Patterns of deoxygenation in the global ocean

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Dissolved Oxygen in the Ocean

$\sigma = 26.9$ isopycnal (upper ocean, 0-400 m)

Atmospheric inventory
37,500 Pmol

2.3% $\text{CO}_2$, 97.7%

Oceanic inventory
227 Pmol

99.4% $\text{O}_2$, 0.6%
• **O$_2$ uptake**: Gas exchange with atmosphere
• **O$_2$ transport**: supply via vertical mixing & circulation
• **O$_2$ consumption** via respiration of organic matter
• **O₂ uptake**: Gas exchange with atmosphere
• **O₂ transport**: supply via vertical mixing & circulation
• **O₂ consumption** via respiration of organic matter

(Karstensen et al., 2008)
Subtropical thermocline
zonally averaged view of the upper ocean

(=) Subtropical thermocline
zonally averaged view of the upper ocean

(Oschlies et al., Nat. Geosci., 2018)
Effects of warming

Drop in solubility, enhanced stratification

(Oschlies et al., Nat. Geosci., 2018)
Effects of warming

enhanced stratification, reduced mixing

(Oschlies et al., Nat.Geosci., 2018)
Effects of warming

shallower thermocline $\rightarrow$ faster ventilation, less mixing, more oxygenated waters

(Oschlies et al., Nat.Geosci., 2018)
Effects of warming

“Abiotic O₂” in tropical thermocline (yr 2100 – 1990)

ΔO₂,abiot at z=300m

LATITUDE

LONGITUDE

mmol m⁻³

90
70
50
30
10
-10
-30
-50
-70
-90

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Effects of warming

Elevated $O_2$ in tropical thermocline (yr 2100 – 1990)

(Oschlies et al., GBC 2008; also Takano et al., GBC 2018; less pronounced in NCAR large ensemble, Long et al., GBC 2016)
What do the data say?

Declining $\text{O}_2$ in tropical thermocline (yr 2010 – 1960)

$\Delta \text{O}_2$ at $z=300\text{m}$

(Stramma et al., BG 2012)
Observational pattern estimate & simulated CMIP5 model patterns

μmol kg⁻¹ yr⁻¹
Diapycnal mixing? (UVic, 1960-2010)

\[ k_v = 0.15 \text{cm}^2\text{s}^{-1} \]

\[ k_v = 0.3 \text{cm}^2\text{s}^{-1} \]

\[ k_v = 0.01 \text{cm}^2\text{s}^{-1} \]

\( \Delta O_2 \) at \( z=300\text{m} \)

All model configurations show \( O_2 \) increase in tropical thermocline!

(Strammas et al., BG 2012; also: Bahl et al., GBC 2019)
Pronounced impact of winds!

$\Delta O_2$ at $z=300m$ (2010 – 1960)

Identical forcing with CORE winds after 1958

NCAR/NCEP climatology prior to 1958

CORE climatology prior to 1958

Legacy of winds prior to 1960s!

(Stramma et al., BG 2012)
Conclusions (i)

- Observed deoxygenation in the tropical thermocline still not fully understood.
  - Likely not driven by warming (at least not directly)
  - Wind changes play dominant role
  - Natural and anthropogenically forced variability
Total oxygen change (1960-2010)

Observational estimate:
Oceanic O₂ loss: ~1 Pmol/decade
i.e. ~2 % during past 50 years.

(Schmidtke et al., Nature 2017)
Oxygen change (1960-2010)

Observational estimate:
Oceanic \( O_2 \) loss: \( \sim 1 \) Pmol/decade

What do the models say?
Oxygen change (1960-2010)

Observational estimate:
Oceanic $O_2$ loss: $\sim 1$ Pmol/decade

CMIP5 models
2%
0.6%

$O_2$ loss in CMIP5 models:
$\sim 0.3$ Pmol/decade.
(0.12 Pmol/decade in NCAR large ensemble)

Models underestimate obs. trend estimate by factor 2-3 or more.

What do the models say?

(Bopp et al., BG 2013)
Oxygen change (1960-2010)

Have not yet been able to reach observed O$_2$ loss.

CMIP5 models

Sensitivity experiments (mixing, stoichiometry)

Obs

Oxygen Change (Tmol/decade)

<table>
<thead>
<tr>
<th>Model Experiment</th>
<th>CESM1</th>
<th>CMCC CESM</th>
<th>GFDL ESM2G</th>
<th>GFDL ESM2M</th>
<th>HadGEM2 ES</th>
<th>IPSL CM5A LR</th>
<th>MPI ESM LR</th>
<th>MRI ESM1</th>
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<tbody>
<tr>
<td>Obs. estimate</td>
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Possible causes for systematic underestimate?

- Mapping? Data treatment?
- Solubility, biotic or circulation part? → Solubility?
Total and solubility part of O$_2$ change

Less O$_2$ loss in upper water column than to be expected from warming

300-600m O$_2$ loss equivalent to loss expected from solubility changes

Deep ocean O$_2$ loss (75% of total below 1000m) not related to solubility change

(Schmidtko et al., Nature 2017)
Total and solubility part of $O_2$ change (2010 - 1060)

CMIP5 models

obs

Good CMIP5 model-data agreement for solubility-driven part!

$\rightarrow$ Circulation & biology cause discrepancies

incomplete spin-up
Regions of above-average O₂ decline

Equatorial Pacific, Southern Ocean

Models underestimate mainly deep-ocean deoxygenation (not a solubility effect!)

(Schmidtko et al., Nature 2017)
Sensitivity to isopycnal mixing upon doubling of atmospheric CO$_2$

**Stronger deoxygenation in deep ocean for strong mixing.**

(A) $\Delta O_2$ and $\Delta$Age AREDI400, 3000m

(B) $\Delta O_2$ and $\Delta$Age AREDI800, 3000m

- Abernathey and Marshall, zon.av.

(Bahl et al., GBC 2019)
Conclusions (ii)

• Wherever we look, (global) models underestimate O$_2$ trends & variability.
• Good agreement for solubility-driven part & often OK for upper ~1000m (except trop.Pac.).
• Most models underestimate deep-ocean deoxygenation (not a solubility effect) (or are data-derived estimates too high???)
• Need to understand impact of circulation changes, particularly in the deep ocean.
• Overlooked biogeochemical feedbacks?
Thank you!
CMIP5 oxygen trends

Little agreement among models for Arctic & Trop. Pac. & Southern Ocean O₂ change
CMIP5 models

Atlantic

Indian Ocean

Pacific
O\textsubscript{2} air-sea flux variability

(Eddebbar et al., GBC 2017)
Models forced with realistic atmospheric forcing (CORE-2) underestimate interannual $O_2$ air-sea flux variability by factor 2 or more.

(Eddebbar et al., GBC 2017)
$O_2$(annual mean) variability at time-series sites

Models underestimate interannual $O_2$ variability by factor 2 or more.

(after Long et al., GBC 2016)
Isopycnal mixing?
GFDL (CM2Mc) @ doubling of atmospheric CO$_2$

- O$_2$ increase in tropical thermocline
- Strong deoxygenation in subpolar N.Pac. for low mixing.

(Bahl et al., GBC 2019)