Understanding ocean "dead zones": Hypoxia and global ocean circulation

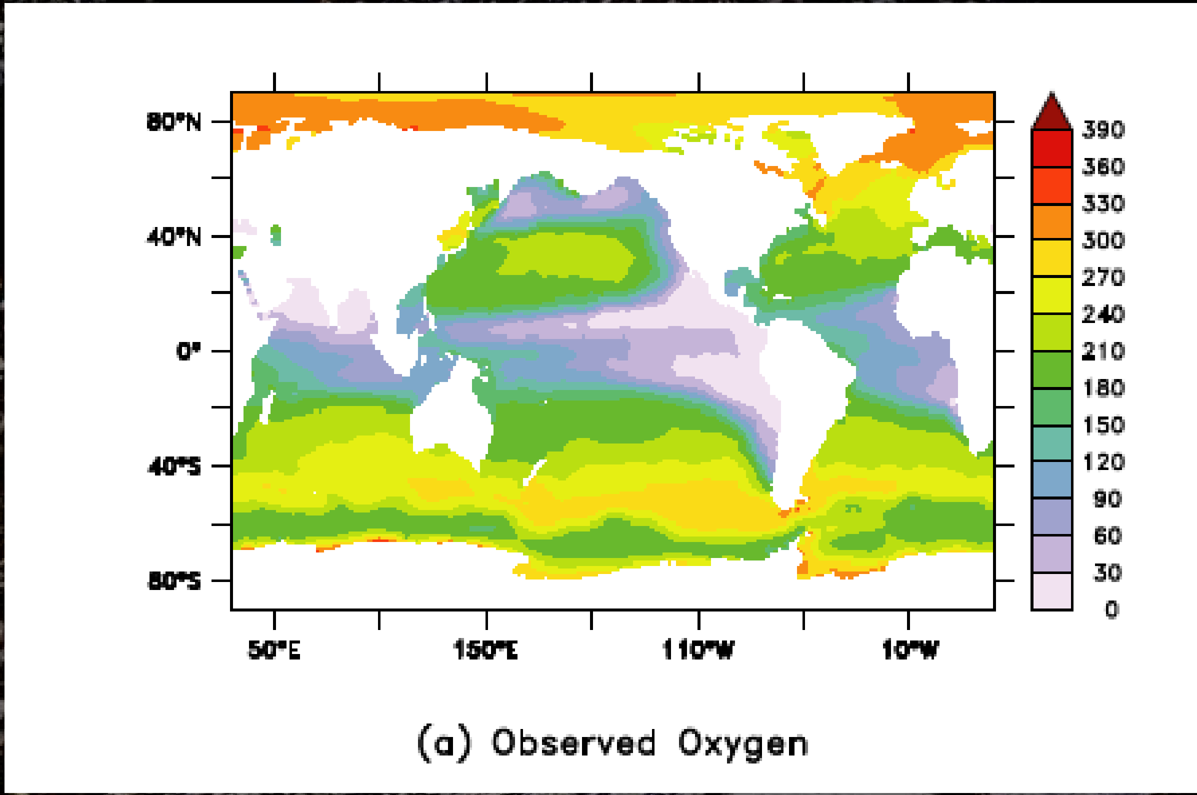
Anand Gnanadesikan[1], Irina Marinov[2], Daniele Bianchi[3], Jaime Palter[3] and Marie Aude Pradal[1]

1: Johns Hopkins University
2. University of Pennsylvania
3: McGill University

Geological record shows widespread past anoxia, possibly associated with mass extinctions

Much of open ocean sees low oxygen

- Hypoxia
  - 126 Mkm^2 (~1/3 of ocean area)
  - 148 Mkm^3 (~1/10 of ocean volume)
- Suboxia
  - ~14 Mkm3 (~1% of ocean volume, Bianchi, 2011)



What is expected sensitivity to lower rates of mixing?

Model 1: Nutrients flux through, oxygen supplied by mixing

Prod is the rate of nutrient throughflow (mol phosphate/m^3/sec)

V is volume of lower layer

M is the exchange of mass

O2(s) is the surface oxygen concentration

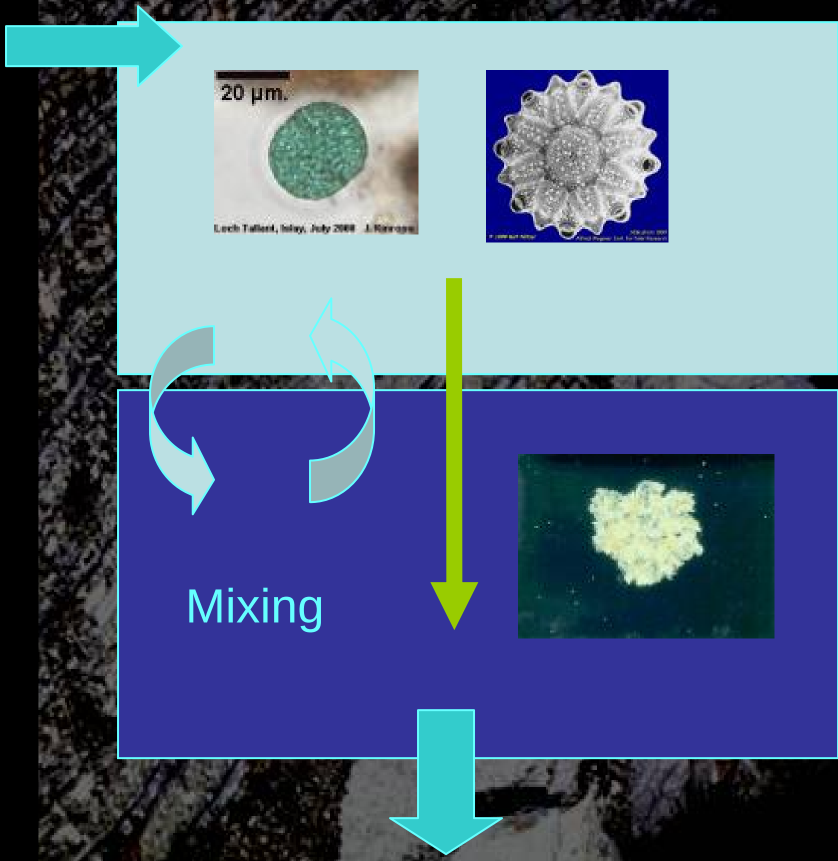
O2(d) is the deep oxygen concentration

R_{OP} is the ratio of phosphate remineralization to oxygen consumption.

$V*R_{OP}*Prod=M(O2(s)-O2(d))$

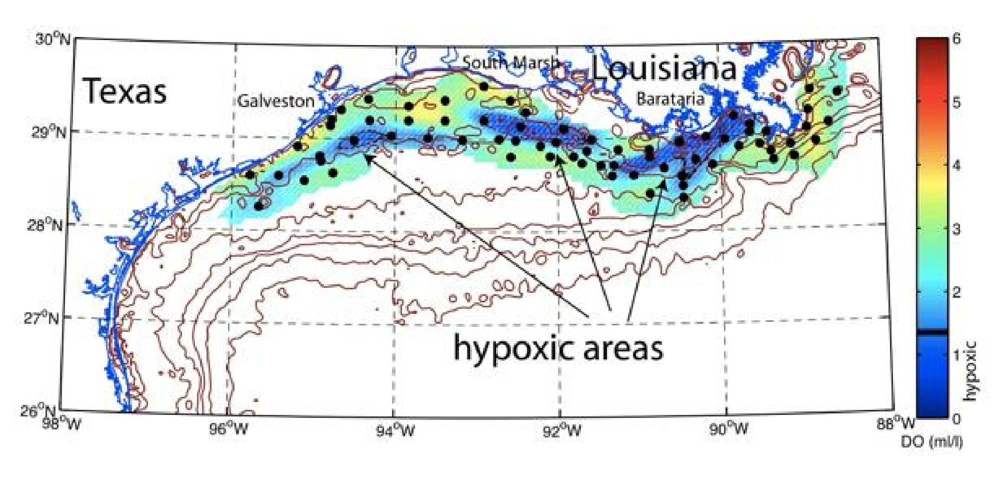
$O2(d)=O2(s)-(V/M)*R_{OP}*Prod$

Dropping mixing increases hypoxic intensity



Where does this model likely hold?

- Coastal zones
  - Chesapeake
  - Gulf of Mexico
- Black Sea



Requirement is that throughflow dominate mixing flux of nutrient.

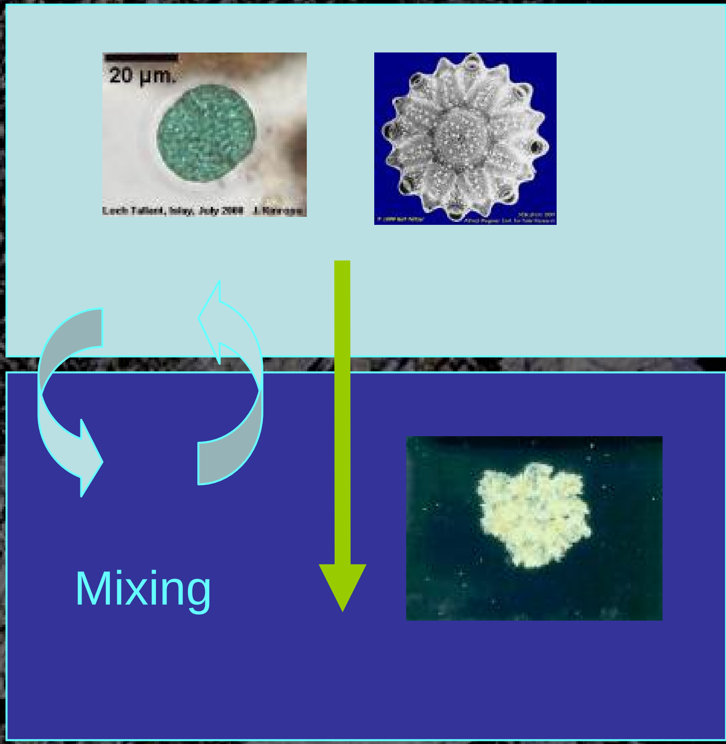
Model 2: Nutrients and oxygen both supplied by mixing

$$O2(d)=O2(s)-(V/M)*R_{OP}*Prod$$

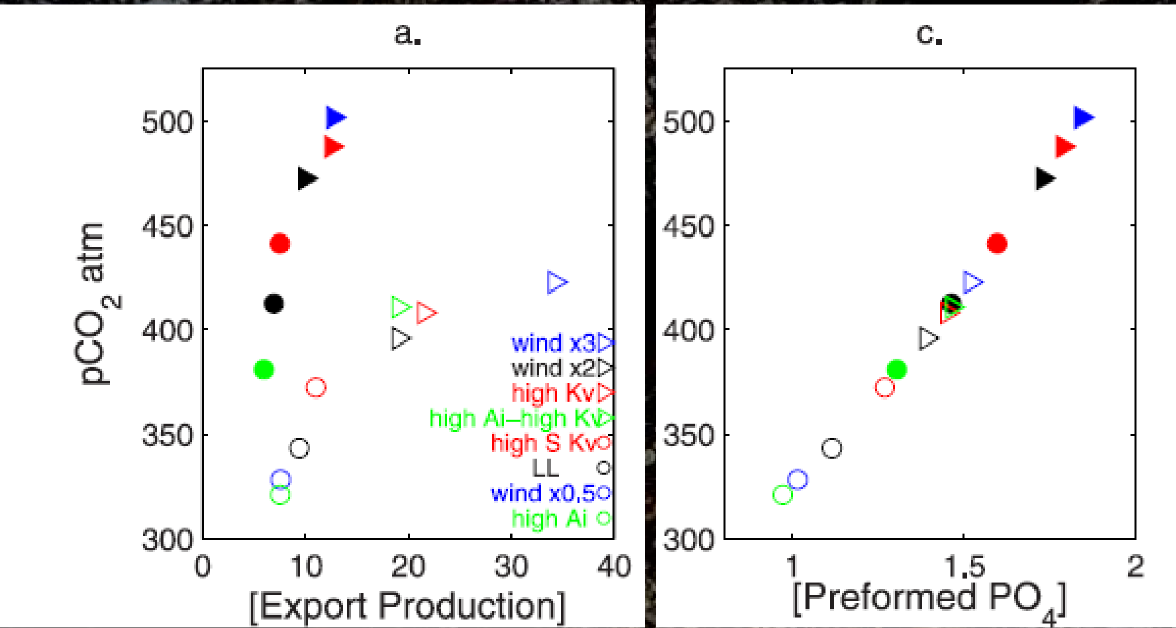
$$Prod=M*\{P(d)-P(s)\}$$

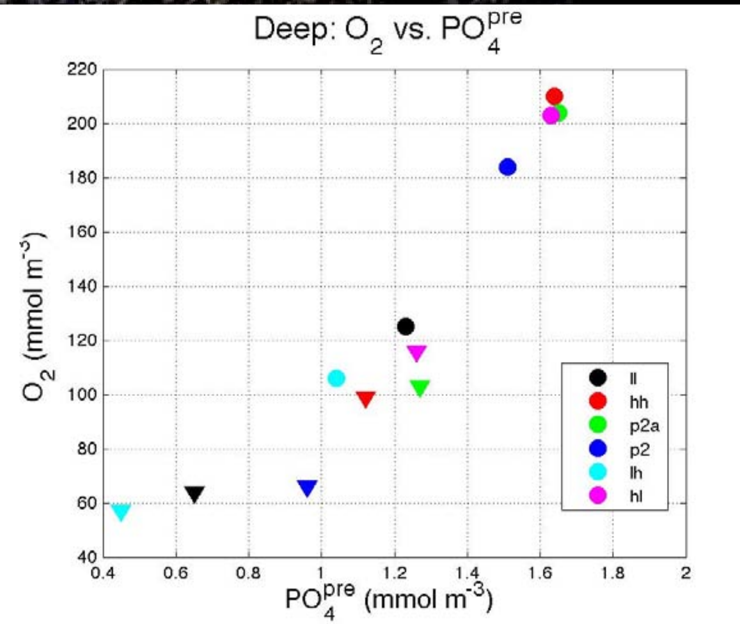
$$O2(d)=O2(s)-V*R_{OP}*(P(d)-P(s))$$

- Mixing of nutrient drives production as well as oxygen supply.
- Surface (preformed) nutrients control deep oxygen.
- Rate of mixing less important than balance of sources.



Where this holds- deep ocean





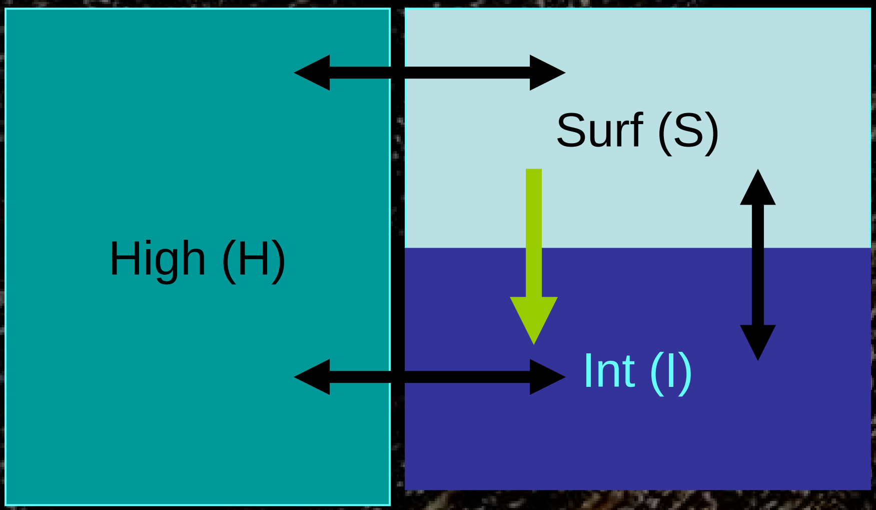
Marinov et al., Global Biogeochemical Cycles, 2008, Bianchi, pers. comm.

Weak relationship between production and atmospheric CO2.

Excellent relationship between preformed nutrient (high preformed=high O2).

Higher mixing gives more O2- but only because mixing predominantly affects southern source waters.

Model 3: Nutrients/oxygen supplied laterally



$$M_{HI}(P_I - P_H) - M_{HS}P_H = 0$$

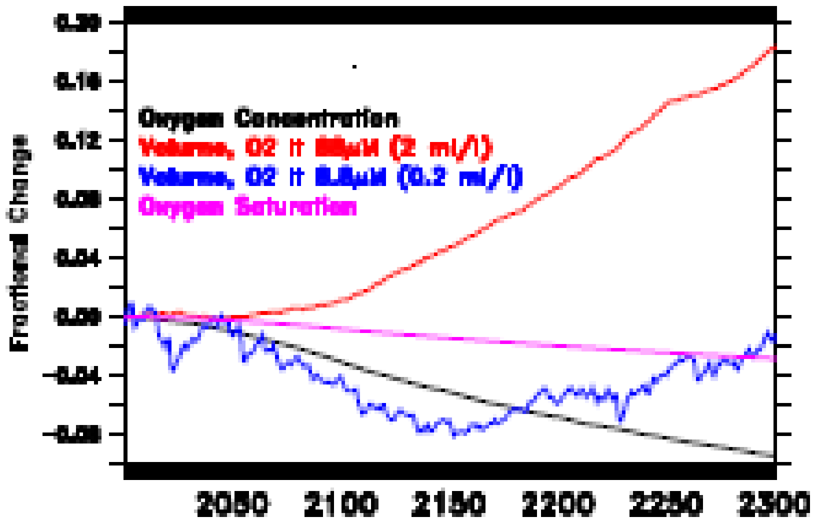
$$P_I = P_H(1 + M_{HS} / M_{HI})$$

$$PO^*_{4I} = \frac{PO^*_{4H}M_{HI} + PO^*_{4S}M_{SI}}{M_{HI} + M_{SI}}$$

Lateral mixing determines trapping.
High vertical mixing lowers oxygen!

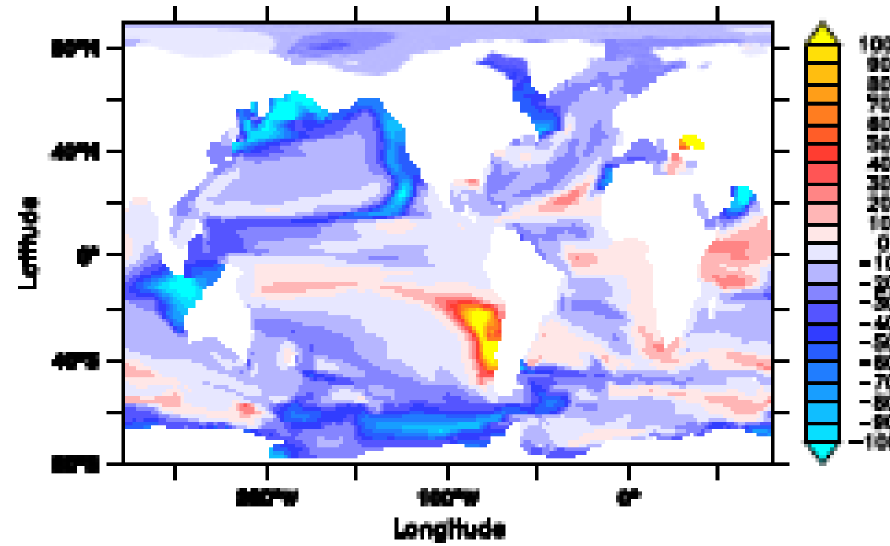
Under climate change…

Hypoxic volume goes up



(a) Relative Changes (A2 Scenario)

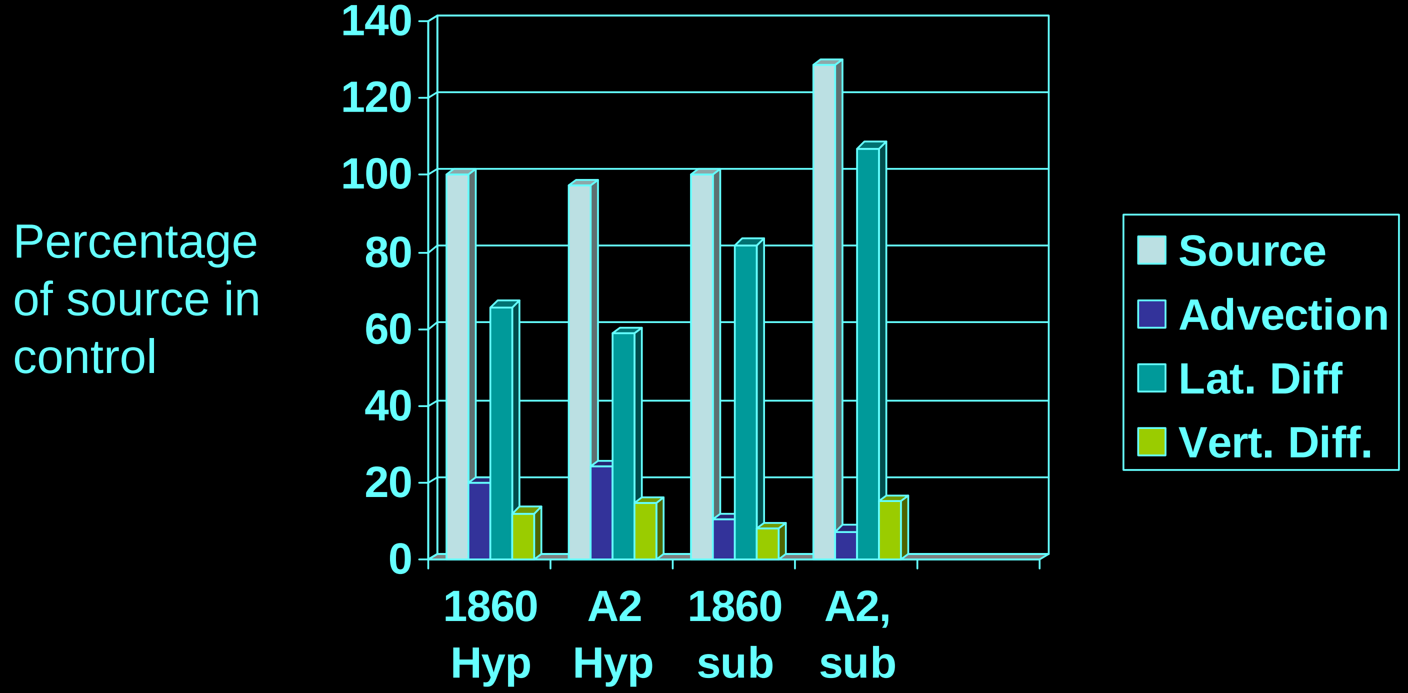
Suboxic volume more constant



(b) Oxygen Change at Year 2300, 300m

Similar changes seen by Bopp et al. (2002) Matear and Hirst (2003), Duteil and Oschlies (2011) for subset of runs.

Budget analysis shows role of lateral diffusion

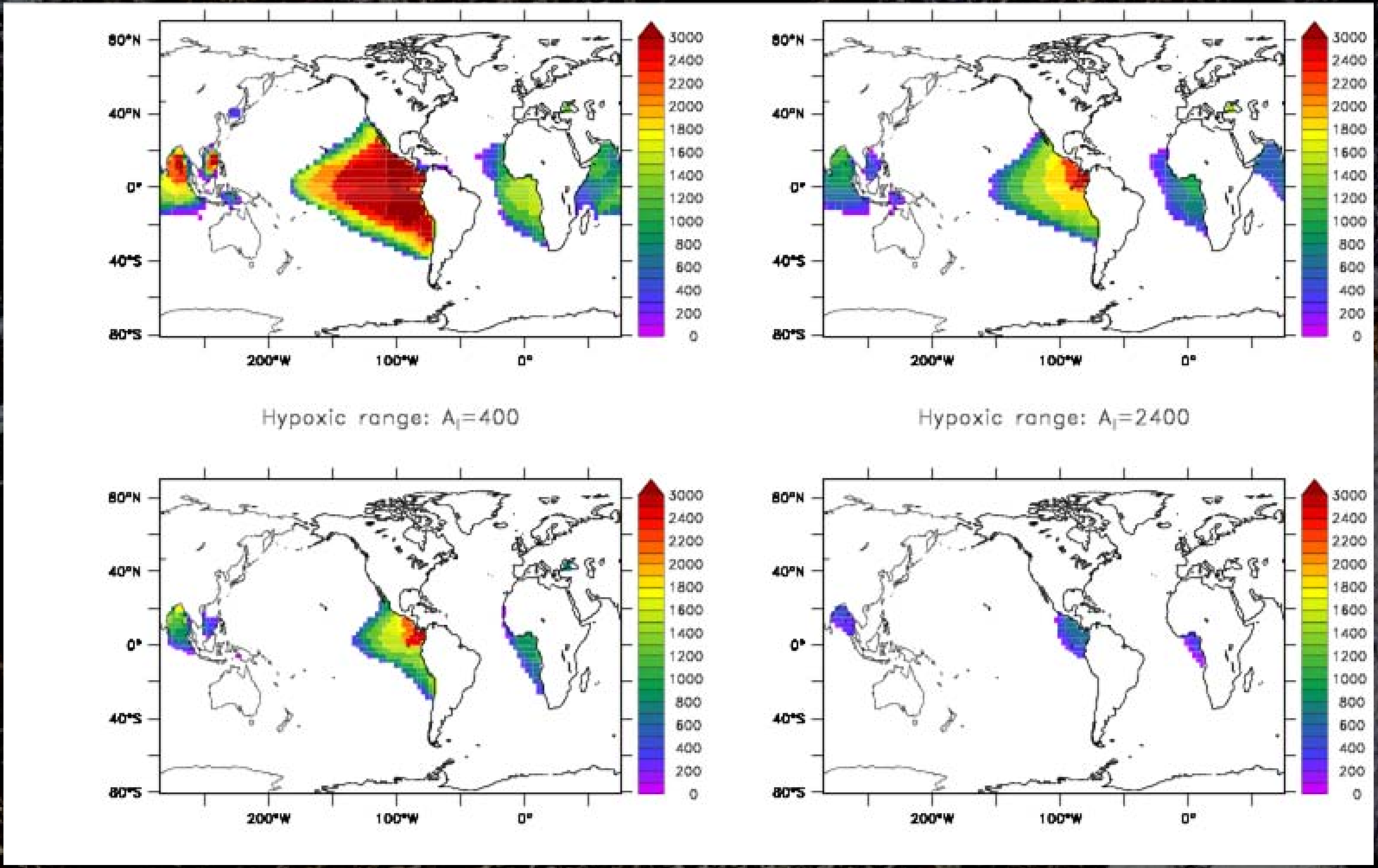


Gnanadesikan, Dunne and John, Biogeosciences, 2012.

Ocean oxygen and global warming- Three regimes

- Coastal- reduction in surface solubility, oxygen supply increases hypoxia, hypoxic intensity.
- Deep ocean- reduction in Southern Ocean vs. North Atlantic results in increased hypoxia, but this may not be realistic.
- Intermediate waters- Decrease in vertical exchange relative to lateral exchange decreases hypoxic intensity.

New results on lateral mixing and oxygen



Pradal and Gnanadesikan in prep.

Instead of rates, key is **ratios**

- Ratio of throughflow to mixing flux.
- Ratio of high vs. low preformed nutrients in source waters.
- Ratio of high latitude supply (high PO4*) to vertical low-latitude supply (low.
- Ratio of surface lateral supply vs. deep lateral removal.

Because of this, attention to the details of circulation is essential!

References

Marinov, I., A. Gnanadesikan, B.K. Mignone, J.R. Toggweiler, J.L. Sarmiento and R.D. Slater, Impact of oceanic circulation on biological carbon storage in the ocean and atmospheric CO2, *Global Biogeochem. Cycles*, 22, GB3007, doi:10.1029/2007GB002958, 2008.

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Bianchi, D., Dunne, J.D., Sarmiento, J.L., Galbraith, E.D, 2011. Data-based estimates of suboxia, denitrification and N2O production in the ocean, and their sensitivities to change, submitted to *Global Biogeochemical Cycles*