Challenges in Projecting Carbon-Climate Feedbacks in the 21st Century

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Coupled Carbon Cycle-Climate Experiments

Fossil Fuel

Atmosphere

\[ \text{CO}_2 = 280 \text{ ppmv (560 PgC)} + \ldots \]

Ocean Circ. + BGC

37400 Pg C

90±

Turnover Time of C

\(10^2 - 10^3\) yr

Biophysics + BGC

2000 Pg C

60±

Turnover time of C

\(10^1\) yr

• Specify emissions from FF combustion and landuse modification
  • 19\textsuperscript{th}-20\textsuperscript{th} century – historical emissions
  • 21\textsuperscript{st} century – SRES A2 and A1B
• Prognostic CO\textsubscript{2} in atm
• Model Expts:
  • Coupled: radiatively active CO\textsubscript{2} = prognostic CO\textsubscript{2}
  • Uncoupled: radiatively active CO\textsubscript{2} = 282 ppmv (control climate)
<table>
<thead>
<tr>
<th>Model</th>
<th>Atm</th>
<th>Ocean</th>
<th>Land C</th>
<th>Ocn C</th>
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<tr>
<td>Hadley</td>
<td>HADCM3 2.5°x3.75°, L20</td>
<td>2.5°x3.75°, L20 flux-adjusted</td>
<td>MOSES/TRIFFID – DynVeg, stomates, GCM soil moisture, 1 soil pool</td>
<td>HadOCC: NPZD, DIC, TALK</td>
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<tr>
<td>IPSL-CM2</td>
<td>LMD5 64x50, L19</td>
<td>OPA, no flux-adj</td>
<td>LUE*APAR, 4 soil pool, 1 water bucket</td>
<td>OCMIP’</td>
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<tr>
<td>LLNL</td>
<td>PCM 2.8°x2.8°, L18</td>
<td>POP 0.6° x0.6°, L40</td>
<td>DynVeg, IBIS- CENTURY</td>
<td>OCMIP’</td>
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<tr>
<td>NCAR-CSM1.4</td>
<td>CSM1, T31 L18</td>
<td>NCOM3.6x3</td>
<td>Stomates, 9 soil pools, LSM 6-layer water</td>
<td>OCMIP’+Fe patch</td>
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<tr>
<td>MPI</td>
<td>ECHAM</td>
<td>MPI-OM</td>
<td>JSBACH</td>
<td>HAMOCC5</td>
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<td>FRCGC</td>
<td>CCSR/NIES/ FRCGC T42L20</td>
<td>COCO; No flux-adj, (0.5-1.4)x1.4</td>
<td>Sim-CYCLE</td>
<td>NPZD</td>
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<td>UVIC</td>
<td>1-layer Energy Balance</td>
<td>MOM-2.2</td>
<td>TRIFFID DynVeg, stomates, 1 soil bucket</td>
<td>DIC-abiotic</td>
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<td>UMD</td>
<td>QTCM</td>
<td>Mixed layer-Qflux</td>
<td>VEGAS DynVeg, 3 soil pools</td>
<td>OCMIP-abiotic</td>
</tr>
<tr>
<td>CLIMBER</td>
<td>2.5D stat-dynam 10°x51°</td>
<td>X-avg,2.5° lat, 3 basins</td>
<td>LPJ</td>
<td>NPZD</td>
</tr>
<tr>
<td>Bern-CC</td>
<td>EBM 2.5°x3.75°</td>
<td>HILDA box-diffusion model</td>
<td>LPJ</td>
<td>perturbation</td>
</tr>
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</table>
Global Carbon Budget, 1990’s

Apparent Airborne fraction = Atm incr / FF emission
~50-60%

6 models OK
2091-2100 cou minus 1991-2000 cou: \( \Delta \text{CO2} > 0; \; \Delta T > 0 \)

At the end of the 21st C
\( \Delta \text{CO2}: \; 350-650 \text{ ppmv} \)
Warming: \( 1.5->3.5 \text{C} \)

Carbon-climate feedback
- Positive
- Magnitude not proportional to actual increase
Land Carbon Storage Capacity

Increases with
- Rapid NPP increase
- Longer lag between NPP and Respiration

Norby et al (2005)
CO2 step increase
375→550 ppmv
23% increase in NPP

\[ \frac{[\text{NPP}_{\text{unc}}(600) - \text{NPP}_{\text{unc}}(300)]}{\text{NPP}_{\text{unc}}(300)} \]
Changes in Land C storage

Climate forcing of land C
Size of bubble: Climate sensitivity $\Delta T_{\text{cou}} (600-300 \text{ppmv})$

Carbon-Climate Feedback
Size of bubble: $\delta \Delta \text{Land fraction of emission UNC}(600-300) - \text{COU}(600-300)$
(decr in land frac from 300-600)

reduction in land storage due to climate feedback not proportional to sink capacity or to climate sensitivity of model
NPP in the tropics (30S-Equator)

Carbon-climate feedbacks → NPP
• decreases in 6 models
• Little change in 3 models
• Increases in 2 models

Climate feedback on NPP in the tropics shows no obvious relationship with $\Delta T$
Hydrologic Cycle

With warming, $\text{EVAP}(T) > \text{Precip}$

Soil moisture decreases even though precip increasing

$\{\delta T, \delta \text{Soil Moisture Index}\}$

Warm-wet

Warm-dry
Carbon-Water Coupling

Models differ in degrees of
• Soil water-rainfall coupling
• Soil water-evap coupling
• Evap-rainfall coupling
(Koster et al. 2004)

Hypothesis: magnitude of carbon-climate feedback depends on bias in precip and soil moisture in control runs
N.B. Uncertainties due to
• representation of BGC processes as well as
• propagation of biases in control climate and uncertainties in climate projection
Summary: C⁴MIP Robust Result

Carbon-climate feedback accelerates warming
Carbon Data Assimilation

$\text{Model: } x^b_n = M(x^a_{n-1})$

Find best estimate of $x$ ($x^a_n$) given imperfect model ($x^b_n$) and incomplete obs ($y^o$)

$$J(x) = (x-x^b)^T B^{-1} (x-x^b) + [y^o-H(x)]^T R^{-1} [y^o-H(x)]$$

3D Var

Minimize $J(x)$: $\nabla J(x^a) = 0$ at $J(x^a) = J_{\text{min}}$

Kalman filter

$x^a = x^b + K[y^o-H(x^b)]$

and other more sophisticated methods
Currently: a Relay Effort

- Global Inversion $M=\text{atm transport}$:
  - $\text{CO}_2 \rightarrow \text{fluxes}$
  - $\text{CO}_2 \rightarrow \text{LightUseEff, Q10 QED}$ [e.g. Kaminiski et al. GBC 2002; Still et al. GCB 2005]

- Local Data assim
  - $x=[\text{C stock, fluxes, EcoParam}]$
  - $M=\text{forest dynamics model}$
  - Oregon, EnKF, e.g. Williams et al. GCB 2005

- Towards C Data assim
  - $x=[\text{CO}_2, \text{fluxes}]$
  - $M=\text{atm transport}; \text{persistence of fluxes (no Eco model)}$
  - e.g. Peters et al. JGR 2005

- NEED JOINT SCIENCE: INTEGRATE ATM and ECO systems into a single framework
Challenges

• Model enhancement – multiple resource competition, disturbances, …
• Need data assimilation system
  – to synthesize atm, eco obs in the same framework
  – to improve the representation of carbon-climate models for the current climate
• Need new class of obs to formulate model representation of ecosystem function in the climate-CO2 space of the 21st century
• IPCC5! Carbon-climate models a “standard” contribution