#### **CLIMATE CHANGE**

# Oceans on the edge of anoxia

Environmental crises can tip the ocean into  $O_2$  depletion

#### By Andrew J. Watson

or the past several hundred million years, oxygen concentrations in Earth's atmosphere have been comparatively high (1, 2). Yet, the oceans seem never to have been far from anoxia (oxygen depletion) and have occasionally suffered major oceanic anoxic events (OAEs), recognized in the rock record through accumulations of dark, organic-rich shales (3). OAEs seem to be promoted by warm climates, and some have been associated with

major environmental crises and global-scale disturbances in the carbon cycle. New insights into the causes of OAEs are now emerging (4, 5). Furthermore, ocean oxygen concentrations are declining in the modern ocean (6). A full-scale OAE would take thousands of years to develop, but some of today's processes are reminiscent of those thought to have promoted OAEs in the distant past.

Even today, the oceans are on the edge of anoxia: Every ocean basin has an oxygen minimum zone (OMZ) at a depth of a few hundred meters, where respiration consumes oxygen and depresses oxygen concentrations. Over large areas of the Eastern Pacific and the northern Indian Ocean, oxygen levels in the OMZ are close to zero. In modern times, some OMZs have expanded, a process called ocean deoxygenation (6). In addition, nutrient input from rivers has led to eutrophication and local anoxia in many coastal regions. An example of these "dead zones" is the Gulf of

Mexico near the Mississippi Delta, but there are now several hundred anoxic coastal regions worldwide. Mostly, these are the result of human activities that have led to muchincreased nutrient levels in rivers.

Why is the deep ocean deoxygenating? Human-caused eutrophication may be a con-

College of Life and Environmental Sciences, University of Exeter, Exeter, UK, Email: andrew.watson@exeter.ac.uk tributing factor, but climate change is also implicated. Warming promotes deoxygenation because it slows the formation of deep waters and decreases the solubility of oxygen in the surface. At a recent discussion meeting at the Royal Society in London, all these possible causes were discussed (7). Yet, none of them seems to fully explain the observed declines in oxygen, especially those seen in the tropical oceans.

As to the persistence of OMZs in the oceans past and present, a simple calculation, first made by Alfred Redfield (8), suggests

## Oxygen crises in the ocean

Major environmental crises can lead to oxygen depletion (anoxia) throughout the ocean's oxygen minimum zones, which become deadly for animal life.

Limiting processes

More burial of carbon leads to an

increase in atmospheric oxygen,

phosphorus input to the oceans.

causing more wildfires that reduce

forest vegetation (4). This lowers the

#### Positive feedbacks

High phosphate inputs (1) enhance marine production, reducing oxygen in the OMZ (2). The resulting phosphorus release from sediments (3) further increases marine production and carbon burial.



oceans recover from their deoxygenated state.

that the global ocean is chronically close to the edge of anoxia. When water leaves the sea surface, it carries oxygen absorbed from the atmosphere into the interior. An equivalent volume of deep water must upwell to the surface, carrying the limiting nutrient phosphate up from the deep ocean. (The deep waters must also carry up nitrate, but geochemists think of phosphate as the limiting nutrient because nitrogen can always be fixed by plankton from the atmosphere if it is in short supply.) Photosynthetic plankton then use up all the nutrients in the upwelling water, and the fixed organic matter sinks into the deep sea. There, it is respired back into inorganic carbon and nutrients by microbes, in the process consuming the oxygen supplied by the sinking water. Using the stoichiometry of carbon and nutrients now called the "Redfield ratios," Redfield found that the amount of oxygen consumed is almost equal to that carried down by the sinking water (8).

The oxygen demand in the interior of the modern ocean is thus constrained to be close to the oxygen supply. This near-equality seems paradoxical because demand and supply are set by two apparently independent variables: Demand is governed by the amount of phosphate in the deep ocean, whereas the supply is set by the amount of atmospheric oxygen that dissolves in surface water. A little more phosphate, and much more of the ocean would be hypoxic (low in oxygen). Doubling ocean phosphate would be sufficient to bring on a full-scale ocean anoxic event.

Past natural events are believed to have suddenly increased the supply of phosphorus, especially the massive outpourings of magma that form large igneous provinces (LIPs). Prominent OAEs occurred at the same time as, or very shortly after, the eruption of LIPs (4, 5, 9, 10). A possible mechanism is that the fast-weathering rocks emplaced by these events increase the supply of nutrients to the oceans for thousands of years, forcing the ocean into anoxia.

Once anoxia takes hold, it may be self-sustaining. Phosphorus is removed from the ocean through sedimentation, but if anoxic waters overlay these sediments they tend to leach out much of this phosphorus; in contrast, if the water is oxygenated the phosphorus stays in the sediments. Sediments in contact with anoxic water are thus an inefficient phosphorus sink and may even be a source of phosphorus to the ocean. Models suggest that once anoxia begins to spread over continental shelves

and slopes, this positive feedback may drive the ocean into prolonged deoxygenation that lasts hundreds of thousands of years (see the figure) (*11*, *12*).

Since the industrial revolution, land-use changes, agricultural runoff, and sewage discharges have more than doubled the amount of phosphorus entering the ocean via rivers (13). The coastal dead zones that have developed as a result are often lethal to animal

life. However, the increase in nutrient input would need to be sustained for at least a thousand years to produce a change in phosphate levels sufficient to bring on a full-scale OAE. Whole-ocean anoxia is thus not an immediate global concern. If sustained for long enough, the deoxygenation occurring today could nevertheless have lasting negative consequences for the global environment.

On yet longer time scales, the paradox noted by Redfield may be explained by another feedback. A sustained increase in phosphate entering the ocean would increase not only anoxia but also marine productivity, causing more carbon to be buried in sediments. Carbon burial is the source of free oxygen because burial is the only process by which photosynthetically fixed carbon can escape reoxidation on a geologically short time scale. The resulting atmospheric oxygen increase would start to be significant on time scales of 100,000 years or more, eventually alleviating the ocean anoxia (see the figure). Rising molecular oxygen might also limit forest vegetation on land because of the increased prevalence of wildfire; given that forests increase the rates of weathering of continental rocks, limiting them would provide a negative feedback on the supply of phosphorus to the oceans, bringing the system back to a new steady state (14).

Atmospheric oxygen and ocean phosphorus are thus linked in a network of multiple feedback loops. Negative feedbacks help to explain the longevity and stability of atmosphere and ocean composition, but some feedbacks are of opposite sign and may at times destabilize the Earth system, as during OAEs. The role of these positive feedbacks in sustaining OAEs remains an open question, however, as does a complete description of the underlying causes of modern-day deoxygenation; conceivably, natural feedbacks may act to amplify the effects of global change on ocean oxygen concentrations.

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### **GLOBAL CHANGE**

## A stitch in time saves nine...billion

Acting now to limit global temperature change will help to ensure global food security

#### By Elizabeth A. Fulton<sup>1,2</sup>

uman intuition often does not lead to thoughtful long-term decisionmaking (1). In partial remedy to this, a long history of storytelling conveys messages about what is worth remembering, worth doing, or best avoided. Stories also help to shape visions of what is possible and desirable (2). Scientific models are used in the same way. For example, the modeling study by Cheung et al. (3) on page 1591 of this issue indicates that making the effort to keep global temperature increases to 1.5°C would minimize impacts on marine food security and resilience. The work is an important addition to the discussion of the costs and benefits of keeping the average global temperature rise to less than 2°C.

A temperature change of 2°C does not seem like a lot, especially given much wider daily temperature ranges in many locations. However, in terms of global mean temperature, it marks a point where climate change would have broad-scale effects on many locations and aspects of life, ultimately leading to a less productive world with reduced capacity to support basic human needs (4). This was the motivation for the Paris Agreement, adopted by consensus on 12 December 2015 and ratified on 4 November 2016. The aims at the heart of this agreement highlight the basic tension in today's public policy decision-making: how to achieve economic development, meet basic human needs, and limit environmental impacts as the global population grows toward 9 billion by 2050. The agreement aims to hold the global average temperature rise to less than 2°C-and ideally less than 1.5°C-above preindustrial levels while also increasing adaptive capacity, resilience, and food security.

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#### The authors use models of changing species distributions, based on the physiological and habitat needs of each species and their capacity to move to suitable habitats as conditions change, to explore the potential future abundance and catch of 892 species currently fished around the world. They show that a global temperature rise of 1.5°C is enough to reduce fisheries catches on a global scale. As the temperature rise climbs from 1.5° to 3.5°C, global catch losses jump from 2.5 to 8.0%. Modeled changes in species diversity are even greater as species migrate or go locally extinct: Species turnover more than doubles from 8.3 to 21.6% as the temperature increase rises from 1.5° to 3.5°C.

Meeting these targets seems like a daunt-

ing task. The International Energy Agency

has concluded that a \$16.5 trillion USD

investment would be needed to meet the energy-related climate pledges of the agree-

ment by 2030 (5). Nevertheless, models show

the value of action and the costs of inaction.

For example, Cheung et al.'s findings indicate

that meeting the agreement's temperature

target may also be the best means to deliver

on food security and achieve resilient com-

munities and economies.



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