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Case Report

Oxygen declination in the coastal ocean over the twenty-first century: Driving forces, trends, and impacts

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ABSTRACT

Oxygen declination in coastal oceans has accelerated drastically in recent decades, both in terms of severity and spatial extent, and such disappearance of oxygen leads to dead zones where life can't survive. This phenomenon is mainly attributed to nutrient pollution and climate change due to intensified anthropogenic activities. The annual statistical oxygen mean concentrations showed the current deoxygenation trends based on (WOA_2001–2018) data comparison of 200 m below the surface water from the first two decades of the 21st century. A relatively similar significant oxygen loss of 0.5–3 ml/L was indicated in the first decade (2001–2009) over the water of continental shelves (200 m) in the tropical oceans and the areas of subtropical Pacific, Atlantic, and southern Indian oceans gradually started to fall from their moderate oxygen concentrations 4–5 ml/L between 2005 and 2009. Consequently, in the next decade (2013–2018), the negative oxygen trend persisted at a similar depth in the global oceans, and its expansion to more regions suggested that this trend of oxygen loss will continue in the future. This is a serious threat that has to be made more widely known since declines in oxygen levels in coastal oceans could have a wide range of negative impact on marine life, biogeochemical cycles, coastal habitats, economies that run on the sea, and ultimately humans. Therefore, it is crucial to investigate and put into practice management alternatives in order to lessen the effects of continuous deoxygenation on marine life and the supply of services by marine ecosystems.

1. Introduction

Declining oxygen concentrations in the world's oceans are a major worry in the twenty-first century. Dissolved oxygen in water is almost as critical as it is on land for the survival of all life on our planet. It maintains a balanced population of fish, shellfish, and other aquatic animals in both estuarine and coastal waterbodies. According to Woods Hole Oceanographic Institution (WHOI), coastal oceans are those shallow water basins less than 200 m (650 feet) deep and that are adjacent to continents or islands [1]. They include systems such as estuaries, coastal lagoons, semi-enclosed seas, and the areas from the shoreline to the outer edge of the continental margin [2]. Nearly two-thirds of global GDP is generated by human activity in coastal areas on land and water, yet many of these resources are at risk due to runoff, pollution, habitat modification, and overfishing [1]. Only about 5–7% of the total ocean surface area is covered by coastal oceans which support 10–15 Gt C yr^{-1} of total primary productivity and sustain 95 % of total marine life in this region [3].

The overall decrease in the oxygen concentration of marine and coastal waters is referred to as ocean deoxygenation [4]. It happens when the amount of oxygen consumed exceeds the amount of oxygen replenished. Low oxygen zones, sometimes known as "dead zones," can develop naturally, but due to human activity, these zones are growing much larger. Nearly the entire 164,000 sq km Gulf of Oman is covered by the largest dead zone in the world, which is located in the Arabian Sea. The Gulf of Mexico in America has the second-largest dead zone, measuring more than 15,000 square kilometers [5]. By combining with the air at the ocean's surface or through plant photosynthesis, oxygen

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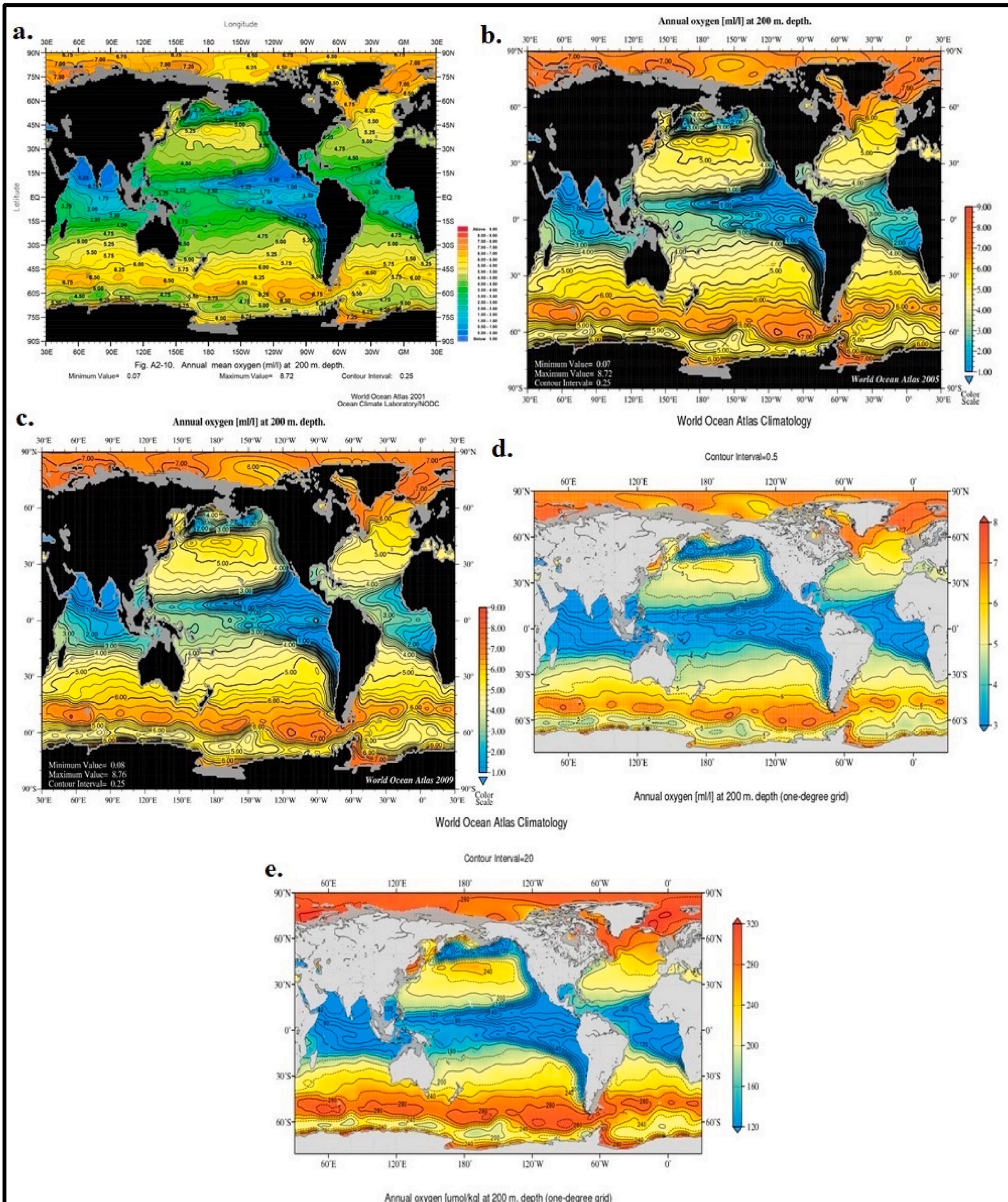

Fig. 1. A temporal comparison of annual average oxygen concentration trends in global coastal oceans at ml L^{-1} at 200 m depth (one-degree grid, World Ocean Atlas) and to identify their changes between the last two decades 2000s and 2010s. a) 2001 b) 2005 c) 2009 d) 2013 e) 2018. The low DO values (blue zones, DO $\leq$ 2mg L^{-1}; light blue zones, DO 2–3mg L^{-1}) show the continuous prominent decline of oxygen from year to year; high DO values (red zones, 6< DO < 9mg L^{-1}) are highlighted on the map, although the proportion of oxygen depletion is lower in the 2000s (Fig1.a-c) compared to the 2010s (Fig.1d and e). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

can reach the water [6]. Warming, nutrients, and carbon dioxide emissions are the main causes of ocean deoxygenation [7]. It interferes with the ocean ecosystem's natural balance.

When dissolved oxygen levels fall below 6 mg/L (192 μmol/kg), an area is said to be oxygen deficient, and when the levels are below 2 mg/L (64 μmol/kg) the situation is considered hypoxic [8]. Therefore, both acute and chronic oxygen deficiency may have detrimental effects on coastal and marine ecosystems, including metabolic processes, the loss of necessary habitats for much bottom-dwelling fish and benthic fauna, habitat compression for pelagic fish, direct mortality, increased predation, and reduced food resources [9].

Dissolved oxygen was a topic of interest in research and management by the early 1990s, but it was recognized by the 1920s that a lack of oxygen was a severe hazard to fish. It wasn't until the 1970s and 1980s, when vast areas of low dissolved oxygen started to form along with extremely high invertebrate and fish mortality, that it became evident that dissolved oxygen would become essential in shallow coastal ecosystems [10,11].

According to regional time-series data, the worldwide ocean oxygen concentrations have decreased by 2 % from 1960 to 2010, indicating a persistent loss in oceanic dissolved oxygen, and more than 700 coastal systems up from only 45 have recorded low oxygen levels [12]. While the change may appear insignificant, scientists say even minor changes in the gas levels can significantly lead to a complete change in whole ecosystems. No other environmental parameter with such ecological significance to estuarine and coastal marine ecosystems has altered dramatically as dissolved oxygen in such a short time [13]. Even in recent decades, an increase in the spatial range and duration of lower oxygen concentrations has been identified in the bottom waters of coastal and marine seas [14]. Some well-documented productive areas where oxygen concentrations are losing rapidly such as the northern Gulf of Mexico, the upwelling regions of California and the Pacific Northwest, the Chesapeake Bay, and the Baltic, Black, Bohai, Yellow, and Mediterranean Seas [12]. Coastal deoxygenation in the coming years is projected to even become more severe environmental issue with an increase in incidence, frequency, intensity, and duration as climate and land use change [15]. Although receiving little attention until recently, climate warming is becoming an increasingly critical factor driving the loss of dissolved oxygen in the world's oceans, estuaries, and seas [12].

Numerous research has been conducted on the deoxygenation of coastal waters and the main objectives of the current review were: i) to summarize the key findings of those studies with a focus on several perspectives and disciplines; ii) to identify the current global deoxygenation trends of the last two decades; iii) to provide information regarding its mechanisms underlying ongoing decrease in the oxygen content of coastal and marine ecosystems as well as their consequences of being exposed to low dissolved oxygen concentrations; and iv) to address fundamental knowledge gaps for better understanding and find out the possible areas on which future studies can be carried out to effectively minimize the problem.

2. Methodology

Being an emerging threat to the coastal environment the concurrent scenario of oxygen declination should be given the utmost priority for marine life and ecosystem. Data is collected from the World Ocean Atlas (WOA) figures at roughly 4 years intervals, 1° grid between 2001 and 2018 based on dissolved oxygen climatological fields. For this review, a systematic search approach has been performed. Most information on ocean deoxygenation and its consequences has been collected from various internet resources, including articles published in the journals of Springer, Elsevier, Frontiers, and other reputed international Journals, reports published by non-profit and advocacy organizations, and other peer-reviewed literature. Search keywords were either closely related to coastal deoxygenation, such as Eutrophication, Deoxygenation, Climate change, Hypoxia, Biodiversity, Biogeochemical cycle, Seagrass meadows, Coral reef, and Mangrove ecosystems. Moreover, each search was further expanded with combinations of different words, including "hypoxia associated eutrophication," "ocean deoxygenation and climate change," "effect of deoxygenation on coastal habitats," "effect of deoxygenation on marine biodiversity," and "ocean deoxygenation impact on the fishery." We performed Google, Google Scholar, Science Direct, Research Gate and Web of Science searches using all these mentioned search terms and stopped exploring further when the searches were unrelated or duplicative. The literature review identified approximately 140 scholarly journal articles on ocean deoxygenation, its mechanisms, and the individual impacts of deoxygenation and climate change on the environment. We then analyzed these search results and extracted the relevant information for review writing.

3. Current scenario of oxygen declination trends along the outer edge of the continental shelf

The concentration of dissolved oxygen gradually increased before the mid-1980s, but it began to abruptly fall after that time along with an increase in the global ocean heat content [16]. This pattern matches the earlier research which focused on the upper 100 m inventory from 1955 to 1998 [17]. Due to geographic differences in the effects of global warming, the variability and direction of change in oxygen content are likely to vary among individual coastal water bodies [18,19]. Globally, the incidence of hypoxic zones is rising alarmingly. There were about 500 of them by the turn of the 20th century, and hypoxia had developed into a severe environmental problem on a global scale. Among them, several hypoxic systems about 70 showed signs of improvement in about 15 % of cases. By the first decade of the twenty-first century, there had been reports of hypoxia from about 640 different locations. The approximately 65 sites found in the Baltic region are not included in this total of 640. The total dead zones rise to roughly 700 when these are included [20].

In this section, the most recent oxygen figures (WOA 2001–2018 global database: Annual Oxygen Statistical Mean, one-degree grid, with an interval of 4 years) were compiled to compare the trends of the ongoing deoxygenation of the first two decades over the twenty-first century in global oceans at 200 m depth, encompassing the area of the outer edge of the continental shelf. Both low and high latitudes exhibited decadal O_2 decline during the 2000s and 2010s despite having different temporal variabilities. The lower (negative) oxygen trend was seen at low latitudes (30°S-30°N) between 2001 and 2009, then it gradually moved to mid-latitude nearshore waters in 2013 and 2018 (Fig. 1). In 2001, the annual mean concentration of oxygen was lowest (0.5–3 ml/L) at 200 m depth in the central portions of the Pacific, Atlantic, and most of the Indian Ocean which lie in the tropics and a little decline (<6 ml/L) began to be noticed in the Southern Ocean (Fig. 1a). And while in 2005 and 2009, the trend of oxygen declination was almost identical (1–3 ml/L) in the tropical oceans and the oxygen-deficient areas of the Southern Ocean. In contrast to the subtropical North and South Pacific, the North and South Atlantic Oceans, and the southern Indian Ocean, which had moderate oxygen levels (4–5 ml/L), the waters of the Arctic Ocean had saturated oxygen content (>7 ml/L), indicating the highest oxygen content, and the middle of the Southern Ocean had a gradually increasing oxygen trend (>6 ml/L) (Fig. 1b and c).

At the same specific depth of the continental shelf areas of the global oceans between 2013 and 2018, a generally negative oxygen trend persisted, and its expansion to more locations suggested the loss of oxygen (Fig. 1d and e). If this pattern of deoxygenation continues at this continental waterborders, there will be a greater chance to create more dead zones within a couple of decades.

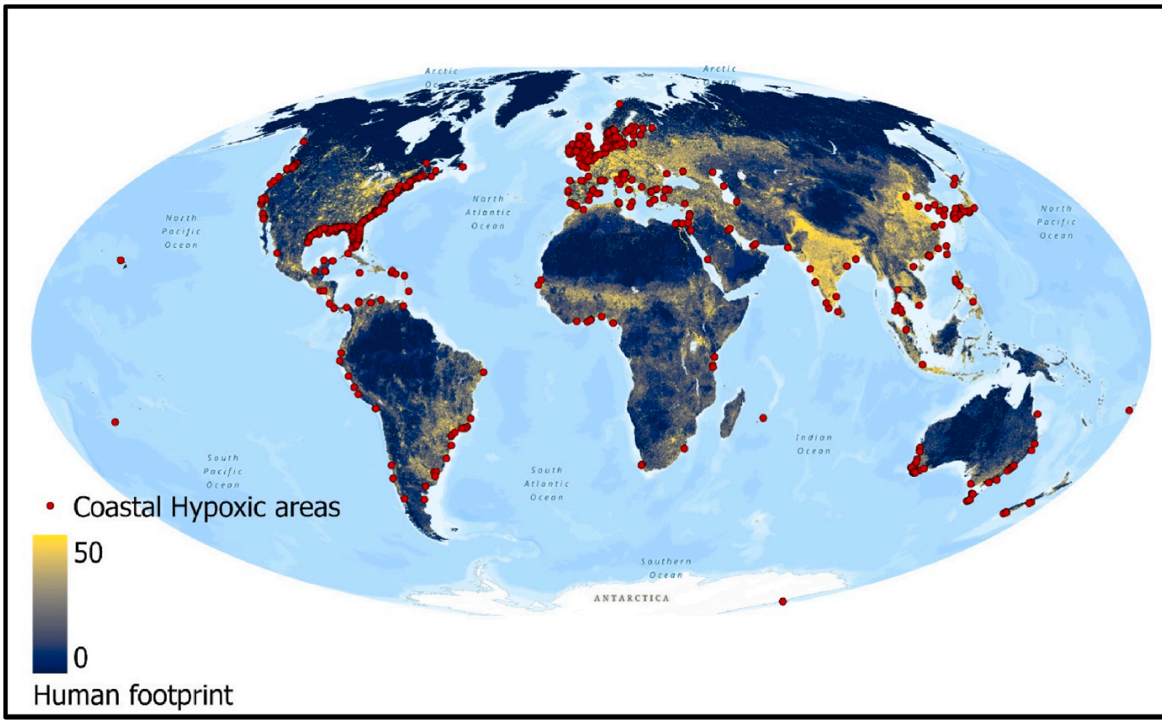

Fig. 2. The global distribution of hypoxic systems corresponds with the normalized portion of the global human footprint, especially in the Northern Hemisphere where data is more abundant [27].

Table 1
Major anthropogenic inputs of nutrients in coastal watersheds [36,37].

Nutrients	Non-point sources	Point sources	Input to coastal watersheds
Phosphorus (P)	Runoff from agriculture	Sewage industrial discharges	~22 Tg P per year
Nitrogen(N)	Synthetic fertilizers, Combustion of fossil fuels, Legume agriculture, Animal husbandry	Municipal wastewater, Finfish aquaculture	~160 Tg N per year

4. Drivers of coastal deoxygenation

4.1. Nutrient over-enrichment

The process of eutrophication, which encourages the excessive growth of algae and other species, occurs when nutrients from human waste, agricultural runoff, industry, and nitrogen deposition from fossil fuel combustion are added to coastal waterways. Coastal rivers, bays, and oceans are degraded by increased nutrient loads, although a recent study has shown that N is more hazardous to these systems. In contrast, research from freshwater lakes has shown that P is more important for controlling water quality [21]. The coastal water may become murky as the number of algae grows as a result of the addition of nutrients to the water. As a result, the algae start to decompose and die, and oxygen levels in subterranean waters and sediments start to drop more often (hypoxia and anoxia). Despite very high rates of photosynthesis causing dissolved oxygen in surface waters to be supersaturated, the amount of oxygen in the bottom water is not restored quickly enough [22].

The key factor that increases the risk of worldwide distribution of coastal hypoxia is linked to significant population centers and watersheds that provide substantial quantities of nutrients (Fig. 2). Coastal eutrophication is now a worldwide problem particularly in the northern hemisphere, in the Atlantic and Pacific oceans' western borders, and in European-coastal waters [23–26].

According to estimates, coastal ecosystems get about 24 % of the anthropogenic nitrogen (N) released in coastal watersheds globally [28] and due to anthropogenic activities, the global supply of dissolved inorganic nitrogen (DIN) doubled in the middle of the last century [29–31]. The anticipated planetary threshold of 62 Tg N yr^{-1} as well as all-natural N-fixation in the ocean is currently exceeded by anthropogenic N inputs into the global ecosystem (160 Tg N yr^{-1}) [32].

Nonetheless, the largely one-way movement of phosphorus (P) from the land to the oceans, where it is eventually buried in ocean sediments, dominates the global flux of phosphorus [33], which is now predicted to be 22 Tg P per year almost threefold to current loadings (Table .1) [34]. The proportional magnitude of these sources changes depending on the watershed's population density, regulations, and land-use practices [35]. Enclosures allow for anthropogenic nutrient loading as well as the freshwater that contributes to stratification is more vulnerable to the creation of "dead zones". The consequence of excess nutrient loading in coastal ocean than in the open ocean will be made worse by interactions with other pressures like overfishing, coastal development, and climate-related changes.

4.2. Climate change influenced coastal deoxygenation

Climate change is thought to be a major cause of oxygen declination because it reduces the amount of oxygen available and alters circulation patterns that bring oxygen-rich water to deeper waters [38]. The recent period of global warming is happening at a faster rate than any previous one. It has become evident that humans are responsible for the majority of the warming over the previous century by generating heat-trapping gases, mainly excess carbon gas emissions from pre-industrial levels to power our modern lives [39].

The ocean is the primary thermal reservoir in the climate system and has absorbed more than 90 % of the surplus heat that has been accumulating in the Earth's system since the beginning of the industrial revolution [40,41]. If such heat is not easily sequestered in the deeper ocean, the excess heat would have accumulated in the near-surface ocean and the earth would be warmed [42–44]. At present, the global

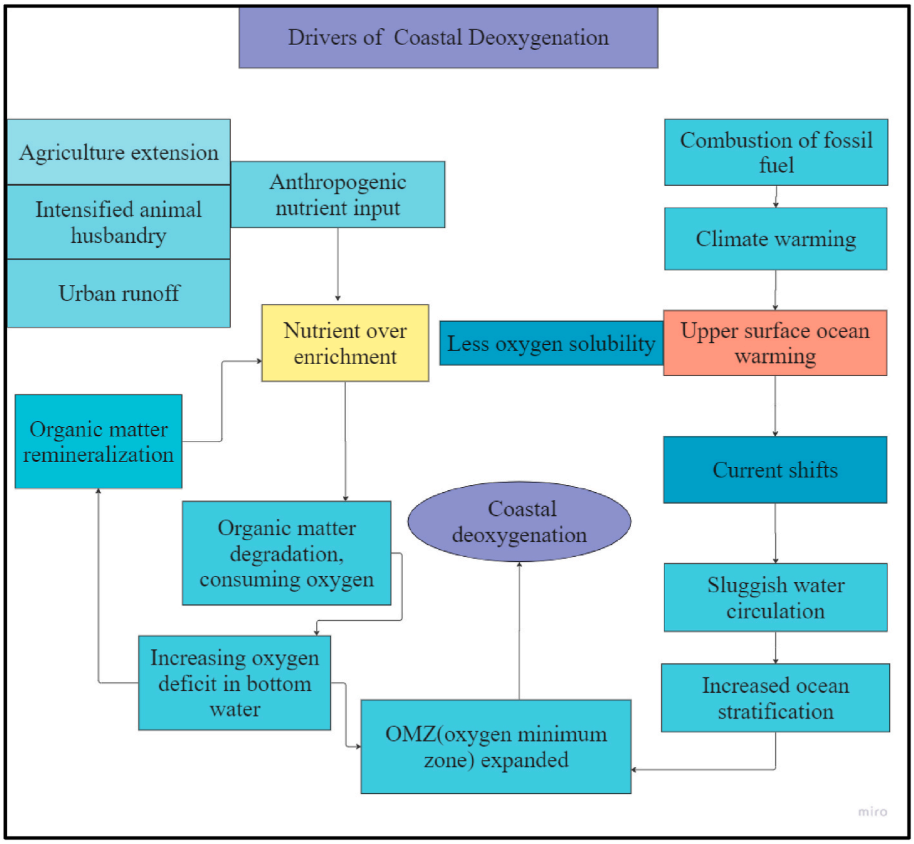

Fig. 3. A schematic view of drivers of coastal deoxygenation. This diagram shows the link between nutrient loading drives the excess primary productivity and climate-driven deoxygenation by increased stratification, and changing circulation in coastal oceans. The interactions of these processes make systems more susceptible to the development of hypoxia.

Table 2
The adverse effect of multiple climate factors on the extent and severity of hypoxia in coastal waterbodies. Positive (+) indicates worsening and negative (−) indicates lessening of hypoxic systems [22].

Climate factor	Primary effect	Secondary effect	Coastal hypoxia
Temperature	Warmer coastal water temperature	Increased stratification	+
		High metabolic rates	+
	Less snow cover	additional nitrogen retention	–
Rainfall	Increased streamflow	Stronger stratification	+
		More nutrient loading	+
Weaker summer wind	Less mixing of the water column	More persistent stratification	+
Stronger summer wind	Well mixed	Less persistent stratification	–
Sea level rise	Higher volume	Stronger stratification	+
		Higher bottom water volume	+
		Less hydraulic mixing	+
	Less tidal marsh	Reduced nutrient trapping	+

oxygen loss due to decreasing solubility is roughly 15 %, and the oxygen loss in the top 1000 m of the ocean is more than 50 % [40,45]. As a result of increasing temperatures, seasonal stratification (a physical factor) restricts the vertical exchange and less diffusion of oxygen between surface and bottom waters and the input of nutrients from numerous sources to nearshore water play an important factor in the establishment of hypoxia (Fig. 3). However stratifying the water column would be more likely to be caused by eased salinity (for example, from increased freshwater runoff in the upper layer of coastal waterbodies [19]. Regional wind patterns may also be impacted by increased temperatures, changing the circulation and reducing vertical mixing. If wind patterns or intensity vary, coastal currents and their impact on coastal waters may also alter. This could exacerbate or potentially enhance a low-oxygen state by mechanisms similar to those in the open ocean [18,19]. In the most recent decades (1960–2018), stratification expanded significantly by 5.3 % globally; a pace of 0.90 % per decade. The upper 200 m of the ocean had the majority of the rise (71 %), which was mostly (>90 %) caused by temperature changes [46]. Several climate factors, aside from temperature, impact the intensity and spread of dead zones; for instance, rising temperatures, changes in the amount and timing of precipitation, sea-level rise, and changes in the frequency and intensity of winds and storms primarily influence the creation of dead zones [22]. These will interact in a variety of ways to aggravate hypoxia (Table 2).

5. Continuing oxygen decline and its impacts on coastal ecosystem

The loss of oxygen in the water can be attributed to two major factors. Beginning with a decrease in dissolved oxygen due to rising ocean temperatures, less oxygenated water from deeper regions and oxygenated water at the surface mixed less [47]. Additionally, warmer waters raise species' oxygen requirements, lowering the amount of oxygen that is readily available to marine life. The most dramatic and widely noticeable effects of low oxygen occurrences in coastal waters are undoubtedly harmful to marine biodiversity, disruptions in species

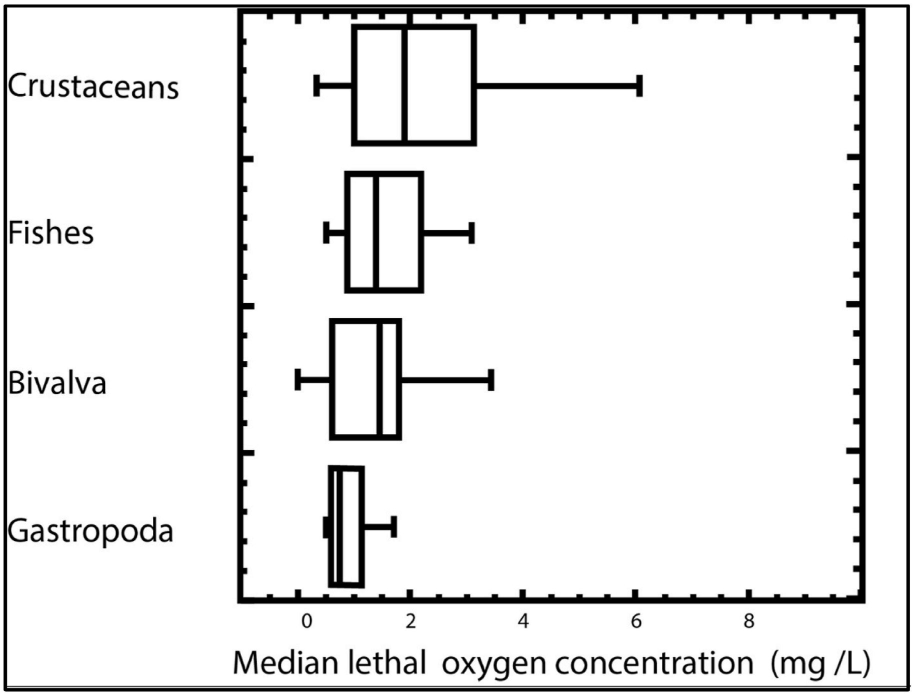

Fig. 4. Wider taxonomic variations of marine species in tolerance to oxygen deficiency. This diagram shows the concentration at which half of the animals die under experimental conditions [56].

distribution, displacement or decline of fisheries resources, and growing algal blooms in coastal ecosystems [48].

5.1. Loss of biodiversity

The biological processes and life forms are compromised by low dissolved oxygen, although not all of them. Lack of oxygen can impact an animal's ability to survive, grow, and reproduce; it can also change organism's distribution and make it more vulnerable to disease and predators that can handle hypoxia. As oxygen levels drop, a series of physiological responses occur [12] Every year tens of thousands to millions of fish have been killed. It happens mostly in coastal areas on all continents except Antarctica because of episodes of low oxygen caused by nutrient levels [48]. High nutrient loadings can cause hypoxia as well as be linked to the development of toxic algal blooms [49]. Some of these bloom-forming species are detrimental to fish. Therefore, the possibility of interactions between hypoxia and hazardous algal blooms can enhance the risk to fish populations which might create a threat to the existence of fish. The Norwegian lobster industry was completely destroyed by hypoxia in the Kattegat, a branch of the Baltic Sea that separates Denmark and Sweden. Several other fisheries in the region have also been negatively impacted, including those in the Sea of Azov, the Baltic Sea, the Adriatic Sea, and the Seto Island Sea [50].

The distinctions between oxic and anoxic depths deoxygenation has the power to significantly alter the microbial community in marine habitats by severely reducing the available niches for aerobic organisms and greatly increasing the range of anaerobes [51]. However, if O_2 levels fall too low for an extended period, the organism experiences several stresses that might eventually result in death [52]. The sensitivity of organisms to low O_2, particularly fish and crustaceans usually have the

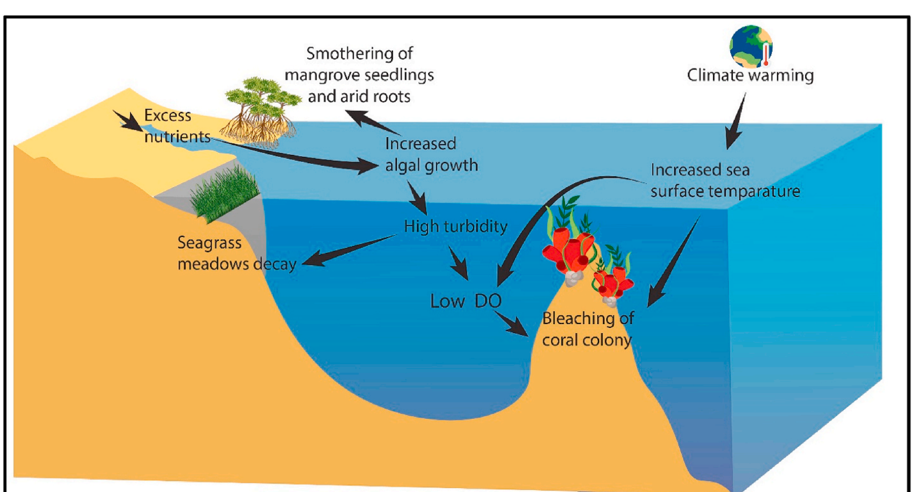

Fig. 5. Decline of coastal habitats due to the adverse effects of oxygen depletion. Corals, seagrass, and mangroves are all susceptible to hypoxia, and they can also change the oxygen levels in the water around them, which can result in positive feedback effects that can change deoxygenation rates.

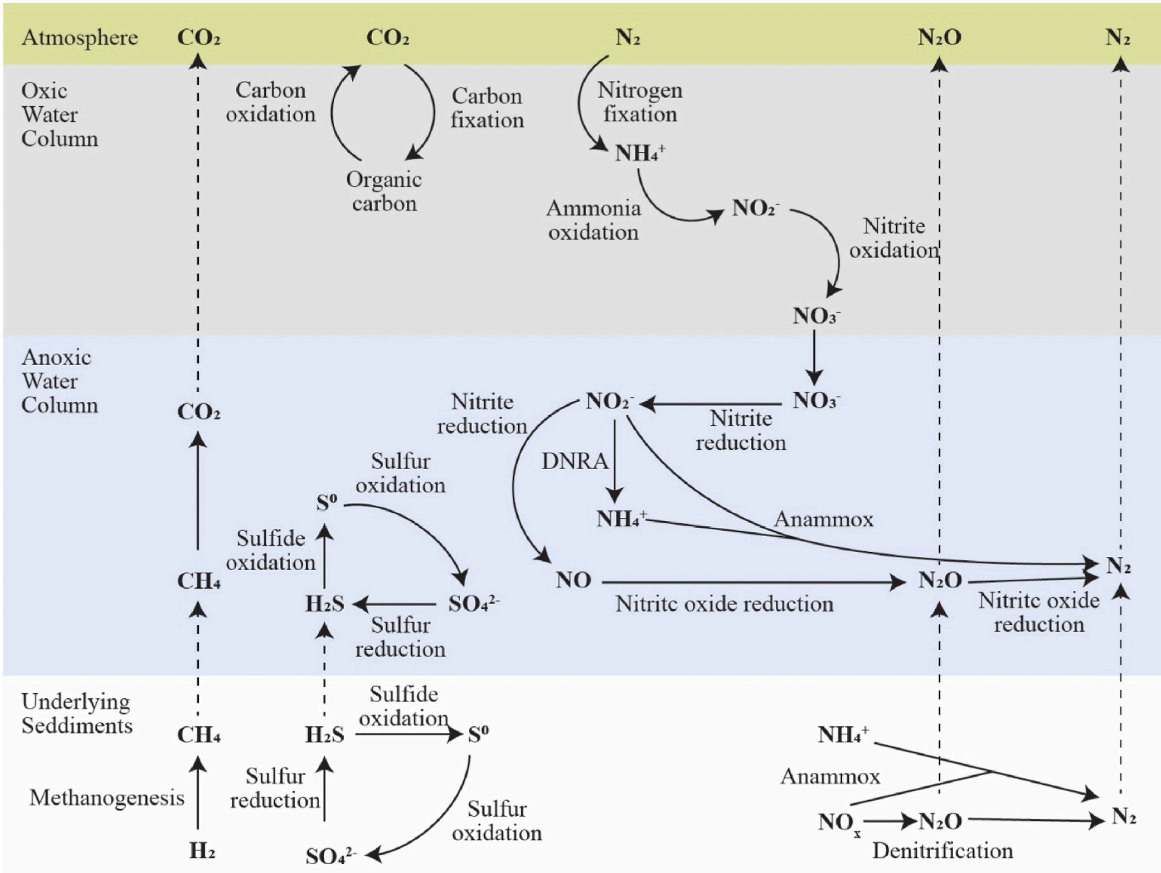

Fig. 6. A schematic illustration of the alteration to biogeochemical cycles of carbon, nitrogen, and sulfur cycles by microbes beneath-surface sediments and above-surface oxic waters. This is notably influenced by increasing the release of nutrients into the water from anoxic sediment, expanding low-oxygen areas in coastal oceans [51].

lowest tolerance levels others, followed by mollusks with an intermediate level of tolerance and bivalves and gastropods with the highest levels (Fig. 4). This indicates that the community's composition (i.e., the mix of species) and the interactions between species will change if the tolerance limits of different species are approached or exceeded [12]. The relationship between growing hypoxic stress and decreased biodiversity reflects wider species variances in tolerance to oxygen depletion [53–55].

5.2. Coastal habitat reduction

Coastal estuaries and bays provide crucial habitats for a variety of aquatic species, including estuaries, salt marshes, mangroves, seagrass beds, and coral reefs, which are essential ecosystems in tropical shallow water for activities like feeding, breeding, and migration. Tropical coastal marine ecosystems have been documented as being hypoxic when oxygen values are 2.8 mg L^{-1}, though to a lesser extent than their temperate equivalents [55]. The key three biogenic coastal habitats among other ecosystems show signs of deoxygenation and its deleterious impacts. In some cases, hypoxia may cause such crucial habitats to disappear or become insufficient (Fig. 5).

5.2.1. Coral reefs

Coral reef ecosystems have experienced severe reductions in coral biodiversity and abundance during the past few decades [57–59]. When there is a greater need for oxygen and conditions make it harder for the system to replenish its supply, dead zones on coral reefs form [60,61]. Oxidative stress that forms at coral-algal interfaces can have devastating effects on corals, including bleaching and death [62,63]. However, algae are much more tolerant to conditions with very low oxygen levels [64]. Moreover, a hazardous disease termed black band disease (BBD) spreads out which is correlated with oxygen depletion and amplifies this feedback by creating hypoxic conditions and high concentrations of sulfide in the BBD [65,66]. The fish and invertebrates that inhabit coral reefs exhibit a variety of behavioral and physiological responses to hypoxia [67].

5.2.2. Seagrass meadows

Continued ocean deoxygenation is concerning in coastal areas because ocean heat waves have caused die-offs of aquatic macrophytes such as seagrasses. Globally, seagrasses are disappearing greater than mangroves, coral reefs, and tropical rainforests and the current loss is 1.5 % per year [68,69]. Seagrass ecosystem biodiversity is impacted by deoxygenation in both direct and indirect ways [60]. High turbidity caused by available nutrients reduces the amount of light available for seagrass photosynthesis, limiting seagrass's ability to recolonize areas where mass death events have occurred [70]. Seagrasses lose their ability to oxygenate the sediments as algae and plant debris decay on the oxygen-starved seafloor, and algal blooms may lead to high levels of sulfide in the sediments of seagrass beds. These high sulfide levels may either impede their growth or even poison them, leading them to decline, as they obtain the majority of their nutrition from the sediment rather than the water column [21].

5.2.3. Mangrove forests

In comparison to coral reefs and seagrass beds, the mangrove ecosystem experiences oxygen deprivation more frequently naturally. Land use changes and anthropogenic fertilizer additions frequently

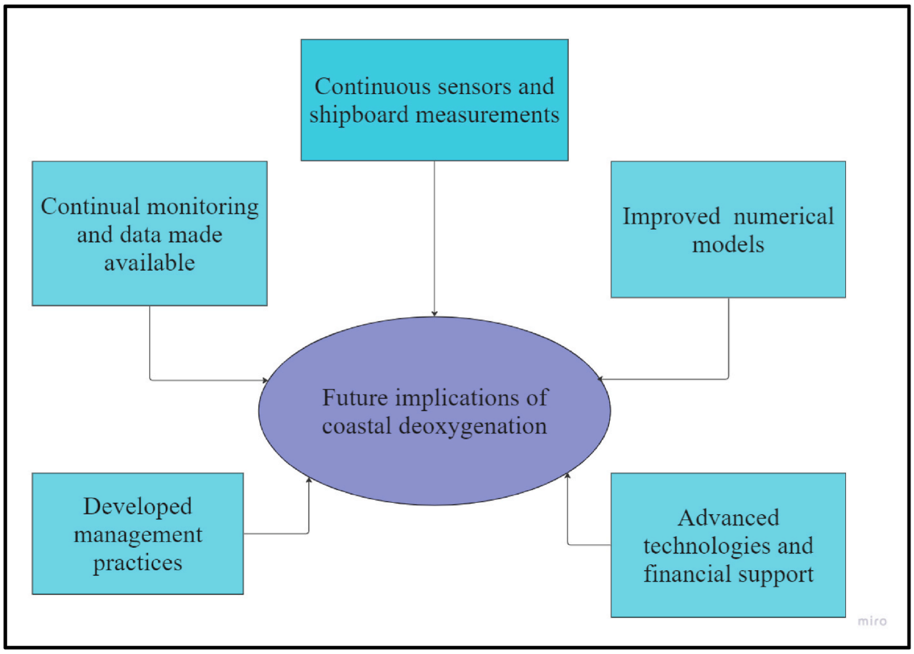

Fig. 7. Conceptual framework of overriding initiatives that can be taken to develop solutions for restoring the coastal ocean's oxygen and minimizing the impacts of the current deoxygenation trends in coastal oceans.

make it worse [60]. Mangroves offer a variety of ecological functions that support various biochemical processes [71]. By collecting and chemically altering the dissolved material that travels through them, they serve as filters that reduce the number of toxins that reach other coastal habitats from the land [72]. Mangroves are frequently tolerant of hypoxic circumstances. Moreover, most of their structure is exposed to the atmosphere. As a result, these structures receive oxygen from above, and the roots that suffer from hypoxia in the water and sediments receive oxygen from above [73].

Mangroves are only exposed to flooding during high tide, and as the tide recedes, the forest eventually drains [74,75]. In general, larger tides had higher oxygen saturation, smoother patterns, and longer-lasting increases than smaller tides [76]. However, in mangrove settings, the availability of DO changes greatly throughout the tidal and diurnal cycles, sometimes reaching levels that might cause physiological stress [76–79]. The core of mangrove forests cannot provide the same benefits to fisheries or fish habitats as fringe or riverine mangroves because of the ongoing hypoxic conditions [80].

5.3. Disruption of biogeochemical cycles

The presence of low dissolved oxygen in the bottom waters causes the sediment beneath them to become oxygen-starved. In the anoxic sediment bacterial breakdown changes the normal geochemistry, releasing phosphates and nitrates for microorganisms to use. This increases organic production and maintains the hypoxic system (Fig. 6). The marine phosphorous cycle is influenced by oxygen, with higher rates of recycling of phosphorus from sediments occurring under anoxic and hypoxic conditions [81]. This increased phosphate release into the water column enhances the eutrophication process by stimulating more phytoplankton growth and consequent oxygen depletion [82]. For instance, as hypoxia spreads more widely in the Baltic Sea, less phosphorus is buried and absorbed into sediments and more phosphorus is readily mobilized in the water column [83]. Denitrification is only possible when oxygen levels are exceedingly low. Because nitrate is a limiting nutrient for global ocean productivity, the extent of suboxic affects the amount of fixed nitrogen lost from the ocean through denitrification [84,85]. Since the oxygen level has been declining, both pathways of N_2O production will rise [86–88], potentially accelerating global warming [89]. Additionally, when nitrate is used up and oxygen levels are significantly reduced, anoxic conditions are imposed, and the biogeochemistry is predominantly controlled by sulfate-reducing bacteria. These bacteria convert sulfate into sulfide, which produces the poisonous gas hydrogen sulfide (H_2S) [90]. This gas may have major consequences for fishing along the coast and other living things. H_2S causes the unusual migration of mobile species (like lobsters) towards the coast in places that are extensively impacted, kills a variety of invertebrates and fish, and also induces seabirds to feed on floating dead marine animals [91].

6. Future implications of coastal ocean deoxygenation

There is no doubt that hypoxia-related coastal water quality is already declining and will continue to do so in the absence of a significant change in nutrient loading or climate change. While nutrient loads have declined to some extent over the previous three decades, coastal eutrophication remains a serious issue, exacerbated by open sea eutrophication and other ongoing hydroclimatic and ecological changes [92]. Hypoxia can be made worse and easier to form in more coastal waters just by the possibility of intensified stratification brought on by rising surface water temperatures as the world's climate increases. Therefore, predicting how susceptible coastal regions will be to future deoxygenation is very challenging. Coastal models can support the implementation of regional management strategies, such as managing excessive nutrient runoff through rivers, which can result in a deficiency of coastal oxygen. In estuaries and other coastal areas, researchers are becoming increasingly interested in ecosystem-based modeling and hypoxia predictions. While there has been advancement in modeling oxygen dynamics and making short-term projections, there are still no long-term forecasts that incorporate numerous inputs including climatological variables like El Nino-Southern Oscillation (ENSO) occurrences [93]. These forecasts can be made using numerical models that project the impacts of climate change and eutrophication on oxygen availability in the open-ocean and coastal systems [94]. In the modern ocean, accurate time series of oxygen concentrations are surprisingly rare, making it challenging to identify patterns of changes in oxygen levels with certainty. Improving our ability to predict future coastal water deoxygenation and their potential comprehension of such long-term actions to prevent oxygen loss is shown in (Fig. 7). It is essential for gathering time series data on ocean oxygen and physical, chemical, and biological phenomena in response to changing conditions require: 1. Continuous sensors and shipboard measurements gather a lot of data to spot trends and issues 2. Data made available to administrators, researchers, and the general public 3. Management practices are designed to keep nutrient loads below thresholds that provide oxygen concentrations appropriate for supporting life 4. Statistical analyses and numerical models show correlations between land usage, nutrient levels, and oxygen concentrations 5. Operate and develop oxygen monitoring technologies with adequate financial support. Without a commitment to such broad observational initiatives, it will be difficult to assess the coastal waters' long-term health and predict whether people will able to sustainably explore their bounds for resources in the coming decades.

Authors' contribution

Md Mesbah Uddin Bhuiyan- Conceptualization, methodology, investigation, data curation, review and editing, visualization; Mahfuzur Rahman- Resources, writing, review and editing; Samsun Naher-Methodology, original draft preparation, formal analysis, review and editing; Zahid Hasan Shahed- Original draft preparation, review and editing; Mir Mohammad Ali- Validation, formal Analysis, review and editing, supervision. Abu Reza Md. Towfiqul Islam-formal Analysis, review and editing.

CRediT authorship contribution statement

Md Mesbah Uddin Bhuiyan: Conceptualization, Formal analysis, Writing – original draft. **Mahfuzur Rahman:** Data curation, Formal analysis, Resources, Software, Visualization. **Samsun Naher:** Methodology, Validation, Visualization, Writing – review & editing. **Zahid Hasan Shahed:** Formal analysis, Investigation, Visualization, Writing – review & editing. **Mir Mohammad Ali:** Funding acquisition, Project administration, Writing – review & editing. **Abu Reza Md Towfiqul Islam:** Supervision, Validation, Writing – review & editing.

Declaration of Competing interest

I hereby declare I have no financial relation and conflict of interest to the submitted manuscript titled An analysis of the oxygen declination of coastal oceans over the twenty-first century for consideration by the Estuarine Coastal Sciences Journal.

Data availability

Data will be made available on request.

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