Dynamical Response of the Arabian Sea Oxygen Minimum Zone to the Extreme Indian Ocean Dipole Events in 2016 and 2019

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1. Introduction

Oxygen availability is vital for the survival and maintenance of marine life and ecosystem. The presence of low oxygen level in ocean interia is recognized as the oxygen minimum zone (OMZ), where the dissolved oxygen (DO) concentration is less than 60 mmol·m^{-3} (Stramma et al., 2008). Major OMZs in the global ocean are predominantly found in areas dominated by upwelling, poorly ventilated zones, and large estuaries, including but not limited to the eastern Tropical Pacific (Karstensen et al., 2008), Arabian Sea (McCreary et al., 2013; Lachkar et al., 2016, 2018), Bay of Bengal (Sarma, 2002; Al Azhar et al., 2017) and Gulf of Mexico (Rabalais et al., 2002; Bianchi et al., 2010). Recent research has indicated that deoxygenation in the world's ocean is exhibiting an accelerating trend, with oxygen levels decreasing by approximately 2% since the 1950s (Breitburg et al., 2018; Oschlies, 2021; Li et al., 2020).

The Arabian Sea oxygen minimum zone (ASOMZ) is globally recognized as one of the largest and most extreme OMZs (Figure 1), with suboxic regions (DO < 4 mmol·m^{-3}) prevalent in the majority of its intermediate water depths, ranging from 200 to 1,000 m (Morrison et al., 1998). The Arabian Sea is strongly influenced by monsoon. Although the monsoon causes significant spatial and temporal variability in ocean dynamics and biological activity (McCreary et al., 2013; Chen et al., 2022; Chu et al., 2023), the annual cycle of the ASOMZ is weak (Resplandy et al., 2012; Rixen et al., 2014; Shenoy et al., 2020). It is noteworthy that the core region of the ASOMZ is located in the eastern and central Arabian Sea, which is significantly distant from the upwelling region in the western Arabian Sea where the primary production is considerably high (Naqvi, 1991; Acharya et al., 2016). The Indian Ocean Dipole (IOD) which is analogous to the El Niño-Southern Oscillation (ENSO) has a significant impact on the ocean-atmospheric circulation over the entire basin (Saji et al., 1999; Ashok et al., 2001; Izumo et al., 2010). Previous studies have reported surface chlorophyll blooms in the west IOD zone during an extremely nIOD event in 2016, whereas an extensive reduction in surface chlorophyll was observed during an extremely pIOD event in 2019 (Thushara and Vinayachandran, 2020; Shi and Wang, 2022).

Although the impact of the IOD on SST anomalies and chlorophyll fluctuations in the western Indian Ocean is well known, its role in the interannual variability of the ASOMZ remains uncertain (Rixen et al., 2020). This study utilized a coupled physical-biogeochemical model (ROMS-CoSiNE) to investigate how the ASOMZ responds to extreme IOD events. Specifically, the study analyzed the variation of the ASOMZ during the positive and negative IOD events, using 2019 and 2016 as representative years. The study also examined the response mechanisms of the Gulf of Aden in the upwelling region and the less-ventilated central Arabian Sea to the IOD events.

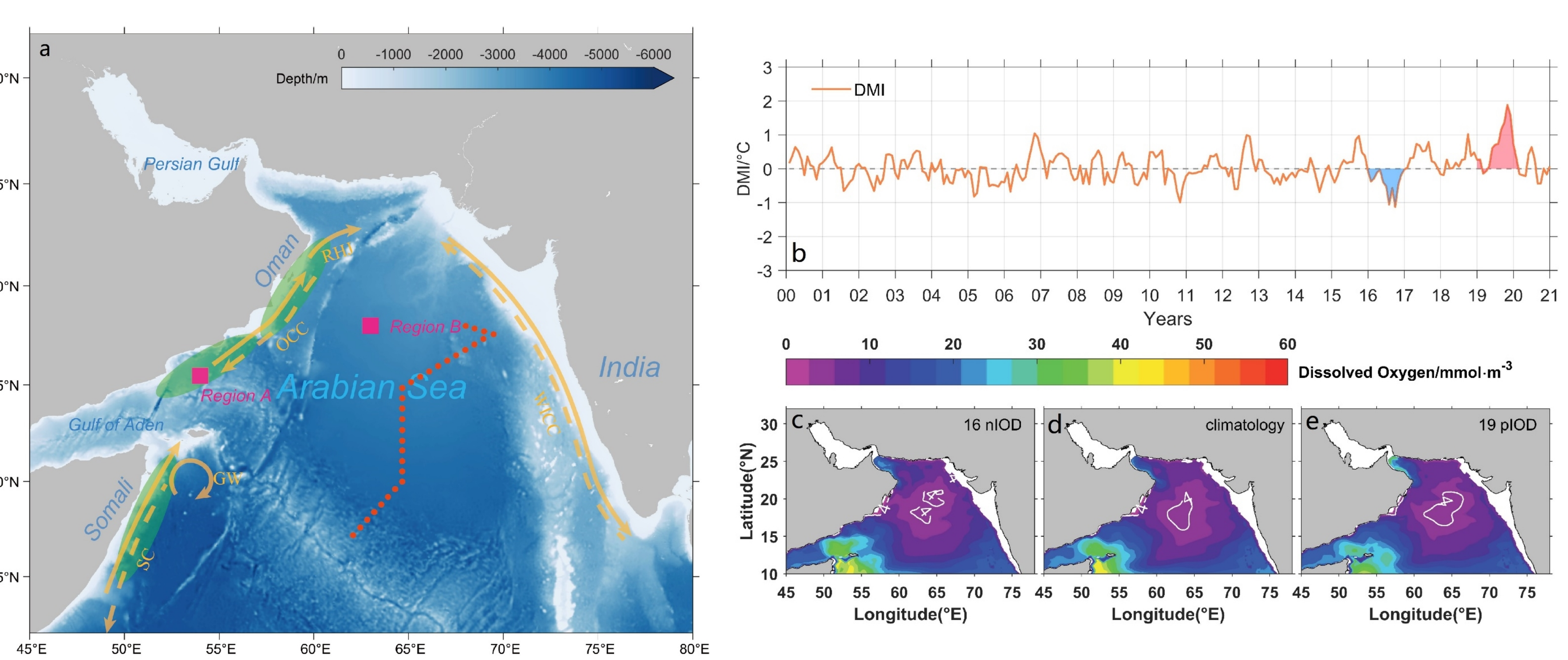

Figure 1. (a) Bathymetry of the Arabian Sea. Coastal upwelling systems (green shading) and coastal circulations are marked after Schott and McCreary (2001). The solid and dashed arrows represent the Somali Coastal Current (SC), the Great Whirl (GW), the Oman Coastal Current (OCC), Ras al Hadd Jet (RHJ), and the West Indian Coastal Current (WICC) during the winter and summer monsoons, respectively. Red dotted line represents the cruise track in April-June 2018. Two squares represent the two regions (i.e., Regions A and B) selected for analysis. (b) Monthly DMI (Dipole Mode Index; Saji et al., 1999) from the OISST dataset from 1982 to the present. (c-e) Modeled horizontal distributions of dissolved oxygen (200-1000 m) during IOD periods (September-October-November, SON) in 2016 (c), climatological state (d), and 2019 (e).

2. Responses of Gulf of Aden to the IOD events

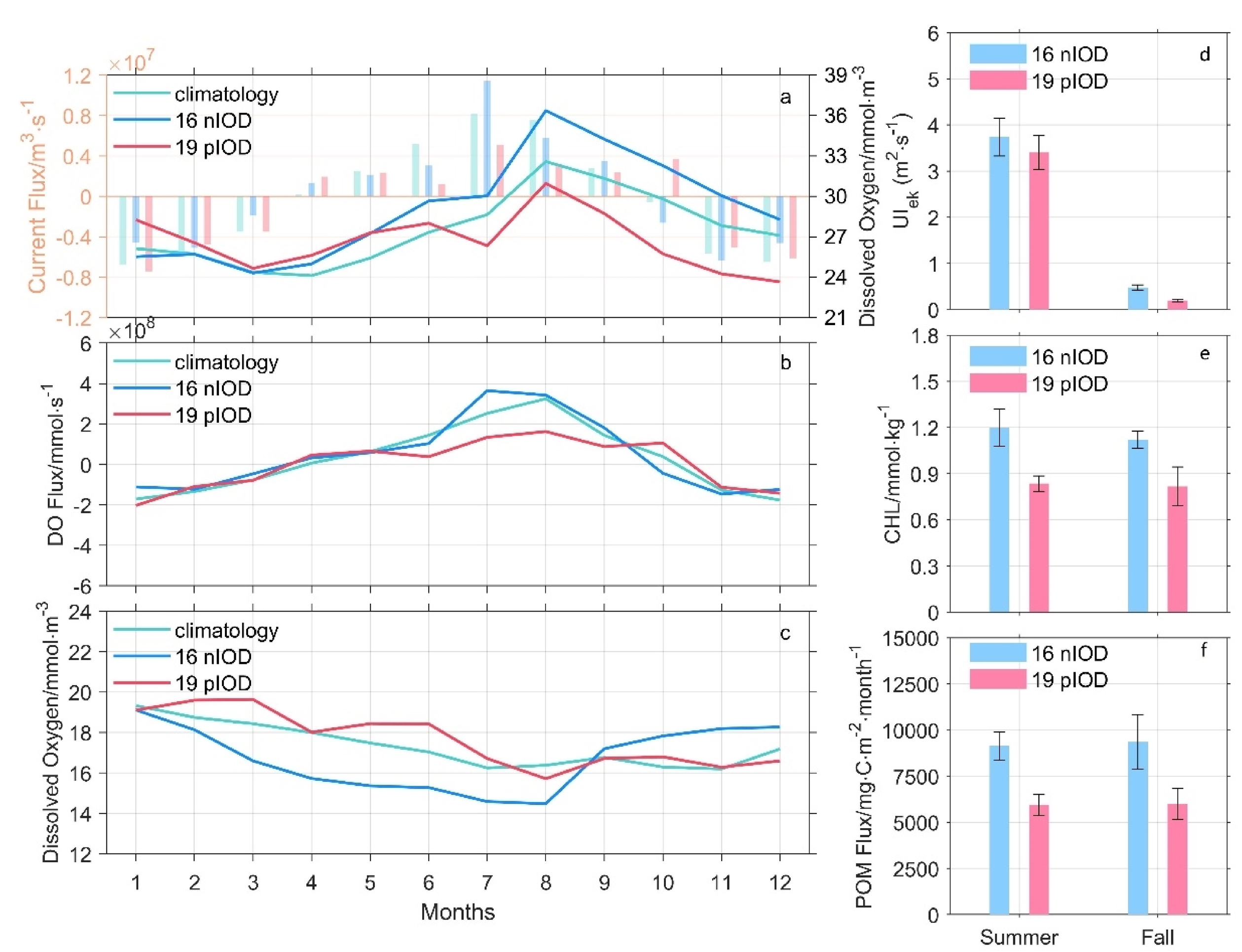

Fig.2 (a) Current flux (bars, left y-axis) and dissolved oxygen concentration (lines, right-axis) averaged between 200 and 1000 m near 11.8°N in the western side of the Arabian Sea (50°-55°E). (b) Associated dissolved oxygen fluxes (200-1000 m) for the same section as in (a). (c) Time series of averaged dissolved oxygen concentration (200-1000 m) at Region A (Gulf of Aden). Upwelling index (d), chlorophyll concentration (e), POM flux at 200 m (f) in the Gulf of Aden during summer and autumn. Error bars represent the standard error around each mean (P<0.05).

The Somali Coastal Current played a significant role in influencing the DO concentration near the Gulf of Aden. Associated DO flux averaged between 200 and 1000 m in the Somali Coastal Current would increase by approximately 12.6×10^{14} mmol·m^{-3} during the 2016 summer monsoon (Jun-Aug), which was about 2.5 times higher than in the 2019 summer monsoon. Consequently, the DO concentration at Region A (the Gulf of Aden) significantly increased from ~14.5 mmol·m^{-3} in August to ~17.2 mmol·m^{-3} in September 2016.

On the other hand, the chlorophyll in the upwelling region were 44.6% higher in the summer and 36.6% higher in the autumn compared to those during the 2019 pIOD event. As a consequence of this increase in chlorophyll, the flux of POM (FPOM200) at 200 m also increased in the summer (~53.7%) and autumn (~55.9%) of 2016. The elevated POM subsequently led to an increase of ~13.9% and ~51.3% in DO consumption in the summer and autumn, respectively.

Such abundant DO not only replenished the DO consumed by increased POM remineralization due to stronger upwelling but also elevated the DO concentration.

3. Responses of central Arabian Sea to the IOD events

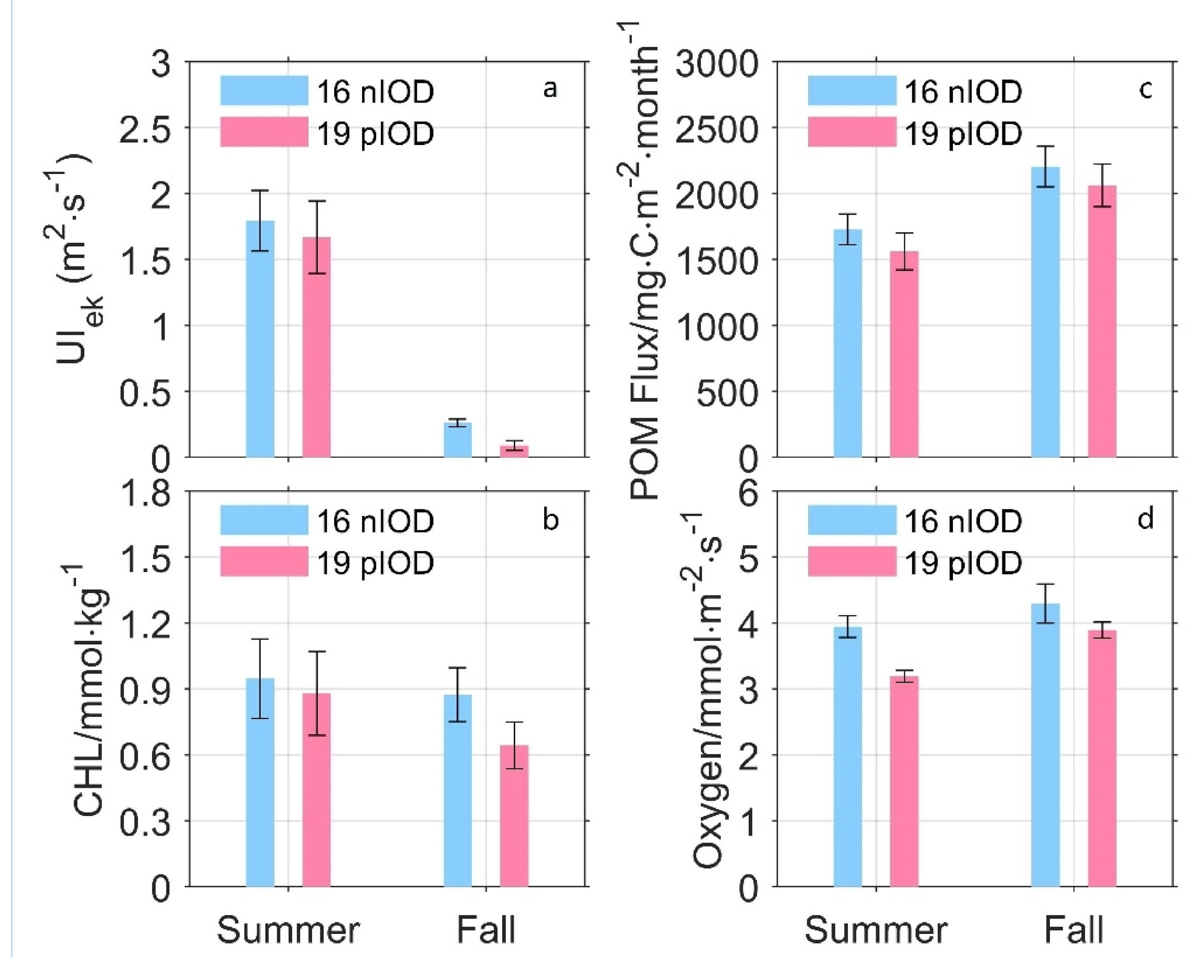

Figure 3. Upwelling index (a) and chlorophyll concentration (b) during summer and autumn off the Coast of Oman. POM flux at 200 m (c) and Oxygen consumption (d) in the central Arabian Sea. Error bars represent the standard error around each mean (P<0.05).

The enhanced coastal upwelling off the coast of Oman brought more nutrients to the euphotic zone during the 2016 nIOD event, thereby promoting primary production in the upper water column. The higher primary productivity generated more POM, which were subsequently transported to the central Arabian Sea by the stronger offshore Ekman transport during the 2016 nIOD event (McCreary et al., 2013).

Consequently, this increased quantity of POM consumed a large amount of DO through remineralization without sufficient DO replenishment (Zhang et al., 2022), resulting in a decrease in DO concentration in the central Arabian Sea during the 2016 nIOD event.

Additionally, more (less) relative oxygen-rich water (DO<60 mmol·m^{-3}) and stronger (weaker) upwelling uplifted (deepened) the upper edge of the ASOMZ around 20 m in the region during the 2016 nIOD event (the 2019 pIOD event) in the Gulf of Aden. Differently, the lower SST during the 2016 nIOD event led to higher DO saturation, thereby increasing the DO concentration in the upper water column and deepening the upper edge of the ASOMZ in the central Arabian Sea. Instead, shallower ASOMZ's upper edge was presented during the 2019 pIOD event due to lower DO saturation in the upper layer.

4. Summary

- The response of the Arabian Sea OMZ to the Indian Ocean Dipole events in the Gulf of Aden was modulated by physical factors. During the 2016 negative IOD (nIOD) event, the intensification of the southwest monsoon in the North Indian Ocean resulted in an augmentation of the Somali Coastal Current. The Arabian Sea experienced an influx of oxygen-rich water approximately 2.5 times greater than that observed during the 2019 positive IOD (pIOD) event, courtesy of the Somali Coastal Current.
- The Arabian Sea OMZ in the central Arabian Sea was regulated by both biological and physical processes. During the 2016 nIOD event, the intensified coastal upwelling transported more POM originating from the Oman coast to the central Arabian Sea, leading to increased oxygen consumption there. However, there was no corresponding replenishment of dissolved oxygen, leading to a decline in the dissolved oxygen concentration there. Furthermore, the lower SST led to higher dissolved oxygen saturation, thereby increasing the DO concentration in the upper water column and deepening the upper edge of the ASOMZ.
- The upper edge of the Arabian Sea OMZ invaded the lower euphotic zone (100-200 m) under the impact of Indian Ocean Dipole events.