Southern Ocean carbon in the Community Earth System Model

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with thanks to
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Human perturbation of the global carbon cycle

Anthropogenic CO$_2$: emissions and sinks


1 Pg = $10^{15}$ g

:: Motivation ::
Human perturbation of the global carbon cycle

The ocean carbon sink

Carbon inventories* (Pg C)

- Natural \( C_{ant} \)
- Emissions:
  - Atm: \([ 590 + 165 ]\)
  - Land: \([ 2,300 + 65 - 124 ]\)
  - Ocean: \([ 38,000 + 118 ]\)

*mid-1990s

Sabine et al. 2004
Southern Ocean dominates uptake of $C_{ant}$

Anthropogenic CO$_2$

Khatiwala et al. 2009
Southern Ocean meridional circulation

Gruber et al. 2009
Highly sensitive to climate change

- Westerlies drive Antarctic Circumpolar Current;
- Divergence pulls deepwater from ocean interior;
- Wind position & strength modulates ventilation;
- Winds respond to climate variability & change.

Southern Annular Mode

Windstress anomaly [N m$^{-2}$]

(1$^{st}$ EOF of SLP in 1000-yr control simulation.)
Models show large discrepancies in Southern Ocean fluxes

Gruber et al. 2009
Community Earth System Model

- Atm CAM4
- Land CLM4
- Ocean POP2
- Ice CICE4
- Coupler CPL7

- Energy and mass conserving;
- Internal climate variability;
- External perturbations (i.e. CO$_2$ emissions).
CESM Biogeochemical Element Model (BEC)

- Inorganic tracers: NO$_3$, NH$_4$, PO$_4$, Si(OH)$_3$, Fe, O$_2$, DIC, & Alkalinity
- Phytoplankton:
  - pico/nano diatoms, diazotrophs
  - Growth, N$_2$ fixation, Calcification
  - Excretion
  - Mortality & aggregation
- Zooplankton (adaptive):
  - Grazing
  - Mortality & sloppy feeding
- Detritus:
  - suspended/DOM
  - large (POM, silica, CaCO$_3$, dust)
  - Remineralization & dissolution
  - Sinking
- Chlorophyll:
  - pico/nano diatoms, diazotrophs
  - Photoadaption

- 4 Plankton functional types:
  - 3 autotrophs, 1 grazer
  - implicit calcifiers
  - explicit N fixers

- Nutrients: N, P, Si, Fe

- Fixed C:N:P stochiometry

- Variable Fe:C, Si:C, & Chl:C

- Nonlinear carbon chemistry

- Atm. deposition: Fe & N

- Dynamic Fe cycle

References:
Moore, Doney, & Lindsay, *GBC*, 2004.

Doney et al., *J. Mar. Systems*, 2009
Two 20\textsuperscript{th}-Century experiments: ocean-ice & coupled

1. CORE20C: CORE-forced hindcast (60 year repeating cycle)

Physical fields & dynamical tracers reinitialized at each cycle.

2. CPLD20C: fully-coupled 20\textsuperscript{th} Century integration

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

Control: prescribed $p\text{CO}_2\text{atm}$
One ocean model, different atmospheric forcing

Zonal-mean zonal windstress

Coupled model winds:
- max wind stress $\sim 50\%$ greater;
- shifted poleward.
Antarctic circumpolar current

Barotropic streamfunction

Stronger winds in coupled model drive accelerated ACC flow.

Model validation
Seasonal $p\text{CO}_2^{SW}$-cycle is well simulated

:: Model validation ::

- Takahashi (Obs)
- Hindcast
- Coupled

<table>
<thead>
<tr>
<th>Obs. mean</th>
<th>CORE bias</th>
<th>Coupled bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.8</td>
<td>+1.5</td>
<td>+2.3</td>
</tr>
<tr>
<td>-2.8</td>
<td>+0.5</td>
<td>+2.2</td>
</tr>
<tr>
<td>-6.8</td>
<td>-1.8</td>
<td>+3.0</td>
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<td>-3.8</td>
<td>+0.6</td>
<td>+2.7</td>
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<tr>
<td>-5.6</td>
<td>-1.2</td>
<td>+2.4</td>
</tr>
<tr>
<td>-4.0</td>
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<td>+2.3</td>
</tr>
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<td>+2.4</td>
</tr>
</tbody>
</table>
Air-sea CO$_2$ flux: mean seasonal cycle

(Obs: $\Delta p$CO$_2$ climatology)

:: Model validation ::
Zonally integrated air-sea fluxes

Contemporary fluxes

(Obs: ocean inversion, $\Delta p\text{CO}_2$ climatology)

- CORE20C
- CPLD20C
- Ocean Inversion
- $\Delta p\text{CO}_2$ climatology

$\text{CO}_2$ flux [Pg C yr$^{-1}$]

<44°S | 44°S-18°S | 18°S-18°N | 18°N-49°N | >49°N

Takahashi et al. 2009; Gruber et al. 2009

:: Model validation ::
Zonally integrated air-sea fluxes

(Flux components)

(Obs: ocean inversion)

Gruber et al. 2009
Mechanisms governing variability in air-sea CO$_2$ flux

RMS of air-sea CO$_2$ flux

Components of variability

Air-sea exchange:

\[ F_{co2} = (k\alpha)\Delta pCO_2 \]

\[ F'_{co2} = (k\alpha)'\Delta pCO_2 + (k\alpha)\Delta pCO'_2 \]

\[ + \left( (k\alpha)'\Delta pCO'_2 - (k\alpha)'\Delta pCO'_2 \right) \]

\[ k = \text{piston velocity, } f(U_{10}, T); \alpha = \text{solubility, } f(T, S) \]
Mechanisms governing pCO$_2$ variability

\[ pCO'_2 \approx \frac{\partial pCO_2}{\partial T} T' + \frac{\partial pCO_2}{\partial S_{FW}} S' + \frac{\partial pCO_2}{\partial DIC} sDIC' + \frac{\partial pCO_2}{\partial Alk} sAlk' \]

Doney et al. 2009
Mechanisms governing DIC variability

RMS of annual ($\Delta$DIC/Δt) vs. Contribution of CO$_2$ flux

Contribution of net biological uptake vs. Contribution of horizontal and vertical advection

Contribution of horizontal and vertical diffusion vs. Contribution of CO$_2$ virtual flux

Doney et al. 2009
Trends in coupled model Southern Hemisphere winds

Maximum zonal-mean zonal windstress

11-year running mean

Control ± 1σ (900 years)
Trends in coupled model Southern Hemisphere windstress

Maximum zonal-mean zonal wind

NCEP reanalysis
(+0.1 N m$^{-2}$ offset)

Control ± 1σ
(900 years)

11-year running mean
Trends in Southern Ocean CO₂ fluxes

Spatially-integrated fluxes (south of 45°S)

Trends (Pg yr⁻²)

<table>
<thead>
<tr>
<th>CORE¹</th>
<th>Coupled</th>
<th>CCSM3²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern: -0.003</td>
<td>-0.007</td>
<td>-0.004</td>
</tr>
<tr>
<td>Natural: +0.007</td>
<td>+0.001</td>
<td>+0.005</td>
</tr>
<tr>
<td>Anthro: -0.011</td>
<td>-0.010</td>
<td>+0.009</td>
</tr>
</tbody>
</table>

¹ Includes 0.004 Pg yr⁻² global correction.
² Lovenduski et al. 2008

CCSM-3 (Lovenduski et al. 2008)
Trends in Southern Ocean CO₂ fluxes

Spatially-integrated fluxes (south of 45°S)

- Little change in CO₂ flux trends with each successive forcing cycle.

MOC components

- 20th Century trends

:: 20th Century trends ::

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Southern Ocean anthropogenic CO$_2$

Time-integrated uptake

Storage (mid-1990s)
Southern Ocean anthropogenic CO₂

Zonal integral of $C_{\text{ant}}$

Time-integrated uptake

Coupled (56 Pg)

CORE-forced (54 Pg)

Storage

Coupled (50 Pg)

CORE-forced (51 Pg)

Meridional overturning circulation

:: Transient tracer uptake ::
Southern Ocean anthropogenic CO$_2$

Observations ($\Delta C^*$)
Southern Ocean tracer uptake

pCFC-11

Anthropogenic CO$_2$

Explanations?

- Surface biases?
- Weak mode and intermediate water formation?
- $C_{ant}$ observations: $\Delta C^*$ method has a known vertical bias, underestimating concentrations at depth.

:: Transient tracer uptake ::
Surface biases

Sea surface temperature bias

Winter mixed layer depth bias

Obs: HadISST

Obs: de Boyer Montégut et al., JGR 2004
Weak mode water formation

Potential vorticity
Low PV = Subantarctic Mode Water

In the model:
Stratification prevents convection and subduction north of the ACC?
Buoyancy forcing is incorrect?

Weak buffering: High Revelle factor $\rightarrow$ reduced CO$_2$ uptake

Revelle Factor

$$RF := \frac{\partial p\text{CO}_2}{\partial \text{DIC}} \frac{\text{DIC}}{p\text{CO}_2}$$

Computed analytically from thermodynamic equilibrium equations.
21st Century response

Atmospheric CO$_2$

Global C$_{ant}$ flux

Southern Ocean C$_{ant}$ flux

negative := ocean uptake

:: 21st Century predictions ::
21st Century response
Mixed layer depth

Sea surface temperature

:: 21st Century predictions ::
Southern Ocean carbon budget

Late 20th Century (1995–2005)

CaCO$_3$ formation

CaCO$_3$

[POC + DOC] [1.1]

[POC + DOC] [0.1]

DIC [288 + 4]

DIC [7,484 + 14]

NPP 7.9

Respiration 6.2

0.07 (vf)

-0.00

0.63

16.3

1.6

17.2

1.8

0.1

1.3

0.3

19.1

2.2

1.3

0.1

0.1

0.1

Inventories (Pg C):
[Natural + $C_{ant}$]

Fluxes: Pg C yr$^{-1}$

:: 21st Century predictions ::
Southern Ocean carbon budget

Late 21st Century (2090–2100, RCP8.5)

Inventories (Pg C):
[Natural + C\textsubscript{ant}]
Fluxes: Pg C yr\textsuperscript{-1}

:: 21st Century predictions ::
In general, modeled ocean C fields and patterns of air-sea exchange compare well with observations.

Advection of DIC is the dominant control on interannual air-sea flux variability in the Southern Ocean, with biological uptake (related to dust fluxes) making locally important contributions.

Southern Ocean uptake of anthropogenic tracers is weak relative to observationally-based estimates. The representation of physical processes controlling ventilation and subduction is the primary problem; biases at the sea surface may also play a role.