Ocean carbon sink dynamics in CESM1

Matthew Long

Climate and Global Dynamics Division

17 March 2011
The ocean carbon sink

The ocean has absorbed ∼50% of fossil fuel CO$_2$ to date.

What is the fidelity of CESM1’s ocean carbon cycle representation?

What are the dominant mechanisms generating variability in the ocean carbon sink?
Ocean carbon system

**Dissolved inorganic carbon**

\[
DIC = [\text{CO}_2] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}]
\]

**Alkalinity**

\[
Alk = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{OH}^-] - [\text{H}^+] + [\text{B(OH)}_4^-] + \text{minor bases}
\]

**Equilibrium constant**

\[
p\text{CO}_2 = \frac{[\text{CO}_2]}{K_0(T, S)}
\]
Gas exchange depends on surface boundary condition

Air-sea exchange:

\[ J_{ex} = (1 - A_{ice})k\gamma (pCO_2^{atm} - pCO_2^{sw}) \]

where

- \( k \) = piston velocity (empirical), and
- \( \gamma \) = solubility, \( f(T, S) \)

Sarmiento & Gruber 2006
Numerical experiments

Fully coupled run (BDRD)*:

- Control: prescribed $p\text{CO}_2^{\text{atm}}$
- Transient: prescribed $p\text{CO}_2^{\text{atm}}$ (branched at year 151)

*Notation:

$\text{b[cdp]}\cdot \text{r[cdp]} = \text{b[BGC CO}_2^{\text{option}}]\cdot \text{r[radiative CO}_2^{\text{option}}]$

[cdp]: $\text{CO}_2^{\text{atm}}$ options
- $c = \text{constant, [1850 value]}$
- $d = \text{diagnostic (specified), [1850 value, historical record, RCP trajectory]}$
- $p = \text{prognostic, [zero emissions, historical emissions, RCP emissions]}$
Hindcast ocean-ice spin-up and forcing

60 year repeating CORE forcing

Physical fields & dynamical tracers reinitialized at each cycle.
Hindcast ocean-ice spin-up and forcing

Global mean fields in hindcast transient
Validation datasets

3D fields

- GLobal Ocean Analysis Project (GLODAP)

Surface

- Takahashi et al. [2009] $pCO_2$
- McNeil et al. [2007] Southern Oc. C
Accounting for model drift
Change in DIC inventories in 1850-bdrd

Simulations and datasets
$pCO_{2}^{sw}$ spatial structure about right, positively biased

**Annual mean**

**Biases**

<table>
<thead>
<tr>
<th></th>
<th>$\Delta$(mean)</th>
<th>RMS error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hindcast</td>
<td>1.4%</td>
<td>17.0 $\mu$atm</td>
</tr>
<tr>
<td>Coupled</td>
<td>0.9%</td>
<td>18.8 $\mu$atm</td>
</tr>
</tbody>
</table>

**Results:** Surface fields
Seasonal Variability in $pCO_2^{sw}$: thermal & biological effects

**Magnitude comparable to spatial variability in annual mean.**

**Mechanisms:**
- $\Delta SST$
- $\Delta DIC, \Delta Alk$ (biology)

Thermal effect computed using:

$$
\Delta pCO_2^{sum} = pCO_2^{win} \exp[0.0433(T^{sum} - T^{win}) - 4.35 \times 10^{-5}((T^{sum})^2 - (T^{win})^2)]
$$

Biological component computed as residual.

**Summer = JFM (south) and JAS (north)**

**Winer = JAS (south) and JFM (north)**

Results: Surface fields
Seasonal Variability in $p\text{CO}_2^{SW}$: thermal & biological effects

Takahashi

Hindcast

Results: Surface fields
Dissolved inorganic carbon

Results: Surface fields

<table>
<thead>
<tr>
<th></th>
<th>Δ(mean)</th>
<th>RMS error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hindcast</td>
<td>-0.6%</td>
<td>22.9 mmol m$^{-3}$</td>
</tr>
<tr>
<td>Coupled</td>
<td>-1.9%</td>
<td>43.0 mmol m$^{-3}$</td>
</tr>
</tbody>
</table>
Alkalinity

Biases

<table>
<thead>
<tr>
<th></th>
<th>Δ(mean)</th>
<th>RMS error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hindcast</td>
<td>–1.4%</td>
<td>28.1 mmol m⁻³</td>
</tr>
<tr>
<td>Coupled</td>
<td>–2.8%</td>
<td>55.0 mmol m⁻³</td>
</tr>
</tbody>
</table>

Results: Surface fields
DIC is largely underestimated by CESM1

Dissolved inorganic carbon

Coupled, bDrD, years 1990–2000

Results: Surface fields
... but $p\text{CO}_2$ is overestimated, except near the continent

$p\text{CO}_2$

Coupled, bDrD, years 1990–2000

Results: Surface fields
Does alkalinity underestimation cause $pCO_2$ biases?

Alkalinity

Sep-Nov  Dec-Feb  Mar-May  Jun-Aug

Obs  

CESM1  

Bias  

Coupled, bDrD, years 1990–2000

Results: Surface fields
DIC: Alk ratio controls $pCO_2^{sw}$

At DIC = 2150 µmol kg$^{-1}$ and Alk = 2280 µmol kg$^{-1}$

\[
\frac{\partial pCO_2}{\partial DIC} \approx +2.8 \mu\text{atm}
\]

\[
\frac{\partial pCO_2}{\partial Alk} \approx -2.6 \mu\text{atm}
\]
Zonal distributions of CO$_2$ flux

Results: Surface fields

Close correspondence, except in Southern Ocean
Zonal distributions of CO$_2$ flux

Different flux estimates show largest discrepancies in Southern Oc.

Gruber et al. 2009
Zonal distributions of CO₂ flux

$pCO_2$ accumulation under ice

Takahashi et al. 2009

Results: Surface fields
Models show large range of variability in Southern Oc. fluxes; a component of this is related model physics and variation in intermediate, deep, and bottom water formation.

Gruber et al. 2009
Anthropogenic CO$_2$ and CFC uptake biases, CCSM3

- Overall structure similar to observations; but
- Low biases in the Southern Ocean: Weak Antarctic intermediate and mode water formation?
- CFC pattern indicates too strong ventilation along Antarctic margin; N. Atlantic deep convection too far south—and/or SST biases.

Thornton et al. 2009
CESM1 anthropogenic CO$_2$ inventories

Inventories

GLODAP: $118 \pm 19$ Pg C  ($\pm 16\%$)

Hindcast: 88.1 Pg C  (25% low)

Coupled: 90.3 Pg C  (23% low)

Results: Anthropogenic inventories
CO$_2$ uptake too weak in both forced and coupled runs

Results: Anthropogenic inventories
CFC-11 uptake in forced and coupled runs

<table>
<thead>
<tr>
<th>Inventory</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLODAP</td>
<td>$5.44 \times 10^8$ mol</td>
<td>$\pm 15%$</td>
</tr>
<tr>
<td>Hindcast</td>
<td>$4.90 \times 10^8$ mol</td>
<td>10% low</td>
</tr>
<tr>
<td>Coupled</td>
<td>$5.14 \times 10^8$ mol</td>
<td>5% low</td>
</tr>
</tbody>
</table>

*Inventories exclude Arctic

Results: Anthropogenic inventories
Regional trends in air-sea CO$_2$ flux

Contemporary CO$_2$
Regional trends in air-sea CO$_2$ flux

Anthropogenic CO$_2$
Regional trends in air-sea CO\textsubscript{2} flux

Anthropogenic CO\textsubscript{2}
Summary

- Getting carbon uptake right requires accurate representation of both
  1. surface processes affecting air-sea exchange; and
  2. physical subduction and transport.

- Spatial and temporal variability in $pCO_2^{sw}$ compares favorably with observations; model $pCO_2^{sw}$ is too high compared to observations, alkalinity cycling may play a role.

- Anthropogenic CO$_2$ uptake is improved relative to CCSM3; although weak uptake persists and the structure of biases is similar: high latitude regions remain problematic.

- Dramatic 20th century changes in regional sink performance are not evident in the model.