Ocean Oxygen and deoxygenation

Marilaure Grégoire, Liège University, MAST research group Belgium

ICES Biennial Workshop VIII, 28 September - 2 October 2026, Geneva, Switzerland

Outlines

1. History of oxygen on Earth and relationship to life
2. The oxygen budget at geological scales and the modern oxygen cycle
3. Does every second breath we take come from the Ocean?
4. Current Ocean deoxygenation and impacts
5. Methods to study Ocean oxygen: observing and predicting oxygen
6. Addressing Ocean deoxygenation through mitigation and adaptation

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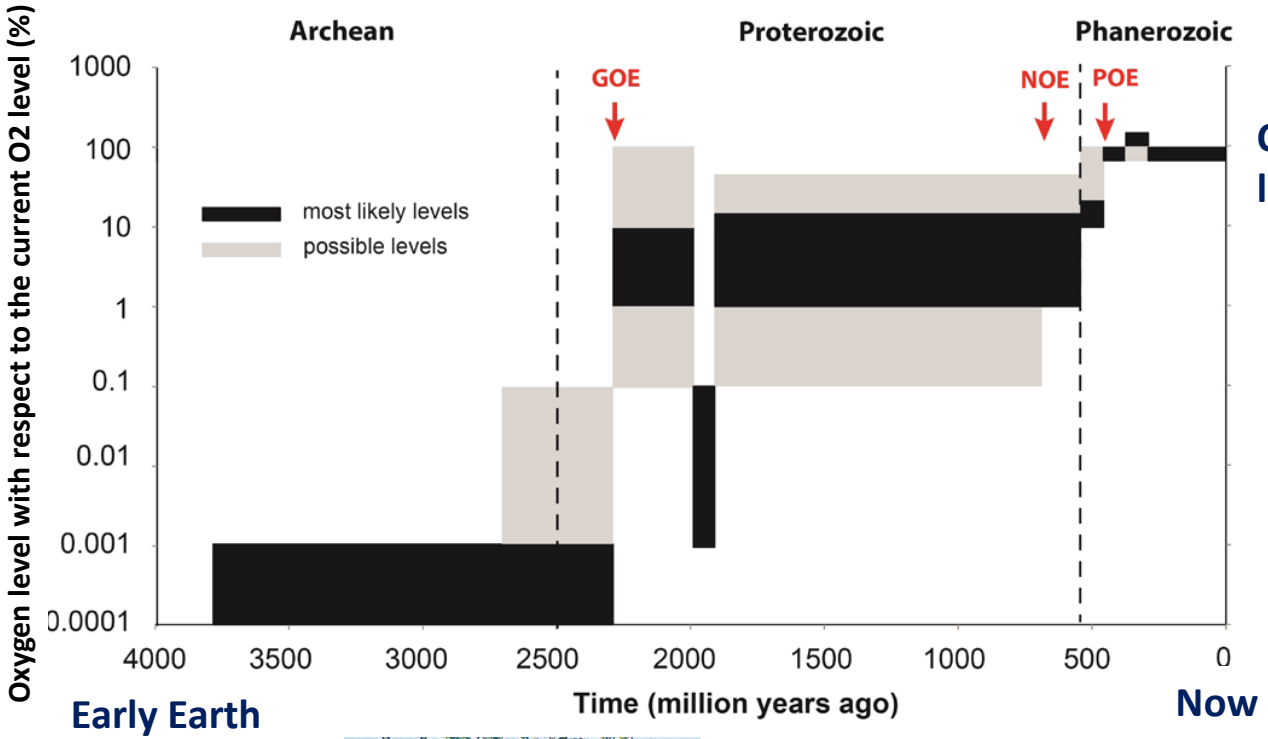
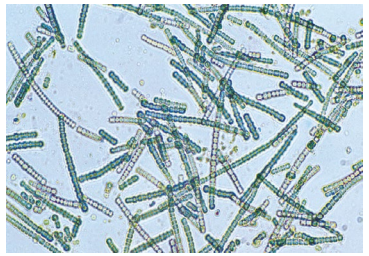
History of oxygen on Earth and relationship to life

Evolution of atmospheric oxygen

- For **most of Earth's history: almost no free oxygen (O_2)** in the atmosphere or the Ocean
- **Bifurcation 1: Great Oxidation Event (GOE)**: oxygen-producing **cyanobacteria** evolved & oxygen started accumulating in the Ocean and atmosphere
- **Paleozoic Oxygenation Event (POE)**: another drastic increase in oxygen, due to **evolution of land plants**





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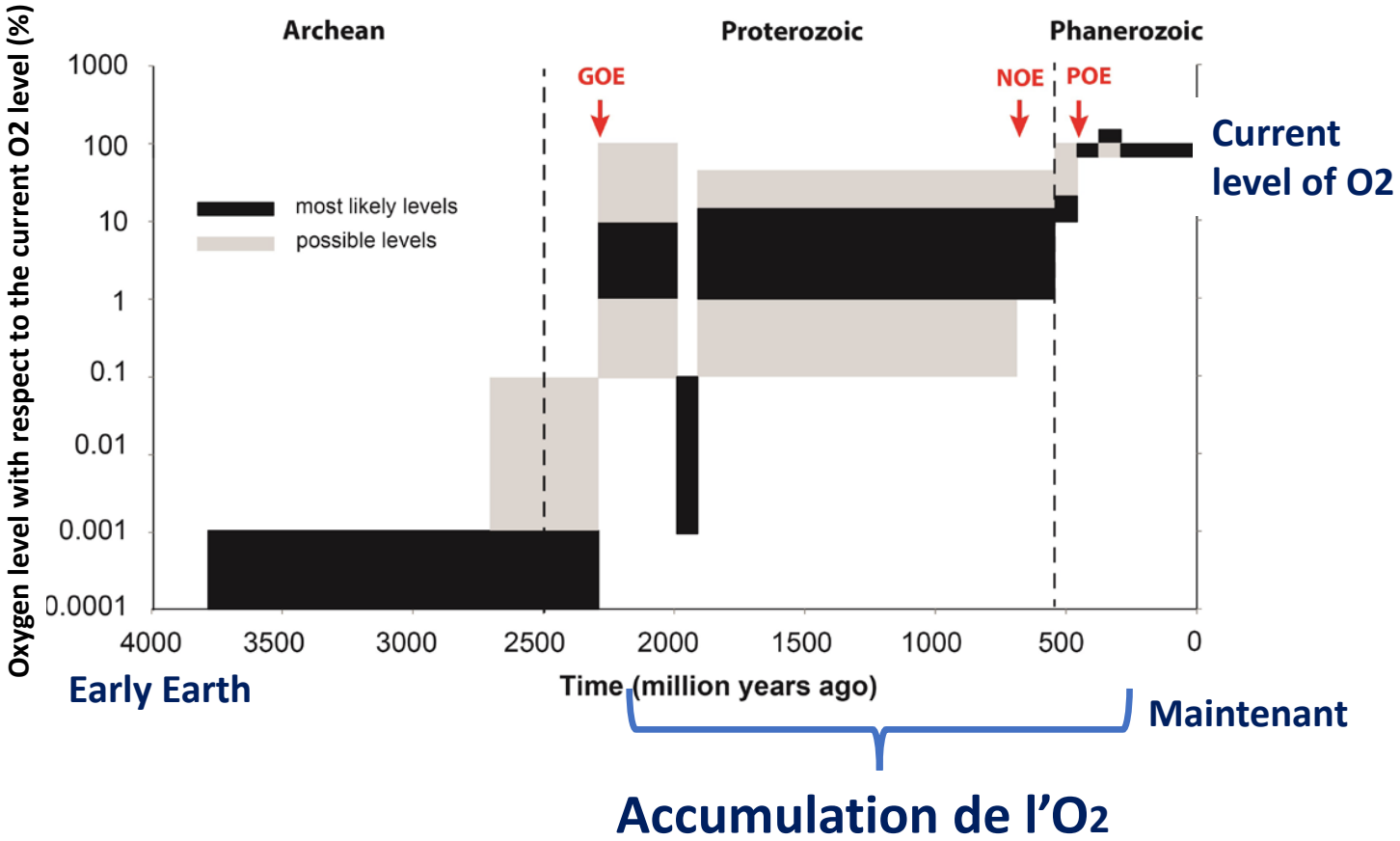

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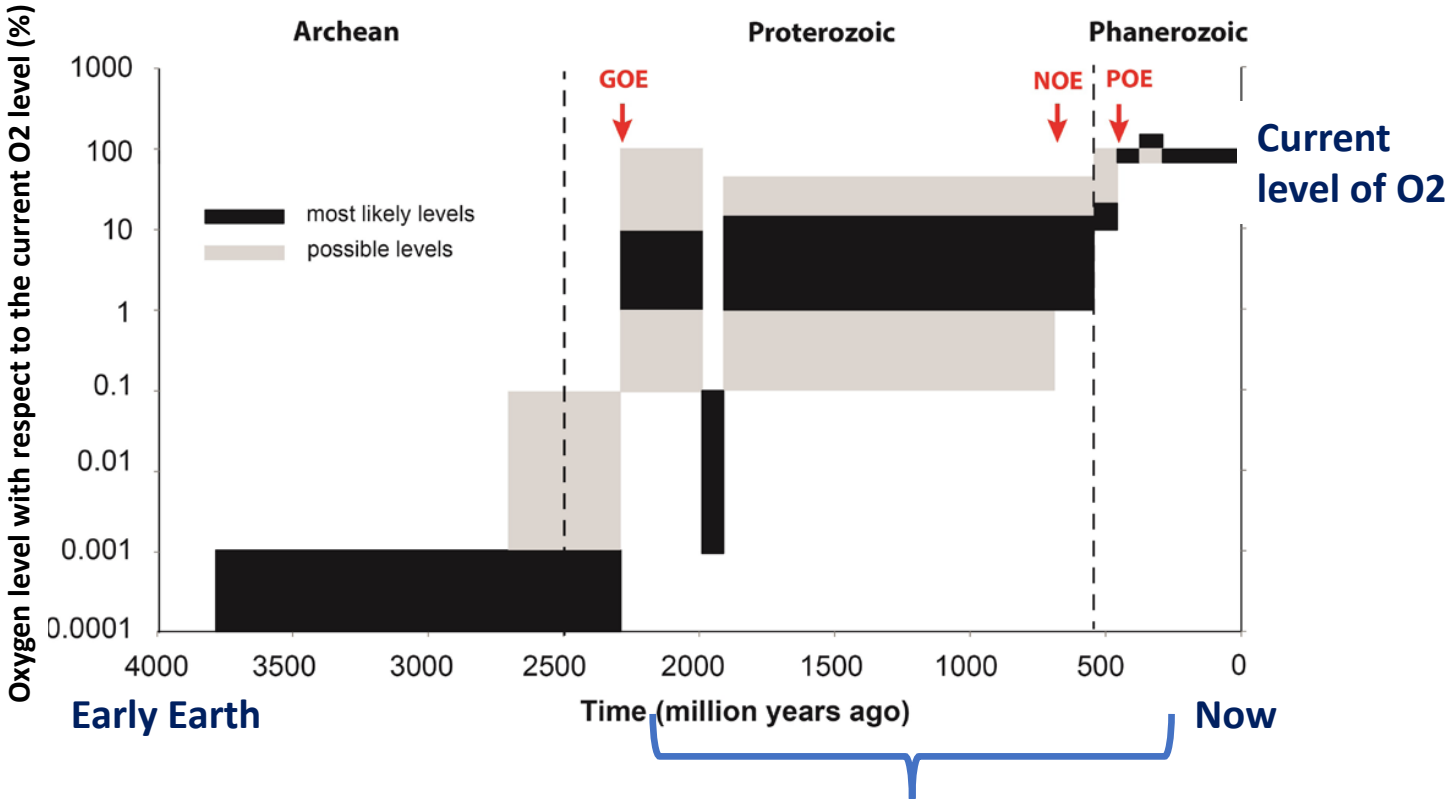
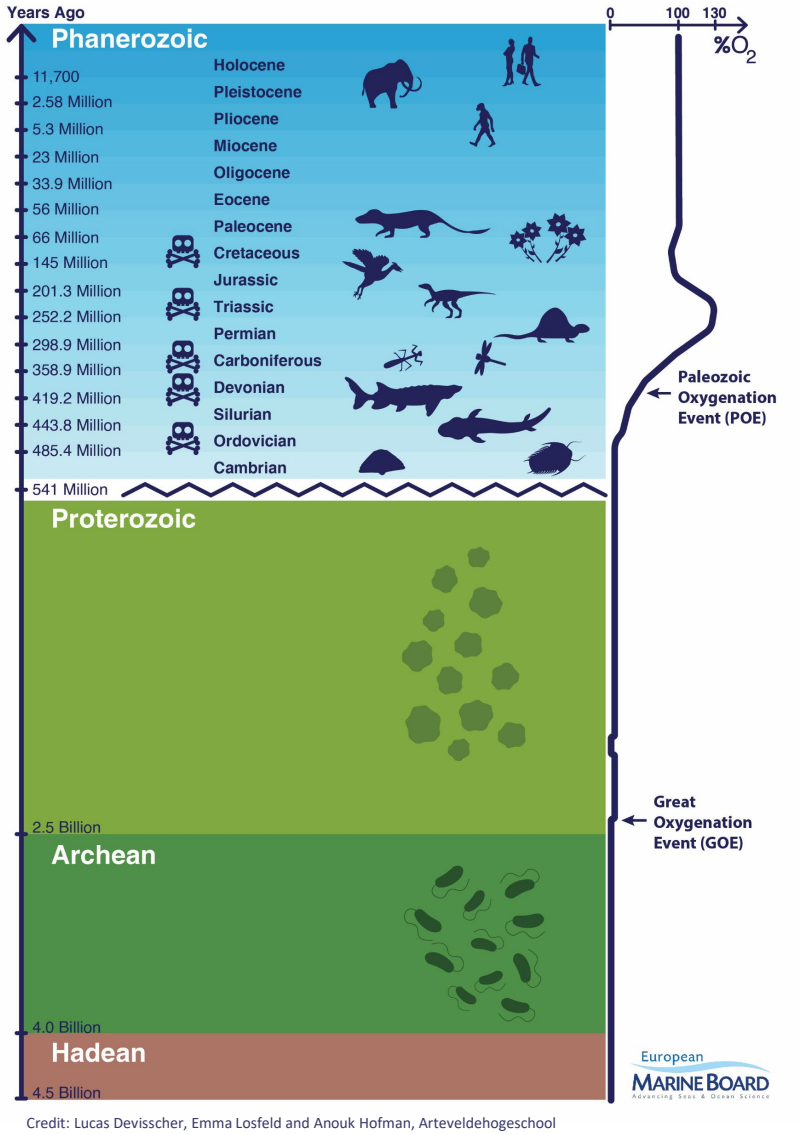


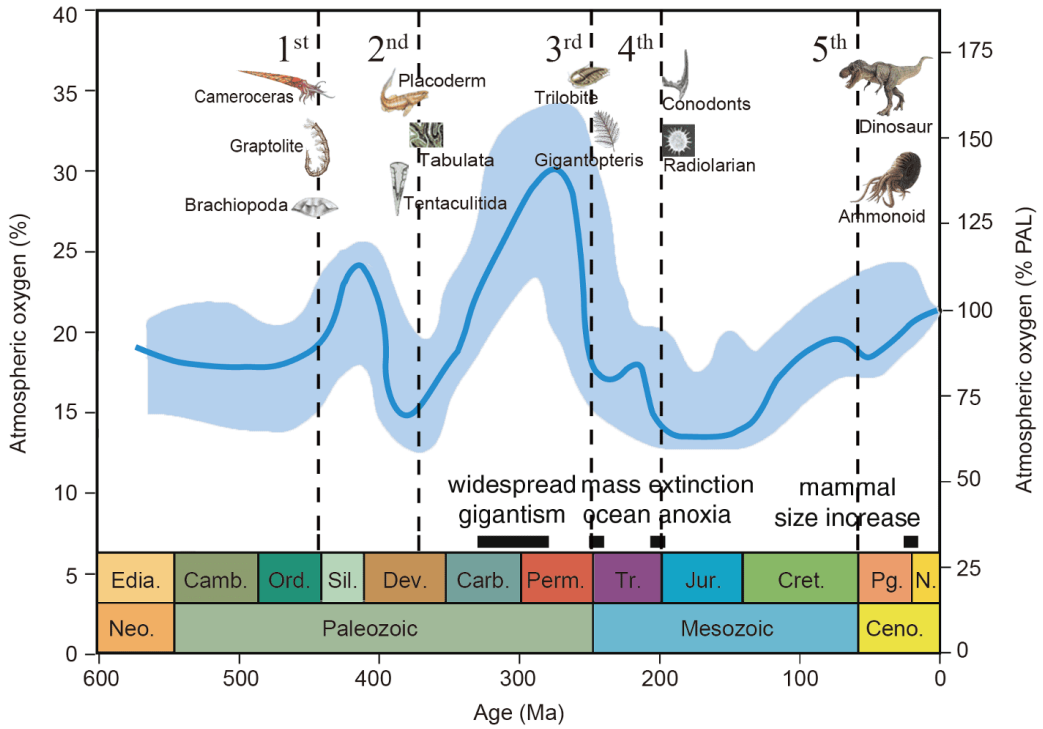
History of oxygen on Earth and relationship to life



Credit: Lucas Devisscher, Emma Losfeld and Anouk Hofman, Arteveldehogeschool

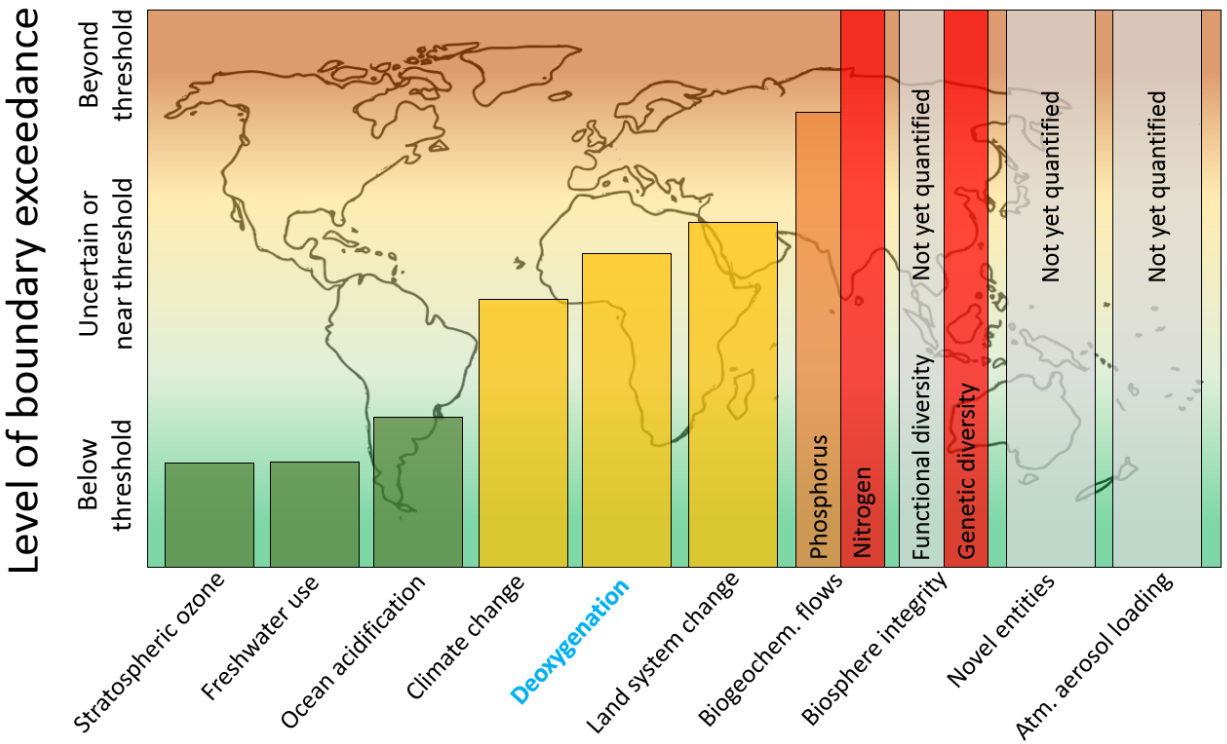
Oxygenation has added biodiversity

Deoxygenation has been associated with extinctions : at least **three out of five mass extinctions** were **associated with Ocean deoxygenation**



Huang et al., 2021

Aquatic deoxygenation as a planetary boundary



nature ecology & evolution

Perspective

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Aquatic deoxygenation as a planetary boundary and key regulator of Earth system stability

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Check for updates

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Planetary boundaries represent thresholds in major Earth system processes that are sensitive to human activity and control global-scale habitability and stability. These processe
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to include deoxygenation as

The concept of planetary boundaries, initially proposed by Rockström et al.[1], describes processes disrupted by human activities that are critical to sustaining Earth's ecological and societal integrity. The designation of nine processes—atmospheric aerosol loading, biogeochemical flows (especially of nitrogen and phosphorus), loss of biosphere integrity, climate change, freshwater use, land system change, introduction of novel entities, ocean acidification and stratospheric ozone depletion—provides a framework to characterize the envelope of safe operating spaces in which ecosystems and society can function sustainably[2–5]. More recently, the inclusion of justice issues that integrate human well-being into the framework[4] and a re-evaluation of the boundaries[5] indicate that most planetary boundary processes have already exceeded safe levels. The nine planetary boundaries are also interconnected, such that shifts in one process can impact many others[6,7]. Since its introduction, the planetary boundaries framework has become an important guiding concept in the natural and social sciences a
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A full list of affiliations appears at the end of the paper. e-mail: rosekk4@rpi.edu

PLOS Climate

OPINION

Why aquatic deoxygenation belongs in the planetary boundary framework

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Editor: Jamie Males, PLOS Climate, UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND

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Aquatic systems under the planetary boundary framework

In an epoch dominated by human activities, Planetary Boundaries (PBs) have emerged as a powerful overarching framework for tracking global environmental change [1]. In this framework, PBs constitute limits to processes and stressors that threaten a sustainable "Holocene-like" Earth, including: Climate Change, Novel Substances, Stratospheric Ozone Depletion, Atmospheric Aerosol Loading, Ocean Acidification, Disruption of Biogeochemical Flows, Freshwater Change, Land System Change, and Loss of Biosphere Integrity [Rockstrom et al., 2009]. Since its inception, the PB Framework (PBF) has been widely adopted by both scientists and policy makers, with several notable iterations, expansions, and updates [2]. Application of the PBF to marine and freshwater ecosystems has been relatively limited, however, as PBs are disproportionately weighted toward terrestrial and atmospheric systems [3]. Of the original nine PBs, only three specifically apply to aquatic systems – Ocean Acidification (OA), Freshwater Change, and Disruption of Biogeochemical Flows – and appropriate thresholds for OA as a boundary are still being refined [4].

Given that water covers 70% of the planet, monitoring changes to aquatic ecosystems is of paramount importance and should be included under a PBF. However, one major threat to both freshwater and marine systems remains overlooked within the PBF: Aquatic Deoxygenation.

Aquatic Deoxygenation (AD) refers to the contemporary, human-driven loss of dissolved oxygen in aquatic environments, and is a lesser known but highly detrimental consequence of human disruptions to climate, land-use, and nutrient-cycling [5]. Most forms of life require oxygen to function, and the cycling of nutrients is tightly coupled

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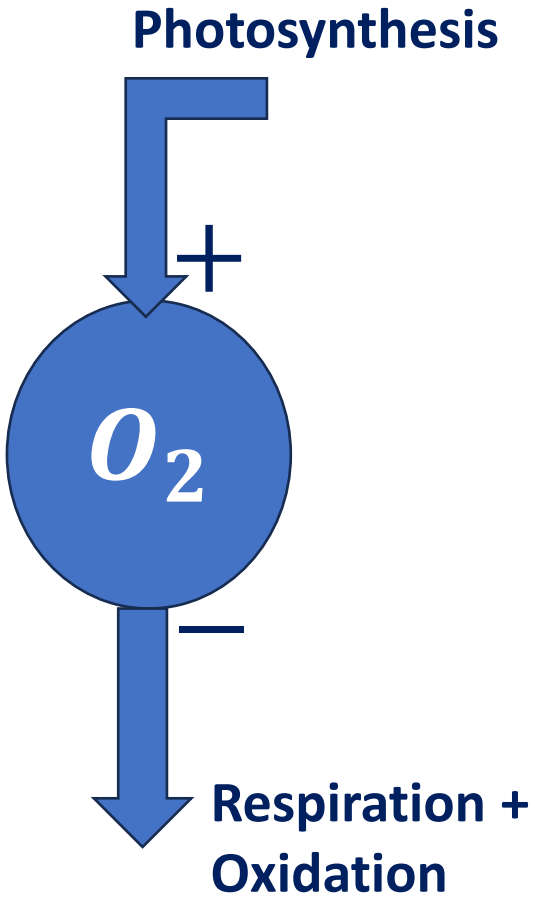
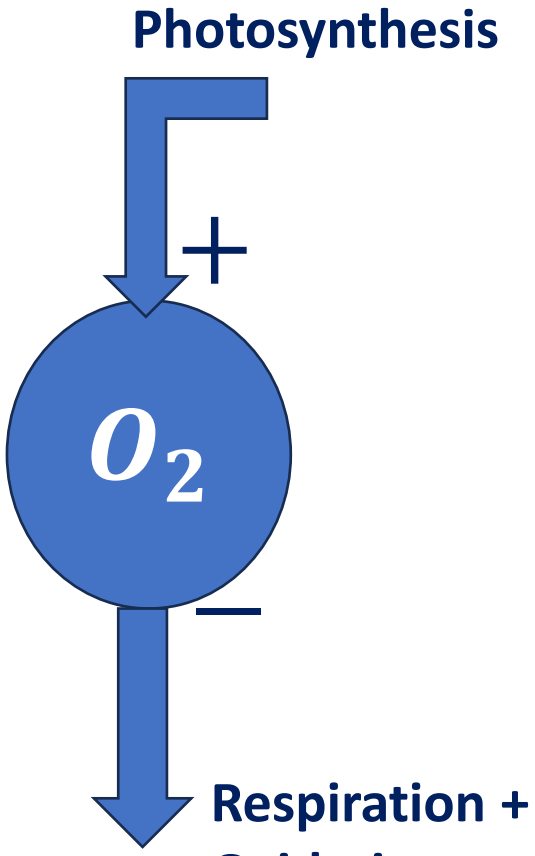
Oxygen budget



Photosynthesis ~ Respiration (Ocean, Atmosphere)

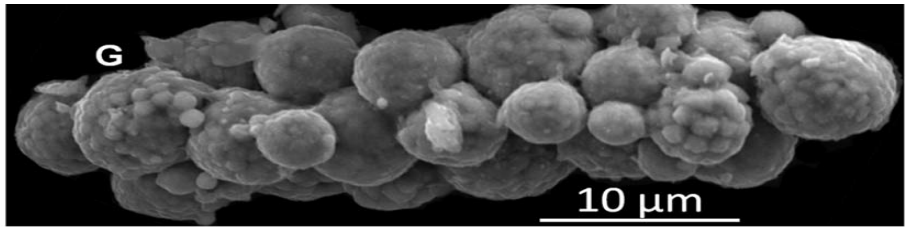
Oxygen budget



Photosynthesis ~ Respiration (Ocean, Atmosphere)

EXCEPT: organic matter **burial** and **pyrite framboids** formation (ocean).

FES_2 Framboid Pyrite, Robinet et al., 2022



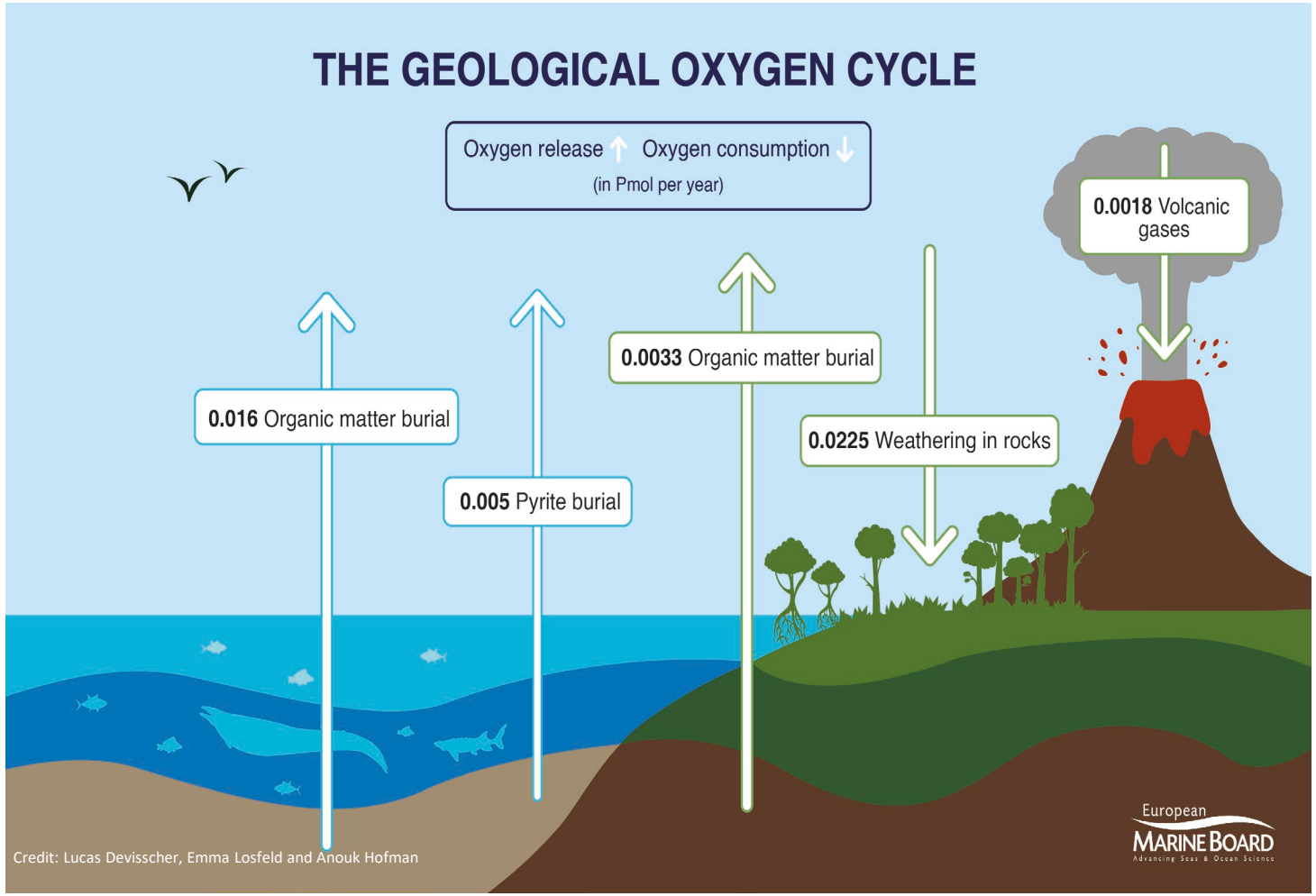
Oxygen budget at geological time scales

Oxygen accumulation in the atmosphere:

- **Burial** of **organic matter** and **pyrite** (mineral) creates a small imbalance between oxygen production and consumption
  - ➢ Oxygen escapes respiration and can accumulate in the atmosphere (**over geological time**)

86% of the oxygen humans breathe (6 of 7 breaths) came from the Ocean over geological time scales

Numerous **feedbacks stabilise oxygen** content of the **atmosphere at geological scales**



The modern oxygen cycle

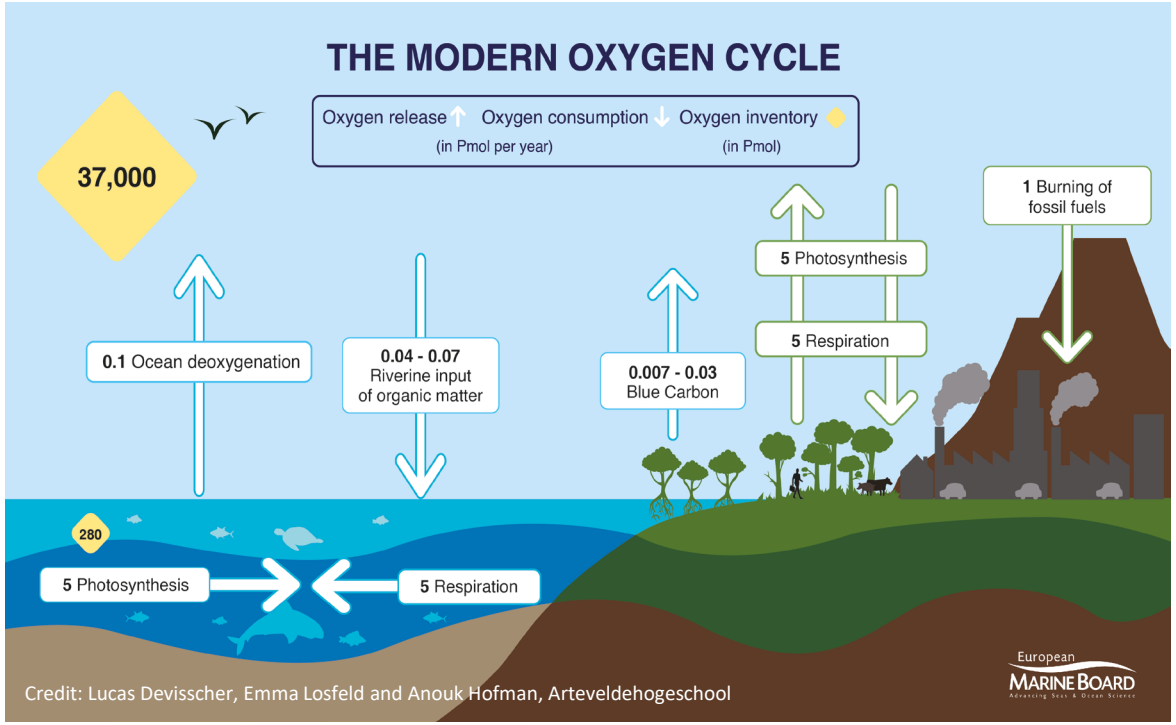
>99% of all freely available oxygen (O_2) is in the atmosphere

<0.01% is in the Ocean

Current oxygen production on Earth:

- The **land and Ocean each produce** about **50% of Earth's oxygen**
- **Almost all this oxygen is consumed again** (respired) by terrestrial and marine organisms, respectively

  → **virtually no net accumulation of oxygen** in the atmosphere or Ocean at the scale of a human life



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Does every second breath we take come from the Ocean?







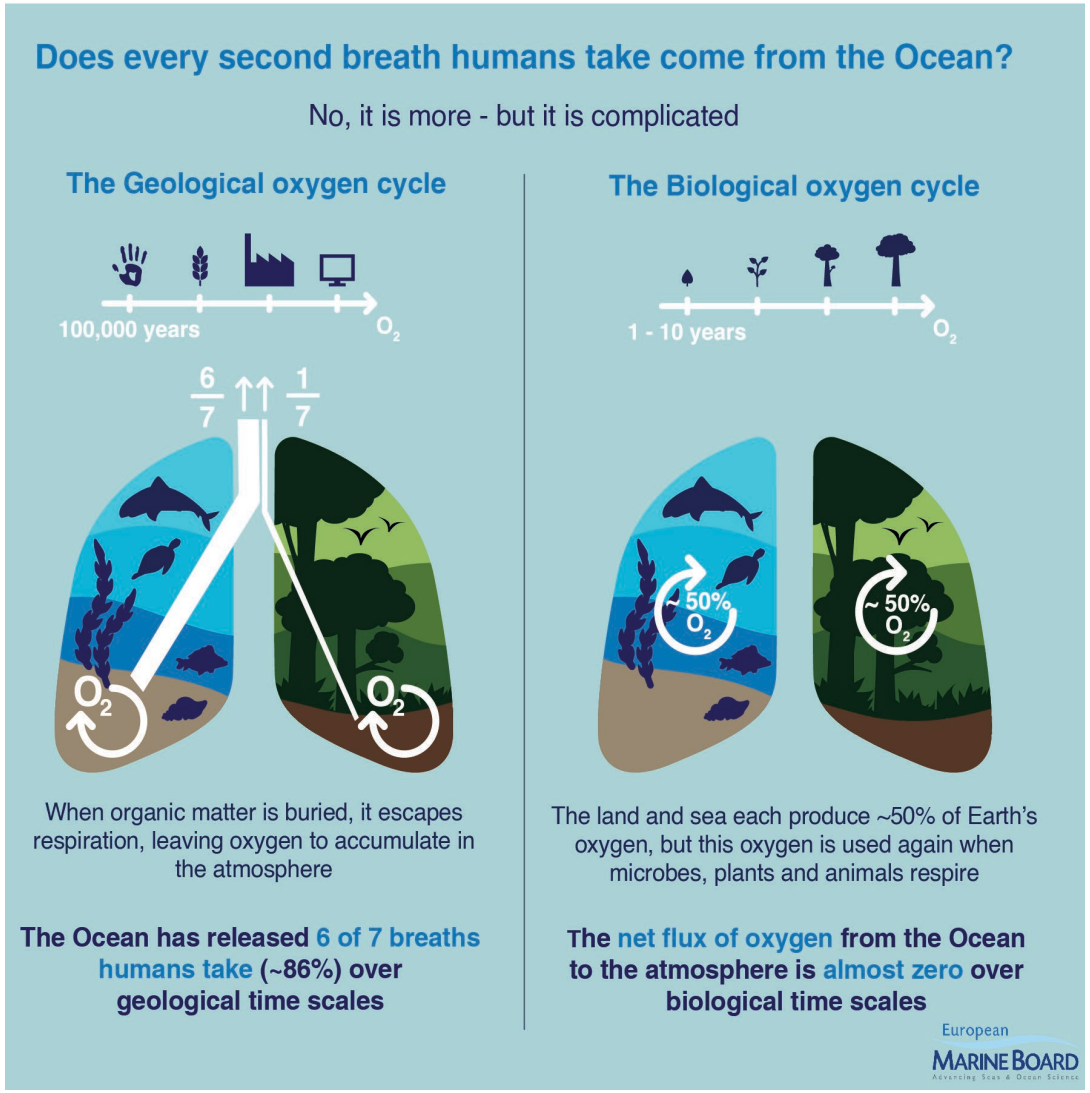






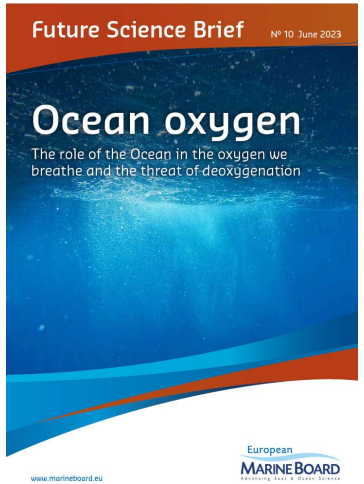


Does every second breath we take come from the Ocean?



Credit: Lucas Devisscher, Emma Losfeld and Anouk Hofman, Arteveldehogeschool

✓ **Since the origin of life on Earth, the Ocean has provided most of the oxygen in the atmosphere, and is responsible for 6 of 7 breaths humans take**



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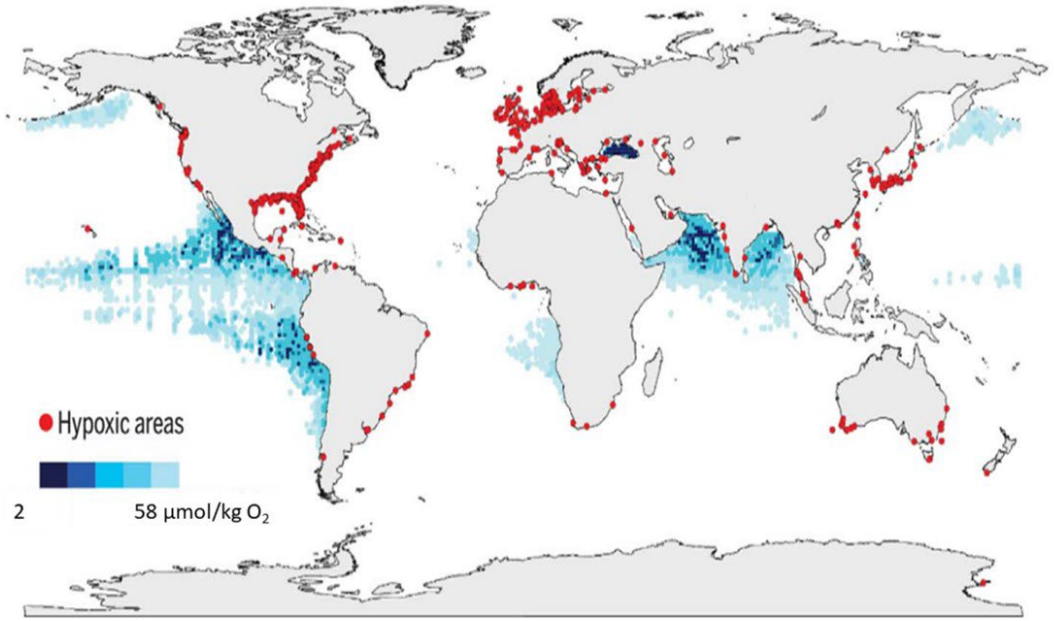
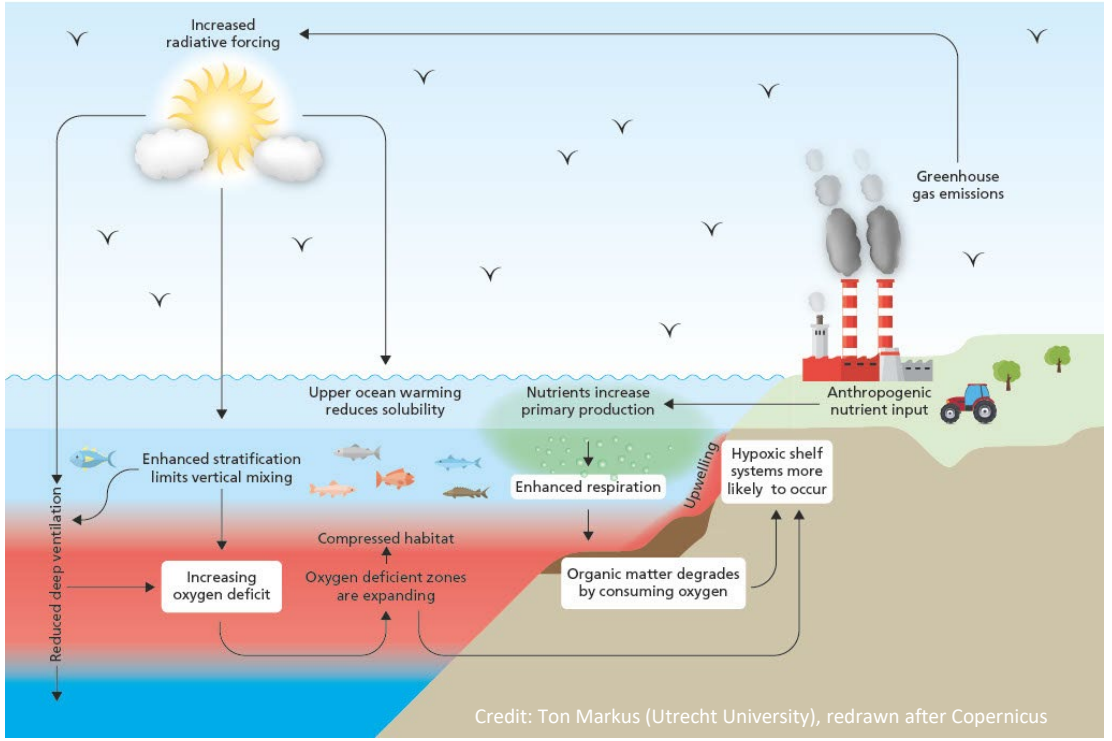
Current Ocean deoxygenation and impacts

- The **Ocean** has been **losing oxygen since the 1950s**
- **In open Ocean**: oxygen loss is **primarily due to** physical changes due to **human-induced climate change**
- **In coastal waters**: the **main cause** is **excessive anthropogenic nutrient input** (run-off from agriculture)



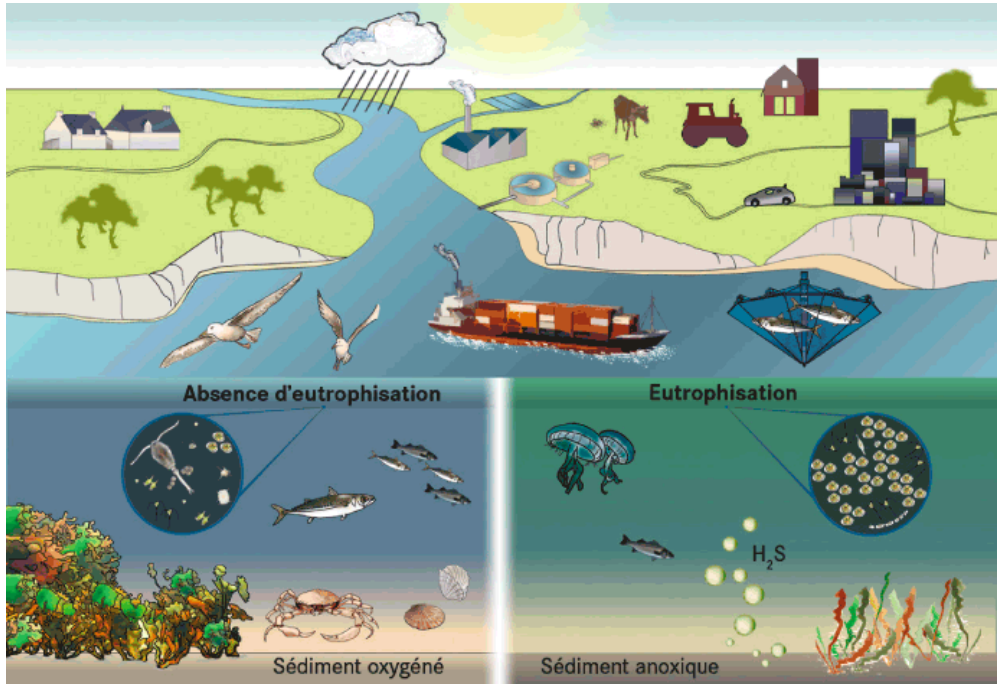
Breitburg *et al.* 2018



Breitburg *et al.* (2018) Declining oxygen in the global ocean and coastal waters. Science, 359(6371), eaam7240. https://doi.org/10.1126/science.aam7240

Current Ocean deoxygenation and impacts

- **Low oxygen levels alter** the **cycling of many elements** in the marine environment that **important for life & promote** the **production of the greenhouse gases** nitrous oxide and methane
- **Deoxygenation strongly impacts life in the Ocean** and can lead to:
  - Habitat loss
  - Major changes in diversity, food-web interactions and ecosystem structure
  - Acute or chronic low oxygen levels can result in mass mortality



https://qsr2010.ospar.org/fr/ch04_01.html



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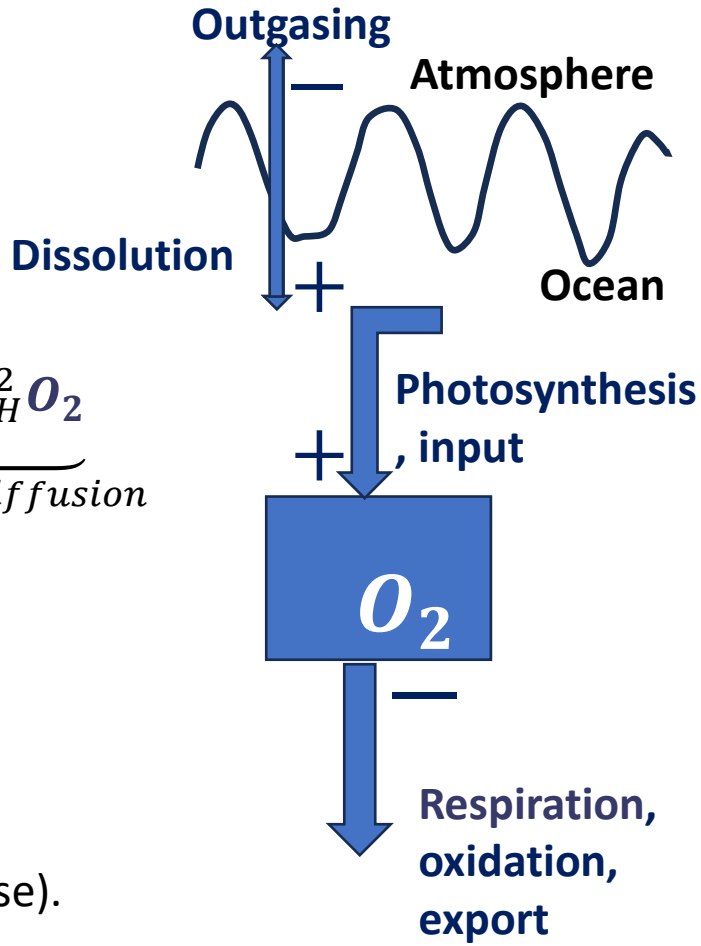
Predicting Oxygen

$$\frac{dO_2}{dt} = Input - Export + Photosynthesis - respiration - oxidation + dissolution - outgasing$$

$$\frac{\partial O_2}{\partial t} + \underbrace{\nabla_H.(\underline{u}O_2) + \frac{\partial}{\partial x_3}(wO_2)}_{horizontal\ and\ vertical\ advection} = \underbrace{Q^y}_{production/destruction} + \underbrace{\frac{\partial}{\partial x_3}(\tilde{\lambda}\frac{\partial O_2}{\partial x_3}) + \lambda_H \nabla_H^2 O_2}_{horizontal\ and\ vertical\ diffusion}$$

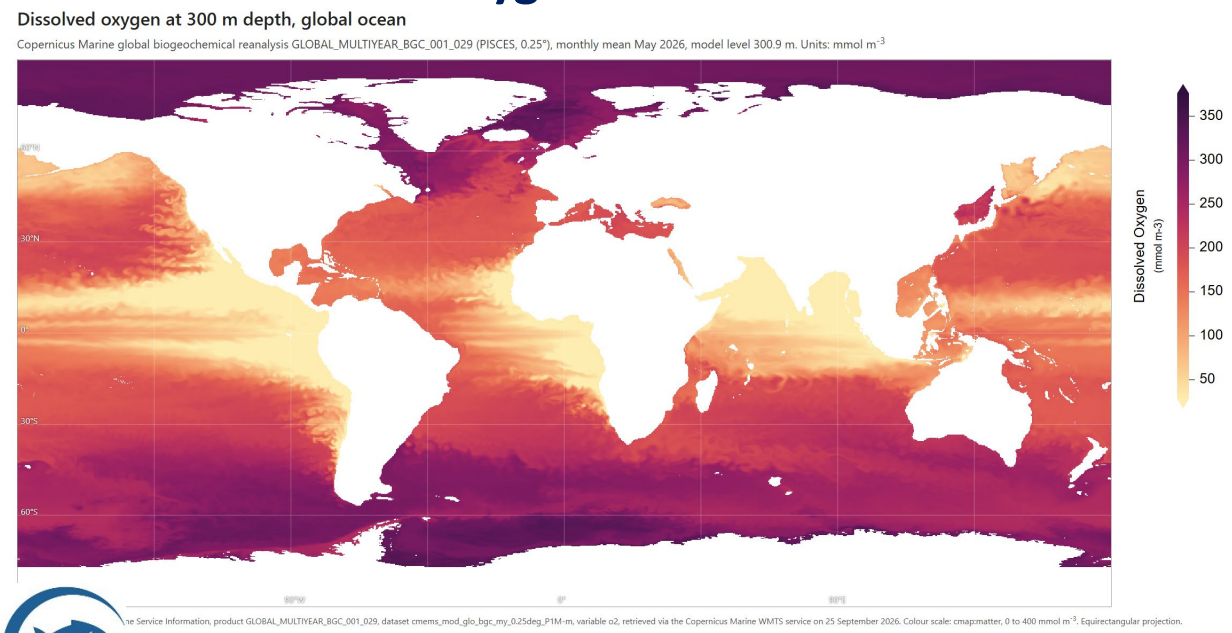


- No equivalent to Navier-Stokes equations for biogeochemistry
- Empirical formulations of biogeochemical interactions (source-sink).
- Poorly constrained parameters (derived from laboratory experiments in the best case).

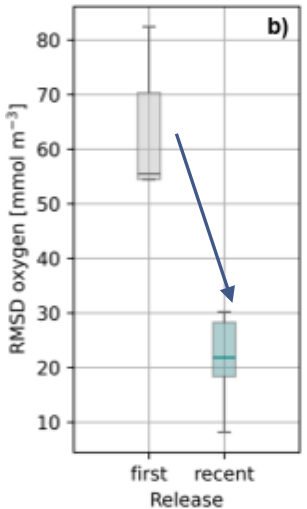
Predicting Oxygen

Weather Scales

Oxygen forecasts at 300m

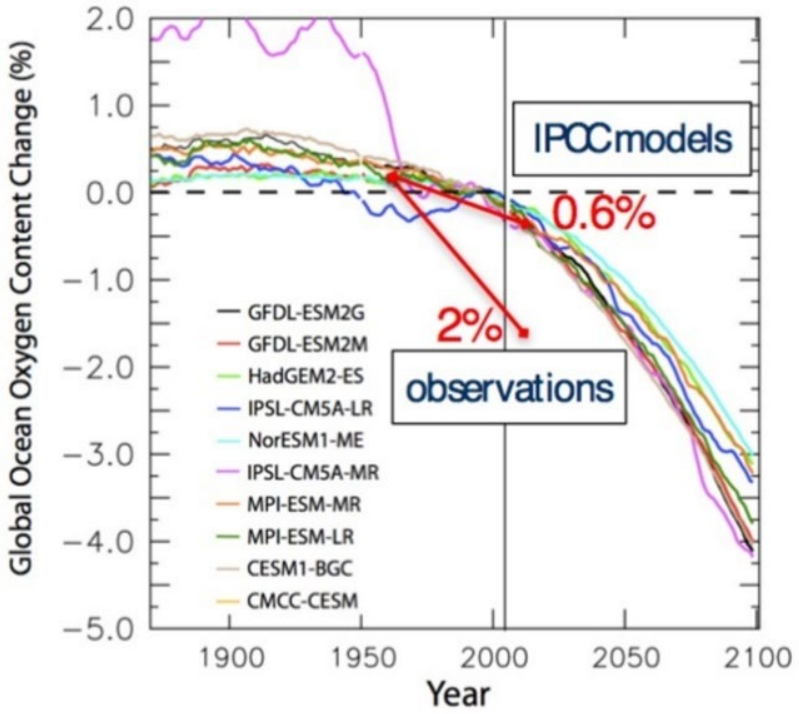


Error reduction by a factor of 3 over 2015-2024



Climate Scales

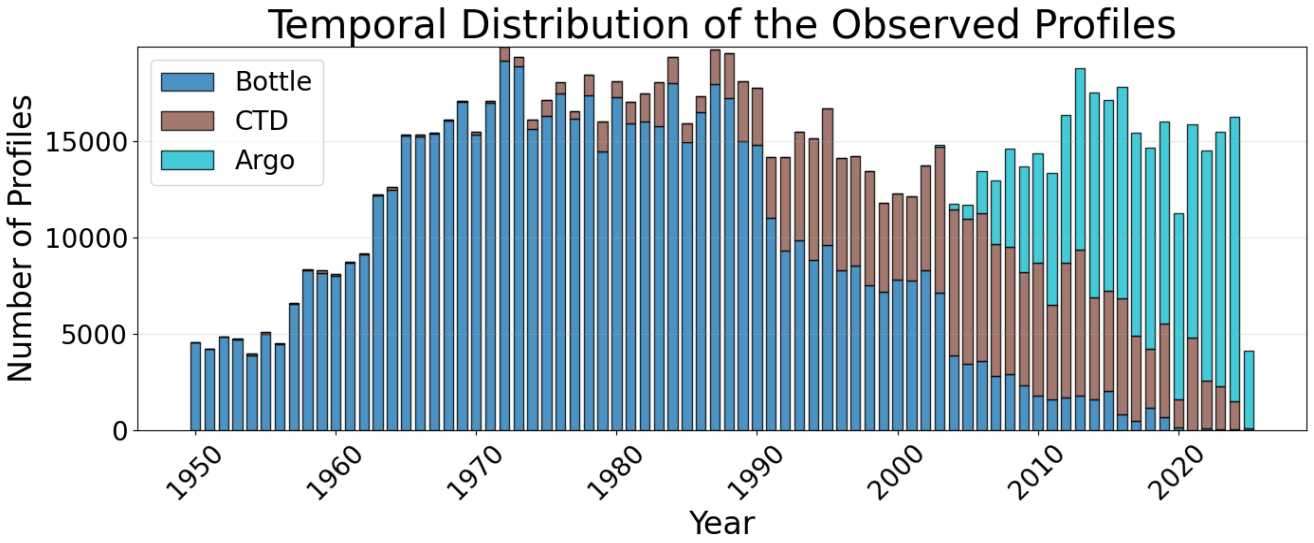
Deoxygenation is not well constrained

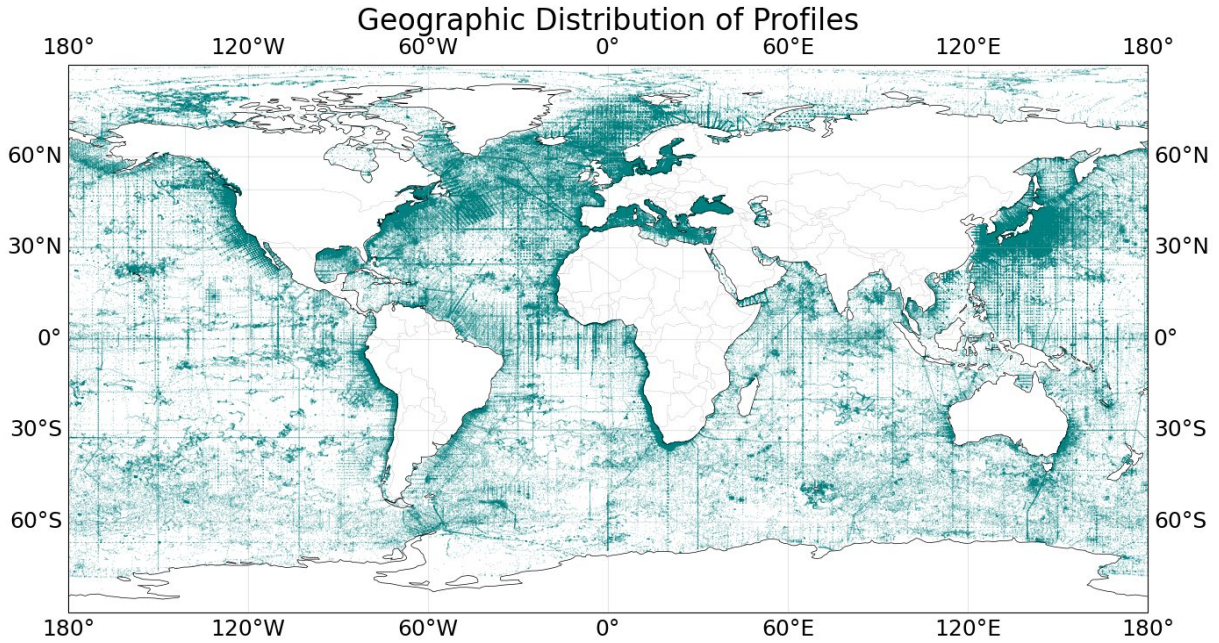


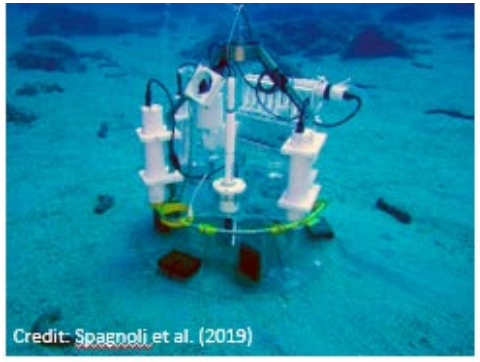
Deoxygenation trend over 1960–2000s differs between 0.6% and 2 %.

Observing Oxygen

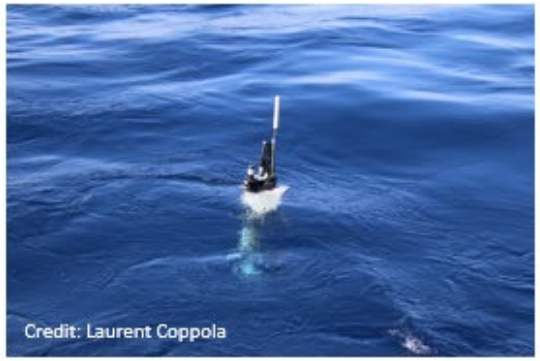
Data over 1950-2025: 1.055.877 profiles, 173.029.700 measurements









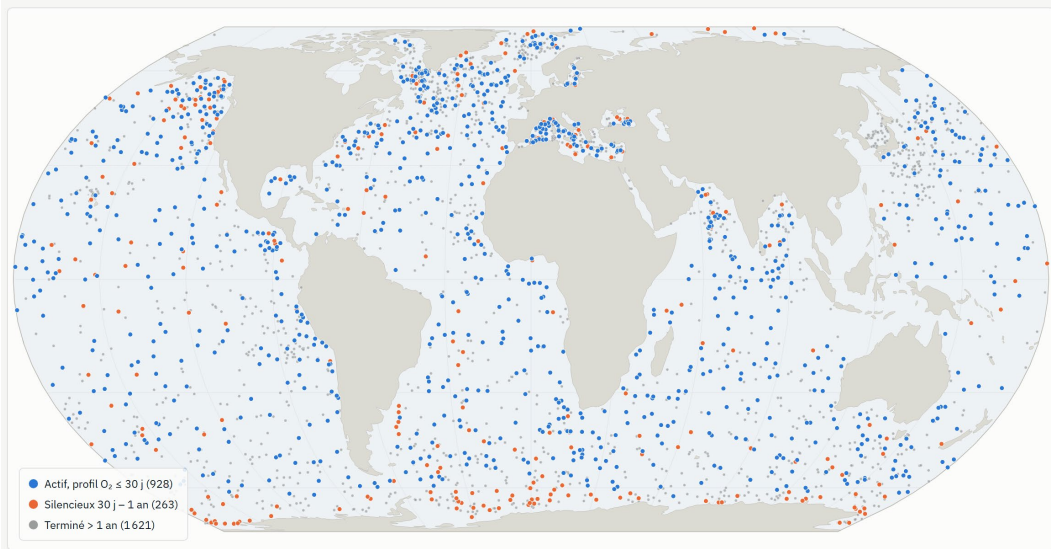




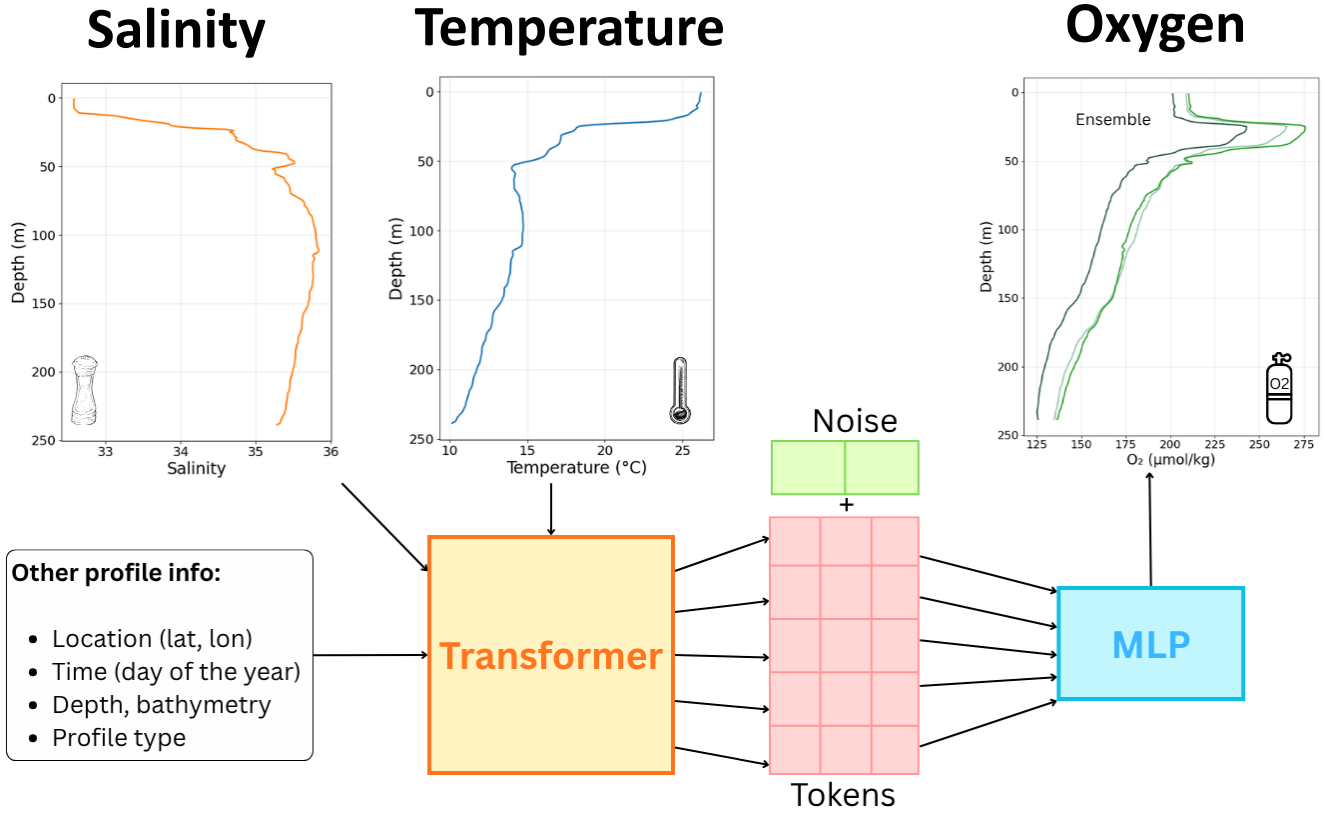
Predicting Oxygen with deep learning

BIOGEOSEA
Ocean Insights for the Future

2812 BGC Argo floats since 2002 (928 currently).



biogeochemical Argo



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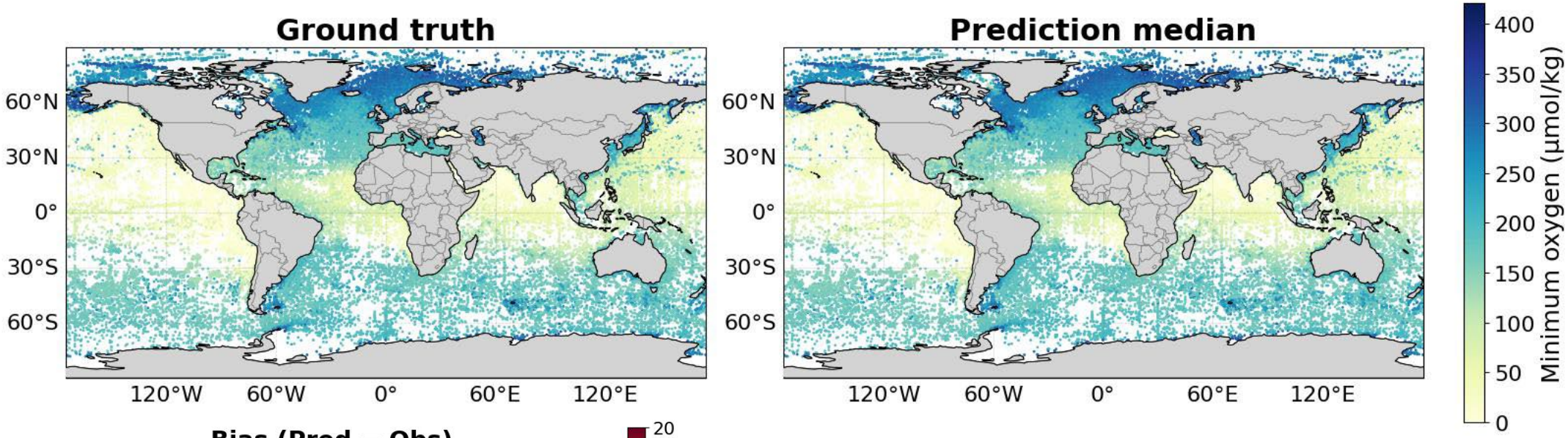
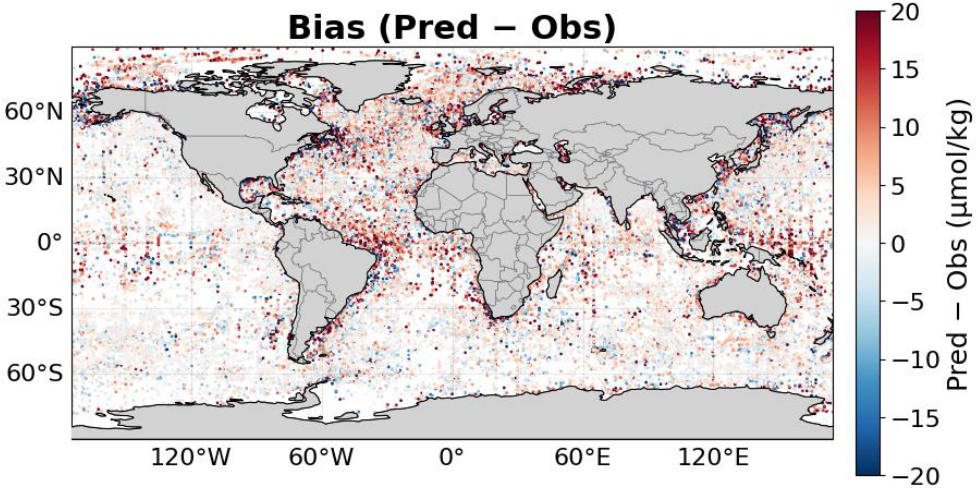
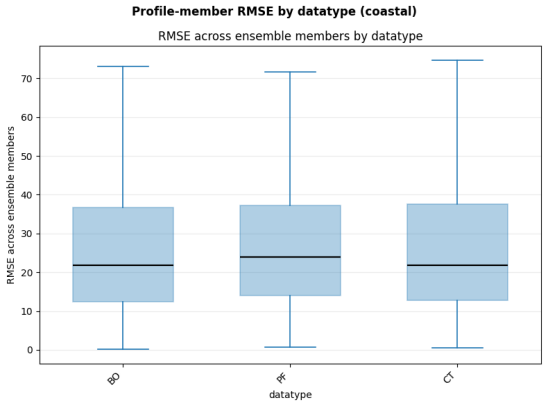
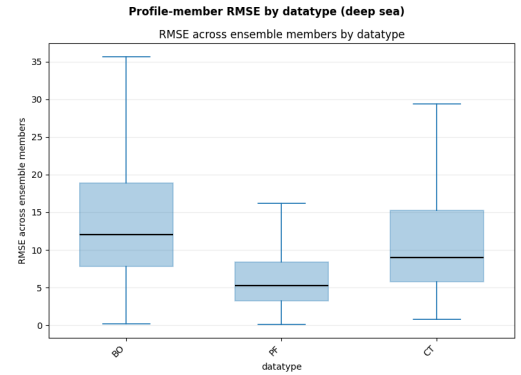
Indicators



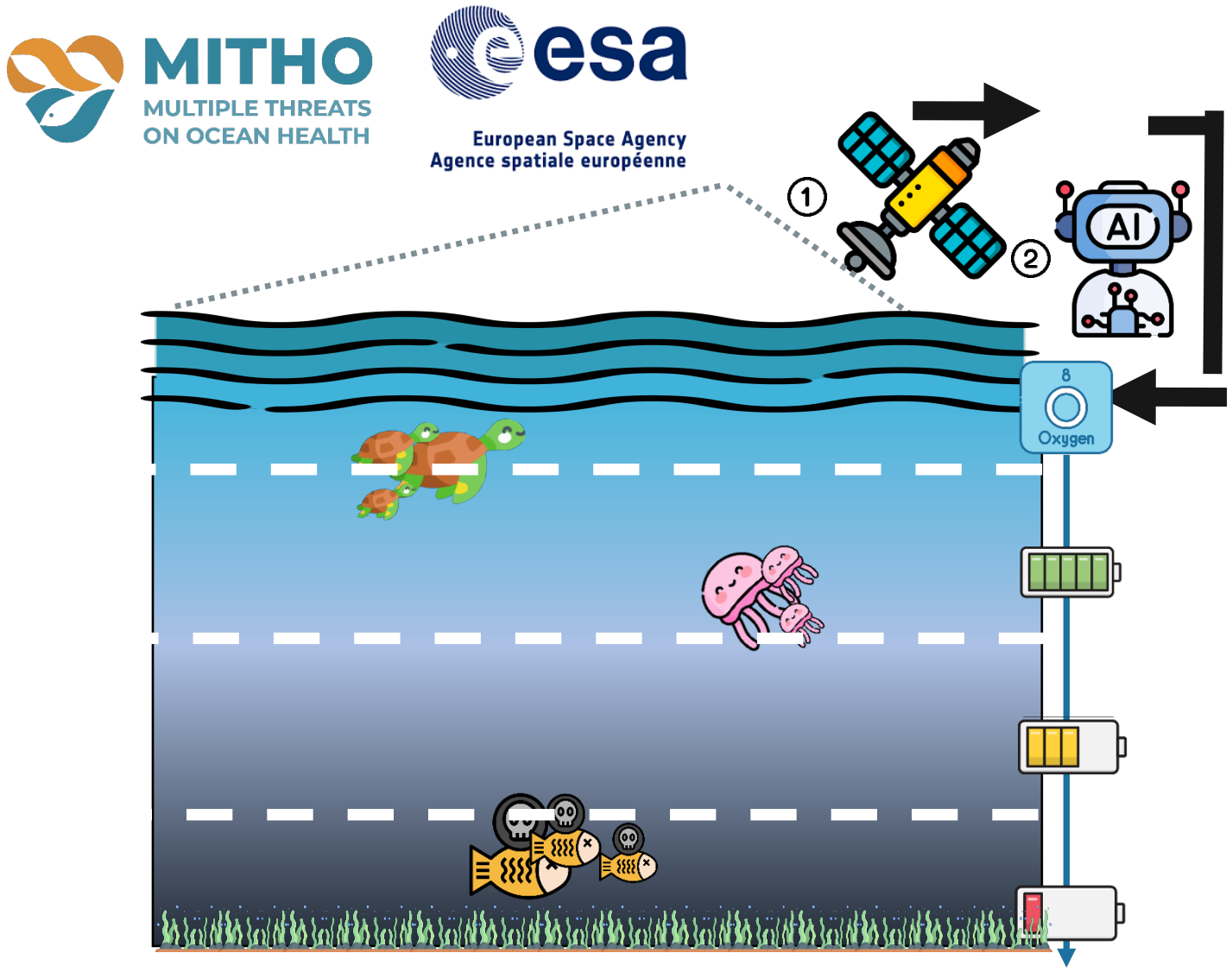






Forecasting hypoxia from space with deep learning

QUESTION: Can we predict bottom hypoxia from surface (satellite) observation?

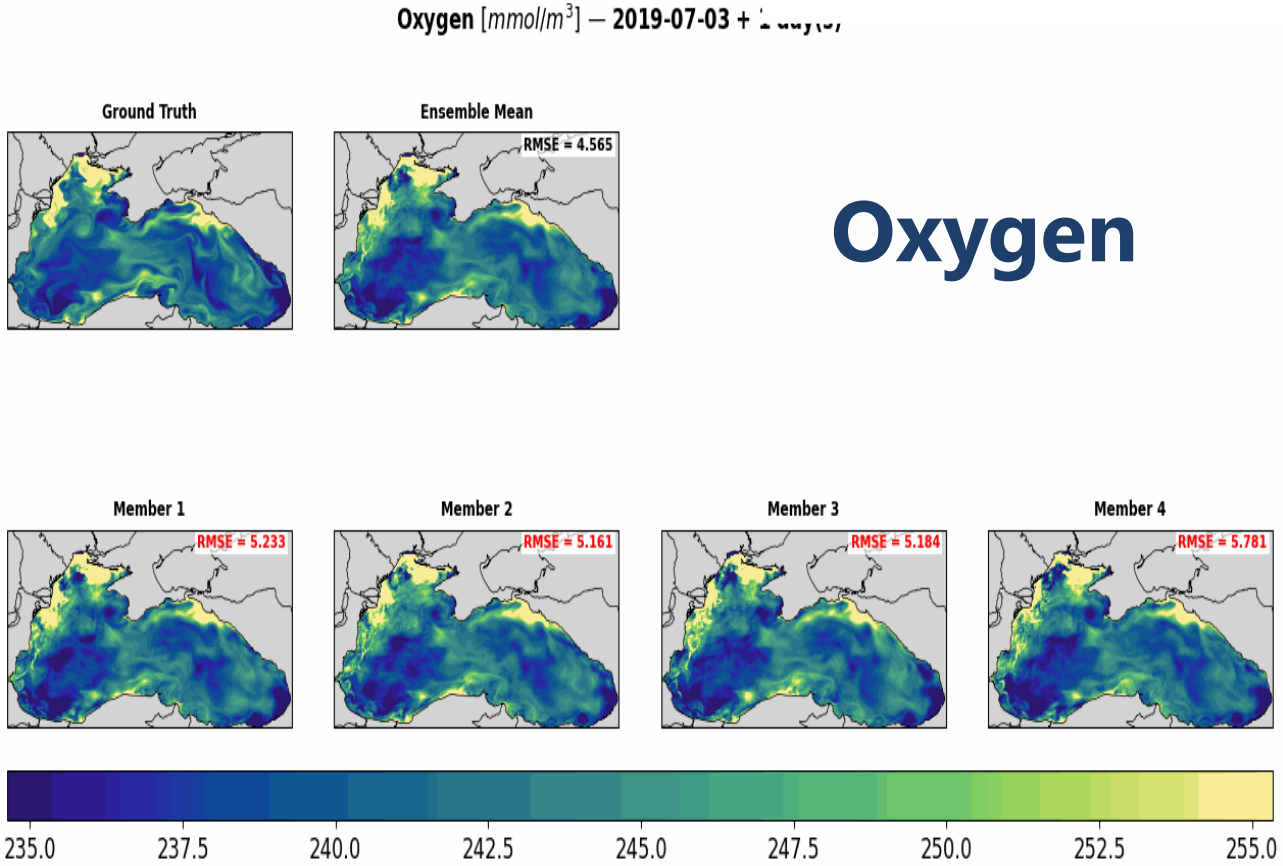


Forecasting hypoxia from space with deep learning

Reference dataset: CMEMS reanalysis (1998-2022). Training (1998 to 2017), validation (2018-2020), test (2021 to 2022).

Deep Learning: deep generative neural network, provides the distribution of state.

The neural network emulator detects **38% of summer hypoxic** events shelf-wide



Oxygen

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1. History of oxygen on Earth and relationship to life
2. The oxygen budget at geological scales and the modern oxygen cycle
3. Does every second breath we take come from the Ocean?
4. Current Ocean deoxygenation and impacts
5. Methods to study Ocean oxygen: observing and predicting oxygen
6. **Addressing Ocean deoxygenation through mitigation and adaptation**

Mitigation and adaptation needs

- **Limiting global warming will** (according to current models) **stop upper Ocean deoxygenation**
  - For this, it is **key to reach net-zero anthropogenic greenhouse gas emissions**
- **Coastal deoxygenation can be efficiently reduced** in many regions by **limiting terrestrial run-off of nutrients and organic waste ->** Important to **implement management strategies**
- **Blue carbon coastal ecosystems can help oxygenate coastal waters** and thereby reduce the impacts of deoxygenation
  - Mitigation is **restricted to small near-shore habitats** where these species can grow
  - These **habitats** are **also impacted by human activities**
- Ensure that **all oxygen data is compiled and shared**, feeding into **global databases**, to accurately document and predict Ocean oxygen changes
- **Engineered addition of oxygen** into Ocean regions that would otherwise experience critical oxygen loss **has been proposed** and **may help to locally increase oxygen levels**
  - **Likely at the expense of non-local side-effects** that may **even accelerate global Ocean deoxygenation**
  - **Better knowledge is required**



Global Ocean Oxygen Decade Program (GOOD)

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2021
2030
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