Oceanic Oxygen Depletion and Dead Zones: Physical Causes and Human Dimensions

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Summary

Up to six decades of measurements show that the concentration of dissolved oxygen in subsurface waters is declining in many parts of the sea. In upper-intermediate waters of the open ocean, the oxygen loss is attributed primarily to increased stratification resulting from warming of surface waters and consequent reduced supply of O_2 via physical circulation. Declining deep-water oxygen concentrations in the Japan Sea reflect diminished wintertime production of “new” deep water in the warming northern reaches of the basin. In the northern Gulf of Mexico oxygen depletion in the shallow subsurface waters has become severe in boreal summers, the combined result of warming-induced stratification and high primary production supported by ‘excess’ nutrient delivery to the Gulf from agricultural activity in the Mississippi River watershed.

The ecological consequences of oxygen loss are currently severe in afflicted coastal waters, and have the potential to become severe in large coastal seas and the open ocean on several-decade to century time scales. Mitigation presents a great challenge, however. In the open sea, the problem stems from global energy generation and the associated warming climate, while in coastal waters, domestic energy and/or agricultural policies—which in the United States are coupled—are having deleterious impacts. Turning the tide on this issue will require concerted international action, an undertaking that is currently elusive.

Introduction

The oxygen concentration in upper-intermediate waters in the open ocean and shallow subsurface waters along many continental margins is declining, to the point where “dead zones” (water masses where the $[O_2] < 20\ \mu\text{mol L}^{-1}$) are proliferating in coastal seas. Two factors are primarily responsible: the warming climate of the last four decades, which appears to be fostering increased stratification in the ocean, and excess nutrient inputs to coastal waters arising from anthropogenic activities on land. The biogeochemical, environmental and economic consequences are negative and serious. Mitigation approaches pose a significant challenge, given that they necessarily must consider overlapping issues related to agricultural, energy and environmental policies, the relative importance of which vary from country to country. We use published data from the Japan Sea, the Pacific and Atlantic oceans, and the Gulf of Mexico to illustrate the scale of the problem. As will become clear, there is no easy solution.

Oxygen Declines in the Open Ocean

Low-oxygen zones have expanded vertically over the last 50 years in both the equatorial Pacific and the eastern equatorial Atlantic (Stramma et al 2008). Observed declines in the heart of the oxygen minima, between 300 and 700 m water depth in these regions, range from ~0.1 to ~0.34 μmol kg^{-1} yr^{-1}. The upper value translates to a decline of about 1% of the saturation level per decade, or minus 10% per century. A steeper decline has been observed in the eastern subarctic Pacific (Whitney et al 2007) where in the 50 years prior to 2006 subsurface waters, below the mixed layer and to a depth of at least 1 km, warmed and lost oxygen at a rate between ~0.4 and ~0.7 μmol kg^{-1} yr^{-1}. The hypoxic boundary in the area (defined as $[O_2]$ = 60 μmol kg^{-1}, the concentration below which mobile macrorganisms are typically stressed and may die (Vaquer-Sunyer and Duarte 2008)) has shoaled by 100 m and is now ~300 m below surface.

The observed oxygen losses are expected to continue as warming of the upper water column enhances the density contrast with underlying waters. Although increased stratification might constrain upwelling—which should in turn reduce export production and associated oxygen demand in the subsurface—physical ventilation, ie oxygen supply, will also be reduced. The net supply:demand balance in coupled models favours the latter, leading to the predictions of a progressive decline in subsurface $[O_2]$ in future decades (Froelicher et al., 2009). Attribution to human activities as a driver of the observed declines is challenging, however. Froelicher et al (2009) caution that natural interannual to decadal variations internal to the ocean have had, and will have, a significant impact on dissolved O_2 concentrations, irrespective of anthropogenic effects.

Oxygen Decline in the Japan Sea

The dissolved oxygen concentration in waters below 3 km in the ~3.5 km deep Japan Sea declined by about 14% between 1950 and 1995 (Chen et al 1999). Continuation of such a trend would lead to anoxia becoming established in the deep waters in two to five centuries. The oxygen decline has been attributed to warming which has reduced deep water formation in the northern reaches of the sea via brine rejection when sea-ice forms in winter (Jenkins, 2008). The reduction in abyssal ventilation may have led to a two-fold decline in new production basin-wide by sequestering nutrients in the deep waters (Jenkins, 2008). Ironically, this could postpone the onset of anoxia lessening respiratory demand for O_2 by at depth.

The Rise of Dead Zones in Coastal Waters

Over 400 hypoxic zones—marked by water with $[O_2]$ <2.0 ml L^{-1}—have now been identified along the coastal zones of the world's oceans and inland seas, and that number "has approximately doubled each decade since the 1960s" (Diaz and Rosenberg 2008). The principal cause is anthropogenic nutrient increases, primarily N, that have fueled increased primary production which in turn has enhanced the settling flux of organic detritus and driven higher oxygen demand is subsurface waters. In specific cases, changes in stratification resulting from warming, varying freshwater inputs, or mixing intensity and upwelling related to storminess and/or shifting wind regimes may also be important, although available data are often insufficient to assign causation confidently to such variables.

The best-studied example is the hypoxic water mass that forms in summer on the continental shelf of the northern Gulf of Mexico west of the Mississippi Delta. Formal surveys conducted almost every year since 1985 show that freshwater discharge from the Mississippi River establishes in most years an estuary-like stratification along the northern edge of the Gulf that is strengthened in summer by warming (Rabalais et al, 2007). The combination of that physical effect and very high biological productivity supported by a large injection by the river of nitrate and nitrite—largely derived from runoff from fertilized agricultural lands upstream, and three times higher now than in 1950—leads to rapid consumption of oxygen in near-bottom waters. Indeed, in some years, free H_2S has been detected in the water column. Although the scale of the footprint over the last several years has been quite variable, it has averaged some 15,000 km^2, and is considered to be a very serious environmental problem for the United States.

Mitigating the Gulf of Mexico Dead Zone is proving to be very difficult. The U.S. Environmental Protection Agency has put in place an 'action plan' designed to reduce the nitrogen load by ~30%, but some argue that in the face of variability in climate and ocean dynamics, N export may need to be reduced nearly twice as much as planned to meet the targeted dead-zone footprint of $\leq$5,000 km^2 (e.g Donner and Scavia 2007, Scavia and Donnelly 2007). An additional, arguably unanticipated impact is related to United States energy policy, which mandates increased production of ethanol. This has led to dramatic increases in corn production and associated application of nitrogen fertilizers that increases the challenge of meeting the EPA objective (Donner and Kucharik, 2008). Thus, the Gulf of Mexico example highlights the difficulty in marrying sound environmental policies with social and industrial imperatives.

Conclusions

Measurements that extend back up to six decades show that the concentration of dissolved oxygen in subsurface waters is declining in many parts of the ocean. In upper-intermediate waters of the open sea, for example in the northeastern Pacific west of Canada, the oxygen loss is attributed primarily to increased stratification resulting from warming of surface waters and consequent reduced supply of O_2 via physical circulation. In the Japan Sea, declining deep-water oxygen concentrations reflect diminished winter-time production of "new" deep water in the warming northern reaches of the basin. Oxygen depletion in the shallow subsurface waters of the northern Gulf of Mexico has become severe in boreal summers, the collective result of warming-induced stratification and 'excess' nutrient delivery to the Gulf from agricultural activity in the Mississippi River watershed.

The ecological consequences of oxygen loss are currently severe in afflicted coastal waters, and have the potential to become severe in large coastal seas and the open ocean on several-decade to century time scales. Mitigation presents a great challenge, however. In the open sea, the problem stems from global energy generation and associated warming, while in coastal waters, domestic energy and/or agricultural policies—which in the United States are coupled—are having deleterious impacts. Turning the tide on this issue will require concerted international action, an undertaking that is currently elusive.

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