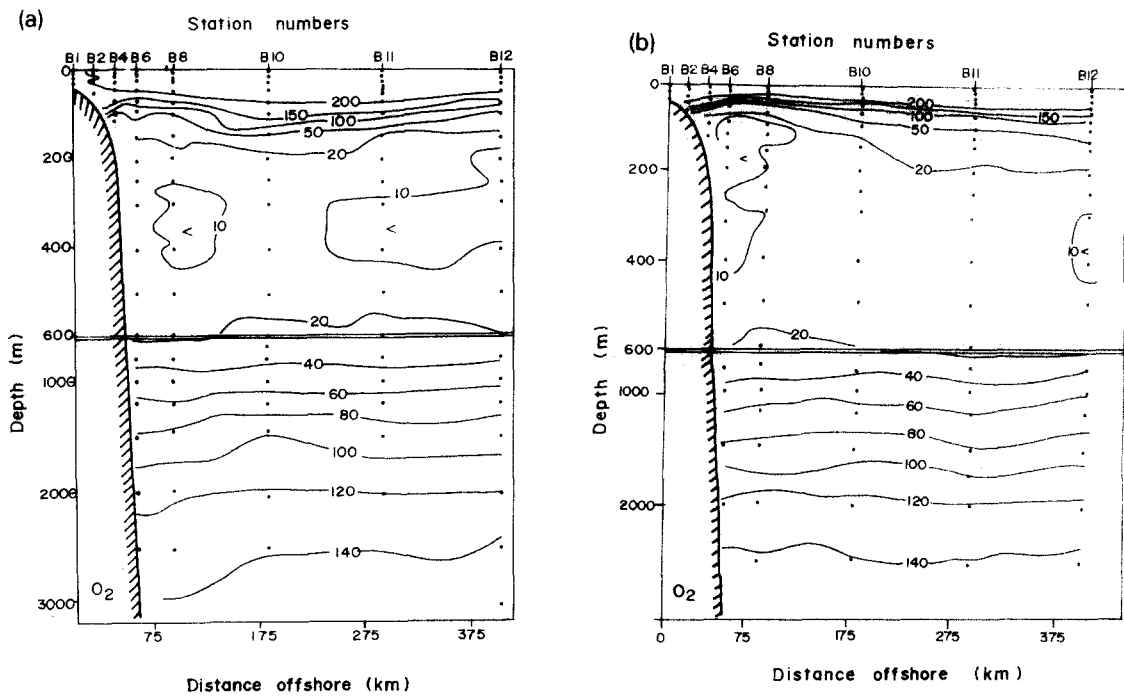


Fig. 7. Distribution of dissolved oxygen ( $\mu\text{M}$ ) along Leg B during (a) pre-southwest monsoon, and (b) northeast monsoon.

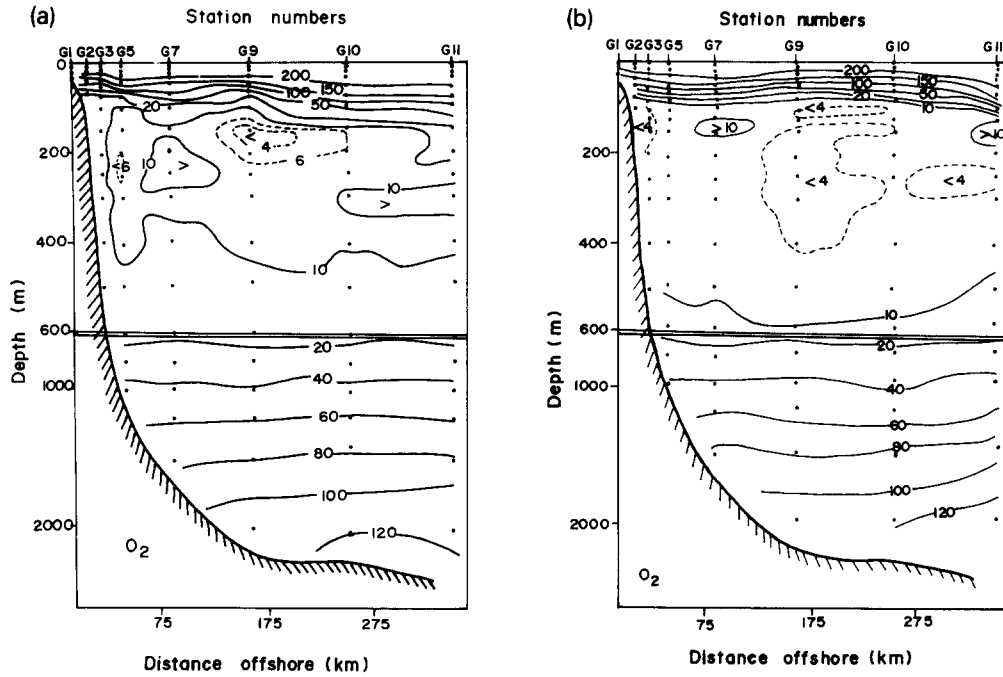


Fig. 8. Distribution of dissolved oxygen ( $\mu\text{M}$ ) along Leg G during (a) pre-southwest monsoon, and (b) northeast monsoon.

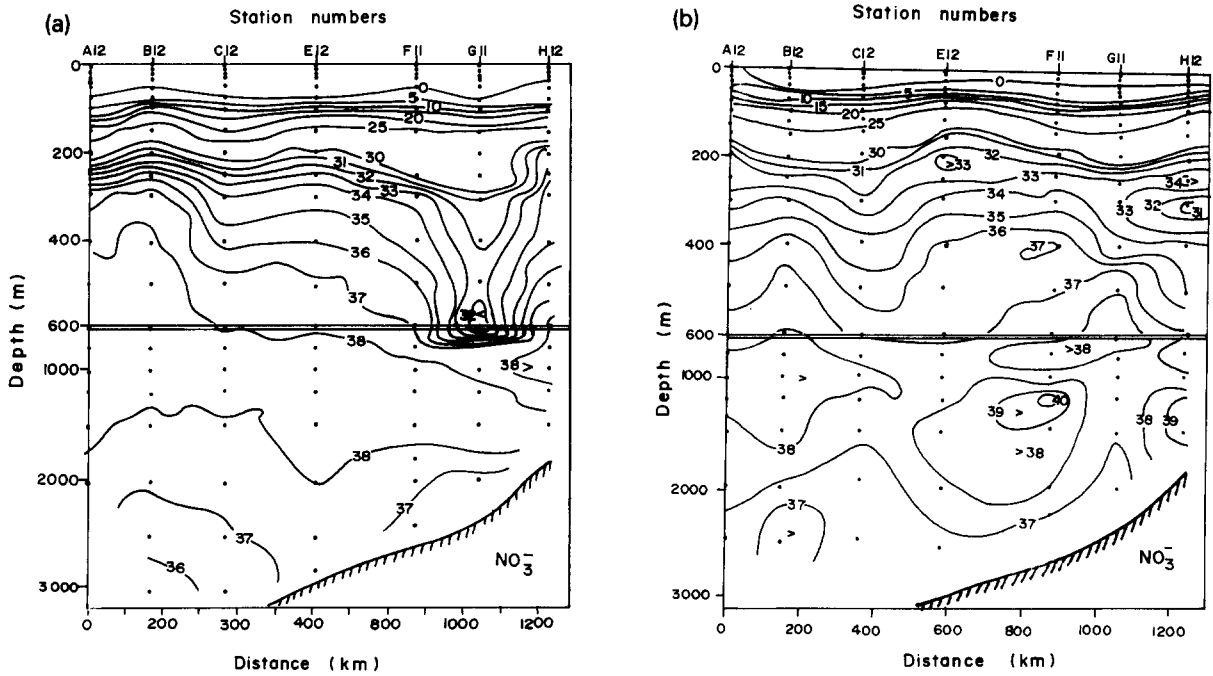


Fig. 9. Distribution of nitrate-nitrogen ( $\mu\text{M}$ ) in the longshore section during (a) pre-southwest monsoon, and (b) northeast monsoon.

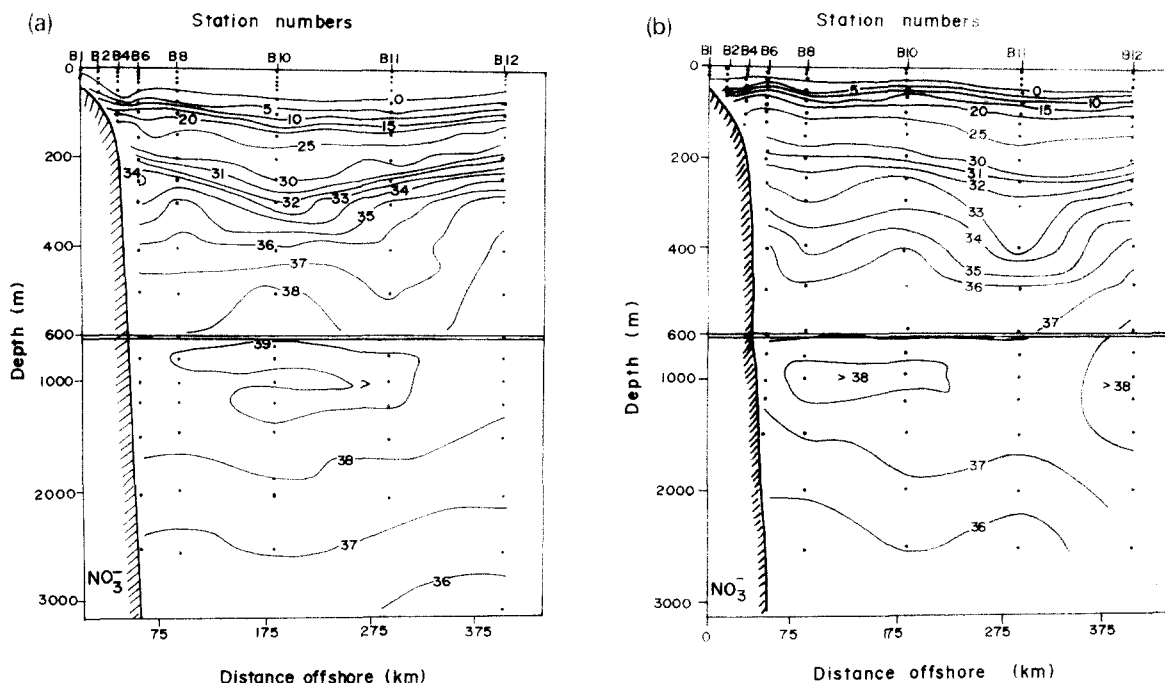


Fig. 10. Distribution of nitrate–nitrogen ( $\mu\text{M}$ ) along Leg B during (a) pre-southwest monsoon, and (b) northeast monsoon.

same stations during the two cruises. Along Leg G, for example, progressively lower nitrate concentrations occurred offshore and the minima were found at the offshore end of the transect during March–April 1991 (Fig. 11a). The upward tilting towards the coast might arise from the northward transport of waters by the WBC (Shetye et al., 1993). Observations made during December 1991, on the other hand, revealed a reverse trend: pockets of nitrate-poor waters were found at mid-depths just off the continental slope (Fig. 11b). These observations suggest that, as in the case of the eastern Arabian Sea, seasonal reversals of water flow could also extend well into the intermediate layers in the western Bay of Bengal.

A puzzling feature of our observations is the occasional occurrence of mid-depth minima in nitrate profiles. We are satisfied that the minima, although defined by single points in most cases, are not artifacts arising from errors in sampling and/or analysis. Significantly, they were invariably found in the northeastern part of the Bay, which has been regarded as “oxygen-deficient” (Deuser, 1975). The oxygen concentrations observed by us in this

region were very often close to the detection limit of the Winkler procedure (Figs. 6 and 8). However, a secondary nitrite maximum was not observed at any station in accordance with the previous results (Sen Gupta et al., 1977; Naqvi et al., 1978; Noronha, unpubl. data based on observations during the southwest monsoon of 1989). Moreover, the nitrous oxide profiles were typical of the non-reducing low-oxygen environments (Fig. 12; also see Naqvi et al., 1994-this issue). Thus, it is obvious that the nitrate minima could not be formed through active water-column denitrification as happens in the Arabian Sea. At the same time, it also seems very unlikely that the nitrate minima were produced by an advection of low-nitrate waters into the region from the Arabian Sea as these were absent in the southern Bay of Bengal (Fig. 10). We speculate that the nitrate minima may originate through the consumption of nitrate in marginal sediments followed by the offshore transport of the low-nitrate waters. A lobe of low-nitrate waters extending offshore during December 1991 is suggestive of a sink of nitrate within the continental margin sediments (Fig. 11b).



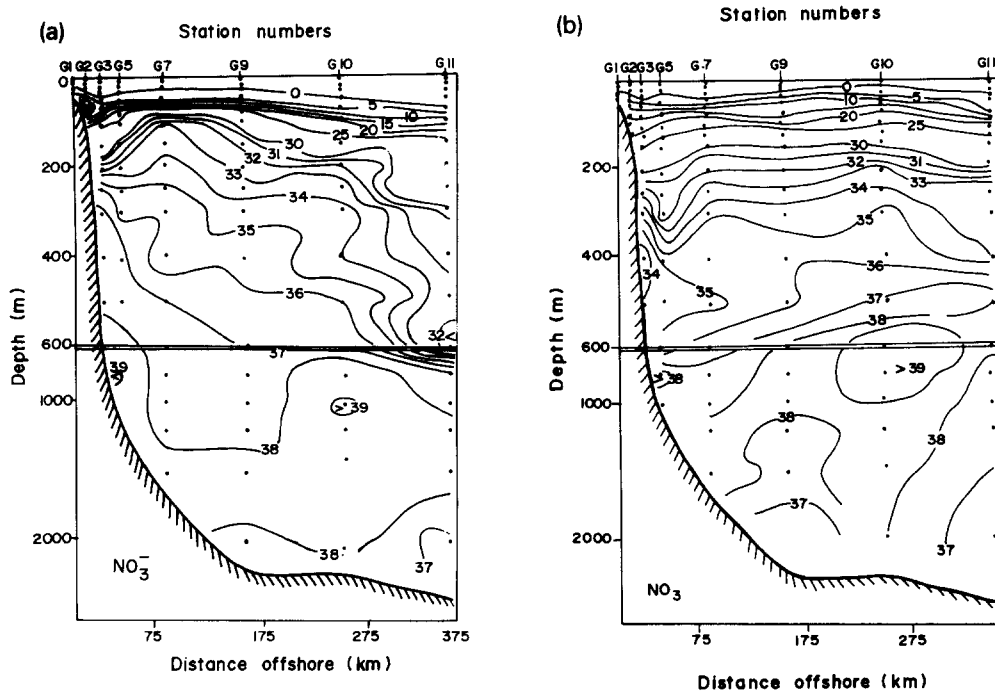


Fig. 11. Distribution of nitrate–nitrogen ( $\mu\text{M}$ ) along Leg G during (a) pre-southwest monsoon, and (b) northeast monsoon.

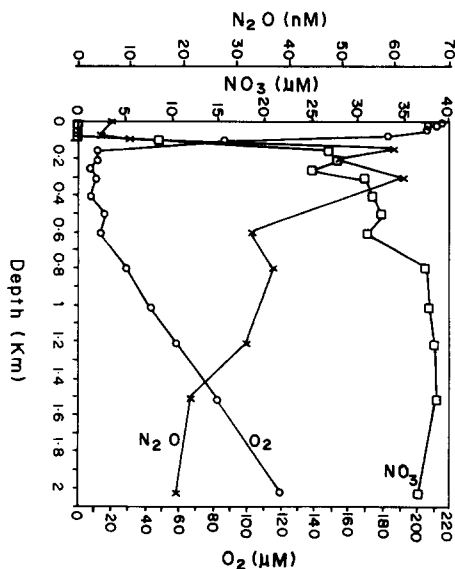


Fig. 12. Vertical profiles of oxygen, nitrate and nitrous oxide at station G-11 during the pre-southwest monsoon season.

The pockets of low-nitrate waters imply the presence of eddies, the occurrence of which has been previously recorded (Babu et al., 1991). We note, however, that the occurrence of denitrification at oxygen levels slightly higher than those found within the marine secondary nitrite maximum zones has been suggested (Betlach and Tiedje, 1981; Broecker and Peng, 1982; Codispoti and Christensen, 1985). The Bay of Bengal is potentially the most important area for such a process to occur as the conditions within a large volume of intermediate waters are just short of being “suboxic”. However, our results appear to negate this possibility since the nitrate minima affect negligibly small volume of water. At most depths, the nitrate concentrations are high even in waters which seem to show nearly complete oxygen depletion [for example, the lowest recorded Winkler oxygen concentrations ( $< 3 \mu\text{M}$ ) were not associated with any apparent nitrate deficit at station G-9; see Fig. 11b]. Thus, barring the isolated instances of the occurrence of nitrate minima, the nitrate concentrations compare very well with the “expected” nitrate concentration in the Arabian

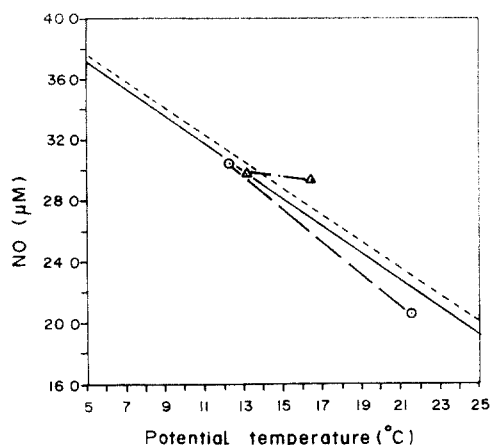


Fig. 13. A comparison of NO– $\Theta$  relationships observed in the northern Indian Ocean. Solid and short-dashed lines represent the vertically-integrated relationships in the Bay of Bengal (this study) and Arabian Sea (Naqvi et al., 1990), respectively. Lines joining the triangles and circles are based on two-end-member isopycnal treatments along  $\sigma_{\theta} = 26.6$  by Naqvi et al. (1990) and Mantoura et al. (1993), respectively.

Sea (see below). This leads us to conclude that the Bay of Bengal does not make any significant contribution to the oceanic water-column denitrification.

#### 3.4. Comparison of NO– $\Theta$ relationships in the Arabian Sea and the Bay of Bengal

Relationships between NO and  $\Theta$  have been utilized to compute expected nitrate concentrations in the Arabian Sea; combining these with the observed data, nitrate losses resulting from denitrification have been quantified (Naqvi and Sen Gupta, 1985; Naqvi et al., 1990; Mantoura et al., 1993). However, the NO values within the temperature range of denitrifying waters have been found to exhibit significant deficiencies even outside the secondary nitrite maximum zone, presumably due to horizontal mixing with the denitrification-affected waters (Naqvi et al., 1990); the NO– $\Theta$  relationship at these depths (used to estimate nitrate losses) was obtained by interpolating the trends seen in the underlying and overlying waters, and should therefore be verified. Mantoura et al. (1993) utilized a two-end-member isopycnal mixing model to compute the expected NO concentrations, getting slightly

different results. The data from the Bay of Bengal may be used to evaluate the relationships previously reported from the Arabian Sea (Fig. 13). The NO– $\Theta$  relationship observed by us in the Bay at  $\Theta > 12^{\circ}\text{C}$  is virtually indistinguishable from that reported by Naqvi et al. (1990) from the Arabian Sea at  $\Theta > 10^{\circ}\text{C}$ . The conservative mixing equation of Mantoura et al. (1993) also yields comparable results except for the near-surface samples. Of the two end-members used by Naqvi et al. (1990) for their isopycnal mixing model, the southern end-member falls in line with the other results. The northern end-member, however, differs significantly presumably due to an overestimation of “preformed” nitrate. These results not only validate the relationships between NO and  $\Theta$  observed in the Arabian Sea, giving more confidence to the estimates of nitrate losses, but also show the lack of a significant overall nitrate deficit in the Bay of Bengal, reinforcing the main conclusion made in the present study that the Bay of Bengal does not house a water column denitrification site.

#### 3.5. Possible reason for differences in redox conditions at mid-depths in the Arabian Sea and the Bay of Bengal

The absence of a water-column reducing environment in the Bay of Bengal helps in evaluating the relative importance of the renewal and consumption processes in the development of reducing conditions in the Arabian Sea. It has long been assumed that the bounding of the Indian Ocean by the Asian landmass at rather low latitudes might cause a very sluggish renewal of subsurface waters in the northern Indian Ocean giving rise to the acute oxygen depletion at intermediate depths (Wyrtki, 1973; Sen Gupta and Naqvi, 1984). Had this been the case, then one would expect the oxygen minimum to be more pronounced in the Bay of Bengal as compared to the Arabian Sea since the intermediate waters in the Bay appear to be ventilated more slowly; this is reflected by a much shallower penetration of tritium and its lower levels in the subsurface waters (Fig. 5). (Note that the higher tritium levels in surface waters are due to the large river runoff). The

slower renewal owes in part to an absence of high-salinity outflows in the Bay and in part to the negligible trans-equatorial water exchange in the upper kilometer in the eastern Indian Ocean (Swallow, 1984). Therefore, the observed weaker oxygen minimum must be the consequence of the lower respiration rates in the Bay of Bengal.

One might argue that a lower export production in the Bay could be directly responsible for the inferred lower respiration rates. Paradoxically, however, recent sediment trap deployments have shown that organic carbon fluxes to the deep Bay of Bengal may be higher than those in the Arabian Sea (Ittekkot et al., 1991). Ittekkot et al. (1991) postulated that a large riverine input of nutrients might support the large export production in the Bay of Bengal. However, the available data on nutrients are not compatible with this interpretation. These show that the rivers flowing into the Bay might not contribute much to the inorganic nutrient pool (Sen Gupta and Naqvi, 1984). A significant enrichment of nutrients in the river plumes (such as the one seen along the coast during the northeast monsoon season) was not observed in the present study. How do we reconcile the observed higher sinking fluxes with the inferred lower respiration rates in the Bay? There are two possible explanations for this anomaly.

First, the export production in the Bay of Bengal may be lower than that in the Arabian Sea, but the extent of water column regeneration from the soft tissue may also be lower as a consequence of the incorporation of organic carbon in the fast-settling matter due to the large terrigenous inputs. The observed weak N–S gradients in oxygen and total carbon dioxide support this view (George et al., 1994–this issue). Thus, the inferred lower respiration rates are not necessarily incompatible with, and may indeed be the cause of, the observed large particulate organic carbon fluxes. It may be added here that there exists good evidence that the organic matter reaches the deep sea floor in relatively undecomposed state in the Bay of Bengal (Broecker et al., 1980).

Second, as a consequence of a reduced advection and a strong stratification, the supply of fresh and labile DOC to the subsurface waters of the Bay may also be less. This difference assumes

significance in view of the reported insufficiency of the vertical sinking fluxes in fuelling subsurface respiration in the Arabian Sea (Ducklow, 1993; Naqvi and Shailaja, 1993). In any case, the difference in the water column redox conditions between the Arabian Sea and the Bay of Bengal appears to be intimately linked with the contrasting hydrography of the two bodies. An implication of these results is that during the times when the two regions did not experience such vastly different conditions (e.g. the last glacial maximum; Duplessy, 1982), the biogeochemical cycling in the two regions might have been more similar.

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