8. Oxygen and the ocean

Aurélien Paulmier

Oxygen (O) is the most common atom on our planet, particularly in the air, in the oceans in the form of water (H_2O), and in the molecules of all living organisms. For the last 2.8 billion years, cyanobacteria and algae in the oceans, and plants on the continents, have been using solar energy for their photosynthesis, thereby allowing the formation of oxygen (O_2), of which the Earth was largely deprived at its origin. The concentration of O_2 in the atmosphere is high (20.8%), and is directly linked to life, which is a chemical aberration compared to O_2 rate on other planets. This gaseous molecule, in dissolved form in aquatic environments, is also a powerful oxidant, able to form compounds with almost all other chemical elements. The appearance of O_2, a waste product of photosynthesis, was a disaster for primitive living organisms, and was the cause of mass mortality until the emergence of breathing or respiratory functions. Breathing O_2 then became vital for all aerobic species: bacteria, plants, and animals. Paradoxically, O_2 also produces free radicals that damage biological molecules and cells, causing mutations and ultimately, death. Consequently, the level of oxygenation, which is relatively stable in the atmosphere, plays a key role in the regulation of life. In return, living organisms control the rate of O_2 through mechanisms that produce oxygen, photosynthesis, and consume oxygen, respiration / remineralization.

The role of the ocean

The oxygen cycle is based on exchanges between compartments, primarily the atmosphere and the oceans, since at least 50% of the oxygen we breathe comes from the ocean. Atmospheric O_2 penetrates the ocean at the poles and is released at the equator. Seasonally, the ocean absorbs O_2 in autumn and winter, and degasses it to the atmosphere in spring and summer. These transfers are explained on the one hand by physical-chemical mechanisms, since O_2 is more soluble in cold conditions, and on the other hand, by biologically-related episodes of phytoplankton blooms and their degradation.

The ocean is oxygenated in the sunlit layer that is in contact with the atmosphere, and is mixed by wind and waves. This is the layer where most marine photosynthesis takes place, but below this layer, the concentration of O_2 tends to decrease with depth. Near the poles, salty cold waters resulting from the formation of sea ice, sink to the bottom (> 4,000 m), enriched in O_2. These deep waters circulate from the northern and southern Atlantic Ocean to the Indian Ocean, and then to the North Pacific, where they upwell after a journey lasting around1,000 years, representing the major oxygenation mechanism in the ocean (cf. II.11). Along the way, driven by current modulation, these

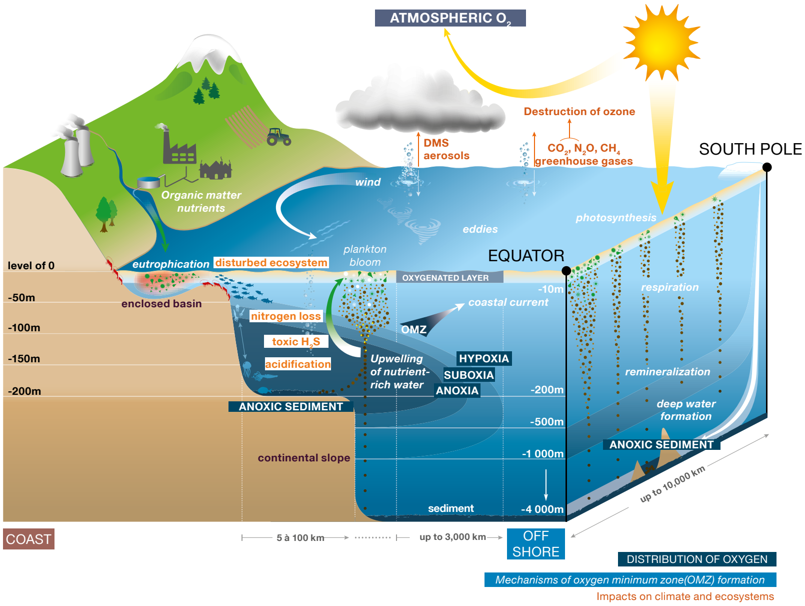

Fig. 1 – Distribution of oxygen (O_2) and OMZs in the ocean (blue) with their main associated mechanisms (white) and areas of impact (orange), at the large offshore scale (on the right) and at a smaller scale near the coast (on the left). © M. P. CHARRIA and A. PAULMIER. ■

waters gradually lose their O_2. They are exposed to a rain of particles produced in the surface layer by phytoplankton and by the trophic network, which when degraded, consumes O_2 during the process of remineralization. As a result, the rate of dissolved O_2 can be used to reconstruct the history of a water mass and as a tracer of its evolution. Remineralization mainly occurs between the surface and a depth of 1,000 m, caused by microbial communities that can travel attached to particles, thereby creating an O_2 minimum in intermediate ocean waters (Fig. 1).

In the most sluggish waters, which are relatively old since they have not been in contact with the atmosphere for between10 and 100 years, the O_2 minimum may intensify (suboxia, anoxia). Often outlined by eddies, these waters form the oxygen minimum zone (OMZ), reaching from about 10 to 1,000 m depth and extending up to 3,000 km from the continental margins in the open ocean like in the eastern Pacific Ocean, or in more closed configurations (*e.g.* North Indian Ocean, Black Sea, deep trenches, estuaries, for instance, Fig. 2).

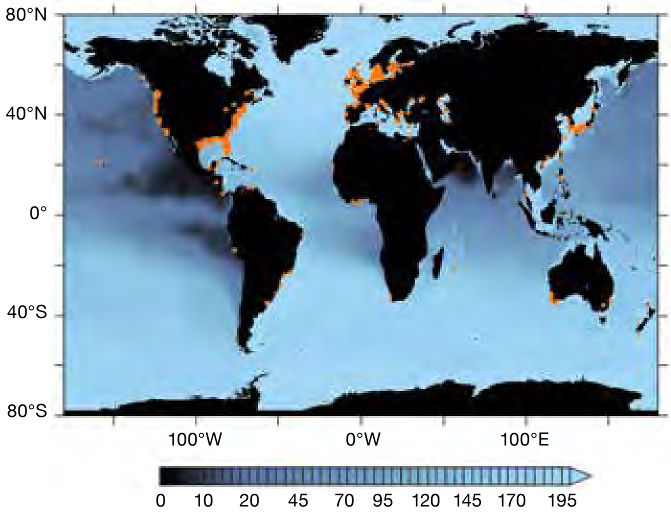

Fig. 2 – **Distribution of areas of oxygen minimum concentration (O_2) in the ocean (µmol/liter). Oxygen minimum zones (OMZs) in dark blue-gray shading. Coastal sites where hypoxic events have been reported are in orange.** Data from the World Ocean Atlas 2013 and Diaz and Rosenberg, 2008. © A. PAULMIER and S. ILLIG. ■

Evolution and impacts on climate and ecosystems

In response to climate variations, periods of oxygenation in the ocean naturally alternated with periods of deoxygenation: from geological time-scales (~million years) to hourly fluctuations. These complex changes result from ventilation and ocean mixing processes, but also from the production of planktonic particles occasionally fertilized by upwelling. However, since the industrial revolution, and especially since the end of World War II, global warming has led to warmer surface temperatures and,as a direct consequence, oceans tend to deoxygenate more. In coastal areas, where sediments play an important role in remineralization, the frequency at which hypoxic events are recorded has increased exponentially in response to effluent discharges. However, the roles of both natural and anthropic causes still need to be better understood.

To conclude, let us emphasize the importance of the oxygen minimum zones (OMZs), given their potentially major feedback to the Earth's biogeochemical cycles impacting the climate: source of greenhouse gases, destruction of stratospheric ozone, role in the formation of clouds *via* marine aerosols, and regulation of albedo. OMZs, which have long been classified as dead zones, also have an impact on ecosystems and fisheries *via* the respiratory barrier, nutrient losses (nitrate), acidification, production of toxic gases, and limitation of biodiversity. OMZs are natural laboratories to study how life adapts to climate change, as they are refuges for unsuspected marine life, favoring the emergence of ecosystems that are among the most active and abundant of the ocean in the transition zone between oxygenated and deoxygenated environments. We must therefore be vigilant and maintain a stable balance in oxygen dynamics between the various compartments of our planet and the ocean, in full interaction with the different forms of living organisms.

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