Carbon-concentration and carbon-climate feedbacks in CMIP5 Earth system models

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Atmospheric carbon budget

\[ \frac{dC}{dt} = E - F_L - F_O \]

\[ E = \frac{dC}{dt} + F_L + F_O \]

\[ F_A = -(F_L + F_O) \]
Our understanding of carbon cycle feedbacks is ....

- Higher C leads to larger $F_L$ and $F_O$, i.e. negative carbon-concentration feedback, GOOOOOD.

- Higher temperatures lead to decreased $F_L$ and $F_O$, i.e. positive carbon-climate feedback, BAAAAD.

Several researchers have attempted to quantify these feedback parameters and their contribution of the atmospheric carbon budget.
Here we analyze results from radiatively-, biogeochemically- and fully-coupled 1% per year increasing CO₂ simulations to quantify the carbon feedback parameters across eight models.

Range across eight models

\[ T'_f = 4.84 \, ^\circ \text{C} \]
\[ T'_r = 4.40 \, ^\circ \text{C} \]
\[ T'_b = 0.32 \, ^\circ \text{C} \]
Atmosphere-surface $\text{CO}_2$ flux

Range across eight models
Cumulative atmosphere-surface CO$_2$ flux

Range across eight models
Compared to a control simulation, flux changes (the Boer and Arora (BA) approach), and reservoir changes (the Friedlingstein et al. (FEA) approach) can be represented in terms of CO₂ and temperature changes.

**BA approach**

Radiatively-coupled

$$\Delta F_i^r = \Gamma_i T'_r$$

Biogeochemically-coupled

$$\Delta F_i^b = \Gamma_i T'_b + B_i C'$$

Fully-coupled

$$\Delta F_i^f = \Gamma_i T'_f + B_i C'$$

$$i = A, L, O$$

$$F_A = -(F_L + F_O)$$

$$\Gamma_A = -(\Gamma_L + \Gamma_O)$$

$$B_A = -(B_L + B_O)$$

**FEA approach**

$$\int \Delta F_i^r \, dt = \gamma_i T'_r$$

$$\int \Delta F_i^b \, dt = \gamma_i T'_b + \beta_i C'$$

$$\int \Delta F_i^f \, dt = \gamma_i T'_f + \beta_i C'$$

$$\gamma_A = -(\gamma_L + \gamma_O)$$

$$\beta_A = (\beta_L + \beta_O)$$

B, β - Carbon-concentration feedback parameter

Γ, γ - Carbon-climate feedback parameter
B, β - Carbon-concentration feedback parameter

BA approach

FEA approach
\( \Gamma, \gamma - \text{Carbon-climate feedback parameter} \)

**BA approach**

**FEA approach**
Comparison of FEA feedback parameters to C⁴MIP study

<table>
<thead>
<tr>
<th>Model</th>
<th>Carbon-concentration feedback parameter, $\beta$ (Pg C/ppm)</th>
<th>Carbon-climate feedback parameter, $\gamma$ (Pg C/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Atmosphere</td>
<td>Land</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>-2.29</td>
<td>1.46</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>-2.04</td>
<td>1.14</td>
</tr>
<tr>
<td>BCC-CSM1</td>
<td>-2.19</td>
<td>1.36</td>
</tr>
<tr>
<td>HadGEM2</td>
<td>-1.95</td>
<td>1.16</td>
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<tr>
<td>UVic ESCM 2.9</td>
<td>-1.75</td>
<td>0.96</td>
</tr>
<tr>
<td>CanESM2</td>
<td>-1.65</td>
<td>0.97</td>
</tr>
<tr>
<td>NorESM-ME</td>
<td>-1.16</td>
<td>0.31</td>
</tr>
<tr>
<td>MIROC ESM</td>
<td>-1.56</td>
<td>0.74</td>
</tr>
<tr>
<td>Model mean (std dev)</td>
<td>-1.82 (0.37)</td>
<td>1.01 (0.36)</td>
</tr>
<tr>
<td>C⁴MIP mean (std dev) (FEA)</td>
<td>-2.48 (0.59)</td>
<td>1.35 (0.61)</td>
</tr>
</tbody>
</table>

Although feedback parameters are scenario-dependent, results show lower strength of both feedback parameters and smaller spread across models compared to the C⁴MIP study.
Carbon budget terms in the fully-coupled run

\[ E = \frac{dC}{dt} + F_L + F_O \]

\[ \Delta H'_A + \tilde{F}_L + \tilde{F}_O = \tilde{E} \]

\[ f_A + f_L + f_O = 1 \]

\[ \tilde{X} = \int_{0}^{t_{4\times}} X \, dt \]
Writing carbon budget equation in terms of feedback parameters

\[ \Delta F^f_A \approx F_C + F_T = B_A C' + \Gamma_A T'_f \]

\[ \int \Delta F^f_A \, dt \approx \int F_C \, dt + \int F_T \, dt = \int (B_A C' + \Gamma_A T'_f) \, dt \]

\[ = \beta_A C' + \gamma_A T'_f \]

\[ \Delta H'_A + \tilde{F}_C + \tilde{F}_T = \tilde{E}_e \]
How well do feedback parameters work in reconstructing emissions?

(a) Diagnosed cumulative emissions

- From the fully-coupled simulation
- Calculated using feedback parameters, $\Delta H_A' + \tilde{F}_T + \tilde{F}_C$
Contribution of **carbon-concentration** and **carbon-climate** feedback parameters to atmospheric carbon budget

\[
\Delta H'_{\text{A}} - \bar{F}_C - \bar{F}_T = \bar{E}_e
\]

**a) Contribution of feedback terms to carbon budget**

**b) Fractional contribution of feedback terms to the carbon budget**

\[ f_A + f_C + f_T = 1 \]

1525 ± 325 (std dev) Pg C

-341 ± 146 (std dev) Pg C
Contribution of land and ocean components of carbon-concentration and carbon-climate feedback parameters to atmospheric carbon budget
Gain \((g)\) in coupled carbon-climate simulations

Another way to quantify **carbon-climate feedback**

\[
\frac{C'}{C^*} = \frac{1}{1 - g}
\]

Friedlingstein et al. (2003, 2004)

\[
\frac{\tilde{E}^*}{\tilde{E}} = \frac{1}{1 - g_E}
\]

Arora, Boer, et al. (2012)

Both \(g\) and \(g_E\) have exact same expressions and mean the same thing. Positive values of both imply positive carbon-climate feedback.

\[
g_{E,e} = \frac{-(\gamma_L + \gamma_O)\alpha}{(m + \beta_L + \beta_O)}
\]
Emissions-based gain ($g$) in coupled carbon-climate simulations
Summary

• Response of land to CO₂ and temperature changes 3-4 times more uncertain than ocean.

• Carbon-concentration feedback’s contribution 4.5 larger and twice as much uncertain compared to carbon-climate feedback.

• Ocean carbon-climate feedback’s contribution really small.

• Inclusion of terrestrial N cycle changes the game – it appears to reduce the contribution of both feedbacks – but still too early to draw firm conclusions.