Existence of perennial oxygen minimum zone in the northern Indian Ocean

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Introduction

Existence of oxygen minimum zone (OMZ) in the water column is found in three major areas in the World Oceans. They are the eastern tropical North Pacific, the eastern tropical South Pacific and the northwestern Indian Ocean [Naqvi, 1994]. The northern Indian Ocean is bounded by landmass in the north, east and west resulting in a sluggish renewal of subsurface waters, giving rise to acute oxygen depletion at the intermediate depths. Though geographical setting are same in both Arabian Sea and Bay of Bengal, however, intense OMZ and denitrification occurs in the Arabian Sea, on the contrary, less intense OMZ and no denitrification is found in the Bay of Bengal [Rao et al., 1996]. It has been thought previously that appreciable changes in the composition of subsurface waters may be caused by the seasonal reversal of water circulation. However, it is unknown to what extent these changes would affect the composition of subsurface waters in the northern Indian Ocean. This issue is an important since it can possibly explain the differences in the biogeochemical cycling of carbon and oxygen in these two regions.

The seasonal variability in oxygen levels in the subsurface is found to be small in the Arabian Sea [Morrison et al., 1999] and Bay of Bengal [Sarma and Narvekar, 2000]. The existence of such reducing conditions lead to intense denitrification in the Arabian Sea that amounted to a nitrate deficit of 10-12 μM in intermediate layers of the Arabian Sea. Despite large variability in productivity [Barber et al., 1998] the sub-oxic conditions prevailed during all seasons in both the regions. Therefore, it is suggested that the influence of productivity does not seems to be a major controlling factor to determine the strength of OMZ in the northern Indian Ocean. The potential influencing factor could be physical processes, however, it is not known. Based on Indian, US-JGOFS, WOCE and other available data sets (Fig. 1),- Levitus [1994] climatology and water transports using Modular Ocean Model (MOM), an attempt has been made here to construct oxygen budgets to understand perennial existence of OMZ in the northern Indian Ocean.

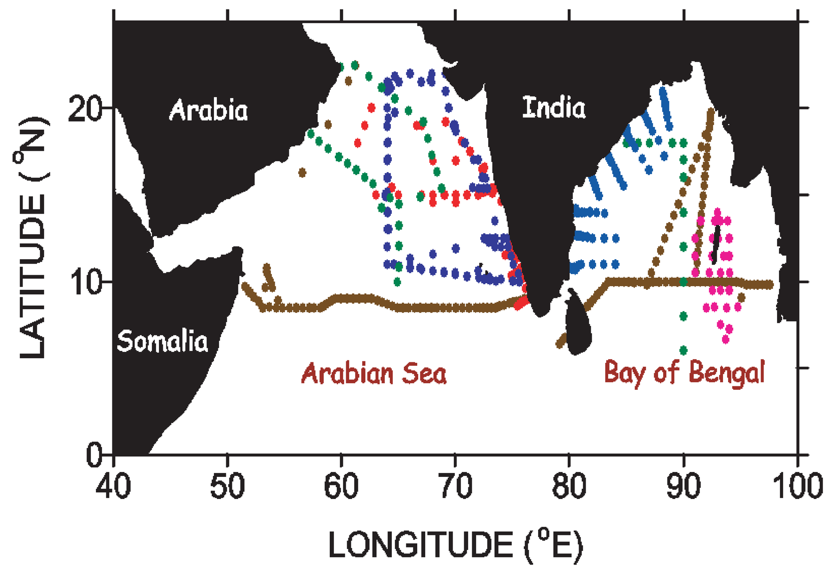

Figure 1: The station locations of the data used in the model

Model description

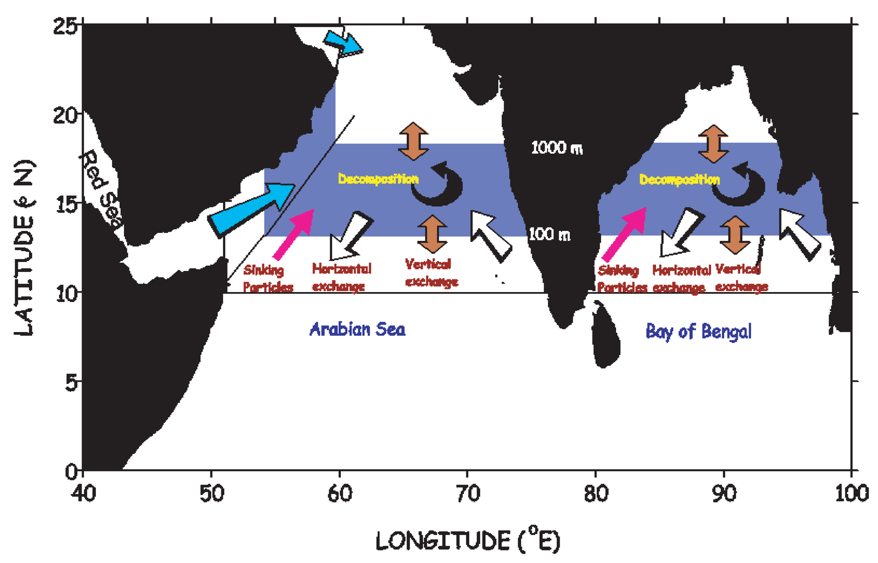

Figure 2. Schematic of the O2 model in the northern Indian Ocean

The 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 northern Indian Ocean (Fig. 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. The oxygen content in the subsurface layers is controlled by efficiency of the biological pump and residence time of organic matter in the intermediate layers. The model domain is constructed by closing the eastern, western and northern boundaries of each basin while the southern boundary is opens to Indian Ocean at 10N where exchanges take place. However, the Arabian Sea has two northern sources from the marginal seas (Persian Gulf and Red Sea) and the exchange of oxygen from these seas is considered. Since low oxygen levels prevail at the depth range of 100-1000 m in the northern Indian Ocean, 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° x 0.3 longitude to latitude with 20 vertical levels. Biological pump is constructed based on sinking fluxes [Ittekkot et al., 1991], bacterial respiration [Ducklow et al., 2000] and electron transport system (ETS) measurements [Naqvi et al., 1996]. The regeneration rates of organic matter are computed using the watermass 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].

Oxygen budget

The annual average oxygen transport along different depth levels in the Arabian Sea and Bay of Bengal are presented in Figure 3. It shows that the major source of oxygen to the subsurface waters is found to be vertical mixing at 100 m in the Arabian Sea (249 TgO2 y-1) which is five times higher than in the Bay of Bengal (42.5 TgO2 y-1). This is probably due to inhibition of vertical mixing in the upper layers due to low salinity river water in the surface layers in the Bay of Bengal. On contrary to this, supply of oxygen from the bottom layer (1000 m) is found to be higher in the Bay of Bengal (64.9 TgO2 y-1) compared to the Arabian Sea (51.8 TgO2 y-1). This is concurrence with the observations of Kumar and Li [1996] who found that more than 10% of Antarctic Bottom water mass (AABW) enters to the Bay of Bengal than the Arabian Sea. Furthermore, oxygen levels at 1000 m are higher in the Bay of Bengal (>60 μmol kg-1) compared to the Arabian Sea (~20 μmol kg-1). The supply of oxygen through horizontal advection was found to be significant in the Arabian Sea with net input of 20.8 TgO2 y-1, whereas net loss of 26.5 TgO2 y-1 occurs in the Bay of Bengal. As a whole, oxygen supply through vertical mixing at 100 and 1000 m boundaries dominates compared to horizontal advection in the northern Indian Ocean.

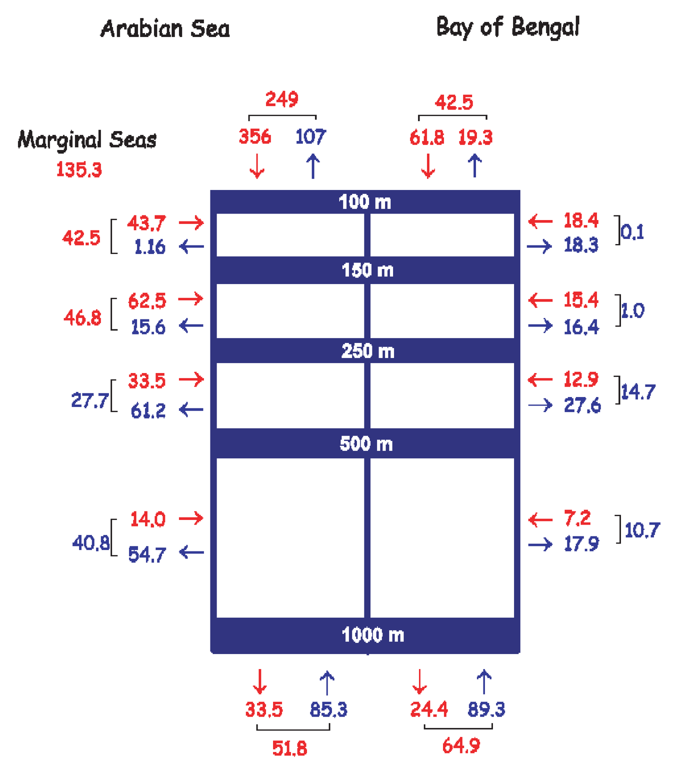

Figure 3: Net flows of oxygen fluxes at different depth levels in the box in the northern Indian Ocean

Residence time of waters in the OMZ (100-1000 m) of the Arabian Sea and Bay of Bengal is computed from

Residence time (t)=total volume of the study domain (box)/rate of water influx

Residence time of water in the 100-1000 m depth layer is computed to be 6.5 and 12 years in the Arabian Sea and Bay of Bengal respectively. This is consistent with the same estimated using CFC tracers.

Oxygen consumption rates

In order to understand the effect of biological processes on OMZ, consumption rates of oxygen have been computed as a product of the difference between the in and out fluxes of oxygen in to/from the OMZ. The net loss, thus, would represent oxygen consumed in the OMZ. The monthly variability in oxygen consumption rates are consistent with the primary productivity and sinking fluxes of organic carbon in the Arabian Sea, which is lower during non-monsoon seasons (April, September and October) compared to other months (Fig. 4). On the contrary, the monthly variability in O2 consumption rates cannot be explained by productivity alone in case of Bay of Bengal. It is because primary productivity is higher during the SW monsoon (June-September) followed by NE (November-February) and inter-monsoon (March-May and October) seasons, contrary to this, oxygen consumption rates increased from February to December in the Bay of Bengal. It was found that Bay of Bengal receives enormous amount of fresh water, nutrients, and suspended load from the sediments of the shelf region that affects biogeochemical cycling of carbon [Ittekkot et al., 1991]. The monthly variability in the consumption rates is consistent with changes in total sinking fluxes (i.e., mass fluxes) at 1000 m depth. Figure 5 shows that higher fluxes (100-400 mg m-2 d-1) in the 1000 m traps during June to November in the northern and central Bay of Bengal, which is consistent with the period of high discharge from Ganges and Brahmaputra rivers. These results suggest that inputs from terreginous 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 suggests that physical pump supplies more oxygen to the OMZ during the period of high oxygen demand and vice versa result in perennial existence of OMZ in the northern Indian Ocean.

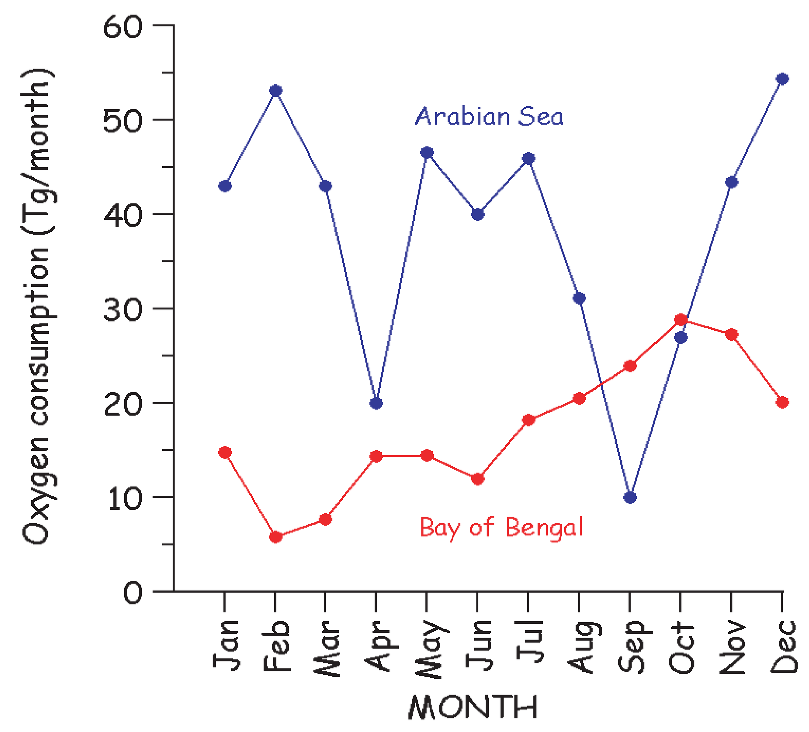

Figure 4: Monthly variability in O2 consumption rates

Despite higher residence time of waters and high sinking fluxes of organic carbon in the Bay of Bengal [2.04-3.59 gC m-2 y-1; Ittekkot et al., 1991] than Arabian Sea [1.53-1.80 gC m-2 y-1; Nair et al., 1989], the oxygen concentrations are low in the latter basin. In addition to this high column productivity is found in the Arabian Sea (1064x106 tonnesC y-1) compared to the Bay of Bengal [394 x 106 tonnesC y-1; Qasim, 1977]. It has been attributed that scavenging of organic matter from the water column in association with mineral particles result in less residence time of organic carbon in the water column in the Bay of Bengal [Ittekkot et al., 1991]. This may also explain why large quantities of labile organic matter reach the deep sea floor of Bay of Bengal and producing the near-bottom anomalies observed by Broecker et al. [1980]. This suggests that though bacterial counts are much higher in the Bay of Bengal (4.3-10.45 x 104 per ml) compared to the Arabian Sea (1.3-3.4 x 104 per ml; Kumar et al. [1998]), however, 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 Tg y-1) than in the Arabian Sea (458 Tg y-1) Table 1 shows the oxygen consumption computed based on different techniques and they are comparable with the present model estimates. However, in agreement found in the Bay of Bengal mainly due to lack of seasonal data to evaluate oxygen consumption rate by alternative methods.

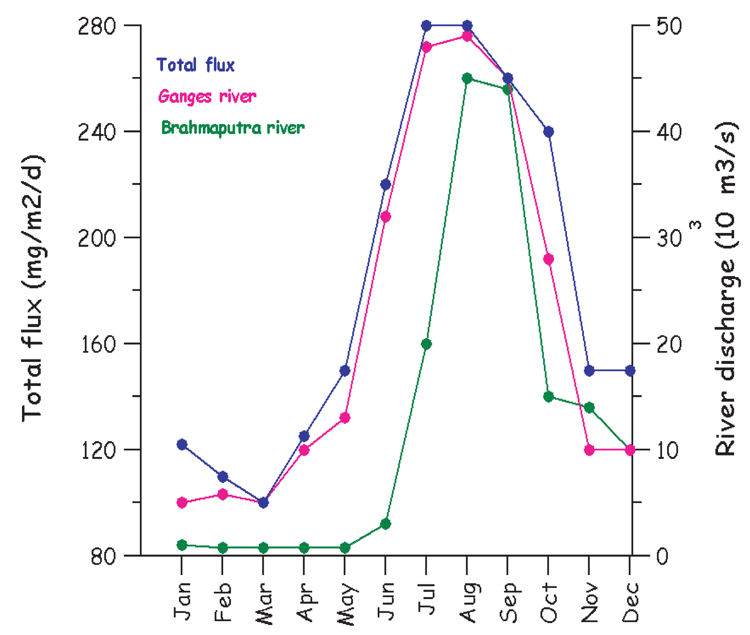

Figure 5: Monthly variability in total mass flux at 1000 m trap and river discharge into the Bay of Bengal [Ittekkot et al., 1991]

Table 1: Comparasion of O2 demand in the OMZ

Method	Oxygen demand (TgO_2/y)	
	Arabian Sea	Bay of Bengal
Physical pump	452-456	76-80
Organic C Mixing model	282-621	102-627
Bacterial respiration	105-610	--
ETS	142-992	26-200
Redfield ratio	96-488	62-326

Conclusions

Despite the strong variability in the productivity in time and space, the oxygen minimum zone in the subsurface waters is intense throughout the year in the northern Indian Ocean. The model results revealed that physical processes associated with biogeochemical cycling of carbon and oxygen regulate OMZ in the Arabian Sea. Although productivity and sinking organic carbon fluxes are low during non-monsoon, OMZ is maintained by low supply of oxygen by physical pump and vice versa. The oxygen consumption rates were higher during monsoons compared to non-monsoon seasons that are in agreement with productivity pattern in the Arabian Sea whereas it is comparable with sinking fluxes of organic matter in the Bay of Bengal. The regeneration of carbon by soft tissue, computed based on the watermass 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. It is suggested that the coupling between physical and biogeochemical processes are responsible for the sustenance of perennial oxygen minimum zone in the northern Indian Ocean.