

## An evaluation of physical and biogeochemical processes regulating the oxygen minimum zone in the water column of the Bay of Bengal

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[1] Monthly oxygen budgets for the intermediate waters (100–1000 m) of the Bay of Bengal were constructed based on Modular Ocean Model (MOM) and oxygen data. The model results reveal that the oxygen levels in the oxygen minimum zone (OMZ) of the Bay of Bengal are controlled by physical and the associated biological processes. It results in maintaining low oxygen levels, with no significant seasonal variability, in the subsurface layer throughout the year. Low oxygen levels in the OMZ are sustained during the period of increased supply of organic matter through river runoff by enhanced supply of oxygen by the physical pump and vice versa. Thus, low oxygen levels in the OMZ are maintained by supply of oxygen by the physical pump to meet the demands of the biological processes. The inconsistency observed among oxygen consumption rates derived based on the present oxygen budget, carbon regeneration rate, and oxygen consumption rates computed based on electron transport system technique could be due to inadequate knowledge of seasonal and spatial variability in oxygen consumption in the latter two estimates. The residence time of intermediate waters (OMZ) of Bay of Bengal was computed to be 12 years.

*INDEX TERMS:* 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 4806 Oceanography: Biological and Chemical: Carbon cycling; 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; 4820 Oceanography: Biological and Chemical: Gases; *KEYWORDS:* dissolved oxygen, suboxic zone, denitrification, budget, Bay of Bengal

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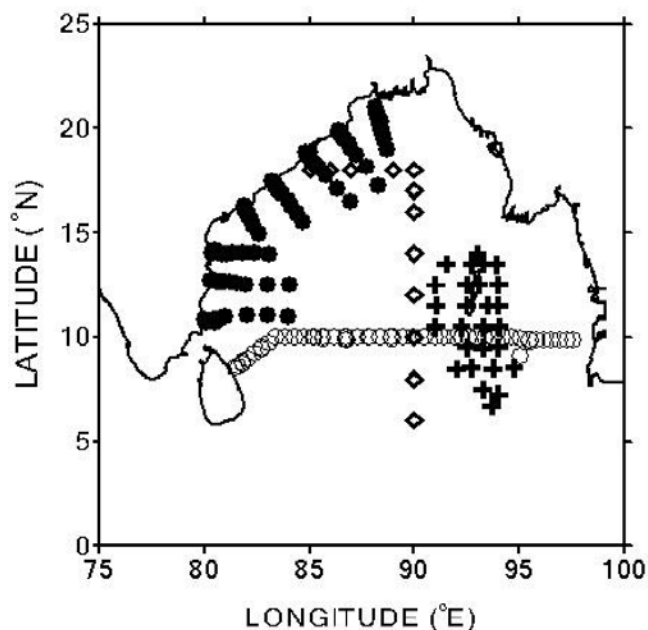
### 1. Introduction

[2] The Bay of Bengal is found to experience intense depletion in dissolved oxygen levels at intermediate depths [Wyrki, 1971; Rao *et al.*, 1994]. These zones are important sites for transformations in redox sensitive elements of which nitrogen is an important one. Such environments are unique for biochemical reduction of nitrate ions into molecular nitrogen (denitrification) by respiratory process [Richards, 1965]. However, unlike the Arabian Sea [Naqvi *et al.*, 1992; Mantoura *et al.*, 1993; de Sousa *et al.*, 1996; Morrison *et al.*, 1998], the influence of oxygen-poor conditions on nitrogen dynamics in the Bay of Bengal is not well understood, especially the role of hydrography on the oxygen minimum zone (OMZ). Naqvi *et al.* [1994] and Rao *et al.* [1994] found an absence of significant denitrification in the Bay of Bengal though random pockets of low oxygen and nitrate waters were observed. The nitrate minimum in these pockets is attributed to the consumption of nitrate in the marginal sediments and their offshore transport by

western boundary currents [Rao *et al.*, 1994]. Nevertheless, no secondary nitrite, which is an indicator of denitrification, was found in the Bay of Bengal [Rao *et al.*, 1994; Naqvi *et al.*, 1994, 1996; Howell *et al.*, 1997].

[3] The northern Indian Ocean is bounded by landmass in the north, east, and west resulting in a sluggish renewal of subsurface waters in the northern Indian Ocean, giving rise to acute oxygen depletion at intermediate depths [Wyrki, 1973; Sen Gupta and Naqvi, 1984]. The penetration of tritium was found to be shallow and at lower levels in the subsurface layers in the Bay of Bengal [Ostlund *et al.*, 1980] due to strong stratification developed by large volume of freshwater from high precipitation and river runoff which is more intense during SW monsoon (June to August). The winds show remarkable seasonal changes in their direction which blow northeast during December, southerly in April, and southwest during July to October [Varkey *et al.*, 1996]. 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; Sarma, 2002]. Surface circulation in the Bay of Bengal also undergoes large seasonal changes [Shetye, 1993], but it is unknown to what extent these changes affect the composition of subsurface waters. This issue is impor-

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**Figure 1.** The station locations of the data used in this study are shown. Closed circles, data collected during pre-SW monsoon and NE monsoon, 1991 [Rao *et al.*, 1994]; open diamonds, collected during SW monsoon, 1996 [Sarma *et al.*, submitted manuscript, 2001]; plus, collected during post monsoon, 1996 [Sarma and Narvekar, 2001]; closed diamonds, WOCE leg I09N, 1995; and open circles, WOCE leg I01E, 1995.

tant since it can possibly explain the differences in the biogeochemistry of the two areas. Hence, an attempt has been made here to evaluate the effects of physical and biological processes on oxygen levels in the OMZ in the Bay of Bengal using the Modular Ocean Model (MOM) and the oxygen data collected by different investigators in the Bay of Bengal [Figure 1; Rao *et al.*, 1994; Sarma and Narvekar, 2001; V. V. S. S. Sarma, *et al.*, Control of total alkalinity in the northern Indian Ocean during SW monsoon, submitted to *Oceanology Acta*, 2001] (hereinafter referred to as Sarma *et al.*, submitted manuscript, 2001), plus World Ocean Circulation Expedition [<http://whpo.ucsd.edu>] and climatological data [<http://Ingrid.lidgo.columbia.edu/SOURCES/NOAA/NODC/WOA98>; Conkright *et al.*, 1998].

## 2. Model Description

[4] The main objective of this study is to make quantitative estimation of supply and demand for oxygen by physical and biological processes, respectively, in the subsurface waters of the Bay of Bengal (Figure 2). In this model, physical pump supplies oxygen through exchanges at the boundaries by physical processes such as upwelling, sinking, and water mass transport. The biological pump consumes oxygen by oxidation of organic matter in the subsurface layers. Though most of the organic matter (85–95%) decomposes in the surface layer itself, only 5–15% of the remaining organic matter sinks to the subsurface layers

where it is subjected to bacterial decomposition [Eppely and Peterson, 1979]. The oxygen content in the subsurface layers is controlled by the efficiency of the biological pump and residence time of organic matter in the intermediate layers.

[5] The model domain is constructed by closing the eastern, western, and northern boundaries while the southern boundary opens to the Indian Ocean at 10°N, where exchanges take place. Rao *et al.* [1994] reported that low oxygen levels prevail at the depth range of 100–1000 m in the Bay of Bengal, hence, the upper and the lower boundaries of the model domain are fixed at 100 and 1000 m depth, respectively. The water fluxes at these boundaries were computed by MOM Ver.2 [Bryan, 1969; Pacanowski, 1995]. In this model, the grid resolution is 0.5° × 0.3° longitude to latitude with 20 vertical levels. The complete details of the model are described elsewhere [Swathi *et al.*, 2001]. Biological pump is based on sinking fluxes [Ittekkot *et al.*, 1991] and electron transport system (ETS) measurements [Naqvi *et al.*, 1996]. The regeneration rates of organic matter are computed using the water mass mixing model of Kumar and Li [1996]. Sedimentary respiration rates in the shelf and slope sediments (water column depths <1000 m) were computed using the equations given by Cai and Reimers [1995].

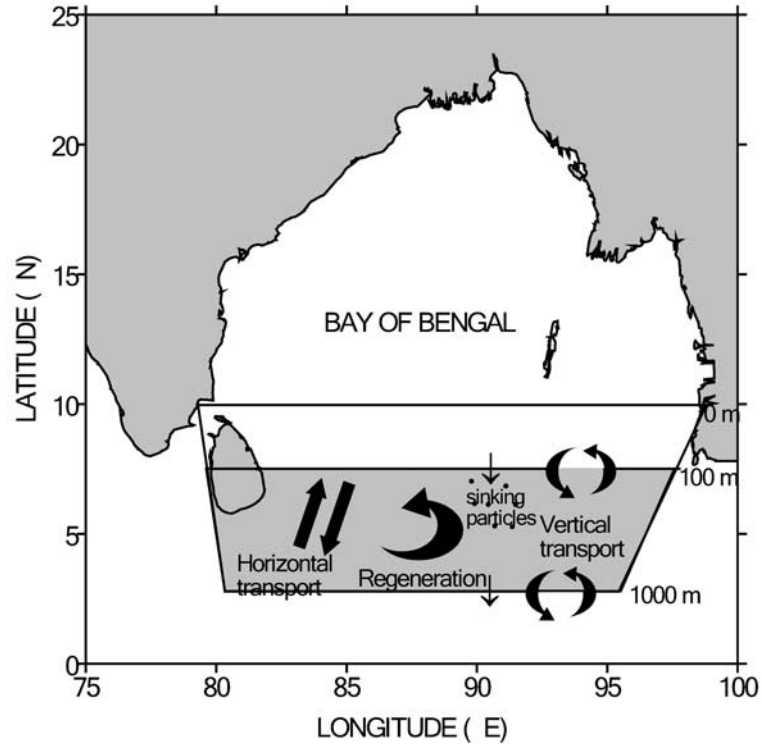
### 2.1. Physical Pump

[6] The physical pump plays an important role in the fate of elements in the oceans. For instance, physical processes such as upwelling, sinking, and transport of waters greatly alter distribution of elements. Rao *et al.* [1994] identified three major water masses in the upper 1000 m of the water column in the Bay of Bengal. They are low-salinity surface waters, formed due to the excessive river runoff, the North Indian high-salinity intermediate waters entering into the Bay after flowing around Sri Lanka, and the deep waters advecting into the region along the eastern flank of the Ninety-east Ridge and northward from the Central Indian Basin [Warren, 1981]. Hence, influence of these water masses on oxygen budgets has been computed using the water transports in the present study domain.

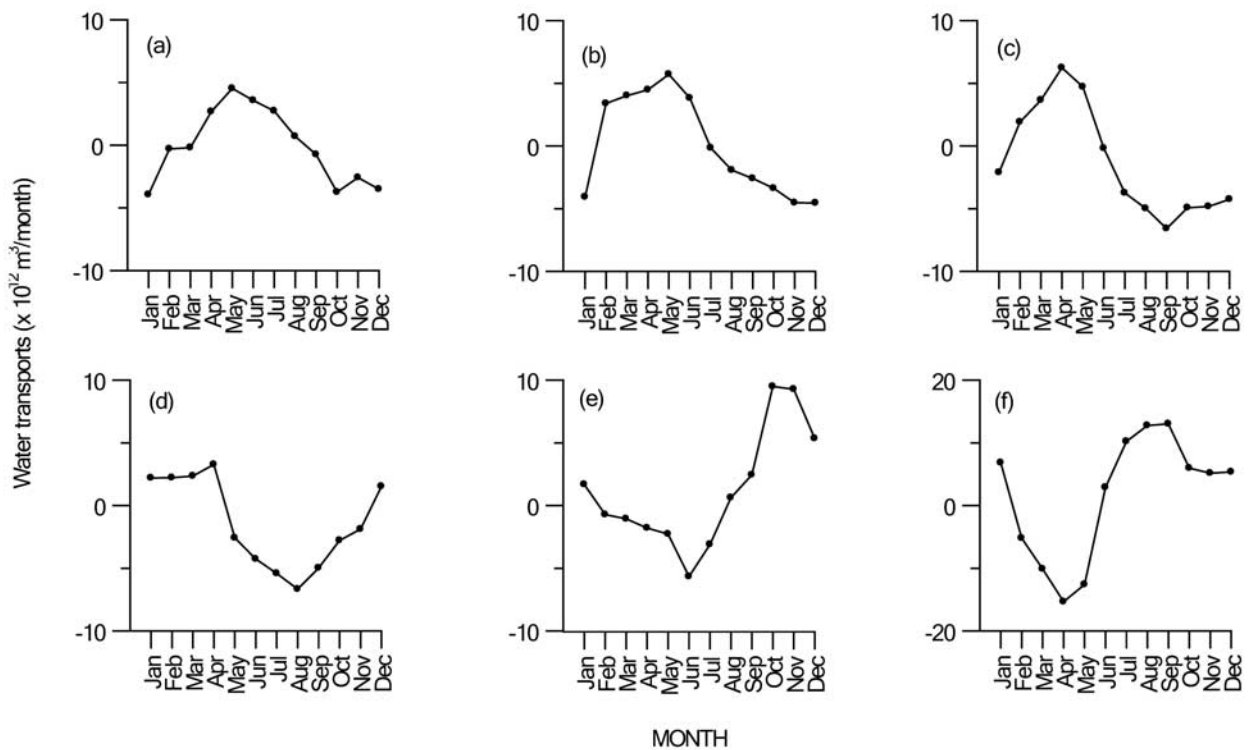
#### 2.1.1. Water Fluxes Within the Box (Bay of Bengal)

[7] The horizontal transports of water between 100–150, 150–250, 250–500, and 500–1000 m and vertical transports across 100 and 1000 m depths were computed using MOM (Figures 3a–3f). Water flow at 100–150 m along 10°N is northward into the Bay of Bengal in mid-year (April–July) and southward in August to February with peak flows of  $5.7 \times 10^{12} \text{ m}^3 \text{ month}^{-1}$  north in May and  $4.5 \times 10^{12} \text{ m}^3 \text{ month}^{-1}$  south in October. The northward peak shifts toward the beginning of the year at greater depths and the peak northward flow in April drops from  $6.2 \times 10^{12} \text{ m}^3 \text{ month}^{-1}$  at 250–500 m to  $3.3 \times 10^{12} \text{ m}^3 \text{ month}^{-1}$  at 500–1000 m. Peak southward flow increases steadily with depth, reaching  $6.6 \times 10^{12} \text{ m}^3 \text{ month}^{-1}$  in August at 500–1000 m.

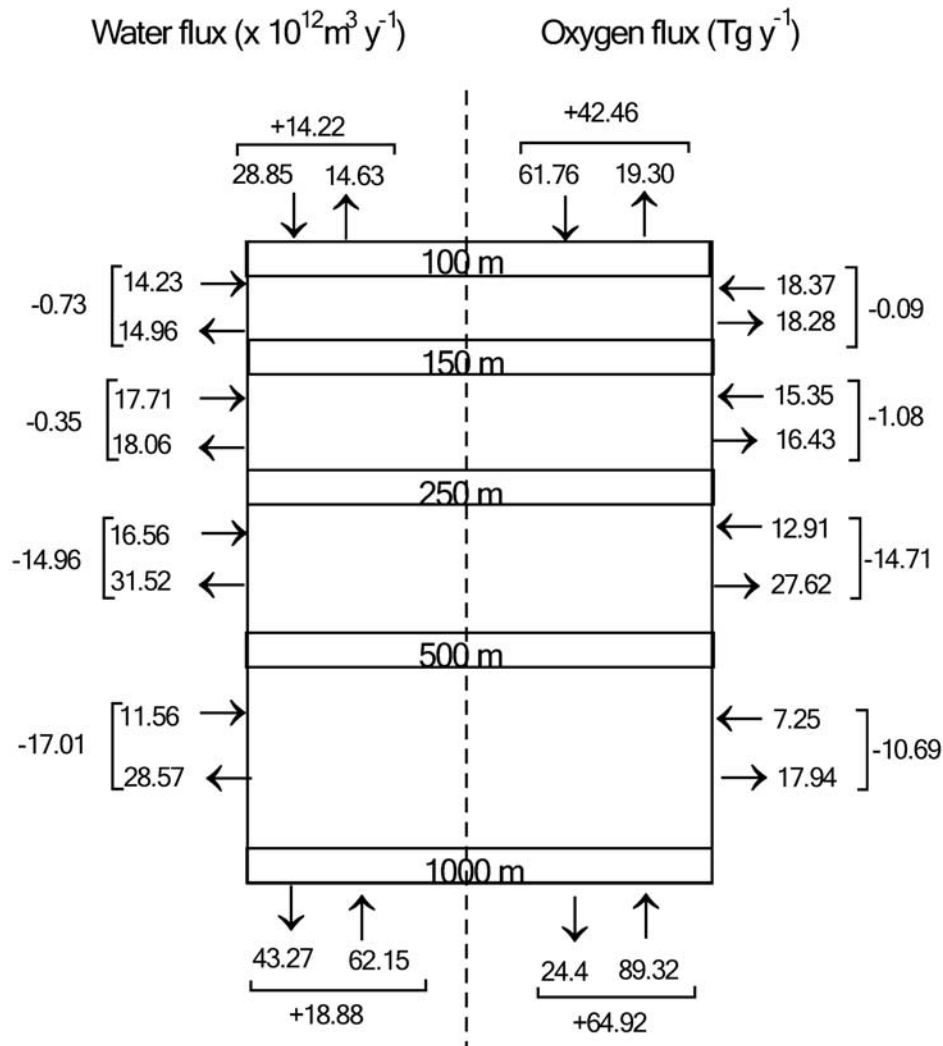
[8] The vertical flux at 100 m shows sinking from February to July and upwelling from August to January with peak flow of  $5.6 \times 10^{12} \text{ m}^3 \text{ month}^{-1}$  downward in June and  $9.5 \times 10^{12} \text{ m}^3 \text{ month}^{-1}$  upward in October (Figure 3e). On the contrary, 1000 m boundary layer shows sinking



**Figure 2.** Schematic diagram showing the description of model and different sources and sinks of oxygen in the Bay of Bengal (north of 10°N).



**Figure 3.** (a–d) Represents horizontal water transports at different depth ranges along 10°N and (e and f) are vertical transports across 100 and 1000 m boundaries in the Bay of Bengal. The positive transport is northward (a–d) and upward (e and f). Please note that the scale in y-axis of (f) is different.



**Figure 4.** Net flows of water fluxes and oxygen fluxes at different depth levels in the box.

from February to May and upwelling from June to January with peak flow of  $15.3 \times 10^{12} \text{ m}^3 \text{ month}^{-1}$  sinking in April and upwelling of  $13 \times 10^{12} \text{ m}^3 \text{ month}^{-1}$  in September (Figure 3f).

[9] The net flow of water at three boundaries of the box is depicted in Figure 4. This shows that net flow is out of the box at all depths (100–1000 m) along  $10^\circ\text{N}$ . However, the net flows in 100–150 and 150–250 m depth ranges are small, i.e.,  $0.73$  and  $0.35 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$ , respectively. The maximum outflow occurs in 250–500 m ( $14.96 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$ ) and 500–1000 m ( $17.01 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$ ). As a whole, about  $33.05 \times 10^{12} \text{ m}^3$  water is transported southward annually along  $10^\circ\text{N}$  in the depth range of 100–1000 m. The net flow along 100 m is downward ( $14.22 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$ ) whereas  $18.88 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$  of water upwells into the box across the deep boundary.

### 2.1.2. Oxygen Fluxes

[10] Oxygen fluxes are computed as a product of net water transports and mean oxygen concentration in a particular depth range. The mean oxygen concentrations along the box boundaries are given in Table 1. The oxygen

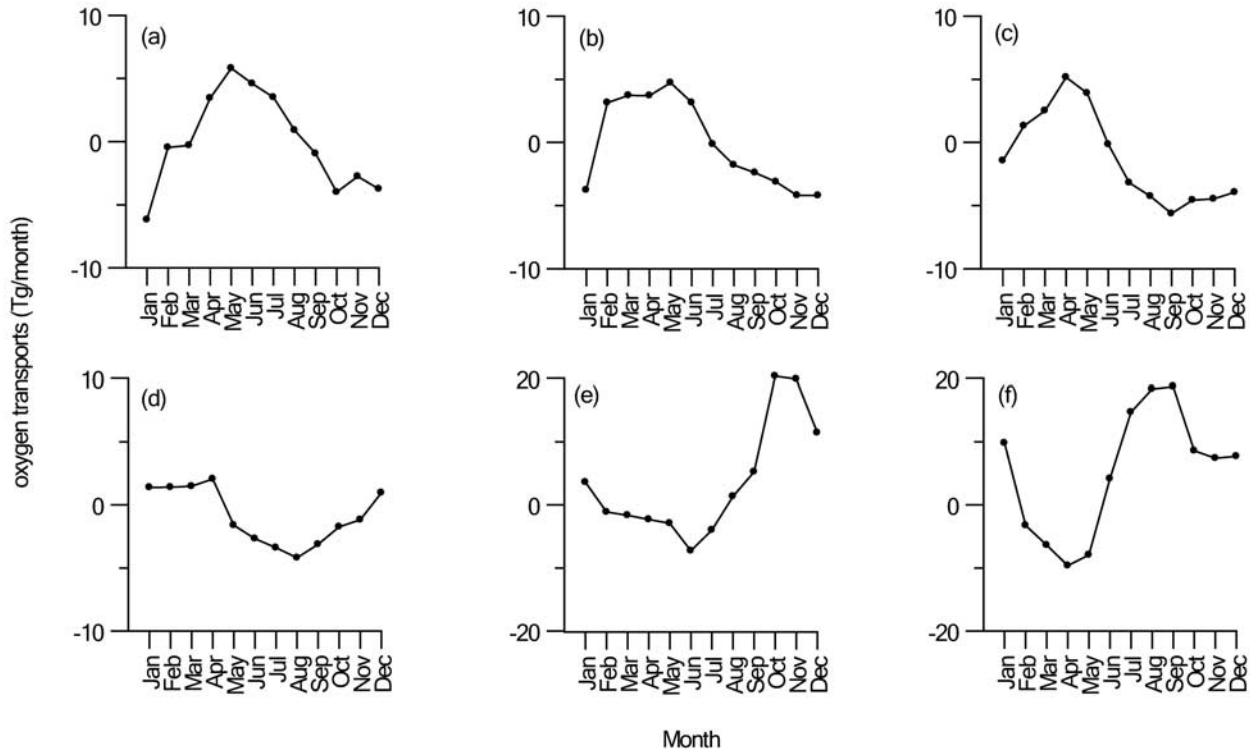
flows at the box boundaries are depicted in Figures 5a–5d. The oxygen fluxes are well balanced for the 100–150 and 150–250 m layers with small losses of oxygen ( $0.09$  and  $1.08 \text{ Tg yr}^{-1}$ , respectively) through the southern boundary

**Table 1.** Concentrations of Oxygen at Different Depth Levels Along  $10^\circ\text{N}$  in the Bay of Bengal During Different Months<sup>a</sup>

Month	100–150	150–250	250–500	500–1000	100	1000
Jan.	1.57	0.93	0.68	0.63	2.14	1.43
Feb.	1.57	0.93	0.68	0.63	1.57	0.63
March	1.57	0.93	0.68	0.63	1.57	0.63
April	1.28	0.83	0.83	0.63	1.28	0.63
May	1.28	0.83	0.83	0.63	1.28	0.63
June	1.28	0.83	0.83	0.63	1.28	0.63
July	1.28	0.93	0.85	0.63	1.28	1.43
Aug.	1.28	0.93	0.85	0.63	2.14	1.43
Sept.	1.28	0.93	0.85	0.63	2.14	1.43
Oct.	1.07	0.93	0.93	0.63	2.14	1.43
Nov.	1.07	0.93	0.93	0.63	2.14	1.43
Dec.	1.07	0.93	0.93	0.63	2.14	1.43

<sup>a</sup> Concentrations of oxygen are averaged levels given in  $\text{g/m}^3$ , and depth levels are given in meters.





**Figure 5.** (a–d) Represents oxygen transports at different depth levels along  $10^{\circ}\text{N}$  and (e and f) denote vertical transports across 100 and 1000 m boundaries in the Bay of Bengal. Note that only inflow of water is shown. The flow directions are same as in Figure 3.

(Figure 4). Between 250 and 500 m, about  $12.91 \text{ Tg yr}^{-1}$  oxygen is injected into the box while  $27.62 \text{ Tg yr}^{-1}$  is exported out of the box with a net exchange of  $14.71 \text{ Tg yr}^{-1}$  to the south. The deeper (500–1000 m) layer is estimated to receive  $7.25 \text{ Tg yr}^{-1}$  of oxygen and exchanges  $17.94 \text{ Tg yr}^{-1}$  from the box. Against these net exchanges, about 61.76 and 89.32 Tg of oxygen is being injected annually into the box across the 100 and 1000 m boundaries, respectively, whereas 19.3 and 24.4 Tg of oxygen is removed out of the box (Figure 4). The overall oxygen flux into the box across  $10^{\circ}\text{N}$  is  $53.8 \text{ Tg yr}^{-1}$  whereas  $80.3 \text{ Tg yr}^{-1}$  is carried away with net loss of  $26.5 \text{ Tg yr}^{-1}$ . While a total of  $151 \text{ Tg yr}^{-1}$  of oxygen enters through vertical exchange,  $43.7 \text{ Tg yr}^{-1}$  of oxygen goes out of the box with a net gain of  $107.3 \text{ Tg yr}^{-1}$ . These results suggest that about 60% of the net oxygen is injected through 1000 m boundary layer while 40% is injected across 100 m boundary layer. Hence, the dominant supply of oxygen to the OMZ in the Bay of Bengal occurs through vertical exchange (Figure 4). In summary, about  $\sim 205 \text{ Tg}$  of oxygen enters the box annually while  $\sim 124 \text{ Tg O}_2 \text{ yr}^{-1}$  goes out, which suggests an annual consumption of  $\sim 81 \text{ Tg}$  in the OMZ.

### 2.1.3. Residence Time

[11] Residence time of waters in the OMZ (100–1000 m) of the Bay of Bengal is computed from

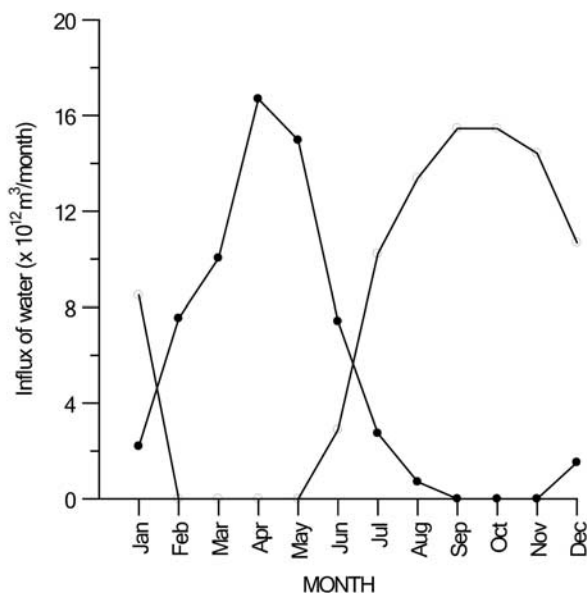
$$\text{Residence time}(t) = \frac{\text{total volume of the study domain}}{\text{(box)}/\text{rate of water influx}}$$

[12] Residence time of water in the 100–1000 m depth layer is computed to be 12 years from an inflow rate of  $155 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$  and the box volume of  $1861 \times 10^{12} \text{ m}^3$ .

[13] In order to examine monthly variability in the movement of waters in the OMZ, water influxes from both horizontal and vertical boundaries are presented in Figure 6 for different months. The water movement is relatively slow during January to March and June months with an influx of  $<12 \times 10^{12} \text{ m}^3$  per month compared to other months ( $12\text{--}17 \times 10^{12} \text{ m}^3$  per month).

### 2.1.4. Loss of Oxygen to the Sediment/Sedimentary Respiration

[14] Several investigators [for example, *Grant et al.*, 1987; *Walsh*, 1991; *Walsh et al.*, 1985] suggested that continental margin sediments are important sites of organic carbon oxidation. The major source of the carbon to these sediments is mostly derived from primary production [*Walsh et al.*, 1985; *Christensen*, 1989; *Jahnke et al.*, 1990]. Organic matter oxidation in the margin sediments may take place in several pathways; however, these areas are important sites for biogeochemical cycling of oxygen. Despite the large importance of margin sediments in the global cycles of elements, this area is not well studied. Though there are few studies conducted in the Atlantic and Pacific Oceans, absolutely no such study was conducted in the Indian Ocean, especially on the benthic exchange of elements at the sediment-water interface. Hence, the loss of oxygen to the sediments is computed here following the work of *Cai and*



**Figure 6.** Total influx of waters into the box from horizontal (closed circles) and vertical (open circles) boundaries during different months. Out fluxes are not shown in this figure and zero fluxes mean no influx.

Reimers [1995] who formulated a general and quantitative correlation between benthic oxygen flux ( $FO_2$ ;  $\mu\text{mole cm}^{-2} \text{yr}^{-1}$ ) to the bottom water oxygen concentration ( $[O_2]_{BW}$ ;  $\mu\text{mole kg}^{-1}$ ) and the core top organic carbon content ( $C_{org, \%}$ )

$$FO_2 = (\pi C_{org} [O_2]_{BW}) / (126 + [O_2]_{BW})$$

where  $\pi$  is  $44.4 (\mu\text{mole cm}^{-2} \text{yr}^{-1} (\% \text{ dry organic C})^{-1})$ . This equation can be used at different environments such as suboxic basins, the continental slope, the continental rise, and oxic open ocean sediments.

[15] Organic carbon content in the surface sediments varied from 0.34 to 2.5% in the slope sediments [Venkatratnam, 1968; Seetharamaswamy, 1968]. Considering bottom water oxygen as  $40 \mu\text{mole kg}^{-1}$  [Rao et al., 1994], the flux of oxygen to the sediments is estimated to be  $36.5\text{--}267.5 \text{ mmole m}^{-2} \text{yr}^{-1}$ . When the area of the seafloor with depth  $<1000 \text{ m}$  ( $0.6 \times 10^{12} \text{ m}^2$ ) is considered, the oxygen loss into the sediments is estimated to be  $0.7\text{--}5 \text{ Tg yr}^{-1}$ .

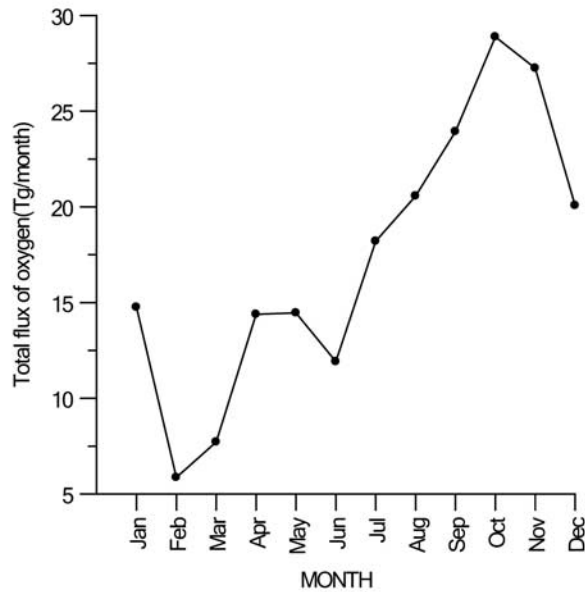
### 2.1.5. Oxygen Demand in the OMZ by Organic Carbon Regeneration

[16] Most of the organic matter, which is produced in the euphotic zone, oxidizes in the upper 1000 m [Suess, 1980] that results in the removal of oxygen from the water column in this depth range. Regenerated  $\text{CO}_2$  in the Bay of Bengal has been computed [Sarma et al., submitted manuscript, 2001] based on water mass mixing model. In this model, the observed DIC in a given sample is considered to be a mixture of preformed, anthropogenic, remineralized, and added through dissolution. Preformed DIC is computed from three end-member water mass mixing model described by Kumar and Li [1996], anthropogenic carbon is calculated from the study of Sabine et al. [1999], and carbon added

through dissolution is computed from the change in TA from that of preformed TA. The difference in sum of these three fractions from that of observed DIC gives regenerated carbon dioxide [Sarma et al., submitted manuscript, 2001]. The regeneration of soft tissue showed significant north-south variability with reference to dissolved oxygen distribution [Sarma et al., submitted manuscript, 2001]. On an average, the release of  $\text{CO}_2$  due to regeneration of soft tissue amounts to  $20\text{--}120 \mu\text{mol kg}^{-1}$  in the OMZ. In order to compute the inventory of regenerated carbon dioxide for the entire OMZ, the same has been integrated from 100 to 1000 m for the entire box. This amounts to 390 to 2350 Tg of carbon released by soft tissue regeneration in the OMZ of the Bay of Bengal. Based on ventilation time of 12 years for OMZ in the Bay of Bengal (see section 2.1.2), the rate of organic carbon oxidation in the subsurface layers is estimated to be  $32$  to  $196 \text{ Tg C yr}^{-1}$ . Based on available data sets (see Figure 1), Redfield ratio of  $\text{O}_2/\text{C}$  is evaluated for Bay of Bengal and observed to be 1.20. Using this ratio, the decomposition rates of carbon are converted to equivalent oxygen. It is found that about 102 to 627 Tg of oxygen per year is required to meet the respiratory demands in the OMZ of the Bay of Bengal. It is much larger than the oxygen consumption of  $81 \text{ Tg yr}^{-1}$  arrived from the oxygen budget. The possible reason could be the inadequate knowledge of spatial and seasonal variability in organic matter regeneration rates in the Bay of Bengal. Sarma et al. [submitted manuscript, 2001] have estimated organic matter regeneration along WOCE section during NE monsoon and this variability during other seasons and with space in the Bay of Bengal is still unknown.

### 3. Discussion

[17] Despite large seasonal and spatial variability in productivity, the oxygen levels in the OMZ are more or less constant in the Bay of Bengal. The present model results suggest that both physical and biological processes are responsible for the existence of such conditions in the OMZ and also for the absence of denitrification in the Bay of Bengal. The physical pump shows strong monthly variability due to the unique circulation pattern that brings changes in the direction of water movements. Especially, it is more important for vertical fluxes as oxygen gradients are high at the depth levels above 100 m ( $100\text{--}150 \mu\text{mol kg}^{-1}$ ) and below 1000 m ( $>60 \mu\text{mol kg}^{-1}$ ) compared to intermediate waters which are already oxygen depleted ( $10\text{--}40 \mu\text{mol kg}^{-1}$ ) [Rao et al., 1994; George et al., 1994; Sarma and Narvekar, 2001]. Figure 6 depicts total influx of waters into the box across horizontal and vertical boundaries of the box. Influx of water occurs through horizontal boundary during January–August and December with highest influx during April–May. On the contrary, influx of water through vertical boundary occurs during January and June–December with highest influx during September and November. Since vertical influx is more during January and June–December, the input of oxygen is also obviously high compared to the other months (Figure 7). Despite such large variability in influx, oxygen levels in the OMZ showed no significant variability with season. For instance,



**Figure 7.** Total oxygen influx from all boundaries into the box during different months.

oxygen levels in the OMZ of the central and western Bay of Bengal ranged from 10 to 40  $\mu\text{mol kg}^{-1}$ , except few pockets of 4–6  $\mu\text{mol kg}^{-1}$ , during pre-SW and NE monsoon seasons [Rao *et al.*, 1994]. Sarma *et al.* [submitted manuscript, 2001] observed 10–40  $\mu\text{mol kg}^{-1}$  of the oxygen in the western and central Bay of Bengal during SW monsoon. Sarma and Narvekar [2001] found 20–40  $\mu\text{mol kg}^{-1}$  oxygen in subsurface water in the eastern Bay of Bengal during post monsoon season. This suggests that oxygen levels in the subsurface waters of the Bay of Bengal are more or less constant, despite a variable productivity pattern. This further suggests that the biological pump plays an important role in the control of oxygen levels in the OMZ.

[18] In order to examine the effect of biological processes on OMZ, consumption rates of oxygen have been computed as a product of the difference between the input and output fluxes of oxygen in the OMZ. The net loss, thus, would represent oxygen consumption in the OMZ. The oxygen consumption rates vary from 1 to 15  $\text{Tg month}^{-1}$  with a minimum during January–June and a maximum during July–December. Though, the primary productivity is higher during the SW monsoon [0.14–5.9  $\text{g C m}^{-2} \text{d}^{-1}$ ] than during NE monsoon [0.99–1.68  $\text{g C m}^{-2} \text{d}^{-1}$ ] or the inter-monsoon [0.063–0.485  $\text{g C m}^{-2} \text{d}^{-1}$ ] [Devassy *et al.*, 1983; Radhakrishna, 1978; Prakash and Raman, 1990] periods, such high rates of consumption might not be due to primary production alone. The Bay of Bengal receives an enormous amount of fresh water, nutrients, and suspended load from the sediments of the shelf region [United Nations Educational, Scientific, and Cultural Organization (UNESCO), 1969, 1971a, 1971b] that affects biogeochemical cycling of carbon in the Bay of Bengal [Ittekkot *et al.*, 1991]. The monthly variability in consumption rates is consistent with changes in total sinking fluxes (i.e., mass fluxes) at 1000 m depth [Ittekkot *et al.*, 1991]. Unfortunately, data for the monthly variability in sinking organic carbon fluxes are not

available, but the ratio of total flux to organic carbon flux is more or less constant, hence, the comparison may be appropriate. Nevertheless, the seasonal organic carbon fluxes are given in Table 2. Ittekkot *et al.* [1991] found higher fluxes (100–400  $\text{mg m}^{-2} \text{d}^{-1}$ ) in the 1000 m traps during June–November in the northern and central Bay of Bengal, which is consistent with the period of high discharges from Ganges and Brahmaputra rivers during this period [UNESCO, 1971a, 1971b]. Similarly, higher total sinking fluxes were noticed during June–October (150–350  $\text{mg m}^{-2} \text{d}^{-1}$ ) in the central Bay of Bengal [Ittekkot *et al.*, 1991; Ramaswamy and Nair, 1994]. The sinking fluxes varied from 50 to 100  $\text{mg m}^{-2} \text{d}^{-1}$  during other months. These results suggest that inputs from terrigenous material, in addition to the organic carbon produced in the surface layers, may influence oxygen consumption rates in the Bay of Bengal. This study further reveals that physical pump supplies more oxygen to the OMZ during July–December, when oxygen demand is more due to influx of organic material by the river discharges and low during low productivity seasons (Figure 7). These results suggest that coupling of the physical and biological pumps is responsible for the maintenance of, more or less, constant oxygen levels throughout the year in the OMZ.

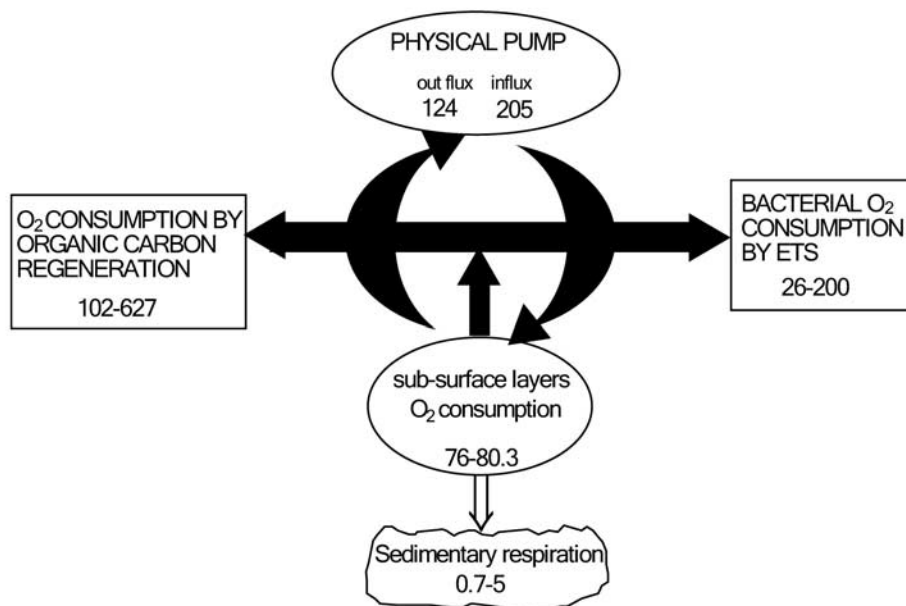
[19] Sarma [2002] studied the occurrence of perennial suboxic conditions in the Arabian Sea. The major supply of oxygen (250  $\text{Tg yr}^{-1}$ ) to a mid-depth box in the Arabian Sea is injected through the upper boundary (100 m) followed by the lateral inputs between 100 and 250 m (90  $\text{Tg yr}^{-1}$ ) and the flux across the lower (1000 m) boundary (52  $\text{Tg yr}^{-1}$ ). In the Bay of Bengal, on the other hand, there is very little supply of oxygen to the subsurface layer through vertical mixing at 100 m (42.5  $\text{Tg yr}^{-1}$ , which is five times lower than that of Arabian Sea probably due to inhibition of vertical mixing in the upper layers due to low salinities) and the major source of oxygen to the OMZ in the Bay of Bengal is the 1000 m boundary. This is in concurrence with the observations of Kumar and Li [1996] who found that more than 10% of Antarctic Bottom water mass (AABW) enters the Bay of Bengal than the Arabian Sea. Furthermore, oxygen levels at 1000 m are higher in the Bay of Bengal (>60  $\mu\text{mol kg}^{-1}$ ) compared to the Arabian Sea [ $\sim 20 \mu\text{mol kg}^{-1}$ ; George *et al.*, 1994], and residence time of waters in the OMZ is computed to be 12 years, which is higher than in the Arabian Sea (6.5 years [Sarma, 2002]; 3–10 years [Howell *et al.*, 1997]; and  $10 \pm 4$  years [Olson *et al.*, 1993]).

**Table 2.** Sinking Fluxes of Particulate Organic Carbon at Northern and Central Bay of Bengal During Different Seasons<sup>a</sup>

Area	Season	Organic Carbon Flux, $\text{g m}^{-2}$
Northern Bay of Bengal	NE monsoon	0.51–0.73
	NE–SW monsoon	0.45–0.91
	SW monsoon	0.72–1.30
Central Bay of Bengal	SW–NE monsoon	0.30–0.34
	NE monsoon	0.72–0.89
	NE–SW monsoon	0.45–0.64
	SW monsoon	0.91–1.30
	SW–NE monsoon	0.27–0.75

<sup>a</sup> Adapted from the work of [Ittekkot *et al.*, 1991].





**Figure 8.** Budget of oxygen in the suboxic waters (100–1000 m) of the Bay of Bengal (in  $\text{Tg yr}^{-1}$ ).

Recently *Kumar et al.* [1998] found a minimum in the concentration of transparent exopolymer particles (TEP) in the suboxic zone of the Arabian Sea and suggested that TEP could serve as a secondary source of carbon to the denitrifying bacteria. On the other hand, no such minimum is found in the Bay of Bengal. Moreover, the percentage of TEP harboring mineral (terrestrial or marine solid) grains was greater (75–86%) in the Bay of Bengal than in the Arabian Sea (33–46%). This trend is in agreement with TEP numbers, which are higher at 500 m in the Bay of Bengal (4400–7790 per ml) than in the Arabian Sea (130–350 per ml) whereas the size of the TEP is smaller in the Bay of Bengal (7–16  $\mu\text{m}$ ) than in the Arabian Sea (21–92  $\mu\text{m}$ ) [*Kumar et al.*, 1998; *Ramaiah et al.*, 2001]. This suggests that TEP coagulate in the water column in the Arabian Sea accounting for the higher concentration whereas it gets removed efficiently from the water column by scavenging in the Bay of Bengal [*Kumar et al.*, 1998]. As a result of scavenging, the residence time of TEP in the Bay of Bengal decreases, thus, they will be removed to the sediment in the unoxidized form resulting in low oxygen consumption rates in the water column. This may also explain why large quantities of labile organic matter reach the deep seafloor producing the near-bottom anomalies observed by *Broecker et al.* [1980]. Furthermore, despite high column productivity in the Arabian Sea ( $1064 \times 10^6$  tonnes  $\text{C yr}^{-1}$ ) compared to the Bay of Bengal [ $394 \times 10^6$  tonnes  $\text{C yr}^{-1}$ ; *Qasim*, 1977] sinking fluxes of carbon at 1000 m are much higher in the Bay of Bengal [ $2.04\text{--}3.59$  g  $\text{C m}^{-2} \text{yr}^{-1}$ ; *Ittekkot et al.*, 1991] than in the Arabian Sea [ $1.53\text{--}1.80$  g  $\text{C m}^{-2} \text{yr}^{-1}$ ; *Nair et al.*, 1989]. This has been attributed to scavenging of organic matter from the water column in association with mineral particles [*Ittekkot et al.*, 1991]. This suggests that though bacterial counts are much

higher in the Bay of Bengal ( $4.3\text{--}10.45 \times 10^4$  per ml) compared to the Arabian Sea ( $1.3\text{--}3.4 \times 10^4$  per ml; *Kumar et al.* [1998]), the residence time of organic matter in the water column is much smaller for complete oxidation in the Bay of Bengal. As a result oxygen consumption rates are much smaller in the Bay of Bengal ( $81 \text{ Tg yr}^{-1}$ ) than in the Arabian Sea ( $458 \text{ Tg yr}^{-1}$ ).

[20] *Naqvi et al.* [1996] have measured oxygen consumption rates using ETS activity. This method involves measuring in situ maximum velocity of the dehydrogenase transferring electrons from their physiological substrates (NADH, NADPH, succinate) to a terminal electron acceptor (for instance,  $\text{O}_2$  or  $\text{NO}_3^-$ ) through their associated electron transfer systems [*Packard*, 1969, 1971]. They found that the maximum in ETS activity is generally observed in the intermediate layers. Interestingly, ETS activity was found to be higher in the Arabian Sea ( $10\text{--}100 \text{ neq l}^{-1} \text{ h}^{-1}$ ) than in the Bay of Bengal ( $2\text{--}50 \text{ neq l}^{-1} \text{ h}^{-1}$ ) suggesting much lower respiration rates in the latter basin compared to former. *Naqvi et al.* [1996] converted ETS activity to oxygen consumption rates and found this to be  $5\text{--}35 \text{ nl l}^{-1} \text{ h}^{-1}$  in the Arabian Sea and  $2\text{--}15 \text{ nl l}^{-1} \text{ h}^{-1}$  in the Bay of Bengal. This amounts to an oxygen utilization of  $141\text{--}992$  and  $26\text{--}200 \text{ Tg yr}^{-1}$ , in the Arabian Sea and Bay of Bengal, respectively, which is in broad agreement with the oxygen consumption rate ( $81 \text{ Tg yr}^{-1}$ ) computed in the present study.

[21] The oxygen budget for the OMZ in the Bay of Bengal is depicted in Figure 8. Based on the budget calculations, about 81 Tg of oxygen is consumed in the OMZ annually. Out of this, about  $0.7\text{--}5 \text{ Tg yr}^{-1}$  of oxygen is consumed during sedimentary respiration. Hence, a net  $76\text{--}80.3 \text{ Tg}$  of oxygen is utilized in the subsurface waters of the Bay of Bengal annually. The amount of carbon dioxide released due to decomposition of soft tissue ( $32\text{--}196 \text{ Tg C}$



yr<sup>-1</sup>) consumes 102–627 Tg of oxygen annually. Direct oxygen consumption rates in the OMZ of the Bay of Bengal by ETS suggest that 26–200 Tg of oxygen is consumed annually. The difference between consumption rates of oxygen computed based on budget and water mass mixing models and ETS studies could be due to inadequate knowledge of spatial and seasonal variability of these rates in the latter two estimates in the Bay of Bengal.

#### 4. Conclusions

[22] Despite strong seasonal and spatial variability in the productivity, the oxygen levels in the OMZ of the Bay of Bengal are more or less constant throughout the year. Model results revealed that physical together with biological cycling of oxygen regulate OMZ in the Bay of Bengal. Although sinking and river driven organic carbon fluxes are high during the monsoon, the observed low oxygen levels are maintained through a higher supply of oxygen from the physical pump at that time. The oxygen consumption rates are found to be higher during July–December, which is in agreement with sinking fluxes at 1000 m depth. This model results are not in close agreement with oxygen consumption rates computed based on ETS activity and organic matter regeneration rates due to inadequate knowledge of spatial and seasonal variability of the latter two estimates.

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