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Eastward shift and maintenance of Arabian Sea oxygen minimum zone: Understanding the paradox

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A B S T R A C T

The dominance of Oxygen Minimum Zone in the eastern part of the Arabian Sea (ASOMZ) instead of the more bio-productive and likely more oxygen consuming western part is the first part of the paradox. The sources of oxygen to the ASOMZ were evaluated through the distributions of different water masses using the extended optimum multiparameter (eOMP) analysis, whereas the sinks of oxygen were evaluated through the organic matter remineralization, using the apparent oxygen utilization (AOU). The contributions of major source waters to the Arabian Sea viz. Indian Deep water (dIDW), Indian Central water (ICW), Persian Gulf Water (PGW) and Red Sea Water (RSW) have been quantified through the eOMP analysis which shows that the PGW and RSW are significant for the eastward shift of ASOMZ instead of voluminous ICW and dIDW. The distribution of Net Primary Production (NPP) and AOU clearly suggest the transport of organic detritus from the highly productive western Arabian Sea to its eastern counterpart which adds to the eastward shifting of ASOMZ. A revised estimate of the seasonal variation of areal extent and volume occupied by ASOMZ through analysis of latest available data reveals a distinct intensification of ASOMZ by 30% and increase in its volume by 5% during the spring-summer transition. However, during this seasonal transition the productivity in the Arabian Sea shows 100% increase in mean NPP. This disparity between ASOMZ and monsoonal variation of productivity is the other part of the paradox, which has been constrained through apparent oxygen utilization, Net Primary Production along with a variation of core depths of source waters. This study reveals a subtle balance between the circulation of marginal oxygen-rich water masses from the western Arabian Sea and organic matter remineralization in the eastern Arabian Sea in different seasons that explains the maintenance of ASOMZ throughout the year.

1. Introduction

Oxygen minimum zones (OMZ) occur at intermediate depths in the water column of world ocean characterized by low dissolved oxygen concentration (≤ 0.5 ml/l, e.g. Helly and Levin, 2004). This suboxic condition in the water column is due to the high oxygen demand and low oxygen supply to the subsurface water. The major OMZs of the global ocean are developed in the upwelling dominated systems or in the regions where ventilation by subsurface currents are restricted. The major OMZs occur in the eastern northern and the southern Pacific Ocean and the northern Arabian Sea, where oxygen concentration drops to ≤ 20 μmol/l (≤ 0.5 ml/l) (Helly and Levin, 2004; Fuenzalida et al., 2009; Paulmier and Ruiz-Pino, 2009). The OMZs have significant impact on global ecosystem in two ways: (1) they modulate the carbon and nitrogen cycles in ocean and thus regulate the release of greenhouse gases like CO_2 and N_2O to the atmosphere (Codispoti et al., 2001; Naqvi et al., 2006; Lam and Kuypers, 2011; Bianchi et al., 2012); (2) they influence the ecosystem structure by providing a respiratory barrier in subsurface water (Levin et al., 2009; Stramma et al., 2012; Resplandy et al., 2012). Based on the time series analysis of dissolved oxygen concentration, Stramma et al. (2008) showed an increase in the volume of OMZs in tropical oceanic regions (except the Indian Ocean) over the last fifty years. This expansion may further get intensified with the increase in the rate of global warming (Keeling et al., 2010) which will have a significant impact on coastal ecosystems. Therefore, in order to understand the nature of changes in the oceanic domain that might occur because of the increasing global warming phenomenon, the extent of the major OMZs and the factors influencing their intensity need to be evaluated. In the present study, we focus on Arabian Sea OMZ (ASOMZ) which is inferred to be the third most voluminous OMZ in the world and covers the fourth largest area in

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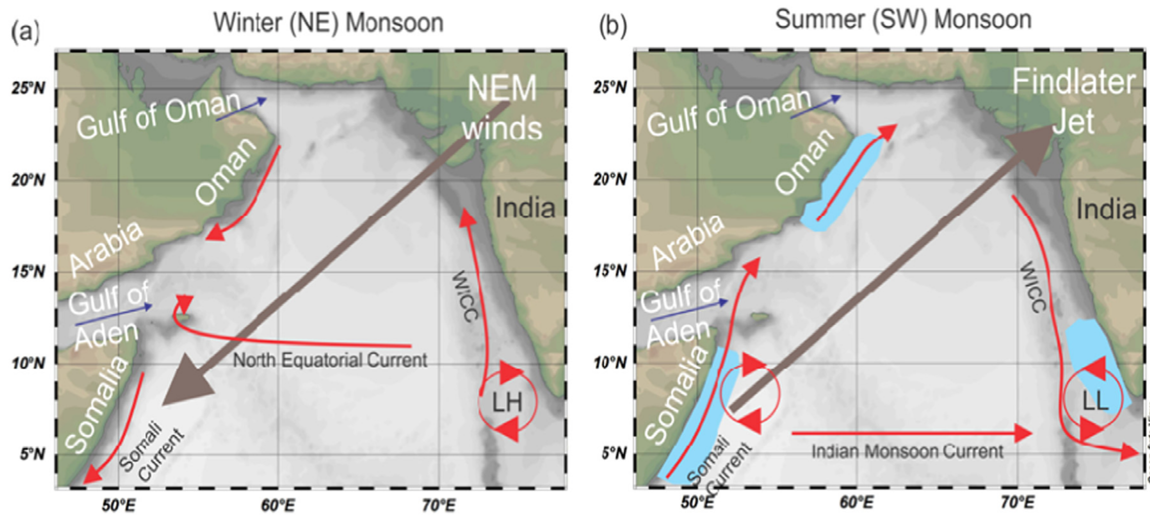

Fig. 1. Schematic representation of dominant winds (Brown arrow), oceanic circulation (red arrows), and coastal upwelling systems (light blue shading) during (a) NE Monsoon and (b) SW Monsoon (adopted from Prasad et al. (2001) and Resplandy et al. (2012) and references therein). WICC: western Indian Coastal Current; LH: Lakshadweep High; LL: Lakshadweep Low. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the global ocean (Fuenzalida et al., 2009; Paulmier and Ruiz-Pino, 2009). The monsoonal wind affects both the oceanic circulation pattern and biological activities across seasons in the Arabian Sea. These large scale seasonal variations (Fig. 1) make Arabian Sea as one of the complex system in the global ocean. Despite this considerable spatio-temporal variability in the ocean dynamics and biological activity, no remarkable seasonal and spatial variations has been reported in the oxygen concentrations within the OMZ in the Arabian Sea (Resplandy et al. (2012) and references therein). This is inferred as a spatial and seasonal maintenance of ASOMZ, which is an intriguing aspect to investigate.

1.1. Background

The ASOMZ shows near total depletion of oxygen at intermediate water depths from 200 to 1000 m (Morrison et al., 1999), where the dissolved oxygen concentration drops to <10 μmol/l. The upper water column of Arabian Sea (<1200 m) receives water from three major sources. They include Persian Gulf water (PGW), Red Sea water (RSW) and Indian Central Water (ICW) (Rhein et al., 1997). The PGW enters the Arabian Sea just beneath the thermocline (200–400 m, Prasad et al., 2001) and spreads both southward along the Omani coast and around the perimeter of the basin (Shenoi et al., 1993; Prasad et al., 2001), whereas the RSW enters the Arabian Sea at intermediate water depths (300–1000 m, Beal et al., 2000; Bower et al., 2000) and spreads across the basin (Shankar et al., 2005). The dense, saline PGW and RSW enter the Arabian Sea through narrow, shallow straits: the former through the strait of Hormuz and the latter through the Bab-al-Mandeb (BAM). They flow over very shallow sills - the sill depth is nearly 160 m in BAM strait and ~80 m in the Strait of Hormuz (Bower et al., 2000). The estimates of the annual mean volume transport of the PGW and RSW across their respective straits, ~0.4 Sv ($Sv=1\times10^6\ m^3\ s^{-1}$) and ~0.2–0.5 Sv. These values are small as compared to the other marginal sea outflows like ~1 Sv for the Mediterranean (Bower et al., 2000 and references therein). Both these water masses (PGW and RSW) show significant seasonal variability in transport due to the effects of the monsoon wind (Donguy and Meyers, 1996; Beal et al., 2000; Bower et al., 2000; Prasad et al., 2001). The details of the flow regimes of RSW and PGW were furnished by Donguy and Meyers (1996), Bower et al. (2000), Beal et al. (2000) and Prasad et al. (2001). Although the physicochemical properties of these oxygenated water masses have been studied well, their circulation paths in the Arabian Sea are not yet well understood (McCreary et al., 2013). A proper evaluation of the contributions from these sources is expected to provide better insight to the maintenance of ASOMZ across seasons.

An interesting characteristic of ASOMZ is that unlike other OMZs it is located well away from the '*intense*' upwelling zone (Fig. 1(b), Naqvi, 1991) in the western Arabian Sea and best developed in the least productive region of the eastern/central Arabian Sea (Fig. 2, Naqvi, 1991). Various hypotheses proposed to explain this eastward shift include: (i) northward advection of well oxygenated waters by the swift Somali and Omani coastal currents (Sarma, 2002); (ii) rapid sinking of large species (diatoms) in strong upwelling rich regions of western Arabian Sea (Wiggert and Murtugudde, 2007) and (iii) enhanced advection and vertical eddy mixing in the western Arabian Sea which carries small detritus from western to eastern/central basin to provide an additional sink of oxygen (McCreary et al., 2013).

The Arabian Sea is an integral part of the monsoon-dominated system, where the surface productivity and mid-depth water circulation respond to this seasonal phenomenon and control the O_2

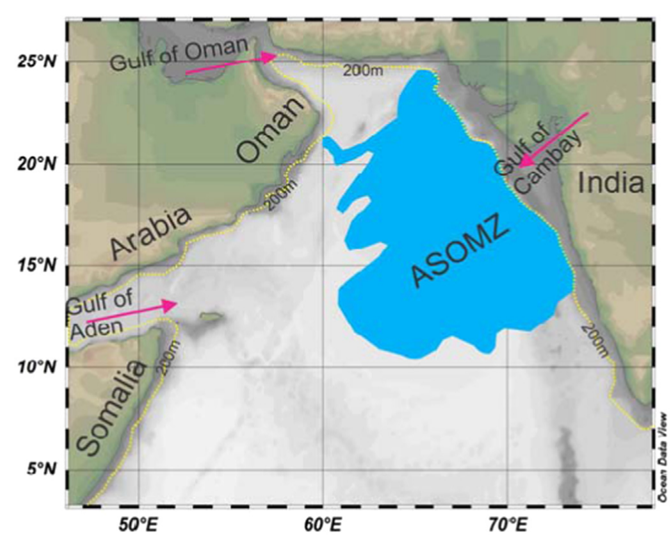

Fig. 2. A map of ASOMZ as demarcated by the 0.5 μmol/l NO_2^- contour (Redrawn after Naqvi (1991)) depicting the eastward shift.