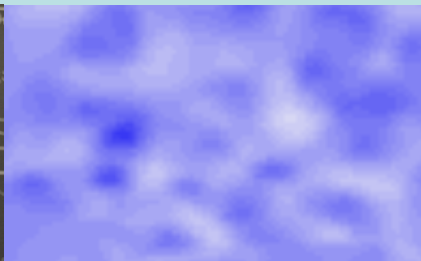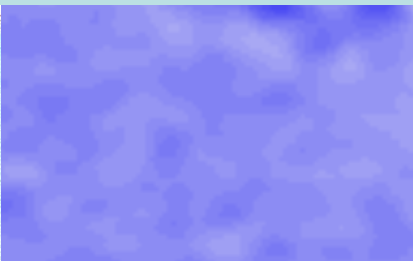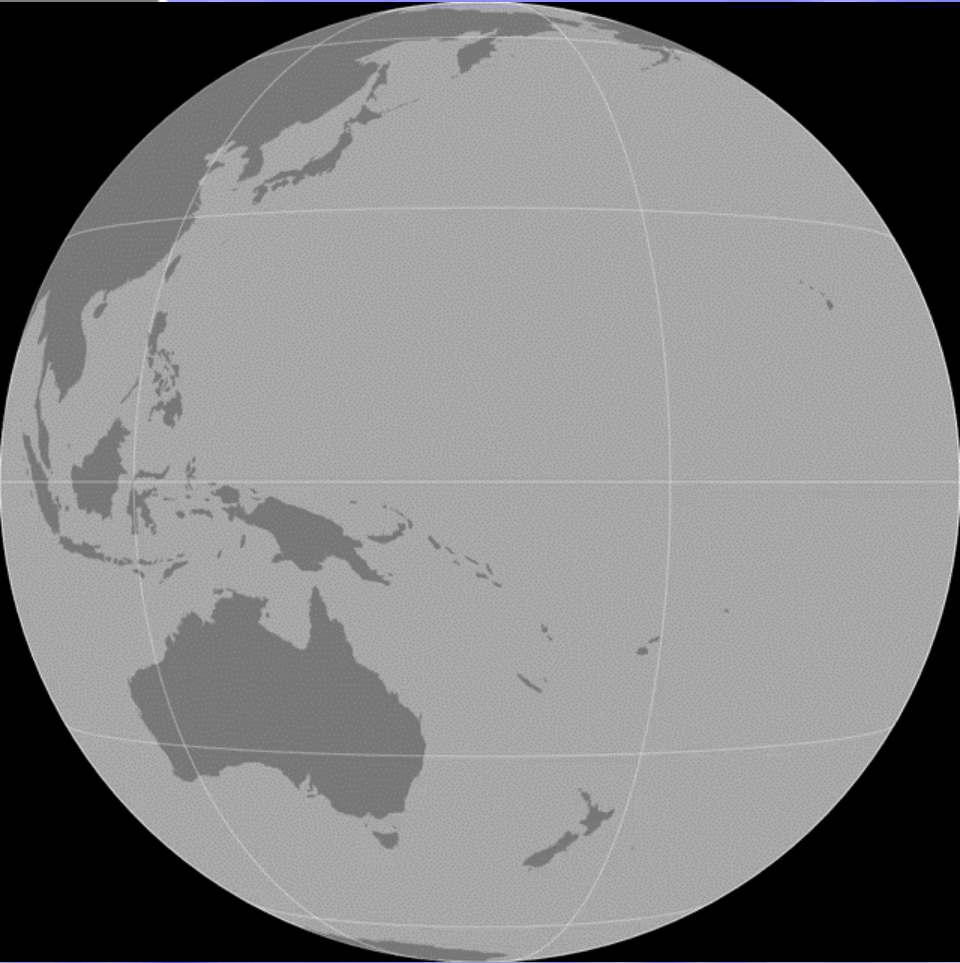# Impact of parameterized lateral mixing on global biogeochemical cycling in Earth System Models

Anand Gnanadesikan, Marie-Aude Pradal, Alexis Bahl (JHU), Ryan Abernathey (LDEO),
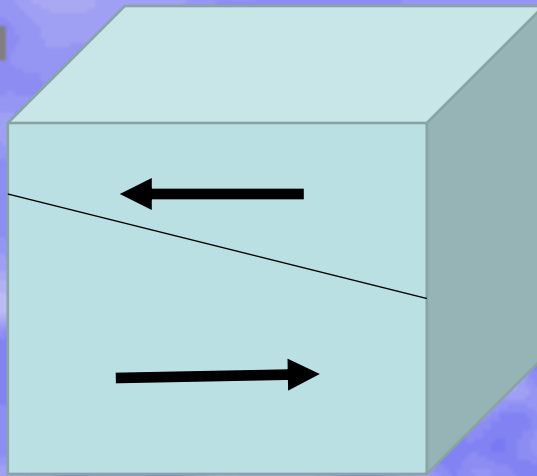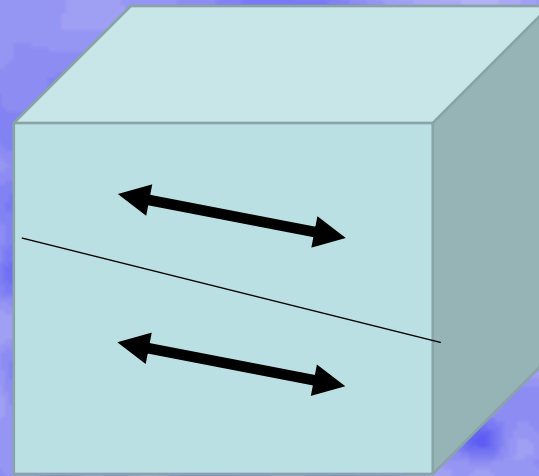
Basic problem

- Ocean is full of turbulent eddies.
- What do they do?

Credit: Ryan Abernathey

Answer

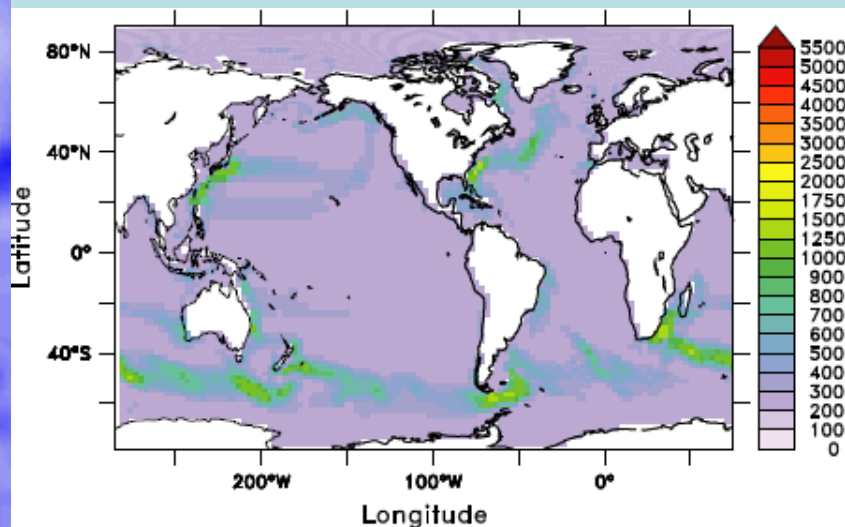Advection- flattens isopycnals, removes energy

Diffusion-stirs along isopycnal surfaces.

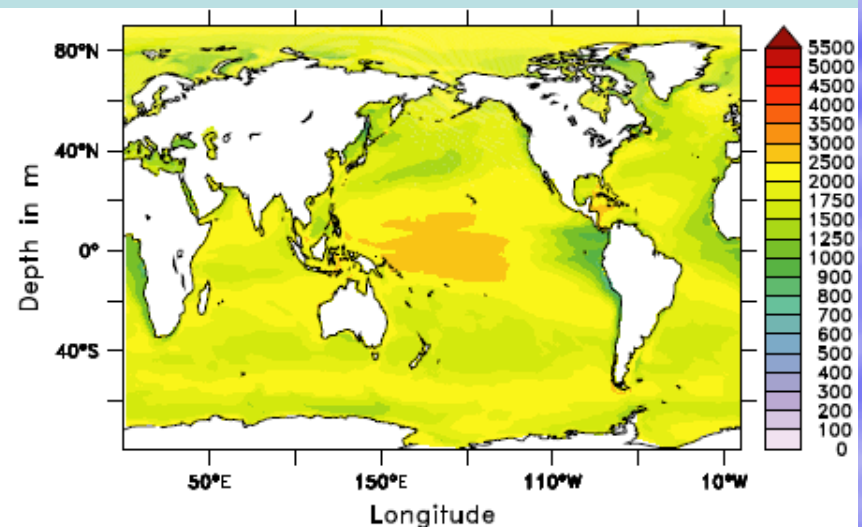$$\langle uhC \rangle = -A_{GM} \frac{\partial h}{\partial x} \langle C \rangle$$

$$\langle uhC \rangle = -\langle h \rangle A_{Redi} \frac{\partial \langle C \rangle}{\partial x}$$

Different models use different representations of A_{Redi}

- Spatially constant (HadGEM 500, GFDL ESM2M, 600, CMCC, 2000)

- Depends on grid spacing (MPI, <400)

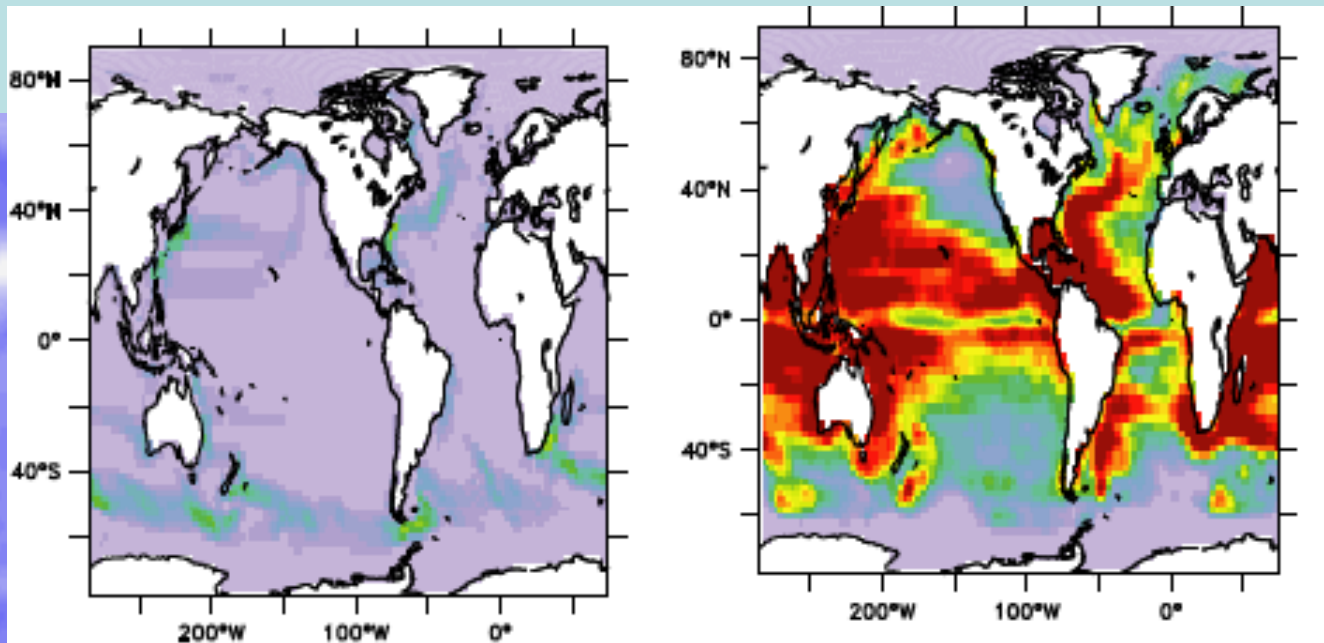- Equal to A_{GM}, highest in boundary currents (GFDL ESM2G, <900, CESM 200-3500)

(A) A_{GM}, GFDL CM2Mc

(B) $(A_{GM}=A_{Redi})$, NCAR CESM

The isopycnal mixing paradox

- Theory suggests **low** values in gyre interiors/tropics where slopes are low.

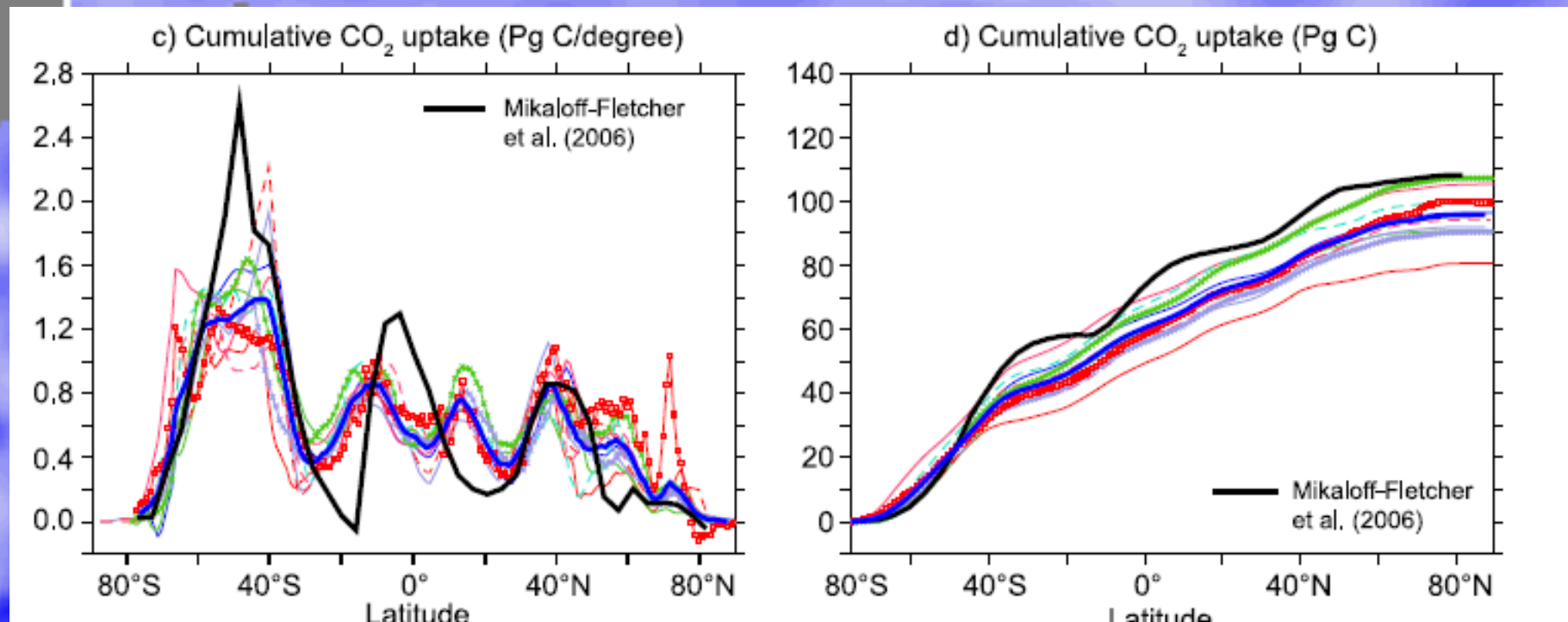- Direct observations suggest **high** values in gyre interiors/tropics.

What we did

- Take a single climate model

- Run it with different representations of mixing coefficient

  – Constants: 400, 800, 1200,2400

  – Spatially varying: Abernathey and Marshall, 2013 (ABER2D), Zonally averaged version of this (ABERZONAL).
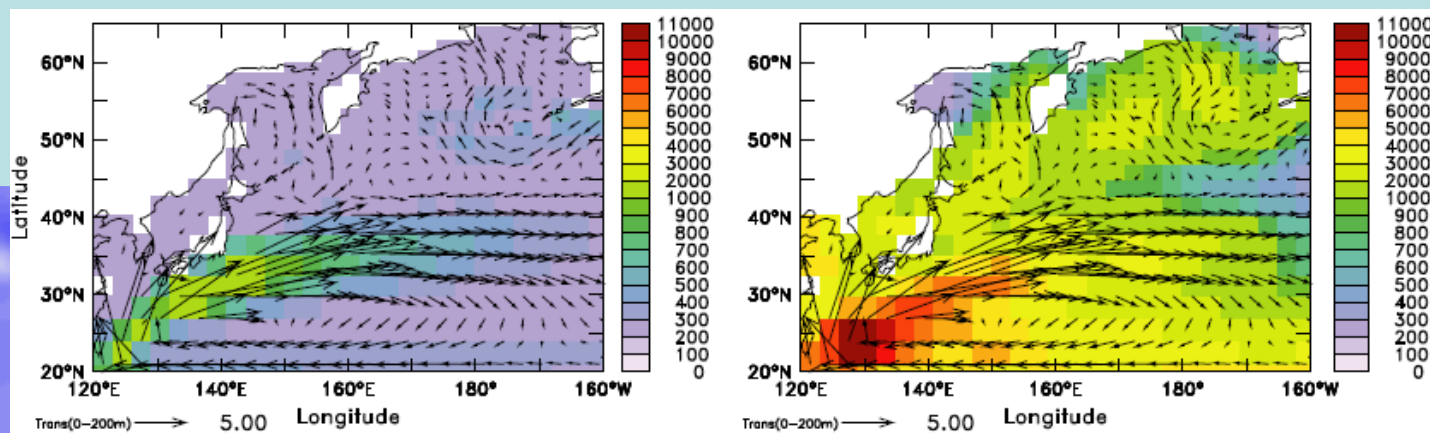
Part 1: Anthropogenic carbon dioxide

Gnanadesikan, Pradal and Abernathey, Geophysical Res. Lett, 2015

What we are trying to explain

c) Cumulative CO_2 uptake (Pg C/degree) — Mikaloff-Fletcher et al. (2006)

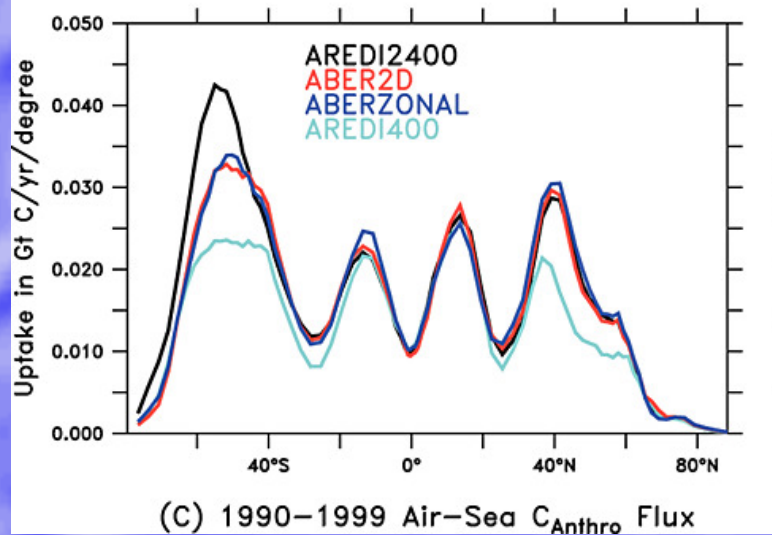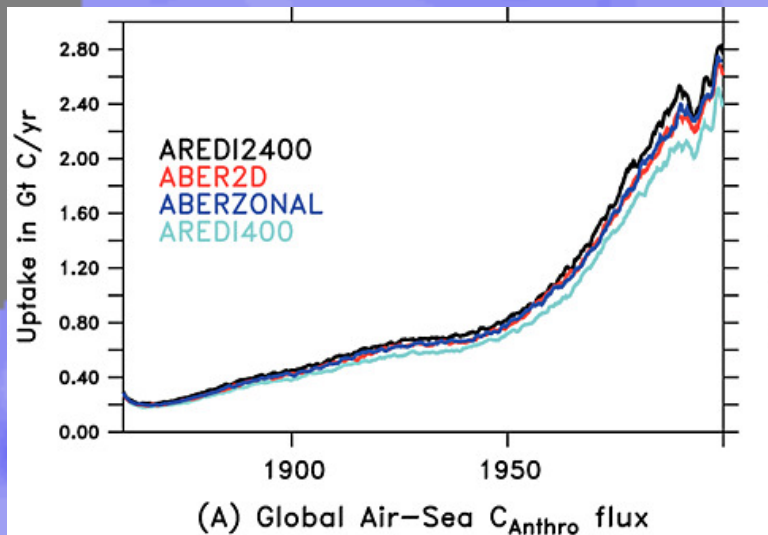d) Cumulative CO_2 uptake (Pg C) — Mikaloff–Fletcher et al. (2006)

CMIP5 models show range of about 30% in carbon uptake (80-110 Gt at 1995).

Much of the uncertainty comes from the Southern Ocean.

Frohlicher et al., J. Clim. 2015

Historical carbon uptake

(A) Global Air–Sea C_{Anthro} flux

(C) 1990–1999 Air–Sea C_{Anthro} Flux

- Total range at 1990 ~16%
- Low lateral mixing has the lowest value (2.2 Gt C/yr, 104 Gt total)
- High lateral mixing has the highest uptake (2.6 Gt C/yr, 122 Gt toal)
- Satellite-based mixing lie in between.
- Southern Ocean range accounts for 2/3 of total.

Comparing with Integrated Assessment Models

$$\frac{\partial C}{\partial t} = K_v \frac{\partial^2 C}{\partial z^2}$$
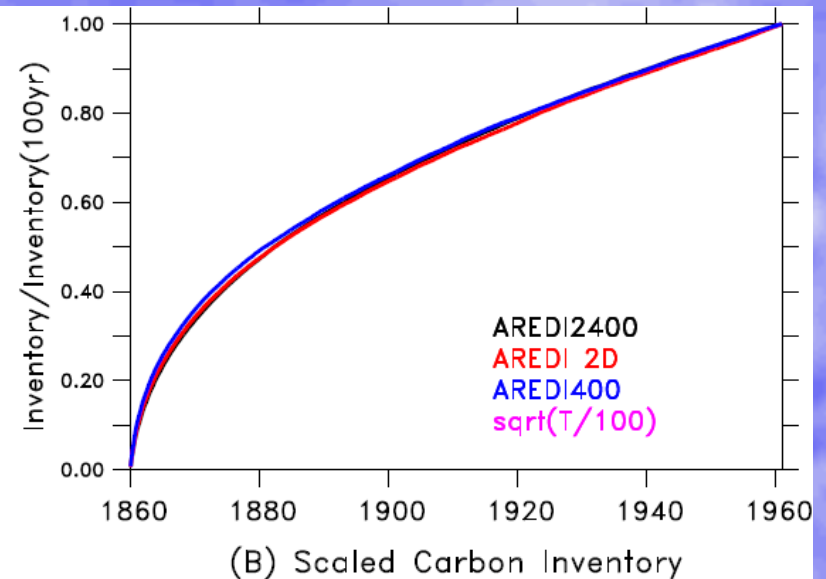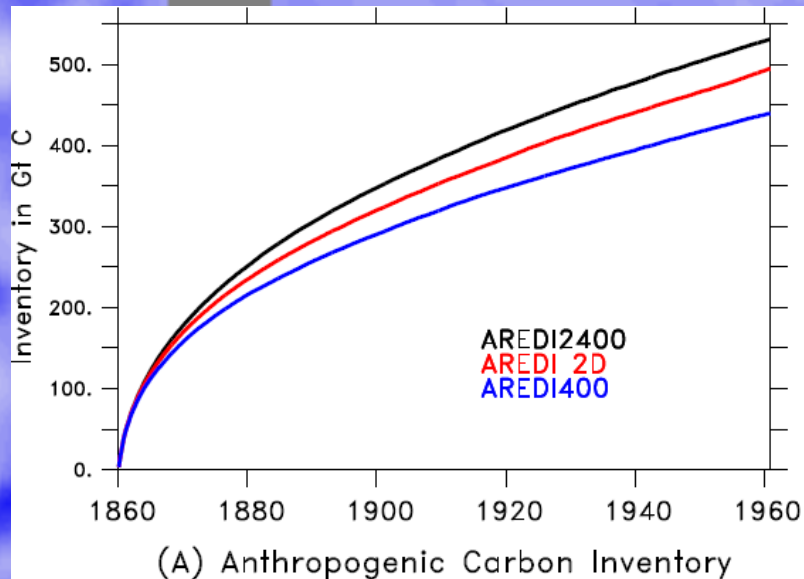
$$C = 0 \quad t < 0$$

$$C = C_1 \quad t > 0$$

- Integrated assessment models traditionally used a diffusive parameterization.
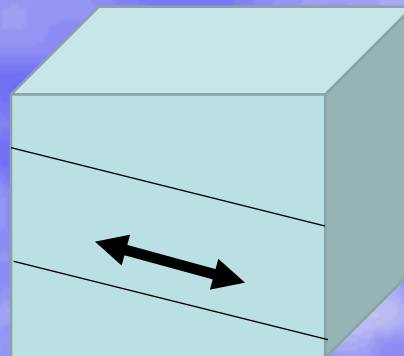- Solution of this equation

$$Burden = C_1 \sqrt{K_v t}$$

If we double CO2 overnight…

(A) Anthropogenic Carbon Inventory

(B) Scaled Carbon Inventory

Uptake looks like diffusion.

Effective diffusion

- AREDI400: 2.23 cm^2/s
- AREDI800: 2.48 cm^2/s
- AREDI1200: 2.81 cm^2/s
- AREDI2400: 3.26 cm^2/s

$$K_v^{eff} = K_{v0} + A_{tracer}S^2$$

Contribution from tracer diffusion consistent with about 4% of ocean being covered with slopes of order 1/1000, along-isopycnal diffusion accounting for up to 1/3 of vertical transport.

Qualitatively validates Integrated Assessment Model approach.

Illustrates importance for E3SM

Lessons

- Differences in lateral mixing coefficient can produce differences in CO_2 uptake similar in magnitude to what is seen across ESMs.

- Differences can be understood in terms of effective vertical diffusion, with relatively small portion of ocean involved.

Part 2: Oxygen
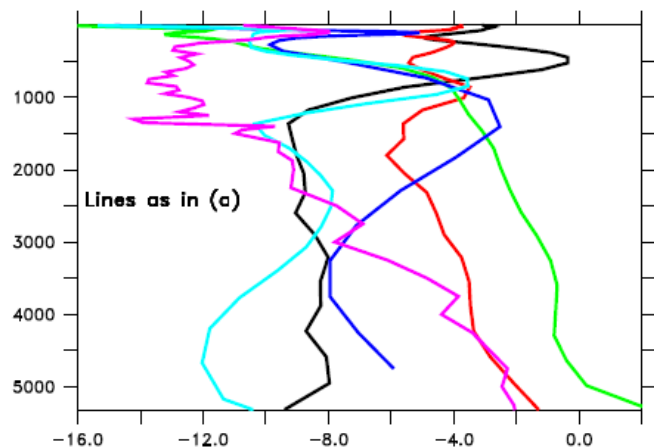
Bahl, Gnanadesikan and Pradal, in rev. for GBC
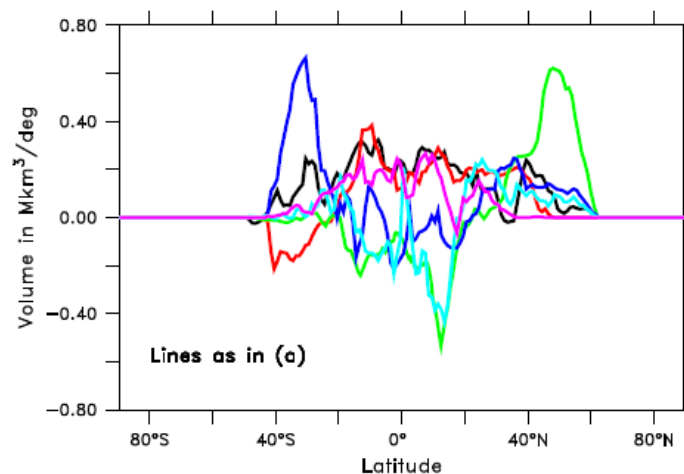
What we are trying to explain
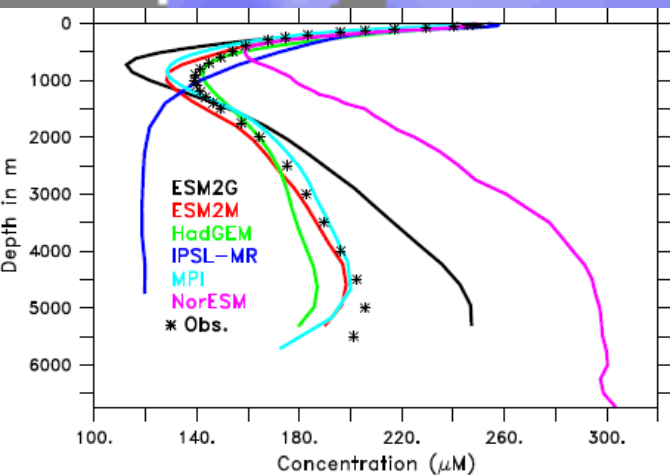
(A) Global mean O$_2$, CMIP5 Control
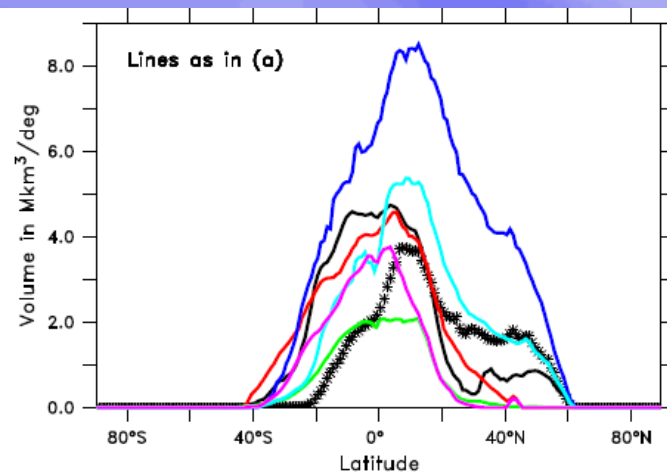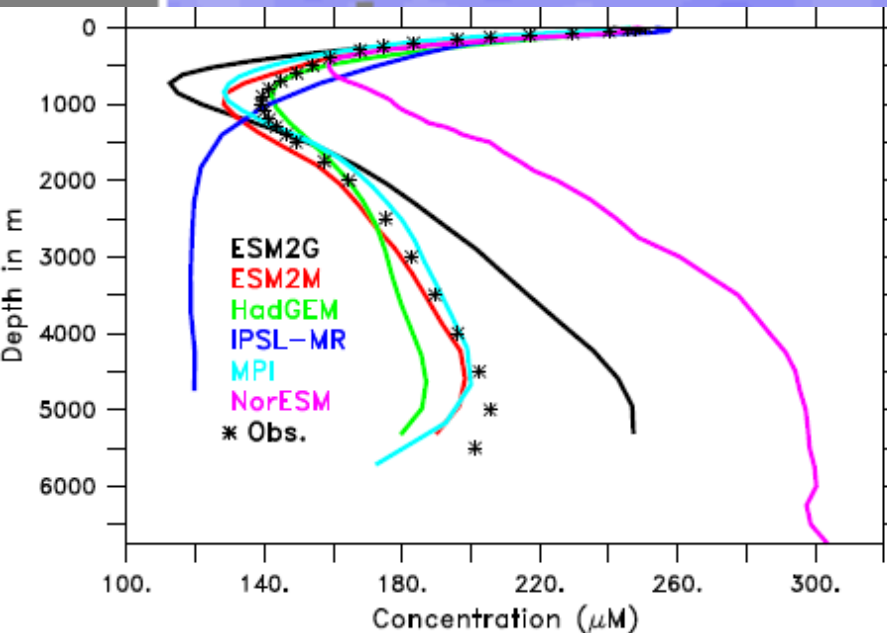
(B) Volume of hypoxic waters, CMIP5 Control

(C) ΔO$_2$, CMIP5 Model, 1pct Runs

(D) ΔVolume of hypoxic waters, CMIP5 1Pct

Differ in

Mean O2

Hypoxic volume

Change in O2

Change in hypoxic volume

Bahl, Gnanadesikan and Pradal., subm. GBC
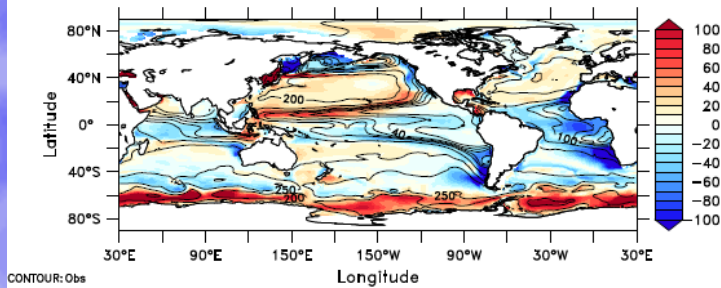
Mean oxygen

(A) Global mean O$_2$, CMIP5 Control
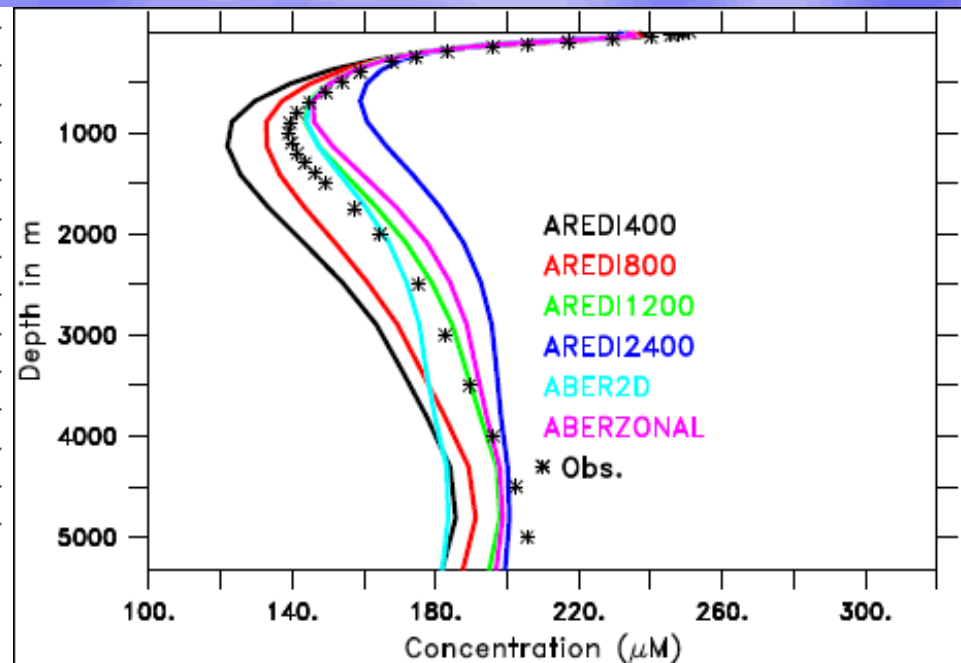
(A) Global mean O$_2$, JHU runs

Large spread in horizontally averaged oxygen.

Significantly smaller spread at depth similar spread at intermediate depths.

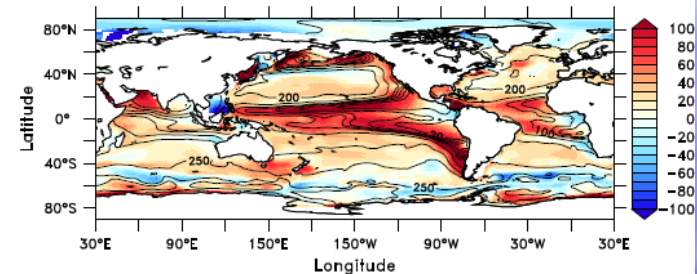Spatially variable mixing models lie in between low and high mixing
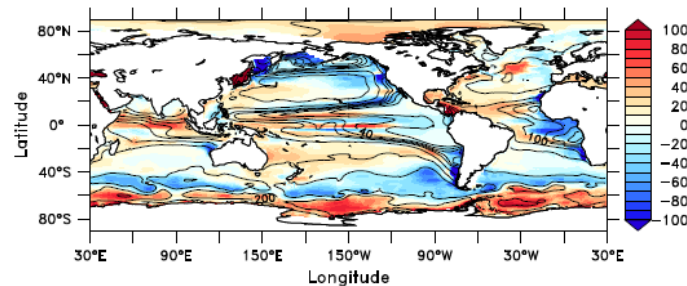
CMIP5 biases, 300m

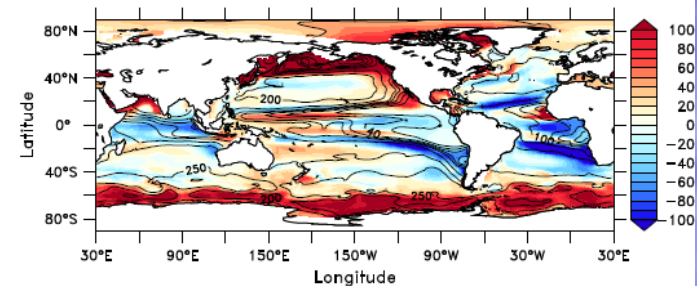(A) ESM2G O$_2$ Bias, 300m
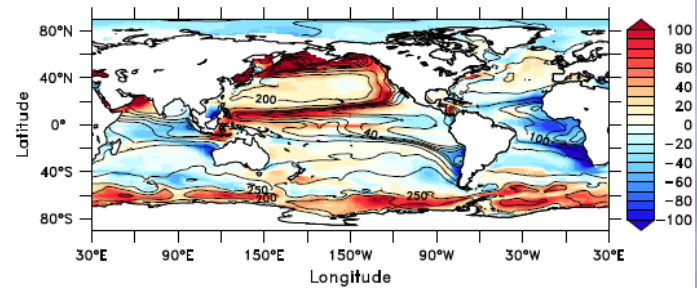
(B) ESM2M O$_2$ Bias, 300m
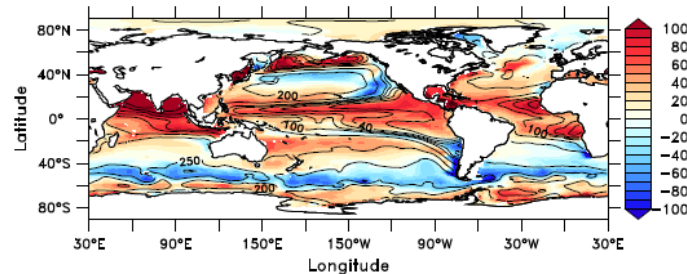
(C) HadGEM O$_2$ Bias, 300m
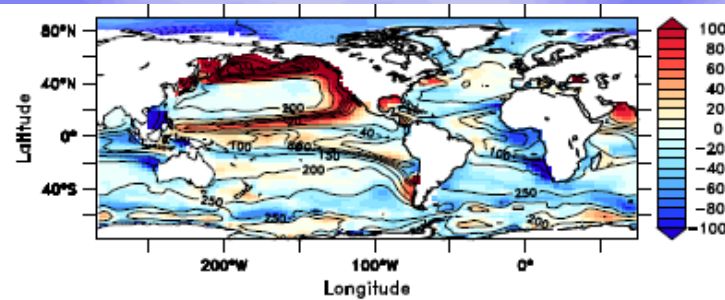
(D) IPSL−MR O$_2$ Bias, 300m

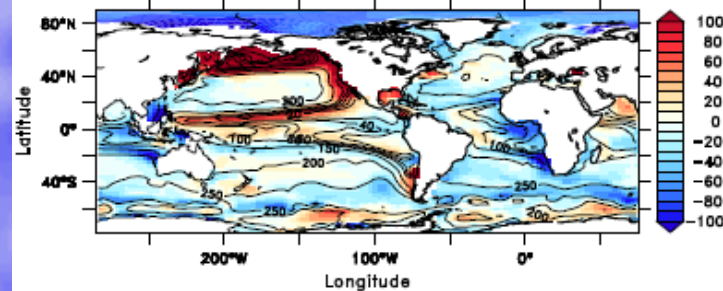(E) MPI O$_2$ Bias, 300m

(F) NorESM O$_2$ Bias, 300m
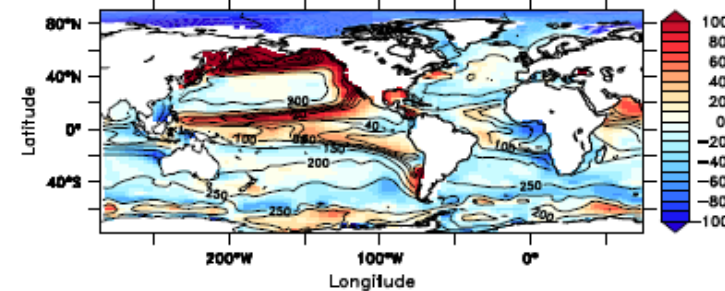
JHU suite biases, 300m
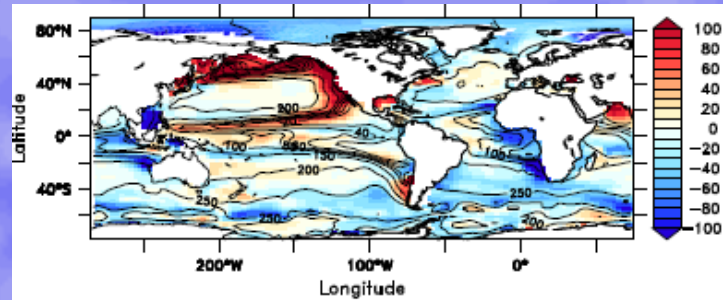
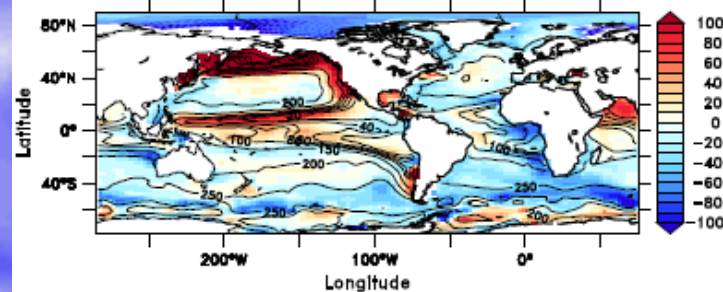(A) O$_2$ Error AREDI400, 300m

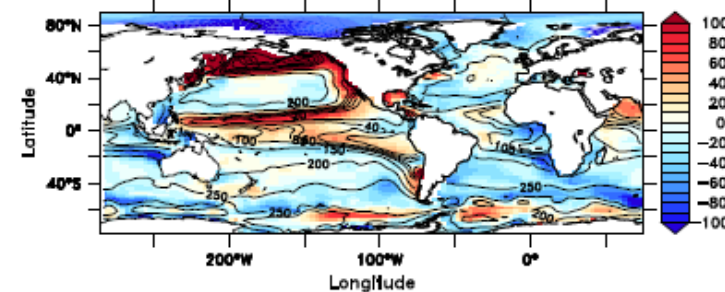(B) O$_2$ Error AREDI800, 300m

(C) O$_2$ Error AREDI1200, 300m

(D) O$_2$ Error AREDI2400, 300m

(E) O$_2$ Error ABER2D, 300m

(F) O$_2$ Error ABERZONAL, 300m

CMIP5 biases, 3000m

(A) ESM2G O$_2$ Bias, 3000m

(B) ESM2M O$_2$ Bias, 3000m

(C) HadGEM O$_2$ Bias, 3000m

(D) IPSL-MR O$_2$ Bias, 3000m

(E) MPI O$_2$ Bias, 3000m
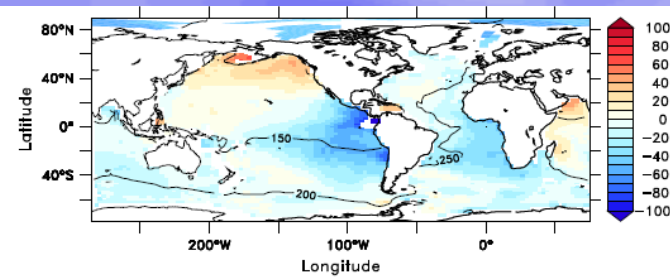
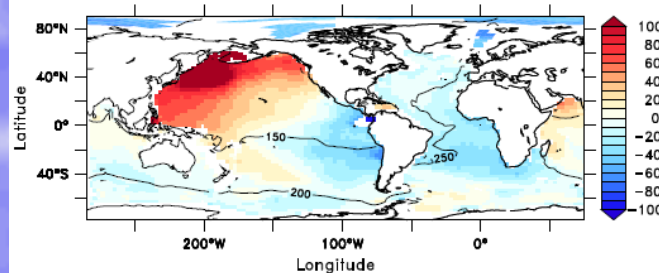(F) NorESM O$_2$ Bias, 3000m
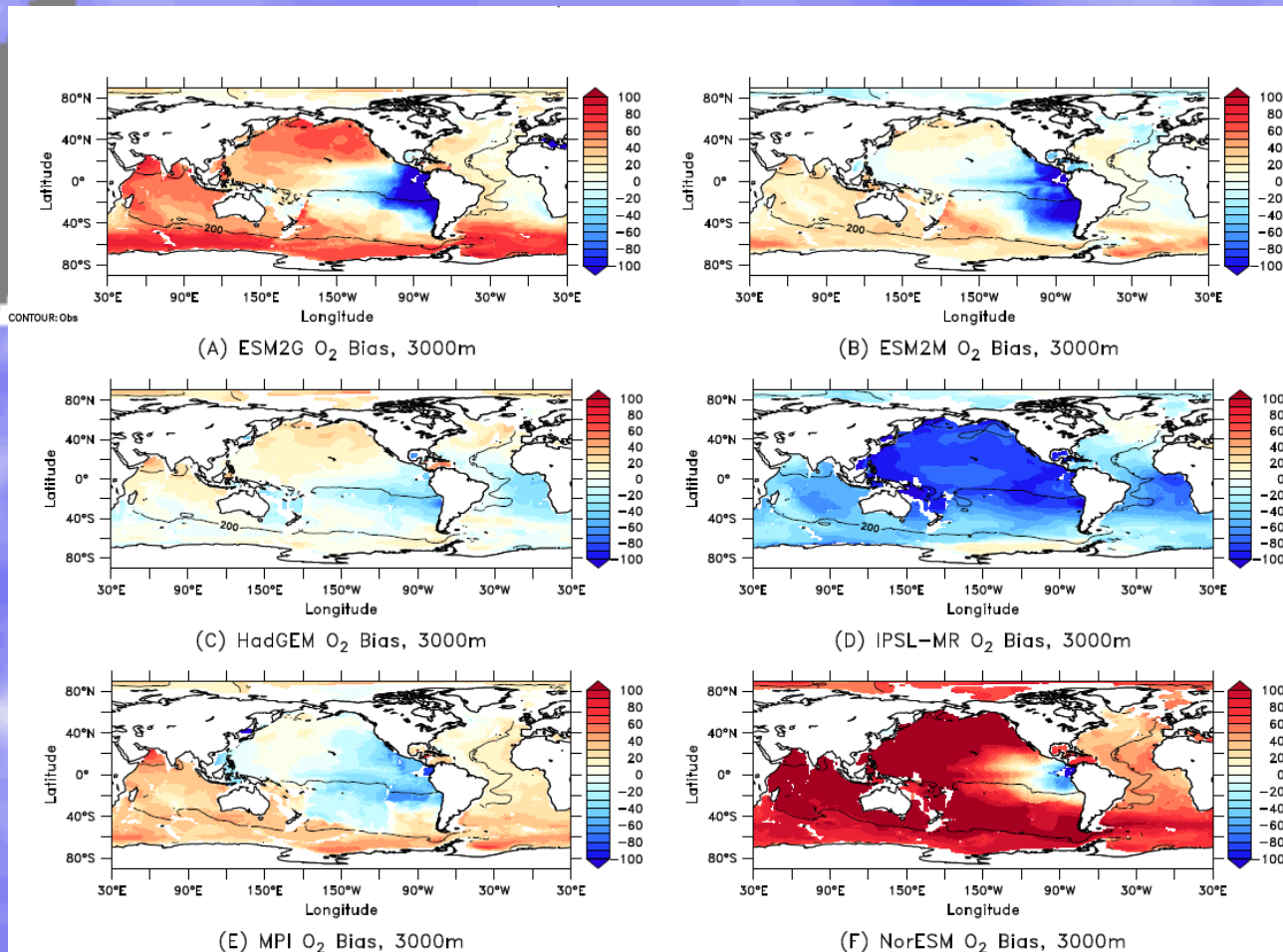
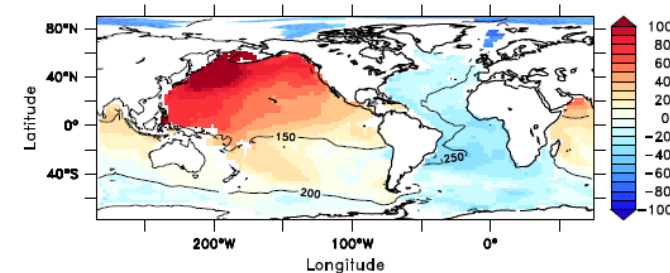# JHU model suite, 3000m
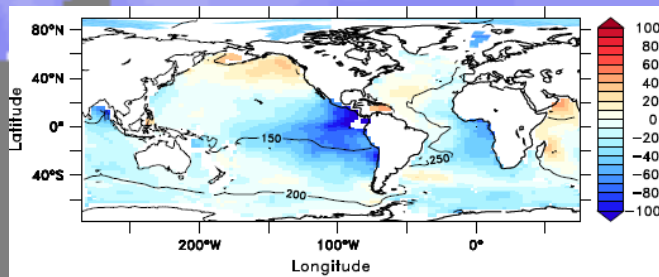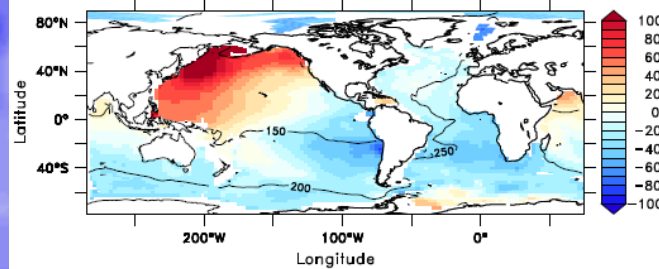

(A) O$_2$ Error AREDI400, 3000m
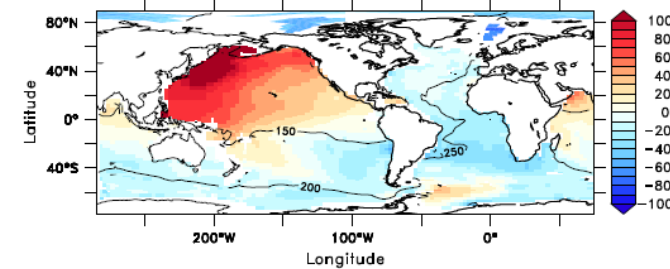
(B) O$_2$ Error AREDI800, 3000m

(C) O$_2$ Error AREDI1200, 3000m
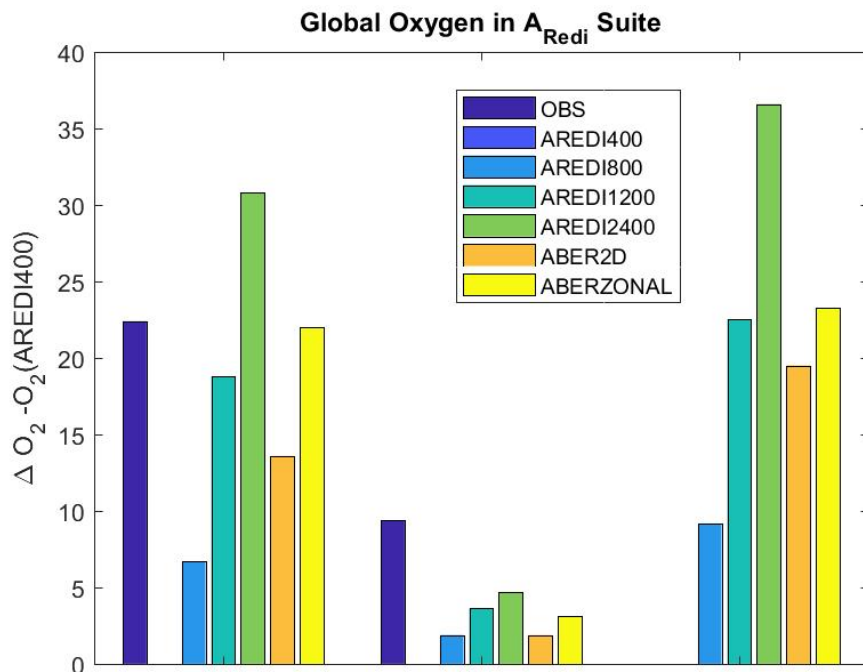
(D) O$_2$ Error AREDI2400, 3000m

(E) O$_2$ Error ABER2D, 3000m

(F) O$_2$ Error ABERZONAL, 3000m
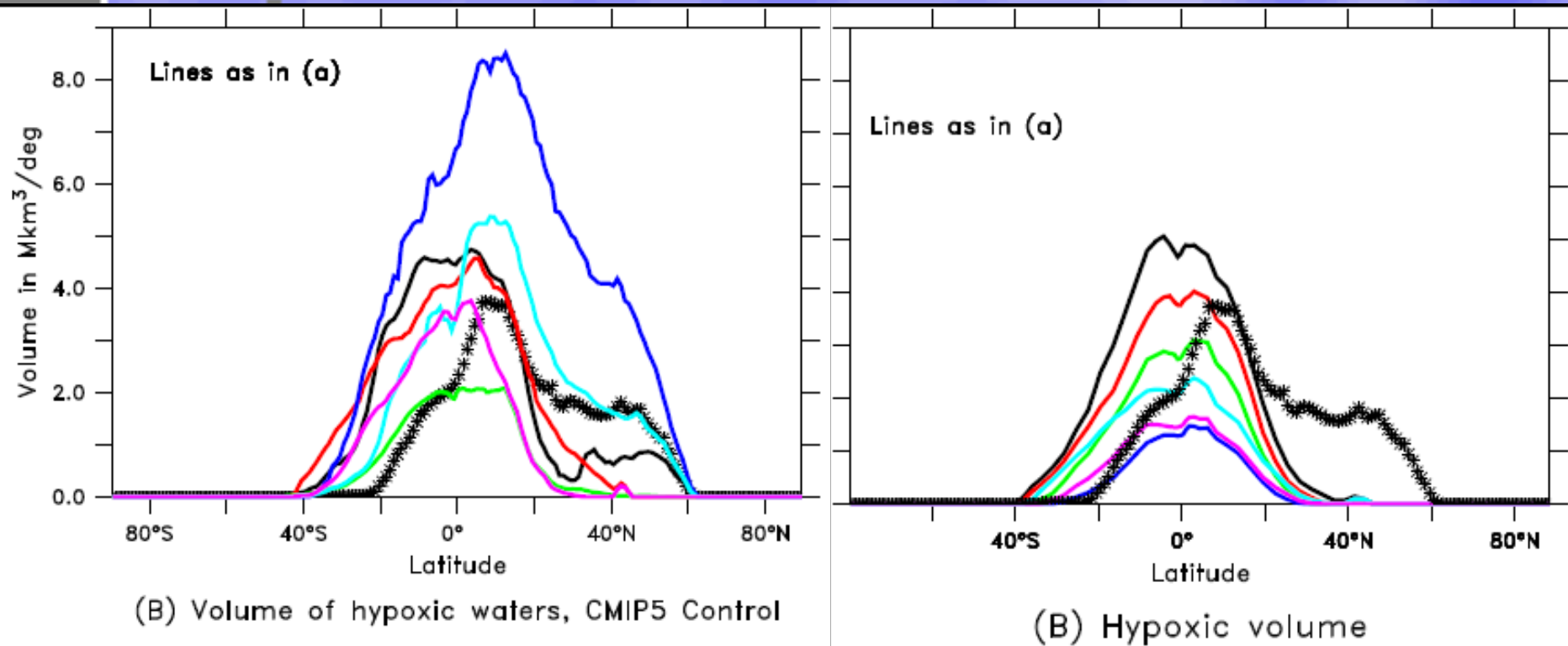
What drives variation in oxygen

$$O_2^{deep} = O_2^{surf} - AOU$$

$$O_2^{deep} = O_2^{surf} - R_{C:P}\left(PO_4 - PO_4^{surf}\right)$$
$$= O_2^{surf} - R_{C:P}PO_4^{remin}$$

Global Oxygen in A_{Redi} Suite

Cross-model differences in oxygen largely driven by differences in biological drawdown.

Hypoxic volume
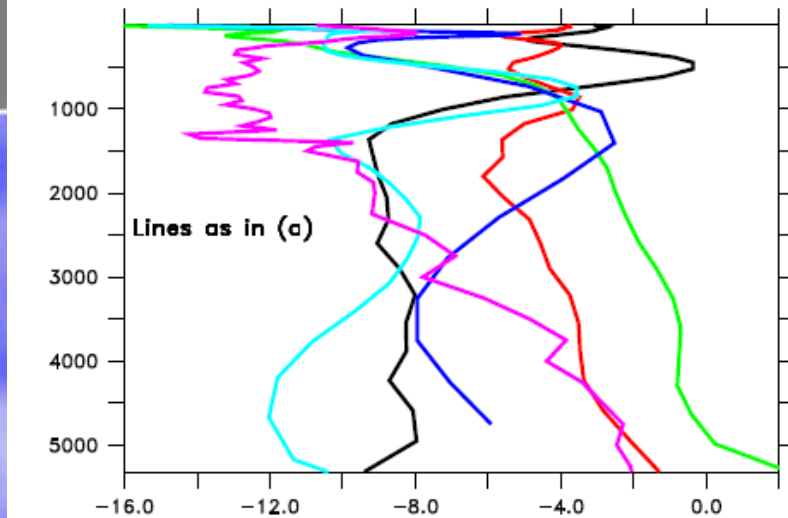

(B) Volume of hypoxic waters, CMIP5 Control
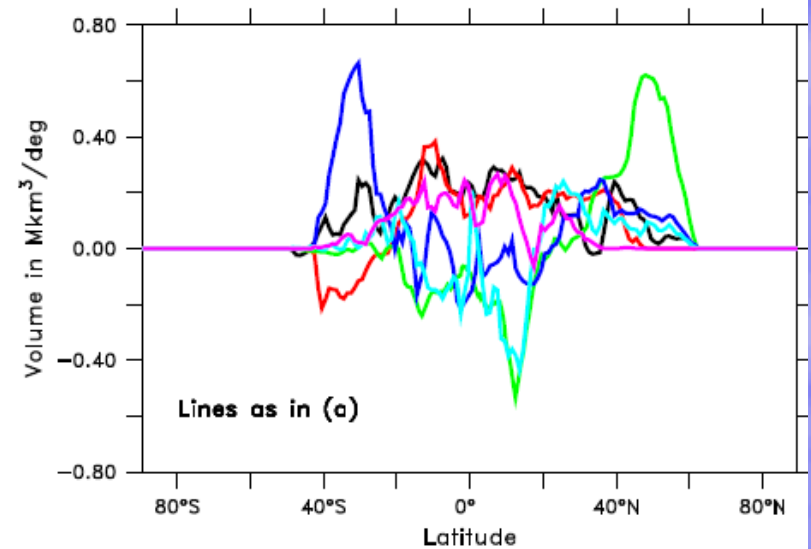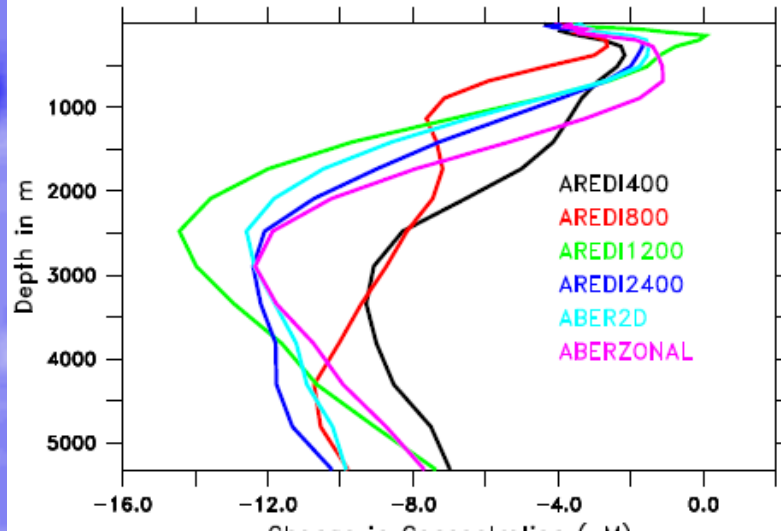
(B) Hypoxic volume

While there is no clear relationship with mixing coefficient in CMIP5 models…

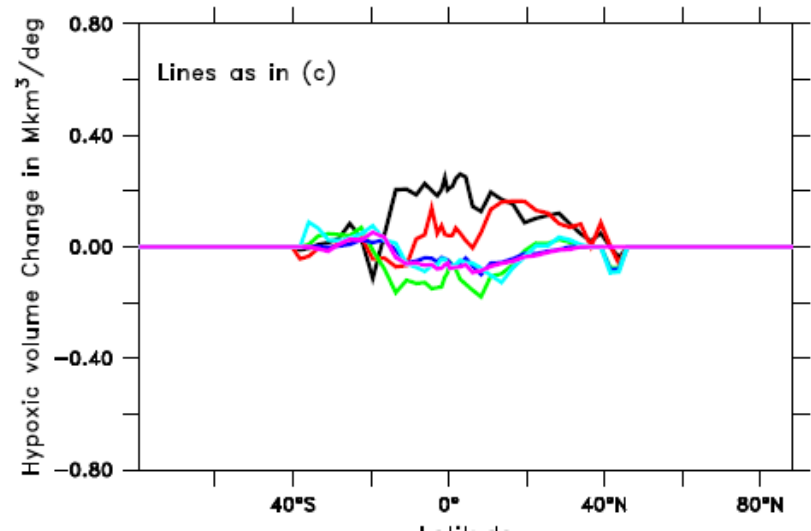Large range in hypoxic volume across model suite (54-182 Mkm^3)

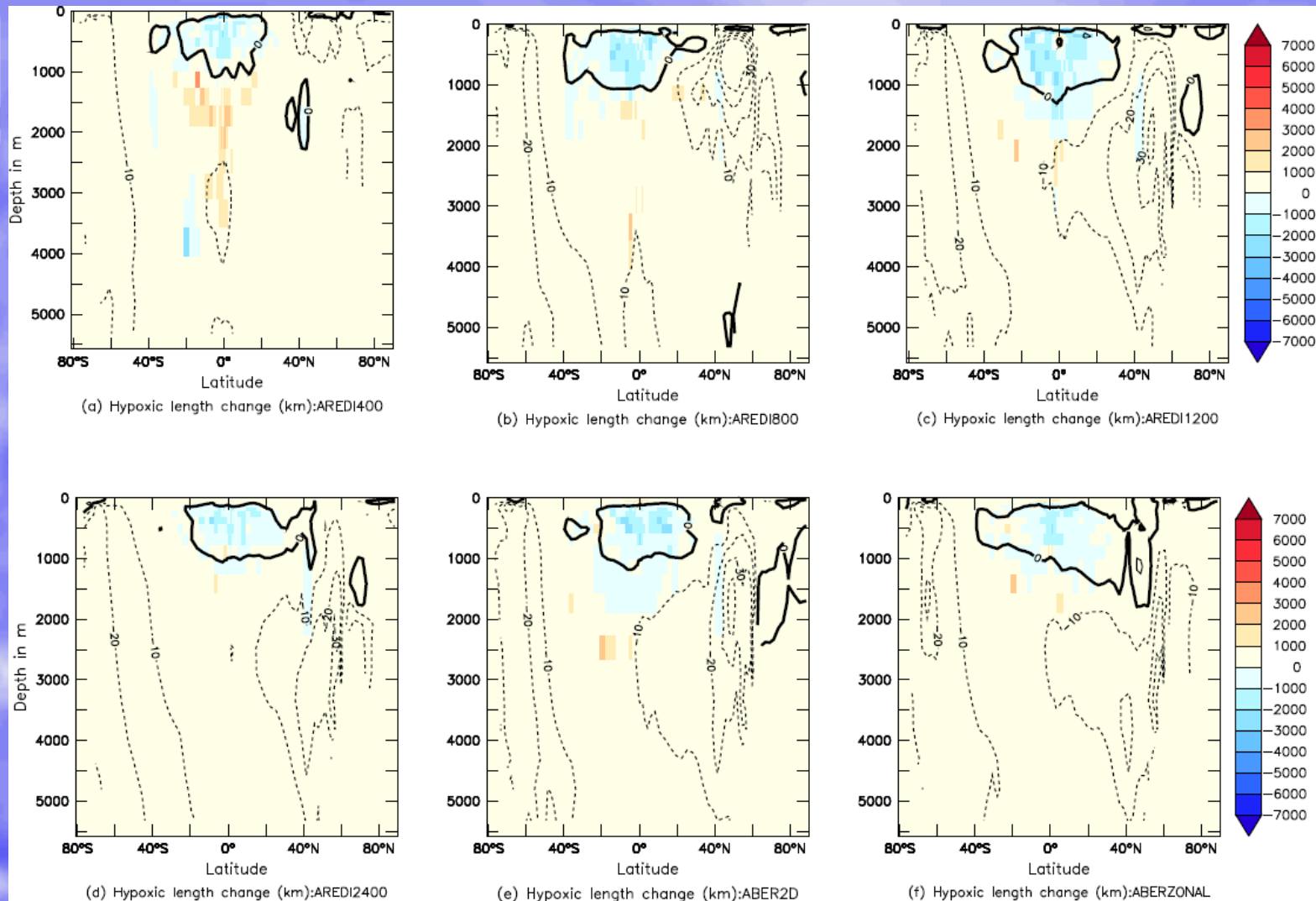# Change in oxygen and hypoxic volume

(C) ΔO₂, CMIP5 Model, 1pct Runs

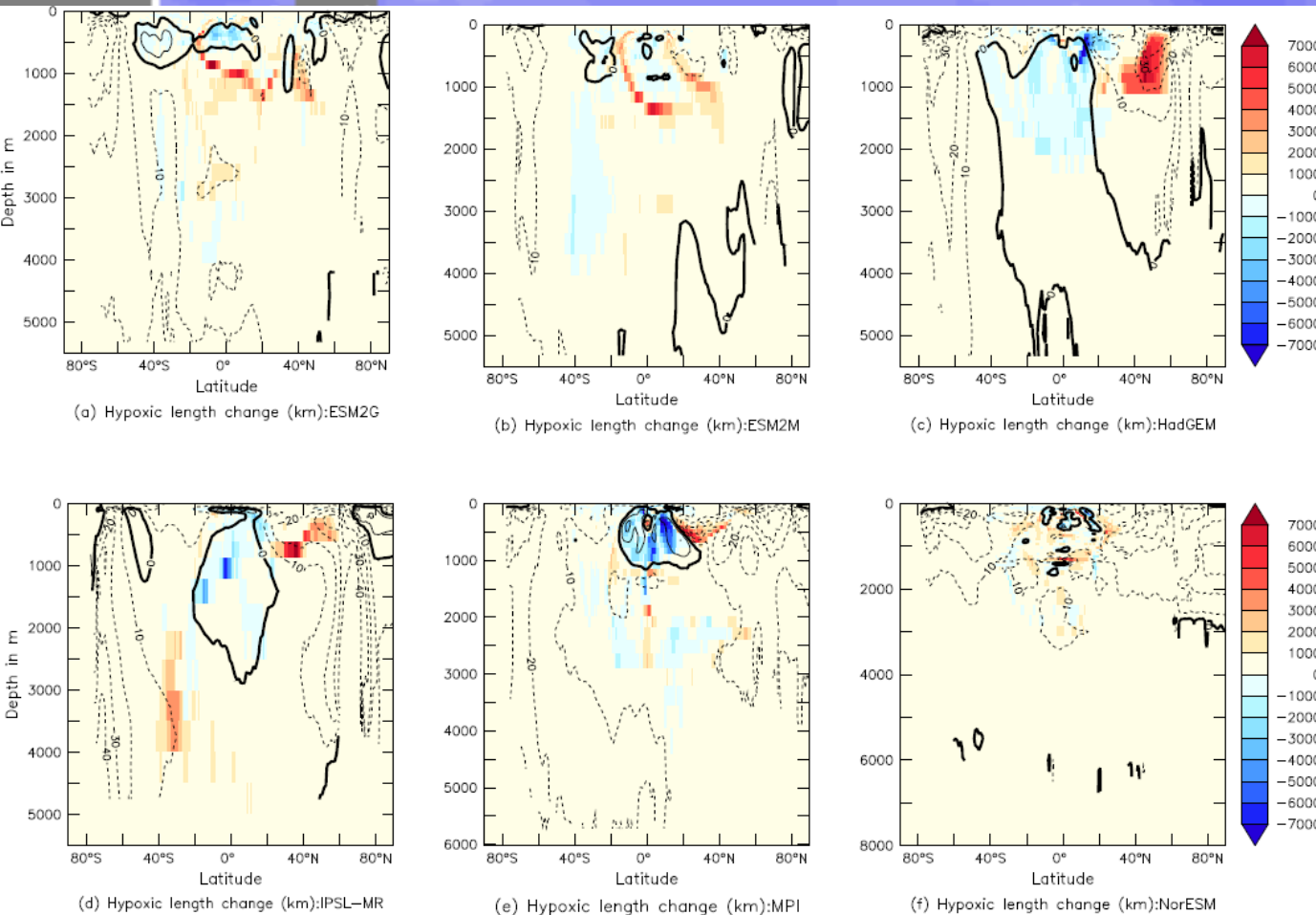(D) ΔVolume of hypoxic waters, CMIP5 1Pct

Results

- Range in mixing suite is about half that in CMIP5 models.

- Both sets of models show differences in whether hypoxic waters expand or contract in the tropics.

- Results not tightly related to oxygen changes!

- Low mixing models in JHU suite show expansion, high mixing models show contraction.

Reason for this 3-d structure

(a) Hypoxic length change (km):AREDI400

(b) Hypoxic length change (km):AREDI800

(c) Hypoxic length change (km):AREDI1200

(d) Hypoxic length change (km):AREDI2400

(e) Hypoxic length change (km):ABER2D

(f) Hypoxic length change (km):ABERZONAL

Oxygen increases slightly in low latitude, decreases in deep.

Similar behavior seen in CMIP5 models

(a) Hypoxic length change (km):ESM2G

(b) Hypoxic length change (km):ESM2M

(c) Hypoxic length change (km):HadGEM

(d) Hypoxic length change (km):IPSL−MR

(e) Hypoxic length change (km):MPI

(f) Hypoxic length change (km):NorESM

All models show:

Decrease in at least part of tropics

Plumes of lower oxygen emanating from high latitudes.

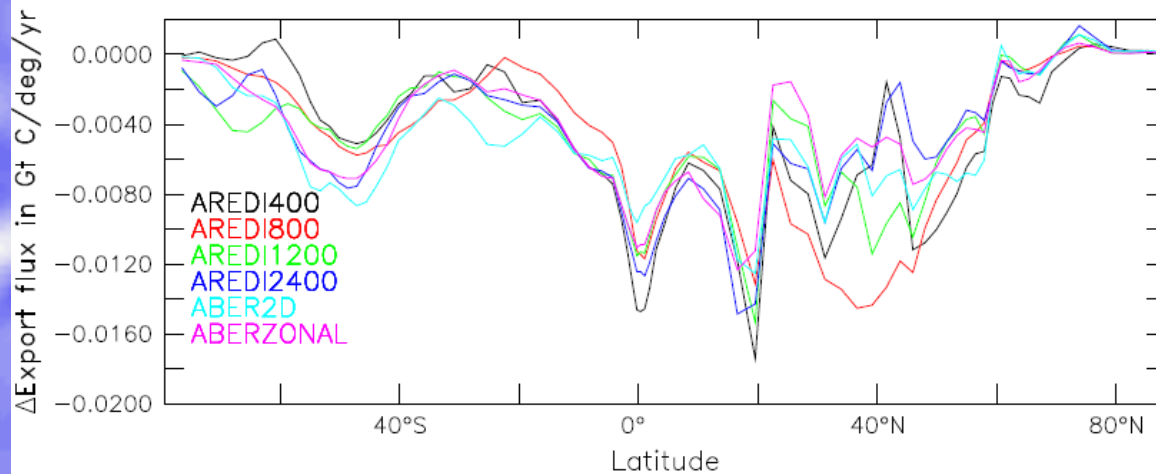Intersection with low oxygen regions varies across models

What drives differences

- Temperature rise almost identical across models.

- Oxygen utilization accounts for almost all of the intermodel differences.

- Can think of AOU as consumption rate multiplied by age.
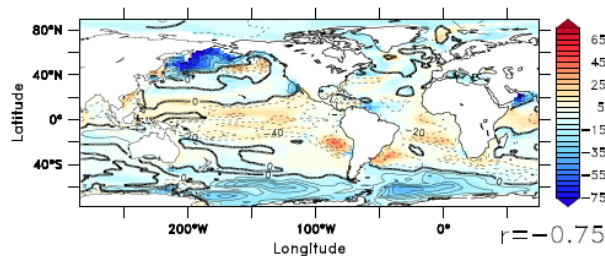
Hard to explain with productivity
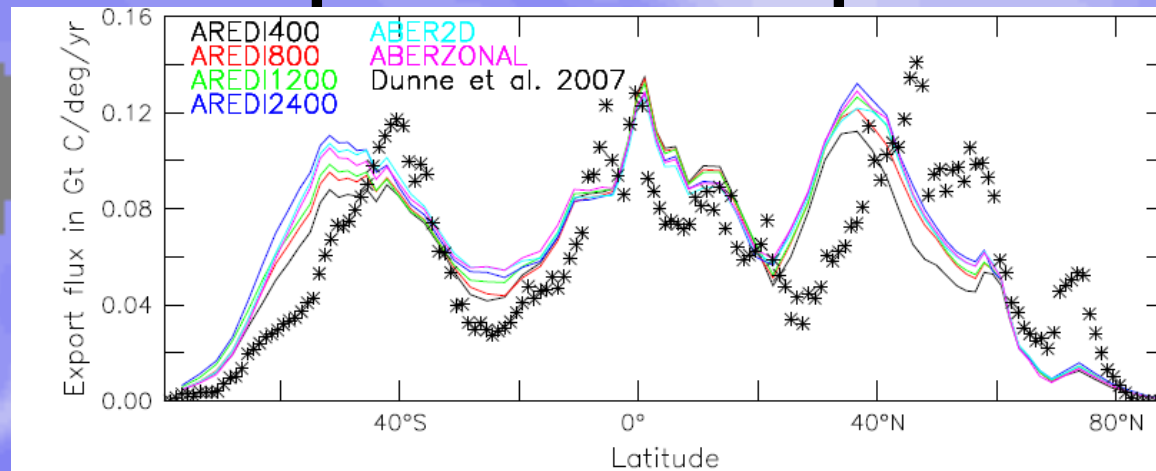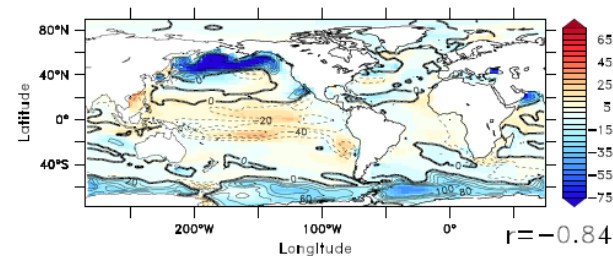

(A) Particle export flux (100m)

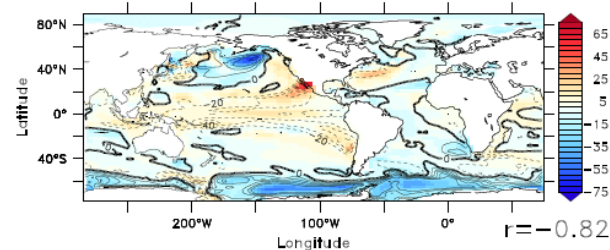(B) Change in Export Production 40—140 yrs after CO_2 doubling

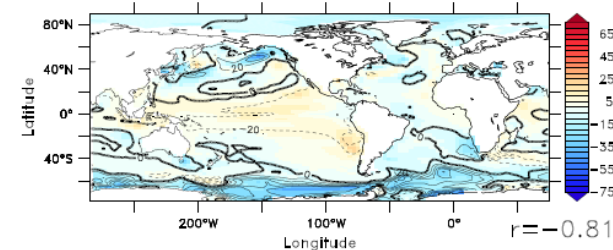# Changes in oxygen correspond to changes in age at 300m…
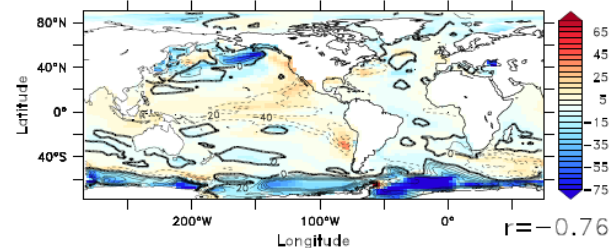

(A) ΔO_2 and ΔAge AREDI400, 300m
r=−0.75

(B) ΔO_2 and ΔAge AREDI800, 300m
r=−0.84

(C) ΔO_2 and ΔAge AREDI1200, 300m
r=−0.82

(D) ΔO_2 and ΔAge AREDI2400, 300m
r=−0.81

(E) ΔO_2 and ΔAge ABER2D, 300m
r=−0.76
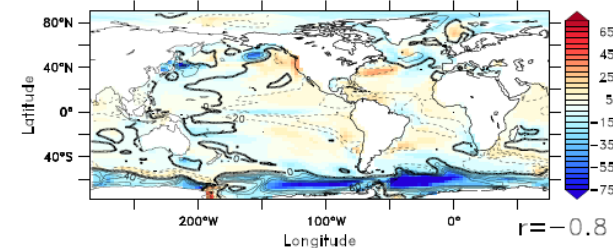
(F) ΔO_2 and ΔAge ABERZONAL, 300m
r=−0.8
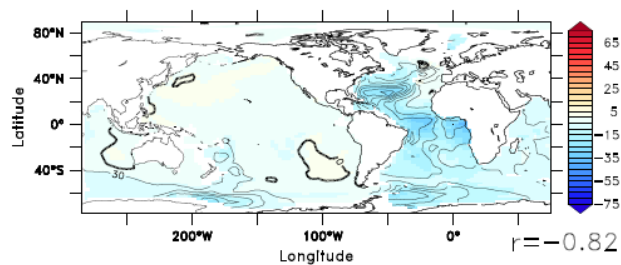
…and at 3000m

(A) ΔO_2 and ΔAge AREDI400, 3000m
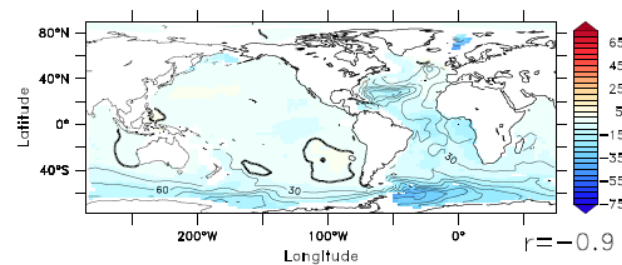
(B) ΔO_2 and ΔAge AREDI800, 3000m
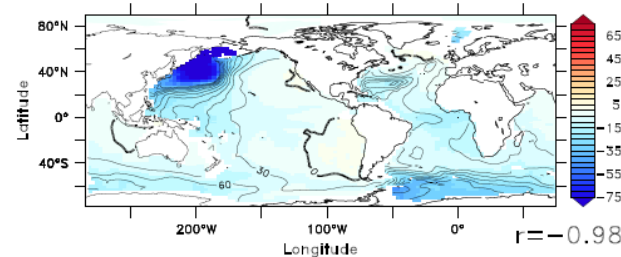
(C) ΔO_2 and ΔAge AREDI1200, 3000m
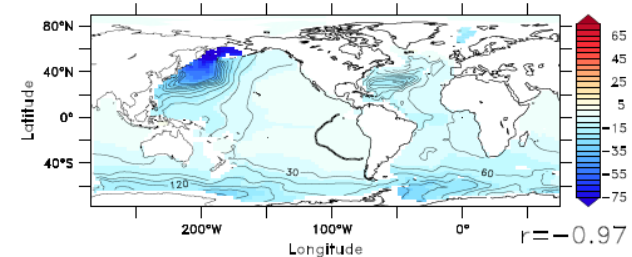
(D) ΔO_2 and ΔAge AREDI2400, 3000m
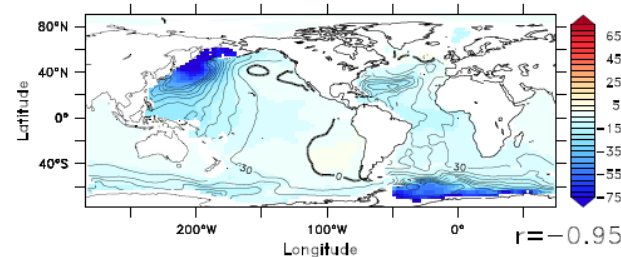
(E) ΔO_2 and ΔAge ABER2D, 3000m
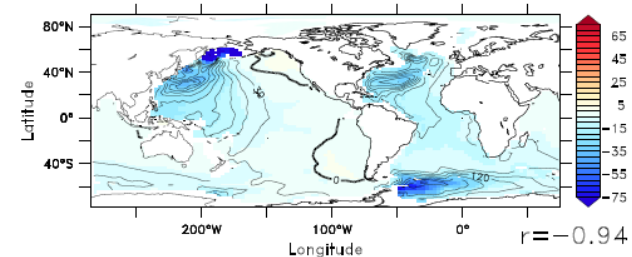
(F) ΔO_2 and ΔAge ABERZONAL, 3000m

…and at 3000m
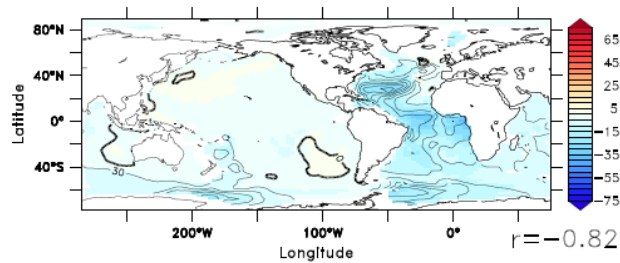
(A) ΔO_2 and ΔAge AREDI400, 3000m r=−0.82

(C) ΔO_2 and ΔAge AREDI1200, 3000m r=−0.98
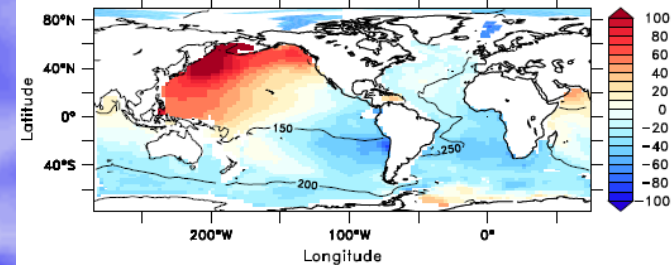
(E) ΔO_2 and ΔAge ABER2D, 3000m r=−0.95
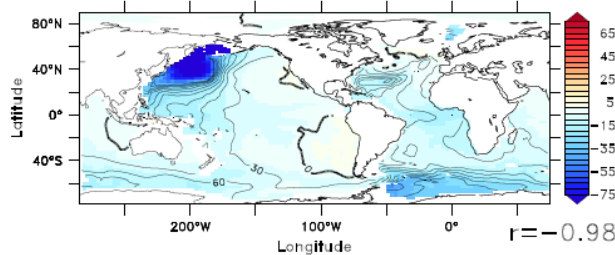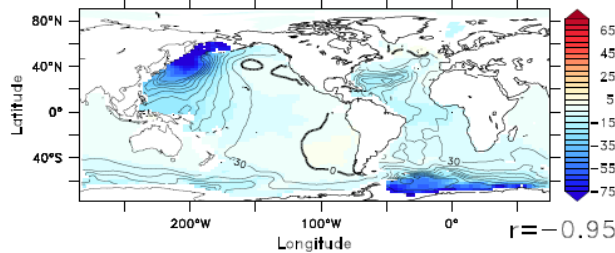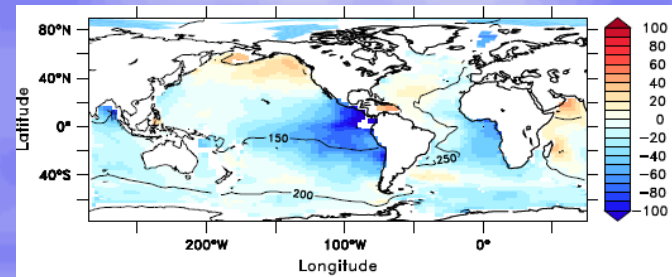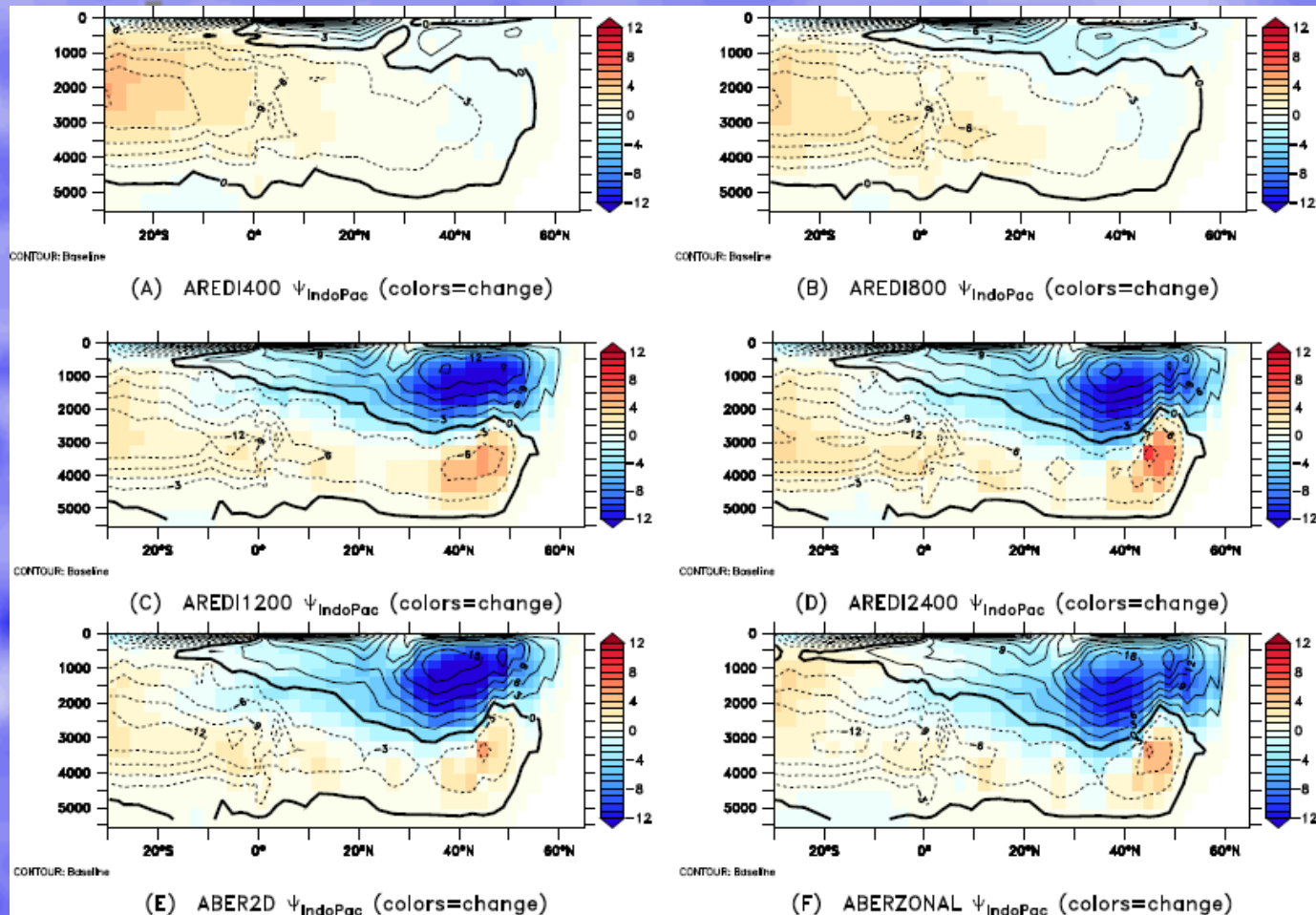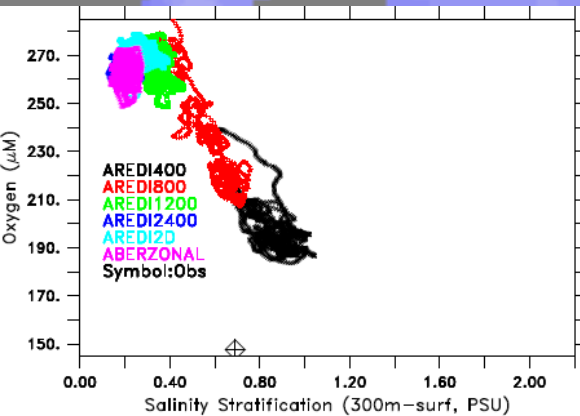
(A) O_2 Error AREDI400, 3000m
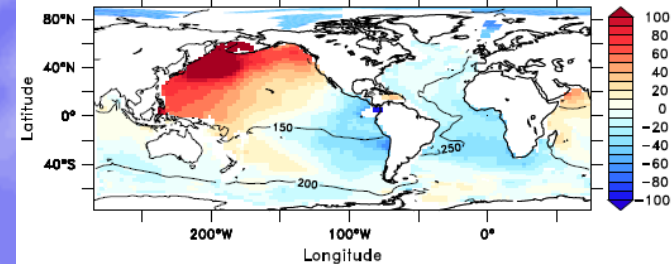
(C) O_2 Error AREDI1200, 3000m

(E) O_2 Error ABER2D, 3000m
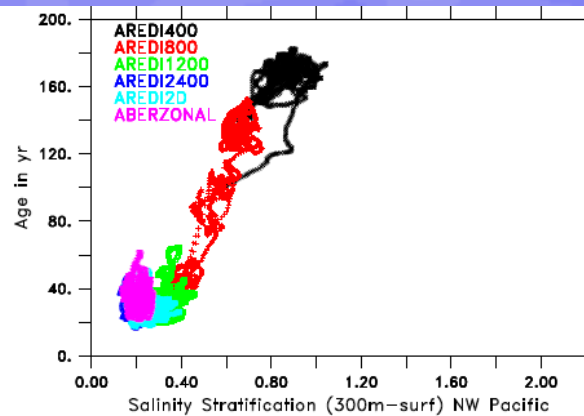
Changes under GW largely remove biases in base state.

What's happening in NW Pac?

(A) AREDI400 $\Psi_{IndoPac}$ (colors=change)

(B) AREDI800 $\Psi_{IndoPac}$ (colors=change)

(C) AREDI1200 $\Psi_{IndoPac}$ (colors=change)

(D) AREDI2400 $\Psi_{IndoPac}$ (colors=change)

(E) ABER2D $\Psi_{IndoPac}$ (colors=change)

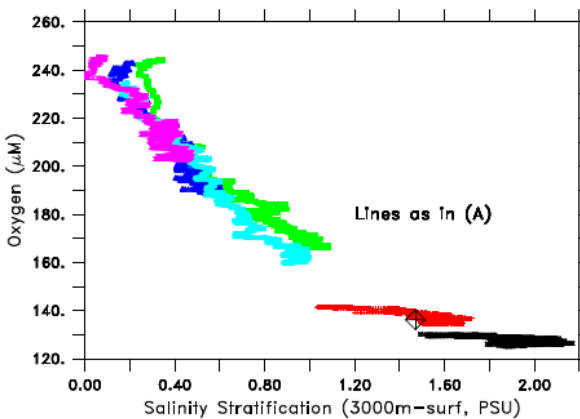(F) ABERZONAL $\Psi_{IndoPac}$ (colors=change)
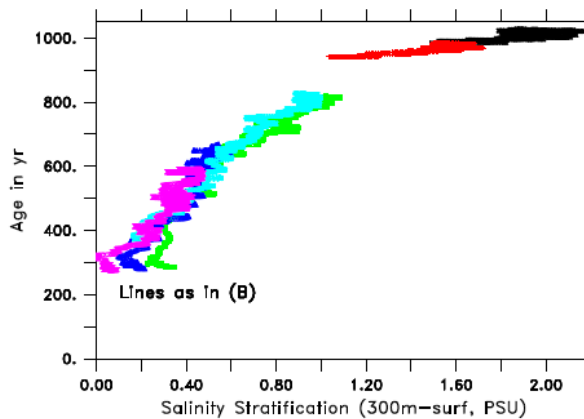
Stratification and vertical exchange

(A) NW Pacific, 300m

(B) NW Pacific, 300m

(C) NW Pacific, 3000m

(D) NW Pacific, 3000m

At 300m:

High mixing cases maintain convection.

Low mixing cases shut if off.

At 3000m

Low mixing cases are always shut off.

High mixing cases experience instability

Lessons for oxygen

- Changing mixing changes oxygen by a lot.

- Changes are driven by differences in biological utilization.

- Changes in biological utilization driven by ventilation, not productivity

- Whether or not we get a change in hypoxia depends on depth at which convection turns off, whether resultant plumes of oxygen loss intersect low oxygen zones.
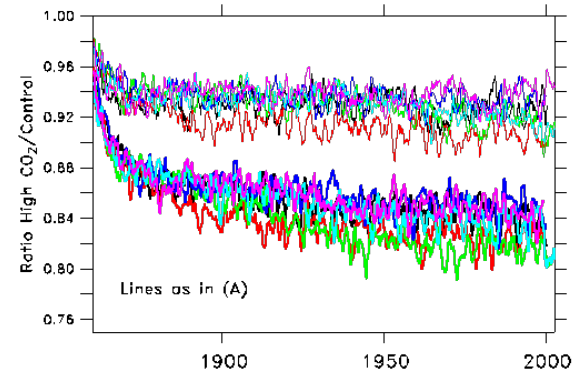
Part 3: Linearity

Bahl, Gnanadesikan and Pradal, manuscript in prep.
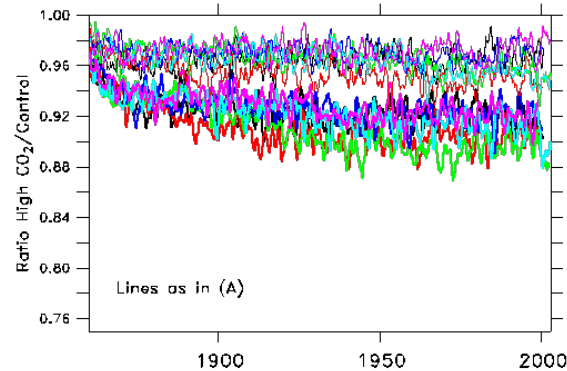Gnanadesikan, Pradal and Bahl, manuscript in prep.
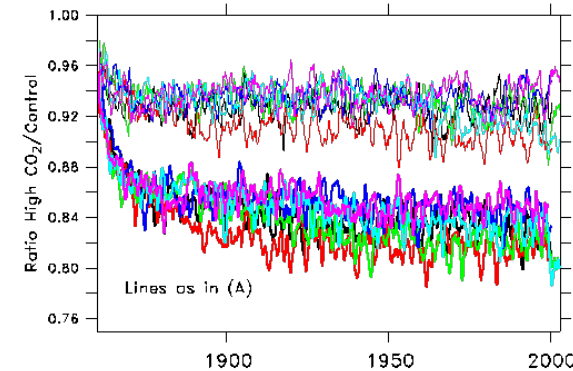
Linearity of changes under GW
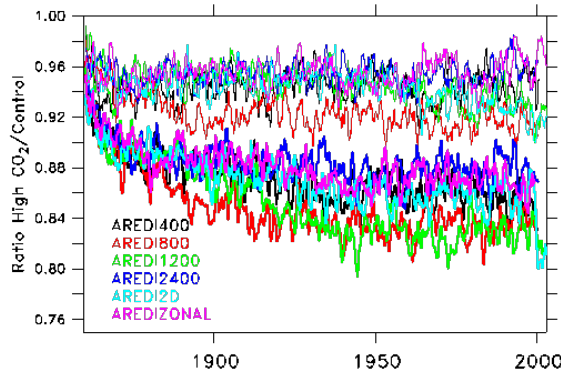
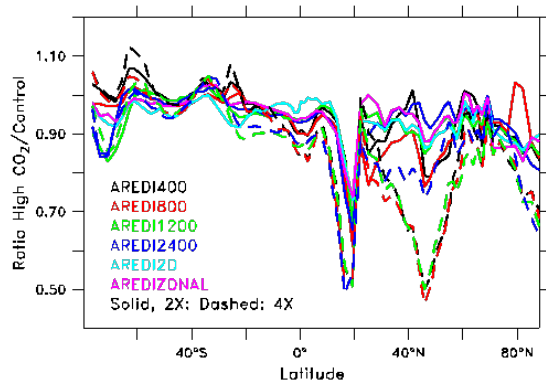(A) Global Surface Chlorophyll Change

(B) Global Surface Biomass Change

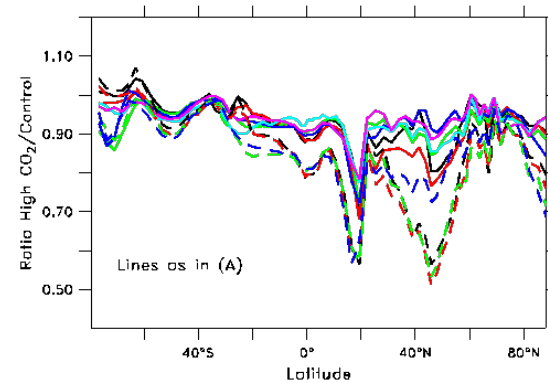(C) Global Prim. Prod. Change
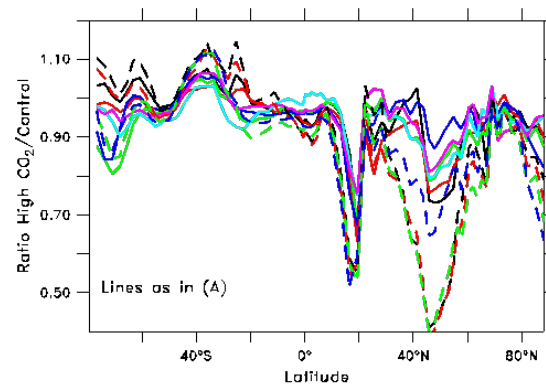
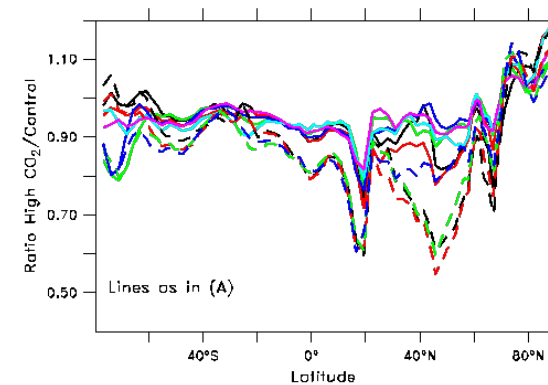(D) Global Export change

Linearity of changes under GW
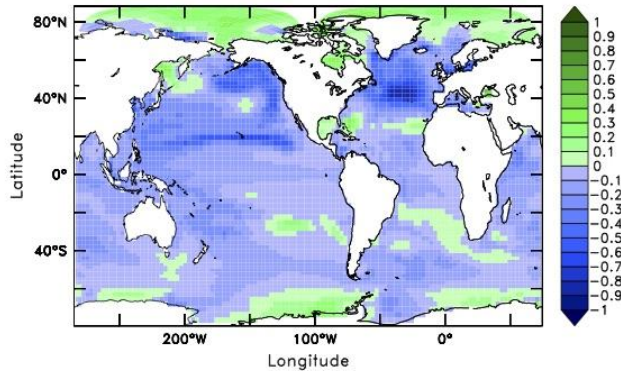

(A) Chl

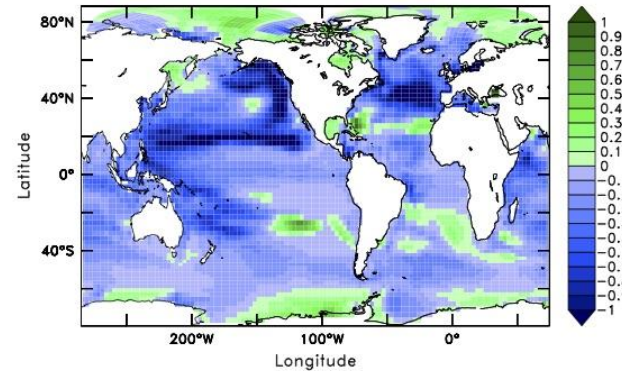(B) Particulate carbon

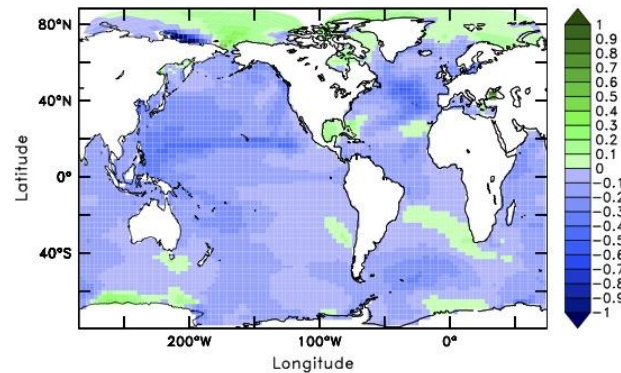(C) Primary Productivity

(D) Particle Export
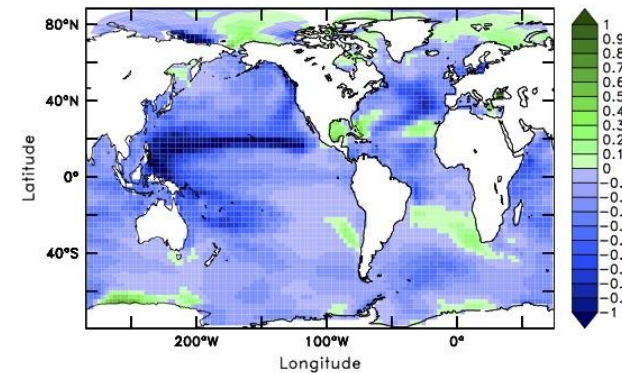
Where are changes in biomass?

(A) Ln(Biomass(4X)/Biomass(Ctrl)), AREDI400

(B) Ln(Biomass$_{Lg}$(4X)/Biomass$_{Lg}$(Ctrl)), AREDI400

(C) Ln(Biomass(4X)/Biomass(Ctrl)), AREDI2400

(D) Ln(Biomass$_{Lg}$(4X)/Biomass$_{Lg}$(Ctrl)), AREDI2400

Preliminary lessons

- Spread across models similar to spread across scenarios.

- Significant nonlinearities appear across models/scenarios.

- Changes in convective show up in terms of changes in biomass at edge of subpolar gyre, nutrients run out sooner.

Conclusions

- Eddy mixing produces
  - O(1) differences in hypoxic volume, change of hypoxia under global warming, change in oxygen under global warming.
  - O(0.2) differences in carbon dioxide uptake.
- Differences are dominated by impact of eddy mixing in convective regions.
- Realistic parameterizations don't break system- but need to be aligned with actual convection.