

Physical and biological controls on the ocean carbon storage

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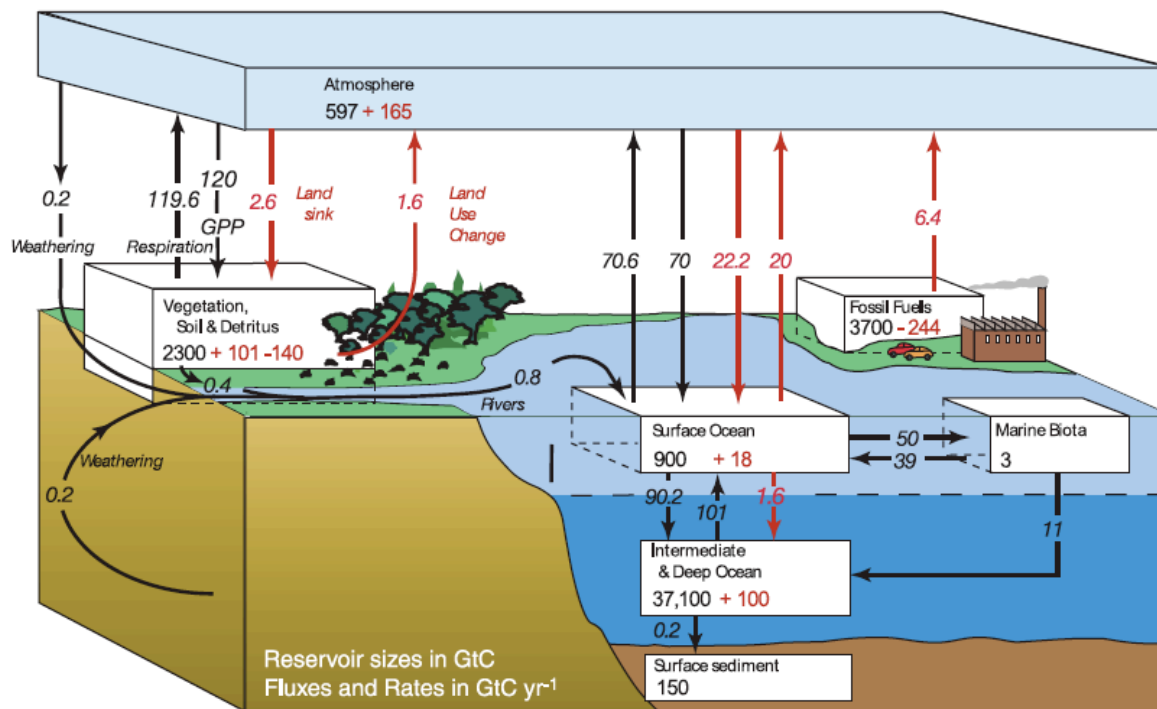
⁺MIT

Outline

- Oceanic C inventory, carbon pumps
- *Surface C dynamics, and air-sea disequilibrium*
- *A new scaling theory for steady state atmospheric CO₂*

Global CO₂ fluxes and inventories

- 90+% of the global (atmos+land+ocean) carbon is stored in the deep ocean
- DIC and buffer chemistry: $DIC = \underbrace{[CO_2^*]}_{<1\%} + \underbrace{[HCO_3^-]}_{\sim 90\%} + \underbrace{[CO_3^{2-}]}_{\sim 10\%}$
- ~2 PgC/yr of fossil fuel CO₂ is taken up by the oceans



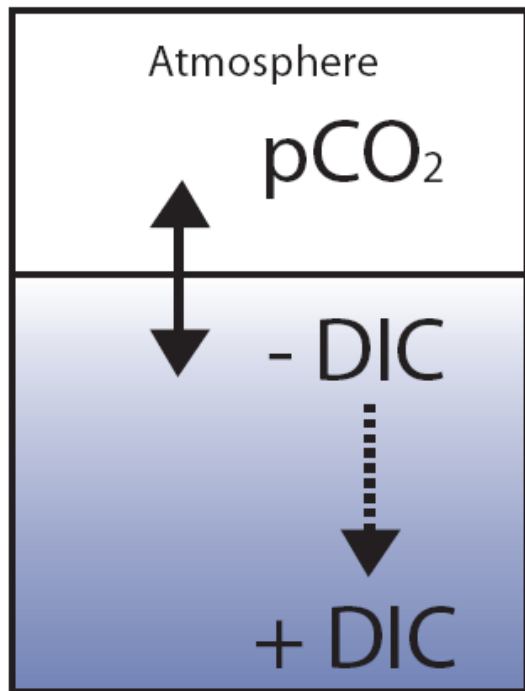
Air-sea exchange,
ocean ventilation
~ 100 PgC/year

Biological export
~ 10 PgC/year

N. Gruber

Ocean carbon storage

- **Carbon pumps** (*Volk and Hoffert, 1985*)
 - Vertical gradient of DIC
 - Assume air-sea equilibration and mass balance

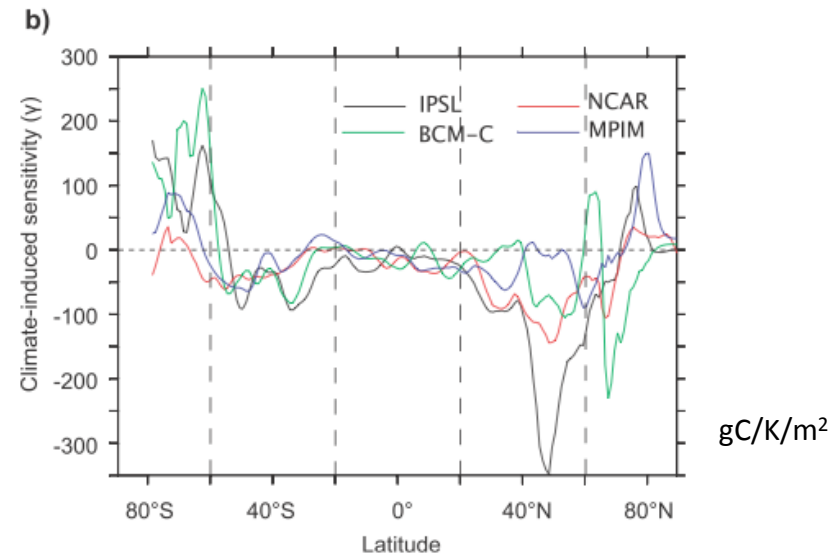
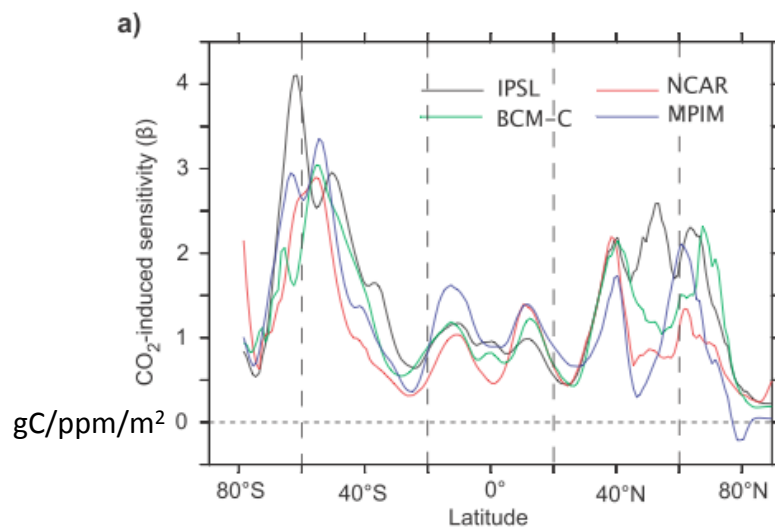


- Solubility pump
 - Vertical T gradient
 - Cooling (+) vs warming (-)
- Biological pump
 - Sinking organic particles
 - Sinking C_{org} (+) vs upwelling of respired carbon (-)

Transient climate change impacts

- Roy et al., (2011): In the future climate simulations (SRES A2), climate-ocean carbon coupling is mainly through the “solubility” pump

(2010-2100) Ocean C uptake sensitivity to (a) $p\text{CO}_2$ and (b) mean surface T



Solubility

Increase $p\text{CO}_2 \rightarrow$ higher DIC

Increase $T \rightarrow$ lower DIC

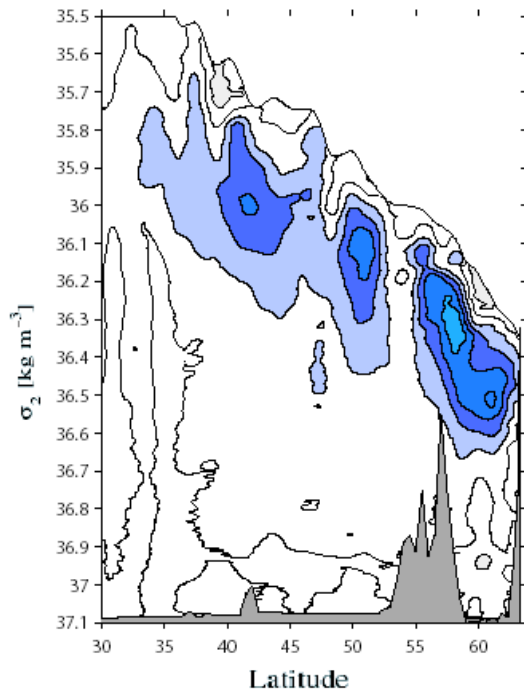
Ventilation

Increase stratification \rightarrow lower C uptake

Is ocean ventilation changing?

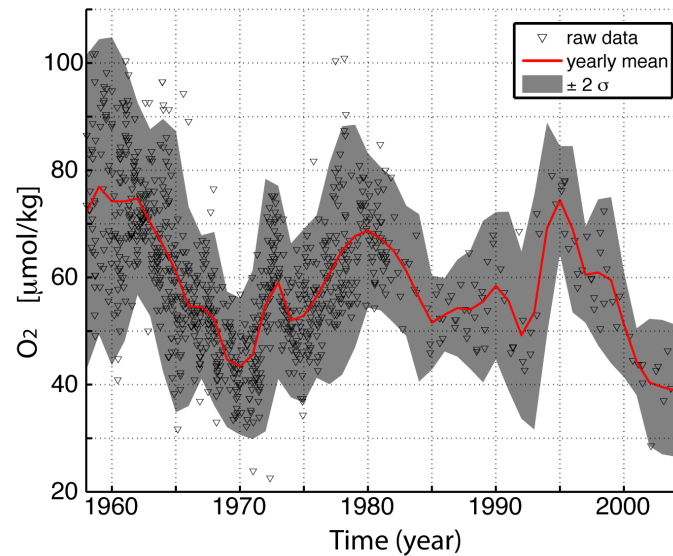
- Dissolved oxygen observation
 - Supplied by ventilation, consumed by respiration
 - Warmer T, weaker ventilation → lower O₂ level
 - Strong decadal variability

Atlantic transect 20W



Johnson and Gruber (2007)

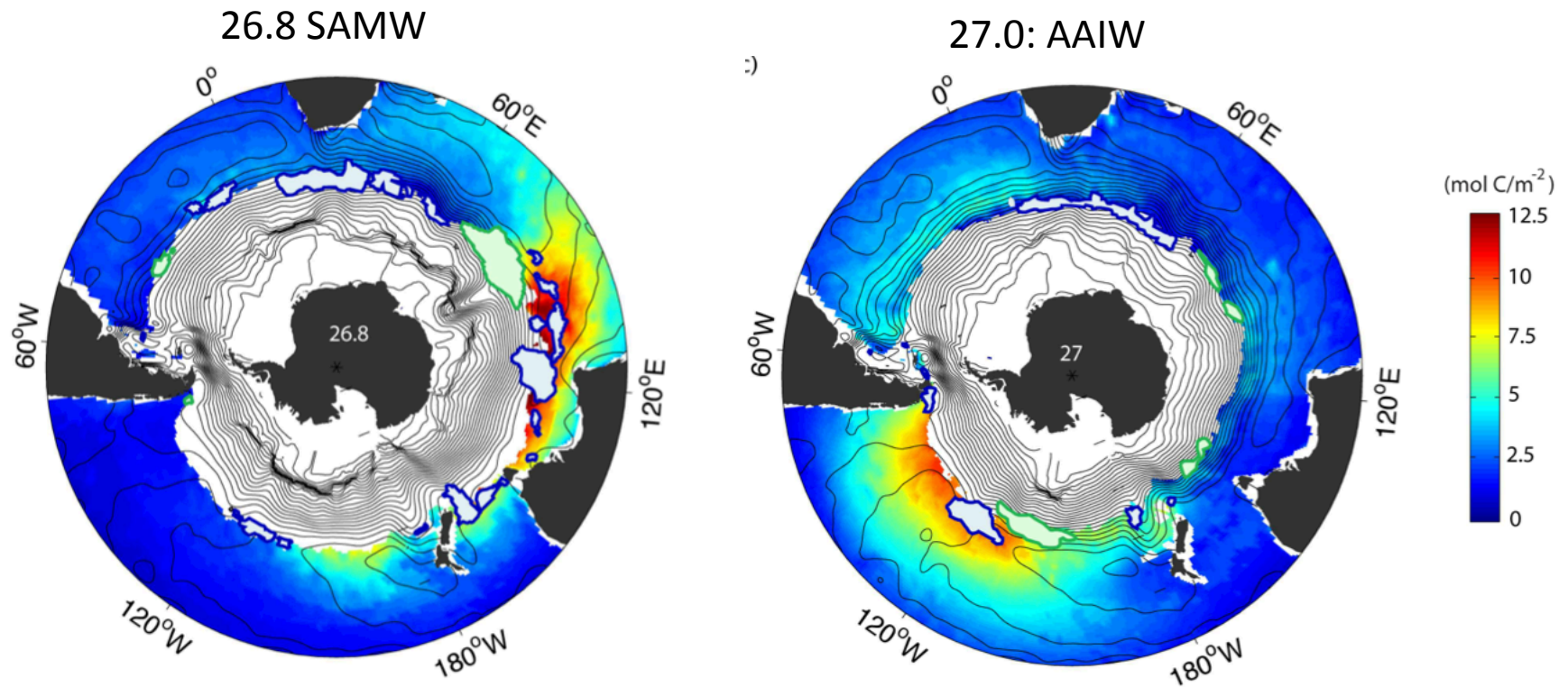
Gulf of Alaska (OSP) NPIW ~ 300m



Whitney (2007)

Localized ventilation

- Salleé et al. (2012): subduction of C is localized (blue circle)
- Significant amount of C is re-ventilated (obduction)
- Anthro C reflects the subduction/obduction pattern



Quantifying the ocean carbon storage

- Two pathways for nutrient and carbons to reach the deep ocean
- Physical transport (preformed)
- Biological flux (regenerated)

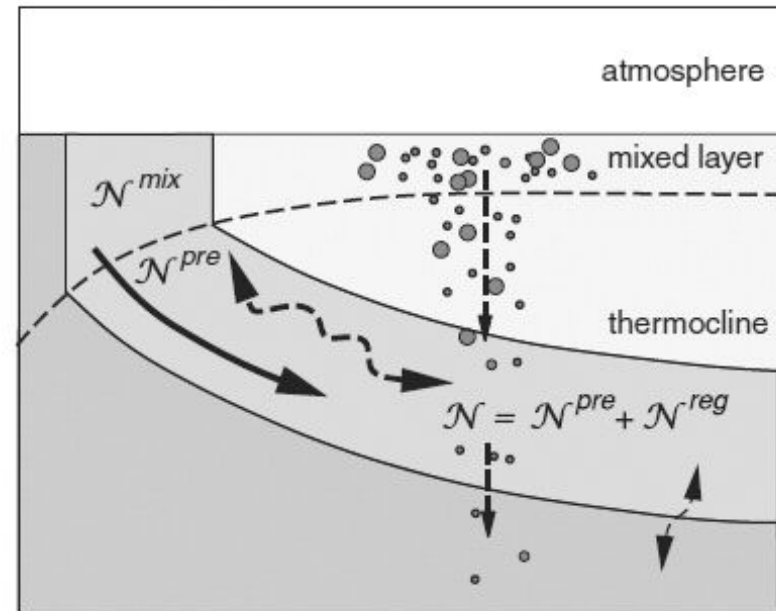
$$N = N_{pre} + N_{reg}$$

$$DIC = \underbrace{C_{sat} + \Delta C}_{\text{Physical (Preformed)}} + \underbrace{C_{soft} + C_{CaCO_3}}_{\text{Biological (Regenerated)}}$$

| C reservoir | Global integral (PgC) | Mean conc. (μmolCkg^{-1}) |
|--------------|-----------------------|--|
| DIC | 35,538 | 2,253 |
| C_{sat} | 33,330 | 2,113 |
| ΔC | 38 | 2 |
| C_{soft} | 1,672 | 105 |
| C_{CaCO_3} | 502 | 33 |

Follows and Williams (2011)

Broecker 1974; Brewer and Goldman 1976; Chen and Millero 1979; Gruber et al., 1996; Sabine et al., 2004; Ito and Follows 2005; Goodwin et al., 2007



Equilibrium theory for carbon pump

- Mass balance for carbon, nutrients, alkalinity

$$\frac{d}{dt}(\text{Inventory}) = \text{div}(\text{Flux}) = 0$$

- Integral constraint in the perturbation form

$$I_{ATM} + I_{OCN} + I_{LAND} = \text{Constant} \quad \delta I_{ATM} + \delta I_{OCN} + \delta I_{LAND} = 0 \text{ (pre-industrial) or Emission}$$

- For preindustrial condition (setting no change on land),

$$\underbrace{M_A \delta pCO_2^{atm}}_{atmos} + \underbrace{V(\delta C_{sat} + \delta \Delta C + \delta C_{soft} + \delta C_{CaCO3})}_{ocean} = 0$$

- Combining carbonate chemistry, we get an expression for pCO_2

$$\delta C_{sat} = f_T \delta T + f_S \delta S + f_A \delta Alk + f_P \delta pCO_2^{atm}$$

$$\delta pCO_2^{atm} = g_T \delta T + g_S \delta S - g_C (\delta \Delta C + \delta C_{soft}) + g_A \delta C_{CaCO3}$$

Solubility pump

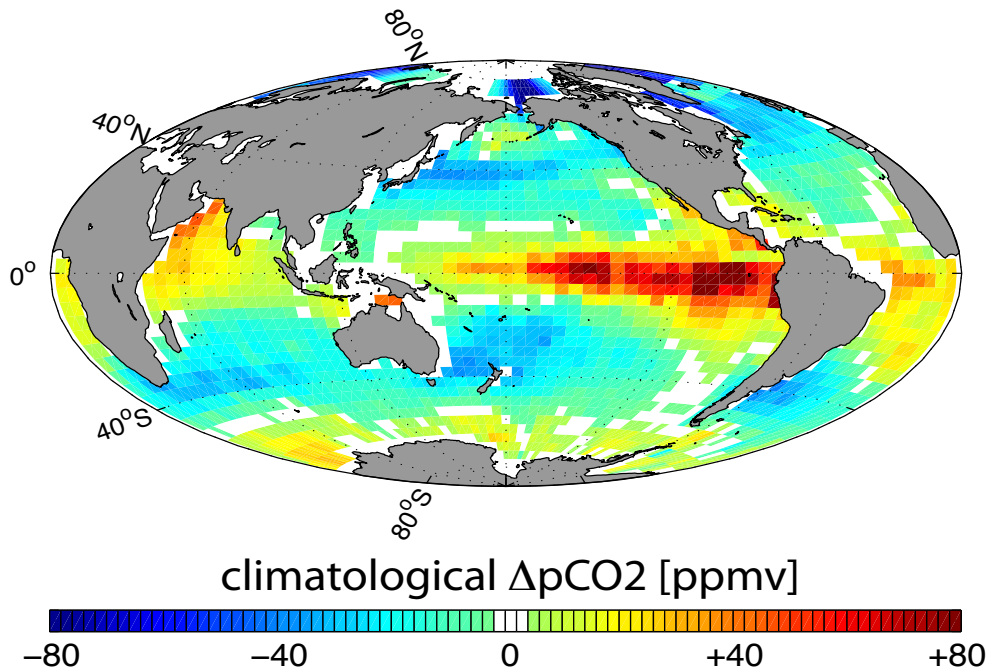


Biological pump

References:

Ito and Follows (2005; subm.);
 Goodwin et al., (2007; 2008;
 2009); Omta et al., (2010; 2011)

Air-sea disequilibrium : ΔC



Takahashi et al. (2009)

- Mid-latitudes and North Atlantic are undersaturated ($-\Delta C$)
- Tropics and Southern Ocean are supersaturated ($+\Delta C$)
- A 50 ppm of ΔpCO_2 is equivalent of $\Delta C \sim 30 \mu\text{molC/kg}^{-1}$

$$\Delta C = C_{surf} - C_{sat}(S, T, Alk, pCO_2^{atm})$$

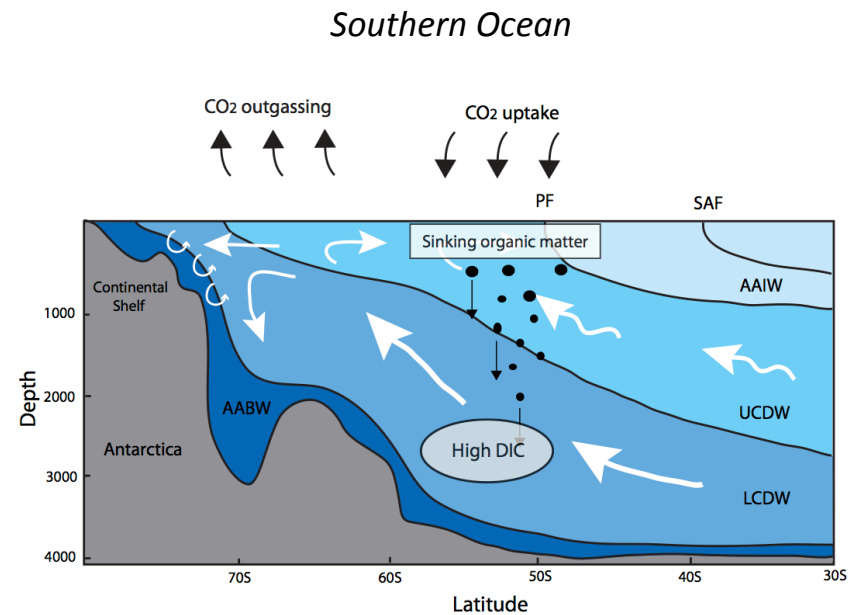
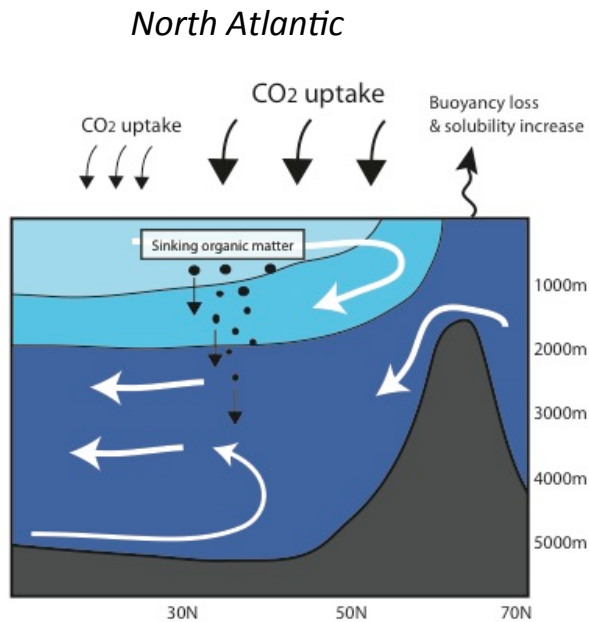
$$\frac{\Delta pCO_2}{pCO_2} = B \frac{\Delta C}{C_{sat}}$$

B : Buffer factor

$$F_{CO_2} = GK_H \Delta pCO_2$$

Upper ocean carbon dynamics

- What sets the surface ΔC distribution?



$$\frac{DC}{Dt} = \frac{1}{h} \left\{ -F_{CO_2} - EP_{soft} - EP_{CaCO_3} + C(E - P) \right\}$$

$$C = C_{sat}(T, S, Alk, pCO_2^{atm}) + \Delta C$$



$$\frac{D\Delta C}{Dt} = -\tau_{gas}^{-1} \Delta C + f(H, EP, R_{CaCO_3}, Ent, E - P)$$

Air-sea CO₂ equilibration

- ΔC anomaly decays over the timescale of τ_{gas} .

$$\frac{D\Delta C}{Dt} = -\tau_{gas}^{-1}\Delta C + f(H, EP, R_{CaCO_3}, Ent, E - P)$$

- Scaling for gas exchange timescale

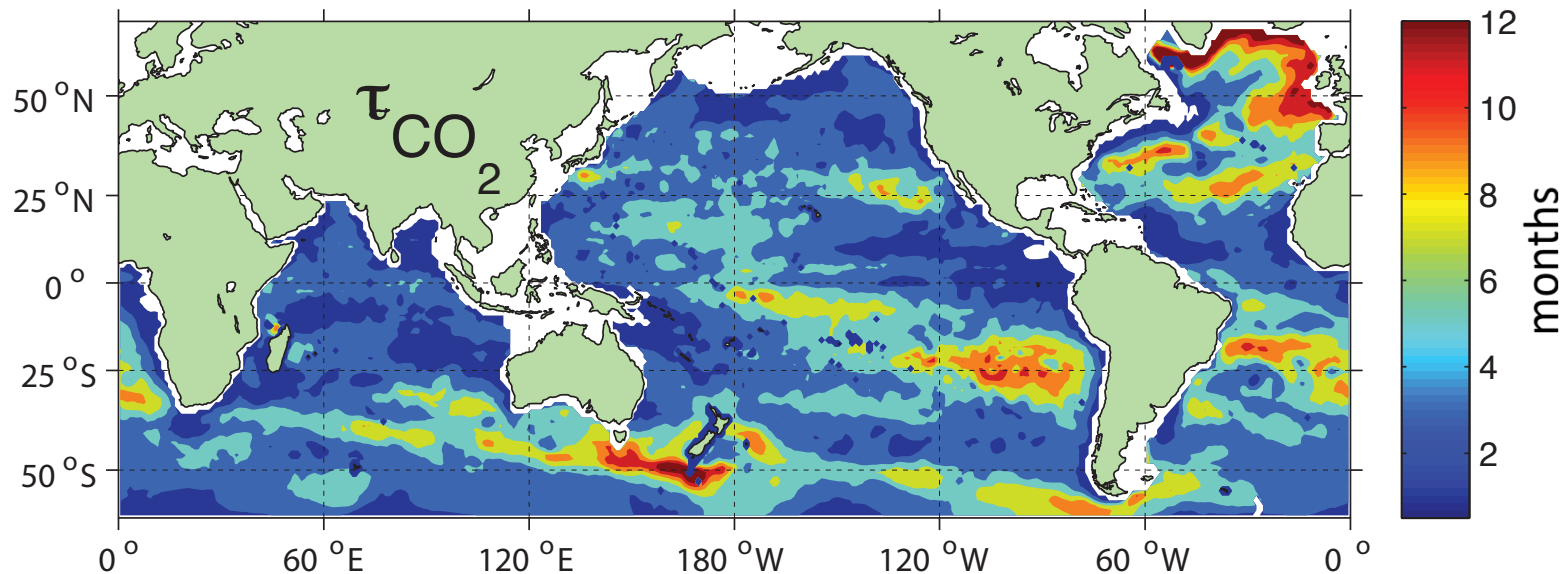
$$\tau_{gas} = \frac{hR}{GB} \left\{ \begin{array}{l} h \quad \text{mixed layer depth} \approx 100\text{m} \\ R \quad \quad \quad \frac{DIC}{[CO_2^*]} \approx 100 \\ G \quad \text{Gas transfer coeff} \approx 5\text{m/day} \\ B \quad \quad \quad \text{Buffer factor} \approx 10 \end{array} \right\} \approx 200\text{days}$$

Broecker and Peng (1974) Tellus

Pattern of annual mean τ_{gas}

$$\tau_{\text{gas}} = \frac{hR}{GB} \left\{ \begin{array}{l} h \quad \text{ARGO float data (60S-60N)} \\ G \quad \text{QuikSCAT + gas ex parameterization} \\ \text{Chem} \quad \text{Takahashi pCO}_2 + \text{Alk (Lee et al., 2006)} \end{array} \right.$$

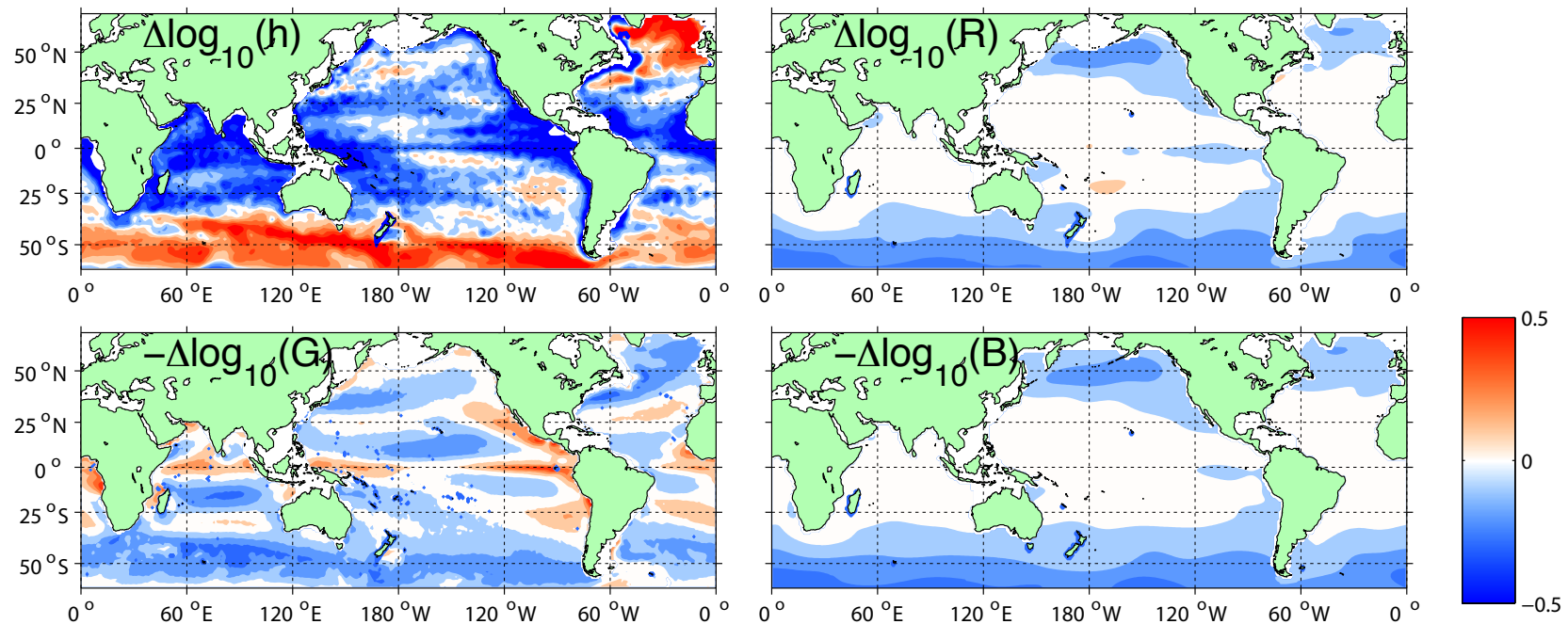
Annual mean CO₂ exchange timescale



Jones et al. (in prep)

Decomposition of τ_{gas}

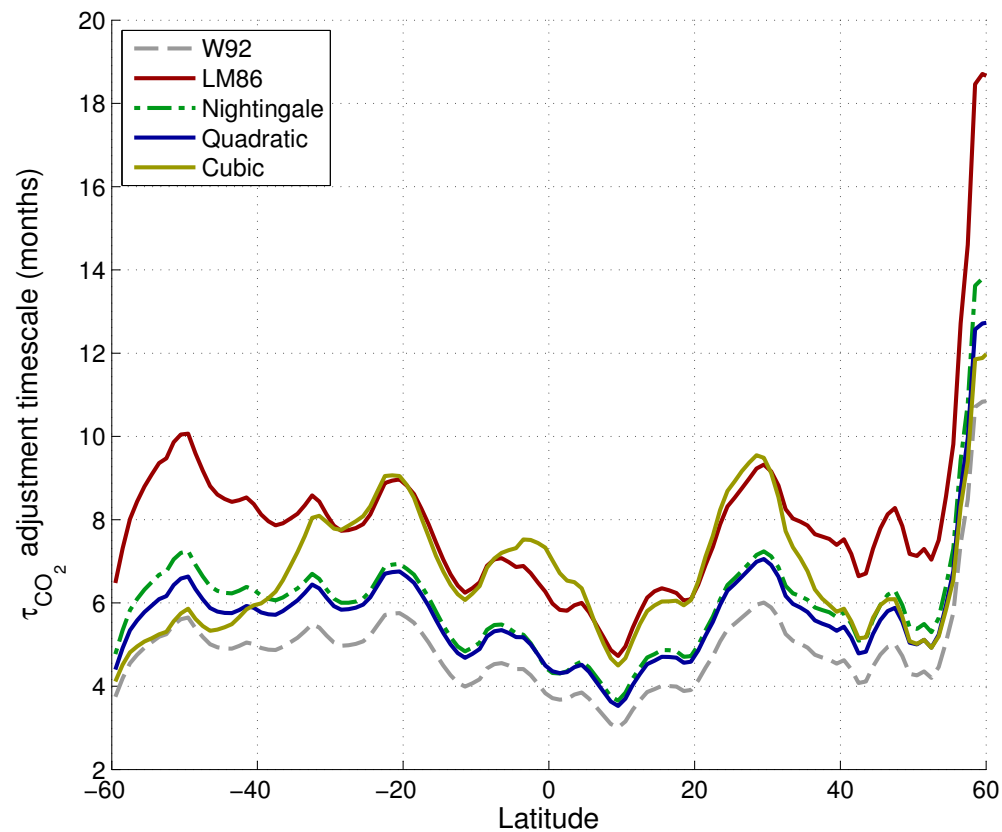
$$\log \tau_{gas} = \log h - \log G - \log B + \log R$$



- MLD (h) has the strongest influence, making high latitude ocean slow to equilibrate with the atmosphere.
 - Polar oceans also have seaice cover (Stephens and Keeling, 2000)

Uncertainties

- Gas exchange parameterization is the largest source of uncertainty \sim up to a factor of two.



Magnitude of air-sea disequilibrium

- Surface residence time (τ_{res}), measuring how long a water parcel has been in contact with the atmosphere.

Efficiency of air-sea equilibration

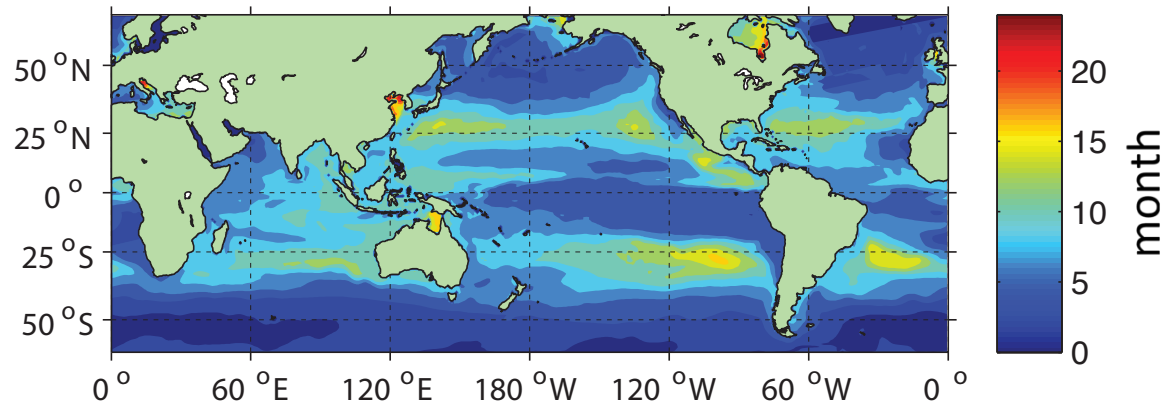
$$\eta_{gas} = \frac{\tau_{res}}{\tau_{gas}}$$

- Use a GCM to calculate the surface residence time.
 - MITgcm offline advection mode
 - ECCO-MIT circulation (ver3 iter73): global 1degree
 - KPP and GM
 - 10 year integration

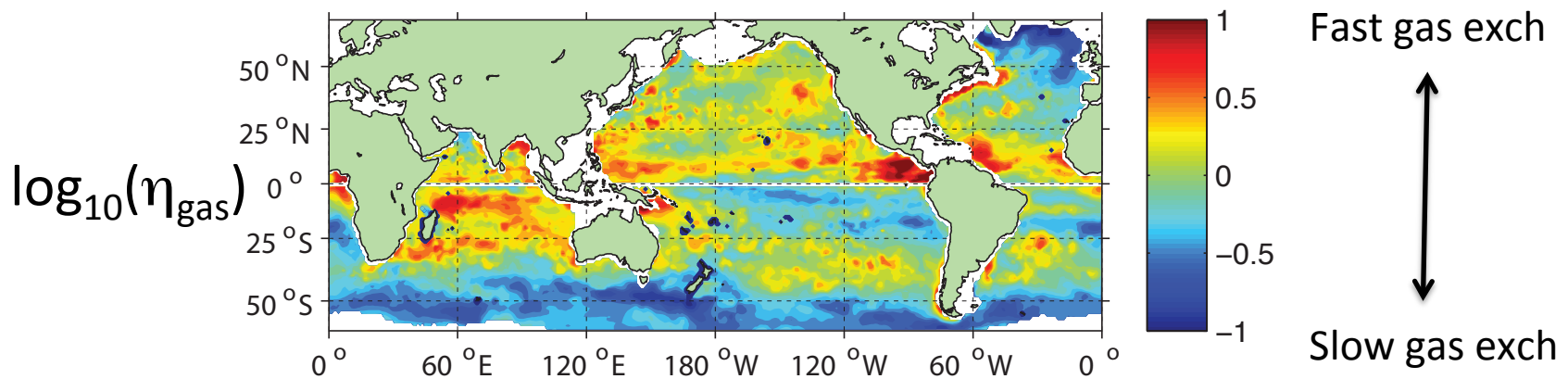
$$\frac{D\tau_{res}}{Dt} = \begin{cases} 1 & \text{in the top layer} \\ 0 & \text{elsewhere} \end{cases}$$

τ_{res} and η_{gas}

- Surface residence time (months)

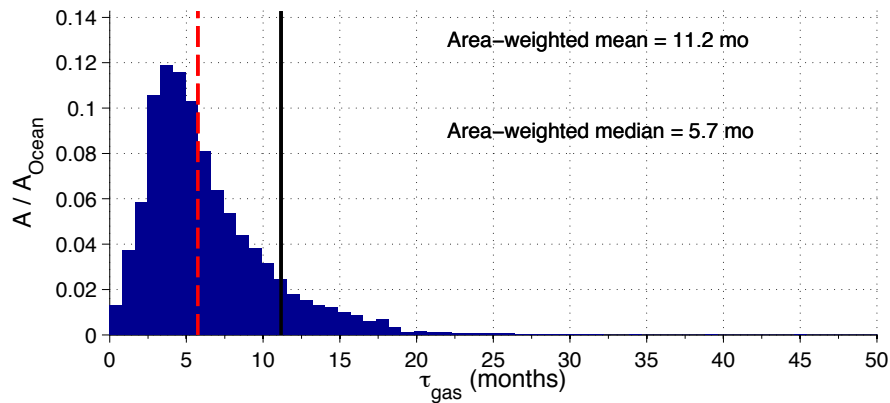


- Gas exchange efficiency (NH = DJF / SH = JJA)

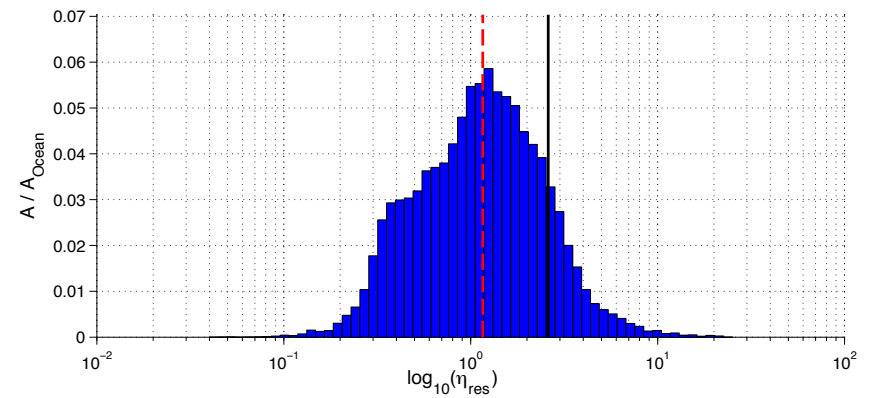
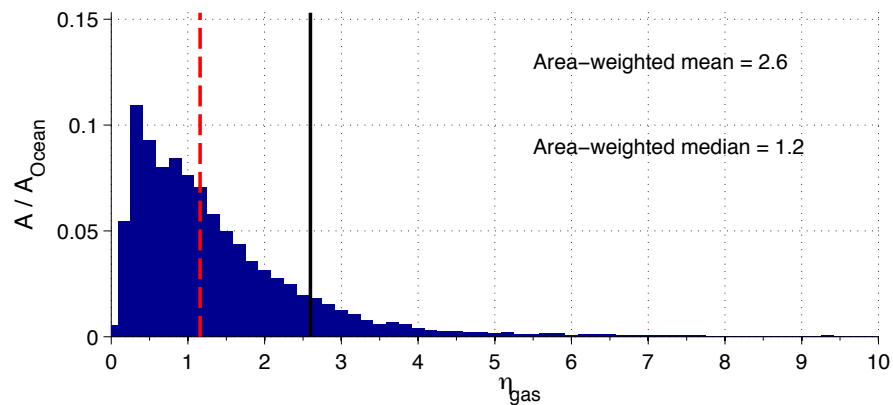


τ_{gas} statistics

- Binning the fractional surface area by the τ_{gas} and η_{gas} data
- Global median $\tau_{\text{gas}} \sim 200$ days
- Global median $\eta_{\text{gas}} \approx 1$
- Log-normal distribution

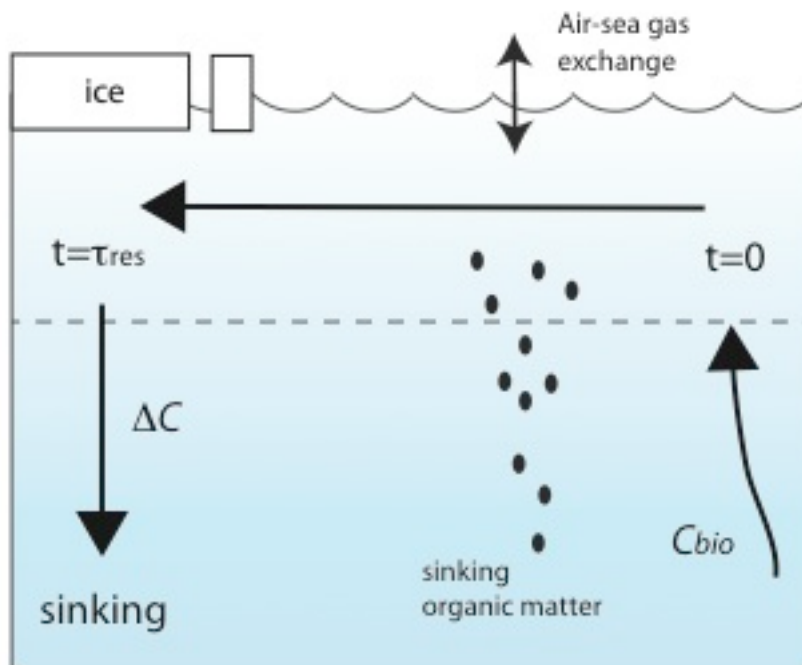


Median
Mean



Application to the Southern Ocean

- A conceptual model



- Supersaturation due to upwelling of C_{bio}
- Attenuation of ΔC due to air-sea gas exchange and biological export

Nutrient and carbon dynamics

$$\frac{DN}{Dt} = -\frac{1}{\tau_{bio}} N$$

$$\frac{D\Delta C}{Dt} = -\frac{1}{\tau_{gas}} \Delta C - \frac{a_0 R}{\tau_{bio}} N$$

Two non-dimensional parameters

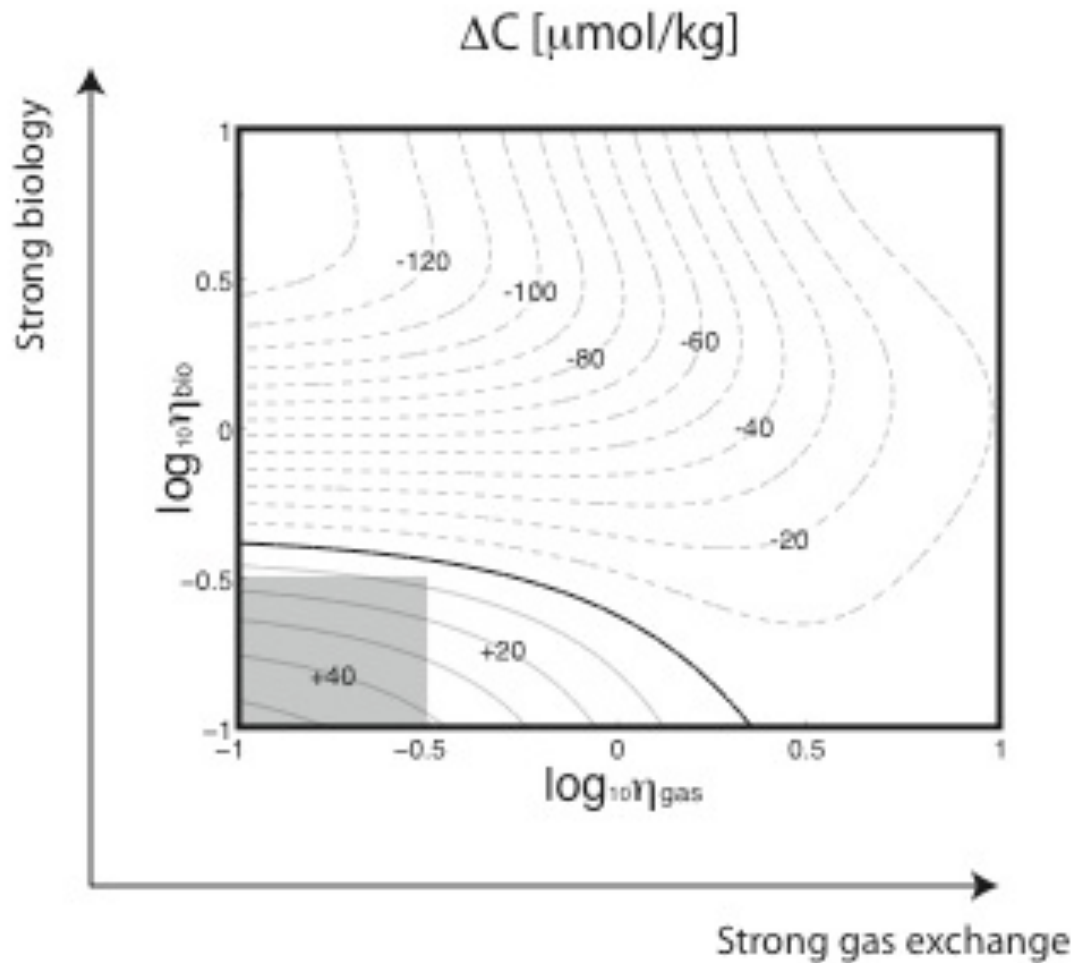
$$\eta_{gas} = \frac{\tau_{res}}{\tau_{gas}}, \quad \eta_{bio} = \frac{\tau_{res}}{\tau_{bio}}$$

Analytic solution

$$\Delta C(\tau_{res}) = R_{CP} N_0 \left\{ P * e^{-\eta_{gas}} - \frac{a_0 \eta_{bio} (e^{-\eta_{bio}} - e^{-\eta_{gas}})}{\eta_{gas} - \eta_{bio}} \right\}$$

Solutions for ΔC

- Analytic solution over a wide range of η_{bio} and η_{gas}



Southern Ocean is in a weak gas exchange regime (shaded region)

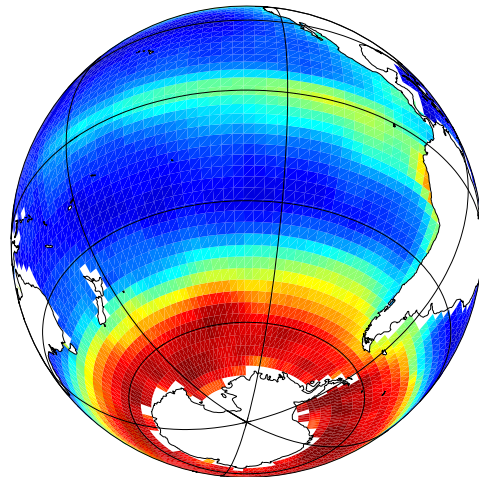
Strong biology $\rightarrow \Delta C < 0$

Weak biology $\rightarrow \Delta C > 0$

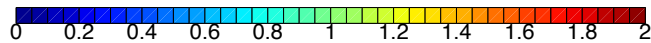
Sensitivity experiments

- MITgcm global 3° lat-lon grid, OCMIP-2 biogeochemistry, coupled to 1-box atmospheric carbon
- Include diagnostic tracers for preformed properties
- Modulate bio pump strength (nutrient depletion exp) and run the model to equilibrium (~2,000 years)

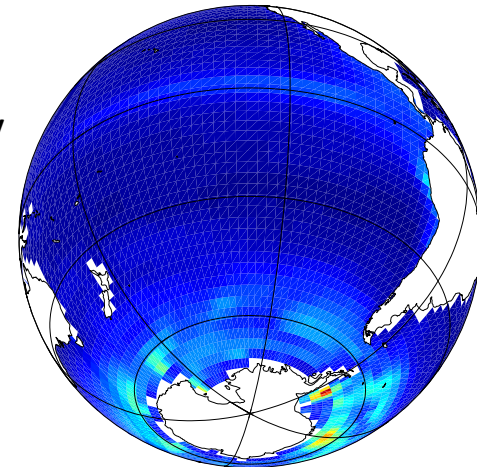
Control



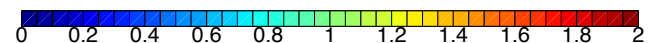
Surface PO4 [m mol P/m³]



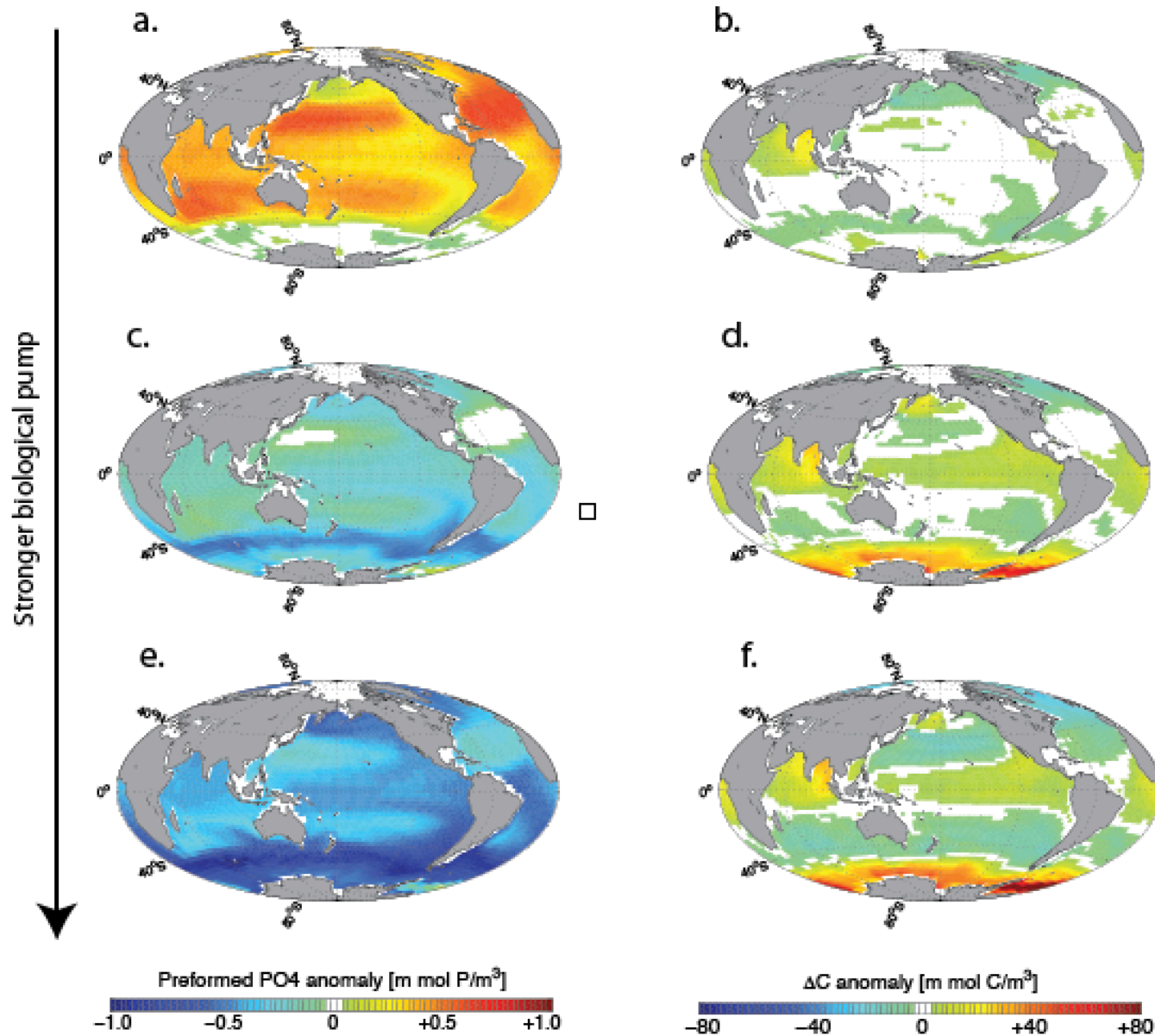
Strong biology



Surface PO4 [m mol P/m³]

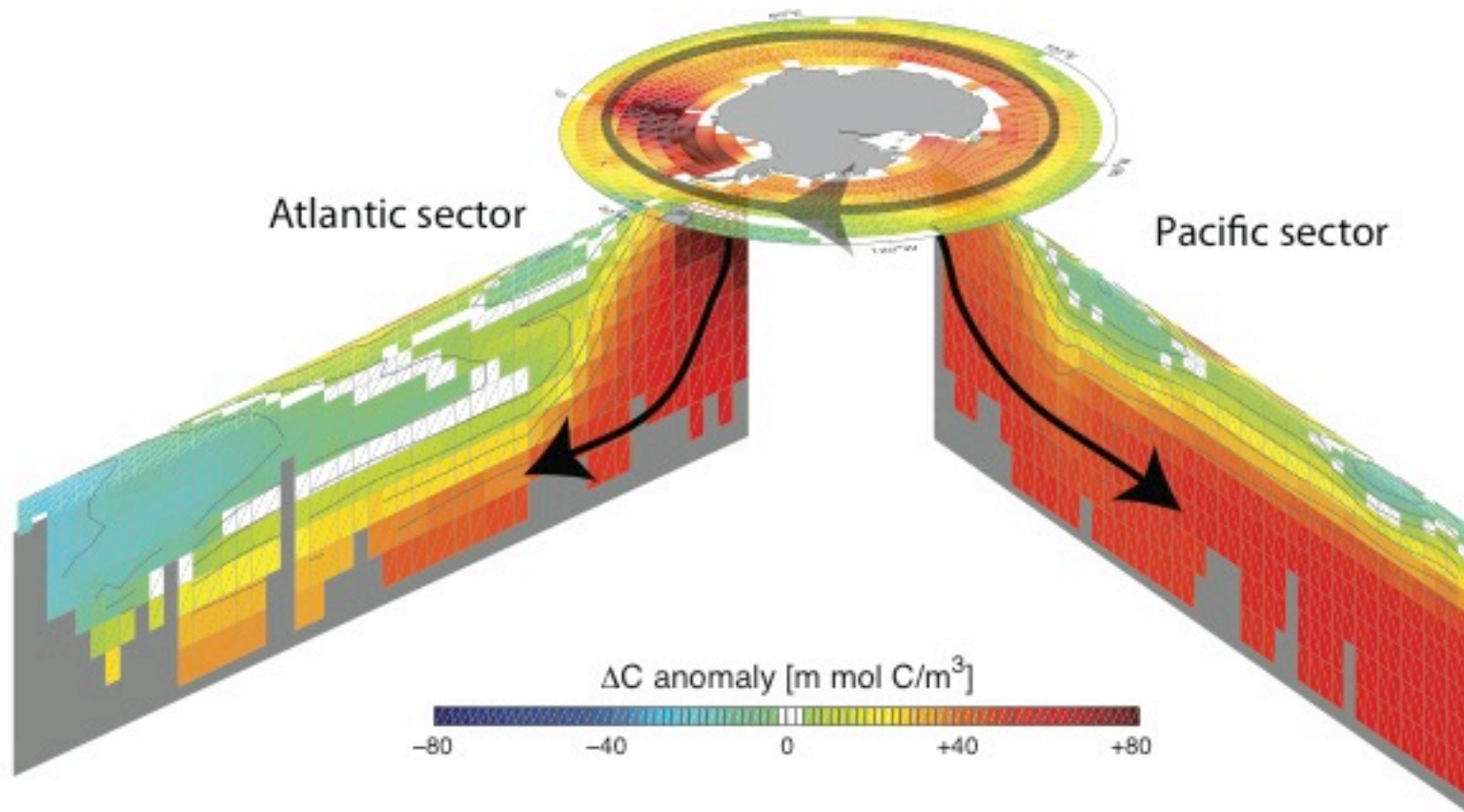


Preformed P and ΔC anomalies



Supersaturation in the southern deep water

ΔC (strong bio) - (control)



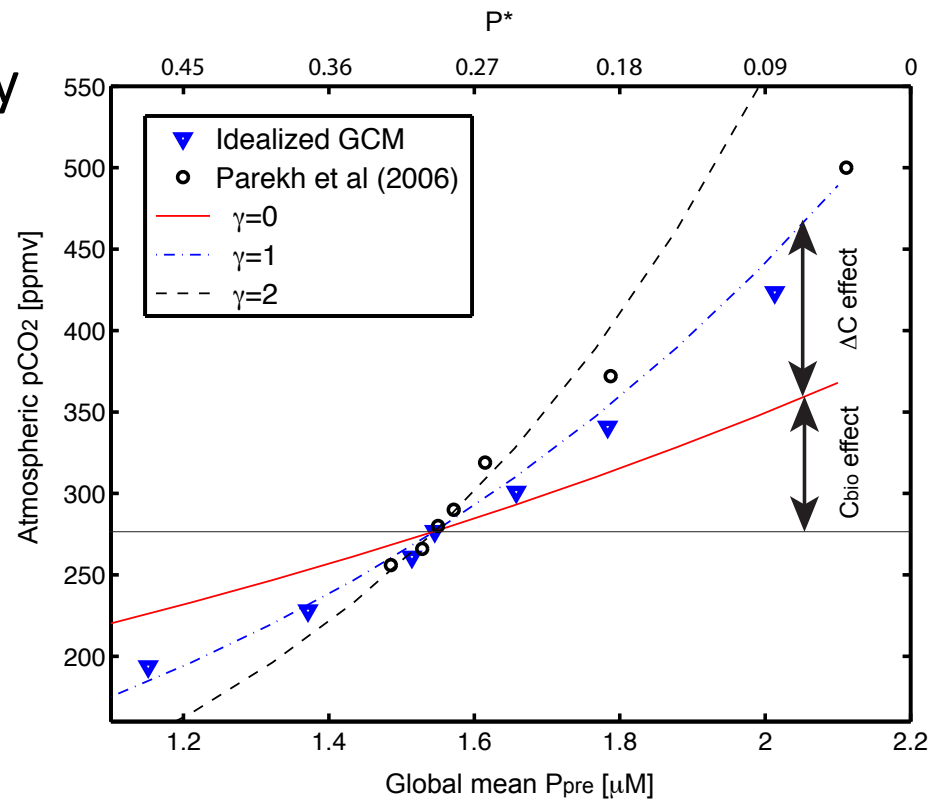
Coupling between C_{soft} and ΔC

- Stronger bio pump \rightarrow Supersaturation in deep water

$$\gamma = \frac{\partial \Delta C}{\partial C_{soft}}$$

$$\begin{aligned} \delta pCO_2^{atm} &\sim -g_C (\delta \Delta C + \delta C_{soft}) \\ &\sim -g_C (1 + \gamma) \delta C_{soft} \end{aligned}$$

- Refined the theory



Conclusions

- Observations suggest that air-sea CO₂ exchange is in the “slow” regime over 50% of the global surface ocean
- Bio pump and ΔC may be strongly coupled
 - Southern Ocean: weak η_{gas} and η_{bio}
 - ΔC effect can enhance the biological carbon storage