The 20th century carbon budget simulated with CCCma first generation earth system model (CanESM1)

Vivek K Arora, George J Boer, Charles L Curry, James R Christian, Kos Zahariev, Kenneth L Denman, Gregory M Flato, John F Scinocca, William J Merryfield

Canadian Centre for Climate Modelling and Analysis
Environment Canada
## CCCma Earth System Model (CanESM1)

<table>
<thead>
<tr>
<th>Physical atmosphere and land surface</th>
<th>Physical Ocean</th>
<th>CO$_2$ and non-CO$_2$ GHGs</th>
<th>Terrestrial carbon cycle component</th>
<th>Ocean carbon cycle component</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGCM3</td>
<td>OGCM3.5</td>
<td>CO$_2$</td>
<td>Canadian Terrestrial Ecosystem Model (CTEM)</td>
<td>Canadian Model of Ocean Carbon (CMOC)</td>
</tr>
<tr>
<td>T47/L31</td>
<td></td>
<td>CH$_4$, N$_2$O, CFC-11 and CFC-12 specified</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~3.75° resolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLASS land surface scheme (v2.7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Canadian Terrestrial Ecosystem Model (CTEM)

CTEM 1.0 Plant Functional Types

1. Needleleaf Evergreen
2. Needleleaf Deciduous
3. Broadleaf Evergreen
4. Broadleaf Cold Deciduous
5. Broadleaf Dry Deciduous
6. C3 Crop
7. C4 Crop
8. C3 Grass
9. C4 Grass
CMOC incorporates an inorganic chemistry module (solubility pump) and an ecosystem model (organic and carbonate pumps).

The inorganic module has dissolved inorganic carbon (DIC) and total alkalinity as prognostic variables.

**N** – Nutrients  
**P** – Phytoplankton  
**Z** – Zooplankton  
**D** – Detritus
Luo et al. [1996], GBC, 10(2), 209-222.

\( J_c \), Rubisco limited photosynthesis rate

\( J_e \), Light limited photosynthesis rate

\[
\mathcal{J}_1 = \frac{1}{J_c} \frac{dJ_c}{dc_i}
\]

\[
\mathcal{J}_2 = \frac{1}{J_e} \frac{dJ_e}{dc_i}
\]
Gross primary productivity (GPP), Pg C/yr

CTEM driven with observed CO₂ and 1979-99 reanalysis repeatedly.

\[ G_p(t) = G_{p0} \left[ 1 + \gamma_g \ln \frac{C(t)}{C_0} \right] \]

\[ \gamma_g = 0.90 \]

Ricciuto et al. [2008], GBC, 22, 2006GB002908.

Friedlingstein et al. [1995], GBC, 9(4), 541-556.

Norby et al. [2005], PNAS, 102, 18052-18056.

Net primary productivity (NPP), Pg C/yr

\[ N_p(t) = N_{p0} \left[ 1 + \gamma_n \ln \frac{C(t)}{C_0} \right] \]

\[ \gamma_n = 1.23 \]

\[ \gamma_n = 0.71 \quad 95\% \text{ CI (0.55-0.84)} \]

\[ \gamma_n = 0.68 \]

\[ \gamma_n = 0.60 \]
Tons of literature suggesting down-regulation of terrestrial photosynthesis due to

- nutrient limitation and
- source/sink imbalance

Although there are experimental sites suggesting that if nitrogen availability keeps up then down-regulation does not occur.

And, of course, N fixing species do not experience any down-regulation.

But the globally-averaged effect of down-regulation remains uncertain.

\[
G_p(t) = G_{p0}\left[1 + \gamma_g \ln \frac{C(t)}{C_0}\right]
\]

\[
G_d(t) = G_{p0}\left[1 + \gamma_{gd} \ln \frac{C(t)}{C_0}\right]
\]

\[
G_d = \xi(C)G_p
\]
Use results from experimental studies that grow plants and ambient and elevated CO$_2$ to infer down-regulation.

<table>
<thead>
<tr>
<th>Study</th>
<th>Study Type</th>
<th>Ambient CO$_2$ (ppm)</th>
<th>Elevated CO$_2$ (ppm)</th>
<th>Estimated down-regulation factor $\xi$</th>
<th>Inferred value of $\gamma_{gd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Ainsworth et al. (2003)</td>
<td>Experimental</td>
<td>360</td>
<td>660</td>
<td>0.18</td>
<td>0.48</td>
</tr>
<tr>
<td>2 Ainsworth et al. (2004)</td>
<td>Experimental</td>
<td>370</td>
<td>550</td>
<td>0.22</td>
<td>0.19</td>
</tr>
<tr>
<td>3 Adam et al. (2004)</td>
<td>Experimental</td>
<td>350</td>
<td>650</td>
<td>0.25</td>
<td>0.31</td>
</tr>
<tr>
<td>4 Bigras and Bertrand (2006)</td>
<td>Experimental</td>
<td>370</td>
<td>710</td>
<td>0.19</td>
<td>0.48</td>
</tr>
<tr>
<td>5 Medlyn et al. (1999)</td>
<td>Meta-analysis</td>
<td>350</td>
<td>700</td>
<td>0.15</td>
<td>0.59</td>
</tr>
<tr>
<td>6 McGuire et al. (1995)</td>
<td>Meta-analysis</td>
<td>~350</td>
<td>~700</td>
<td>0.21</td>
<td>0.44</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>0.42</strong></td>
</tr>
</tbody>
</table>

**What the model response should be?**

$$\gamma_{gd} = 0.42$$

$$\xi(C) = \frac{1 + \gamma_{gd} \ln(C/C_0)}{1 + \gamma_g \ln(C/C_0)}$$

Down-regulation

Model response to CO$_2$

Ambient and elevated CO$_2$
Down-regulation of terrestrial photosynthesis rates as a function of atmospheric CO2

10% down-regulation in year 2000 with CO2 conc. ~370 ppm

Compare that to vegetation type dependent 16% to 40% reduction in Common Land Model (CLM) of Community Climate System Model (CCSM) [Oleson et al., 2008; Stöckli et al., 2008]
\[ G_p(t) = G_{p0} \left[ 1 + \gamma_g \ln \frac{C(t)}{C_0} \right] \]

\[ N_p(t) = N_{p0} \left[ 1 + \gamma_n \ln \frac{C(t)}{C_0} \right] \]

<table>
<thead>
<tr>
<th>Before down-regulation</th>
<th>( \gamma_g = 0.90 )</th>
<th>( \gamma_n = 1.23 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>After down-regulation</td>
<td>( \gamma_g = 0.51 )</td>
<td>( \gamma_n = 0.69 )</td>
</tr>
</tbody>
</table>

Ricciuto et al. [2008], GBC, 22, 2006GB002908.
Friedlingstein et al. [1995], GBC, 9(4), 541-556.
Norby et al. [2005], PNAS, 102, 18052-18056.

\[ \gamma_n = 0.71 \]
\[ \gamma_n = 0.68 \]
\[ \gamma_n = 0.60 \]

95% CI (0.55-0.84)
Can’t simulate historical 1850-2000 CO$_2$ without including anthropogenic land use change
Can’t simulate historical 1850-2000 CO₂ without including anthropogenic land use change

C₅ Crop 1850

Historical changes in crop area. Changes in pasture area are not taken into account, yet.
## Treatment of LUC emissions

<table>
<thead>
<tr>
<th>Interactive LUC</th>
<th>Specified LUC emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>Simulation A</td>
</tr>
<tr>
<td>Yes</td>
<td>Simulation C</td>
</tr>
<tr>
<td></td>
<td>Simulation B</td>
</tr>
<tr>
<td></td>
<td>Simulation D</td>
</tr>
</tbody>
</table>

- **Terrestrial photosynthesis down-regulation**
  - No
  - Simulation A
  - Simulation B
  - Simulation C
  - Simulation D
Observed
Simulation A, no down-regulation + interactive LUC emissions
Simulation B, no down-regulation + Houghton’s LUC emissions
Simulation C, down-regulation + interactive LUC emissions
Simulation D, down-regulation + Houghton’s LUC emissions

Atmospheric CO₂ (ppm)

Land-atmosphere CO₂ flux (Pg C/yr)

Ocean-atmosphere CO₂ flux (Pg C/yr)

Compare 350 – 379 ppm range with 346-400 ppm range from C4MIP models
Zonal distribution of land- and ocean-atmosphere fluxes (gC/m².year) averaged over the 1981-2000 period.

Simulation A, no down-regulation + interactive LUC
Simulation B, no down-regulation + Houghton’s LUC emissions
Simulation C, down-regulation + interactive LUC emissions
Simulation D, down-regulation + Houghton’s LUC emissions

Sink of atm. CO₂
Source of atm. CO₂

Takahashi et al. (2008) ocean CO₂ flux for year 2000

Large tropical source not consistent with inversion studies when using specified LUC emissions.
### Cumulative 1850-2000 fluxes (Pg C)

<table>
<thead>
<tr>
<th></th>
<th>Simulation</th>
<th>Observation-based estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>A</strong></td>
<td><strong>B</strong></td>
</tr>
<tr>
<td><strong>Fossil fuel, cement</strong></td>
<td>299.4</td>
<td>299.4</td>
</tr>
<tr>
<td>and biofuel emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Change in atmospheric</strong></td>
<td>133.4</td>
<td>144.4</td>
</tr>
<tr>
<td>carbon burden</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Land uptake</strong></td>
<td>97.3</td>
<td>80.4</td>
</tr>
<tr>
<td><strong>Ocean uptake</strong></td>
<td>68.8</td>
<td>74.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Land and ocean uptake</strong></td>
<td>166.1</td>
<td>155.2</td>
</tr>
</tbody>
</table>

**Canadian Centre for Climate Modelling and Analysis**  
Centre canadien de la modélisation et de l'analyse climatique
Zonal and temporal behaviour of observation-based and simulated 1991-2000 CO₂ concentrations

a) Observation-based

b) CanESM1

- **TransCom models**
North-South CO$_2$ gradient


10 years of control simulation
**North-South CO\textsubscript{2} gradient**
(difference between Mauna Loa and South Pole CO\textsubscript{2} concentrations)

\[ \text{CO}_2 \text{ N/S gradient} = 0.50 \text{ Emissions} - 0.81 \]
\[ \text{CO}_2 \text{ N/S gradient} = 0.46 \text{ Emissions} - 0.52 \]

AR4, Chapter 7, Denman et al. [2007]
Summary

- Modellers usually don’t quantify their net terrestrial CO₂ fertilization effect.
- Implementation of down-regulation inferred from experimental studies yields rate of increase of NPP with CO₂ that is consistent with other studies.
- Implementation of terrestrial photosynthesis down-regulation yields better agreement with observations.
- Annual CO₂ cycle and inter-hemispheric CO₂ gradient are simulated reasonably well.
- Latitudinal gradient as a function of emissions also compares well with observations.

- Ocean uptake on the lower side.
- Anomalous southern hemisphere ocean uptake and release.