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An evaluation of physical and biogeochemical processes regulating perennial suboxic conditions in the water column of the Arabian Sea

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[1] Monthly oxygen budgets for the subsurface Arabian Sea (100–1000 m) are constructed on the basis of Modular Ocean Model and recently collected oxygen data. The model results are in agreement with the observed pattern. The model results revealed that oxygen minimum zone (OMZ) in the Arabian Sea is regulated largely by physical processes in association with biogeochemical cycling of oxygen. This results in perennial suboxic conditions in the water column with no significant seasonal variability. Maintenance of OMZ during nonmonsoon seasons, when oligotrophic conditions prevail in surface layers, occurs through low supply of oxygen by physical pump aided by continued oxygen consumption in the oxidation of organic matter produced during monsoons. On the other hand, formation of anoxic conditions during monsoons, when higher sinking fluxes of carbon occur, is prevented by higher flux of oxygen by the physical pump. Hence, suboxic conditions in the Arabian Sea are maintained by physical pump with moderation from monsoonal biological pump. The residence time of the Arabian Sea intermediate waters (100–1000 m) was computed to be 6.5 years with rapid replacement during monsoons. The oxygen consumption rates are also high during monsoons compared with nonmonsoon seasons. The carbon regeneration rates computed based on the water mass-mixing model, bacterial carbon demand, and electron transport system activity in the subsurface layers are in agreement with oxygen consumption rates estimated based on this model. *INDEX TERMS:* 4834 Oceanography: Biological and Chemical: Hypoxic environments; 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 4835 Oceanography: Biological and Chemical: Inorganic marine chemistry; 4223 Oceanography: General: Descriptive and regional oceanography; *KEYWORDS:* oxygen minimum zone, intermediate layer, biogeochemical process, Arabian Sea

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1. Introduction

[2] Intense oxygen minima in the water column are found in three major areas in the world oceans [*Codispoti*, 1989]. They are the eastern tropical North Pacific [*Cline and Richards*, 1972], the eastern tropical South Pacific [*Codispoti and Christensen*, 1985], and the northern Arabian Sea [*Sen Gupta et al.*, 1976; *Naqvi*, 1994; *de Sousa et al.*, 1996; *Morrison et al.*, 1999]. The northwestern Indian Ocean (Arabian Sea) contains the thickest low-oxygen layer in the present day oceans. Oxygen concentrations of <10 μM kg^{-1} are frequently found between the bottom of the euphotic zone (~100 m) to about 1000 m in the Arabian Sea [*de Sousa et al.*, 1996; *Morrison et al.*, 1999]. The reducing environment in the oxygen minimum zone (OMZ) has important implication to biogeochemical cycling of nitrogen and carbon. An annual denitrification rate of 10–30 Tg N yr^{-1} has been estimated for this zone [*Mantoura et al.*, 1993; *Naqvi et al.*, 1992]. The other open oceanic sites experiencing mid-depth nitrate reduction are in the eastern tropical Pacific Ocean off Mexico and Peru [*Codispoti et al.*, 1992]. Various hypotheses proposed for the maintenance of OMZ include slow advection of waters [*Severdrup et al.*, 1942], higher respiration rates [*Ryther and Menzel*, 1965], and influx of low oxygen waters from the South Indian Ocean [*Swallow*, 1984]. *Olson et al.* [1993] have computed the residence time of OMZ in the Arabian Sea to be 10 ± 4 years using transient anthropogenic trace gas, trichlorofluoromethane. These authors suggested that near-zero oxygen concentrations are maintained by moderate consumption in waters of initially low oxygen content, which pass through the intermediate layer at a moderate speed [*Olson et al.*, 1993].

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[3] The intermediate waters of the Arabian Sea have three important sources: Persian Gulf and Red Sea out flows and South Indian Ocean waters. Northern flow of oxygen rich South Indian Ocean waters has been observed at equator in a depth range of 500–1000 m [*Quadfasel and Schott*, 1982; *Sharma*, 1976]. *Warren* [1981] described high salinity oxygen rich water formation and sinking in the southern part of the gyre, 30°–40°S, which can be found further north in the top several hundred meters.

[4] Joint Global Ocean Flux Study (JGOFS) revealed that seasonal variability in oxygen levels in the subsurface waters of the central and eastern Arabian Sea is small but found to be more reducing during NE monsoon in the eastern Arabian Sea [*de Sousa et al.*, 1996; *Sarma*, 1999]. On the other hand, no significant variability has been observed in the western Arabian Sea [*Morrison et al.*, 1999]. The existence of such reducing conditions lead to intense denitrification that amounted to a nitrate deficit of 10–12 μM in intermediate layers of the Arabian Sea during monsoon seasons [*de Sousa et al.*, 1996; *Howell et al.*, 1997; *Morrison et al.*, 1998]. Interestingly, although productivity showed large variability [*Bhattathiri et al.*, 1996; *Barber et al.*, 1998] the suboxic conditions prevailed in all seasons. Therefore, the influence of productivity does not seem to be a major controlling factor to determine the strength of OMZ in the Arabian Sea, but the effect of physical processes is not clearly known. Seasonal variability in rates of oxygen supply to the OMZ and respiration in this zone are yet to be known. Based on Indian- and US-JGOFS data, seasonally interpolated oxygen data based on the study of *Levitus* [1994] and water transports using Modular Ocean Model (MOM) results, an attempt has been made here to construct oxygen budgets on a monthly basis to understand the roles of physical and biogeochemical processes in meeting the oxygen demands and in maintaining perennial OMZ in the Arabian Sea.

2. Model Description

[5] The objective of this attempt is to quantify supply and demands of oxygen by physical and biological process in a box considered for the study region. The physical pump is driven by oxygen transported by different physical forcing such as upwelling, convective mixing, and water mass transports. Here, fluxes from the marginal seas (Persian Gulf and Red Sea) and southern Indian Ocean are included. The biological pump involves oxygen production during organic matter synthesis and consumption during regeneration. Most of the organic matter (85–95%) decomposes in surface layers itself and only the remaining sinks to the subsurface layers where it continues to be remineralized by bacteria [*Eppely and Peterson*, 1979]. The relative efficiency of these pumps and residence time of the organic matter in intermediate layers determine oxygen levels in the OMZ.

[6] The box was considered with 10°N as southern boundary while eastern and northern boundaries are closed with landmasses (Figure 1). In the west, the study area is open to exchanges with Persian Gulf and Red Seas. Since the OMZ in the Arabian Sea prevails in the depth range of 100–1000 m, upper and lower boundaries are selected as 100 and 1000 m, respectively. The physical pump was constructed based on water transports obtained from MOM (http://www.cmmacs.ernet.in/cgi-bin/climate_server) and oxygen data of JGOFS (http://usjgofs.whoi.edu/jg/dir/jgofs/) and also the climatology described by *Levitus* [1994] (http://ingrid.ldgo.columbia.edu/SOURCES/.LEVITUS94). The physical model is based on MOM Ver 2 [*Bryan*, 1969; *Pacanowski*, 1995]. In this three-dimensional model bottom topography was represented with multiple subgrid scale mixing options for Indian Ocean. The grid resolution was 0.5° in the longitude. In the latitude, it has a resolution of 0.33°. Twenty vertical levels were considered for this model with 10 in the top 100 m. More details of this model are given elsewhere [*Swathi et al.*, 2001]. The values for primary production and export used in the budgets presented here were taken from the works of *Bhattathiri et al.* [1996], *Barber et al.* [1998], *Buesseler et al.* [1998], and *Sarma et al.* [2000].

2.1. Physical Pump

[7] Physical pump plays a major role in the distribution of oxygen in the oceans. For instance, convective mixing during NE monsoon in the northern Arabian Sea injects oxygen-enriched waters to the subsurface layers. On the other hand, oxygen depleted subsurface waters are pumped into the surface layers by coastal and open ocean upwelling during SW monsoon. In addition to this, horizontal advection of the waters can significantly affect oxygen levels in the Arabian Sea. In the upper 1000 m of the water column, three major water masses have been found in the Arabian Sea. They are Persian Gulf Water (PGW) mass (occurs between 200 and 400 m with increasing depth towards the southeast), the Red Sea Water (RSW) mass (spreads at about 600 m in the north and 800 m near the equator [*Wyrtki*, 1971]), and south Indian Ocean water. PGW and RSW water masses form at the surface of the marginal seas and therefore are comparatively rich in oxygen.

2.1.1. Water Fluxes Within the Arabian Sea

[8] The horizontal transports of water are computed at different depth intervals viz., 100–150, 150–250, 250–500, and 500–1000 m and vertical transports across 100 and 1000 m depths using MOM results. Figures 2a–2f depict water transports along 10°N at different depth intervals and also across 100 and 1000 m boundaries of the box in the Arabian Sea. The water flow at 100–150 m along 10°N is northward (i.e., into the Arabian Sea) at the beginning of the year (January) that turns southward (i.e., out of the Arabian Sea) with very little flow during April–May. From June to December the flow is northward again at this depth range and maximum flow appears to occur in August (Figure 2a). On the contrary, the flow at 150–250 m is southward from January to May with $0.8–4 \times 10^{12}$ m^3 and June to December is the period of northward flow with maximal transport occurring from July to September with $\sim 2–9 \times 10^{12}$ m^3 $month^{-1}$ (Figure 2b). The flow direction at 250–500 m is the same as that of 150–250 m but the magnitude differs in its range from 4 to 11.4×10^{12} m^3 $month^{-1}$ from January to May while in June to October months it is reversed ($0.5–9.5 \times 10^{12}$ m^3 $month^{-1}$). The flow during November and December months on 250–500 m showed southward flow ($3–7 \times 10^{12}$ m^3 $month^{-1}$) (Figure 2c). On the other hand,

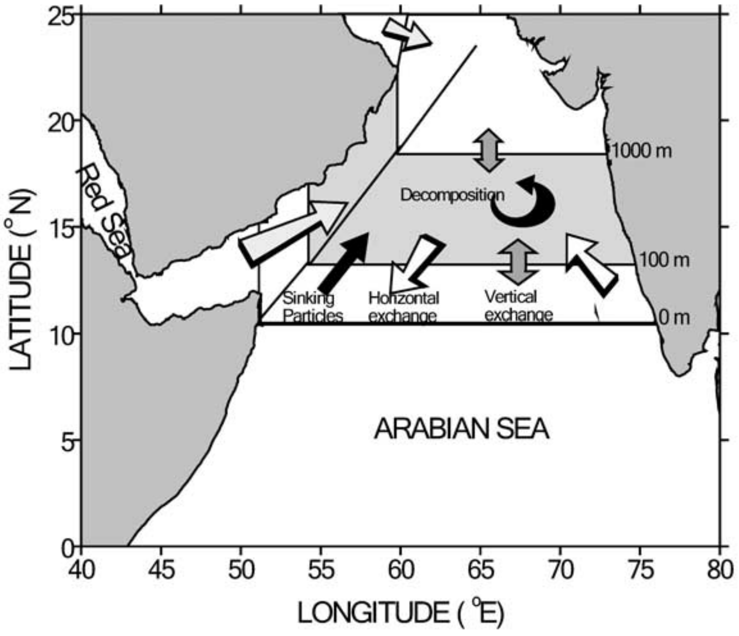

Figure 1. Schematic diagram showing the description of model and different sources and sinks of oxygen considered. The oxygen inputs across Red Sea and Persian Gulf are at 100–1000 m depth ranges.

the flow pattern in 500–1000 m is dominated toward south except in the period from June to August. The southern flow occurred with rates of 0.5–19 × 10^{12} m^3 $month^{-1}$ with higher rates at the beginning and end of the year in this depth range (Figure 2d). Overall, southward flow is dominant along 10°N except during summer monsoon when northward flow is dominant.

[9] The vertical flux pattern at the top boundary of the box (100 m) showed sinking of water (3–25 × 10^{12} m^3 $month^{-1}$) from January to April and October to December (13–32 × 10^{12} m^3 $month^{-1}$), whereas upwelling of the waters (5–47 × 10^{12} m^3 $month^{-1}$) occurs between May and September with the highest flow during June–July (Figure 2e). On the other hand, 1000 m boundary layer showed upwelling with 6–19 × 10^{12} m^3 $month^{-1}$ from January to July and sinking of 0.8–12 × 10^{12} m^3 $month^{-1}$ from August to December (Figure 2f).

[10] The net flow of water in the 100–1000 m box (Figure 1) in the Arabian Sea is presented in Figure 3. It shows that net flow is into the box (study area) in the upper 250 m with water transports of 49.5 × 10^{12} m^3 yr^{-1} (25.5 + 24.0) while the net southward flow occurred between 250 and 1000 m (115.4 × 10^{12} m^3 yr^{-1}; 29.0 + 86.4). The net flow along 100 m is outward (20.1 × 10^{12} m^3 y^{-1}), whereas 54.2 × 10^{12} m^3 y^{-1} of water is injected into the box across the deep boundary.

2.1.2. Exchanges With Marginal Seas

[11] The net combined marginal seas out flux amounted to 31.5 × 10^{12} m^3 yr^{-1} (Figure 3). *Morcos* [1970] computed the outflow of Red Sea based on estimates of the freshwater loss from the sea surface, which is, however, subject to salinities assumed for inflow and outflows. His estimation amounted to a net outflow of 14.5 × 10^{12} m^3 yr^{-1} for the Red Sea. The outflow of Persian Gulf has been computed to be 5.6 × 10^{12} m^3 yr^{-1} [*Olson et al.*, 1993]. Based on these estimates, marginal seas contribute a total influx into the study area of 20.2 × 10^{12} m^3 yr^{-1}. Hence, the presently estimated value (30.9 × 10^{12} m^3 yr^{-1}) is higher than the earlier reported.

2.1.3. Residence Time

[12] Residence time of waters in the suboxic zone (100–1000 m) of the Arabian Sea is estimated from residence time (t) = total volume of the study box/rate of water influx.

[13] Residence time of water in the suboxic layer is computed to be 6.5 years considering that 350 × 10^{12} m^3 yr^{-1} of water enters into the box from all boundaries of the box and 2268 × 10^{12} m^3 (100–1000 m) is the volume of the box. It is in agreement with 10 ± 4 years reported by *Olson et al.* [1993].

[14] In order to examine monthly variability in movement of waters in the suboxic zone, influx of water during different months has been considered (Figure 4). This figure suggests relatively slow movement of waters during nonmonsoon seasons, especially, April and September to November with influx of 10–22 × 10^{12} m^3 per month, whereas faster replacement of water occurs during June–July with influx of 45–47 × 10^{12} m^3 $month^{-1}$. Therefore, physical pump appears to be vigorous during biologically productive seasons (monsoons) compared with the low productive (nonmonsoon) seasons.

2.1.4. Oxygen Fluxes

[15] Oxygen fluxes, computed from the presently calculated net water transports, and mean oxygen concentrations

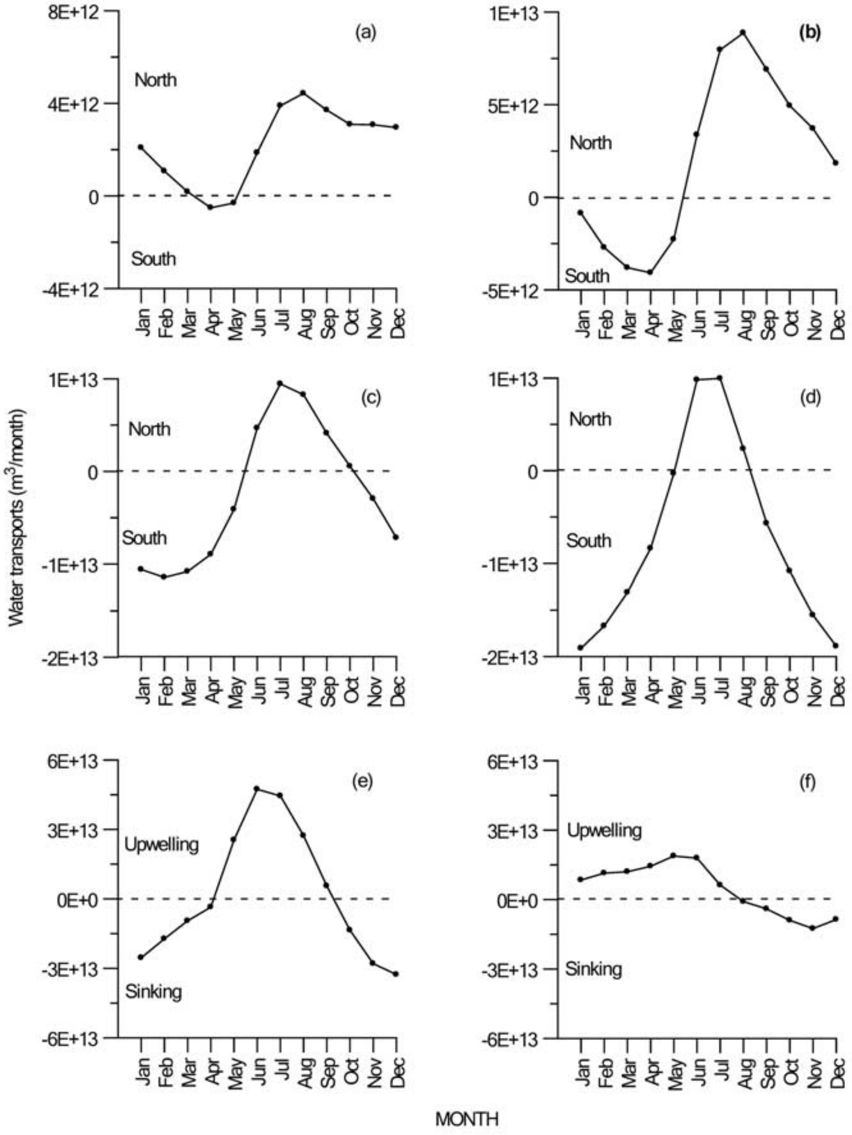

Figure 2. Lateral water transports at different depth ranges across 10°N at the depth levels of (a) 100–150, (b) 150–250, (c) 250–500, and (d) 500–1000 m and vertical transports across (e) 100 and (f) 1000 m in the Arabian Sea.

were averaged over different depth intervals along the sections. The amounts of average oxygen concentrations used along the box boundaries are given in Table 1. Figures 5a–5d show the flows of oxygen into and out of the box at different depth levels along 10°N. It can be observed from the Figure 3 that oxygen is injected through 100–150 and 150–250 m layers from the southern Indian Ocean that amounted to 43.7 and 62.5 Tg yr^{-1}, respectively, whereas 1.2 and 15.6 Tg yr^{-1} of oxygen, respectively, goes out of the box. On the other hand, the substantial oxygen exchange occurs out of the box at 250–500 and 500–1000 m layers accounting to 61.2 and 54.7 Tg yr^{-1}, respectively. However, it also receives comparatively small quantities of oxygen (33.5 and 14 Tg yr^{-1}, respectively) from the southern Indian Ocean. In addition to this, about 356 and 85.3 Tg of oxygen are being injected annually across the 100 and 1000 m boundary layers into the box, respectively, whereas 107.1 and 33.5 Tg of oxygen flows out of the box (Figure 3). The overall oxygen flux into the box across 10°N is 153.7 Tg yr^{-1} whereas 132.7 Tg yr^{-1} flows out. While a total of 441.5 Tg yr^{-1} of oxygen enters through vertical exchange 140.6 Tg yr^{-1} of oxygen goes out of the box. These results reveal that the dominant supply of oxygen to the suboxic layers in the Arabian Sea occurs through vertical exchange across 100 m. Moreover, Marginal Seas, Persian Gulf, and Red Sea, also supply significant quantities of oxygen (135.3 Tg yr^{-1}) to the intermediate layers of the Arabian Sea (Figure 3). Thus, physical pump suggests that about 733 Tg of oxygen enters the box annually while 273 Tg O_2 yr^{-1} goes out. These

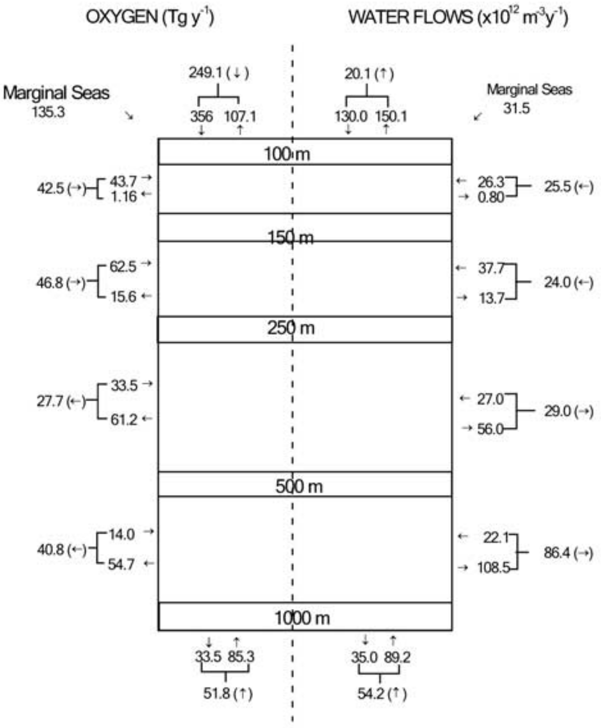

Figure 3. Net flows of water and oxygen at different depth levels in the box.

results suggest that 457 Tg of oxygen is consumed in the box annually.

2.2. Biological Pump

[16] Sinking of a part of the organic matter produced in surface layers and its oxidation in intermediate layers requires oxygen. Once oxygen levels fall below 5 μM l^{-1}, bacteria reduces nitrate to molecular nitrogen in order to meet their respiratory activity. *Naqvi* [1991] calculated the area of denitrification to be 1.37 × 10^{12} m^2 in the Arabian Sea. Although, denitrification occurs throughout the year [*de Sousa et al.*, 1996; *Morrison et al.*, 1998] anoxic conditions do not seem to set in as no H_2S was observed [*Deuser et al.*, 1978]. The extent of oxygen demand by different pools of carbon (dissolved and particulate) has been computed here using the observed O_2/C ratio. This ratio has been derived for suboxic waters (O_2 < 10 μmol kg^{-1}) in the Arabian Sea, using recently collected total carbon dioxide and dissolved oxygen data by US-JGOFS programs, to be 0.51 [*Millero et al.*, 1998].

2.2.1. Oxygen Demand by Sinking Organic Carbon

[17] Significant delay between monsoon driven primary production and export of particulate matter from the surface layers has been found [*Buesseler et al.*, 1998]. This delay may vary from 30 to 90 days depending on the relative balance between phytoplankton production and zooplankton grazing. The percentage of surface organic carbon reaching 100 m varies from 7.0 to 8.2% along the west coast of the Arabian Sea and from 4.3 to 4.7% in the central Arabian Sea [*Lee et al.*, 1998]. *Buesseler et al.* [1998] observed the sinking fluxes of carbon, based on ^{234}Th export, at the same depth to be 0.6–7.0, 0.3–8.5, 0.8–17.1, and 2.5–25.8 mmole C m^{-2} d^{-1} during NE-, Spring inter-, mid SW-, and late SW-monsoon, respectively, in the western Arabian Sea. On the other hand, ^{234}Th export fluxes amounted to 12.5, 15, and 16.6 mmole C m^{-2} d^{-1} during NE-, Inter-, and SW-monsoon seasons, respectively, in the central and eastern Arabian Sea at 130 m depth [*Sarma et al.*, 2000]. The difference in sinking fluxes in the eastern and western basin of the Arabian Sea could be due to spatial variability in surface productivity. Based on these data, the export fluxes in the entire basin was computed to be 2.2–46, 1.1–55.2, and 3.0–95 Tg season^{-1}, respectively, during NE-, Inter-, and SW-monsoon seasons. The annual sinking carbon at 100 m, therefore, amounts to 6.3–196.2 Tg C. *Lee et al.* [1998] found about 0.2–1 mmole C m^{-2} d^{-1} to sink to 1000 m. Extrapolation of this value to the study region (2.52 × 10^{12} m^2) yields 2.2–11 Tg yr^{-1}. Hence, 4–185 Tg of net sinking particulate carbon appears to get remineralized in the suboxic layers of the Arabian Sea annually. This results in 5.4–251 Tg yr^{-1} of oxygen consumption in the intermediate layers.

2.2.2. Oxygen Demand by Dissolved Organic Carbon

[18] The vertical distribution of dissolved organic carbon (DOC) suggests utilization by the subsurface bacteria [*Kumar et al.*, 1990; *Hansell and Peltzer*, 1998]. Surface DOC concentrations varied from 70 to 90 μM, whereas it decreased to ~40 μM below the mixed layer [*Hansell and Peltzer*, 1998]. *Naqvi* [1994] observed that the intense subsurface bacterial carbon demand (340 mg C m^{-2} d^{-1}) cannot be met by the sinking organic matter (188 mg C m^{-2} d^{-1}) alone. He hypothesized that supply of DOC from the southern Arabian Sea supports high bacterial demand, whereas lateral transport of carbon from the shelf regions was proposed by *Somayajulu et al.* [1996]. Though most of

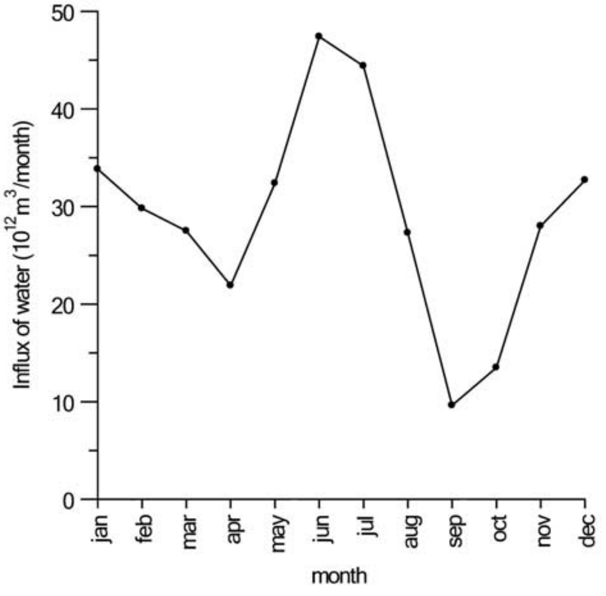

Figure 4. In flux of waters into the box from all boundaries during different months.

Table 1. Concentrations of Oxygen at Different Depth Levels Along 10°N in the Arabian Sea During Different Months[a]

Month	Depth Level, m					
	100–150	150–250	250–500	500–1000	100	1000
January	1.43	1.14	1.07	0.48	2.99	0.95
February	1.43	1.14	1.07	0.48	2.99	0.95
March	1.43	1.14	1.07	0.48	2.99	0.95
April	1.43	1.14	1.07	0.63	2.56	0.95
May	1.43	1.14	0.99	0.63	0.71	0.95
June	1.43	1.14	0.99	0.63	0.71	0.95
July	1.71	1.71	0.99	0.63	0.71	0.95
August	1.71	1.71	1.28	0.63	0.71	0.95
September	1.71	1.71	1.28	0.63	0.71	0.95
October	1.71	1.71	1.28	0.48	2.56	0.95
November	1.71	1.71	1.28	0.48	2.56	0.95
December	1.71	1.71	1.28	0.48	2.56	0.95

[a] Concentrations of oxygen are averaged levels given in g m^{-3}.

the DOC in the suboxic layers is refractile at least 10% of DOC is assumed to be labile and can be utilized by bacteria.

[19] Based on the presently estimated water transports and average DOC concentrations of 90 μM in the top 100 m and 40 μM in the range of 100–1000 m [*Hansell and Peltzer*, 1998], DOC budget has been constructed. Here TOC concentrations reported by *Hansell and Peltzer* [1998] have been assumed to represent DOC since POC concentrations are very low compared with DOC. This shows that the net transport of DOC through southern boundary is southward (i.e., out of the box which amounted to 32 Tg yr^{-1}), whereas intermediate layer receives 30 Tg yr^{-1} across 1000 m and 60 Tg yr^{-1} from 100 m boundaries. In addition to this, marginal seas inject 12 Tg of DOC yr^{-1}. The DOC originating in the surface layers is expected to contain significant percentage of labile fraction, whereas about 10% of the subsurface DOC is labile and the same is considered to be remineralized in this layer. Hence, the net annual remineralization of DOC amount to ~61Tg (60 + 1) in the suboxic zone that requires 83 Tg of oxygen per year. This amount should be considered approximate because DOC oxidation depends on the nature of the compound, i.e., refractory or labile. Further consumption rates of DOC and its nature in the Arabian Sea are not yet known.

2.2.3. Decomposition of Transparent Exopolymer Particles

[20] Recently *Kumar et al.* [1998] have made first ever measurements on transparent exopolymer particles (TEP) in the Arabian Sea. TEP consists of polysaccharides that are easily decomposable. TEP remains mostly in the suspended phase and cannot sink themselves like lithogenic particles. They need scavengers to remove them from the water column, and hence, their residence time in the water column is more. TEP seems to serve as a secondary source of carbon to the subsurface bacteria. Therefore, the reduced level of TEP in the suboxic zone is consistent with occurrence of secondary nitrite [*Kumar et al.*, 1998]. Their study suggested that part of the TEP is oxidized by denitrifiers in the Arabian Sea.

[21] TEP varied from 10 to 105 mg equivalents of alginic acid per liter in the suboxic waters of the Arabian Sea. This can be converted to carbon equivalents using the relation found by *Mari* [1999] using the size of the TEP

$$\text{TEP carbon} = 0.25 \times 10^{-6} r^{2.5}$$

where r is the radius of the particle (μm). Using an average TEP size of 10–20 μm and a number of TEP as 800–1000 ml^{-1}, the TEP carbon is computed to be 27–113 Tg C yr^{-1} using the residence time of suboxic waters (6.5 years). Considering the O_2/C, about 36.7–153.6 Tg of oxygen per year would be consumed to oxidize TEP in the suboxic waters.

2.2.4. Regeneration of Organic Carbon by Nitrate

[22] The Arabian Sea houses intense denitrifying zone in the world oceans [*Naqvi*, 1994]. It was estimated that the loss of nitrate due to denitrification amounts to 6–12 μM in the northern Arabian Sea during different seasons [*de Sousa et al.*, 1996; *Morrison et al.*, 1998]. *Millero et al.* [1998] have constructed stoichiometry for the phytoplankton in the Arabian Sea. They suggested that about 77% of plankton material is oxidized by oxygen, whereas 23% is done by NO_3 with the resultant formation of N_2 and N_2O. The amount of organic carbon oxidized by NO_3 is computed to be 2.5–3.0 μM kg^{-1} in the OMZ [*Millero et al.*, 1998]. Based on these values and considering the area of denitrification in the Arabian Sea to be 1.37×10^{12} m^2 [*Naqvi*, 1991] and residence time of 1 year for denitrifying zone [*Somasundar and Naqvi*, 1988], 37–45 Tg C yr^{-1} is oxidized by NO_3.

2.2.5. Estimation of Oxygen Demand by Organic Carbon Regeneration Using Water Mass-Mixing Model

[23] Most of the organic detritus decompose in the upper 1000 m [*Suess*, 1980] that result in the removal of oxygen from the water column in this depth range. Low oxygen concentrations in intermediate layers of the northern Arabian Sea in all seasons [*de Sousa et al.*, 1996; *Morrison et al.*, 1999] is interpreted to be a result of higher inputs of organic matter from the surface layers.

[24] Based on water mass-mixing model of *Kumar and Li* [1996], regenerated carbon dioxide in the Arabian Sea was computed during different seasons. The regeneration of soft tissue showed significant seasonal variability, which is again in agreement with observed oxygen levels [*Sarma*, 1999]. On an average, it amounted to a CO_2 release of 60–120 μM in the suboxic layer. During all the seasons there was a clear increasing trend of regenerated CO_2 toward northern Arabian Sea at any depth level in the upper 1000 m. In order to find the amount of regenerated carbon dioxide in the subsurface layers, the same has been integrated from 100 to 1000 m for the entire box. Release of CO_2 by soft tissue regeneration amounted to 1.6–3.2 Pg C (1 Pg = 10^{15} g) in the suboxic layers of the Arabian Sea. Using the ventilation time of 6.5 years, it is possible to estimate the rate of organic carbon oxidation in the subsurface layers. This yields an annual decomposition of 250–502 Tg C yr^{-1}. This includes the organic carbon that has been oxidized by nitrate as oxidant that amounts to 37–45 Tg C yr^{-1} (see section 2.2.4). Hence, the net organic carbon decomposition by oxygen amounts to 213–457 Tg C yr^{-1}. This suggests that

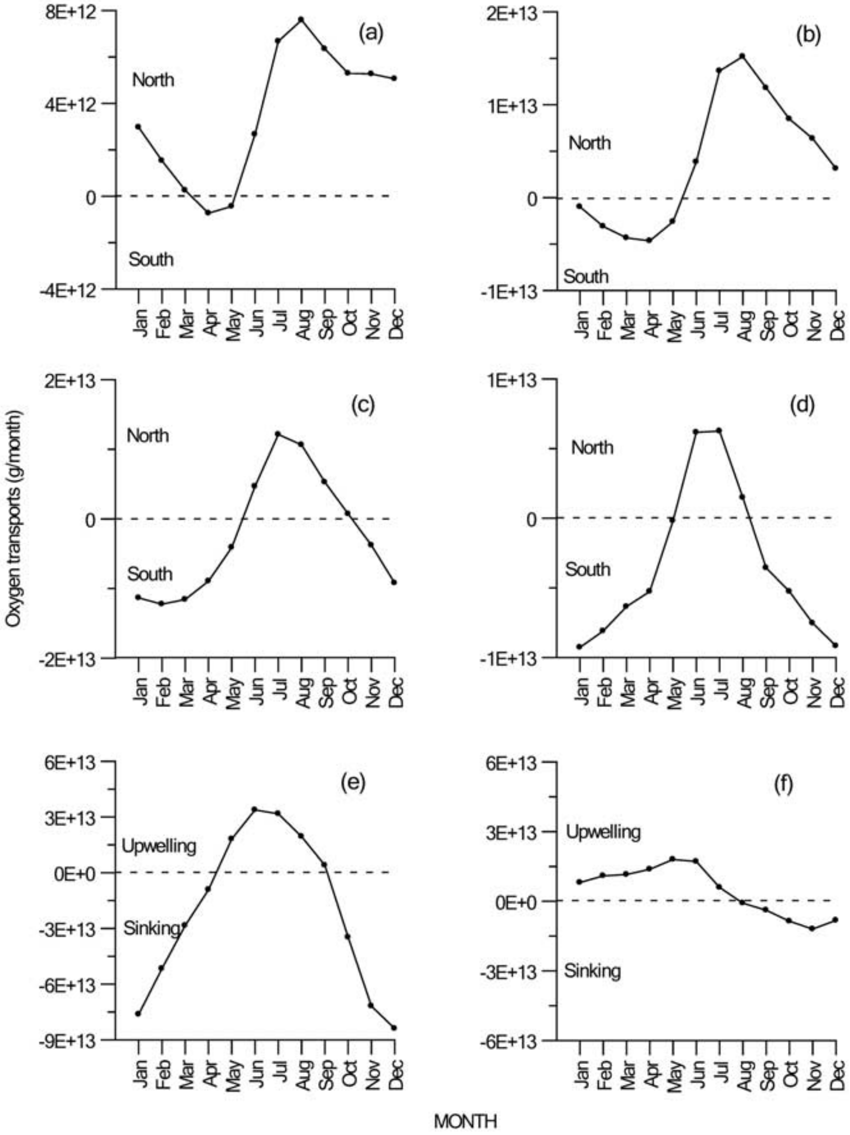

Figure 5. Oxygen transports at different depth levels along 10°N at the depth levels of (a) 100–150, (b) 150–250, (c) 250–500, and (d) 500–1000 m and vertical transports across (e) 100 and (f) 1000 m in the Arabian Sea.

289–621 Tg of oxygen per year (an average of 455 Tg yr^{-1}) is required to meet the respiratory demands in the intermediate layer of the Arabian Sea. This is consistent with the oxygen consumption of 457 Tg yr^{-1} computed from the present budget evaluation.

2.2.6. Loss of Oxygen to the Sediment/Sedimentary Respiration

[25] Continental margin sediments are important areas of organic carbon oxidation and also depocenters for organic carbon [*Grant et al.*, 1987; *Walsh*, 1991; *Walsh et al.*, 1985]. The carbon rain rate to the slope and rise sediments are mostly derived from primary production [*Walsh et al.*, 1985; *Christensen*, 1989; *Jahnke et al.*, 1990]. Due to various pathways by which organic matter can be oxidized margin sediments are important areas for the biogeochemical cycling of oxygen. Despite the obvious importance of margin sediments in the global cycles of many elements, there have been a few studies elsewhere in the Atlantic and Pacific Oceans, but absolutely no information is available on the benthic fluxes of elements from the Indian Ocean. In order to find the loss of oxygen into the sediments, I have used the equation given for computation of oxygen flux using bottom water oxygen and organic carbon contents on the core top by *Cai and Reimers* [1995]. They have formulated a general and quantitative correlation between benthic oxygen flux ($F\mathrm{O}_2$; μmole $\mathrm{cm}^{-2}\ \mathrm{yr}^{-1}$), bottom water oxygen concentration ($[\mathrm{O}_2]_{\mathrm{BW}}$; μmole kg^{-1}), and core top organic carbon content ($\mathrm{C}_{\mathrm{org}}\%$) in the deep northeast Pacific Ocean

$$F\mathrm{O}_2 = \left(\pi \mathrm{C}_{\mathrm{org}}[\mathrm{O}_2]_{\mathrm{BW}}\right) / \left(126 + [\mathrm{O}_2]_{\mathrm{BW}}\right)$$

where π = 44.4 μmole cm^{-2} yr^{-1} (% dry organic C)$^{-1}$. Environments described by this equation include suboxic basins, the continental slope, the continental rise, and oxic open ocean sediments.

[26] Considering the average C_{org} in the continental slopes as 0.2–2% [*Paropkari et al.*, 1992] and bottom water oxygen as 40 μmole kg^{-1} [*Rao et al.*, 1994], the flux of oxygen to the sediments was computed to be 21–214 mmole m^{-2} yr^{-1}. Considering the area of the water column depth above 1000 m as 0.77 × 10^{12} m^2, the oxygen loss into sediments was computed to be 0.52–5.3 Tg yr^{-1}.

3. Discussion

[27] According to *Swallow* [1984] sluggish circulation is the main process responsible for the intense OMZ in the Arabian Sea. However, the present model results reveal the influence of biology along with its strong coupling with physical processes in maintaining the intensity of the OMZ in the subsurface waters throughout the year. *Olson et al.* [1993] suggested that despite the large surface productivity during summer monsoon, the associated regeneration in the suboxic layers does not necessarily make large oxygen demand. In order to examine the effect of biological processes on OMZ, consumption rates of oxygen have been derived here as the difference between in and out fluxes of oxygen. Monthly consumption rates (Figure 6) show wide variability from 10 to 54.4 Tg of oxygen per month with maximal utilization during November-February (NE monsoon; 43–54.4 Tg $month^{-1}$) followed by June–August (SW monsoon; 31–46 Tg $month^{-1}$). Minima were observed during nonmonsoon periods (April and September–October; 10–43 Tg $month^{-1}$). *Sarma* [1999] has noted the occurrence of the lowest dissolved oxygen in subsurface layers during NE and SW monsoons in the eastern and central Arabian Sea that varied between under detection limits and 2–5 μM, respectively. However, they ranged from 5 to 20 μM during inter-monsoon. Even though, primary productivity is lower by 3–4 times in inter-monsoon to that of monsoons, the oxygen minimum is intense during this season as well. This suggests that physical processes play an important role in sustaining oxygen minimum in nonmonsoon seasons. In order to examine this effect, replacement time of waters in the suboxic zone in the Arabian Sea is examined. Figure 4 shows that replacement of water to the suboxic layers is much faster during monsoons compared with the nonmonsoon seasons. As a result, supply of oxygen to the box during nonmonsoon season is much lower (20–65 Tg $month^{-1}$) compared with monsoons (52–84 Tg $month^{-1}$). Since physical pump supplies less oxygen to the suboxic zone, thus, oxygen minimum is maintained during oligotrophic seasons as well. This suggests that the circulation and productivity patterns together sustain low oxygen levels throughout the year in the Arabian Sea.

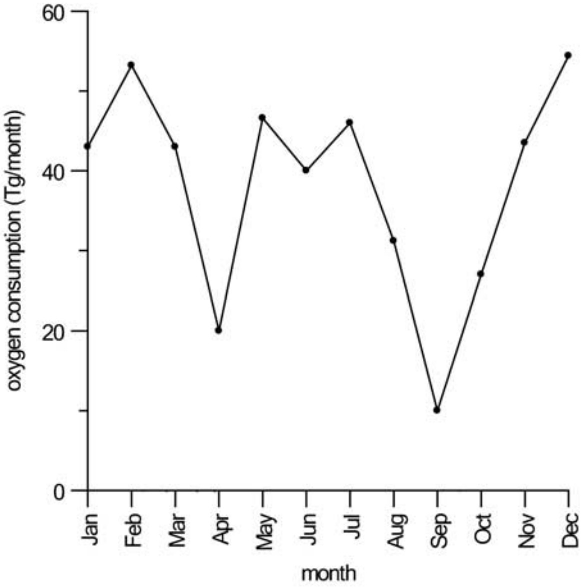

Figure 6. Consumption rates of oxygen in the box during different months.

[28] In addition to this, the observed seasonal variability in intensity of the OMZ can also be explained based on the circulation pattern. More intense OMZ and reducing conditions prevailed during NE monsoon leading to the highest nitrate deficits (10–12 μM) in the northern Arabian Sea [*de Sousa et al.*, 1996; *Morrison et al.*, 1998] in comparison with other seasons. This could result from combined effect of enhanced surface productivity and convective mixing. The water flow in the 100–1000 m range is toward equator (Figure 2). These waters are already depleted in oxygen, hence, physical pump supplies very low quantities of oxygen to the OMZ across 10°N. Enhanced sinking organic carbon fluxes to the OMZ also drive higher oxygen demand in the subsurface layers in NE monsoon. On the other hand, comparatively less reducing conditions in the SW monsoon [nitrate deficit 8–10 μM; *de Sousa et al.*, 1996] can be attributed to the entry of southern Indian Ocean waters to the OMZ, which are comparatively enriched with oxygen [*Swallow*, 1984; Figure 2]. Despite high productivity in the surface layers and the consequent sinking of organic matter to the OMZ during SW monsoon, the OMZ is not as intense as it is during the NE monsoon. This is due to higher supply of oxygen by physical pump compared with that in NE monsoon due to northward movement of waters. On the contrary, though subsurface layers receive waters from the northern Arabian Sea during inter-monsoon the surface productivity is very low that results in less reducing conditions in the OMZ with low nitrate deficit of 6–8 μM [*de Sousa et al.*, 1996].

[29] The oxygen budget computed using different methods is presented in Table 2. The oxygen consumption in the suboxic layers was found to be 457 Tg yr^{-1} based on the physical pump. About 0.5–5.3 Tg yr^{-1} of oxygen is consumed during sedimentary respiration. Hence, a net 452–456.5 Tg of oxygen is utilized in the subsurface waters of the Arabian Sea annually. The amount of carbon dioxide released due to decomposition of soft tissue (213–457 Tg C yr^{-1}) consumes 289–621 Tg of oxygen, with an average of 455 Tg, annually. This value obtained from the water mass-mixing model, which is in good agreement with the consumption rates of oxygen (452–456.5 Tg yr^{-1}) obtained from budget calculations (Table 2). The oxidation of DOC,

Table 2. Oxygen Demand in the Suboxic Waters of the Arabian Sea Using Physical, Chemical, and Biological Methods

Method	Oxygen Demand, Tg yr^{-1}	Reference
Physical pump	452–456.5	this work
Organic carbon regeneration based on water mixing model	289–621	*Sarma* [1999]
Organic carbon regeneration, using DOC, POC, and TEP	75–427	*Lee et al.* [1998], *Hansell and Peltzer* [1998], and *Kumar et al.* [1998]
Bacterial consumption	105–610	*Ducklow* [2000]
Based on ETS	142–992	*Naqvi and Shailaja* [1993]
Redfield ratios	96.5–488	*Millero et al.* [1998]

suspended TEP, and sinking carbon flux requires 83, 36.7–153.6 and 5.4–251 Tg of oxygen, respectively, in the OMZ annually (see sections 2.2.1–2.2.4). Thus, 125–487.6 Tg of oxygen is required to decompose different pools of organic carbon in the study area. On the other hand, 37–45 Tg of carbon is decomposed by nitrate annually, however, the amount of each carbon pool that is involved in the oxidation by nitrate is not known. Nevertheless, I have computed the oxygen demand to decompose organic carbon in the suboxic layer by subtracting the organic carbon oxidized by nitrate from that of total organic carbon oxidized. As it is described in sections 2.2.1–2.2.4, 92–359 Tg of organic carbon (sinking organic carbon, DOC, and TEP) has been oxidized annually in the OMZ. By removing 37–45 Tg C yr^{-1}, the net organic carbon oxidized by oxygen amounts to 55–314 Tg C yr^{-1} and it consumes ~75–427 Tg of oxygen annually using the O_2/C. Recently, *Millero et al.* [1998] evaluated Redfield ratios for the suboxic waters of the Arabian Sea using US-JGOFS data set and suggested that about 77% of the organic carbon is oxidized by oxygen and remaining fraction by nitrate. Based on this estimate, about 71–276 Tg of carbon is oxidized by oxygen annually (total organic carbon oxidized 92–359 Tg C yr^{-1}). This consumes 96.5–488 Tg yr^{-1} oxygen in the suboxic waters of the Arabian Sea based on Redfield ratio. The difference between consumption rates of oxygen computed based on budget, water-mass mixing model, different pools of organic carbon, and Redfield ratios could be due to inadequate knowledge of the nature of DOC and carbon pool of TEP. Because of the disagreement between oxygen consumption obtained from present model and input of organic matter to the subsurface layers, biological oxygen demand has also been computed independently from the bacterial activities and oxygen consumption rates computed using electron transport system (ETS) measurements in the suboxic zone. *Naqvi* [1994] and *Azam et al.* [1994] have observed that bacterial carbon demand in the suboxic layers is much higher than sinking fluxes of carbon from the euphotic zone. *Banse* [1994] and *Naqvi* [1994] have computed the bacterial production in the suboxic zone of the Arabian Sea to be 105–157 mg C m^{-2} d^{-1}. Considering the bacterial efficiency of 20%, bacterial respiration is computed to be 420–628 mg C m^{-2} d^{-1}, which amounts to an oxygen demand of 525–785 Tg yr^{-1}. In contrast, *Ducklow* [2000] reported the bacterial production in the suboxic waters of the Arabian Sea to be 21–122 mg C m^{-2} d^{-1} that leads to a carbon respiration of 84–488 mg C m^{-2} d^{-1} and oxygen demand of 105–610 Tg yr^{-1}. Present estimation of oxygen demand (452–456.5 Tg yr^{-1}) is in agreement with bacterial carbon demand, indicating that the oxidation of organic carbon in the suboxic zone of the Arabian Sea is much higher than expected from sinking particles and DOC fluxes.

[30] *Naqvi and Shailaja* [1993] have measured oxygen consumption rates using ETS in the Arabian Sea and Bay of Bengal. They found that a subsurface maximum in ETS activity generally occurred within the denitrifying layer in the Arabian Sea. The ETS activity was found to be higher in the Arabian Sea than in the Bay of Bengal suggesting higher respiration rates in the former basin. Despite several uncertainties involved in the conversion of ETS to oxygen consumption rates, however, it was observed that about 5–35 nl l^{-1} h^{-1} oxygen is consumed in the suboxic waters of the Arabian Sea. The extrapolation of this value to the entire suboxic zone results in oxygen utilization of 141–992 Tg yr^{-1} (average 566 Tg yr^{-1}) in the Arabian Sea. This estimate is comparatively higher than the present estimate of oxygen demand (452–456.5 Tg yr^{-1}), probably could be due to unavailability of ETS measurement data in nondenitrifying waters in the Arabian Sea where oxygen consumptions are expected to be lower than denitrifying waters. Nevertheless, oxygen demand based on present model is within the range of estimation based on independent estimates of bacterial activities and oxygen utilization rates using ETS measurements.

4. Conclusions

[31] Despite the strong variability in the productivity in time and space, the OMZ in the subsurface waters of the Arabian Sea is intense throughout the year with not so great seasonal variability. The model results revealed that physical processes associated with biogeochemical cycling of carbon and oxygen regulate OMZ in the Arabian Sea. Although sinking organic carbon fluxes are low during nonmonsoon, OMZ is maintained by low supply of oxygen by the physical pump. The residence time of subsurface waters was found to be 6.5 years. The replacement of subsurface waters seems to be rather fast during monsoons compared with nonmonsoons. The oxygen consumption rates were higher during monsoons compared with nonmonsoon seasons that are in agreement with productivity pattern. The regeneration of carbon by soft tissue, computed based on the water mass-mixing model, subsurface bacterial carbon demand, and oxygen consumption rates determined using ETS activity are in agreement with

oxygen consumption rates estimated based on oxidation of carbon pool. Inadequate knowledge of nature of DOC and TEP might have caused disagreement between model consumption rates and that computed from organic carbon fluxes. It is suggested that the coupling between physical and biogeochemical processes are responsible for the sustenance of perennial OMZ in the Arabian Sea.

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