Forced and unforced variations in ocean oxygen

Matthew C. Long
Climate & Global Dynamics Laboratory
National Center for Atmospheric Research

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Earth system models: internally generated variability

Range of future climate outcomes: DJF temperature trends (CCSM3, SRES-A1B)

Deser et al., 2012
Physical & biological controls on interior oxygen

Low latitude outgassing

\[ \text{O}_2 \]

High latitude uptake

\[ \text{O}_2 \]

\[ \text{O}_2 > \text{O}_2^{\text{sat}} \]

\[ \text{AOU} > 0 \]

Organic matter export

\[ \text{O}_2 < \text{O}_2^{\text{sat}} \]

\[ \text{AOU} > 0 \]

Photosynthetic productivity

\[ \text{CO}_2 + \text{nutrients} + \text{H}_2\text{O} \rightarrow \text{Organic Matter} + \text{O}_2 \]

Mixed layer depth

\[ \text{OUR} \]

\[ \text{O}_2 + \text{CO}_2 + \text{nutrients} + \text{H}_2\text{O} \]

Ventilation

Isopycnal surface

Graphic credit: M. Long and R. Johnson (NCAR)
Variance-weighted mean period in CESM 1850-control (400–600 m $O_2$)

$$T_x = \frac{\sum_k V(f_k, x)}{\sum_k f_k V(f_k, x)}$$
Oxygen decline projected to accelerate

CESM-LE*: projected global change in O$_2$ & heat

* Community Earth System Model, Large Ensemble

Long et al., 2019
Long et al., 2019; Moore et al. 2018
**CMIP5 projection: global and regional drivers of deoxygenation (2100)**

**AOU v. \(O_{2}^{\text{sat}}\) phase space: Simulated \(\langle O_2 \rangle\) change \((z > -1 \text{ km})\)**

- **Global**:
  - Tropics: warming compensated by reduced AOU;
  - Extra-tropics: reinforcing AOU and solubility change;
  - Cancelation between tropical & extra-tropical \(\Delta AOU\): global \(O_2\) decline dominated by solubility effect.

\[AOU = O_{2}^{\text{sat}} - O_2 = f(Age, O_2\text{-utilization})\]

*Long et al., 2019*
Oxygen declines related to ocean heat content anomaly

$O_{sat}^2$ v. heat: Simulated $\langle O_2 \rangle$ change ($z > -1$ km)

Long et al., 2019; Obs: Ito et al., 2017
Timescales of natural variability in thermocline $O_2$

Variance-weighted mean period in CESM 1850-control (400–600 m $O_2$)

$$T_x = \sum_k V(f_k, x) / \sum_k f_k V(f_k, x)$$
Superposition of forced signal and internal variability: Total

200 m O$_2$ trends
2006–2055
Superposition of forced signal and internal variability

CESM Large Ensemble: Linear trends in 200 m dissolved oxygen (2006–2055)

\[ \psi_i(t, x) = \tilde{\psi}_i(t, x) + \psi^s(t, x) \quad \tilde{\psi}_i(t, x) \quad \psi^s(t, x) = \frac{1}{m} \sum_{i=1}^{m} \psi_i(t, x) \]
Superposition of forced signal and internal variability: Internal variability

200 m O₂ trends
2006–2055
Can internal variability account for model-observations discrepancy?

Observed and simulated trends: global

Long et al., 2019
Can internal variability account for model-observations discrepancy?

Observed and simulated trends: Subtropical North Atlantic

Long et al., 2019
Natural variability challenges detection and attribution

Thermocline O$_2$
California Current

Time of emergence
Quantifying spatial structure of $[O_2]$ variability and change

Time evolving spatial pattern

$$\psi_i(t, x) = \tilde{\psi}_i(t, x) + \psi^s(t, x)$$

where $t = 1, \ldots, n$ and $x = 1, \ldots, p$ denote discrete time (annual means) and space (model grid points).

The forced signal

$$\psi^s(t, x) = \frac{1}{m} \sum_{i=1}^{m} \psi_i(t, x)$$

Climate anomalies

$$\psi'_i(t, x) = \psi_i(t, x) - \bar{c}(x)$$

EOF decomposition of anomalies

$$\psi'_i(t, x) = \sum_{j=1}^{q} a^i_j(t) e^j(x)$$
Leading EOFs: Large-scale spatial patterns of variability

15.6% 9.6% 6.2% 5.1%

Long et al., 2016
Quantifying spatial structure of $[O_2]$ variability and change

EOF decomposition of anomalies

$$\psi_i'(t, x) = \sum_{j=1}^{q} \alpha_j^i(t)e_j^i(x)$$

Projection of each ensemble member $(\psi_i'(t, x))$ onto EOF of forced signal

$$\alpha^{is}(t) = \sum_{x=1}^{p} \psi_i'(t, x)e_s^s(x)$$

Contribution of forced pattern to overall spatial variance

$$V_i^{is}(t) = \alpha^{is}(t)^2 \left/ \sum_{x=1}^{p} \psi_i'(t, x)^2 \right.$$
Rising dominance of the forced signal

Percentage of total spatial variance attributable to the forced signal

Long et al., 2016
Another forced signal: volcanic eruptions

Global-mean ocean properties
CESM Large Ensemble

Eddebar et al., 2019
Time-evolving distributions under changing external forcing

Branstator & Teng et al. 2010
**Forced ocean sea-ice (FOSI)**

- Reanalysis winds
- Satellite radiation

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**Fully-coupled CESM**

- ATM
- LND
- CPL
- Initialization
- OCN
- CICE
Skillful forecasts of upper ocean heat content on decadal timescale

Heat content anomaly, N. Atlantic Subpolar gyre ($z > -275$ m)

Yeager et al. 2012
Thermocline oxygen concentrations look to be highly predictable

Anomaly correlation coefficient: $O_2$ on $\sigma_\theta = 26.5$

courtesy of S. Yeager
Thermocline oxygen concentrations look to be highly predictable

Anomaly correlation coefficient: Salinity on $\sigma_\theta = 26.5$

courtesy of S. Yeager
Oxygen variability at Ocean Station Papa ($\sigma_\theta = 26.5$)

Detrended annual $O_2$ anomalies

Sun & Ito, in prep
Oxygen variability at Ocean Station Papa ($\sigma_\theta = 26.5$)

Simulated lag correlation between OSP O$_2$ and full field

Sun & Ito, in prep
Oxygen variability at Ocean Station Papa ($\sigma_\theta = 26.5$)

Local autoregressive (AR1) model

$$\frac{dO_2}{dt} = -\lambda O_2 + f'$$

Linear Inverse Model (LIM)

$$\frac{dO_2}{dt} = LO_2 + f'$$

$$C(\tau) = G(\tau)C(0)$$

$$G(\tau) = \exp (L \cdot \tau)$$

$$O_2(t + \tau) = G(\tau)O_2(t)$$

$$L = \tau_0^{-1} \ln \left[ \frac{C(\tau_0)C(0)}{C(\tau_0)} \right]^{-1}$$
Summary

• Forced changes in $O_2$ result from combined effects of solubility and AOU; models show reasonable agreement on changes at high-latitudes, but weak consensus in the tropics.

• Models underestimate AOU-driven deoxygenation in the upper ocean; it is unlikely that internal variability can explain this discrepancy.

• Natural variability challenges definitive attribution of $O_2$ trends.

• Capabilities are emerging that enable predicting $O_2$ on seasonal to interannual timescales.
Acknowledgements


Questions?

Matthew Long
Climate & Global Dynamics Laboratory
National Center for Atmospheric Research
mclong@ucar.edu
A persistent bias in Earth system models: Extensive OMZs

Thermocline (400–600 m) $O_2$ distributions

Observations vs. CESM
Simulated variability is weak

Simulated APO (mostly $O_2$) fluxes versus atmospheric inversion estimates

Eddebbar et al., 2017
CalCOFI dissolved oxygen is skillfully predicted

Thermocline $O_2$ in CalCOFI region

Thermocline $O_2$ tendency

O$_2$ inventory 1-5 year lead

Total tendency 1-5 year lead
What mechanisms provide predictability for $O_2$?

Mean vertical gradients

$O_2^{\text{heave}} = \left( \frac{\partial O_2}{\partial z} \right) \left( \frac{\partial \rho_\theta}{\partial z} \right)^{-1} \rho'_\theta$
East-west difference in anomaly generation mechanism

“Ventilation regime”

Correlation: $O_2$ v. $|PV|$

```
1.00
0.75
0.50
0.25
0.00
0.25
0.50
0.75
1.00
```

- $\partial \rho / \partial z$ low
- $PV$ low
- $O_2$ high

- Negative $PV-O_2$ correlation

```
PV \approx \left( \frac{f}{\rho} \right) \frac{\partial \rho}{\partial z}
```

“Heave regime”

Correlation: $O_2$ v. density

```
1.00
0.75
0.50
0.25
0.00
0.25
0.50
0.75
1.00
```

- $\partial \rho / \partial z$ high
- $PV$ high
- $O_2$ high

- Positive $PV-O_2$ correlation
- Negative $\rho-O_2$ correlation

- Vertical compression

$\rho$
CESM-LE projection: global-mean drivers of deoxygenation

$O_2$ change at 2100

$\Delta O_2 = \Delta O_{2 \text{sat}} - \Delta AOU$

- Warming declines with depth;
- Surface $AOU$ reduction: closer to equilibrium;
- Deep deoxygenation is $AOU$-dominated.

Long et al., 2019
Suboxic and hypoxic volumes projected to increase

Simulated change in oxygen deficient zones

A

$O_2 \leq 60 \text{ mmol m}^{-3}$

B

$O_2 \leq 5 \text{ mmol m}^{-3}$

Long et al., 2019
Imprint of volcanic eruptions on ocean biogeochemistry

Response to Pinatubo (CESM-LE)

Eddebar et al., 2019
Model resolution determines ventilation dynamics

Simulated zonal velocity at 1000 m
O₂ anomalies in the California Current

Pozo Buil & Di Lorenzo, 2017
O$_2$ anomalies in the California Current

Pozo Buil & Di Lorenzo, 2017
Reinforcing drivers at high-latitudes; compensation in tropics

Simulated change in zonal-mean $O_2$

Long et al., 2019