



Ocean deoxygenation: Everyone's problem

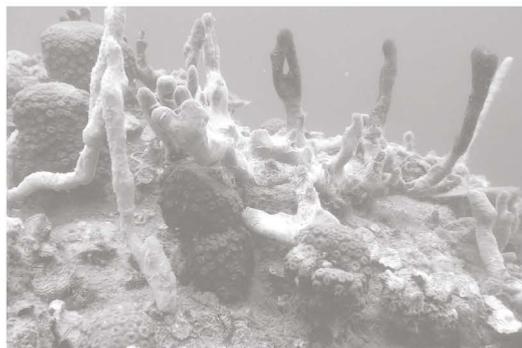
Causes, impacts, consequences and solutions

Edited by D. Laffoley and J.M. Baxter



2.3 Evidence for ocean deoxygenation and its patterns: Indian Ocean

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IUCN GLOBAL MARINE AND POLAR PROGRAMME



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Summary

- Analysis of available data for the past five decades indicates a generally lower and more variable rate of deoxygenation in the North Indian Ocean than in other oceanic areas (i.e. substantial oxygen loss in the upper 300 m in the western Arabian Sea, mixed trends in the central Arabian Sea, and a slight decline in the Bay of Bengal).
- There is no clear evidence for expansion/intensification of the functionally-anoxic oxygen minimum zone (OMZ) in the Arabian Sea, where microbes decompose organic matter via anaerobic pathways, but slight oxygen loss might have brought the relatively more oxygenated Bay of Bengal OMZ close to anoxia.
- Preliminary analysis suggests substantial decrease in oxygen levels below 400 m in the northern Red Sea.
- Emerging hypoxia in conjunction with an increase in organic load in response to eutrophication in the Persian Gulf may lead to expansion/intensification of the Arabian Sea OMZ.
- The world's largest naturally-formed shallow hypoxic zone along India's west coast is more intense now as compared to 1970s; seasonal oxygen-deficiency off Oman and eastern India is also more severe. Hypoxia/anoxia has developed in several Indian estuaries, bays and ports and in some estuaries of western Australia as a result of human activities.
- There is a severe lack of information from potential hotspots, including the mouths of the Indus, Ganges-Brahmaputra, and Irrawaddy rivers. Capacity building and networking are needed to expand/improve monitoring of deoxygenation and other impacts of global change in the region.

Human induced change	Potential consequences
The bulk of excess heat retained by the Earth due to greenhouse warming being absorbed by the ocean.	<ul style="list-style-type: none"> • Ocean deoxygenation occurring at all depths due to: <ul style="list-style-type: none"> ◦ lower solubility of oxygen in warmer waters. ◦ stronger vertical stratification (steeper temperature gradient) inhibiting diffusion of O₂ from surface to deep ocean. ◦ more sluggish deep circulation reducing oxygen supply to deep waters.
Increase in nutrient inputs to the ocean through river runoff and atmospheric deposition.	<ul style="list-style-type: none"> • Nutrient over-enrichment (eutrophication) promoting algal blooms, enhancing O₂ demand and causing development of hundreds of coastal hypoxic (dead) zones as well as intensification of naturally formed low-O₂ zones.
Low - O ₂ zones of the Indian Ocean expected to expand and intensify due to above-mentioned human-induced changes. w	<ul style="list-style-type: none"> • Expansion of volume of hypoxic (O₂<1.4 ml L⁻¹) water has many deleterious effects on marine life including: (i) loss of habitat; (ii) changes in food webs; (iii) reduced growth and reproduction; (iv) physiological stress; (v) migration; (vi) vulnerability to predation; (vii) disruption of life cycles; and, in extreme cases, (ix) mortality. • The northern Indian Ocean contains about 2/3 of the global continental margin area in contact with very low O₂ (<0.2 ml L⁻¹) waters, and also houses the world's largest naturally-formed shallow low-O₂ zone (off western India). With countries surrounding its semi-enclosed basins, accounting for about a quarter of the global human population, its environment, biodiversity and living resources, are most vulnerable to human-induced changes, especially deoxygenation. • When dissolved O₂ is depleted below detection levels, as happens within a large volume of waters at mid-depths within the oxygen minimum zone (OMZ) of the Arabian Sea, the microbial community respire anaerobically, predominantly utilizing nitrate, an essential nutrient, converting it to inert molecular nitrogen (N₂) and nitrous oxide (N₂O), a potent greenhouse gas. While N₂ produced through this process (denitrification) modulates reactive nitrogen balance and marine biological productivity, oceanic N₂O emissions play an important role in Earth's radiation balance. • The OMZ of the Bay of Bengal retains some O₂ in minute traces but enough to inhibit large-scale denitrification. The volume of water containing traces of O₂ (<0.2 ml L⁻¹) in the northern Indian Ocean is much larger than the volume of functionally-anoxic OMZ of the Arabian Sea. This in conjunction with the extreme sensitivity of denitrification to vanishingly low O₂ levels underlines the non-linear response of N₂ and N₂O production to ocean deoxygenation. Thus, expansion and intensification of oceanic OMZs are expected to have large impacts on productivity as a result of reactive nitrogen loss, and on climate through enhanced production of N₂O.

2.3.1 Introduction

Unlike the Pacific and Atlantic Oceans, the Indian Ocean is bound by the Eurasian landmass at nearly tropical latitudes (~25°N, Figure 2.3.1), which has a profound impact on regional climate and oceanography. Differential heating and cooling of land and sea give rise to the unique phenomenon of monsoons, manifested by complete reversals of atmospheric and surface oceanic circulations every six months north of about 10°S latitude (Wyrski, 1973). The monsoons also greatly affect the

chemistry and biology of the Indian Ocean. During the summer or south-west monsoon (SWM), strong winds blow anomalously from the south-west, being strongest in the western Arabian Sea where they drive a vigorous western boundary current and uplift sea water from depth that is rich in nutrient salts. This water spreads far and wide eastward, fertilizing the nutrient-impooverished surface layer and promoting growth of algae that form the base of rich and diverse food webs (Naqvi et al., 2006a). In other ocean basins, this process, called upwelling, occurs along eastern boundaries (i.e. off Namibia and



Figure 2.3.1 Map showing the Indian Ocean and important locations/features mentioned in the text. While the southern boundary of the Indian Ocean is arbitrarily fixed at 60°S latitude, longitudes 20°E and 146.82°E, corresponding to the southern tips of South Africa and Tasmania (Australia), are taken to separate the Indian Ocean from the Atlantic and the Pacific, respectively (https://www.iho.int/mtg_docs/com_wg/S-23WG/S-23WG_Misc/Draft_2002/Draft_2002.htm). This chapter largely focuses on the Indian Ocean north of the equator. The dark blue area in the Arabian Sea marks the functionally anoxic zone defined by concentration of nitrite, a proxy of anoxia, exceeding $0.2 \mu\text{M}$ within the oxygen minimum layer (from Naqvi, 1991).

Mauritania in the Atlantic, and off California and Peru-Chile in the Pacific). As compared to the Arabian Sea, upwelling is much weaker in the Bay of Bengal, partly because of weaker winds and partly because the Bay of Bengal receives enormous runoff from a number of rivers as well as a large amount of rainfall that greatly affects its hydrography and circulation (Naqvi et al., 2006a). The two basins are also differently affected by the winter or north-east monsoon (NEM), when cool, dry continental winds blow from the north-east causing convective mixing and consequently winter algal blooms in the Arabian Sea. This does not happen in the Bay of Bengal, where the upper water column is more strongly

stratified because of low salinities, inhibiting convection (Naqvi et al., 2006a). Consequently, the Arabian Sea is far more productive than the Bay of Bengal on an annual basis (Qasim, 1977).

The other unique feature of the Indian Ocean geography is that it is connected to the Pacific Ocean through the Indonesian seas, which allows the inflow of warmer, low-salinity water (the Indonesian Throughflow) from the Pacific that drives the anomalous poleward-flowing eastern boundary current (the Leeuwin Current), and is primarily responsible for the absence of large-scale upwelling off western Australia (Schott & McCreary,

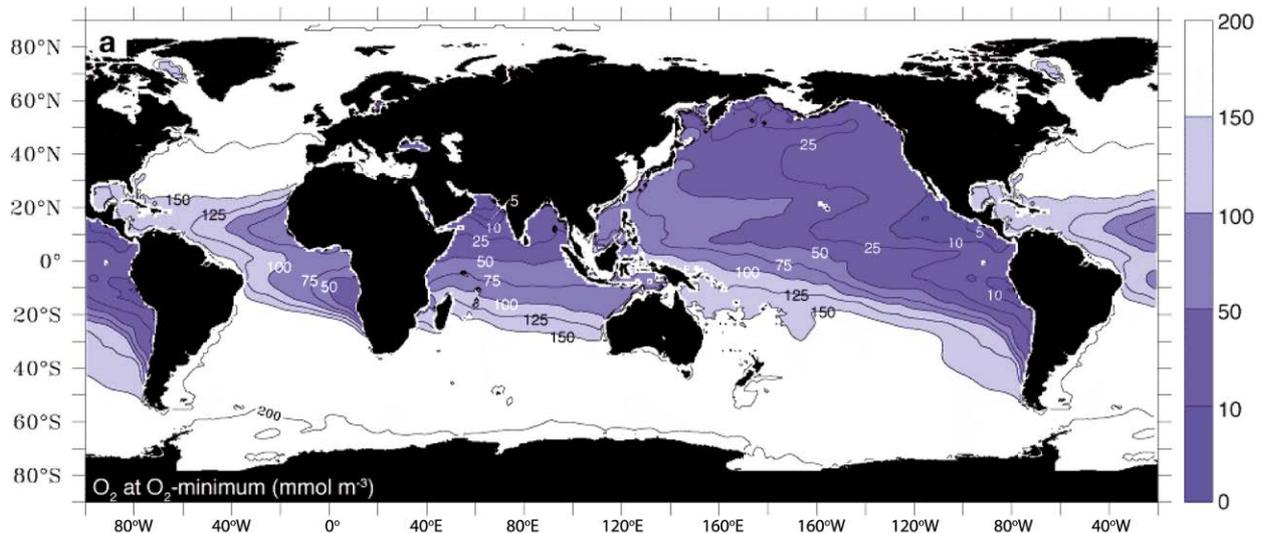


Figure 2.3.2 Distribution of dissolved O_2 (μM) at its minimum (after Keeling et al., 2010). The depth of the minimum varies, but in the northern Indian Ocean the lowest O_2 concentrations are generally found below ~ 150 m and above 800 m (Wyrтки, 1971). Note the anomalous location of the oxygen minimum zones in the northern Indian Ocean. Oxygen supply from the south is indicated by the northward tilt of contours along the western boundary (off Africa and Arabia).

2001). The biogeochemistry of this region is, therefore, completely different from its counterparts in the Pacific and Atlantic Oceans (in the equator-bound Humboldt Current and Benguela Current, respectively).

The low-latitude northern boundary of the Indian Ocean also drastically influences deep water circulation and renewal. As the dense, deep waters are mostly formed in cold, polar areas, the deep Indian Ocean can only be ventilated by waters flowing northward from the Southern Hemisphere. Although two sources of dense intermediate waters do exist in the Mediterranean-type marginal seas - the Persian Gulf and the Red Sea that are located in highly arid zones and receive little river runoff - most of the ventilation below the surface layer in the upper kilometre of the Indian Ocean occurs through waters formed close to or just north of the Polar Front (around 50°S latitude) in the Southern Indian Ocean (Swallow, 1984). These waters do not flow directly northwards but take a circuitous route; carried by the anti-clockwise flow of the southern subtropical Indian Ocean, these waters are fed into the complex equatorial current system of the Indian Ocean from where they cross the equator in the western Indian Ocean during the SWM (Swallow, 1984).

Deviations in patterns of surface and deep currents and related biological productivity in the Indian Ocean from those observed in the Atlantic and Pacific Oceans also result in unusual distribution of dissolved oxygen (O_2) in the Indian Ocean (Wyrтки, 1971). Like other oceanic areas, the water column in the Indian Ocean

also contains mid-depth O_2 concentration minima, maintained by a combination of relatively high O_2 demand by microbes that decompose organic matter sinking from the surface, and restricted O_2 supply as a result of sluggish deep-water circulation and mixing. What is unusual is that while the so-called oxygen minimum zones (OMZs), located in the tropics, are most intense along the eastern boundaries of the Pacific and Atlantic Oceans, they occur along the northern boundary of the Indian Ocean (Figure 2.3.2).

The northward tilt of O_2 contours in the western Indian Ocean (Wyrтки, 1971) is because, as mentioned above, cross-equatorial flow of relatively oxygenated intermediate waters of southern origin occurs only in the west; despite this, O_2 deficiency is clearly more severe in the north-western Indian Ocean than in the north-eastern Indian Ocean (Figure 2.3.2). This is also supported by the distribution of chemical proxies of anoxia. For example, the upper 1/3 or so of the OMZ of the Arabian Sea is distinguished by the accumulation of nitrite (NO_2^-), a transient species of nitrogen usually not present much below the surface layer. This feature, called the secondary nitrite maximum (SNM), is ubiquitous to almost all intense OMZs, but it is not seen in the Bay of Bengal (Naqvi et al., 2006a). The SNM is believed to be produced by bacteria that decompose organic matter using nitrate (NO_3^-), the most abundant form of reactive nitrogen in the sea, once O_2 gets fully consumed. Recent measurements have shown that O_2 levels associated with the SNM are below the detection limit (a few nanomol per litre) of the best O_2 sensor

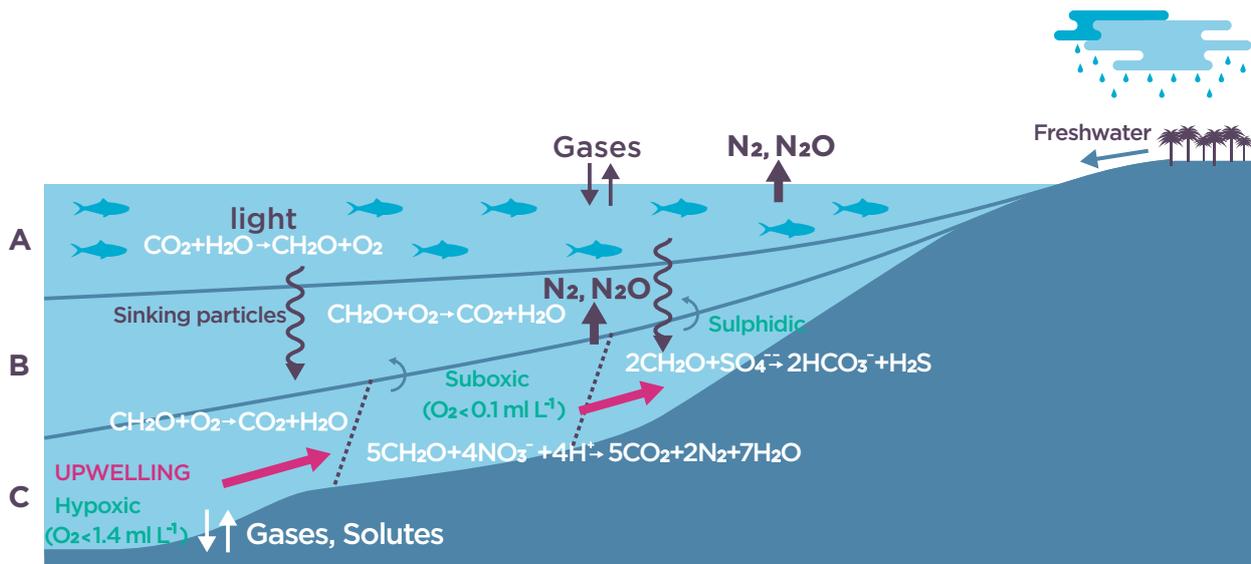


Figure 2.3.3 A schematic representation of processes occurring in the world's largest naturally formed coastal hypoxic zone off the west coast of India (eastern Arabian Sea) in late summer and early autumn. The water column over the shelf can be broadly divided into three layers. (A) The upper layer is warm and has low salinity because of intense monsoon rainfall; being in contact with the atmosphere, it is also well oxygenated. (B) The middle layer is a transient zone where salinity (\uparrow), temperature (\downarrow), density (\uparrow) and O_2 (\downarrow) change rapidly with depth. This layer acts as a barrier, strongly inhibiting mixing of the overlying and underlying waters. (C) The lower, near-bottom layer comprises cold, saline water that is derived through upwelling from the oxygen minimum zone (OMZ) located offshore. The little O_2 it initially contained gets used up over the shelf by bacteria that decompose copious organic matter sinking from the surface. Removal of O_2 triggers microbial conversion of nitrate (NO_3^-) to gaseous nitrogen (N_2) (denitrification). Unusually large amounts of nitrous oxide (N_2O) are also produced through denitrification ($5CH_2O + 4NO_3^- \rightarrow 5CO_2 + 2N_2O + 5H_2O$) making this region a hotspot for oceanic N_2O emissions. As this water ascends further and loses all NO_3^- , sulphate reduction sets in, producing obnoxious and toxic hydrogen sulphide (H_2S). Conditions in the deep layer are harsh for higher life forms including fish.

(Switchable Trace Oxygen, STOX) presently available (Thamdrup et al., 2012). Nitrite is further converted to elemental nitrogen (N_2), with nitrous oxide (N_2O), laughing gas, being another intermediate of this reaction chain, called denitrification (Deuser, 1975). This process is also known to occur in several other anaerobic environments, such as groundwaters and soils. Denitrification is of immense geochemical importance because it regulates the N_2 inventory of the atmosphere; but for this process, N_2 , the most abundant (78%) gas in the Earth's atmosphere would be depleted in a few tens of million years (Deuser, 1975). In addition to denitrification, N_2 can also be produced by microbes that oxidize ammonium (NH_4^+), another common nitrogen species, with NO_2^- in the absence of O_2 . Although the relative importance of anaerobic ammonium oxidation (Anammox) and denitrification continues to be debated (Lam et al., 2011; Ward et al., 2009), both processes require anoxic conditions. It is estimated that the Arabian Sea accounts for at least 1/3 of the global N_2 production in oceanic OMZs (Codispoti et al., 2001; Naqvi, 1987). Surprisingly, the SNM zone, where most of this loss is believed to occur, is located in the central and north-eastern parts of the Arabian Sea (Figure 2.3.1), that are biologically less productive than the upwelling centres off Somalia and Arabia, underscoring the importance of circulation in the

formation and sustenance of SNM (Naqvi, 1991). While the biogeochemistry of OMZs is dominated by nitrogen cycling, the OMZs also affect cycling of several other elements, such as manganese, iron, iodine and sulphur (Briertburg et al., 2018). Thus, changes in the volume and intensity of OMZs are potentially of global significance.

Based on physical considerations alone (poorer ventilation), the OMZ is expected to be more intense in the Bay of Bengal than in the Arabian Sea. The OMZ in the latter region is indeed *nearly* devoid of dissolved O_2 ; however, unlike the Arabian Sea it does not support large-scale anaerobic respiration as evident from the absence of SNM (Naqvi et al., 2006a) and associated N_2 production (Bristow et al., 2017). This is in large part due to the fact that the Bay of Bengal is considerably less productive than the Arabian Sea (Qasim, 1977) as a result of much weaker coastal upwelling and strong stratification that restricts nutrient entrainment from subsurface waters into the sun-lit surface layer through wind-induced and convective mixing. However, rivers also bring large quantities of particulate organic carbon (POC) to the Bay of Bengal along with enormous amounts of lithogenic material, and it is hypothesized that incorporation of dense mineral material into particle aggregates facilitates rapid sedimentation of POC to

the sea floor with less degradation in the water column (Ittekkot et al., 1992; Rao et al., 1994).

The extent and intensity of deoxygenation in the estuarine, coastal and shelf waters of the Indian Ocean also vary regionally. In the western Arabian Sea, strong seasonal upwelling brings up low O_2 waters over the shelf off the Somali and Arabian coasts. However, vigorous circulation means the upwelled waters do not stay long enough over the narrow shelves to allow the development of intense anoxia. Over the western Indian shelf, upwelling is much weaker, and the upwelled waters rarely reach the surface because of the presence of a thin (5-10 m) low-salinity lens that is formed as a result of intense monsoon rainfall (Figure 2.3.3). With the cold, high-salinity, O_2 -depleted water capped by the warm, low-salinity surface layer, bottom waters with O_2 content below 0.5 ml L^{-1} ($22.3 \text{ } \mu\text{M}$; $1 \text{ ml L}^{-1} = 44.6 \text{ } \mu\text{M}$), about 10% of value expected if these waters were in equilibrium with the atmosphere, seasonally cover the entire shelf (area $\sim 200,000 \text{ km}^2$), making it the largest shallow water O_2 deficient zone in the world (Naqvi et al., 2000). The bottom waters over the inner shelf experience some of the most extreme anaerobic phenomena, including denitrification and reduction of sulphate to noxious and toxic hydrogen sulphide (H_2S), another pathway of organic matter degradation, observed along an open coast anywhere in the world. Sulphate reduction is activated when NO_3^- also gets fully consumed by microbes. Such conditions do not occur in the Bay of Bengal despite immense river runoff which has been postulated to be highly enriched in nutrients (Seitzinger et al., 2002). This is perhaps due to reduction of nutrient loads in freshwater ecosystems before the river water reaches the sea (Naqvi et al., 2018).

The low O_2 systems described above are naturally-formed and have existed in the geological past, albeit with varying intensity driven by natural climate variability (Reichert et al., 1998). These systems are expected to be highly sensitive to human-induced climatic and environmental changes of both global and regional nature, such as warming and eutrophication, one major effect of which is ocean deoxygenation (Breitburg et al., 2018). In the following sections, an attempt is made to document ongoing trends of further deoxygenation in and around these systems and their potential ecological and socio-economic consequences. While ocean deoxygenation is global and would obviously occur in other parts of the Indian Ocean as well, this

chapter focuses largely on the northern basins, not only because being already affected by severe O_2 deficiency these basins are most vulnerable to human-induced deoxygenation, but also because sufficient data are available from these basins to discern ongoing changes. Information from the equatorial and southern parts of the Indian Ocean is mentioned briefly, where available.

2.3.2 Trends and impacts

2.3.2.1 Open-ocean

Analysis of global data sets has revealed steady declines in subsurface O_2 concentrations since 1960 in many parts of the ocean, especially close to OMZs in the tropics (Helm et al., 2011; Stramma et al., 2008). The rate of O_2 loss has been reported to be highest ($0.34 \text{ } \mu\text{mol kg}^{-1} \text{ yr}^{-1}$) in the North Pacific and lowest ($0.09 \text{ } \mu\text{mol kg}^{-1} \text{ yr}^{-1}$) in the equatorial Indian Ocean. In a more detailed follow-up study, Schmidtko et al. (2017) demonstrated that the ocean has already lost over 2% (4.8 petamol) of its O_2 content (227.4 petamol) since 1960 (1 peta or $10^{15} \text{ mol} = 32 \text{ billion tonne of } O_2$). The computed O_2 decline rate was highest ($0.210 \pm 0.125 \text{ petamol per decade}$) for the equatorial Pacific followed by the North Pacific ($0.173 \pm 0.040 \text{ petamol per decade}$), with these two regions accounting for $\sim 40\%$ of the global oceanic O_2 loss rate ($0.961 \pm 0.429 \text{ petamol per decade}$). In contrast, the combined contribution by the equatorial Indian Ocean ($0.055 \pm 0.049 \text{ petamol per decade}$) and the southern Indian Ocean ($0.027 \pm 0.034 \text{ petamol per decade}$) was just 8.5%. Based on Schmidtko et al. (2007; Figure 1), the change in dissolved O_2 in the Arabian Sea and Bay of Bengal put together would be $\ll 0.055 \text{ petamol per decade}$. Their results also indicated a substantial decrease in O_2 along the west coast of India, in the Gulfs of Aden and Oman, and in parts of the northern Bay of Bengal. As in most other areas, the decreases in O_2 concentration in the upper water column appear to have been driven primarily by lower O_2 solubility in warming sea water. In deeper water, however, the O_2 decrease was attributed to basin-scale multi-decadal variability, slow-down of oceanic overturning circulation and enhanced remineralization. Significantly, the highest rate of decrease in the equatorial Indian Ocean was recorded along the western boundary (off Africa) where more oxygenated intermediate waters of southern origin cross the equator (Swallow, 1984). Since these waters are responsible for $\sim 90\%$ of O_2 supply to OMZs of the North Indian Ocean, the observed loss of O_2 in the western equatorial Indian Ocean has potentially

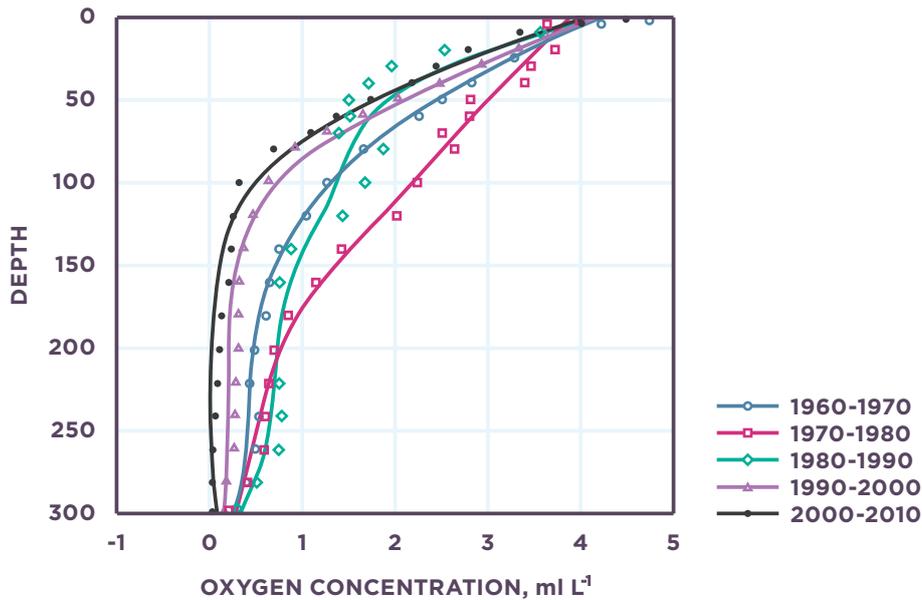


Figure 2.3.4 Decadal changes in oxygen content in the upper 300 metres in the western Arabian Sea (after Piontkovski & Al-Oufi, 2015).

important implications for future intensification of these OMZs.

2.3.2.1.1 Arabian Sea and Gulf of Oman

Three recent studies have specifically dealt with changes in dissolved O_2 in the upper water column of the north-western Indian Ocean over the past few decades. Two of these (Piontkovski & Al-Oufi, 2015; Queste et al., 2017) focused on the western Arabian Sea and the Gulf

of Oman. The western Arabian Sea contains the world's only major western boundary upwelling system where, as stated earlier, low O_2 waters are brought up to the continental shelves during the SWM. Analysis of data from this region collected during 53 cruises conducted from 1960 to 2008 revealed significant decadal changes in the upper 300 metres. While the water temperature has risen by ~ 1.5 °C over five decades, the oxycline (the horizon below the surface where O_2 concentration begins to fall rapidly) shoaled up at a rate of ~ 19 m per decade. Significantly, the observed decrease in O_2 concentration within the OMZ is quite large during the SWM, when waters derived from the southern hemisphere ventilate the OMZ, with the most recent data (for 2000-2010) indicating near anoxic conditions (Figure 2.3.4). In a more recent study, Queste et al. (2017) combined historical data with recent time series measurements made with automated gliders equipped with O_2 sensors to show that within the core of the OMZ in the Gulf of Oman O_2 levels have fallen from $6\text{--}12 \mu\text{mol kg}^{-1}$ at the time of the International Indian Ocean Expedition (IIOE) in the 1960s to $< 2 \mu\text{mol kg}^{-1}$ in recent times. Although, this shift is subtle, and could to some extent be accounted for by the improved quality of recent data, it is potentially significant given the above-mentioned sensitivity of respiratory processes to vanishingly low O_2 levels.

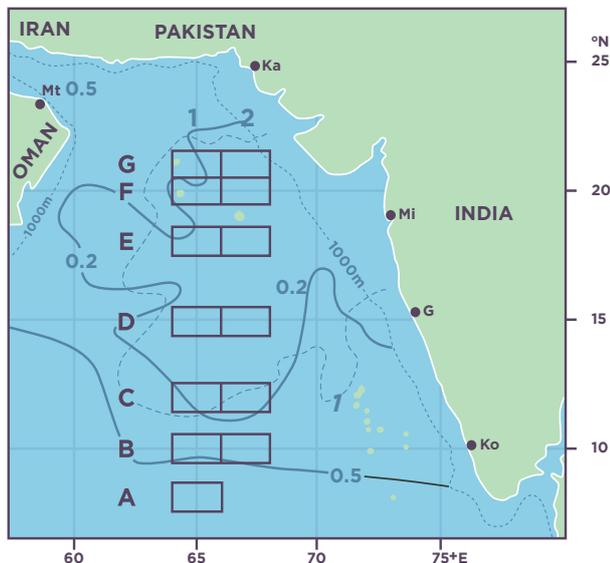


Figure 2.3.5 “Boxes” selected by Banse et al. (2014) to investigate decadal changes within the oxygen minimum zone of the Arabian Sea. The left boxes are numbered “1” while the right boxes are numbered “2”. Oxygen distribution at 200 m is shown by the 0.2 and 0.5 mL l^{-1} contours (solid) from Wyrski (1971); the zone of denitrification is demarcated by the $1 \mu\text{M}$ nitrite contour (dashed) from Naqvi (1991).

The third investigation (Banse et al., 2014) that concentrated on the more intense OMZ in the central Arabian Sea yielded less clear trends. This study utilized discrete O_2 measurements made between 1959 and

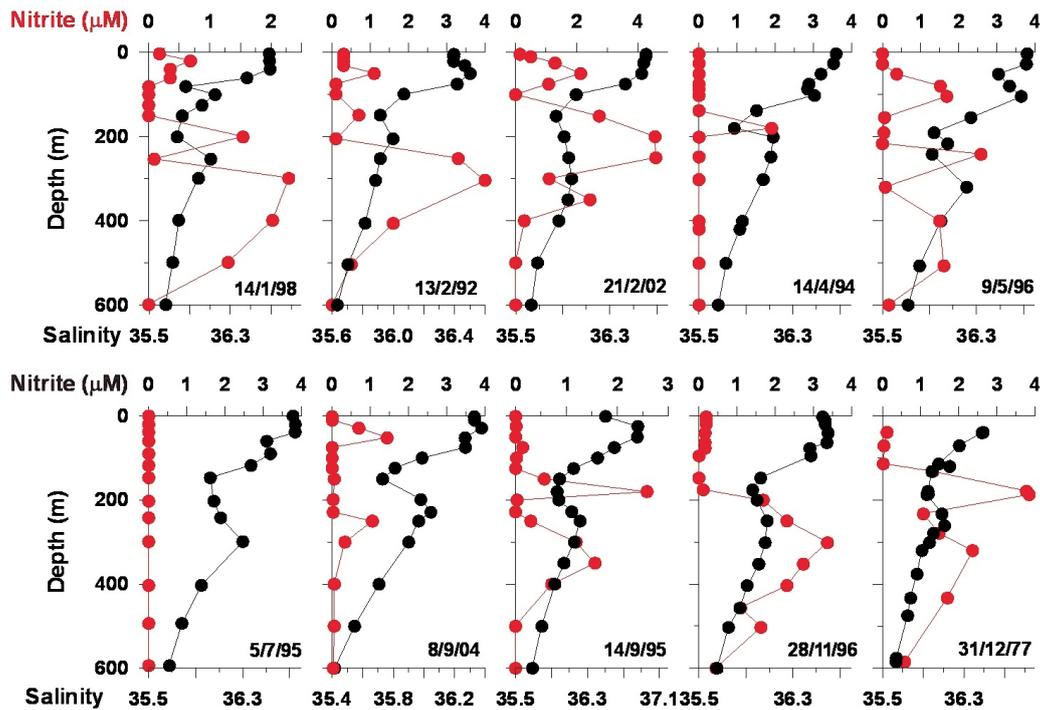


Figure 2.3.6 Vertical profiles of nitrite (red symbols) and salinity (black symbols) at a fixed site (Lat. 19.75°N, Long. 64.62°E) sampled repeatedly between 1977 and 2004 (arranged by month of visit). The station is located close to the north-western boundary of denitrification zone and the observed variability is largely caused by the flow of the high salinity water mass originating in the Persian Gulf (modified from Banse et al., 2014).

2004 near 150, 200, 300, 400, and 500 m water depths at stations located within zonally-paired boxes of 1° latitude x 2° longitude that were centred at 8, 10, 12, 15, 18, 20, and 21°N latitudes along 65° and 67°E longitudes (Figure 2.3.5). Except for 8 – 12°N, all boxes were located within the zone having SNM. On many recent cruises in the Arabian Sea (e.g. US JGOFS Arabian Sea Process Study, 1994-1995; Morrison et al., 1999), O₂ analysis by the automated Winkler procedure involved photometric end-point detection. As this technique yields consistently lower values (by ~0.04 ml L⁻¹) than manual titrations involving visual end point detection, Banse et al. (2014) only considered O₂ data generated with the latter procedure to minimize analytical bias. However, about a quarter of the O₂ data used might still have been accompanied by substantial NO₂⁻ (Karl Banse, pers. comm.), but exclusion of these data is unlikely to alter the major conclusions of this study.

Linear regression analysis, carried out for each depth and box separately for NEM and SWM to see if the O₂ concentration varied systematically with time, revealed conflicting trends (Banse et al., 2014). Within the three southern boxes (A-C), located at 8-12°N, outside the OMZ having SNM, O₂ concentration seemingly increased with time in the majority of cases, although

the correlation was significant at $p < 0.1$ on only three occasions. In contrast, within the OMZ the overwhelming trend was of declining O₂ concentrations with time in all boxes except F2, G1 and G2, situated at 20-21°N during both monsoon seasons. Although the median value for significant positive slopes (~-0.12 µM yr⁻¹), was close to the lower range of rates of O₂ decline reported by Stramma et al. (2008), it was somewhat higher than the concentrations measured within the SNM (<0.090 µM) with the STOX sensor (Jensen et al., 2011; note that the limit of detection of the sensor was higher on this cruise). An important result of this study was that the long-term declining trends within the OMZ were different during the NEM and SWM seasons with a more pronounced decrease occurring during the NEM when O₂ concentrations were slightly higher. The seasonal variability points to O₂ supply to the OMZ through vertical mixing and horizontal advection. Within the three northern boxes (F2, G1 and G2), although the majority of slopes were positive, none of them were statistically significant, with the maximal rate of increase being only ~0.10 µM yr⁻¹.

Banse et al. (2014) also used NO₂⁻ (within the SNM) as a proxy of functional anoxia (Thamdrup et al., 2012). Nitrite concentration broadly reflects the extent of

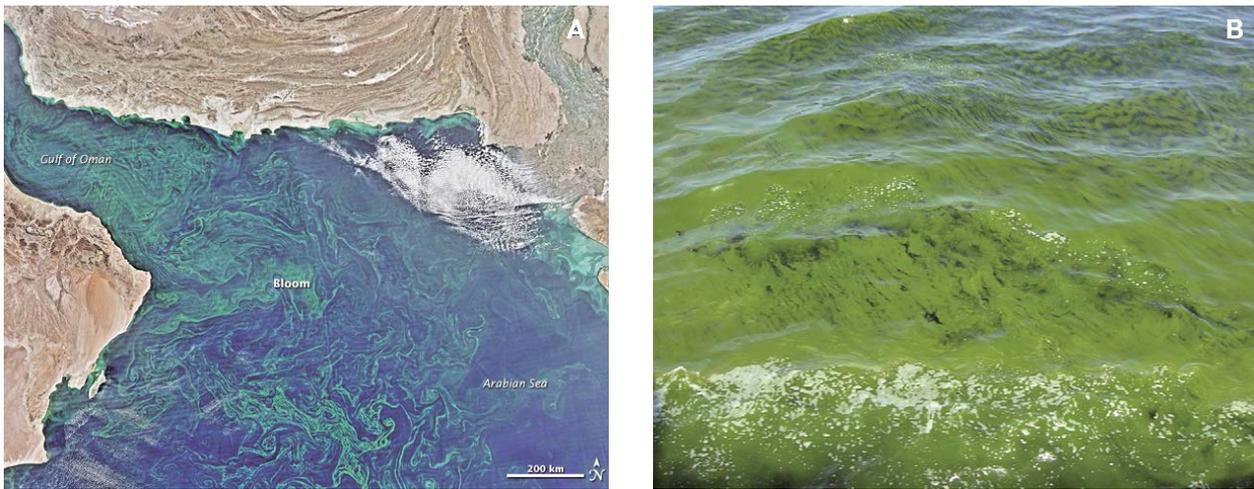


Figure 2.3.7 A) Convective mixing in winter leads to the development of phytoplankton blooms in the northern Arabian Sea, which are identifiable by satellite-based ocean colour measurements. Source: Image obtained on 14.02.2015 by the Moderate Resolution Imaging Spectrometer (MODIS) on NASA's Aqua satellite (<https://earthobservatory.nasa.gov/images/85718/winter-blooms-in-the-Arabian-Sea>). Earlier algal blooms in this region largely comprised diatoms, the major group of phytoplankton with glassy shells. Diatoms were grazed by copepods that were, in turn, eaten by fish. B) Replacement of diatoms by larger sized dinoflagellates (*Noctiluca scintillans* bloom in February 2009 (from <http://helgagomes.com>)), attributed to incursions of low O_2 waters into the surface layer (Gomes et al., 2014), may disrupt this important food chain. Instead the photosynthesized organic matter may now end up as 'useless' salps and jellyfish with potentially large socio-economic consequences.

denitrification (Bulow et al., 2010; Naqvi, 1991) or the intensity of the OMZ. The SNM in the Arabian Sea has been known to occur since 1933/34 (Gilson, 1937), which implies that parts of the OMZ in the Arabian Sea have been functionally anoxic for at least 80 years. Repeat measurements at two locations - 19.75°N , 64.62°E , going back to 1977 (Figure 2.3.6), and $\sim 15^\circ\text{N}$, 68°E , going back to 1979 (data not shown) - showed large interannual changes in NO_2^- concentration but no secular long-term trend. The amplitude of variability was larger at the former site, it being closer to the north-western boundary of the denitrification zone and to a large extent affected by the warm, saline outflow from the Persian Gulf that serves as a source of O_2 to the OMZ (Codispoti et al., 2001). Consequently, at depths where this water mass is found, as identified by its characteristic salinity maximum, NO_2^- and salinity were inversely related (Banse et al., 2014). Linear regression analysis between NO_2^- concentration and year of measurement yielded both negative and positive slopes, with the number of positive slopes exceeding that of negative values indicating that the NO_2^- concentration mostly increased with time, i.e. OMZ intensified. The Arabian Sea was extensively surveyed during the Joint Global Ocean Flux Study (JGOFS) project. Utilizing the data collected during the US JGOFS cruises, Rixen et al. (2014) demonstrated that the area with NO_2^- concentrations exceeding $2 \mu\text{M}$ was 63% larger in 1995 than what was estimated from the earlier data (Naqvi, 1991). However, Rixen et al. (2014) also pointed out that these observations

probably indicated considerable seasonal and interannual variations in denitrification rather than a secular trend of increase. Combining this data set with their own observations made in September-October, 2007, Rixen et al. (2014) showed that the seasonal and interannual variations were driven by the monsoons. During the SWM, the boundary of the denitrification zone, determined by a complex interplay between circulation and productivity, moved eastward as a result of advection of the more oxygenated water across the equator in the western Indian Ocean. Reversal of circulation during the NEM led to westward expansion of the denitrification zone. Rixen et al. (2014) proposed that during those years when the SWM was weaker, the denitrification zone expanded toward the west, and vice versa. The sedimentary records presented by Rixen et al. (2014) indicated an intensification of denitrification in the Arabian Sea during the past few thousand years, supporting this view (see also Kessarkar et al., 2018), but the longer sedimentary records show the opposite trend (Altabet et al., 2002). Thus, it is still not clear whether or not denitrification in the Arabian Sea has intensified in recent decades. In any case, the monsoons play an important role in regulating the intensity of the OMZ and the associated biogeochemical transformations, and since global warming is projected to impact the SWM significantly (Turner & Annamalai (2012), and references therein), this represents an additional region-specific human-induced forcing that may potentially modify O_2 distribution in the North Indian Ocean.

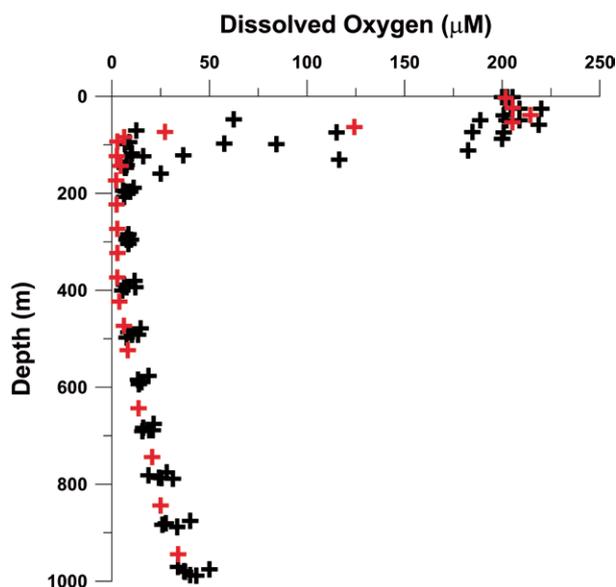


Figure 2.3.8 Comparison of O_2 distribution in the northern Bay of Bengal in the vicinity of Lat. $18^\circ N$, Long. $89^\circ E$ based on sampling in April 1963 (black symbols) and April 2007 (red symbols).

It has been reported that global warming has already led to an intensification of upwelling in the western Arabian Sea (Goes et al., 2005). These authors analysed satellite data off Somalia to demonstrate an increase in phytoplankton biomass by over 350% from 1997 to 2003. It was suggested that the increase in productivity of the Arabian Sea would have far-reaching consequences for the OMZ. However, intensification of upwelling and a consequent increase in phytoplankton biomass have not been confirmed either from satellite data or by *in situ* measurements by subsequent workers (e.g. Naqvi et al., 2010). An expansion of the OMZ has been invoked by Gomes et al. (2014) to explain a radical shift in the composition of winter phytoplankton blooms in the Arabian Sea, where the dinoflagellate *Noctiluca scintillans* was reported to have replaced diatoms over the past decade (Figure 2.3.7). The remarkable ability of its endosymbiont *Pedinomonas noctilucae* to fix carbon under hypoxic conditions is believed to give *Noctiluca* an ecological advantage over other phytoplankton. However, incursions of low O_2 waters into the surface layer in winter have not been subsequently verified (Prakash et al., 2017).

2.3.2.1.2 Bay of Bengal

Reliable O_2 data from the Bay of Bengal date back only to the International Indian Ocean Expedition (IIOE) in the early 1960s. In order to determine whether any change in O_2 concentration has occurred since that time, unpublished O_2 data collected on a cruise of R.V. *Anton Bruun* in the vicinity of Lat. $18^\circ N$, Long. $89^\circ E$ during 20-22 April 1963 are compared in Figure 2.3.8 with measurements made on a cruise of R.V. *Roger Revelle* at about the same time of the year 44 years later. Besides being located in the northern Bay where the OMZ is most intense, the choice of this location was determined by data availability over a long period. The *Anton Bruun* occupied five stations within latitudes $17.1-20.07^\circ N$ and longitudes $88.4-90.28^\circ E$. In 1963, O_2 concentrations, measured with visual end point detection within the depth range $\sim 200-400$ m averaged $8.33 \pm 2.11 \mu M$ ($0.187 \pm 0.047 \text{ ml L}^{-1}$), with a minimum of $5.36 \mu M$ (0.12 ml L^{-1}). Corresponding average and minimum values observed on the *Roger Revelle* Sta. 199 (Lat. $18^\circ N$, Long. $89.85^\circ E$) sampled on 27 April 2007 were $2.63 \pm 0.26 \mu M$ ($0.059 \pm 0.006 \text{ ml L}^{-1}$) and $2.26 \mu M$ (0.051 ml L^{-1}), respectively, based on automated Winkler titrations. Even after allowing for the difference ($1.8 \mu M$ or $\sim 0.04 \text{ ml L}^{-1}$) between the two techniques, the decrease, even though small, is still significant considering, as in the case of Gulf Oman, the extreme sensitivity of anaerobic respiratory pathways to minor changes in O_2 in the low range. More recent data at this site (collected in January-February 2014 on board R.V. *Sagar Kanya*) using STOX sensors yielded a minimum O_2 concentration of 36 nM (0.0008 ml L^{-1}) - Bristow et al., 2017). Elsewhere, O_2 concentrations fell below the detection limit of the sensor ($7-12 \text{ nM}$) in six samples; otherwise O_2 was always present, albeit in traces ($10-200 \text{ nM}$), within the OMZ at all seven stations sampled.

Broad anoxic zones, characterized by SNM, were not observed, except for a thin layer having secondary NO_2^- up to 180 nM at Lat. $18^\circ N$, Long. $89^\circ E$. Despite the absence of SNM, Bristow et al. (2017) recorded the presence of $2-3 \mu M$ of excess N_2 within the Bay of Bengal OMZ. This quantity is an order of magnitude smaller than the N_2 excess found within the Arabian Sea OMZ (Naqvi et al., 2006b), but it still indicates some biological N_2 production. Moreover, analysis of microbial genes revealed adequate presence of microbes capable of denitrification and Anammox that were not very different from other OMZs, and incubations of samples with isotopically labelled nitrogen compounds

demonstrated a potential for Anammox, provided NO_2^- was present. This means that while the system is primed for the conversion of reactive nitrogen to N_2 , rates of the processes involved (denitrification and Anammox) are far lower within the OMZ of the Bay of Bengal compared to other OMZs that contain SNM. Bristow et al. (2017) proposed that traces of O_2 present facilitate NO_2^- oxidation to NO_3^- , thereby restricting its availability for Anammox or denitrification for the production of N_2 , and removal of this residual O_2 may result in an abrupt shift in the biogeochemistry of the Bay of Bengal OMZ. The O_2 change referred to above seems to indicate that the Bay of Bengal is on the verge of such a shift (Bristow et al., 2017). The vertically-integrated O_2 inventory in the upper 1 km was computed to have decreased from 33.77 ± 4.5 to 28.38 M m^{-2} between 1963 and 2007. However, this decrease was mostly caused by a change in the thickness of the mixed, oxygenated surface layer, which was lower in 2017 compared to 1963; by contrast, the lower OMZ appears to have remained remarkably stable for over four decades (Figure 2.3.8). Should the OMZ of the Bay of Bengal cross the tipping point which it seems to be at right now, the loss of reactive nitrogen to N_2 is expected to increase, throwing the nitrogen budget further off balance (Codispoti et al., 2001). Moreover, production of N_2O may also be enhanced, providing positive feedback to global warming.

2.3.2.2 Red Sea and Persian Gulf

A unique feature of the OMZ of the north-western Indian Ocean is that it is ventilated by freshly formed water masses in the two Mediterranean-type marginal seas (Red Sea and Persian Gulf). Both of these seas are located in highly arid zones, experiencing excessive evaporation and receiving little river runoff. Cooling of consequently high salinity waters in winter elevates densities of these waters, causing them to sink and fill deeper parts of the two seas. While in the Red Sea such deep water formation occurs in the extreme northern parts, particularly in the Gulfs of Suez and Aqaba (Morcos, 1970), in the Persian Gulf it takes place off the coasts of the United Arab Emirates (UAE) and Kuwait (Reynolds, 1993; Swift & Bower, 2003). The Red Sea is much deeper (average depth 491 m, maximum depth $>2500 \text{ m}$ - Morcos, 1970) than the Persian Gulf (average depth 36 m, maximum depth $\sim 90 \text{ m}$ - Al-Said et al., 2018). The Red Sea is separated from the Gulf of Aden by a shallow sill (depth 137 m) at the Bab-el-Mandeb Strait - Naqvi & Fairbanks, 1996). The Hormuz Strait, which separates the Persian Gulf from the Gulf of

Oman, does not have a similar sill. Both basins receive less saline waters from the Indian Ocean, transported by near-surface currents to make up for the excessive water loss through evaporation. However, in order to maintain the salt balance these semi-enclosed seas also export dense waters to the north-western Indian Ocean through the Gulfs of Oman and Aden as near-bottom outflows over the two straits. These water masses, called the Persian Gulf Water (PGW) and Red Sea Water (RSW), easily identifiable by their high salinities, are found at depths of $\sim 200\text{-}350 \text{ m}$ and $\sim 500\text{-}800 \text{ m}$, respectively, in the Arabian Sea (Wyrki, 1971). Because of greater depth, volume and presence of a sill at its entrance, the ventilation time of the Red Sea is much longer ($\sim 36 \text{ yr}$ - Naqvi & Fairbanks, 1996) than that of the Persian Gulf (1.2 yr - Al-Said et al., 2018), and the patterns of O_2 distribution are quite different. The Red Sea water column is remarkably homogenous in terms of temperature and salinity below the sill depth. However, chemical data do not show such homogeneity (Morcos, 1970), with the O_2 profiles showing a pronounced mid-depth minimum that generally intensifies toward the south with values going down to $\sim 0.2 \text{ ml L}^{-1}$ (Figure 2.3.9). The low- O_2 concentrations are associated with relatively high temperature ($\sim 22 \text{ }^\circ\text{C}$) which is an important determinant of hypoxia tolerance to marine organisms (Seibel et al., 2016). Natural O_2 depletion in the Persian Gulf is more modest, restricted only to the central and southern parts and largely to the summer season where/when the water column is stratified (Al-Yamani & Naqvi, 2018). Because both PGW and RSW contribute significantly to water mass composition of the OMZ of the north-western Indian Ocean, changes in the amounts of O_2 carried by these water masses are important.

Ongoing deoxygenation trends in the Red Sea have not been documented so far, and there is a dearth of recent O_2 data in the publicly available data bases to investigate such trends. Fortunately, two Argo floats generated O_2 profiles in the northern Red Sea (north of $\sim 23^\circ\text{N}$) - one from 29.09.2015 to 19.02.2017 and the other from 30.09.2015 to 29.12.2016. The data from these floats are compared with measurements made during a cruise of R.V. *Sagar Kanya* in the same region in May 1983 (Naqvi et al., 1986) (Figure 2.3.9). While it would be hazardous to draw definite conclusions based on just two sets of measurements, O_2 values recorded by the floats during 2015-2017 are generally and quite substantially lower than those obtained during the *Sagar Kanya* survey. Also included in Figure 2.3.9A is an O_2 profile from the GEOSECS Sta. 407 (Lat. 19.92°N , Long.

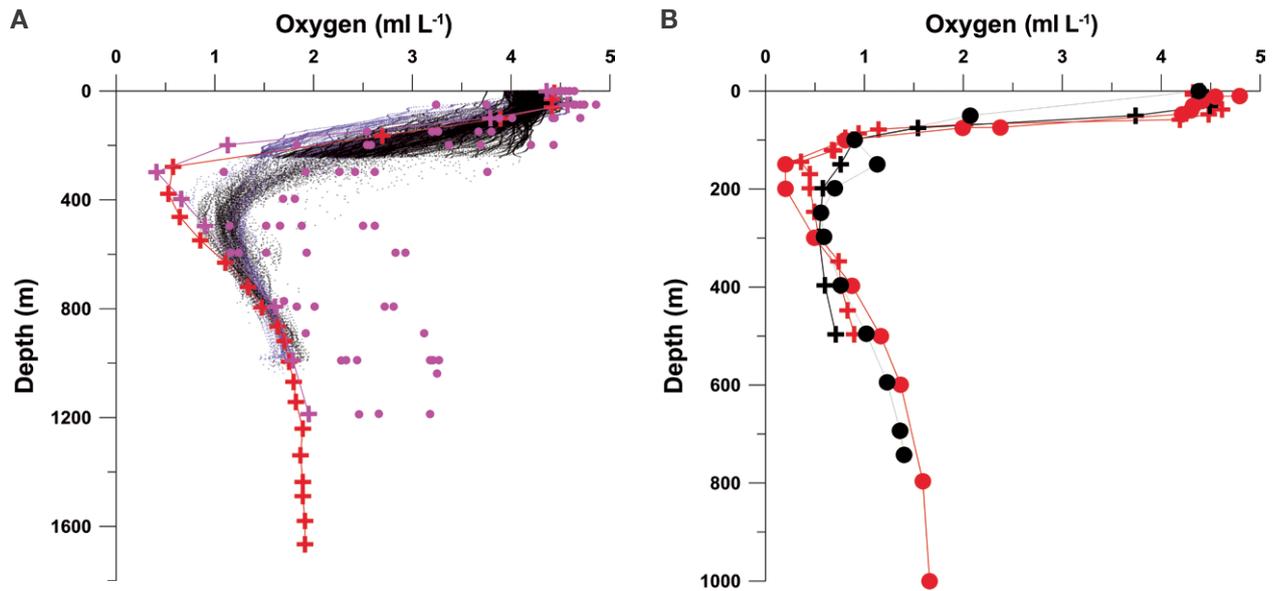


Figure 2.3.9 (A) Comparison of O_2 profiles from two Argos floats deployed in the Red Sea north of $\sim 23^\circ N$ latitude: #146, from 29.09.2015 to 19.02.2017 (black symbols) and #147, from 30.09.2015 to 29.12.2016 (blue symbols) with Winkler O_2 measurements (magenta unconnected circles) made by the author in the same area in May 1983 on board R.V. *Sagar Kanya*. O_2 profiles at a site in the central Red Sea obtained during the GEOSECS Expedition (Sta. 407 - Lat. $19.92^\circ N$, Long. $38.48^\circ E$, sampled on 22.12.1977) and at a nearby *Sagar Kanya* station (Sta. 40 sampled on 24.05.1983) are shown by red and magenta crosses, respectively. (B) Comparison of O_2 profiles at two *Sagar Kanya* stations (Sta. 70 - $16.03^\circ N$, $41.39^\circ E$ - black circles, and Sta. 74 - $14.78^\circ N$, $42.12^\circ E$ - black crosses) with O_2 profiles from two closely located stations sampled during cruises of R.V. *Tyro* on 27.05.1992 (Cast 7168075 - red circles) and 03.02.1993 (cast 7160570 - red crosses). These data were obtained from the National Oceanographic Data Center, USA.

$38.48^\circ E$) taken on 22.12.1977 and another from the closely located Sta. 40 sampled on 24.05.1983 on the same *Sagar Kanya* cruise. The GEOSECS and *Sagar Kanya* data match very well with each other, as do O_2 profiles from two other *Sagar Kanya* stations (Sta. 70 - Lat. $16.03^\circ N$, Long. $41.39^\circ E$, and Sta. 74 - Lat. $14.78^\circ N$, Long. $42.12^\circ E$) with the profiles from two closely located stations sampled during cruises of R.V. *Tyro* on 03.02.1993 and 27.05.1992, respectively. This shows that the *Sagar Kanya* observations were not abnormal. Thus, it appears that substantial deoxygenation has already occurred in deep waters of the Red Sea over the past three decades. However, this trend needs to be confirmed by recent data from the southern Red Sea where seasonality is smaller and the O_2 minimum is more pronounced. The very low O_2 values measured on the *Tyro* cruises, incidentally the most recent bottle data in the database of the National Oceanographic Data Center (NODC), underline the potential vulnerability of the Red Sea to anthropogenic deoxygenation.

The RSW undergoes substantial modification through mixing as it descends from the Bab-el-Mandeb Strait and finds its density level in the Gulf of Aden (Grasshoff, 1969; Morcos & AbdAllah, 2012). With an initial O_2 content of $\sim 1.5 \text{ ml L}^{-1}$ (Morcos & AbdAllah, 2012), the RSW is a source of O_2 to the O_2 -depleted ($< 0.5 \text{ ml L}^{-1}$)

waters it mixes with in the Gulf of Aden. Deoxygenation within the Red Sea is thus expected to affect O_2 distribution in the Gulf of Aden and the adjacent Arabian Sea where RSW spreads horizontally. Trends of any deoxygenation in the Gulf of Aden are not yet known but are expected to be similar to those described above for the western Arabian Sea.

Flowing directly into the core of the OMZ where denitrification is most intense, PGW is perhaps more important than RSW in regulating biogeochemical cycling in the Arabian Sea. Although O_2 supply from this watermass is small, it is nevertheless enough to prevent the onset of denitrification in the north-western Arabian Sea. The PGW also has a relatively elevated concentration of total organic carbon (TOC) compared to the water it mixes with (Hansell & Peltzer, 1998). Changes in the initial concentrations of both TOC and O_2 in this watermass have the potential to alter the extent and intensity of the OMZ. There is compelling evidence to suggest that such changes are already occurring. Emergence of summertime hypoxia in the central Persian Gulf has been reported by Al-Ansari et al. (2015) who observed an O_2 decrease by as much as 1 ml L^{-1} relative to the historical data. More recently, high TOC concentrations (up to $543 \mu M$) have been observed in the northern Gulf (Al-Said et al., 2018). Significantly,

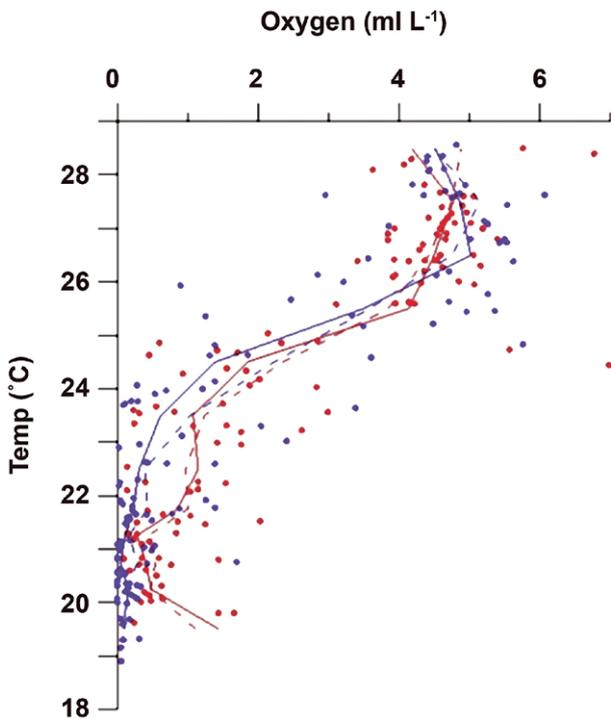


Figure 2.3.10 Comparison of O_2 concentrations with reference to temperatures over the inner and mid-shelf regions (depths < 60 m) off Karwar (see Figure 2.3.1), central west coast of India, during the upwelling period in 1971–1975 (red symbols) and 1997–2004 (blue symbols). Mean and median values for 1 °C-bins are shown by the dashed and solid curves, respectively (modified from Naqvi et al., 2006c).

a reduction in runoff from the Shatt al-Arab river has made surface waters in the region seasonally (in winter) the densest found anywhere in the Gulf implying that the organic matter derived from sewage or produced by phytoplankton in the northern Gulf would be quickly injected into Gulf Deep Water, to be eventually flushed into the core of the OMZ of the Indian Ocean (Al-Said et al., 2018). In addition, model simulations show that the size and intensity of this OMZ are very sensitive to warming of waters in the Persian Gulf and Red Sea (Lachkar et al., 2019). Thus, the ongoing physico-chemical changes in the marginal seas are likely to lead to expansion and intensification of the Arabian Sea OMZ.

2.3.2.3 Coastal waters

The available information suggests that O_2 concentrations in bottom waters over the Omani shelf might have decreased in recent decades (Piontkovski & Al-Oufi, 2015). This is also supported by data presented by Naqvi et al. (2010). However, there is a dearth of recent O_2 measurements from this region. In contrast to this, the seasonal low O_2 zone over the western Indian shelf, the largest of its kind in the world (Figure 2.3.3), has been fairly well studied. Although O_2 deficiency off India has

been known since the 1950s (Banse, 1959; Carruthers et al., 1959), its regular monitoring was initiated by the National Institute of Oceanography (NIO), Goa, only in the 1990s. A number of cruises were undertaken during which multi-disciplinary observations were made along transects running perpendicular to the coast. In 1997 a time series station, the Candolim Time Series (CaTS), was also established off Goa at a depth of ~28 m. The CaTS data show marked interannual changes in the duration as well as intensity of O_2 deficiency but no clear long-term trend (Naqvi et al., 2009). The most intense anoxic conditions were recorded in the early 2000s (especially in 2001) when high hydrogen sulphide (H_2S) concentrations were recorded over large parts of the shelf at depths as shallow as 5 m and as deep as 65 m. This was attributed to an intensification of O_2 deficiency over the western Indian shelf due to enhanced anthropogenic nutrient loading (Naqvi et al., 2006c). Although anoxic events of comparable magnitude have not occurred since, current conditions are still more severe than those indicated by the historical data. The most extensive of such data, although restricted only to salinity, temperature and O_2 , were obtained under the UNDP/FAO-sponsored Integrated Fisheries Project (IFP). Repeat observations were made under this programme from 1971 to 1975 along a number of coast-perpendicular transects, including one off Karwar, just south of Goa. A comparison of the O_2 data generated during the IFP with those collected by NIO for the same shelf segment (depth < 60 m) and the same season (August–September) between 1997 and 2004 (Figure 2.3.10) shows considerable scatter. However, the means and medians of subsurface concentrations are significantly lower for 1997–2004 than for 1971–1975. Significantly, zero O_2 concentrations, characteristic of sulphidic waters, were never recorded on the IFP cruises, implying the absence of H_2S . Other data subsequently collected by NIO (Naqvi et al., 2000 - Supplementary Information) also show that the subsurface environment was denitrifying but not sulphate reducing at least until the 1980s. It is still not clear what caused a shift to sulphidic conditions that have persisted but have not intensified steadily since the monitoring began at the CaTS site. It has been suggested that the intensity of anoxia may be modulated by basin scale events especially the Indian Ocean Dipole (IOD) (Vallivattathillam et al., 2017). The IOD is the Indian Ocean counterpart of the El Niño and La Niña events that are well known to occur in the Pacific Ocean (Saji et al., 1999). Positive IOD years, of which 1997 is an extreme example, are distinguished by anomalously low sea surface temperatures (SSTs) in the

eastern equatorial Indian Ocean and high SSTs in the western Indian Ocean, a reversal of the normal trend, accompanied by wind and precipitation anomalies. Isolation of human-induced environmental changes including changes in O_2 distribution from those resulting from irregular but naturally caused climate modes, like IOD, continues to be a major challenge.

Further south along the same coast, monthly observations for one year in 2012 at a station located over the mid-shelf (Lat. 9.969°N, Long. 75.831°E, depth 52 m) off Kochi, which was also sampled on a monthly basis by Banse (1959) from July 1958 to January 1960, revealed remarkably little change in O_2 concentrations over the intervening period (Gupta et al., 2016). However, 2012 was an IOD year when upwelling was weaker, and so the prevalence of lower O_2 concentrations during a normal year cannot be ruled out.

High population density and rapid industrialization have led to large increases in waste discharges, often untreated, into most Indian rivers, resulting in the development of low O_2 conditions in several estuaries, creeks, bays and fishing harbours such as Ratnagiri, Veraval and Porbandar Harbours; Mahim Bay and Versova Creek (Mumbai); and the estuaries of rivers Ulhas (near Mumbai), Kolak (near Daman), Tapi (near Surat) and Sabarmati (at the head of the Gulf of Cambay) along the north-west coast of India (Figure 2.3.1), with the O_2 concentration sometimes falling below 0.15 ml L^{-1} . For example, measurements in the Tapi Estuary from 1983 to 2011 revealed a change from normoxic to hypoxic conditions (Ram et al., 2014). The estuary remains hypoxic/anoxic during all seasons, but anoxia is more pronounced during the summer and at low tide. The environmental condition of the Tapi Estuary has impacted coastal waters, resulting in fish kills (Ram et al., 2014). Development of anoxia has also been observed in the bottom layers of Kochi Backwaters along the south-west coast of India (Martin et al., 2010). Like most estuaries along the Indian west coast, the intrusion of O_2 -poor upwelled water also occurs in this estuarine system. High O_2 demand in bottom waters arising from eutrophication maintains anoxic (including sulphidic) conditions up to 6 km upstream from the bar mouth of the estuary.

Despite immense runoff from numerous major rivers that are believed to bring large quantities of nutrients into the Bay of Bengal (Seitzinger et al., 2002), O_2 deficiency in shallow waters over the continental shelf is not as

intense in the Bay of Bengal as in the Arabian Sea. Even though as stated above the OMZ in the Bay of Bengal is almost as intense as that in the Arabian Sea, it is located offshore at depths exceeding ~100 m. Unlike the Arabian Sea, it does not come up over the continental shelf close to the surface because of the lack of large-scale upwelling along the Indian east coast, except locally in some areas such as the Andhra coast where some intensification of low O_2 conditions has been reported (Sarma et al., 2013). A more severe event was observed off the south-east coast of India in 2010 leading to prevalence of hypoxic conditions even in shallow waters with O_2 concentrations going down to 0.1 ml L^{-1} at 59 m depth (Satpathy et al., 2013). Although this event was attributed to land-based pollution, the data presented point to an offshore origin of nearly-anoxic waters, possibly associated with an eddy. While O_2 deficiency may develop to a very limited extent close to points of sewage discharge from large population centres, the absence of big hypoxic (dead) zones, like the one in the Gulf of Mexico (<https://gulfhypoxia.net/>), off the mouths of major rivers such as the Ganges-Brahmaputra (Mitra et al., 2018) in the Bay of Bengal is counter-intuitive. This supports the view (Naqvi, 2008) that nutrient runoff by rivers flowing into the Bay of Bengal is not as large as predicted (Seitzinger et al., 2002). Unfortunately, reliable recent O_2 data are nearly non-existent to assess the extent of O_2 change along the coasts of all other countries (Bangladesh, Myanmar, Malaysia, Thailand and Indonesia).

Some estuaries in western Australia near Perth (e.g. Swan-Canning Estuary and Peel-Harvey Estuary), have been impacted by eutrophication and, at some times of the year have O_2 levels below hypoxia threshold (1.4 ml L^{-1}) (Hipsey et al., 2014; Thomson et al., 2017; Tweedley et al., 2015). However, the scale of the problem is far smaller than in other major hypoxic estuarine systems such as the Chesapeake Bay along the US east coast (Officer et al., 1984).

2.3.4 Ecosystem consequences

Oxygen depletion in sea water has a wide variety of impacts on marine biogeochemistry and ecosystems (Briertburg et al., 2018, and references therein), all of which are seen in the low O_2 waters of the Indian Ocean as well. Benthic ecosystems in the Indian Ocean are worst affected by this phenomenon because of the unusually large area of continental margins exposed to hypoxic/anoxic waters (Helly & Levin, 2004).

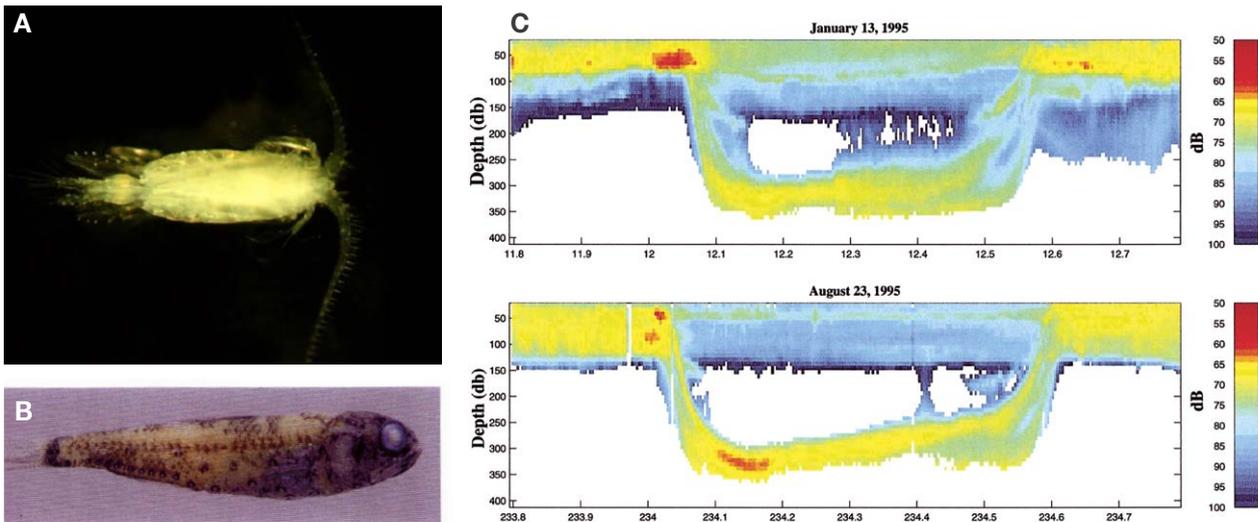


Figure 2.3.11 Life in anoxic environments is dominated by bacteria that are able to utilize chemical species such as nitrate and sulphate to decompose organic matter and gain energy. However, a few multi-cellular organisms are capable of tolerating low O_2 concentrations by suppressing their metabolism (Seibel et al., 2016). Examples from the Arabian Sea include (A) the copepod *Pleuromamma indica* (Saraswathy & Iyer, 1986) (from http://www.mmcer.ynu.ac.jp/shimo/my_site/photos1/peji/Planktonic_copepods.html#70) and several species of myctophids (lanternfish), of which (B) *Benthosema pterotum* (image courtesy P.K. Karuppusamy) is most abundant (Gjosaeter, 1984). Estimated stocks of myctophids in the Arabian Sea (~100 million tonne) slightly exceed total annual global marine fish catch. This huge biomass undergoes spectacular diurnal migration to the functionally anoxic core of the OMZ to escape from predators during the day as shown by the Acoustic Doppler Current Profiler (ADCP) back-scatter records (C) at a location near the heart of the denitrification zone for 24 hours on 13/01/95 and 23/08/95 (after Morrison et al., 1999).

Oxygen deficiency greatly reduces benthic biodiversity, promoting dominance of hypoxia-tolerant groups like polychaetes (Ingole et al., 2010; Levin et al., 2009; Raman et al., 2015). Where O_2 -depleted waters reach the sun-lit zone, they strongly impact phytoplankton community structure. A dramatic shift in phytoplankton composition, with massive blooms of *Noctiluca scintillans* replacing diatoms thereby altering the trophic structure, has been ascribed to the emergence of hypoxic conditions close to the surface during winter in the northern Arabian Sea (Figure 2.3.7) (Gomes et al., 2014). As in other areas, O_2 depletion also affects vertical distribution and diurnal migration of zooplankton in the open ocean (Morrison et al., 1999; Wishner et al., 1998) and in coastal waters (Madhupratap et al., 1996) of the Indian Ocean. At the higher trophic level, while most fishes are excluded from O_2 deficient waters, some species of myctophids (lanternfish) are adapted to live in the functionally anoxic core of the OMZ to which they migrate during the day to avoid predation (Figure 2.3.11; Morrison et al., 1999). The total biomass of myctophids in the Arabian Sea is incredibly high (~100 million tonne; Gjosaeter, 1984). Diurnal migration of such a huge biomass up and down the water column is of great ecological and biogeochemical relevance.

Complete loss of O_2 from the water column favours the development of diverse microbial populations that

utilize anaerobic pathways to derive energy, mediating elemental transformations that are of immense geochemical significance (Wright et al., 2012). For example, denitrification is by far the most important sink term in the reactive nitrogen budget (Codispoti et al., 2001), producing N_2 , the most abundant gas in the atmosphere, thereby countering biotic and abiotic N_2 fixation. The OMZs that support anaerobic respiration pathways are distinguished by an increase in total bacterial numbers to the extent that it causes a significant increase in water turbidity (Naqvi et al., 1993). These bacteria evidently support unusual food chains that are yet to be fully explored.

2.3.5 Societal consequences

The most important consequence of deoxygenation is its adverse effect on biodiversity and living resources. Unfortunately, published information available on this important aspect from the Indian Ocean is scarce. However, several instances of fish kills (Figure 2.3.12) suspected to be caused by hypoxia often associated with algal blooms have been documented (e.g. Naqvi et al., 1998; Piontkovski et al., 2012; Ram et al., 2014). Along the west coast of India, demersal fish landings appear to be strongly linked with the intensity of seasonal anoxia, showing pronounced declines during strong anoxic events, for example in 2001 when sulphidic conditions



Figure 2.3.12 An incident of severe fish mortality observed on Caranzalem Beach (Goa, west coast of India) on 24th August, 2019. Such fish kills are commonly caused by the upwelling of low-oxygen subsurface water from offshore during late summer/early autumn. © D.M. Shenoy, National Institute of Oceanography.

prevailed on a large scale over the western Indian shelf (Naqvi et al., 2009). The recently reported dominance of dinoflagellates over diatoms in the northern Arabian Sea in the winter, attributed by Gomes et al. (2014) to expansion of hypoxia in the upper water column, may potentially affect fisheries, since diatoms have been the principal primary producers, forming the base of food chains leading to commercially important species (Figure 2.3.7). Potential socio-economic impacts of such ecosystem shifts remain to be evaluated. Another notable effect of deoxygenation is its positive feedback to climate change through enhanced production of greenhouse gases, especially N_2O . The Indian continental shelf is an especially important hotspot of N_2O production during seasonal anoxia (Figure 2.3.3; Naqvi et al., 2000) implying that an expansion of the OMZs may substantially increase oceanic N_2O emissions. On a longer timescale, enhanced loss of reactive nitrogen as N_2 from the expanded/intensified oceanic OMZs and in sediments would affect biological productivity, and therefore ocean's capacity to sequester atmospheric CO_2 , thereby affecting climate; this has been hypothesized to have happened in the geological past (Altabet et al., 2002).

2.3.6 Implications of continuing ocean deoxygenation

The Indian Ocean contains a very large volume of water that has extremely low O_2 concentrations but is still not

functionally anoxic (i.e. it does not support anaerobic processes such as denitrification). Even though rate of O_2 loss appears to be generally slower in the region than, for example, in the North Pacific, with continuing deoxygenation and expected decrease in O_2 supply from the south as well as increase in productivity, an expansion of the volume of anoxic water seems inevitable. If and when that happens, it will greatly impact biogeochemical fluxes such as a substantial increase in oceanic nitrogen loss (Bristow et al., 2017). Expansion/intensification of the existing coastal hypoxic/anoxic (dead) zones and the emergence of new ones as a consequence of enhanced nutrient loadings are, in all likelihood, also going to happen, if they are not already happening, given the large population density in countries surrounding the North Indian Ocean. South Asia is a hot spot of nutrient export to the ocean, accounting for 28% of the global total nitrogen (TN) and total phosphorus (TP) exports, the majority (>60%) of which is received by the Bay of Bengal (Figure 2.3.13) (Mayorga et al., 2010). It is estimated that the TN runoff to the Bay of Bengal alone will increase from 7.1 million tonne in 2000 to 8.6 million tonne in 2050, whereas TP export may remain unchanged at ~1.5 million tonne (Pedde et al., 2017). Coastal areas adjacent to river mouths in the north-eastern Indian Ocean (e.g. off Bangladesh and Myanmar) are particularly vulnerable to eutrophication and consequent deoxygenation resulting from riverine inputs of nutrients. Emergence of hypoxia here will have far reaching impacts on fisheries and associated livelihoods of a large number

of people. Finally, the ongoing rapid deterioration of the marine environment of the two marginal seas (Persian Gulf and Red Sea), especially through eutrophication and deoxygenation (Al-Ansari et al., 2015; Sheppard et al., 2010) and warming (Lachkar et al., 2019) will have a potentially large impact on the extent and intensity of the mid-water O₂ deficiency in the north-western Indian Ocean.

2.3.7 Conclusions / Recommendations

The information presented above does not show as consistent and as large a trend of deoxygenation in the upper water column in the Indian Ocean as in other oceanic areas, perhaps reflecting differences in ventilation of subsurface waters arising from the unusual geographical setting of the Indian Ocean. However, the geographical setting and associated unique climatic conditions in conjunction with high population density of the surrounding landmasses also make biogeochemistry and ecosystems in the region more vulnerable to human-induced deoxygenation. The unique impact of ongoing changes in the two marginal seas on the open-ocean OMZs needs to be evaluated in detail. Also, of particular interest is how conditions in the large volume of water

presently on verge of turning fully anoxic, especially in the Bay of Bengal, will evolve in future in response to changes in physics as well as nutrient loading from land.

A severe lack of information on the health of coastal waters of a majority of countries bordering the Indian Ocean, including potential hotspots off major river mouths (e.g. Indus in Pakistan, Ganges-Brahmaputra in Bangladesh and Irrawaddy in Myanmar), presently limits our ability to evaluate effects of human activities including deoxygenation. As enhanced nutrient loading will eventually lead to development/intensification/expansion of dead zones at the mouths of these rivers, and remedial measures will have to be initiated to contain this problem, capacity building in these countries for sustained observations and development of regional observational networks must be given a high priority. In addition to ocean deoxygenation, such a monitoring programme should also cover other related changes such as warming, eutrophication and acidification arising from human activities. Understanding how these multiple stressors may act in concert is necessary for predicting the impact on the marine environment and ecosystems and their socio-economic ramifications.



Figure 2.3.13 The estuary of River Hooghly, a distributary of the Ganges. The Ganges-Brahmaputra River System, along with several other rivers, brings very large quantities of fresh water and dissolved & suspended matter to the Bay of Bengal. These rivers form extensive deltas that house some of the world's largest mangrove ecosystems. Increases in organic matter and fertilizer loadings to estuarine and coastal water are expected to lead to development of hypoxic zones in coastal Bay of Bengal in the future. © Dr. Sandip Mukhopadhyay, University of Calcutta.

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2.3.8 References

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