Australian Government
Australian Research Council

climate extremes
ARC centre of excellence

MINDEROO FOUNDATION

Ocean Oxygen Loss: If fish could talk.

Katrin Juliane Meissner[1,2], Shanta Claire Barley[3,4,5], JAH Forrest[3,4,5]

[1]ARC Centre of Excellence for Climate Extremes, Sydney, Australia

[2]Climate Change Research Centre, University of New South Wales, Sydney, Australia

[3]University of Western Australia, Perth

[4]Minderoo Foundation, Perth, Australia

[5]Fortescue, Perth, Australia

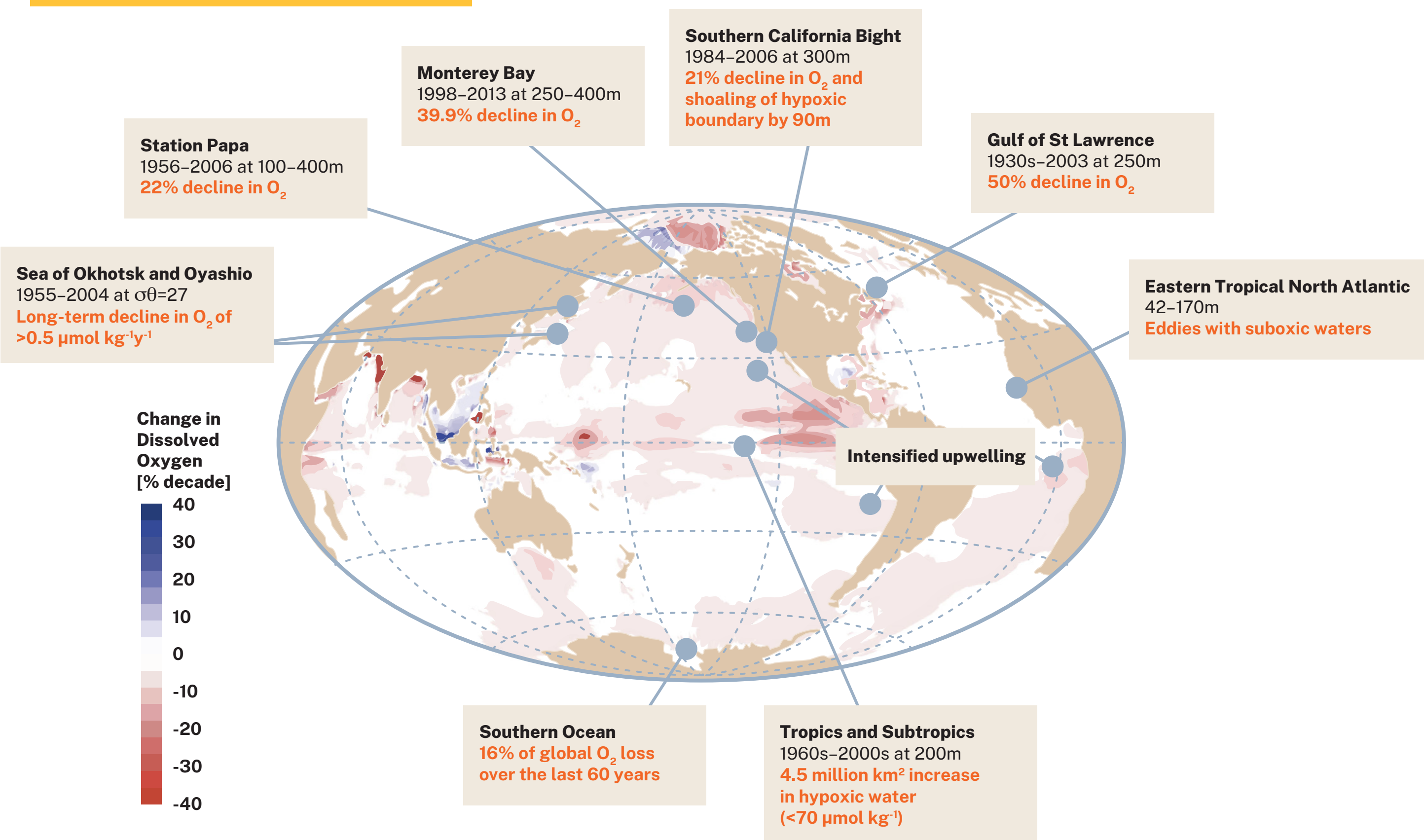
Summary

The global oceans are currently losing oxygen due to global warming. This loss of oxygen is known as deoxygenation. A major threat to marine ecosystems, biodiversity, fisheries and humanity, deoxygenation has not yet gained much public awareness, despite posing as much of a risk as warming and acidification. Deoxygenation can also lead to emissions of greenhouse gases, such as nitrous oxide, methane, and carbon dioxide, from the ocean, potentially worsening global warming. Ocean deoxygenation can only be mitigated if fossil fuel use is rapidly phased out, and greenhouse gas emissions are rapidly reduced to zero.

Key points

- Dissolved oxygen in the global ocean has decreased by over 2 per cent since 1960, with localised declines of up to 50 per cent.
- Persistent, low oxygen zones have expanded by 4.5 million km² at 200m depth, an area ~60 per cent of the size of Australia.
- Lack of oxygen causes respiratory failure in marine wildlife and is already driving mass mortality events.
- Deoxygenation can lead to a rise in ocean emissions of the potent greenhouse gases, nitrous oxide and methane, in addition to toxic hydrogen sulphide.
- The ocean is an important "sink" of carbon, absorbing around 30 per cent of human emissions of CO_2. The impact of deoxygenation on that uptake and cycles of nitrogen and other essential elements is poorly understood and warrants further, urgent research.
- Ocean deoxygenation due to global warming will persist for centuries, but rapid reductions in fossil fuel use and greenhouse gas emissions can limit impacts on marine ecosystems and fisheries.

Percentage change in dissolved oxygen per decade since 1960. (Redrawn from Levin, 2018; base map adapted from Schmidtko et al., 2017).



Introduction

Many regions of the ocean are already starved of oxygen. Contrary to the atmosphere, oxygen concentrations in the ocean vary spatially, and there are large zones where ocean oxygen levels have been declining for decades due to climate change and nutrient pollution. Oxygen loss (also called deoxygenation) is already causing mass deaths in marine wildlife and, in the past, has been associated with mass extinctions.
Low oxygen conditions can also cause the ocean to emit greenhouse gases and toxic gases.

Declining ocean oxygen

Total ocean oxygen content has decreased by more than 2 per cent and the volume of anoxic waters – which have almost no oxygen – in the Pacific Ocean has quadrupled since 1960. Since that time, persistent low oxygen zones at a depth of 200 meters have expanded by 4.5 million km^2, corresponding to ~60 per cent of the size of Australia and new, low oxygen regions are appearing.

Oxygen levels are declining faster in coastal oceans than in the open ocean. The largest declines in the open ocean have been observed in the tropical and north Pacific Ocean, the Arctic, the Southern Ocean, and the South Atlantic Ocean. On coral reefs, hypoxia is already widespread, with 84 per cent of reefs globally experiencing weak to moderately low oxygen and 13 per cent experiencing severe losses.

Climate change and nutrients

Changes in oxygenation in the open ocean are mainly due to global warming, rather than nutrient run off. Put simply, a warmer surface ocean holds less oxygen. In addition, warmer surface waters are also less dense, leading to stronger vertical stratification of the ocean, which results in less oxygen exchange with deeper ocean layers.

The direct effect of warming on the ability of the water to hold oxygen (also known as "solubility") is responsible for over half of the observed oxygen loss in the upper 1,000 meters of the ocean, and for ~15 per cent of the total oxygen loss across all depths. The remaining 85 per cent is caused primarily by warming-triggered changes in stratification and large-scale circulation.

In contrast, in coastal waters, changes in oxygenation have to date primarily been caused by nutrient run-off from rivers. Fertilisers have doubled the amount of nutrients carried by rivers into coastal waters since the early 1900s. Many coastal regions experience seasonal eutrophication – excessive levels of nutrients in the water – as a consequence, and this phenomenon is exacerbated by the increased warming of shallow coastal waters due to climate change in recent decades.

The global oceans are currently losing oxygen due to global warming.

What level of oxygen can animals live with underwater?

The ability to adapt to low oxygen concentrations varies between species.

- Regions with oxygen concentrations below 61 µmol/kg are defined as "hypoxic." Most organisms exposed to such low concentrations display unusual behaviour and low survival rates.
- If oxygen levels fall to 5-10 µmol/kg, the conditions are called "suboxic" and cannot be survived by multicellular life.
- Below 1 µmol/kg of oxygen, conditions are "anoxic" and only specially adapted anaerobic micro-organisms can survive.

Impacts of deoxygenation on fish

Deoxygenation has been linked to reduced growth in a vast range of ocean wildlife.

Exposure to low oxygen conditions can also delay when fish produce eggs, reduce how many eggs they produce and even cause blindness by impacting the shape and function of the light detecting cells in eyes, with damage to these cells potentially occurring within minutes.

Deoxygenation is particularly harmful when water is warm, as warm water increases the metabolism of many species, meaning that they need more oxygen to stay alive. Respiratory failure and death can result.

Impacts on fisheries

Deoxygenation has significant, negative implications for fisheries and the world's future food supply.

Already, many marine species have shifted to new habitats to escape low oxygen waters. Tuna, sharks and billfish, are shifting higher in the water column, while blue marlin in some parts of the ocean have experienced an annual loss of vertical habitat of one metre per year, equating to a 15 per cent loss of habitat between 1960 and 2010.

In Peru and California, anchovies are forecast to lose half of their habitat by the end of the century due to oxygen loss. Habitat "compression" increases the risk of overfishing at the surface and the likelihood that at-risk species are falsely considered to be rebounding. Declining oxygen can also drive major declines in biodiversity.

Mass wildlife mortalities

Marine heatwaves and mass mortality events due to deoxygenation are increasing in intensity and frequency. Why? Because in response to low oxygen, many species decrease activity and metabolic rate, limiting their escape response and increasing the risk of mass death.

To date, over 50 mass mortality events due to hypoxia have been recorded in the tropics and mass deaths have even been recorded in sharks and rays. The impacts of deoxygenation on coral reefs can be particularly severe and may outweigh the impacts of mass bleaching events.

Mass mortality events can also occur when deep, oxygen-poor water upwells, impacting shallow water ecosystems.

Low oxygen event at the Texas Gulf Coast in the United States (Photo by QUINTANA BEACH COUNTY PARK / Handout/Anadolu Agency via Getty Images)

Emissions of greenhouse and toxic gases

When oxygen levels are low, microbes start to use other chemical compounds to break down organic matter. This can lead to the production of nitrous oxide (N_2O), a potent greenhouse gas that is 273 times more powerful than CO_2 on a 100-year timescale and that causes stratospheric ozone depletion. Most low-oxygen zones in the ocean are already significant emitters of N_2O today, with record emissions observed in recent years.

Low oxygen conditions can also lead to the release of methane (CH_4) from sediments. Most CH_4 is converted into carbon dioxide in the water column, but some methane may reach the atmosphere.

Deoxygenation caused by ocean warming also drives the release of the toxic gas hydrogen sulphide from sediments into the water column. Together, these factors are considered potential drivers of one of the largest extinction events in history, which occurred 252 million years ago during the Permian-Triassic and led to the extinction of 90 per cent of marine species.

How oxygen loss is impacting the ocean's capacity to store CO_2 remains poorly understood. When oxygen levels are low, bacteria use one of the two macronutrients essential for life, nitrate, to consume organic matter. Oxygen loss in the ocean could therefore lead to global nutrient loss and thus lower primary productivity, which could weaken the "biological pump" that takes CO_2 at the ocean surface and stores it deep in the ocean. However, other processes that kick in when oxygen is very low can also result in an increase in nutrients. Future research is urgently needed to better understand and quantify these complex processes.

Future projections

Current ocean deoxygenation due to global warming will persist for centuries, even if greenhouse gas emissions were to cease today. Until atmospheric CO_2 emissions decline to zero, surface oceans will continue to warm, and the oceans will continue to lose oxygen.

Even under the most optimistic emissions reductions scenarios, climate models predict that ocean oxygen will have declined further by several per cent by the end of the century. Under a "business as usual" scenario, more than 94 per cent and 31 per cent of coral reefs, respectively, are projected to experience weak to moderate and severe hypoxia by the end of the century.

Nonetheless, the simulation of ocean oxygen concentrations remains challenging, as oxygen levels are governed by complex processes. The role of biogeochemistry is particularly poorly understood.

Current ocean deoxygenation due to global warming will persist for centuries.

Conclusion

Ocean oxygen loss is already widespread - and accelerating - due to climate change. Despite gaps in our understanding, we know enough to be profoundly concerned about its consequences for ocean life and humanity. As ocean warming accelerates, the impacts of deoxygenation could surpass those of marine heat waves or ocean acidification, yet these topics receive far more attention.

Beyond its impacts on marine life and fisheries, deoxygenation influences the planet's cycles of carbon, nitrogen and other essential elements, and could increasingly cause ocean emissions of greenhouse gases, further accelerating climate change.

Coordinated research programs that increase our fundamental understanding of oxygen loss and expand observations of current trends, particularly in deeper waters, are urgently needed to improve the accuracy of projections. Widespread oxygen loss throughout the ocean can only be prevented if fossil fuel use and greenhouse gas emissions are rapidly reduced to zero.

> Oxygen loss can only be prevented if fossil fuel use is rapidly reduced to zero.

References

Altieri et al. 2017. Tropical dead zones and mass mortalities on coral reefs. *Proc. Natl Acad. Sci. USA,* 114, 3660–3665.

Arévalo-Martínez et al. 2015. Massive nitrous oxide emissions from the tropical South Pacific Ocean. *Nature Geosci* 8, 530–533.

Bejda et al. 1992. The effect of dissolved oxygen on the growth of young-of-the-year winter flounder, Pseudopleuronectes americanus. *Environmental Biology of Fishes* 34, 321.

Benton 2018. Hyperthermal-driven mass extinctions: killing models during the Permian–Triassic mass extinction. *Phil. Trans. R. Soc. A.* 37620170076.

Beusen et al. 2016. Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. *Biogeosciences*, 13, 2441–2451.

Bograd et al. 2008. Oxygen declines and the shoaling of the hypoxic boundary in the California Current. *Geophysical Research Letters*, 35, 12.

Bopp et al. 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences,* 10, 6225–6245.

Breitburg et al. 2018. Declining oxygen in the global ocean and coastal waters. *Science,* 359, eaam7240.

Callbeck et al. 2021. Sulfur cycling in oceanic oxygen minimum zones. *Limnol Oceanogr,* 66, 2360-2392.

Chan et al. 2008. Emergence of anoxia in the California current large marine ecosystem. *Science,* 319, 920.

Clarke et al. 2021. Aerobic growth index (AGI): An index to understand the impacts of ocean warming and deoxygenation on global marine fisheries resources. *Prog. Oceanogr.*, 195, 102588.

Erecińska and Silver 2001. Tissue oxygen tension and brain sensitivity to hypoxia. *Respir. Physiol.*, 128, 263–276.

Fey et al. 2015. Recent shifts in the occurrence, cause, and magnitude of animal mass mortality events. *Proceedings of the National Academy of Sciences,* 112, 1083–1088.

Garrabou et al. 2022. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Global Change Biology,* 28,19.

Gilbert et al. 2010. Evidence for greater oxygen decline rates in the coastal ocean than in the open ocean. *Biogeosciences,* 7, 2283–2296.

Haas et al. 2014. Effects of reduced dissolved oxygen concentrations on physiology and fluorescence of hermatypic corals and benthic algae. *PeerJ,* 2, e235.

Howard et al. 2020. Climate-driven aerobic habitat loss in the California Current System. *Science Advances,* 6, 20.

Humphries et al. 2024. Highly active fish in low oxygen environments: vertical movements and behavioural responses of bigeye and yellowfin tunas to oxygen minimum zones in the eastern Pacific Ocean. *Mar Biol,* 171(2), 55.

Kim et al. 2023. A selected review of impacts of ocean deoxygenation on fish and fisheries. *Fishes* 8(6), 316.

Laffoley and Baxter (eds.) 2019. Ocean deoxygenation: Everyone's problem. Causes, impacts, consequences and solutions. *Summary for Policy Makers.* Gland, Switzerland: IUCN. 28 pp.

Landry et al. 2007. Long term hypoxia suppresses reproductive capacity in the estuarine fish, Fundulus grandis. *Comparative Biochemistry and Physiology Part A Molecular & Integrative Physiology,* 148(2), 317-23.

Lefort et al. 2014. Spatial and body-size dependent response of marine pelagic communities to projected global climate change. *Global Change Biology,* 21:1, 154-164.

Levin 2018. Manifestation, drivers, and emergence of open ocean deoxygenation, *Annual Review of Marine Science,* 10, 229-260.

Mancini et al. 2004. The past to unravel the future: Deoxygenation events in the geological archive and the anthropocene oxygen crisis. *Earth-Science Reviews,* 104664.

McCormick and Levin 2017. Physiological and ecological implications of ocean deoxygenation for vision in marine organisms. *Phil. Trans. R. Soc. A.*, 37520160322.

McNatt et al. 2004. Hypoxia-induced growth rate reduction in two juvenile estuary-dependent fishes. *Journal of Experimental Marine Biology and Ecology,* 311:1, 147-156.

Meyer and Kump 2008. Oceanic Euxinia in earth history: causes and consequences. *Annu. Rev. Earth Planet. Sci.*, 36, 251-288.

Naqvi et al. 2010. Marine hypoxia/anoxia as a source of CH_4 and N_2O. *Biogeosciences,* 7, 2159–2190.

Oschlies et al. 2017. Patterns of deoxygenation: sensitivity to natural and anthropogenic drivers *Phil. Trans. R. Soc. A.*, 37520160325.

Oschlies et al. 2018. Drivers and mechanisms of ocean deoxygenation. *Nature Geosci,* 11, 467–473.

Oschlies 2021. A committed fourfold increase in ocean oxygen loss. *Nat Commun,* 12, 2307.

Penn et al. 2018. Temperature-dependent hypoxia explains biogeography and severity of end Permian marine mass extinction. *Science,* 362.

Pezner et al. 2023. Increasing hypoxia on global coral reefs under ocean warming. *Nature Climate Change,* 13, 403–409.

Rose et al. 2019. Chapter 10: Impacts of ocean deoxygenation on fisheries. Ocean deoxygenation, Laffoley and Baxter.

Rosentreter et al. 2021. Half of global methane emissions come from highly variable aquatic ecosystem sources. *Nature Geoscience,* 14(4), 225–230.

Sampaio et al. 2021. Impacts of hypoxic events surpass those of future ocean warming and acidification. *Nat Ecol Evol,* 5, 311–321.

Salvatteci et al. 2022. Smaller fish species in a warm and oxygen-poor Humboldt Current system. *Science,* 375, 101-104.

Schmidtko et al. 2017. Decline in global oceanic oxygen content during the past five decades. *Nature,* 542, 335–339.

Stramma, et al. 2010. Ocean oxygen minima expansions and their biological impacts. *Deep-Sea Research I* (2010), 57, 4, 587-595.

Stramma et al. 2012. Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. *Nature Climate Change,* 2(1), 33-37.

Vedor et al. 2021. Climate-driven deoxygenation elevates fishing vulnerability for the ocean's widest ranging shark. *eLife,* 10:e62508.

Waller et al. 2024. The vulnerability of sharks, skates, and rays to ocean deoxygenation: Physiological mechanisms, behavioral responses, and ecological impacts. *Journal of Fish Biology,* 1-30.

Wannamaker and Rice 2000. Effects of hypoxia on movements and behavior of selected estuarine organisms from the southeastern United States. *Journal of Experimental Marine Biology and Ecology,* 249: 2, 145-163.

Wong-Riley 2010. Energy metabolism of the visual system. *Eye Brain,* 2, 99–116.