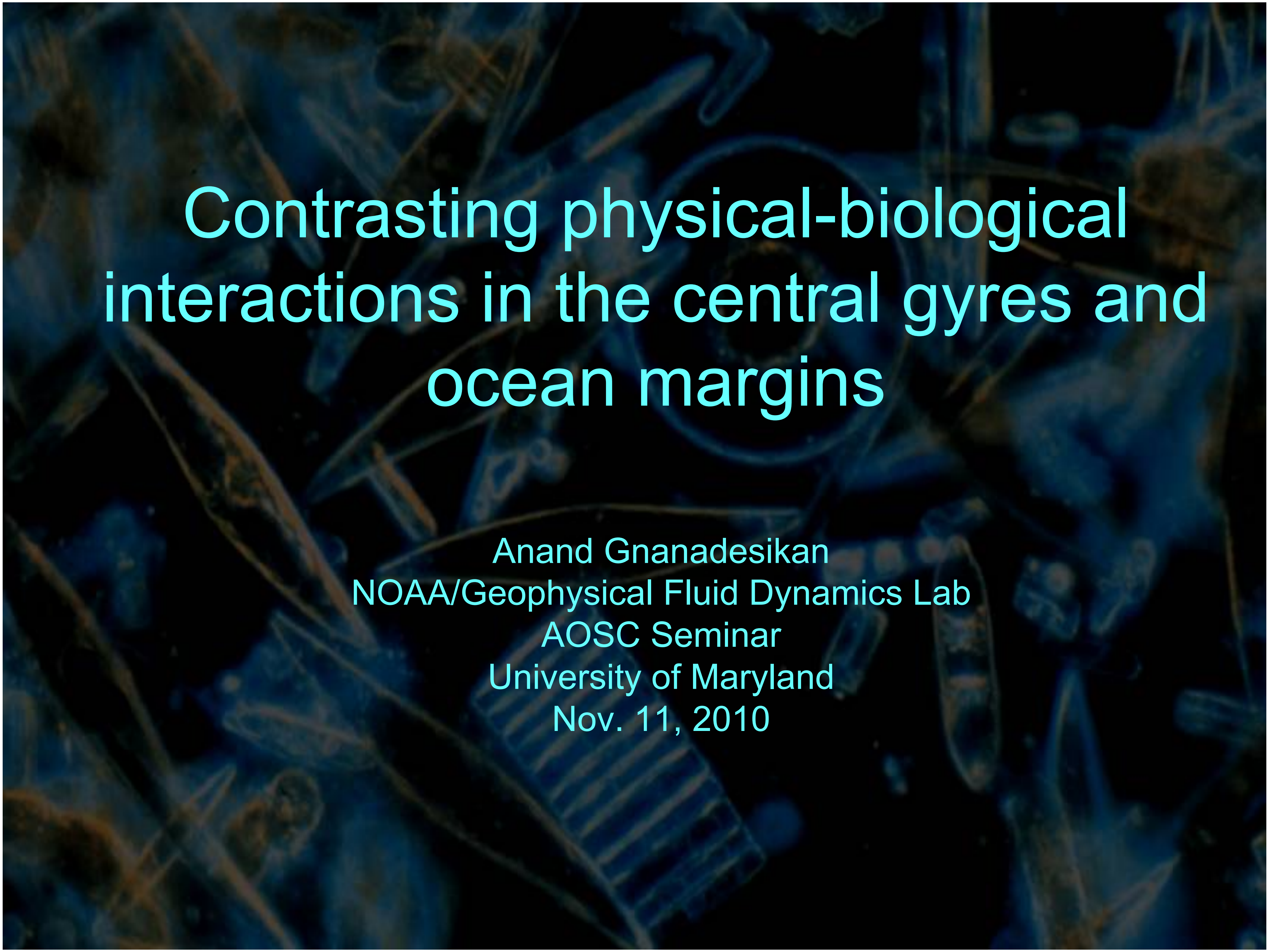

Contrasting physical-biological interactions in the central gyres and ocean margins

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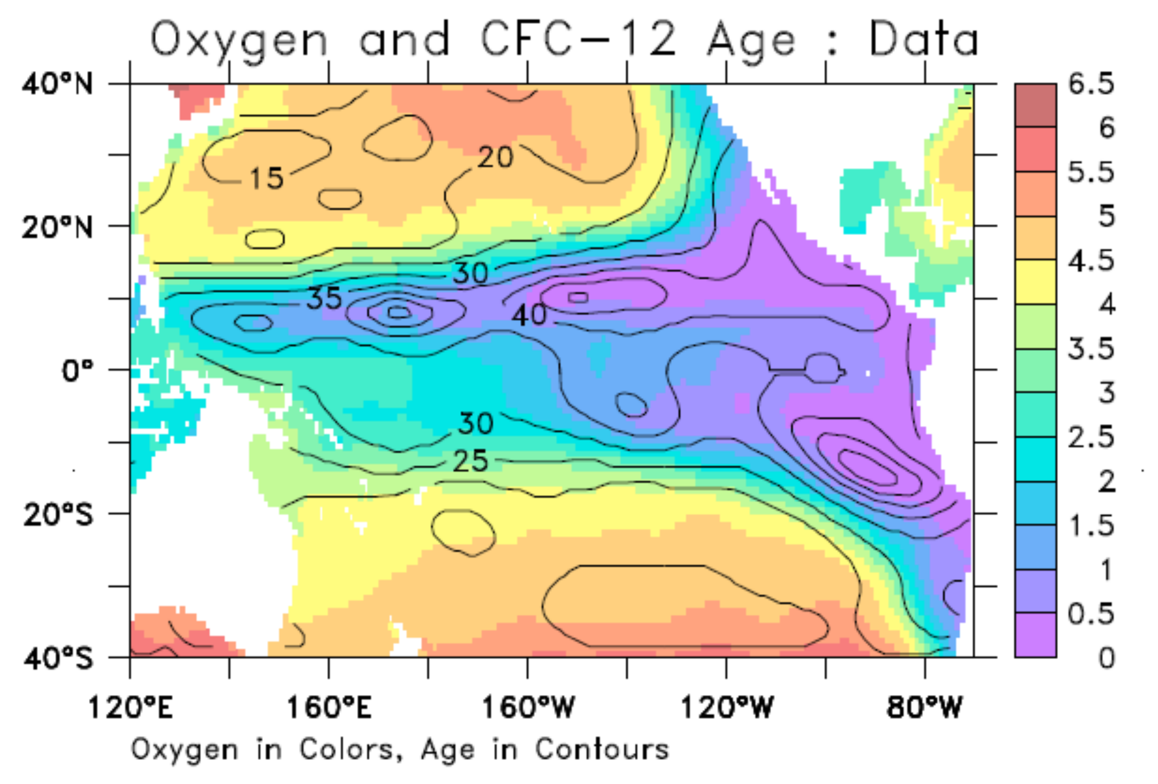
NOAA/Geophysical Fluid Dynamics Lab
AOSC Seminar
University of Maryland
Nov. 11, 2010

Key points

Well ventilated ocean gyres and poorly ventilated ocean margins have

- Different physics to leading order.
- Different biogeochemical sensitivity to changes in circulation.
- Different physical impacts from changes in biogeochemistry/ocean color.

Motivation: What do we mean by "ventilated"?



Well ventilated waters- low age, high CFC and oxygen
Poorly ventilated- high age, low CFC and oxygen

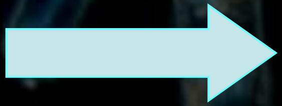
Consider a spinning earth…

Animation courtesy of NASA

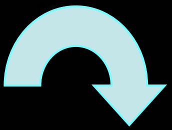
http://visibleearth.nasa.gov

If you look down on a column of water at the north pole, it will seem to spin *counterclockwise*.

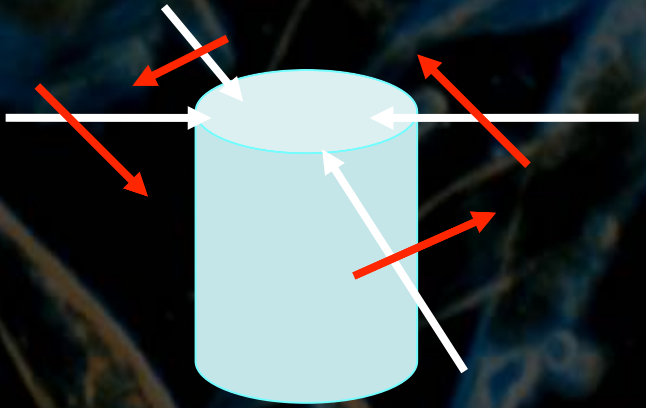
But a column of water at the equator won’t seem to spin at all, it will just move eastward.



And a column of water at the south pole will spin *clockwise*.

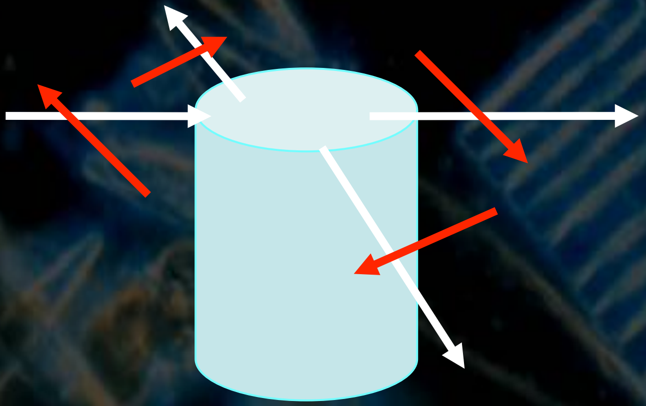


How can this happen? Stretching or squashing



Stretching a column pulls fluid in towards the center.

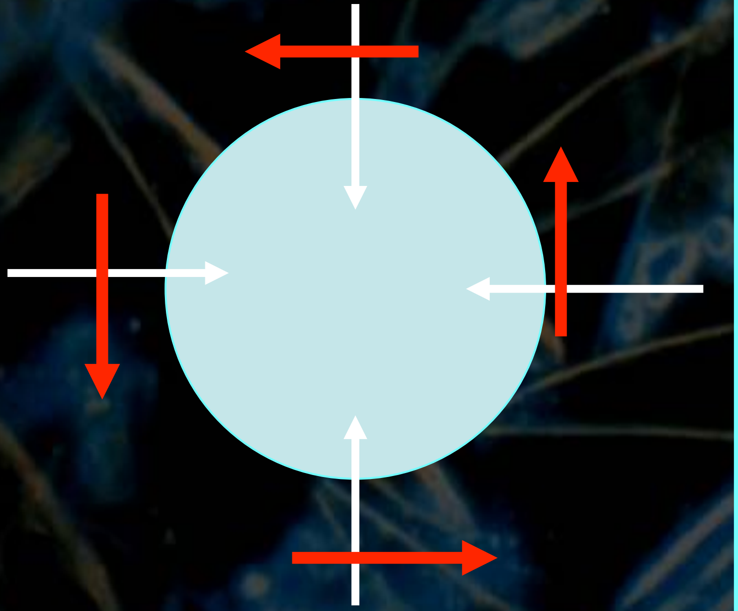
Coriolis force results in torque on column in same direction as rotation.



Squashing a column pushes fluid out from center.

Coriolis force causes column to spin in opposite direction

Implication



$$A\times H\times d\xi \propto H\times r\times(-f\,v)\times dt$$

Change in spin given by torque

$$dh^*A \propto -H\times r\times u\times dt$$

Change in height given by inward flow

$$AH\,d\xi = dhAf \Rightarrow \frac{dh}{H} = \frac{d\xi}{f}$$

So a stretching can balance a poleward flow and a squashing an equatorward flow

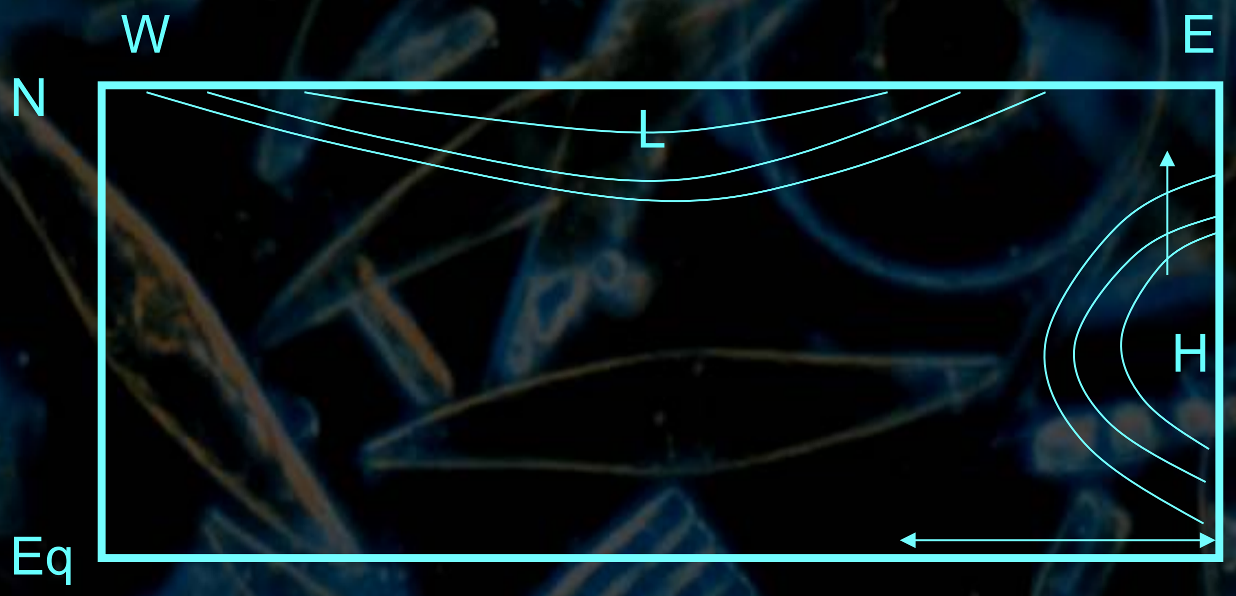
Potential thickness

$$H_{pot} = f_0 H / f$$

In absence of frictional, bottom torques, this quantity is conserved!

Alternatively- flows that do not conserve this quantity are unsteady.

Boundaries and potential thickness

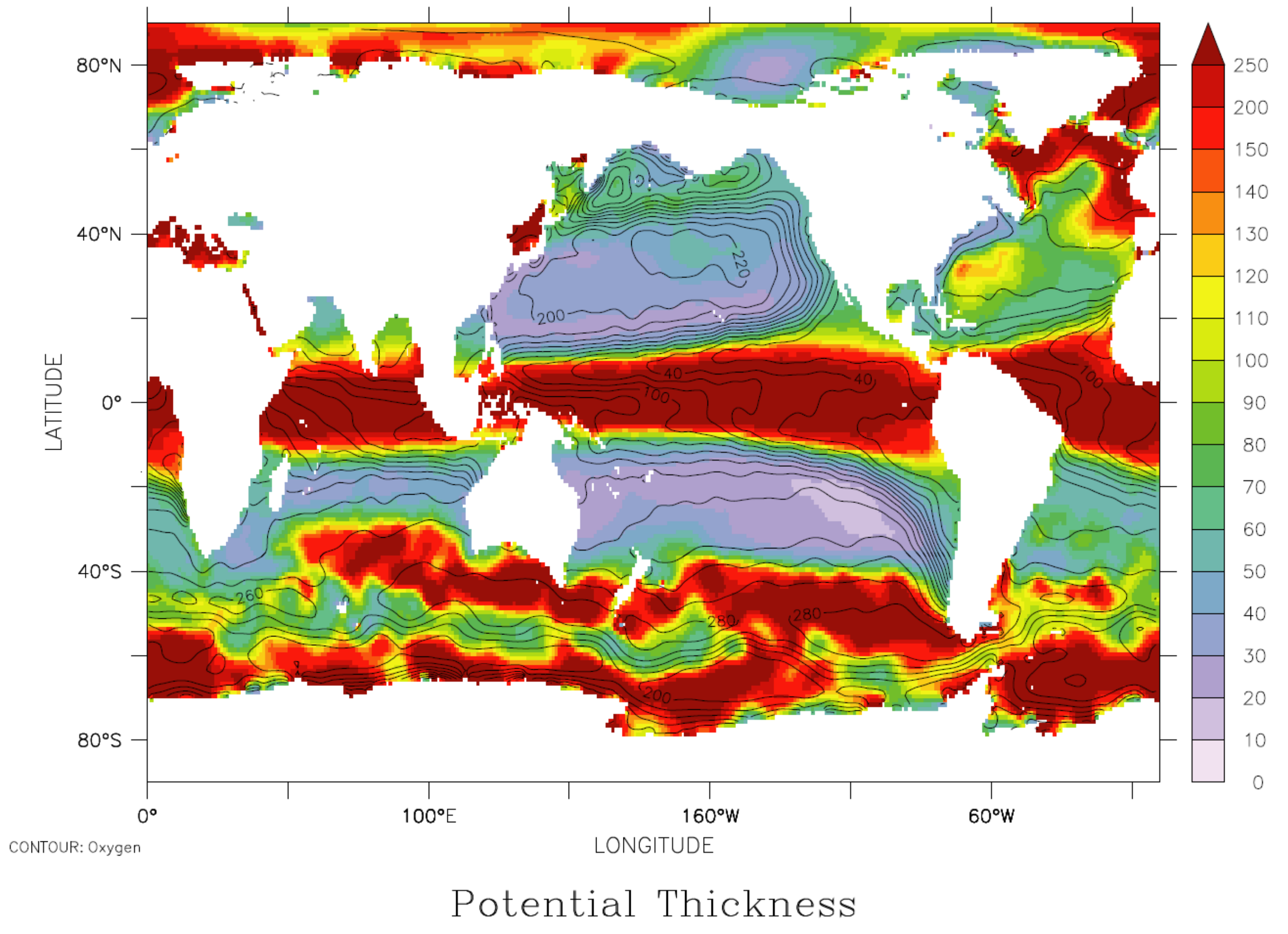


Radius of deformation

Planetary waves homogenize pressure (layer thickness).

This creates gradients in potential thickness H/f!

Observed potential thickness at 300m



Potential Thickness

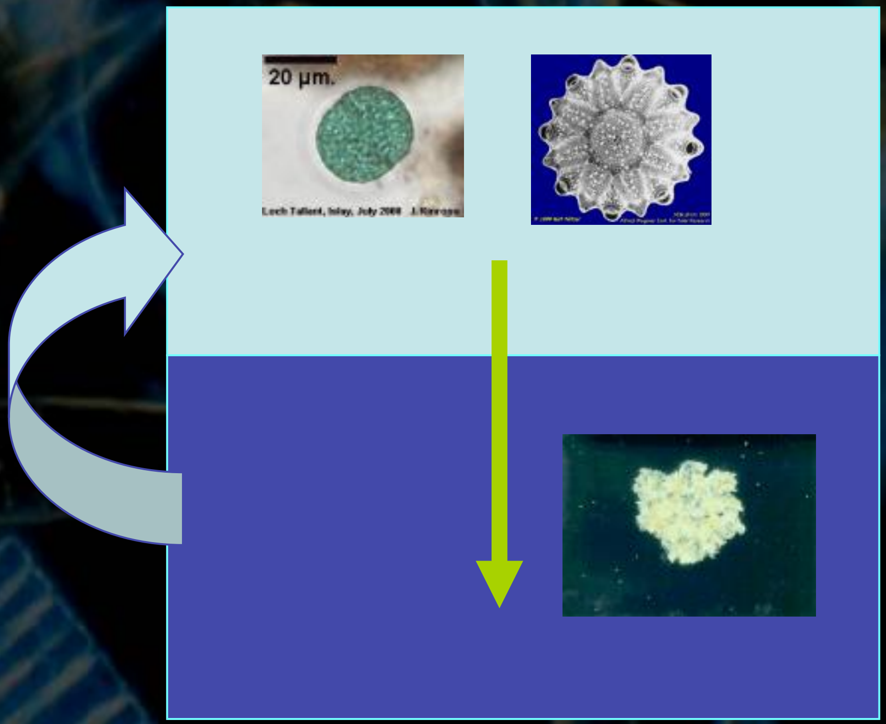
$$f_0 H / f \rightarrow f_0 d\rho / f(\partial\rho / \partial z)$$

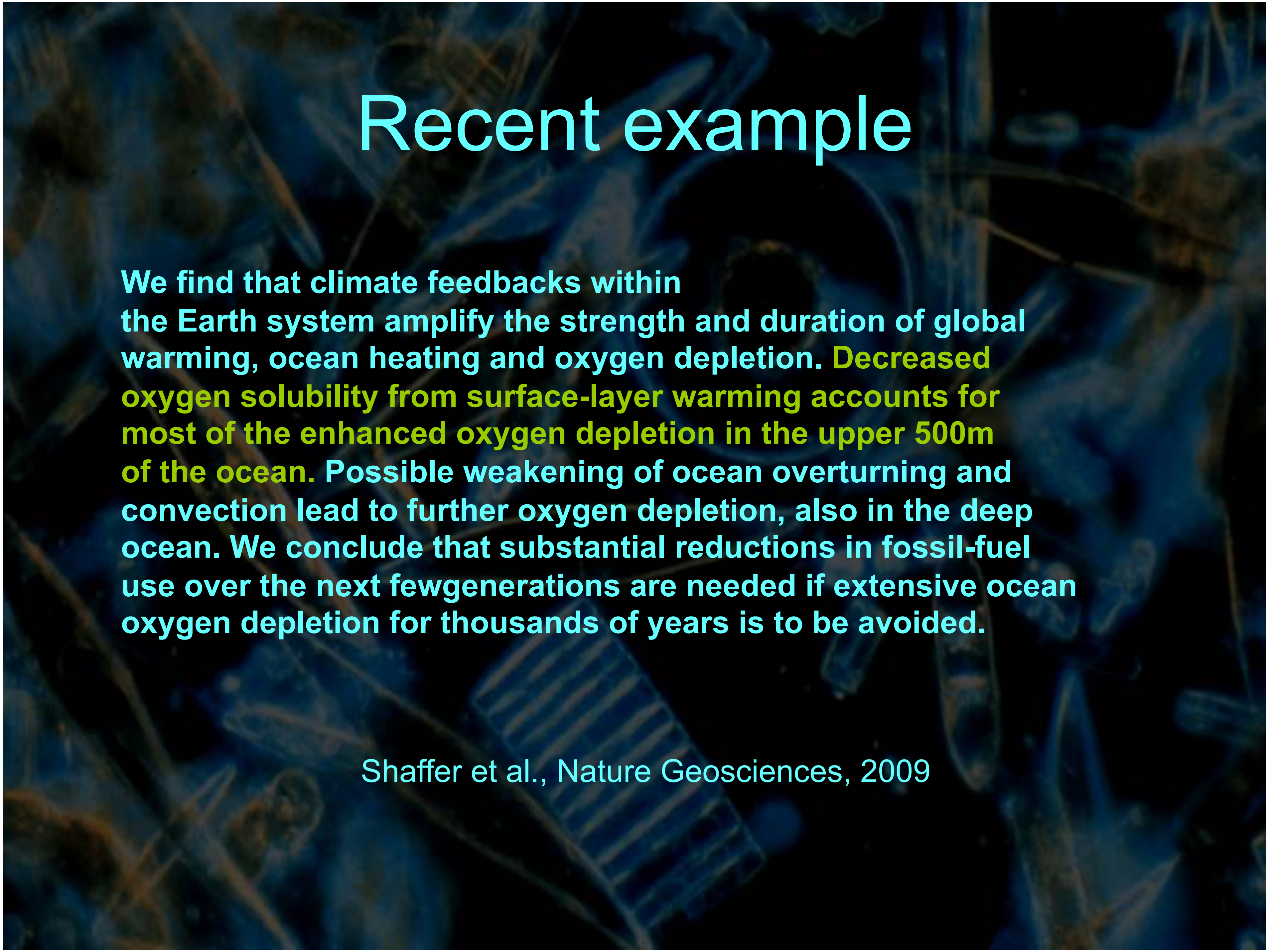
Summary: Part 1

- Well ventilated ocean has potential thickness contours that connect to outcrop regions directly, are relatively high PT. Isopycnal dynamics dominate.
- Poorly ventilated ocean has potential thickness contours that connect with boundaries, are relatively low PT. Diapycnal processes can be more important.
- Oxygen minimum zones are dynamically controlled! (Physics shapes chemistry)

Part 2-Anoxia and global warming

- Higher T gives lower saturation
- Higher stratification means lower circulation, flux.
- Temperature should win.



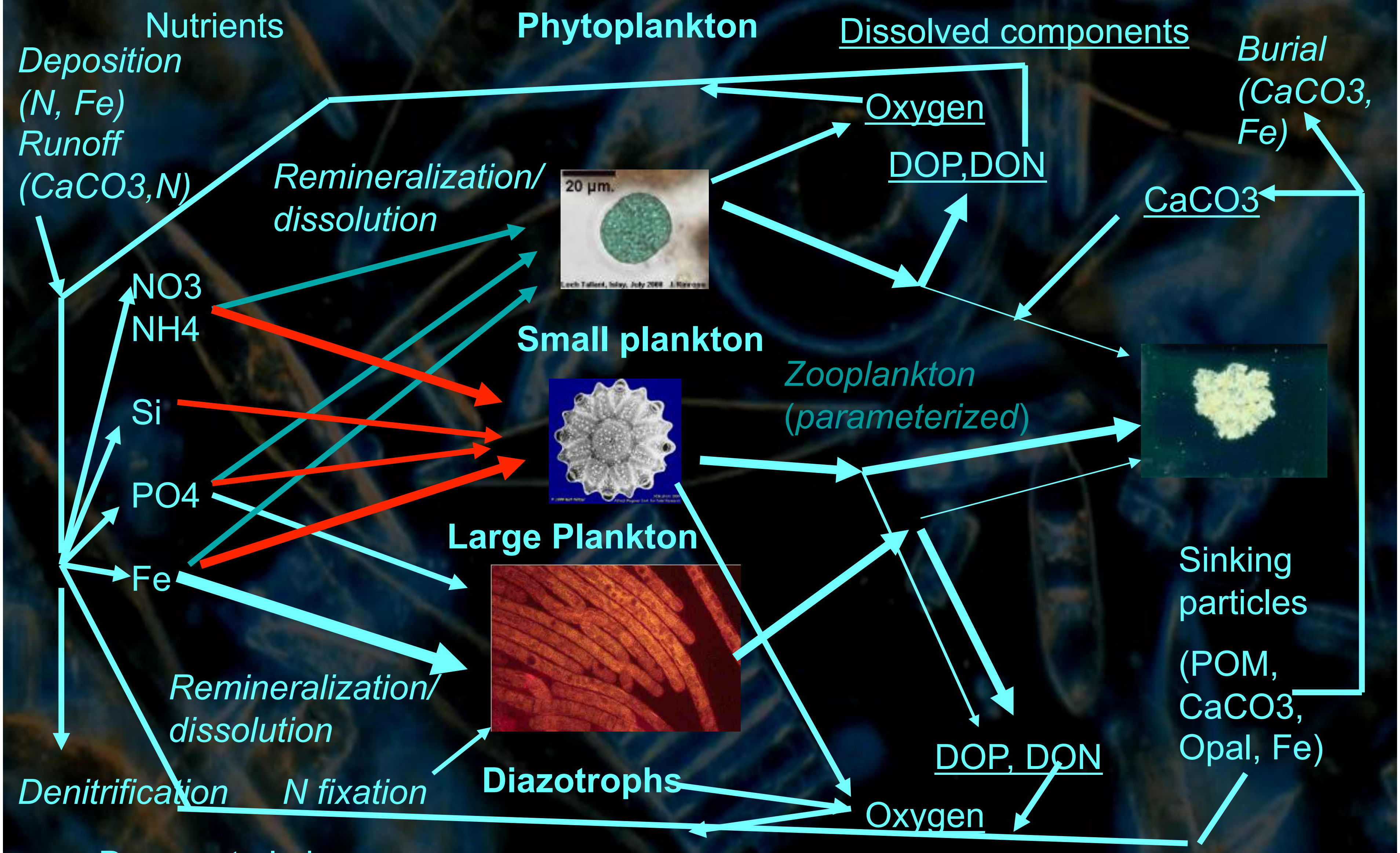


Recent example

We find that climate feedbacks within the Earth system amplify the strength and duration of global warming, ocean heating and oxygen depletion. Decreased oxygen solubility from surface-layer warming accounts for most of the enhanced oxygen depletion in the upper 500m of the ocean. Possible weakening of ocean overturning and convection lead to further oxygen depletion, also in the deep ocean. We conclude that substantial reductions in fossil-fuel use over the next fewgenerations are needed if extensive ocean oxygen depletion for thousands of years is to be avoided.

Shaffer et al., Nature Geosciences, 2009

GFDL's new Ocean BGC model (TOPAZ)



Nutrients

Phytoplankton

Dissolved components

Deposition
(N, Fe)
Runoff
(CaCO3,N)

Burial
(CaCO3,
Fe)

Oxygen

DOP,DON

Remineralization/
dissolution

CaCO3

NO3
NH4

Si

PO4

Fe

Small plankton

Zooplankton
(parameterized)

Large Plankton

Sinking
particles

(POM,
CaCO3,
Opal, Fe)

Remineralization/
dissolution

DOP, DON

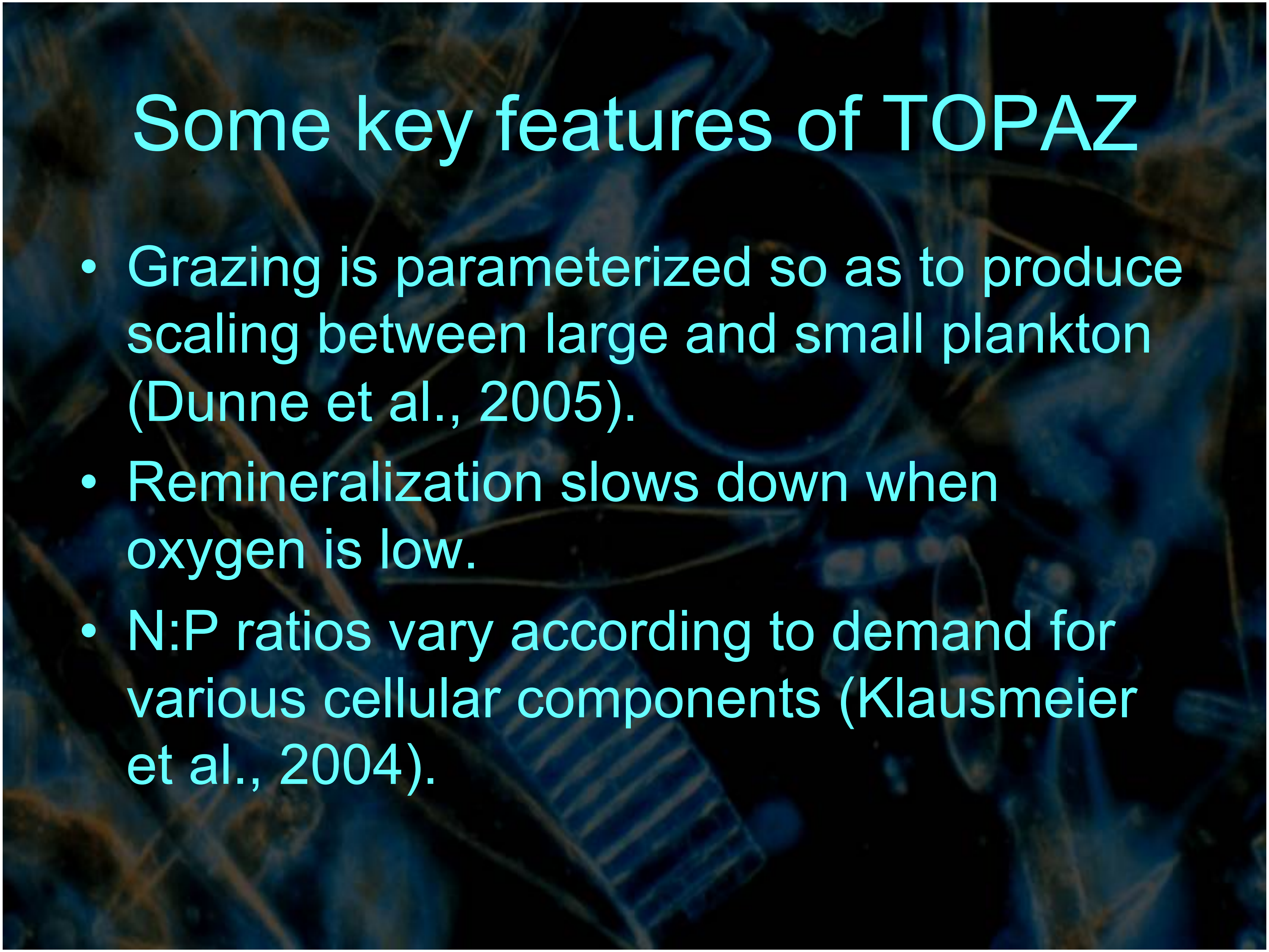
Denitrification

N fixation

Diazotrophs

Oxygen

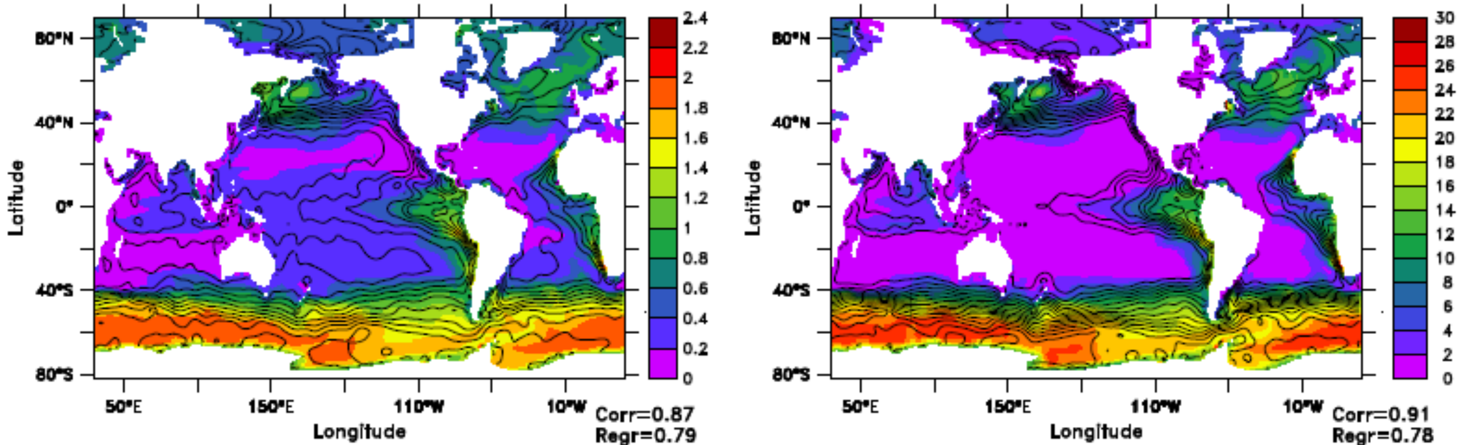
Dunne et al., in prep.



Some key features of TOPAZ

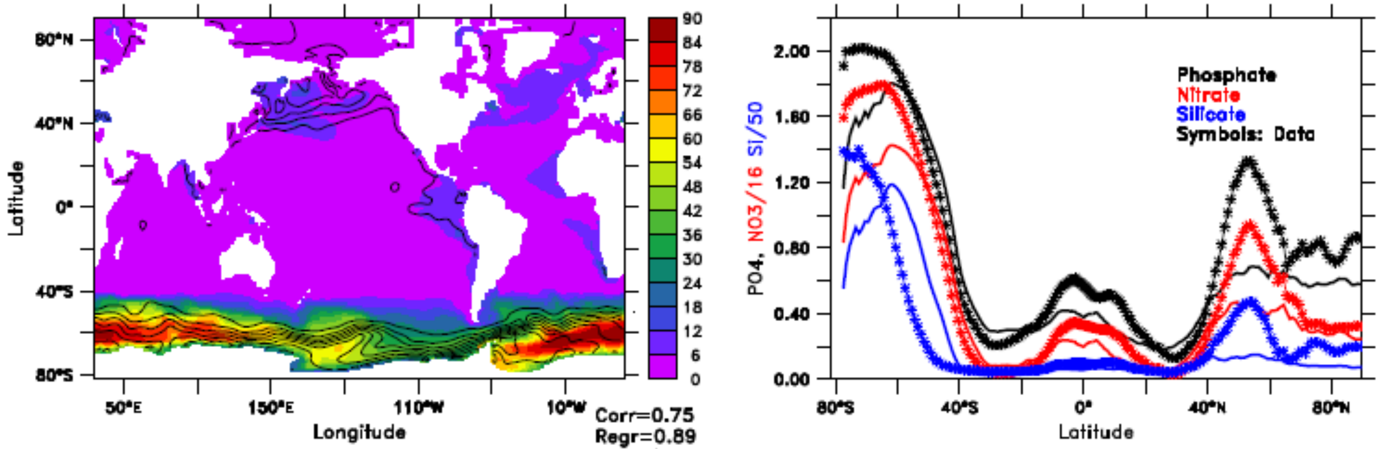
- Grazing is parameterized so as to produce scaling between large and small plankton (Dunne et al., 2005).
- Remineralization slows down when oxygen is low.
- N:P ratios vary according to demand for various cellular components (Klausmeier et al., 2004).

Model solution



(a) PO_4, 0–100m (mmol/m^3)

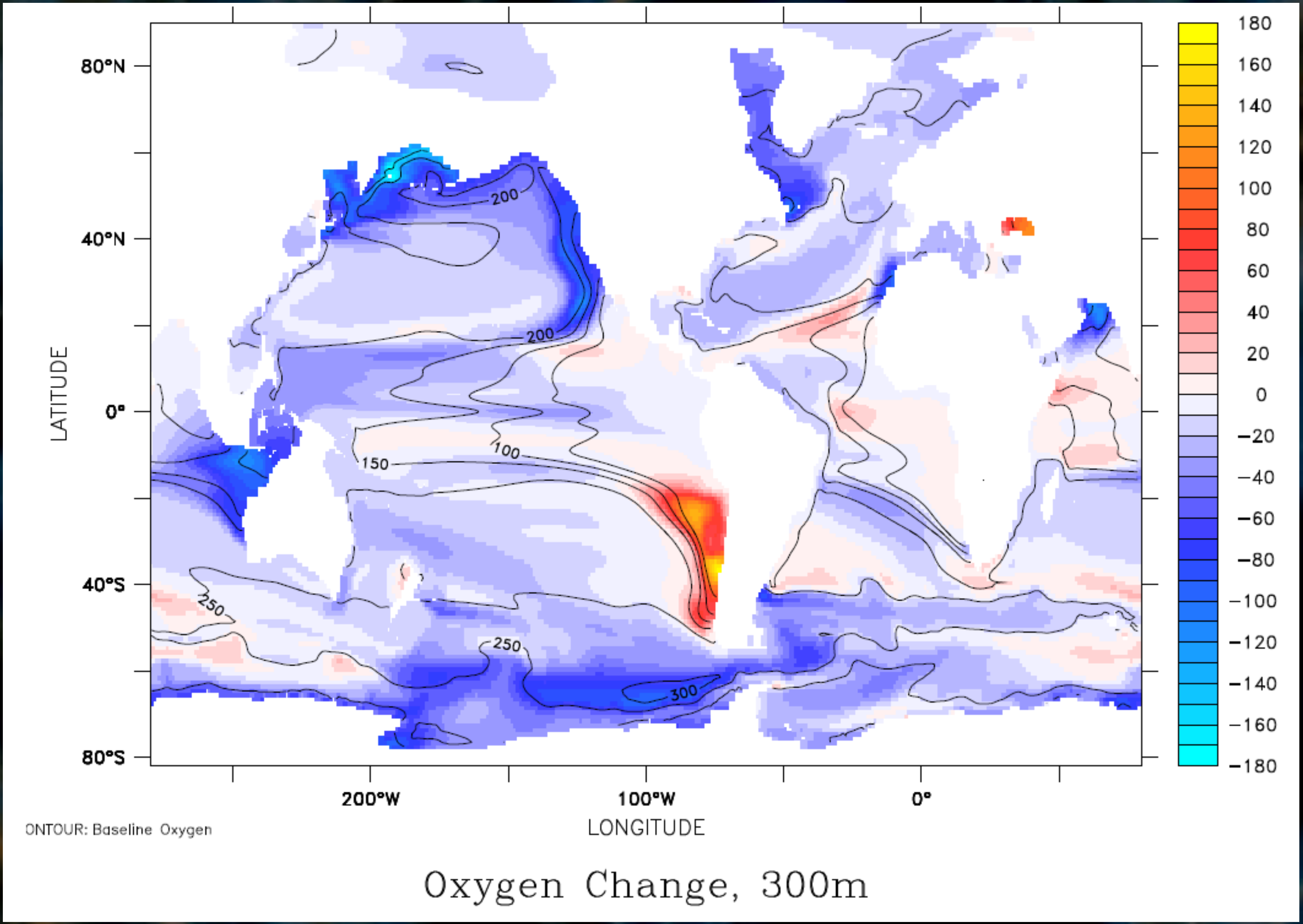
(b) NO_3, 0–100m (mmol/m^3)



(c) SiO_4, 0–100m (mmol/m^3)

(d) Zonal average macronutrients 0–100m

Oxygen change at 300m



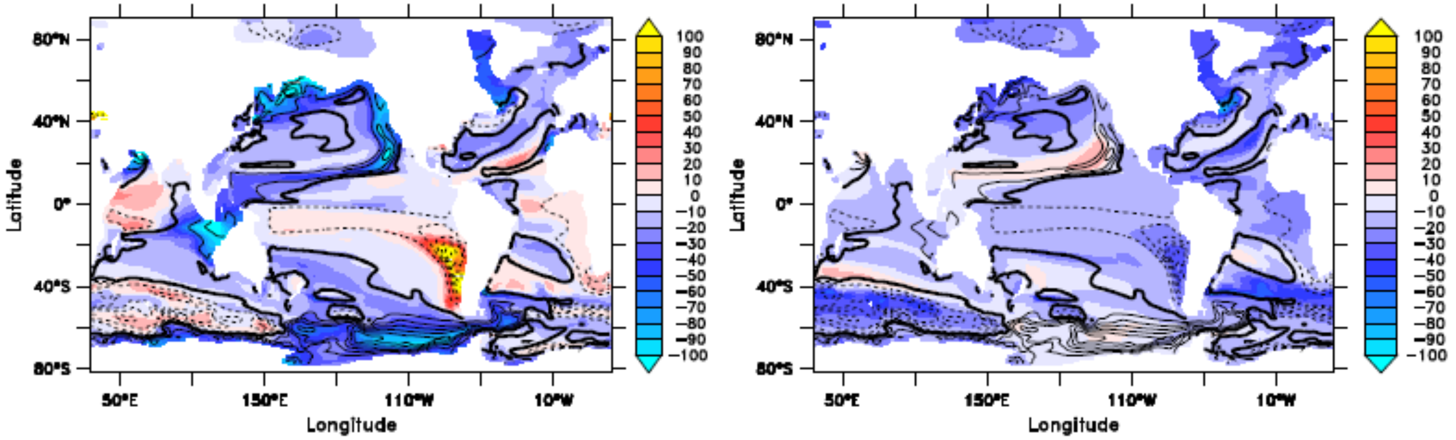
Subtropical gyres and margins show opposite response!

Ideal age simulations in previous coupled model

Ideal age: Set to zero in top layer at each time step. Age one year/year below that level.

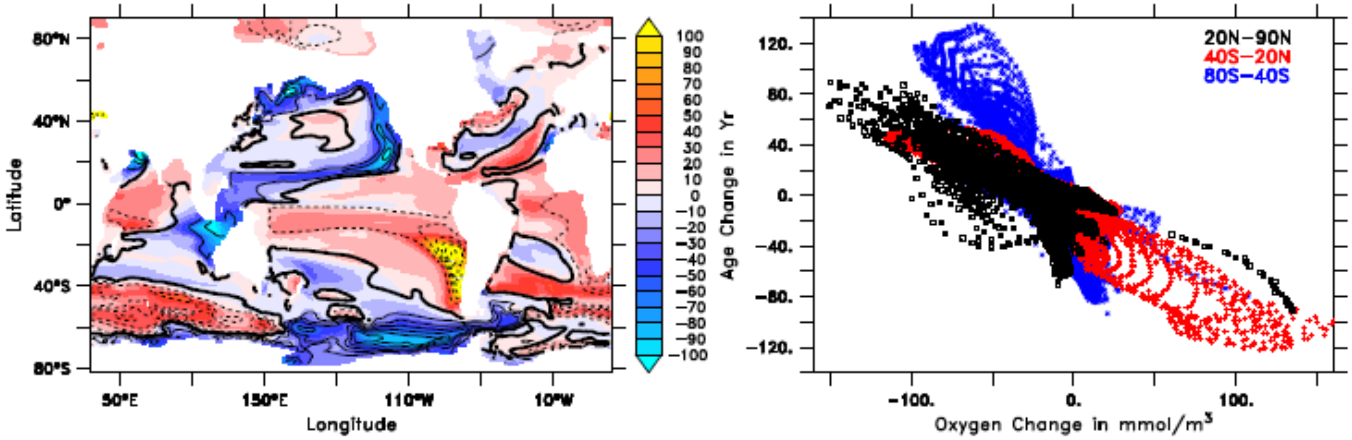
Run in mainstream coupled models at GFDL for over a decade.

Pattern of oxygen change and age



(a) O2 and Age Change, 300m

(b) Saturation O2 and Age Change, 300m

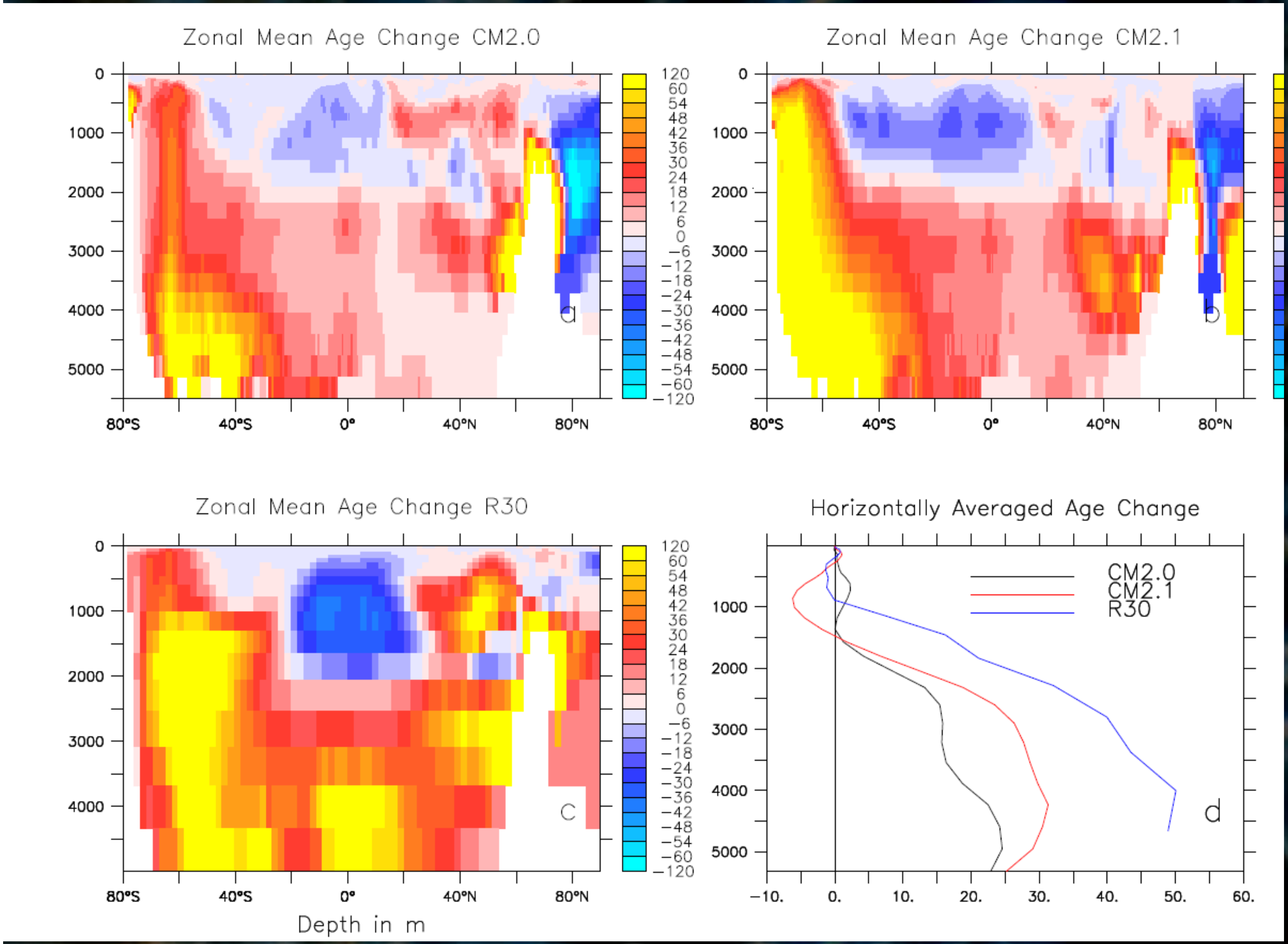


(c) Non-saturation O2 and Age Change, 300m

(d) Oxygen change vs. Age Change

Gnanadesikan, Dunne, Rykaczewksi and John in prep.

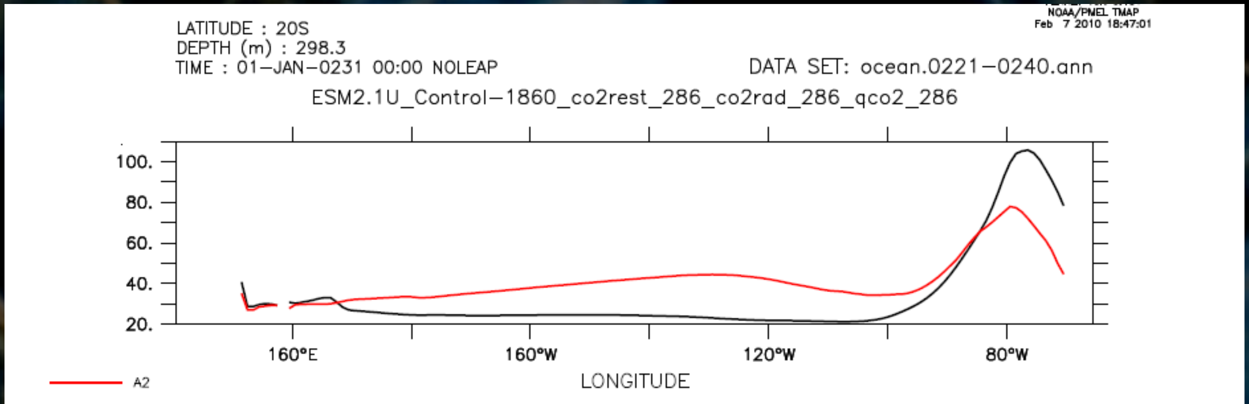
Not just a feature seen in this model!



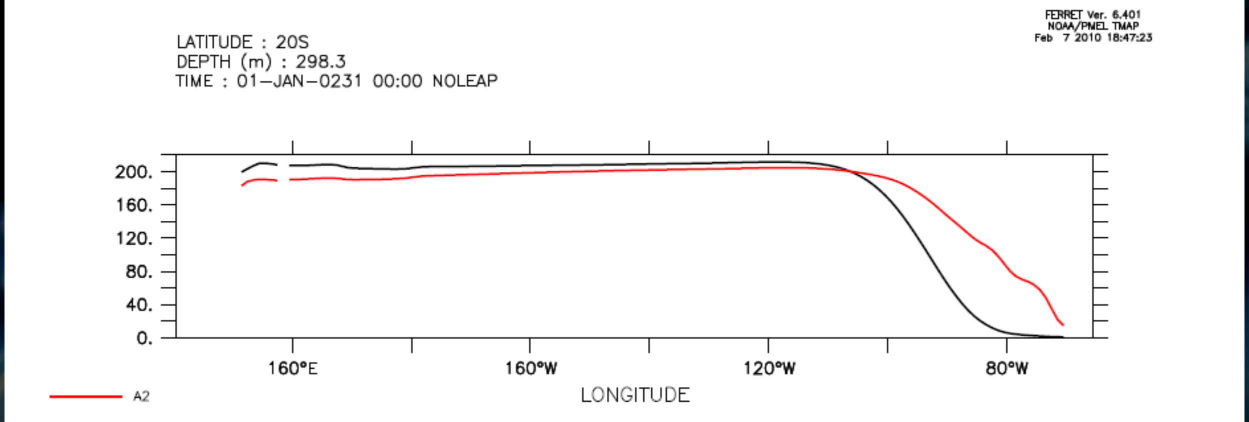
Similar features also seen in NCAR model

Gnanadesikan, Russell and Zeng, 2007

Why the change? Potential thickness explains part…



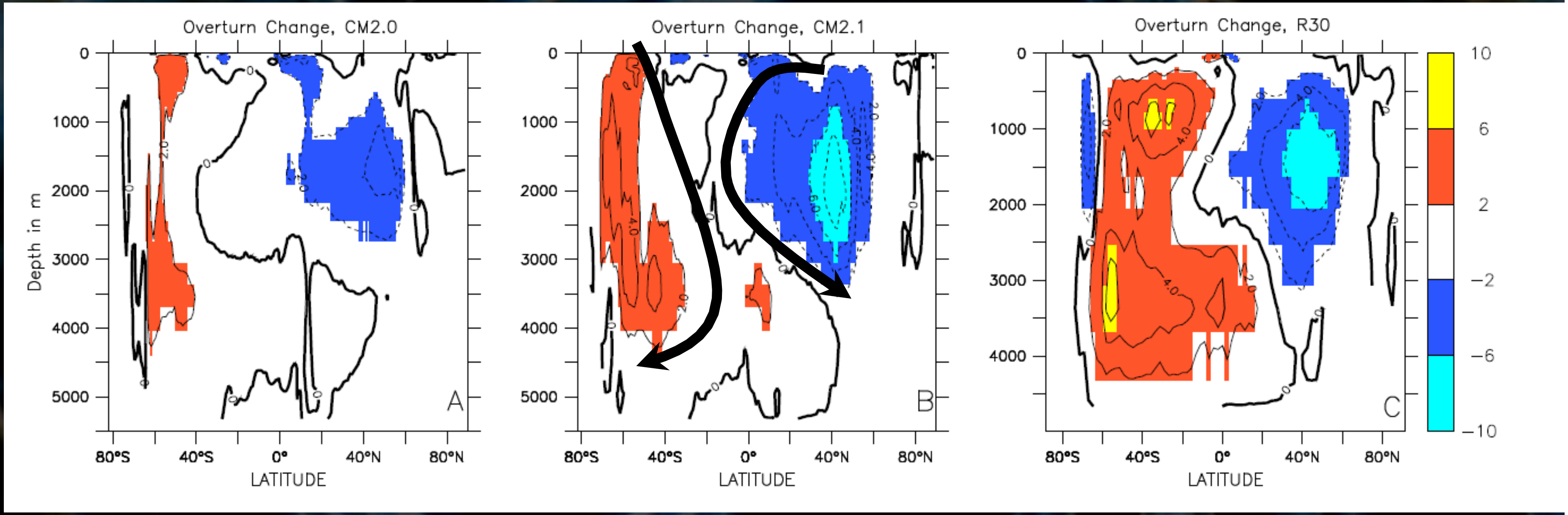
Potential Thickness



Oxygen

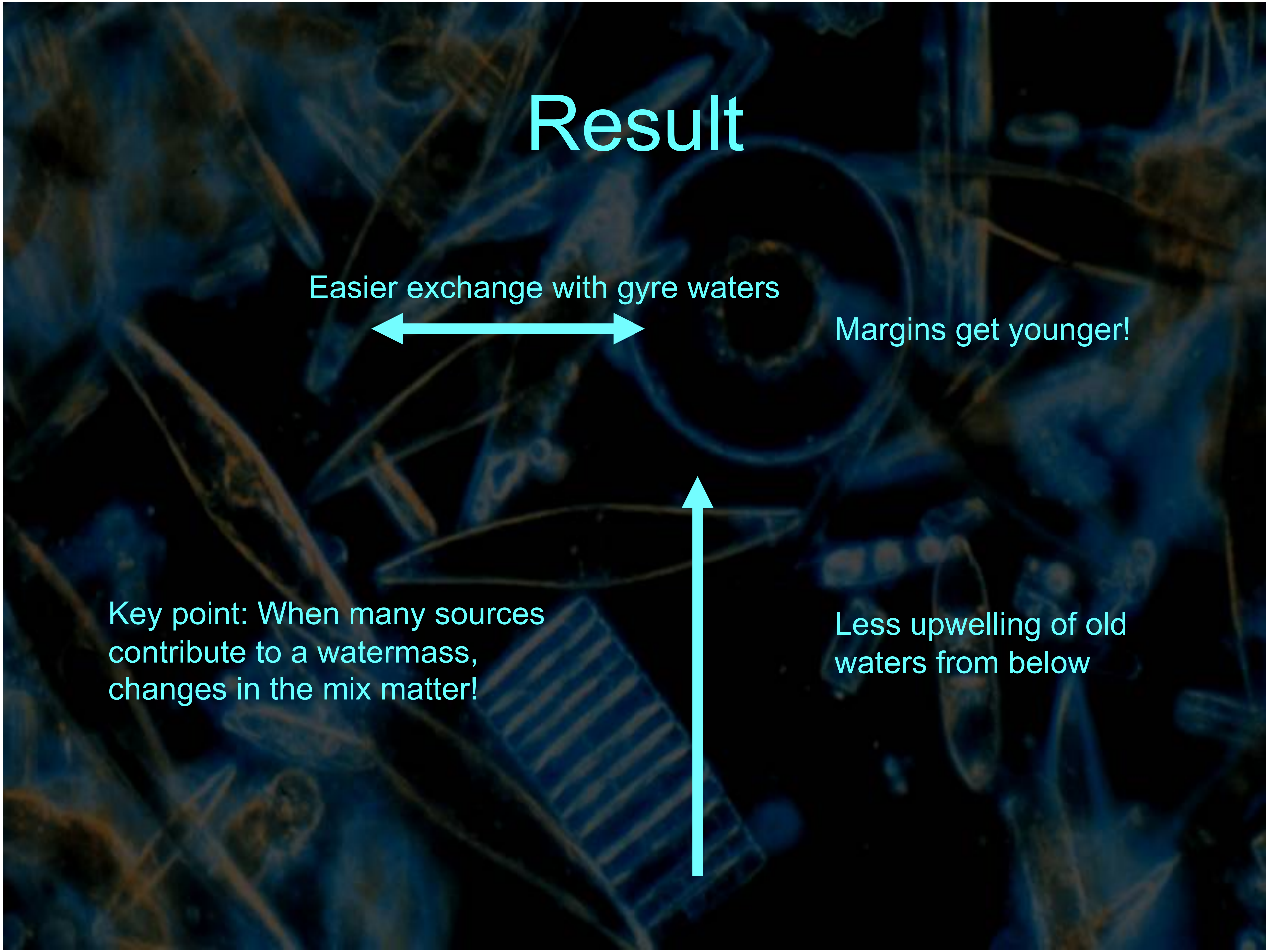
Easier for surface waters to enter oxygen minimum zones.

..and slowdown of deep overturning explains the other



Less old water coming up from below

Result



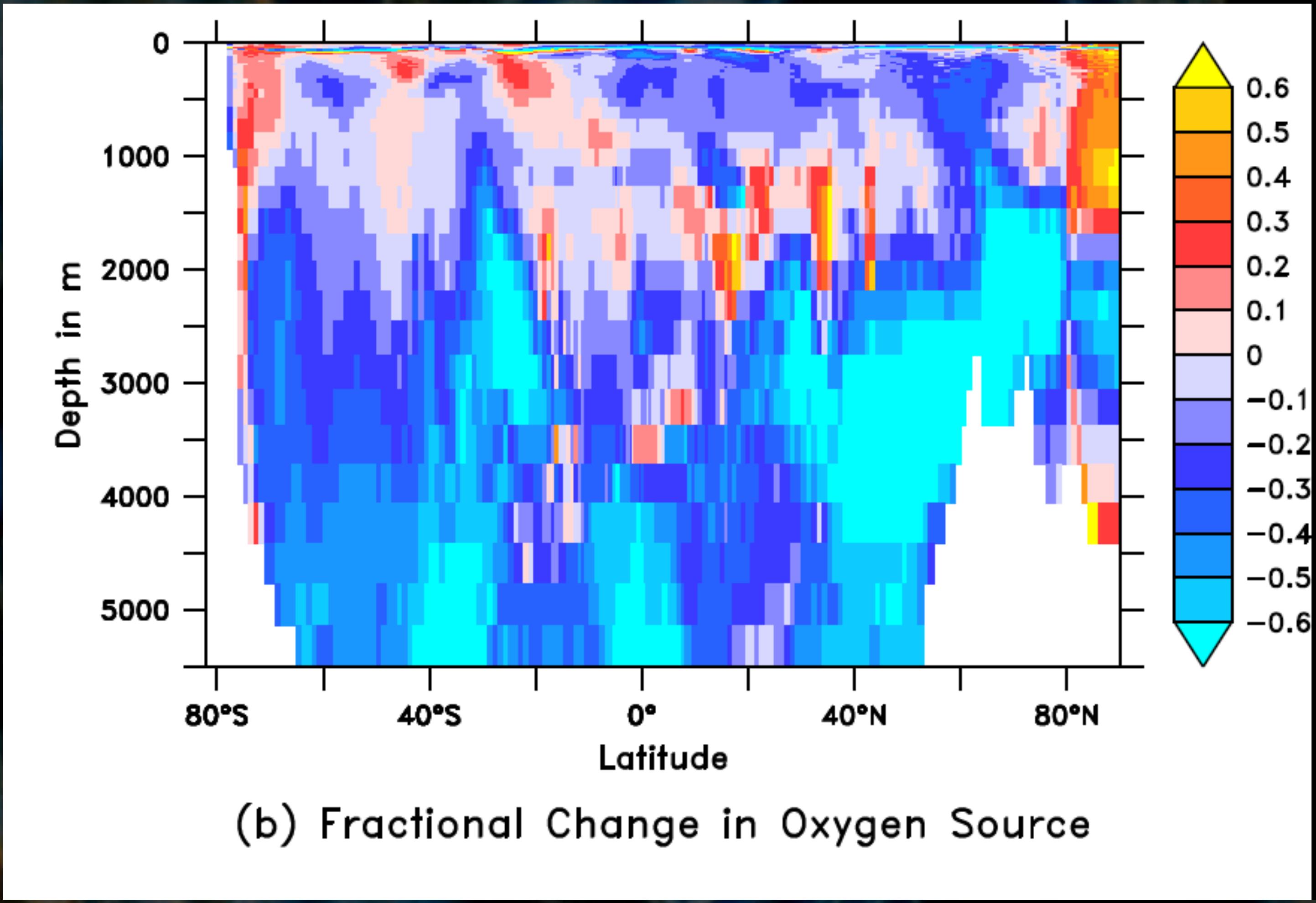
Easier exchange with gyre waters

Margins get younger!

Key point: When many sources contribute to a watermass, changes in the mix matter!

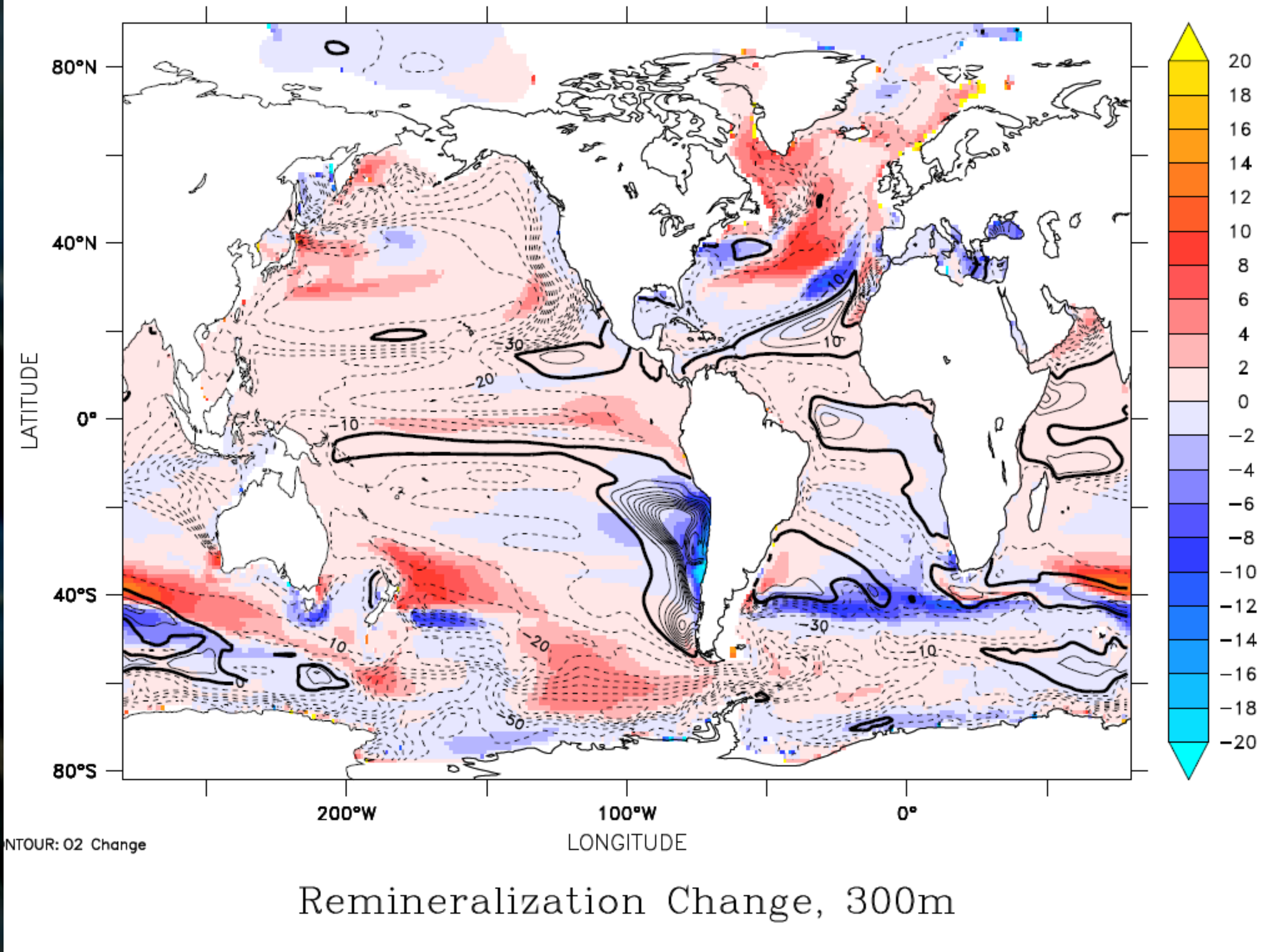
Less upwelling of old waters from below

What about remineralization?



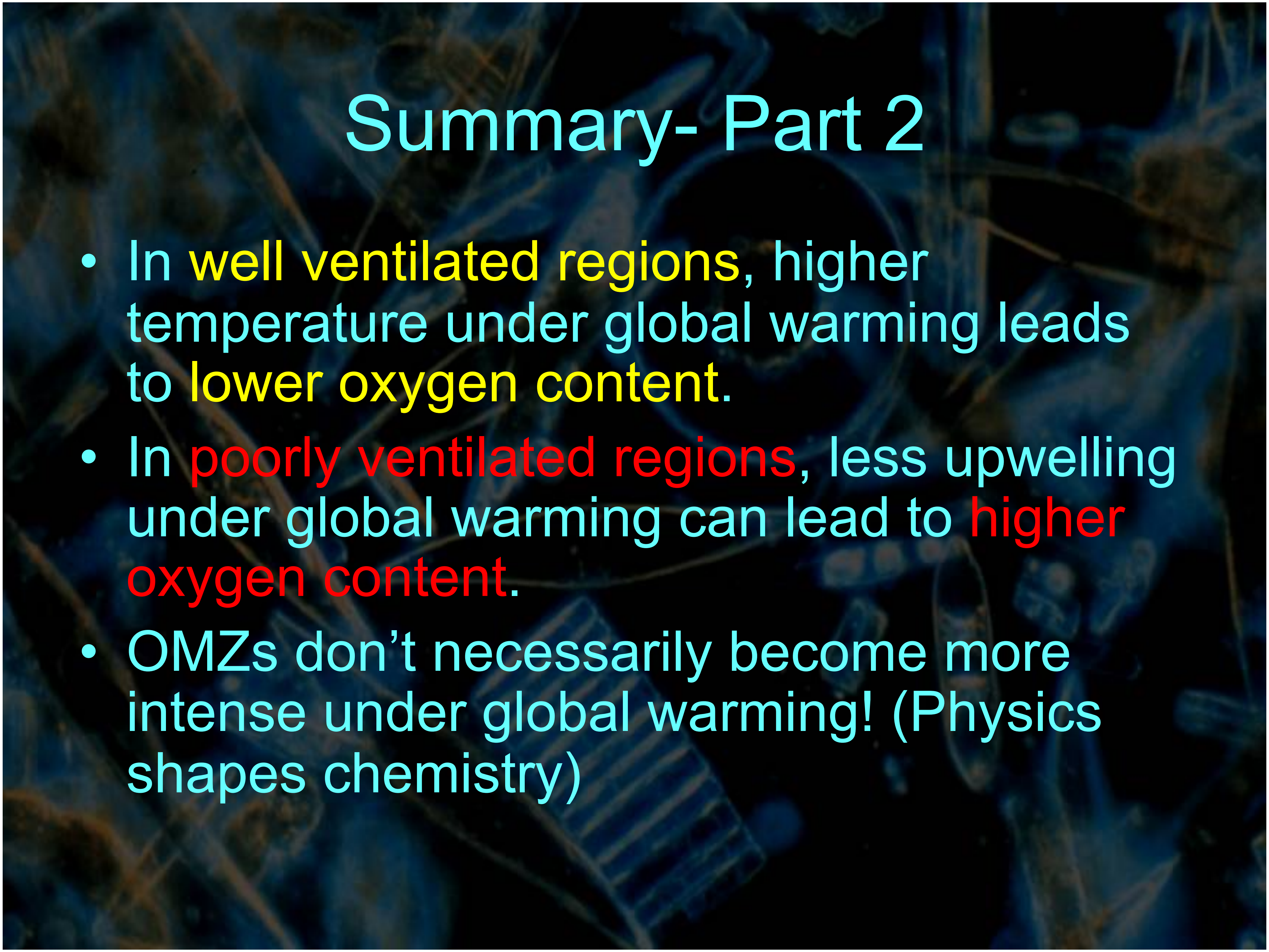
Smaller sink at depth opposes oxygen change.

Remineralization fails to explain change at 300m



Remineralization Change, 300m

Some *inverse* correlation (coefficient =-0.21)



Summary- Part 2

- In well ventilated regions, higher temperature under global warming leads to lower oxygen content.
- In poorly ventilated regions, less upwelling under global warming can lead to higher oxygen content.
- OMZs don’t necessarily become more intense under global warming! (Physics shapes chemistry)

Part 3- Ocean water clarity and climate

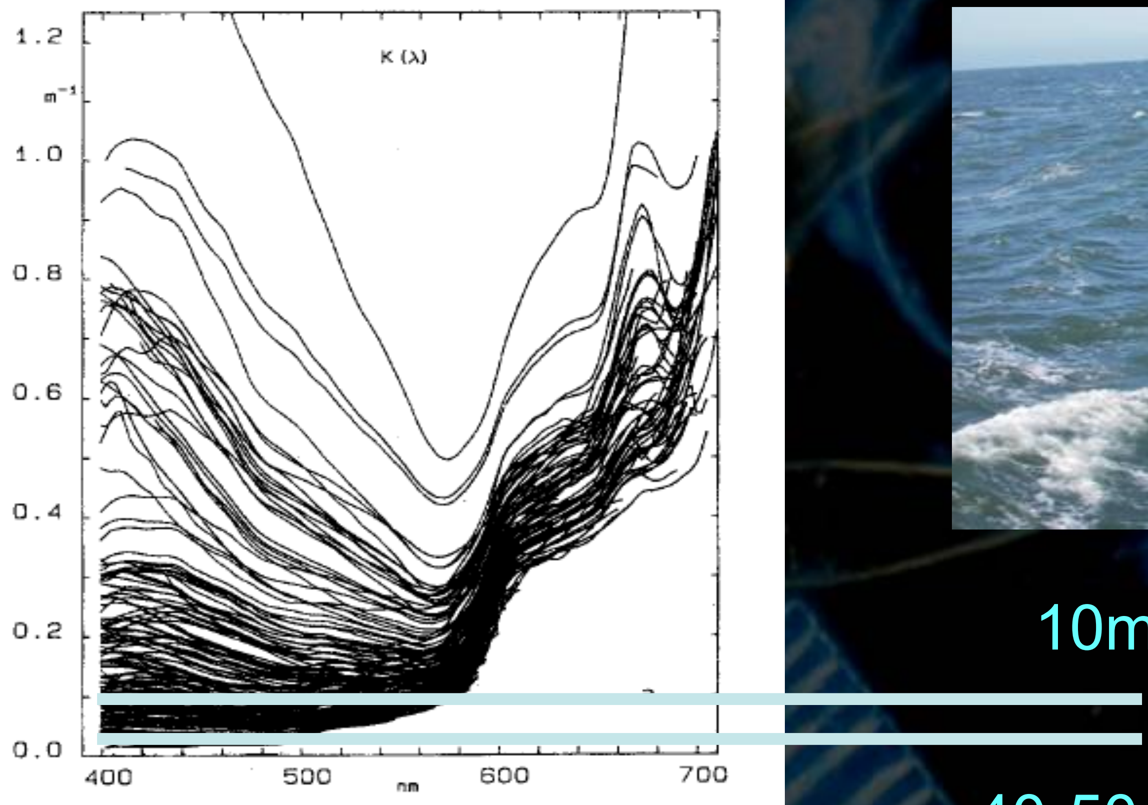


Fig. 5a. Experimental values of the attenuation coefficient for downwelling irradiance $K(\lambda)$ as a function of the wavelength (case I waters only, see text). These spectra (176) form the data bank used in the statistical analysis.

10m e-folding

~40-50m e-folding

How big is this effect?

Morel (1988) extinction coefficients

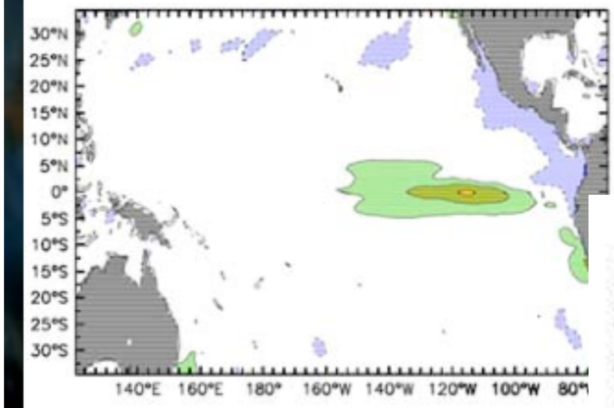
Ocean color and ENSO

- Timmermann and Jin (2002)- ocean color leads to weaker ENSO (biothermostat hypothesis)
- Marzeion et al. (2005) interactive ocean color leads to stronger ENSO.
- Lengaigne et al. (2007) finds same thing as Marzeion but concludes that it is shift of mean state that matters.
- In GFDL ESM2.1, interactive ocean color leaves ENSO spectrum unchanged.

Our strategy

- Use a chlorophyll-dependent shortwave absorption parameterization within a circulation model.
- Set chlorophyll to zero (should always cool surface, warm deep locally)
- Evaluate change in ocean-only models forced with “observed atmosphere”
- Evaluate change in fully coupled climate model (CM2.1 Atmosphere, *isopycnal* ocean)
- Look at sensitivity to *regional* changes in color.

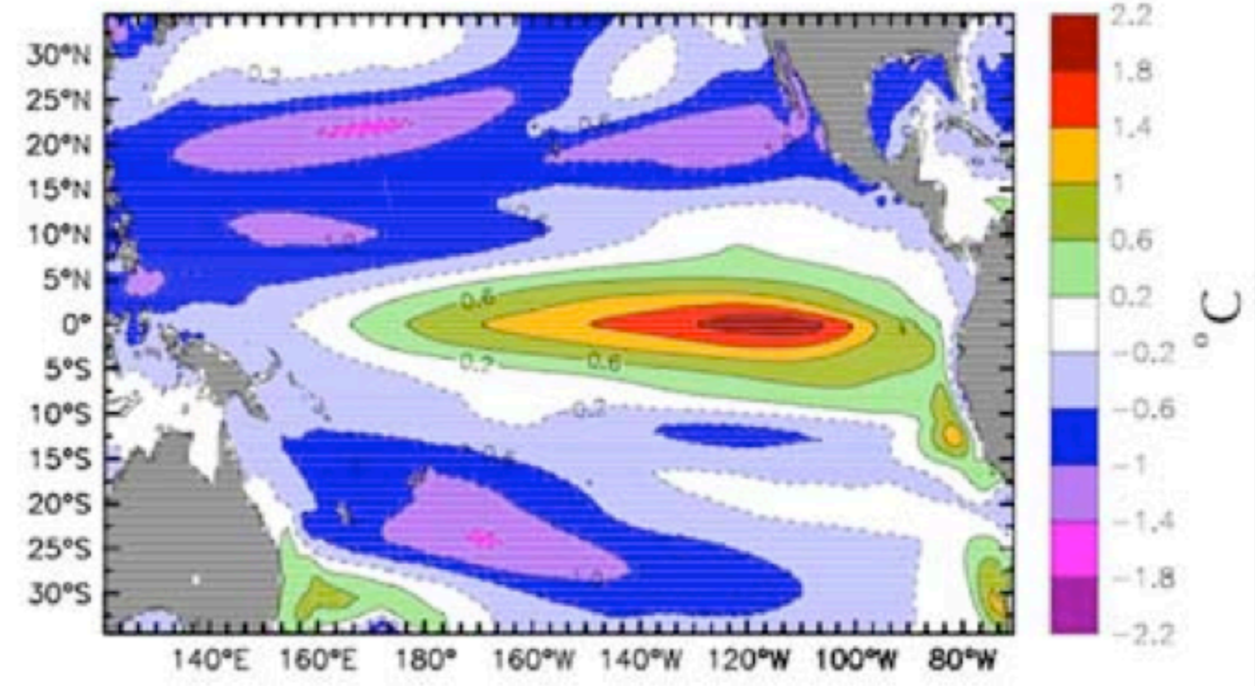
Ocean only vs. coupled



Blue - Green, (ocean only

Coupled (CM2.2)

100 year mean SST

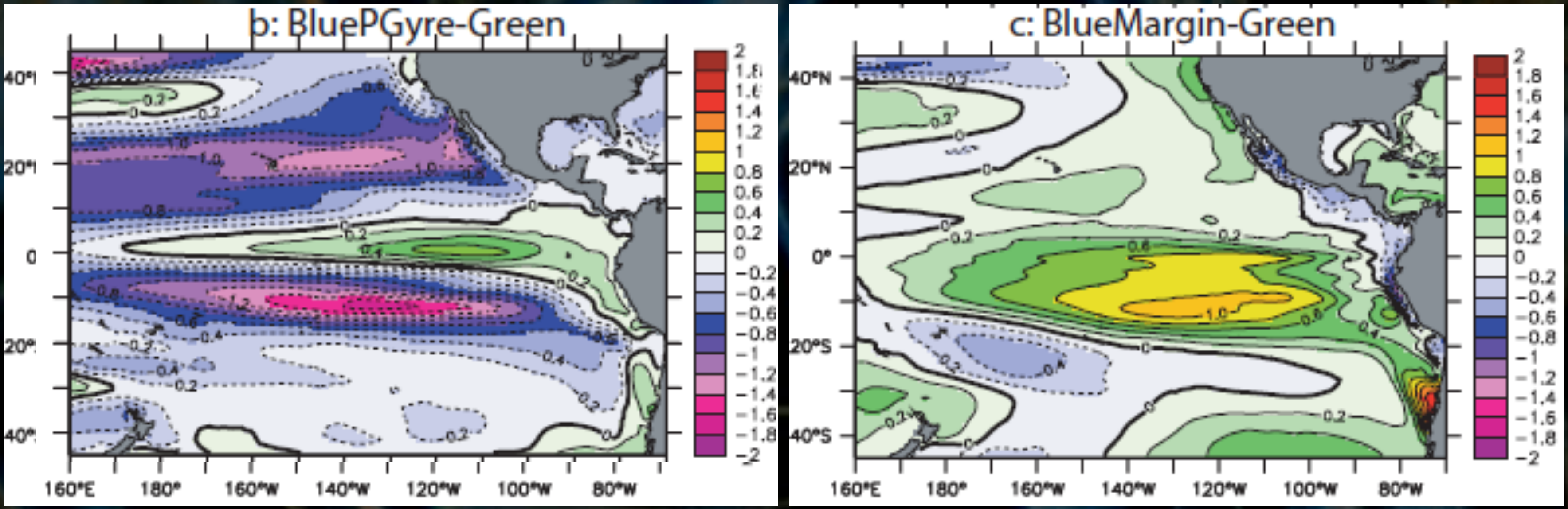


Blue - Green

Coupling enhances off-equatorial response.

Anderson et al, GRL, L11609, 2007

Gyres and margins show opposite response!



In gyres

Less mixing

Lower chlorophyll

Lower stratification

Negative feedback!

In margins

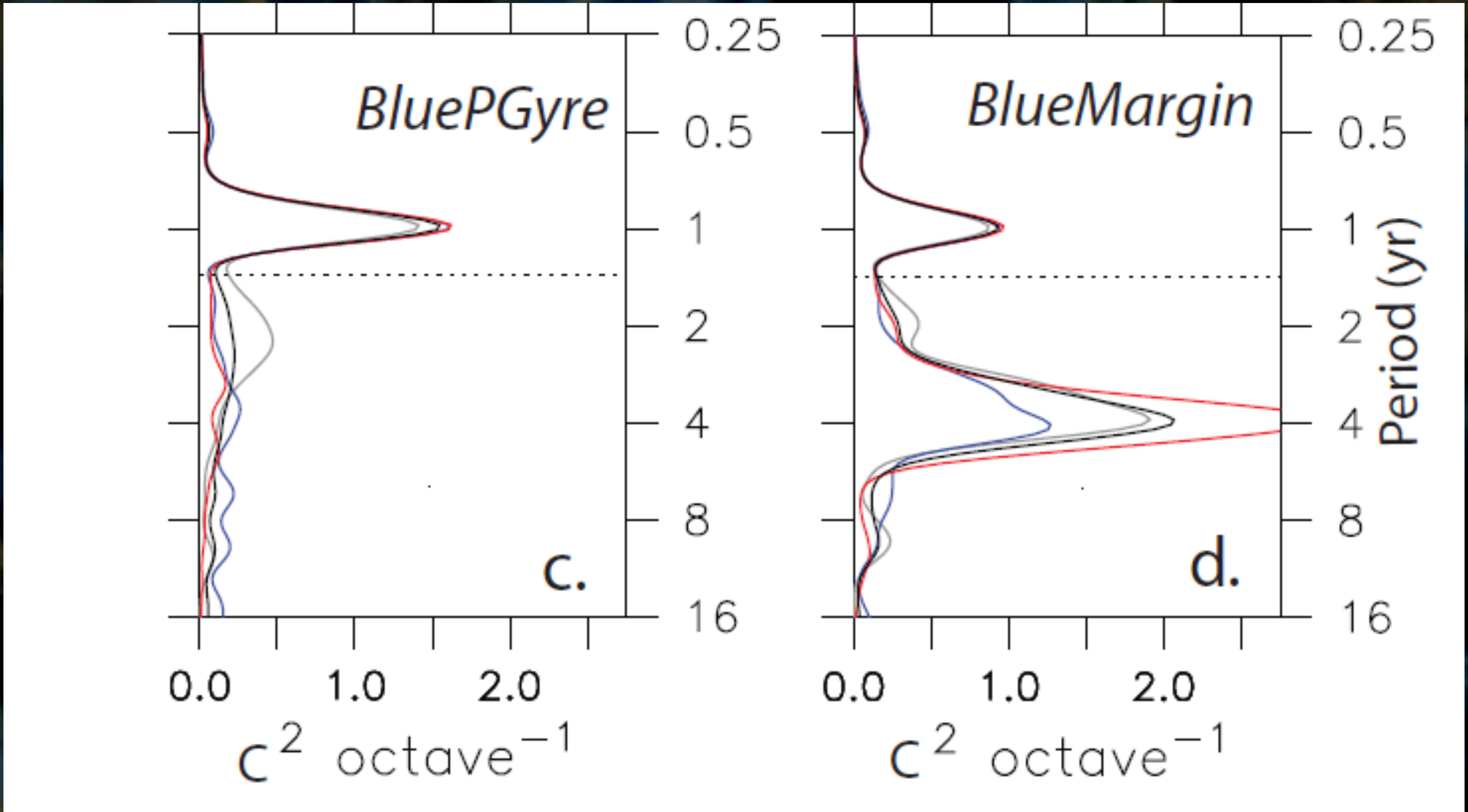
Less mixing

Lower chlorophyll

More stratification

Positive feedback!

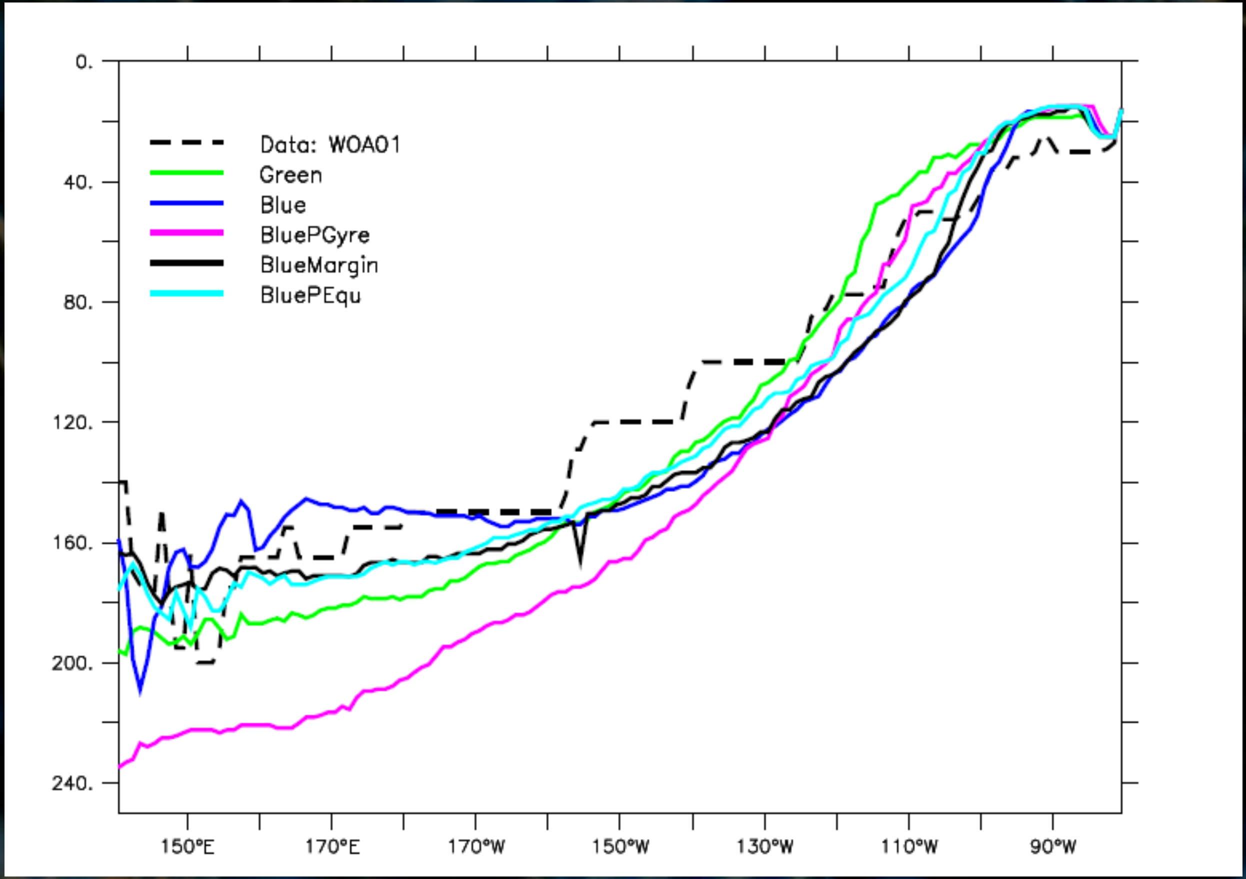
Ocean color can alter ENSO



Clear gyre= Weaker ENSO

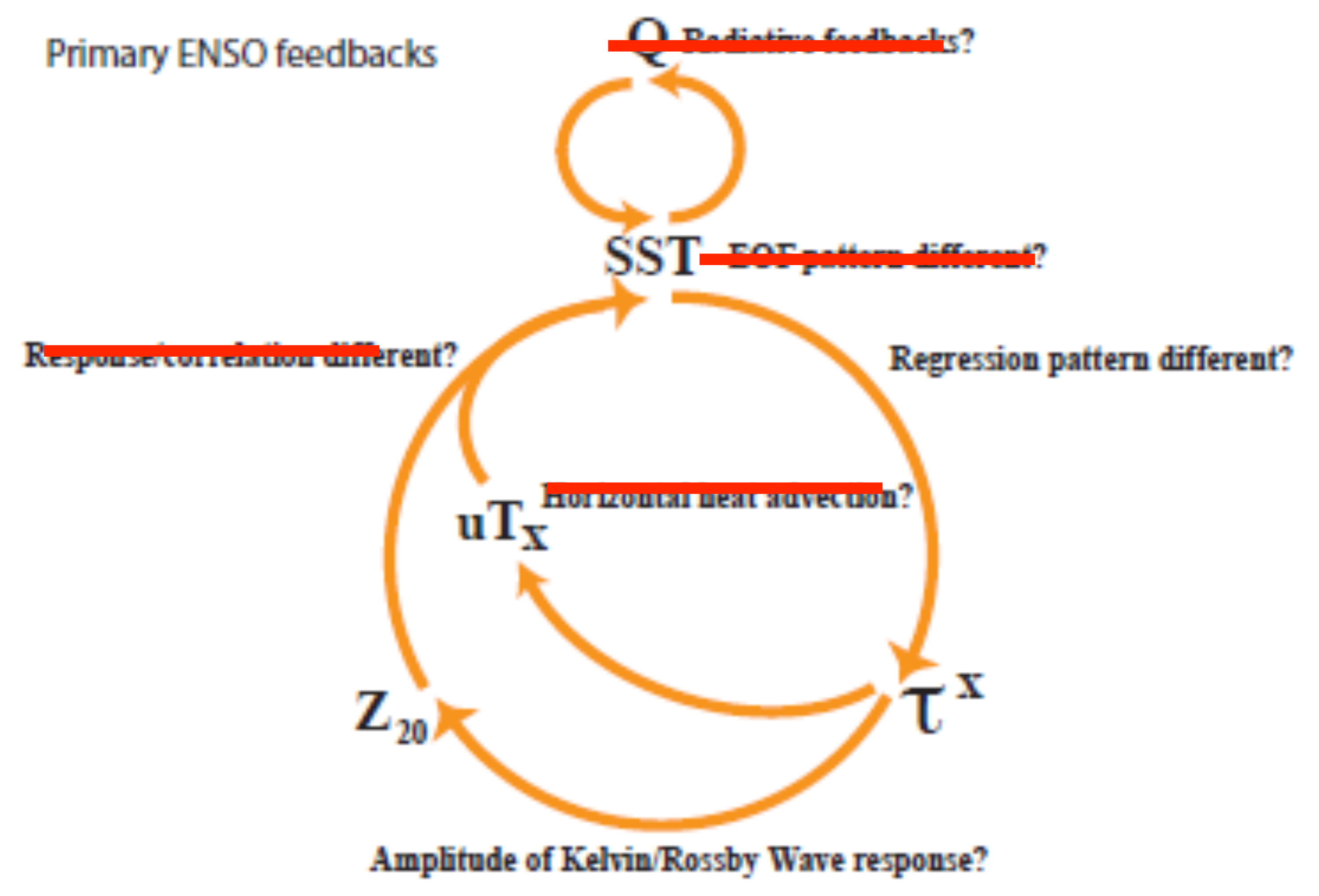
Clear margin= stronger ENSO

Initial hypothesis- thermocline depth

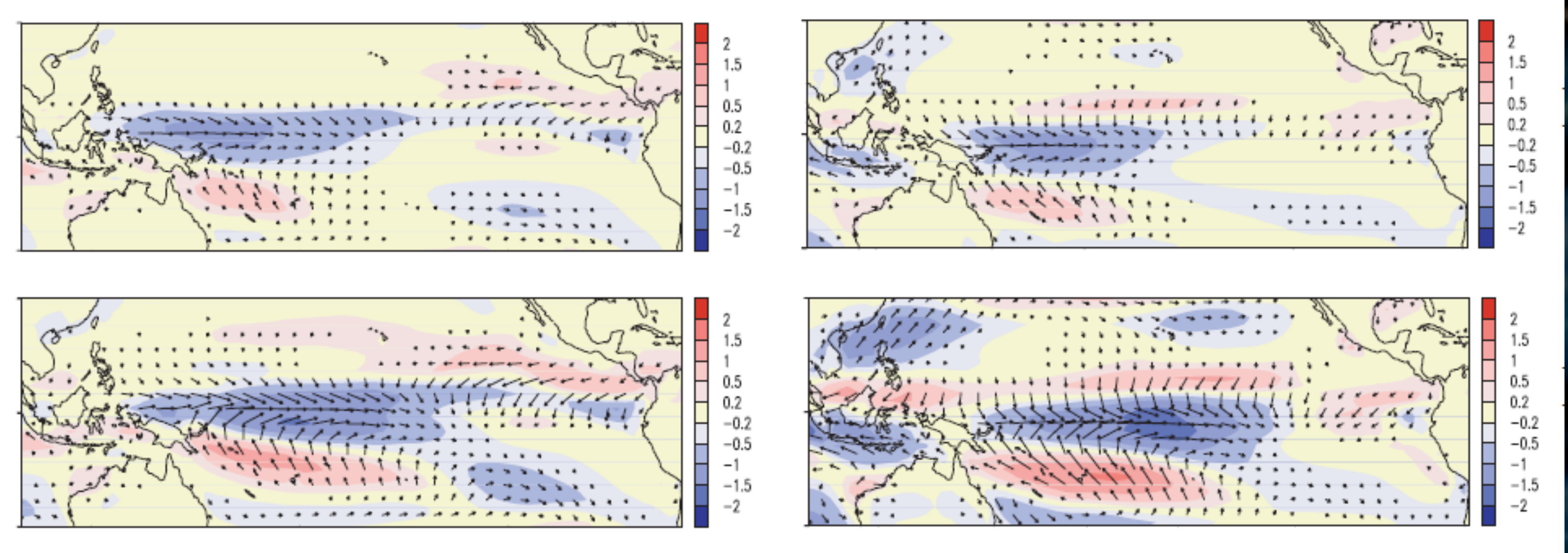


BlueMargin (strong ENSO) and BluePGyre (weak ENSO) both have deeper thermocline!

Brief review of ENSO physics



Wind stress/speed changes



Clear Gyre

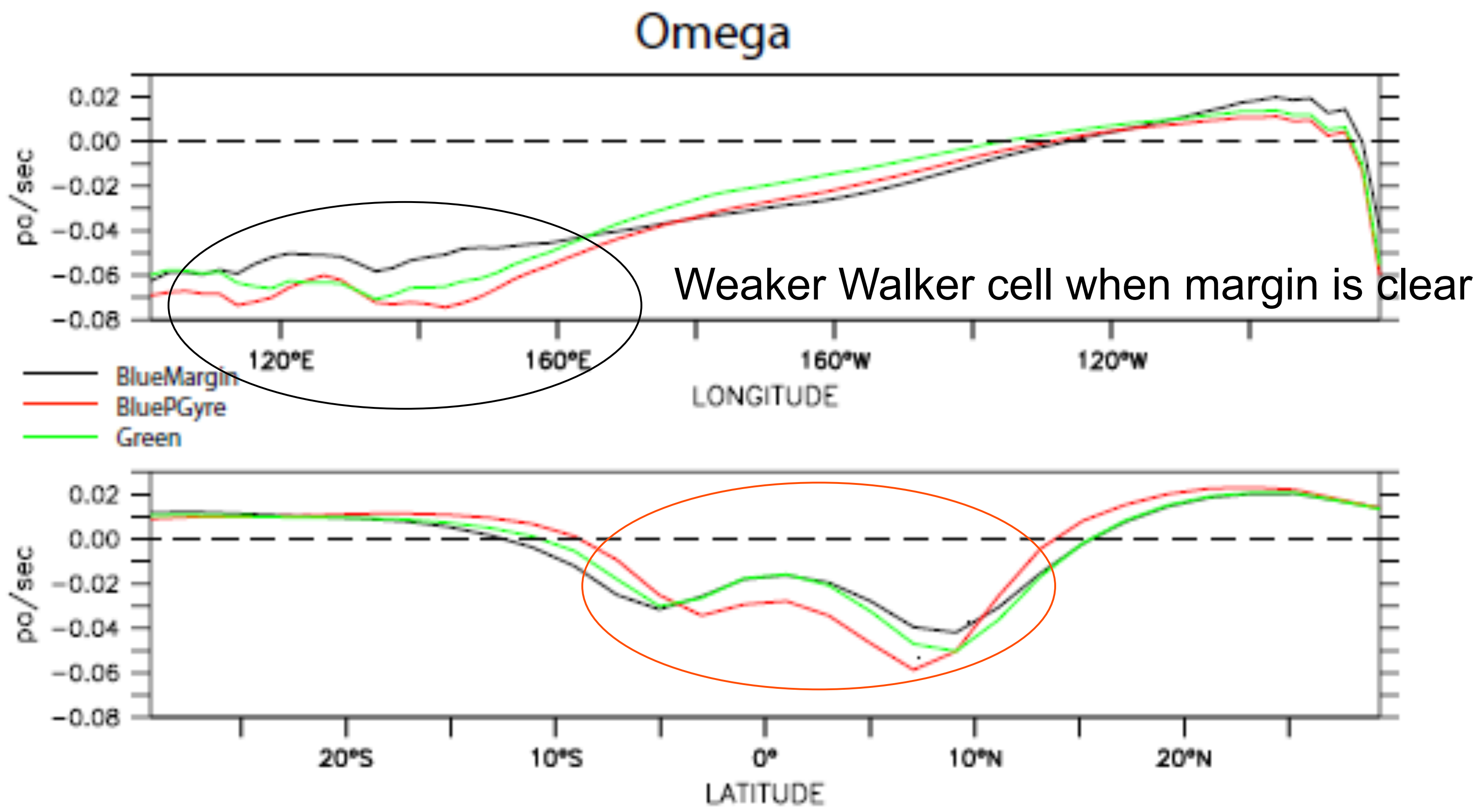
Clear Margin

SON

DJF

Response of wind stress to changes in equatorial SST is stronger over Central Pacific in Clear Margin (BlueMargin) case.

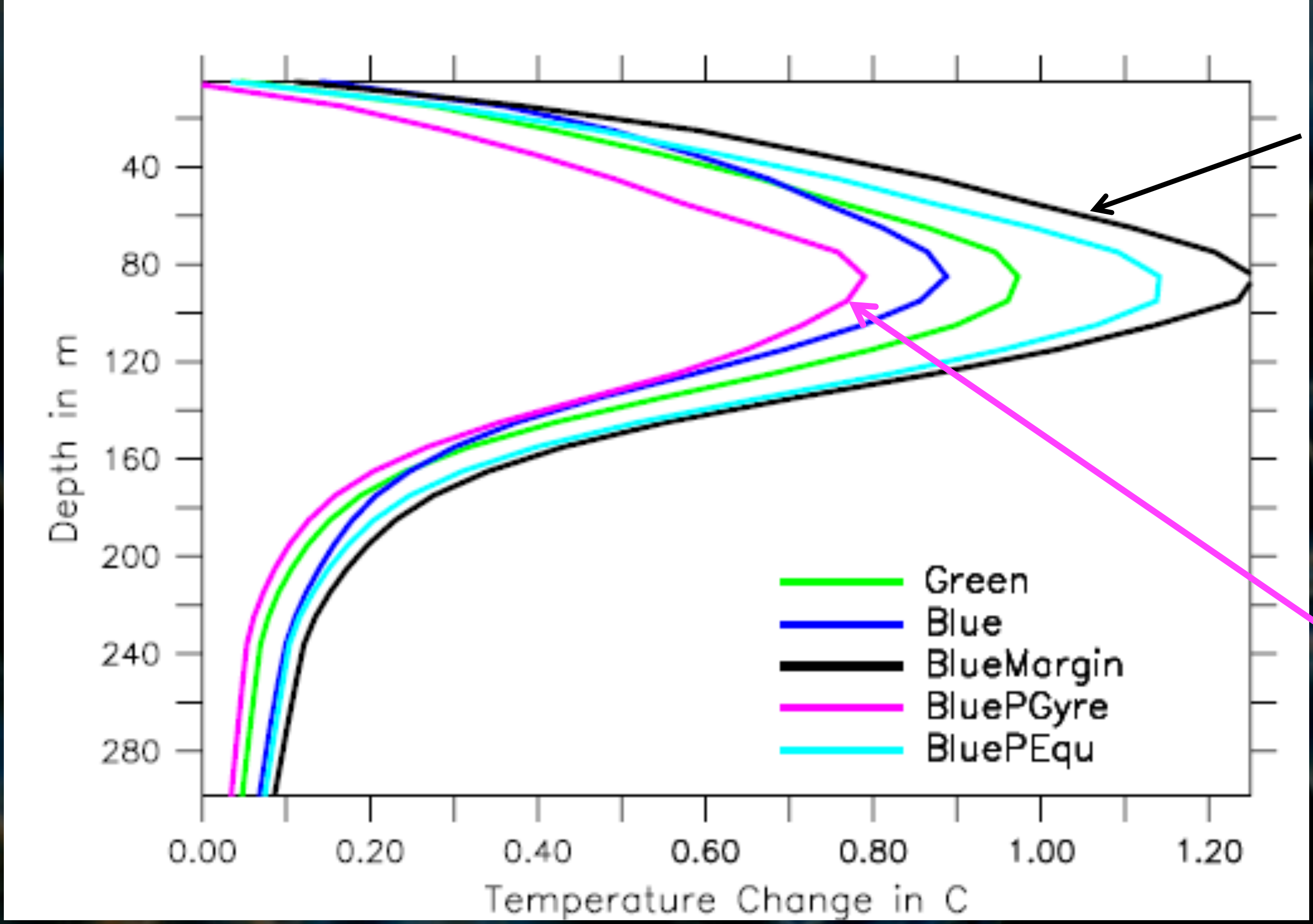
Why the difference?- A hypothesis



Weaker Walker cell when margin is clear

Tighter, more intense Hadley cell when gyres are clear

When different winds are run over the same ocean

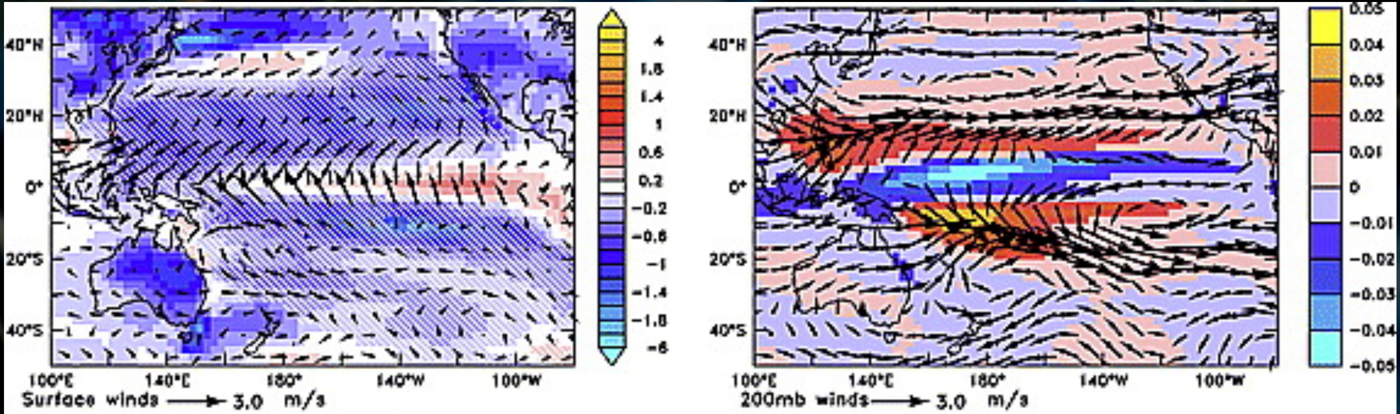


Clear margin- 1C SST gives 1.2C response at depth (positive feedback!)

Clear Gyre-1C SST change gives 0.7 C response at depth (damped).

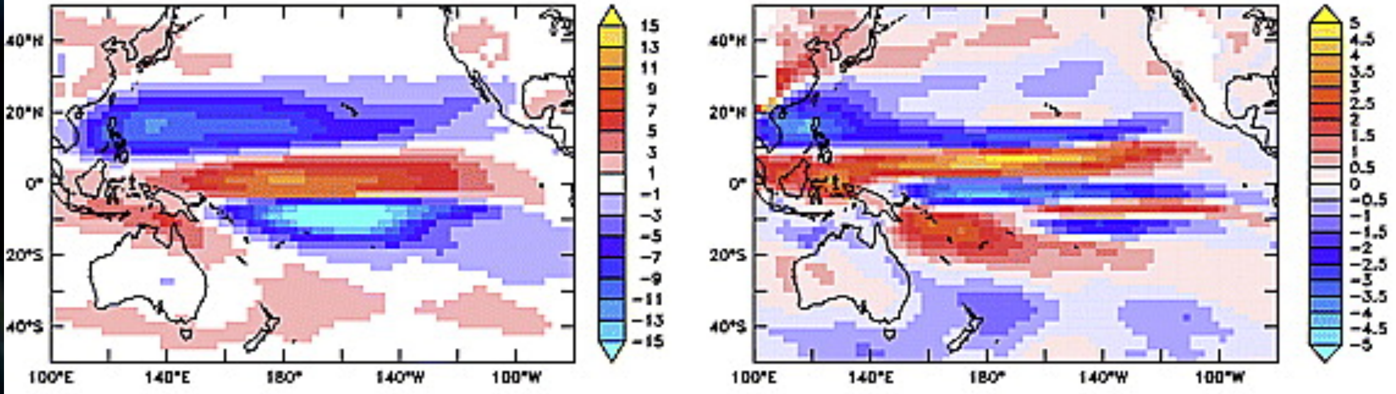
Anderson, Gnanadesikan and Wittenberg, 2009

Other consequences of Hadley cell change



(a) Surface Temperature (C) and Wind

(b) Omega (Pa/s) and Upper Level Wind



(c) Relative Humidity (percent) at 700mb

(d) Vorticity x 10^6 s at 850 mb

Both SST and atmospheric response project onto cyclogenesis

What's the impact on cyclogenesis?

Away from equator

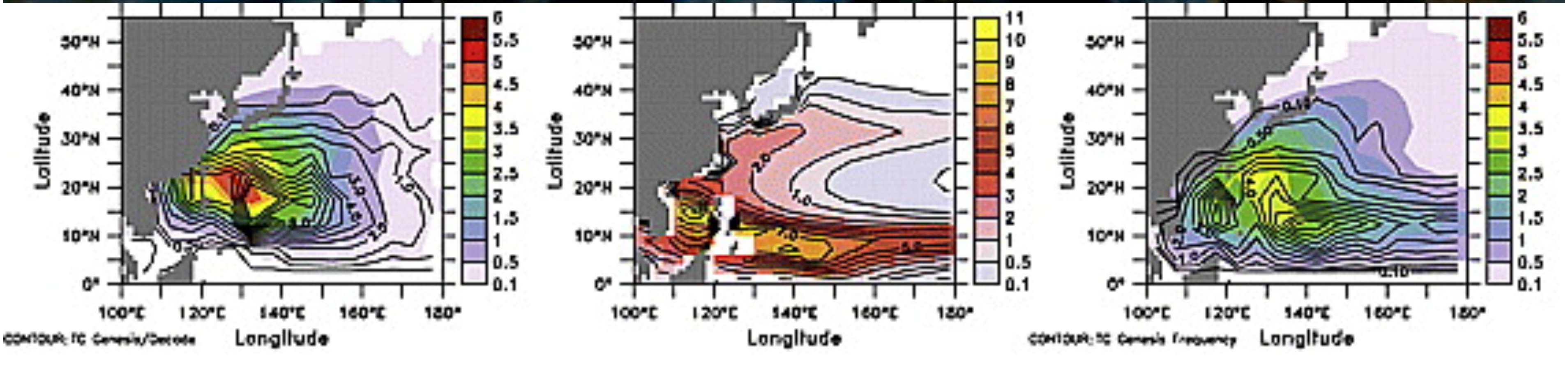
- SSTs go down
- Shear goes up
- RH goes down
- Sinking goes up-> Vorticity goes down

Genesis Potential Index (Camargo, Emanuel and Sobel, 2007)

$$GPI = \left(1+0.1*(U_{200}-U_{850})\right) \quad (RH_{750}/50) \times$$

$$(MPI/70)^{3} \times (Vort$$

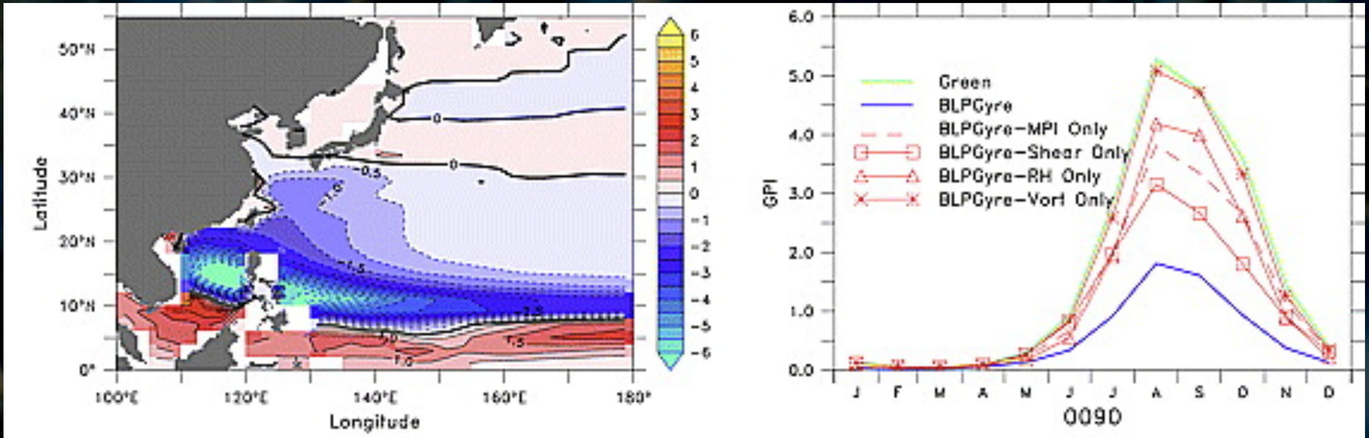
Downscaling techniques simulate aspects of observed distribution



(a) TC Frequency (days/yr/5 deg bin) (b) GPI, Control (c) TC Frequency from Downscaling, Control

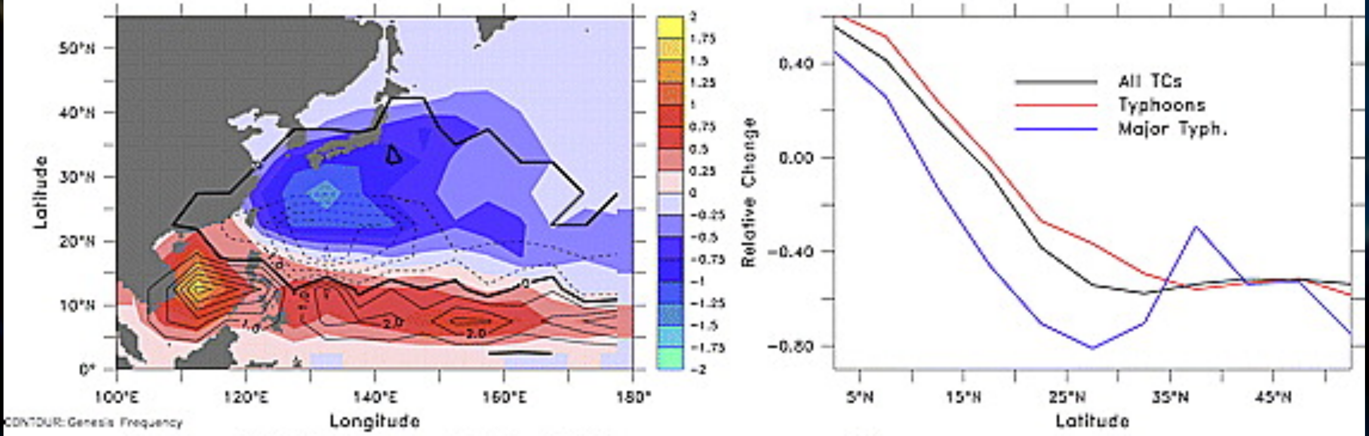
Right-hand plot shows statistical-dynamical downscale from Kerry Emanuel

Cyclogenesis change



(a) GPI Change, BLPGyre–Control

(b) Contributors to GPI Change: 10N–30N



(c) Downscaled TC Freq. Change, BluePGyre–Control

(d) Downscaled TC Freq Change by Category

Gnanadesikan, Emanuel, Vecchi, Anderson and Hallberg, GRL, 2010

Presence of ocean color in gyres makes huge difference in cyclogenesis!

Summary-Part 2

- In well ventilated regions additional penetration of heat results in surface cooling leading to strengthened Hadley cell, weaker ENSO, strong decrease in tropical cyclones.
- In poorly ventilated regions additional penetration of heat results in surface warming leading to weaker Walker cell, stronger ENSO/ moderate increase in tropical cyclones.
- Ocean water clarity plays an important role in climate! (Chemistry shapes physics!)

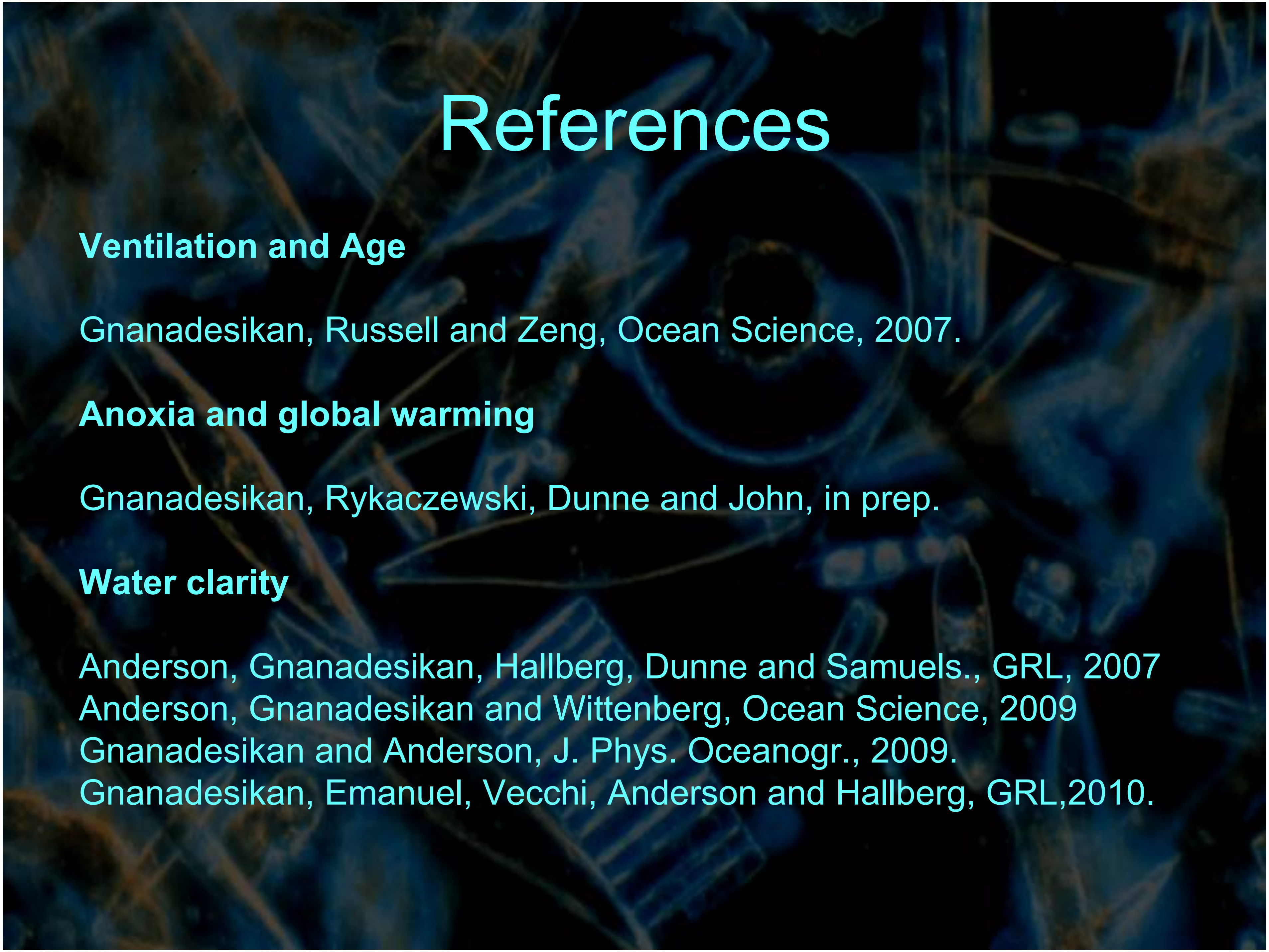
Key points

Well ventilated and poorly ventilated regimes have

- Different physics (isopycnal/advective vs. diapycnal/diffusive)
- Different biogeochemical sensitivity to changes in circulation. Global warming gives lower oxygen vs. higher oxygen.
- Different physical sensitivity to changes in water clarity. More clarity gives surface cooling, lower TC activity,strong Hadley cell vs. surface warming,higher TC activity, weaker Walker cell.

Open questions

- How much deep water actually upwells in the shadow zones? (He-3, radiocarbon)
- Sensitivity to parameterized mixing opposite in margins vs. gyres- why?
- What’s the impact of eddies on the shadow zone (do they break through the front)?
- How much anoxia is there in the open ocean?
- How strong are feedbacks between remineralization and oxygen in/above margins?



References

Ventilation and Age

Gnanadesikan, Russell and Zeng, Ocean Science, 2007.

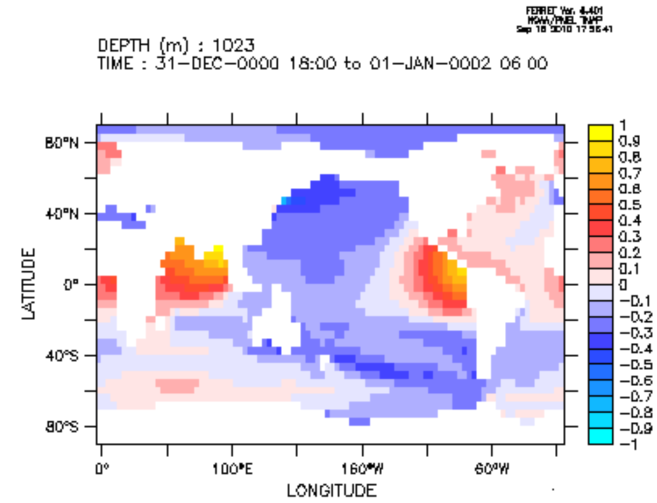
Anoxia and global warming

Gnanadesikan, Rykaczewski, Dunne and John, in prep.

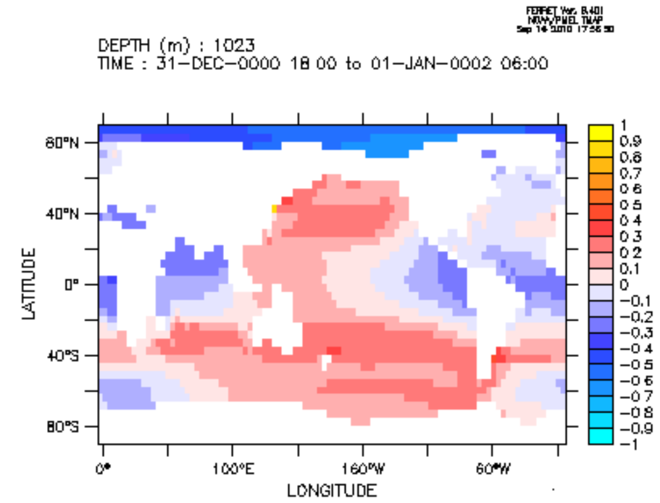
Water clarity

Anderson, Gnanadesikan, Hallberg, Dunne and Samuels., GRL, 2007
Anderson, Gnanadesikan and Wittenberg, Ocean Science, 2009
Gnanadesikan and Anderson, J. Phys. Oceanogr., 2009.
Gnanadesikan, Emanuel, Vecchi, Anderson and Hallberg, GRL,2010.

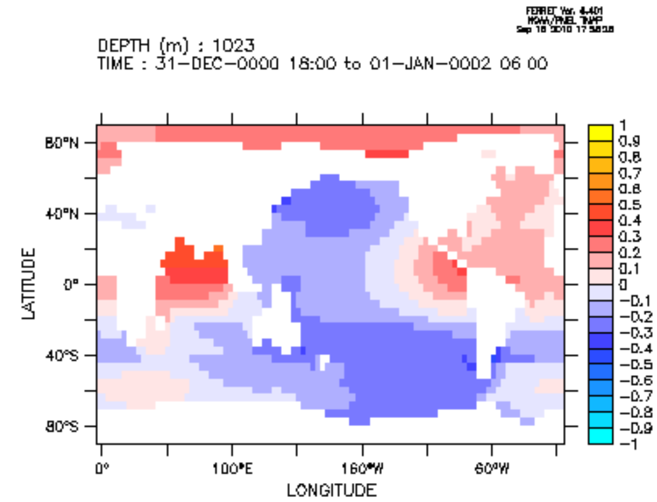
Mixing sensitivity



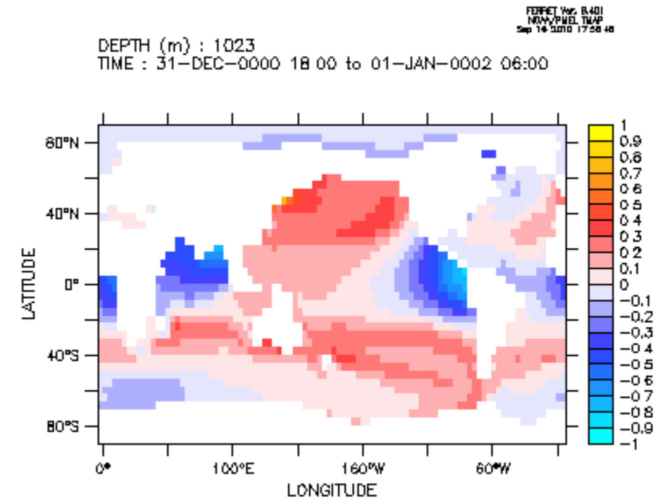
HL−LL



LH−LL



HH−LH



HH−HL