What can oxygen tell us about climate change in the oceans?

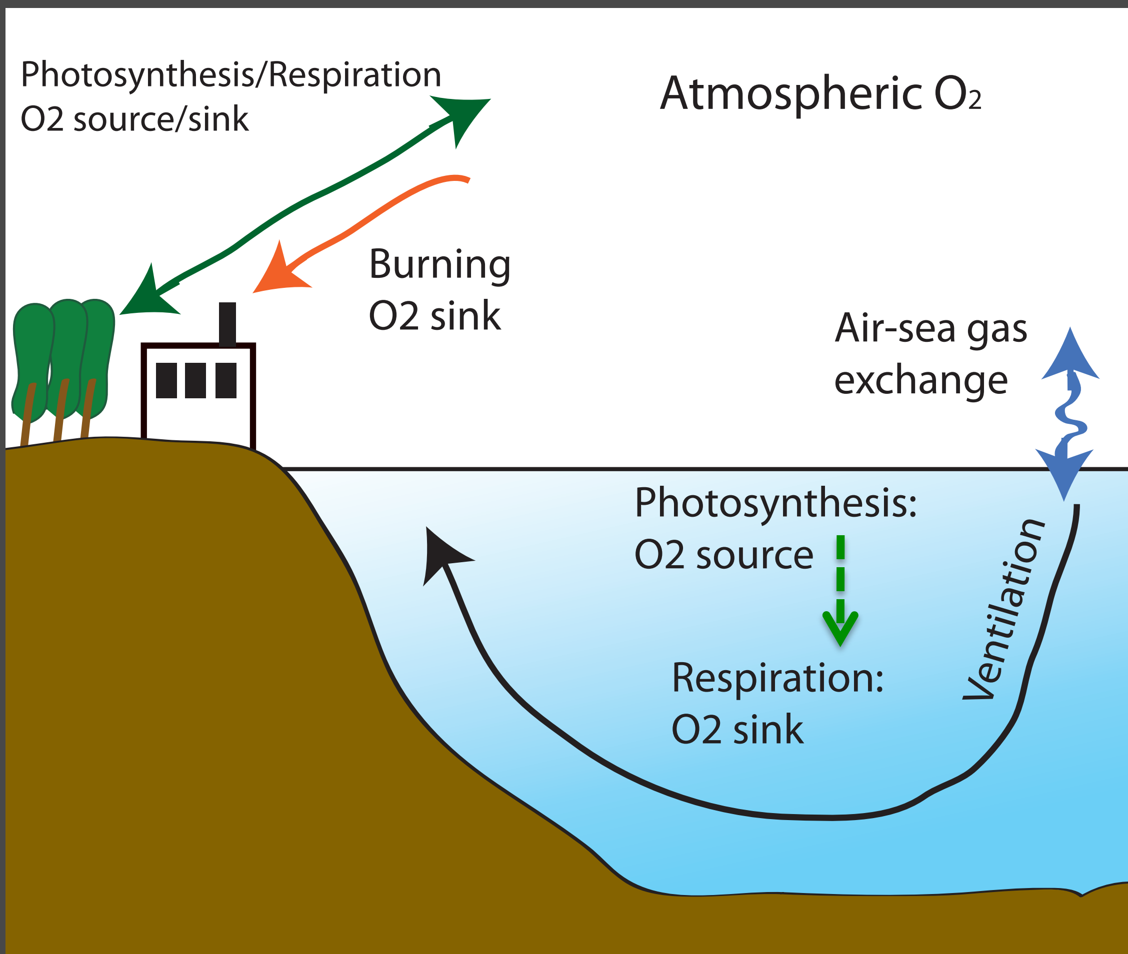
Taka Ito
Colorado State University

In collaboration with
Curtis Deutsch (UCLA)

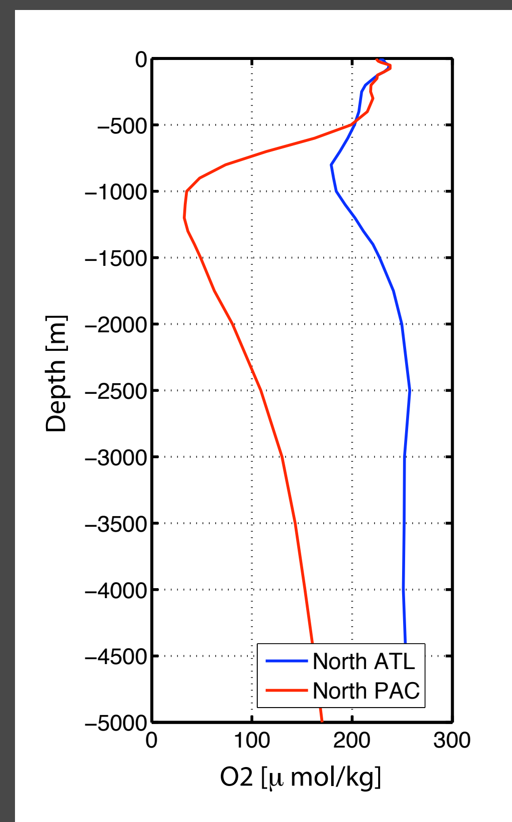
Outline

- Background and motivation
  - Oxygen cycle, biogeochemistry and climate
  - Recent observations
- Understanding observed variability
  - A hierarchy of models
  - Detection: mode of variability
  - Attribution: mechanism
- Questions for future research

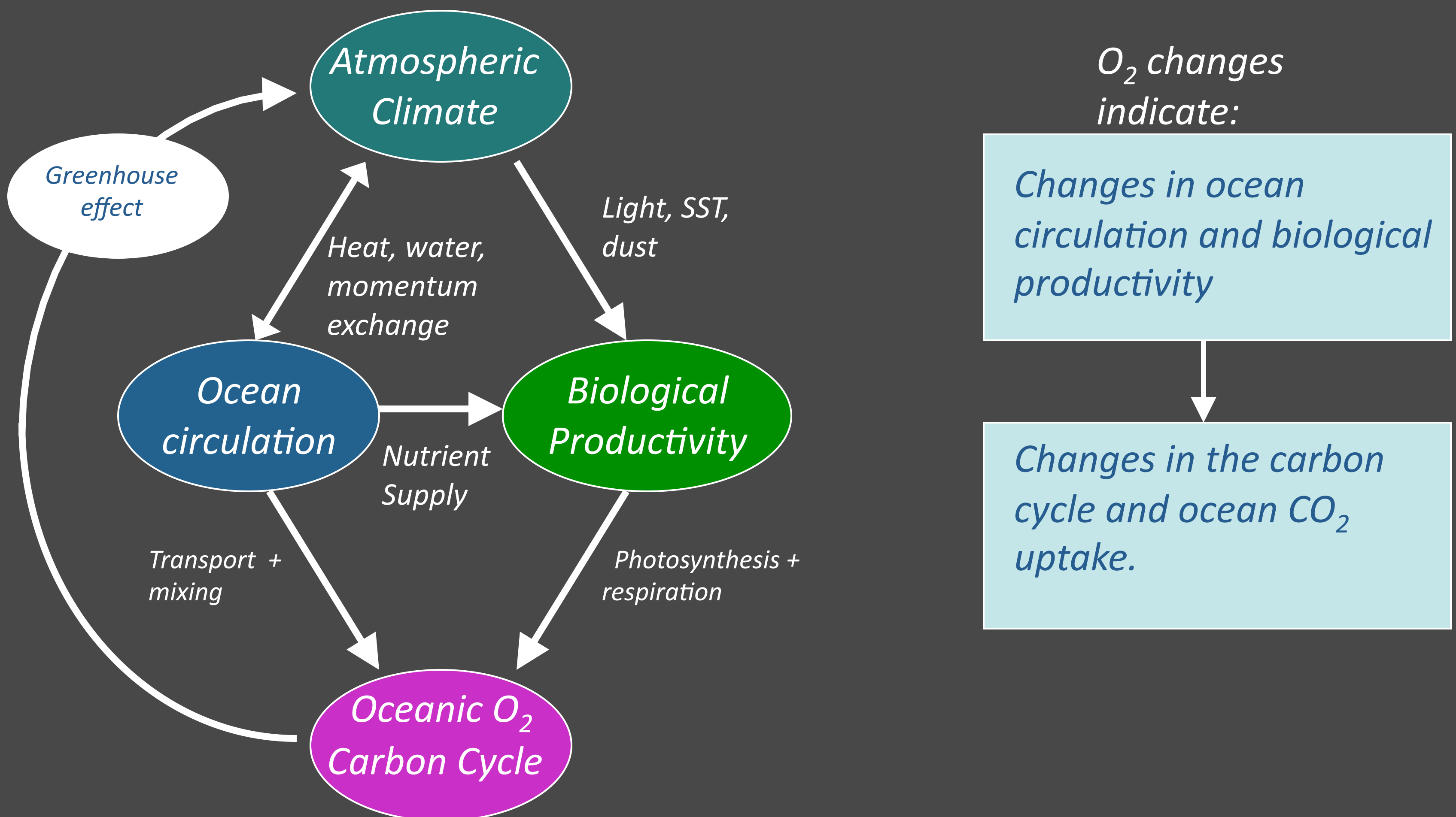
Global oxygen cycle



Vertical profile of observed O2

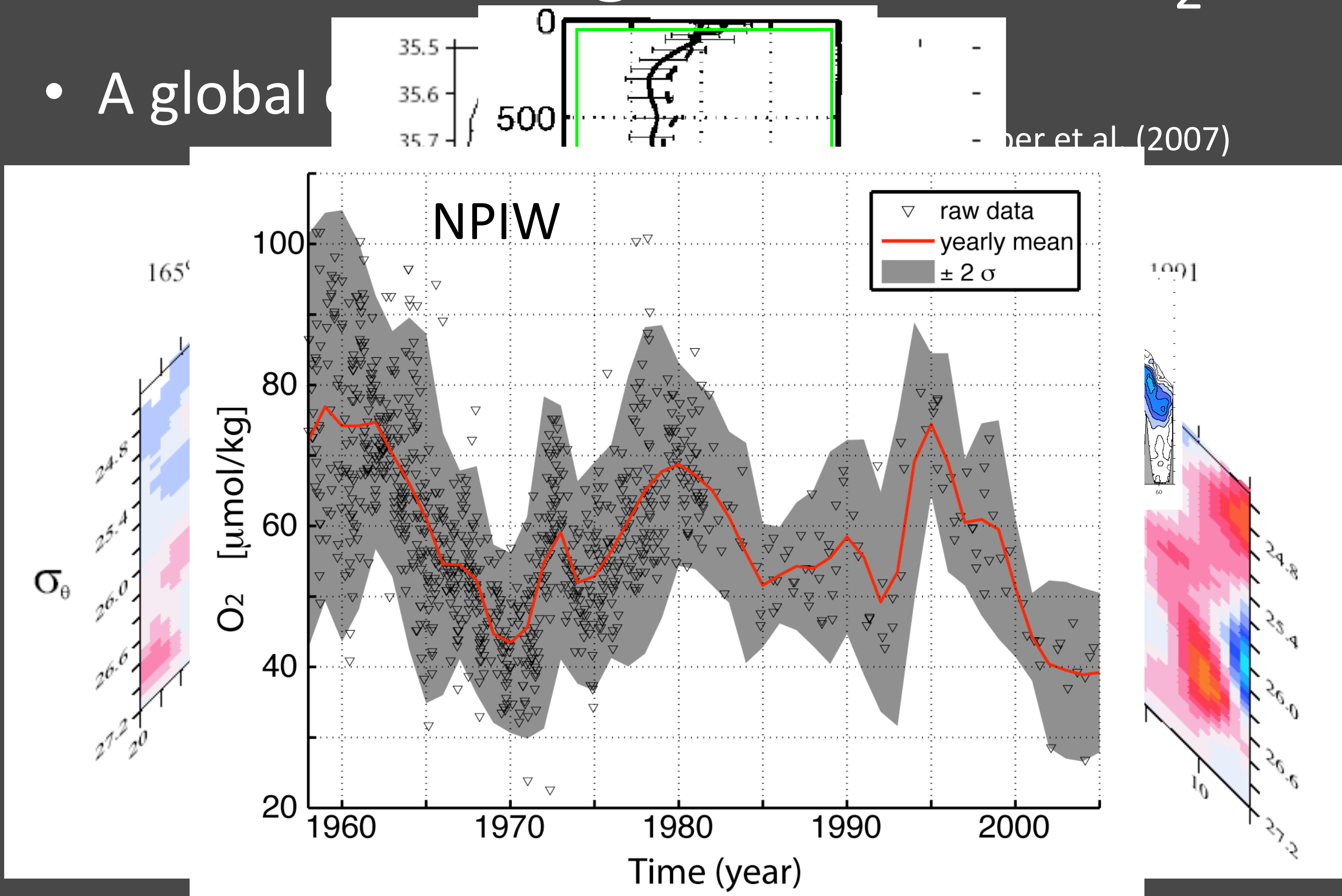


Oxygen, ocean biogeochemistry and climate

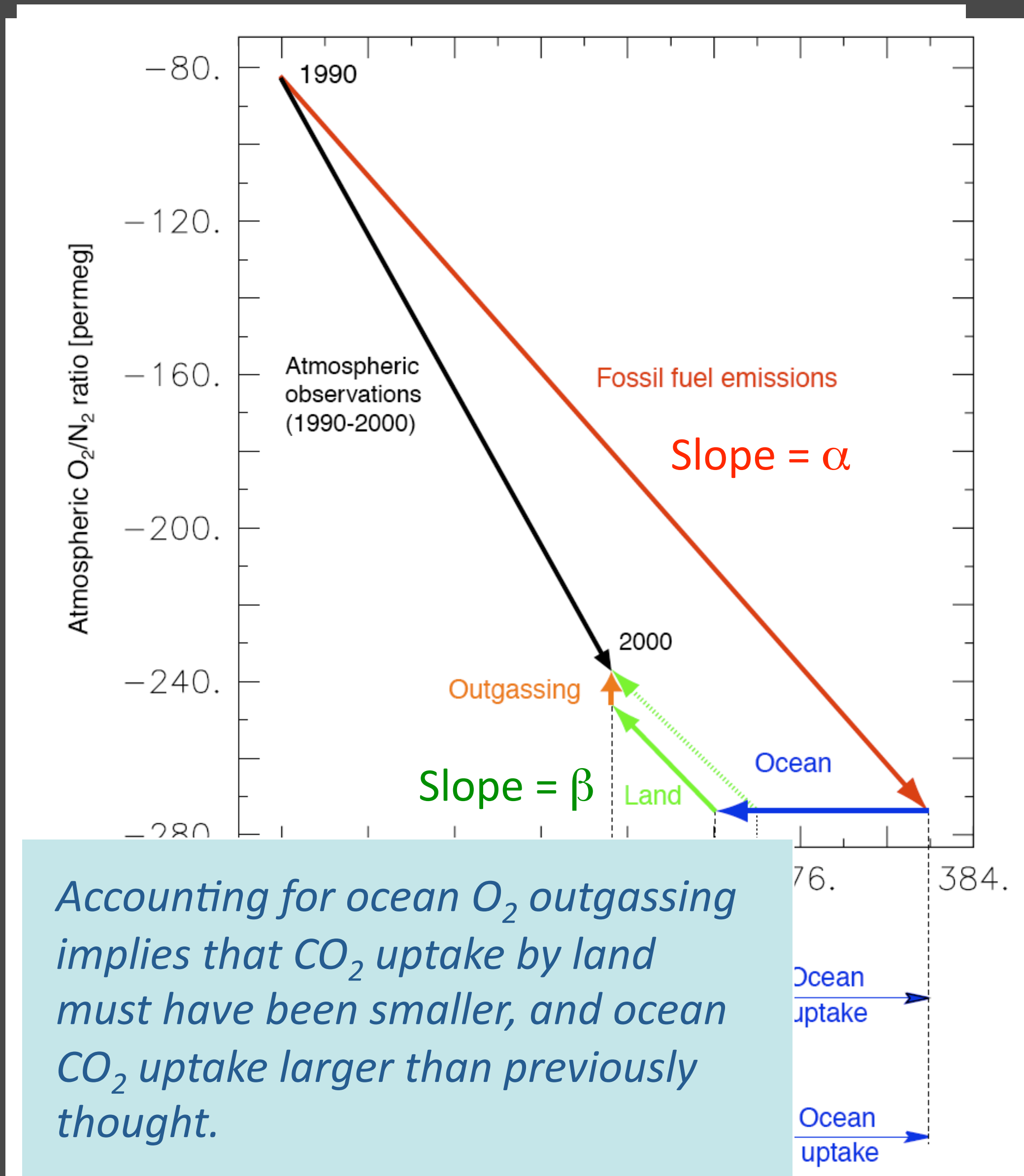


Global changes in oceanic O_2

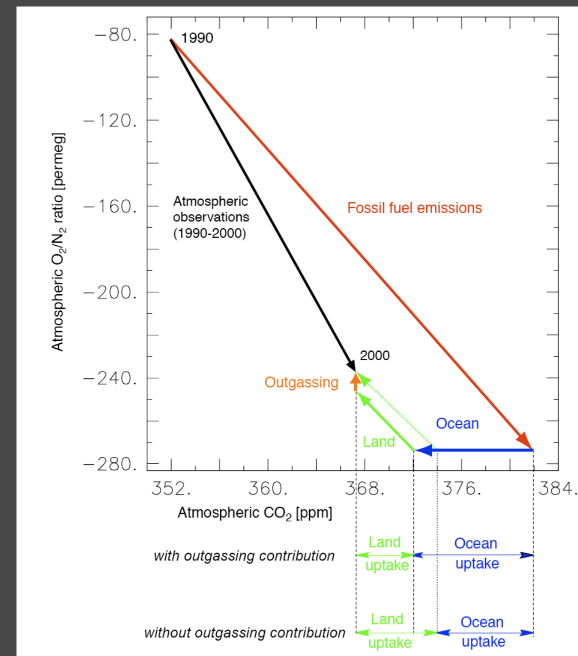
- A global ... ber et al. (2007)



Land vs ocean CO_2 uptake



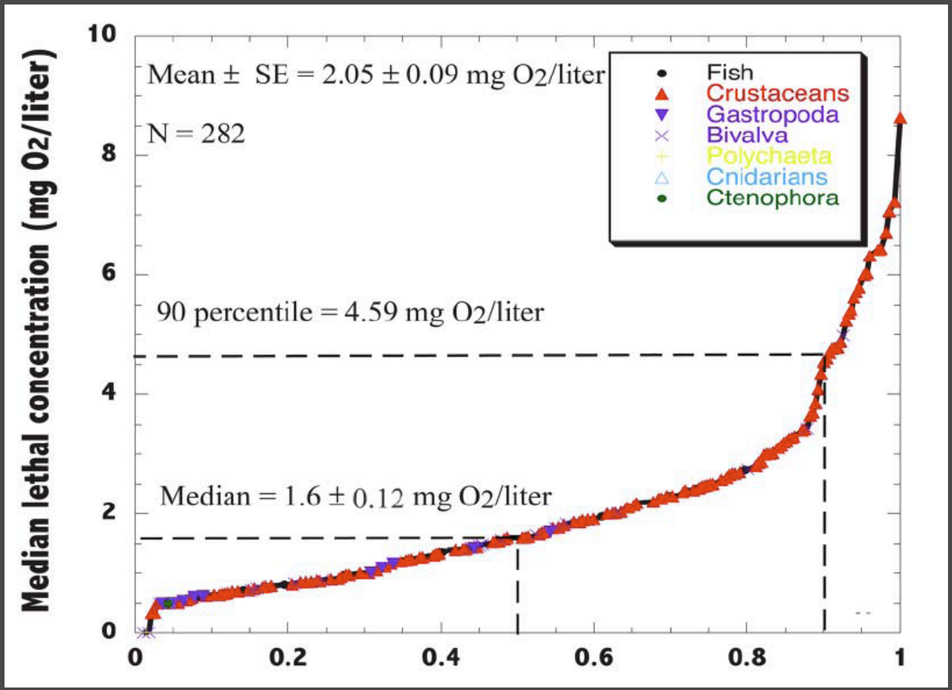
Accounting for ocean O_2 outgassing implies that CO_2 uptake by land must have been smaller, and ocean CO_2 uptake larger than previously thought.



$= \text{Burning} - \text{Land} - \text{Ocean}$

$= -\alpha\text{Burning} + \beta\text{Land} + \text{Ocean outgassing}$

Oxygen and marine ecosystems



Vacquer-Sunyer and Duarte [2008]

Image from an ROV off the Oregon coast

Low O_2 can reduce the respiratory capacity of marine heterotrophs, leading to reduced physiological performance or death.

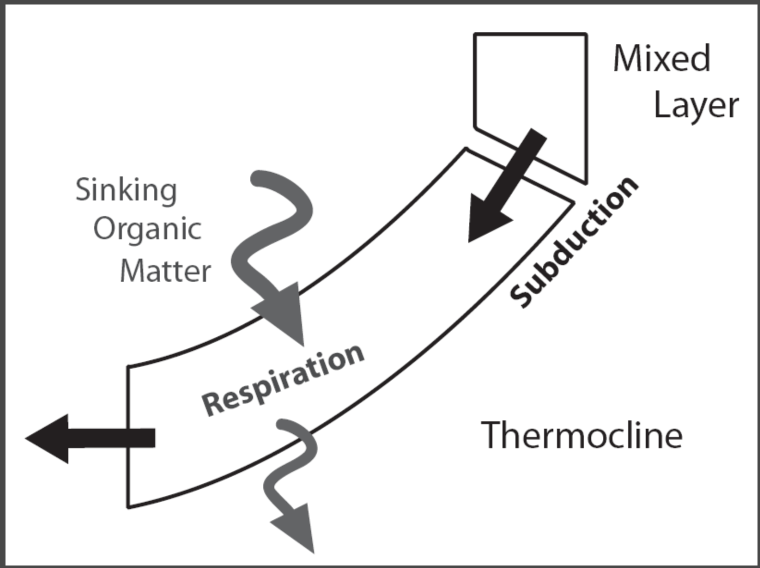
Understanding observed variability

- Outstanding questions
  - What controls the observed O_2 changes?
  - Why O_2 shows strong decadal variability?
  - Why O_2 variability is strongest at the base of thermocline?
- A hierarchy of models for oceanic O_2
  - Simple box model
  - Ocean circulation and biogeochemistry model
  - Interpreting observations

A simple model for thermocline O_2

- SST and gas exchange ($O_{2,sfc}$)
- Ventilation of thermocline (λ)
- O_2 loss by respiration (OUR)

$$\frac{d[O_2]}{dt} = -\lambda\left([O_2] - [O_{2,sfc}]\right) - OUR$$



Steady solution

$$\overline{[O_2]} = \overline{[O_{2,sfc}]} - \frac{\overline{OUR}}{\overline{\lambda}}$$

Long-term O_2 decline can be due to:

- Warmer SST
- Weaker ventilation
- Stronger biological O_2 consumption(?)

Variability of thermocline O_2

- Linearized perturbation equation
  - Three causes of O_2 variability
    - Outcrop variability (SST, gas exchange)
    - Circulation variability (λ’)
    - Biological variability (OUR’)

Three forcing terms :

Outcrop variability

Circulation variability

Biological variability

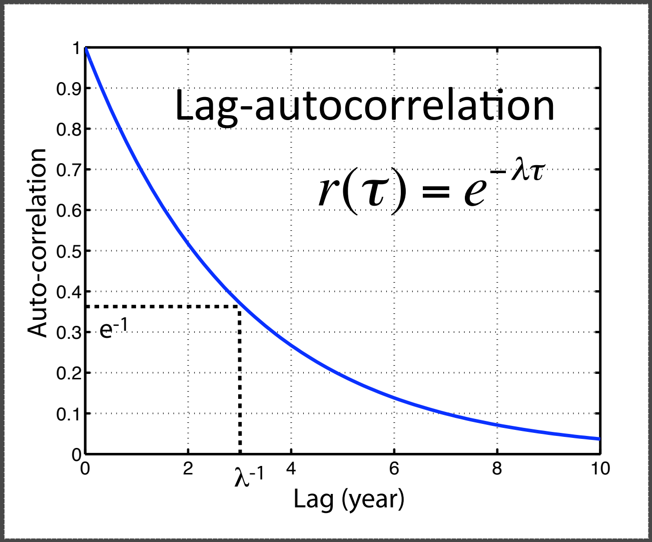
$$\left(\frac{d}{dt} + \bar{\lambda}\right)[O_2]' = \bar{\lambda}[O_{2,sfc}]' + \lambda'\overline{\Delta[O_2]} - OUR'$$

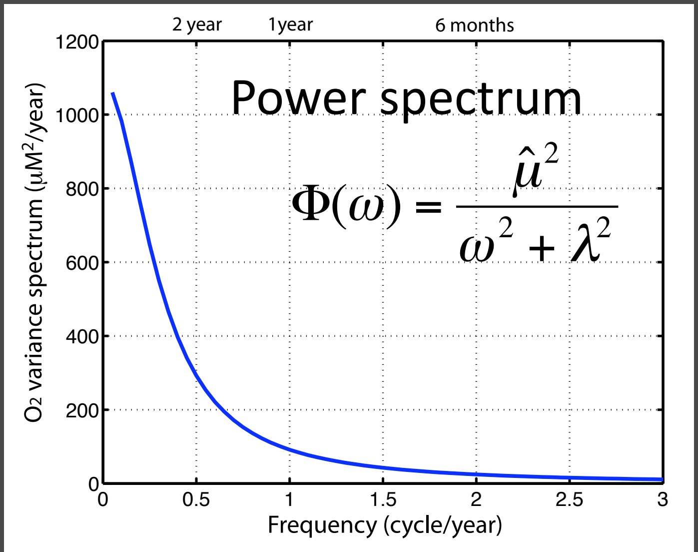
And is damped by the mean ventilation!

Stochastically forced O_2 variability

- What is the response of O_2 to random forcing?
  - $\eta(t)$: white noise
  - Hasselmann (1976) model

$$\left(\frac{d}{dt}+\bar{\lambda}\right)[O_2]'=\eta(t)$$



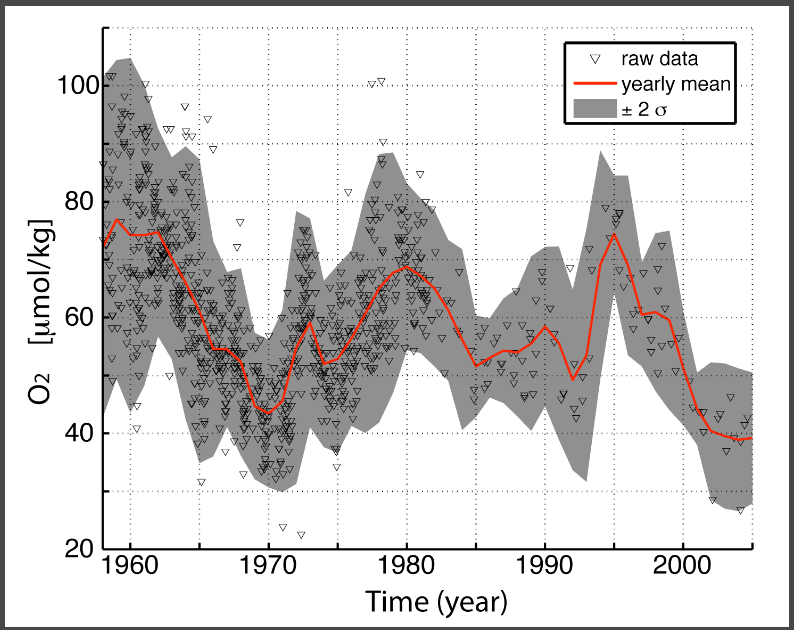


  - Random forcing can result in low-frequency variability due to mean ventilation

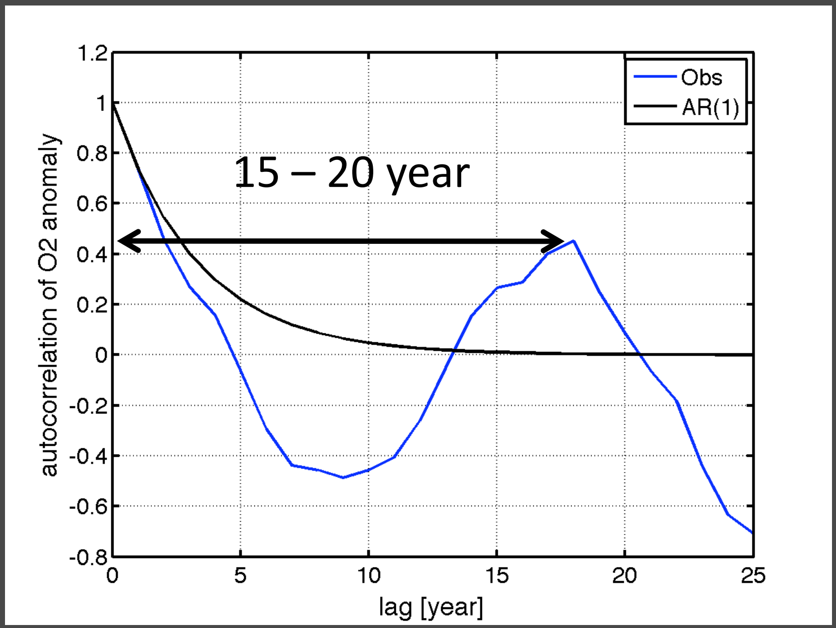
Application to observed O_2 data

- Subpolar North Pacific time-series data
  - Ocean Station Papa (50N,145W)
    - Long-term trend explains 15% of variance
    - Decadal variability (15-20 year timescale)

NPIW : σ_θ = 27.0



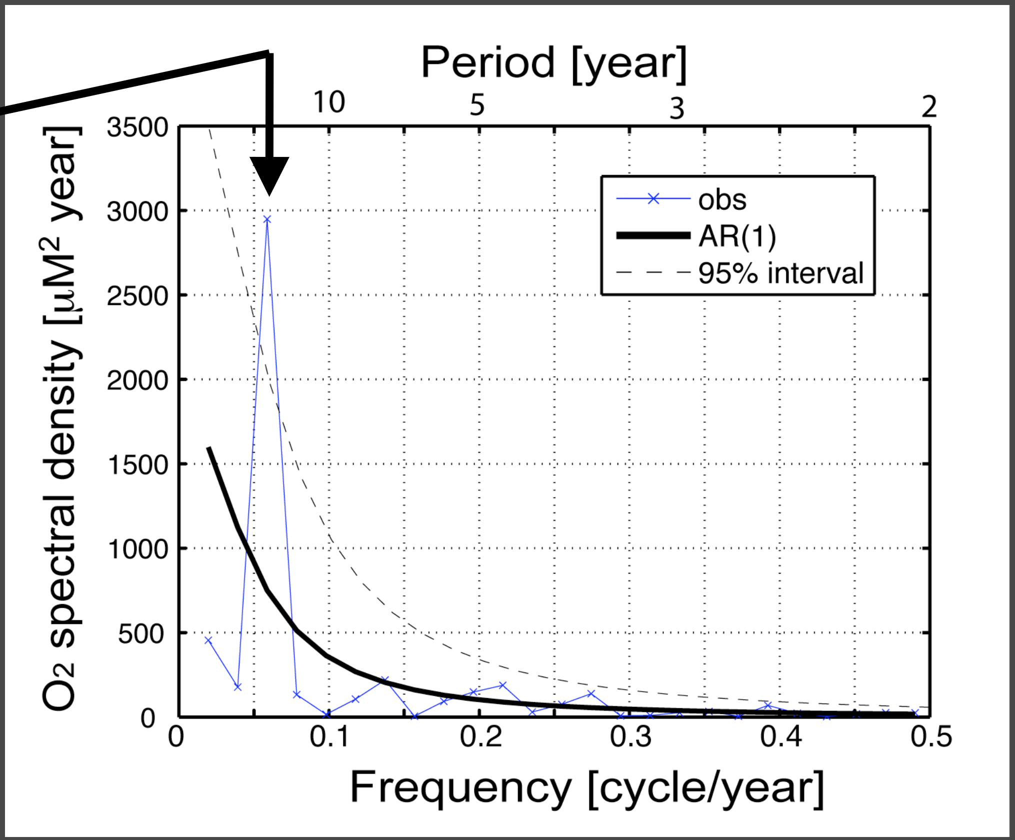
Lag-autocorrelation (de-trended)



Detecting modes of O_2 variability

- Is the signal beyond the noise?
  – Can we reject the stochastic null hypothesis?

About 60% of variance is in 15-20 year timescale



Caveats:
•Slightly above 95% confidence interval
•Length of time series
•Lack of clear mechanism

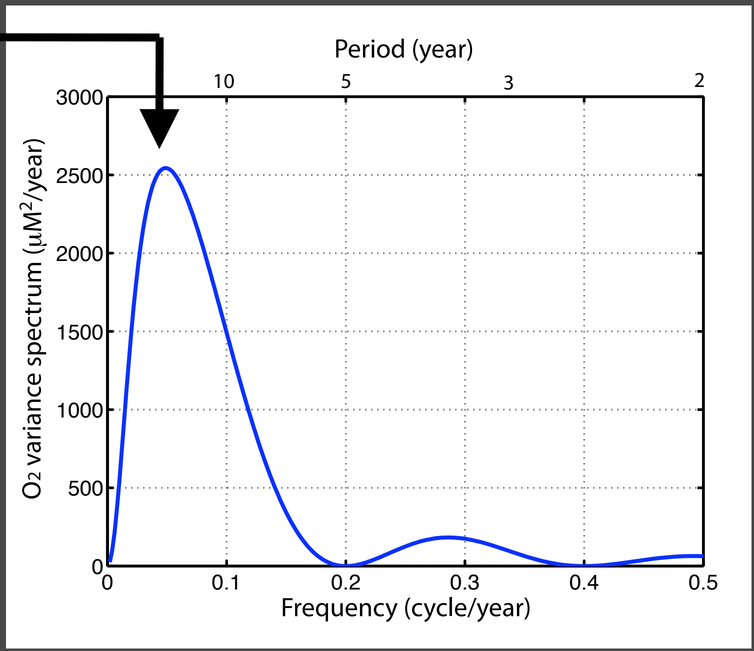
Physical-biological coupling

- Coupling circulation and biology with time lag
  - Nutrient supply depends on circulation

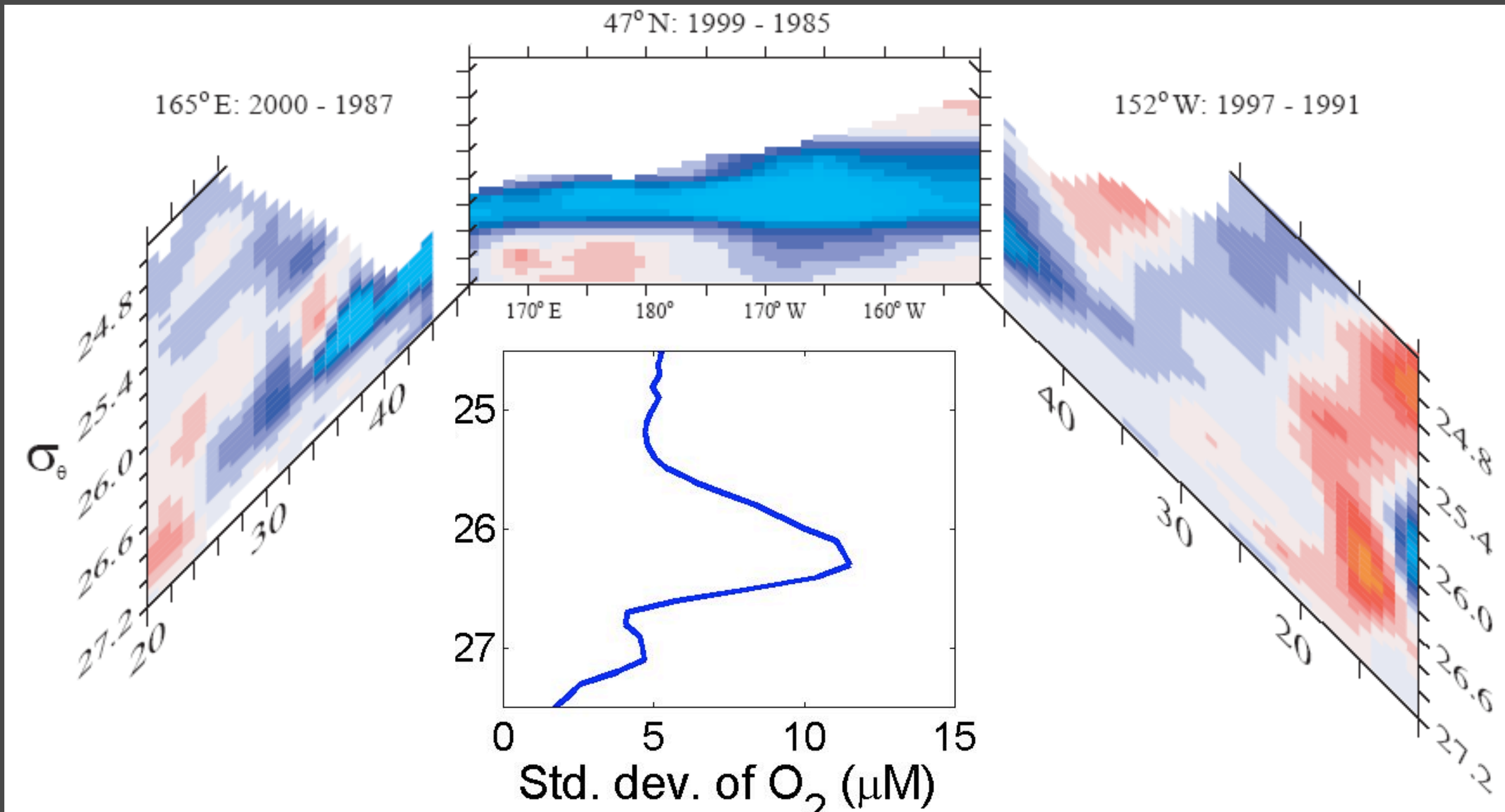
$$\left(\frac{d}{dt}+\lambda\right)[O_2]' = \lambda'(t)\overline{\Delta[O_2]} - OUR'(\lambda'(t+\tau))$$

Increased power at decadal timescale emerges from the delayed response of biology.

τ ~ 5 year leads to a paek at 20 year timescale



Vertical structure of O_2 variability

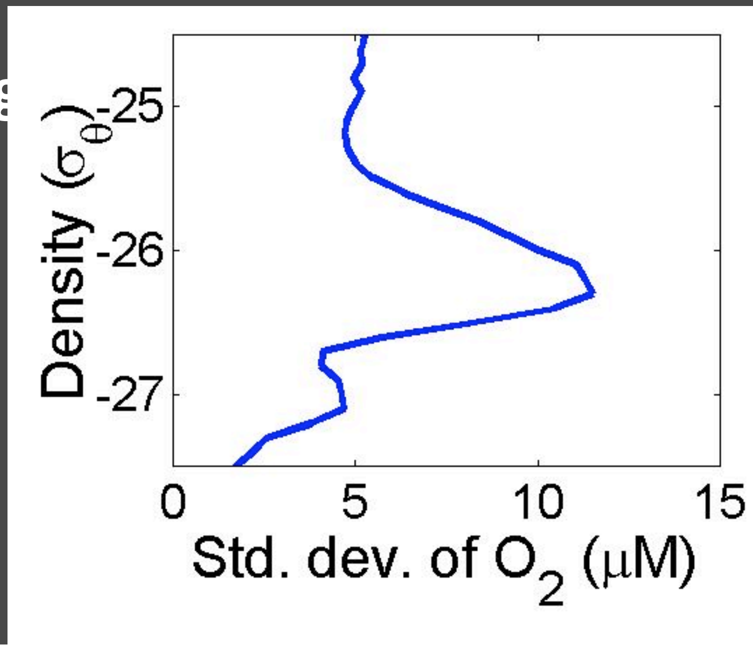


(HOT time series data)

Observations show relatively strong variability in lower thermocline

Explaining vertical structure

Existing



2) Compensation

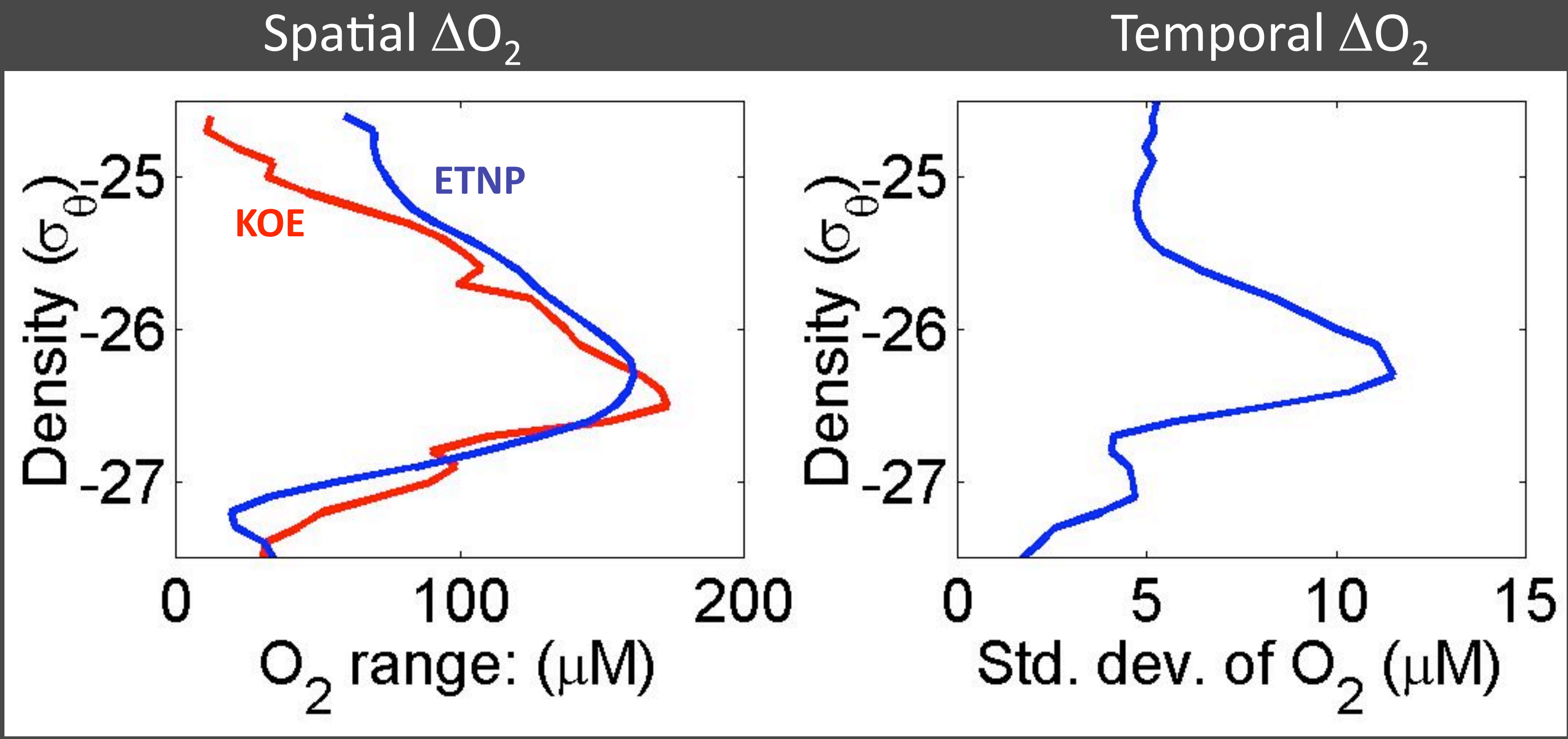
Changes in λ and OUR closely balanced in upper thermocline

Deutsch et al. [2006]

$$\left(\frac{d}{dt}+\bar{\lambda}\right)[O_2]' = \bar{\lambda}[O_{2,sfc}]' + \lambda'\overline{\Delta[O_2]} - OUR'$$

3) Circulation variability acting on spatially varying O_2 gradient

Spatial variation of the isopycnal O_2 gradient



Background O_2 gradient has somewhat similar structure to temporal O_2 variability.

Testing the hypothesis using ocean GCM and biogeochemistry model

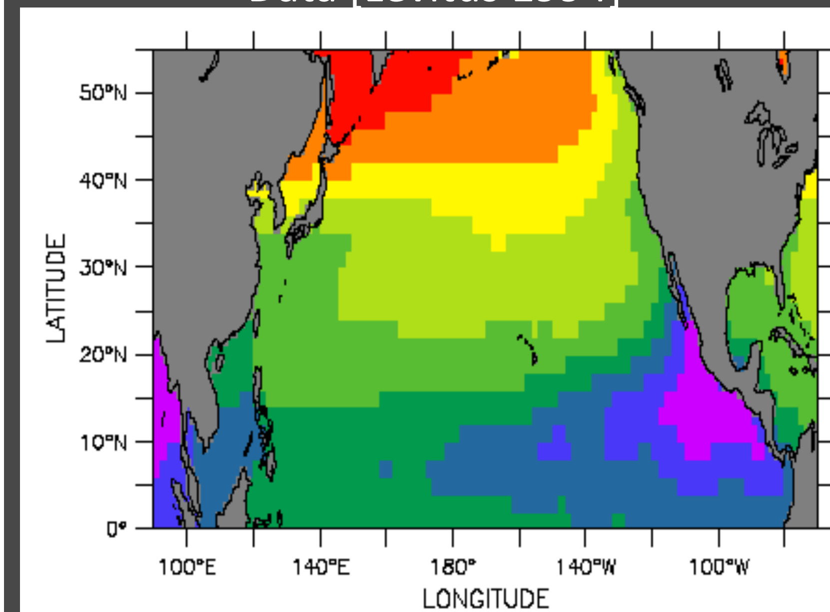
Curtis Deutsch

- Isopycnal coordinate (Hallberg Isopycnal Model)
- North Pacific domain (20^{o}S – 60^{o}N)
- 1 degree horizontal resolution, 14 isopycnal layers
- Hindcast simulation using NCEP forcing (1948-2000)
- Simple ocean biogeochemistry scheme (OCMIP)
  - Circulation variability
  - Biological variability
  - Variability in surface processes (heat, wind, gas ex)

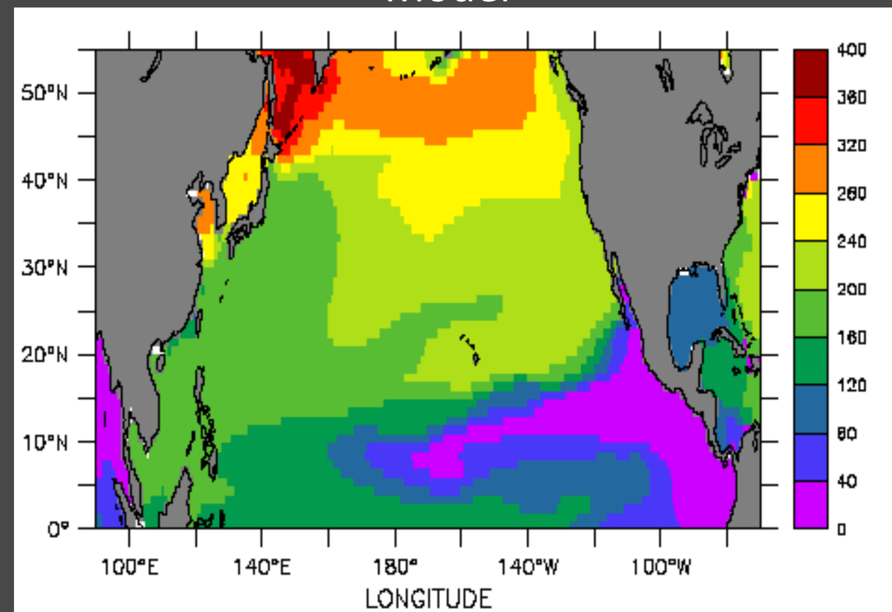
Simulated annual mean O_2

(σ_ϑ 25.8)

Data [Levitus 1994]



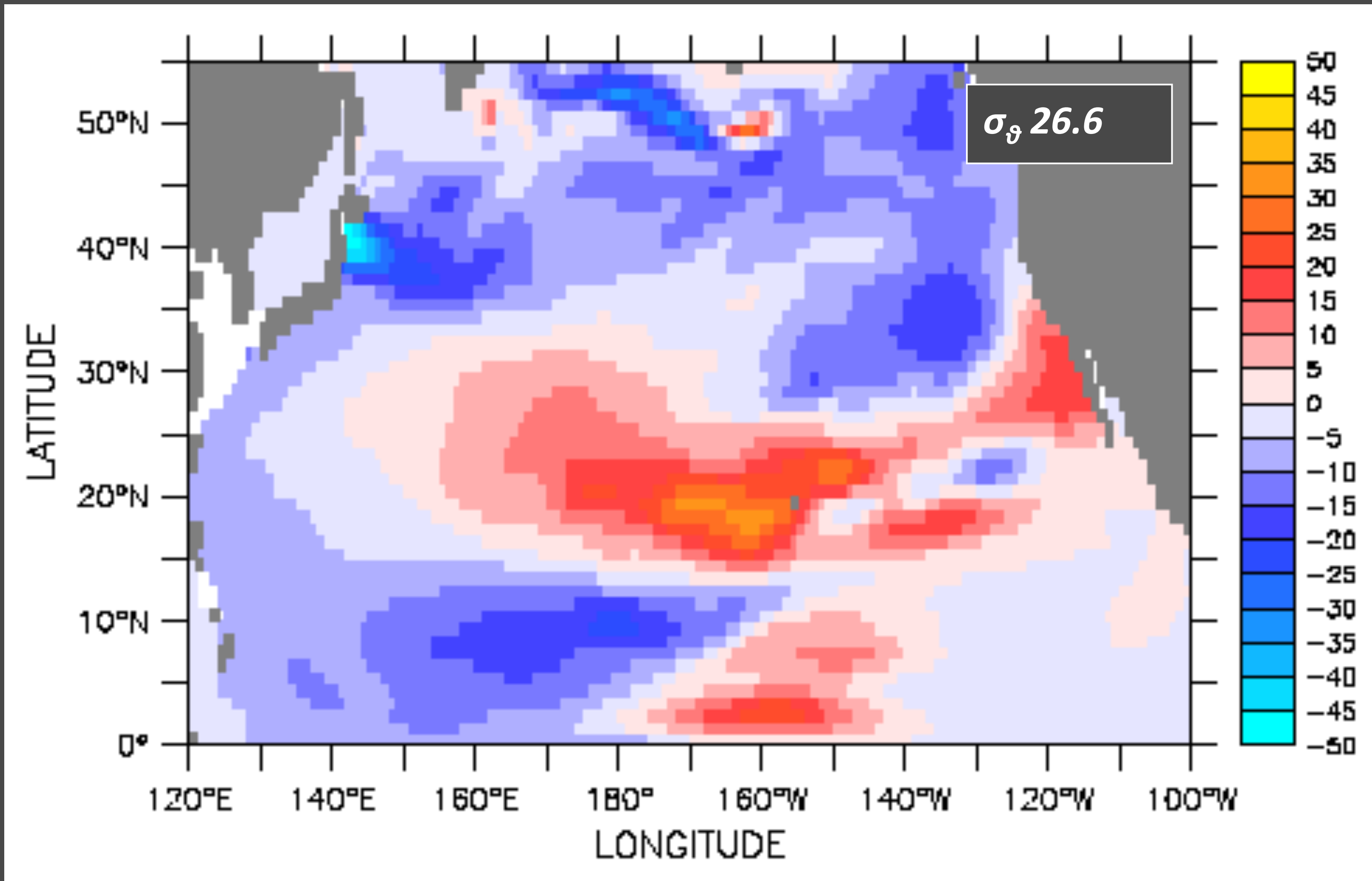
Model



- The model captures the overall magnitudes and the large-scale gradients

Decadal mean O_2 changes

1990's – 1980's



Attribution experiments

• Design sensitivity experiments by turning off each mechanism

• Control run

- Circulation, surface and biological variability

• Constant surface O_2 run

- Circulation and biological variability

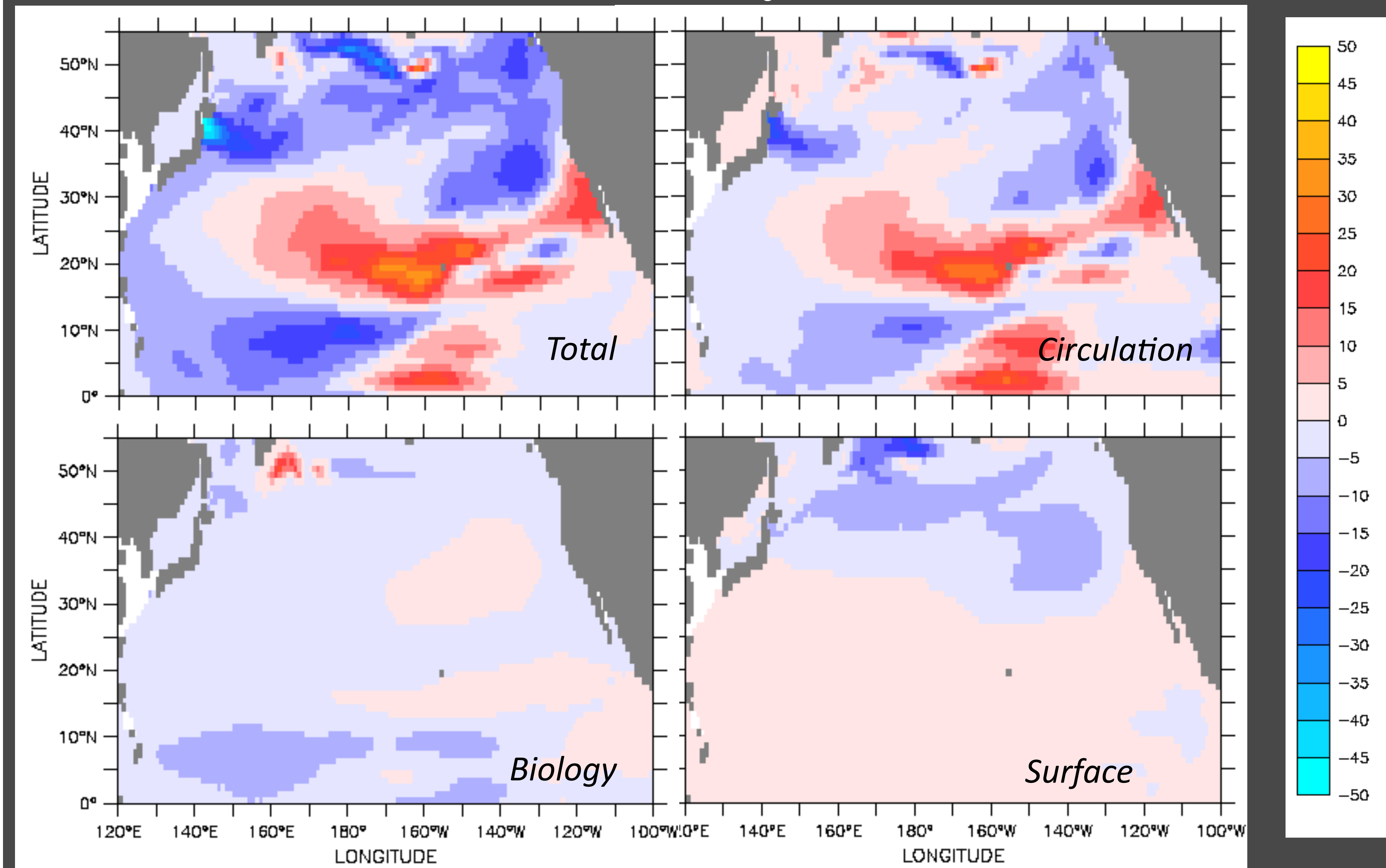
• Constant surface and biology run

- Circulation variability

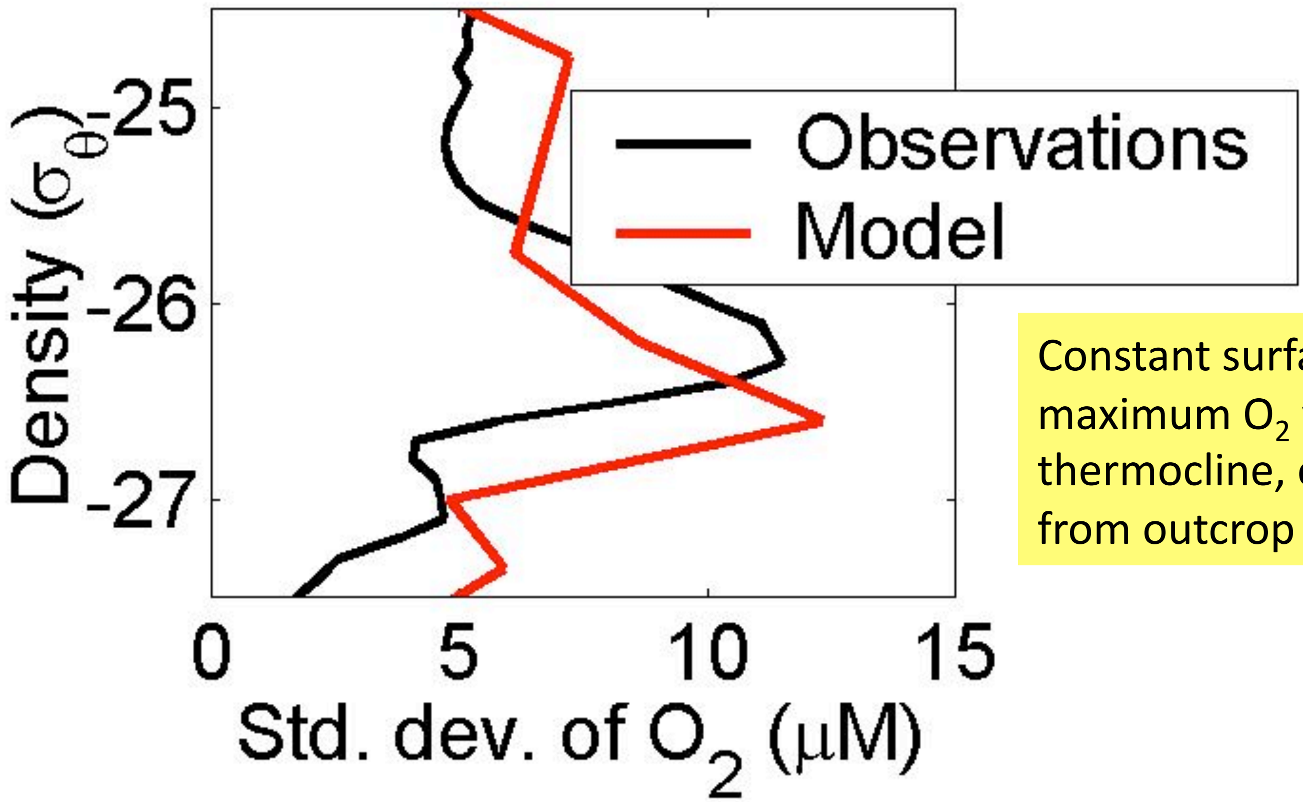
$$\left(\frac{d}{dt} + \overline{\lambda}\right)[O_2]' = \qquad \lambda' \overline{\Delta[O_2]} \cdot$$

Biological/Physical Contributions

1990's-1980's, σ_θ 26.6



Testing the hypothesis



Constant surface and biology run has maximum O_2 variability in lower thermocline, even without changes from outcrop or OUR.

$$\left(\frac{d}{dt} + \overline{\lambda}\right)[O_2'] = \overline{\lambda}[O_{2,sfc}]' + \lambda'\overline{\Delta[O_2]} - OUR'$$

Summary and more questions

- What can O_2 tell us about the climate change in the oceans?
  - O_2 as a tracer of physical and biological changes
  - Sensitivity to ocean circulation and biology
- How do we know that it's changing?
  - Testing the null hypothesis
  - 15-20 year timescale in NPIW
- What causes observed O_2 variability?
  - Attribution experiments using ocean models
  - Circulation dominates in the North Pacific?