



Reconstructing the Breathless Ocean with Spatio-Temporal Graph Learning

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Breathless Ocean: Impeding Survival of Marine Life



■ Oxygen is fundamentally essential for all life.

- Unfortunately, dissolved oxygen (DO) in the ocean has been steadily decreasing over the past 50 years, indicating the acceleration of global ocean deoxygenation.
- Multiple large-scale fish death due to low oxygen concentration has been reported globally.

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MARCH 19, 2023

Millions of dead fish wash up amid heat wave in Australia



In this image from video, dead fish float on the surface of the lower Darling-Baaka River near the New South...

Millions of fish have washed up dead in southeastern Australia in a die-off that authorities and scientists say is caused by **depleted oxygen levels** in the river after recent floods and hot weather.

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Climate > News

Heatwave causes mass fish death as soaring temperatures leave them **gasping for air**

Environment Agency urges public to look out for fish in distress during warm weather

Samuel Webb • Tuesday 21 June 2022 17:12 BST • 11 Comments



The New York Times

Tens of Thousands of Dead Fish Wash Ashore on Gulf Coast in Texas

A “perfect storm” of bad conditions, including high temperatures, **starved the fish of oxygen**, officials said.

BBC

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Low oxygen levels in River Spey may have killed fish

© 22 September

BBC

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'Shocking' Swindon lake fish deaths as **oxygen levels drop**

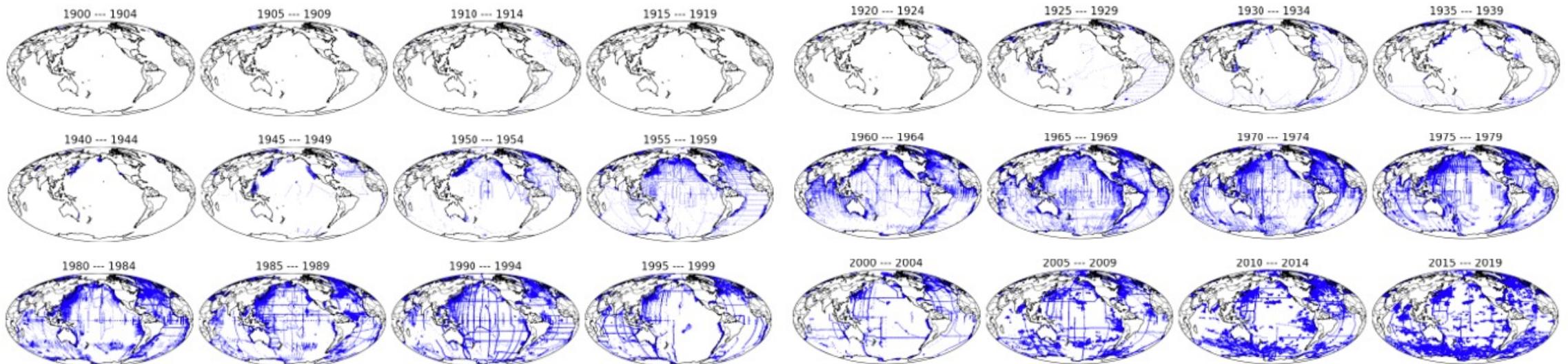
Breathless Ocean: Impeding Survival of Marine Life



■ Understanding the evolution of global dissolved oxygen is crucial but challenging.

1 Historical dissolved oxygen observation is *severely sparse*.

➤ According to World Ocean Database (WOD), more than 96.26% dissolved oxygen observation are missing in the past 100 years, especially in early years.



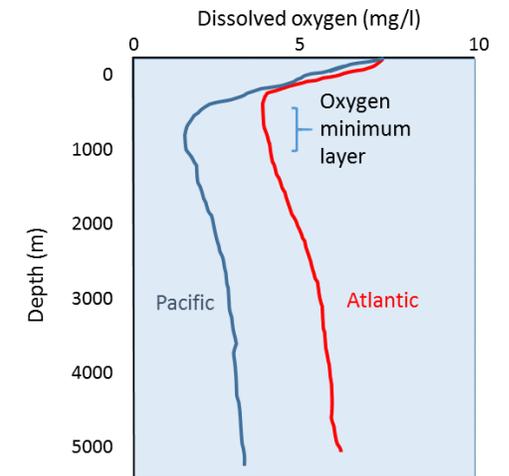
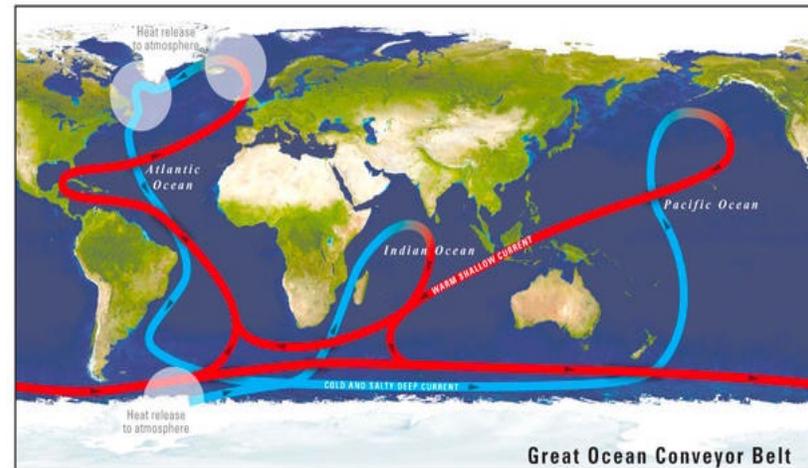
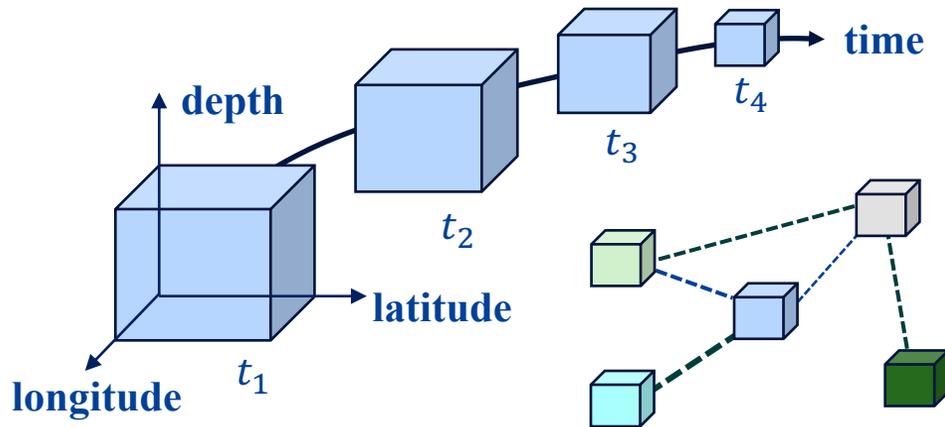
Breathless Ocean: Impeding Survival of Marine Life



■ Understanding the evolution of global dissolved oxygen is crucial but challenging.

2 Global ocean shows irregular *4D spatio-temporal heterogeneity*.

- After data gridding, we denote each grid as a 4D coordinate of [longitude, latitude, depth, time].
- Due to ocean currents, global warming, and other impacts, the spatio-temporal correlations in different regions are heterogeneous.



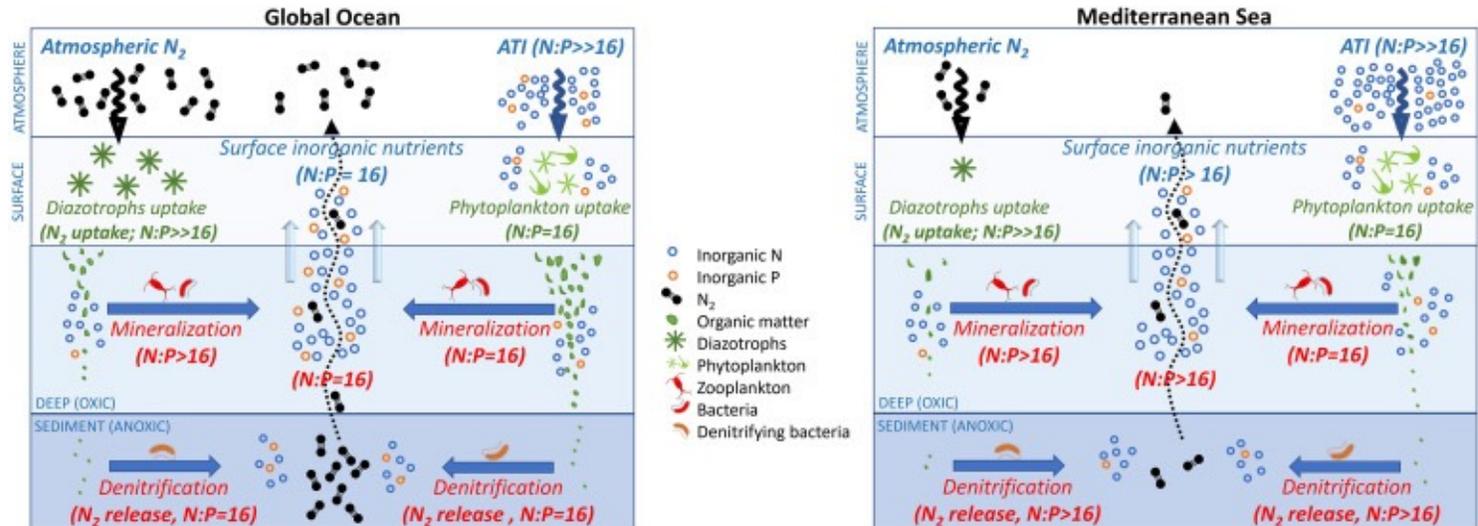
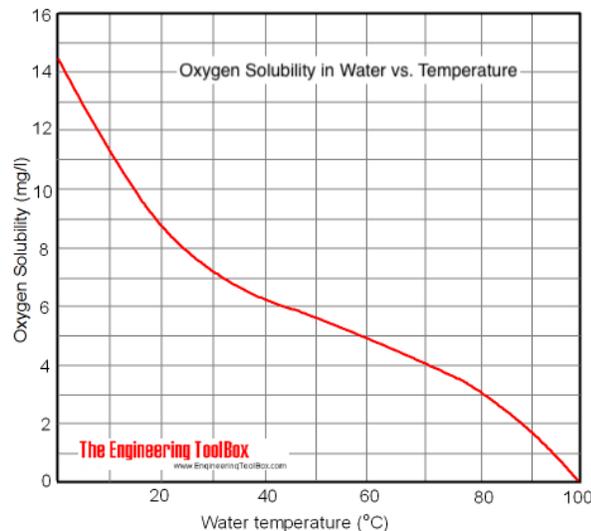
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- Understanding the evolution of global dissolved oxygen is crucial but challenging.

3 Dissolved oxygen is influenced by coupled *physical-biogeochemical properties*.

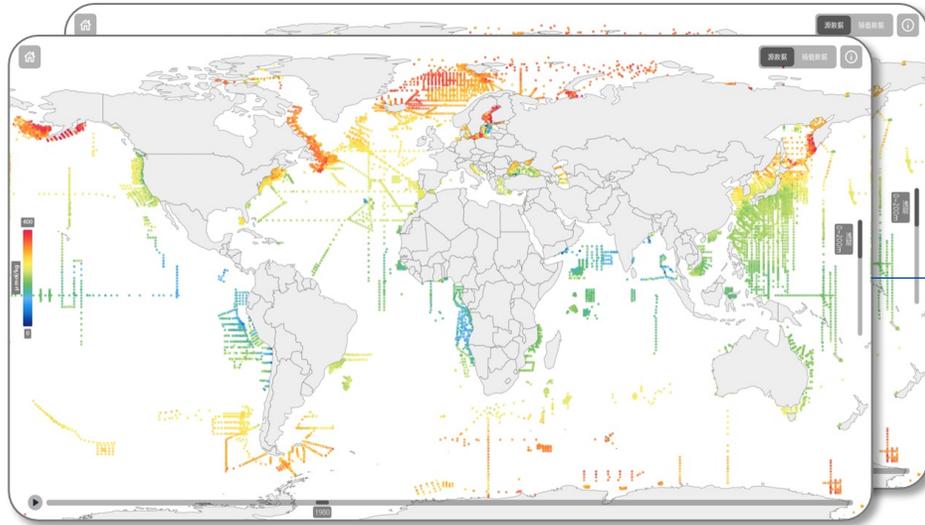
- The solubility of ocean oxygen is related to physical processes such as seawater temperature, salinity, and pressure.
- Active oxygen also participates in chemical reactions and biological activities in seawater.



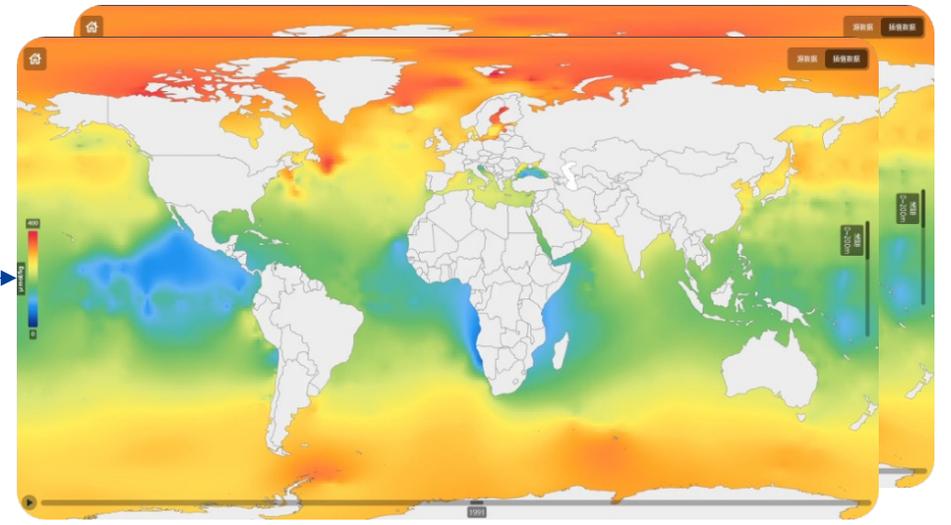
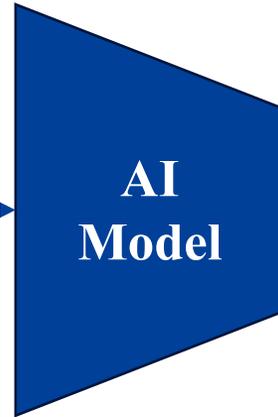
AI for Ocean Deoxygenation Reconstruction



Research Question: Can deep learning methods more accurately reconstruct global ocean deoxygenation over a century under sparse dissolved oxygen observations?



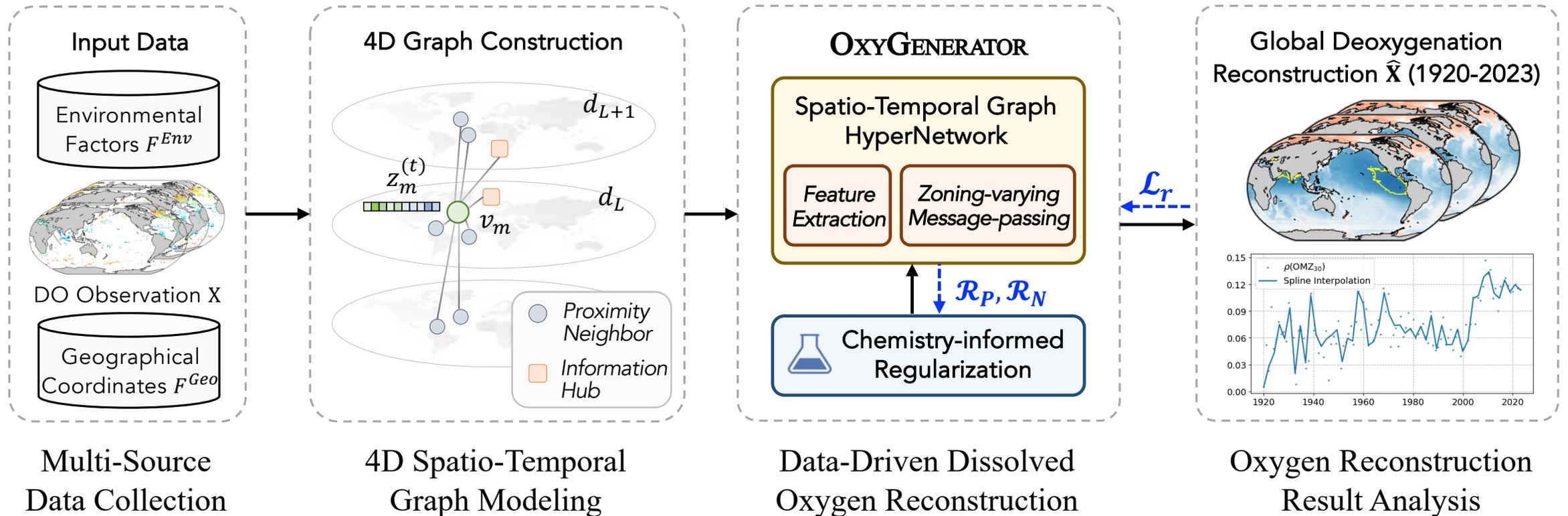
Input: Sparse Dissolved Oxygen Observations



Output: Reconstructed Dissolved Oxygen Atlas

■ OxyGenerator: Spatio-Temporal Graph Learning Model

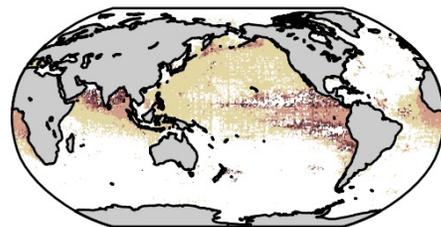
- Construct complex spatiotemporal correlations between missing samples and observed data through graphs.
- ST-Graph HyperNetwork: Inspired-by the zoning strategy in oceanography research.
- Chemistry-informed Regularization: The relationship between oxygen (O), nitrogen (N), and phosphorus (P).



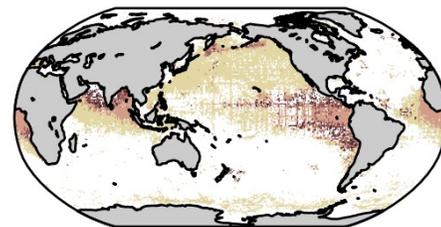
■ Performance Comparison with CMIP6 benchmarks

- Coupled Model Inter-comparison Project Phase 6 (CMIP6): Expert-dominated Earth Science System Simulation
- OXYGENERATOR significantly outperforms CMIP6 numerical simulations, reducing MAPE by 38.77%, demonstrating a promising potential to understand the ocean deoxygenation in data-driven manner.

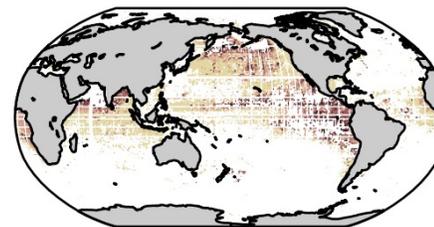
Benchmark	$k = 1$	$k = 2$	$k = 3$	$k = 4$	Average Performance			
	MAPE	MAPE	MAPE	MAPE	MAPE	R2	RMSE	MAE
CESM2 omip1	23.63	23.15	<u>23.67</u>	<u>22.87</u>	<u>23.32±0.38</u>	0.7966±0.0064	37.37±0.34	25.98±0.31
CESM2 omip2	<u>23.62</u>	<u>23.00</u>	24.60	23.13	23.58±0.72	0.7947±0.0096	38.22±0.55	27.12±0.32
GFDL-ESM4 historical	26.13	24.01	26.68	24.33	25.28±1.31	<u>0.8228±0.0051</u>	<u>35.45±0.65</u>	<u>23.69±0.38</u>
OXYGENERATOR (Ours)	14.72	13.48	15.72	13.20	14.28±1.16	0.9026±0.0072	26.31±1.23	17.57±1.10
Improvement	37.67%	41.38%	33.59%	42.28%	38.77%	9.70%	25.78%	25.83%



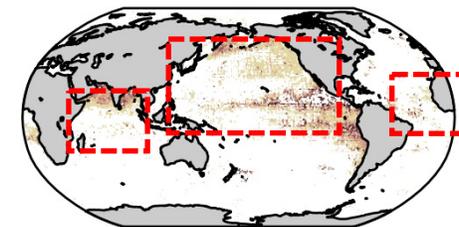
(a) CESM2 omip1



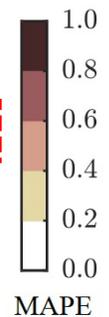
(b) CESM2 omip2



(c) GFDL-ESM4 historical



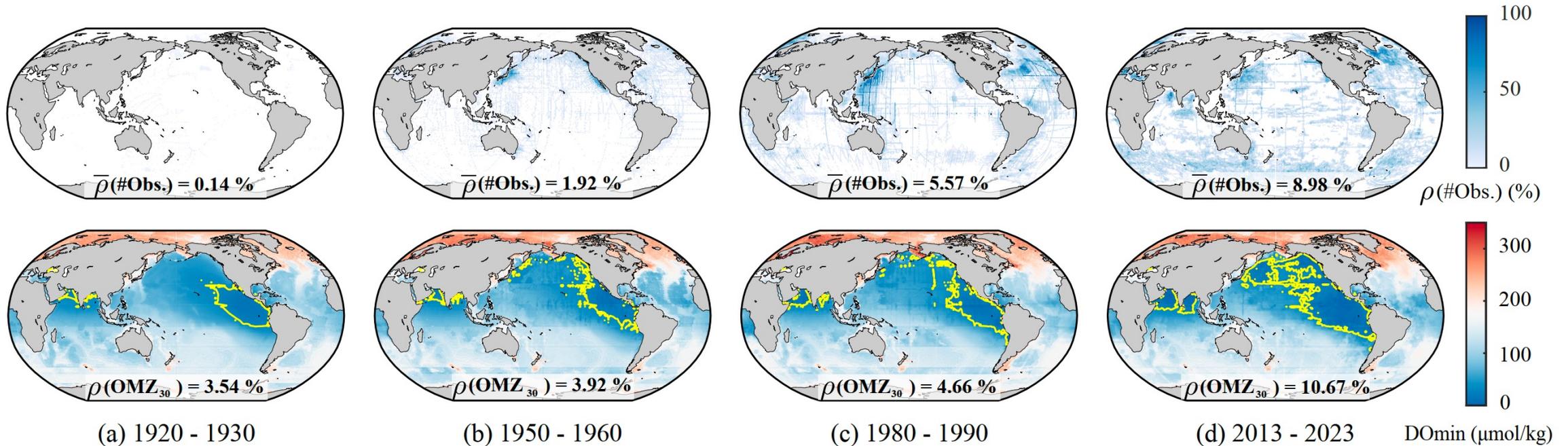
(d) OxyGenerator (Ours)





■ Ocean Minimum Zone (a.k.a. Dead Zone) Analysis

- Oxygen minimum zones (OMZs) are ocean areas where dissolved oxygen is extremely low and thus can negatively affect biogeochemical cycles and marine organisms.
- The yellow line envelopes the oxygen minimum zone (OMZ) where $DO_{min} \leq 30 \mu\text{mol/kg}$. $\rho(\text{OMZ}_{30})$ indicates the proportion of OMZ30 regions to global oceans, which clearly shows a significant increase over a century.





DEOXYGENATION

A Wake Up Call To Save Our Suffocating Seas

Climate change is now accelerating the loss of life-sustaining oxygen from the ocean. This deoxygenation will adversely impact food security and human populations the world over.



DEOXYGENATION IS

activated primarily by

OCEAN WARMING.



Heated ocean water resulting from climate change holds less soluble oxygen and leads to greater

STRATIFICATION.

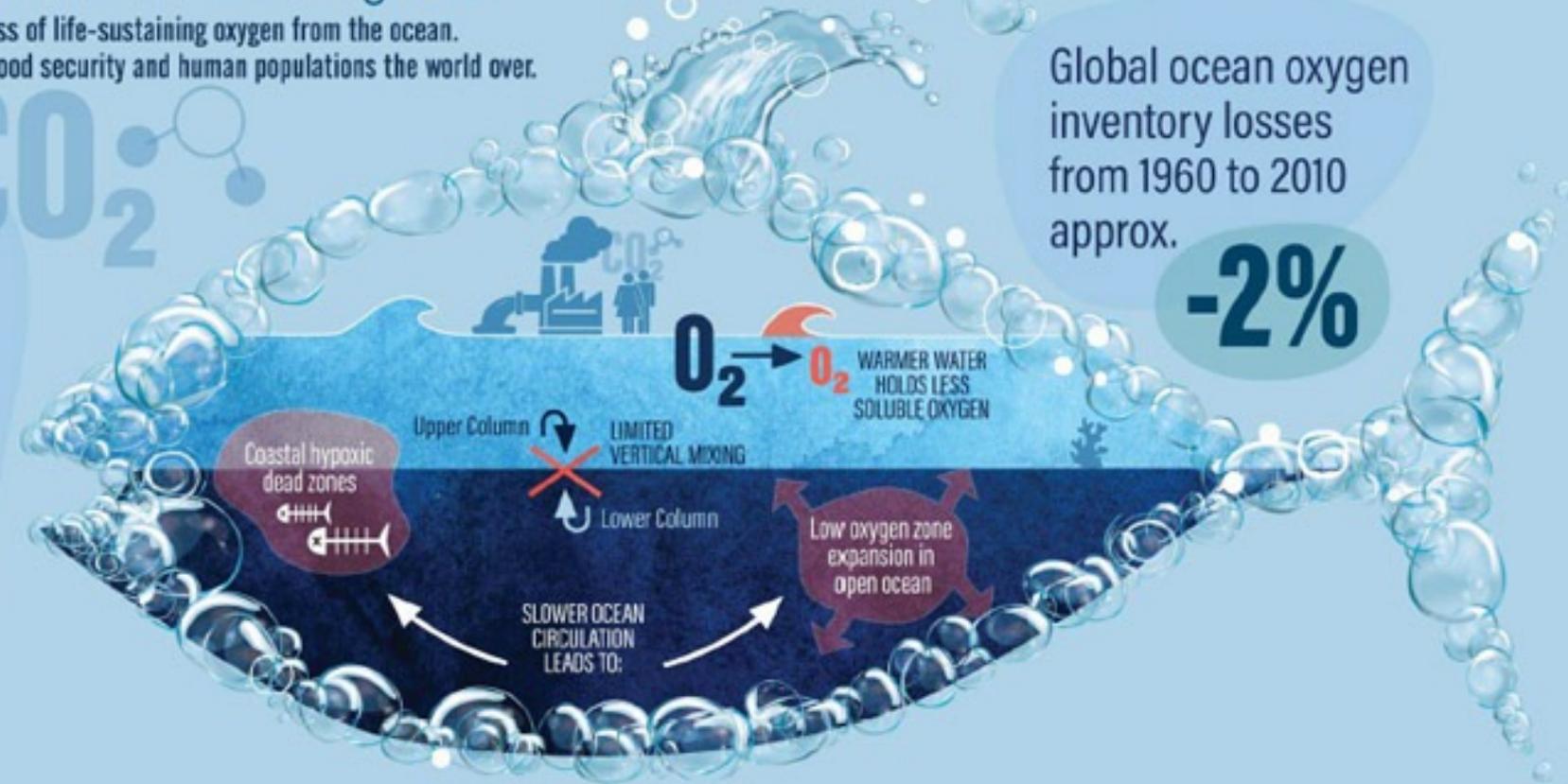
Increased separation of upper and lower water columns reduces circulation and oxygen exchange between atmosphere and water, intensifying stress on marine species throughout the ocean.



CULTURAL EUTROPHICATION.



Excess nutrient runoff from agriculture, sewage and fossil fuels are another key contributor to oxygen decline in coastal waters.



Global ocean oxygen inventory losses from 1960 to 2010 approx.

-2%



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