Physical and biological controls on the ocean carbon storage

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Outline

• Oceanic C inventory, carbon pumps

• *Surface C dynamics, and air-sea disequilibrium*

• *A new scaling theory for steady state atmospheric CO2*
Global CO$_2$ fluxes and inventories

- 90+% of the global (atmos+land+ocean) carbon is stored in the deep ocean
- DIC and buffer chemistry: $DIC = [CO_2^*] + [HCO_3^-] + [CO_3^{2-}]$
  - <1%  
  - ~90%  
  - ~10%
- ~2 PgC/yr of fossil fuel CO$_2$ 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) \(pCO_2\) and (b) mean surface \(T\)

**Solubility**
- Increase \(pCO_2\) \(\rightarrow\) 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 $\rightarrow$ lower $O_2$ level
  - Strong decadal variability

**Atlantic transect 20W**

**Gulf of Alaska (OSP) NPIW ~ 300m**

Johnson and Gruber (2007)

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)

\[
N = N_{pre} + N_{reg}
\]

\[
DIC = C_{sat} + \Delta C + C_{soft} + C_{CaCO3}
\]

<table>
<thead>
<tr>
<th>C reservoir</th>
<th>Global integral (PgC)</th>
<th>Mean conc. (µmolCkg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIC</td>
<td>35,538</td>
<td>2,253</td>
</tr>
<tr>
<td>C_{sat}</td>
<td>33,330</td>
<td>2,113</td>
</tr>
<tr>
<td>\Delta C</td>
<td>38</td>
<td>2</td>
</tr>
<tr>
<td>C_{soft}</td>
<td>1,672</td>
<td>105</td>
</tr>
<tr>
<td>C_{CaCO3}</td>
<td>502</td>
<td>33</td>
</tr>
</tbody>
</table>

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

- For preindustrial condition (setting no change on land),
  \[
  \frac{M_A \delta pCO_2^{\text{atm}}}{\text{atmos}} + V(\delta C_{\text{sat}} + \delta \Delta C + \delta C_{\text{soft}} + \delta C_{\text{CaCO3}}) = 0
  \]

- Combining carbonate chemistry, we get an expression for pCO₂
  \[
  \delta C_{\text{sat}} = f_T \delta T + f_S \delta S + f_A \delta \text{Alk} + f_p \delta pCO_2^{\text{atm}}
  \]
  \[
  \delta pCO_2^{\text{atm}} = g_T \delta T + g_S \delta S - g_C (\delta \Delta C + \delta C_{\text{soft}}) + g_A \delta C_{\text{CaCO3}}
  \]

References:
Ito and Follows (2005; subm.);
Goodwin et al., (2007; 2008; 2009); Omta et al., (2010; 2011)
Air-sea disequilibrium: $\Delta C$

$\Delta C = C_{\text{surf}} - C_{\text{sat}}(S, T, \text{Alk}, p\text{CO}_2^{\text{atm}})$

$\frac{\Delta p\text{CO}_2}{p\text{CO}_2} = B \frac{\Delta C}{C_{\text{sat}}}$

$B$ : Buffer factor

$F_{\text{CO}_2} = G K_{H} \Delta p\text{CO}_2$

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 $\Delta p\text{CO}_2$ is equivalent of $\Delta C \sim 30 \mu\text{molC/kg}^{-1}$
Upper ocean carbon dynamics

- What sets the surface $\Delta C$ distribution?

**North Atlantic**

**Southern Ocean**

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

\[
C = C_{sat}(T, S, Alk, pCO_{2 atm}) + \Delta C
\]

\[
\frac{DAC}{Dt} = -\tau_{gas}^{-1}\Delta C + f(H, EP, R_{CaCO_3}, Ent, E - P)
\]
Air-sea CO2 equilibration

• $\Delta C$ anomaly decays over the timescale of $\tau_{gas}$.

$$\frac{D\Delta C}{Dt} = -\tau_{gas}^{-1} \Delta C + f(H, EP, R_{CaCO3}, Ent, E - P)$$

• Scaling for gas exchange timescale

$$\tau_{gas} = \frac{hR}{GB}$$

$$\begin{cases} 
  h & \text{mixed layer depth} \approx 100\text{m} \\
  R & \frac{DIC}{[CO_2^*]} \approx 100 \\
  G & \text{Gas transfer coeff} \approx 5\text{m/day} \\
  B & \text{Buffer factor} \approx 10 \\
\end{cases} \approx 200\text{days}$$

Broecker and Peng (1974) Tellus
Pattern of annual mean $\tau_{gas}$

$$\tau_{gas} = \frac{hR}{GB}$$

- $h$ : ARGO float data (60S-60N)
- $G$ : QuikSCAT + gas ex parameterization
- $Chem$ : Takahashi $pCO2 + Alk$ (Lee et al., 2006)

Annual mean CO2 exchange timescale

Jones et al. (in prep)
Decomposition of $\tau_{\text{gas}}$

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

- 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 ~ up to a factor of two.
Magnitude of air-sea disequilibrium

• Surface residence time ($\tau_{\text{res}}$), measuring how long a water parcel has been in contact with the atmosphere.

\[
\eta_{\text{gas}} = \frac{\tau_{\text{res}}}{\tau_{\text{gas}}}
\]

• 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

\[
\frac{D\tau_{\text{res}}}{Dt} = \begin{cases} 
1 & \text{in the top layer} \\
0 & \text{elsewhere}
\end{cases}
\]
\( \tau_{\text{res}} \) and \( \eta_{\text{gas}} \)

- Surface residence time (months)

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

\[ \log_{10}(\eta_{\text{gas}}) \]
$\tau_{\text{gas}}$ statistics

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

- A conceptual model

**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**

\[
\Delta C(\tau_{res}) = R_C P N_0 \left\{ P * e^{-\eta_{gas}} - \frac{a_0 \eta_{bio} (e^{-\eta_{bio}} - e^{-\eta_{gas}})}{\eta_{gas} - \eta_{bio}} \right\}
\]

- Supersaturation due to upwelling of $C_{bio}$
- Attenuation of $\Delta C$ due to air-sea gas exchange and biological export
Solutions for $\Delta C$

- Analytic solution over a wide range of $\eta_{\text{bio}}$ and $\eta_{\text{gas}}$

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)
Preformed P and ΔC anomalies
Supersaturation in the southern deep water

$\Delta C$ (strong bio) - (control)
Coupling between $C_{soft}$ and $\Delta C$

- Stronger bio pump $\rightarrow$ Supersaturation in deep water

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

$$\delta pCO_{2}^{atm} \sim -g_C (\delta \Delta C + \delta C_{soft})$$

$$\sim -g_C (1 + \gamma) \delta C_{soft}$$

- Refined the theory

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**Graph:**

- Idealized GCM
- $\gamma=0$
- $\gamma=1$
- $\gamma=2$

**Axes:**

- Atmospheric $pCO_2$ [ppmv]
- Global mean $P_{pre}$ [fm]
Conclusions

• Observations suggest that air-sea CO2 exchange is in the “slow” regime over 50% of the global surface ocean

• Bio pump and $\Delta C$ may be strongly coupled
  – Southern Ocean: weak $\eta_{\text{gas}}$ and $\eta_{\text{bio}}$
  – $\Delta C$ effect can enhance the biological carbon storage