The Causes and Implications of Persistent Atmospheric Carbon Dioxide Biases in Earth System Models

Forrest M. Hoffman, James T. Randerson, Samar Khatiwala, and CMIP5 Carbon Cycle Model Leads

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Lawrence Berkeley National Laboratory

March 21, 2013
Rapidly increasing atmospheric carbon dioxide (CO$_2$) concentrations are altering Earth’s climate.
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Perturbation of the carbon cycle could induce feedbacks on future CO$_2$ concentrations and climate.
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Climate-carbon cycle feedbacks are highly uncertain and potentially large.

Prediction of feedbacks requires knowledge of mechanisms connecting carbon and nutrients with the climate system.
## Research Objectives

<table>
<thead>
<tr>
<th>Objective 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantify climate-carbon cycle feedback responses in global models contributing to the Coupled Model Intercomparison Project Phase 5 (CMIP5) for the IPCC Fifth Assessment Report.</td>
</tr>
</tbody>
</table>
Research Objectives

Objective 1
Quantify climate-carbon cycle feedback responses in global models contributing to the Coupled Model Intercomparison Project Phase 5 (CMIP5) for the IPCC Fifth Assessment Report.

Objective 2
Reduce the range of uncertainty in climate predictions by improving the model representation of feedbacks through comparisons with contemporary observations.
Friedlingstein et al. (2003, 2006) defined the climate-induced change in atmospheric CO\textsubscript{2} in terms of the change due to direct addition of CO\textsubscript{2},

\[ \Delta C_A^c = \frac{1}{1 - g} \Delta C_A^u, \tag{1} \]

where \( g \) is the gain of the climate-carbon cycle feedback.
Feedback Analysis

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The effect of changing CO\(_2\) on temperature is approximated,

\[ \Delta T^c = \alpha \Delta C_A^c, \quad (2) \]

where \( \alpha \) is the climate sensitivity to CO\(_2\) in K ppm\(^{-1}\).
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The effect of changing CO$_2$ on temperature is approximated,

$$\Delta T^c = \alpha \Delta C_A^c,$$

where $\alpha$ is the climate sensitivity to CO$_2$ in K ppm$^{-1}$.

The change in land carbon storage,

$$\Delta C_L^c = \beta_L \Delta CO_2^c + \gamma_L \Delta T^c,$$

where $\beta_L$ is the sensitivity to the change in CO$_2$, and $\gamma_L$ is the sensitivity to climate change.
The 11 C⁴MIP models varied by a factor of

- 8 in the gain of the carbon cycle feedback ($g$),
- 9 in the climate sensitivity of land storage ($\gamma_L$), and
- 14 in the concentration sensitivity of land storage ($\beta_L$).

Spread in the projected atmospheric CO$_2$ increase due to feedbacks (left) and total land carbon uptake (right) from 11 models participating in the C⁴MIP Experiment. From Friedlingstein et al. (2006, Figure 1).
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- 14 in the concentration sensitivity of land storage \( (\beta_L) \).

Spread in the projected atmospheric CO₂ increase due to feedbacks (left) and total land carbon uptake (right) from 11 models participating in the C⁴MIP Experiment. From Friedlingstein et al. (2006, Figure 1).

No comparisons were made with observations. This is the next crucial step for reducing uncertainties!
To reduce feedback uncertainties using contemporary observations,

1. there must be a relationship between contemporary variability and future trends on longer time scales within the model, and
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2. it must be possible to constrain contemporary variability in the model using observations.
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2. it must be possible to constrain contemporary variability in the model using observations.

Example

Hall and Qu (2006) evaluated the strength of the springtime snow albedo feedback (SAF; $\Delta \alpha_s/\Delta T_s$) from 17 models used for the IPCC AR4 and compared them with the observed springtime SAF from ISCCP and ERA-40 reanalysis.
Persistence of Atmospheric CO$_2$ Biases

**Objective:** Quantify and diagnose persistence of atmospheric CO$_2$ biases in Earth System Model (ESMs).

**Hypothesis**

*Biases in prognostic atmospheric CO$_2$ are persistent on decadal time scales because carbon-concentration feedbacks in ESMs ($\beta_L$ and $\beta_O$) are related to processes that do not change rapidly.*

**Approach:**

- Quantify CO$_2$ biases in emissions-forced CMIP5 historical (esmHistorical) and future (esmrcp85) simulation results.
- Use model results to develop an atmospheric CO$_2$ trajectory with reduced bias and uncertainty range.
Schematic Summary of CMIP5 Long-Term Experiments

- **Last millennium**
  - Mid-Holocene & LGM
- **D&A ensembles**
  - Individual forcing
- **Ensembles**
  - AMIP & 20°C
  - RCP2.6, RCP6
  - Extend RCP8.5 & RCP2.6 to 2300
- **Control, AMIP, & 20°C**
- **RCP4.5, RCP8.5**
  - E-driven control & 20°C
  - E-driven RCP8.5
  - 1%/yr CO₂ (140 yrs)
  - Abrupt 4XCO₂ (150 yrs)
  - Fixed SST with 1x & 4xCO₂
  - Radiation code sees 1xCO₂ (1%/yr or 20C + RCP4.5)
  - Carbon cycle sees 1xCO₂ (1%/yr or 20C + RCP4.5)
  - AC & C4 (chemistry)

**Coupled carbon-cycle climate models only**

All simulations are forced by prescribed concentrations except those “E-driven” (i.e., emission-driven)
(a) Most ESMs exhibit a high bias in predicted atmospheric CO$_2$ mole fraction, which ranges from 357–405 ppm at the end of the historical period (1850–2005).

(b) The multi-model mean is biased high from 1945 throughout the 20$^{th}$ century, ending 5.3 ppm above observations in 2005.
(a) Most ESMs exhibit a low bias in ocean carbon accumulation from 1870–1970 as compared with adjusted estimates from Khatiwala et al. (2012).

(b) ESMs have a wide range of land carbon accumulation responses to increasing CO$_2$ and land use change, ranging from a net source of 85 Pg C to a sink of 110 Pg C in 2010.
Once normalized for high atmospheric CO₂ mole fraction biases, most ESMs exhibit a low bias in ocean carbon accumulation.
A relationship exists between contemporary and future CO$_2$ over decadal time scales, so carbon model biases persist over decadal time scales.

The (a) 2060 vs. 2010 and (b) 2100 vs. 2010 atmospheric CO$_2$ mole fraction fit for CMIP5 emissions-forced simulations of RCP 8.5. Observed atmospheric CO$_2$ mole fraction is represented by the vertical line at 385.6 ± 2 ppm.
The coefficient of determination, $R^2$, of the multi-model bias structure relative to the model CO$_2$ predictions for 2010 is statistically significant for 1910–2100.
Contemporary CO₂ Tuned Model (CCTM)

Multi-model estimates and contemporary observations can be used to reduce uncertainties in future scenarios.
Implications for Radiative Forcing and Temperature

Projections for Individual CMIP5 Models

CCTM Relative to the Multi–Model Mean

Radiative Forcing

Temperature Change

Observations
RCP 8.5
BCC–CSM1.1
BCC–CSM1.1–M
BNU–ESM
CanESM2 (x3)
CESM1(BGC)
FGOALS–S2.0
GFDL–ESM2G
GFDL–ESM2M
HadGEM2–ES
INM–CM4
IPSL–CM5A–LR
MIROC–ESM
MPI–ESM–LR
MRI–ESM1

CCTM and 95% confidence interval

Temperature Change

ΔT (°C)

Year

ΔT (K)

Year

1850 1875 1900 1925 1950 1975 2000 2025 2050 2075 2100
0 1 2 3 4 5 6 7
0 1 2 3 4 5 6 7

Radiative Forcing

Climate Change Science Institute

Oak Ridge National Laboratory
MANAGED BY UT-BATTLE for the U.S. Department of Energy
## Implications for CO₂, Radiative Forcing, and Temperature

<table>
<thead>
<tr>
<th>Model</th>
<th>CO₂ Mole Fraction (ppm)</th>
<th>Radiative Forcing (W m⁻²)</th>
<th>Cumulative ∆T (°C)</th>
<th>∆T Bias (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010 2060 2100</td>
<td>2010 2060 2100</td>
<td>2010 2060 2100</td>
<td>2010 2060 2100</td>
</tr>
<tr>
<td>BCC-CSM1.1</td>
<td>390 603 945</td>
<td>1.70 4.03 6.43</td>
<td>1.06 2.60 4.38</td>
<td>0.03 0.02 0.06</td>
</tr>
<tr>
<td>BCC-CSM1.1-M</td>
<td>396 619 985</td>
<td>1.78 4.16 6.65</td>
<td>1.14 2.71 4.54</td>
<td>0.11 0.13 0.22</td>
</tr>
<tr>
<td>BNU-ESM</td>
<td>382 602 963</td>
<td>1.59 4.02 6.53</td>
<td>0.98 2.54 4.44</td>
<td>−0.05 −0.04 0.12</td>
</tr>
<tr>
<td>CanESM2 r1</td>
<td>394 641 1024</td>
<td>1.75 4.36 6.86</td>
<td>1.07 2.80 4.69</td>
<td>0.04 0.22 0.37</td>
</tr>
<tr>
<td>CanESM2 r2</td>
<td>392 641 1023</td>
<td>1.72 4.35 6.85</td>
<td>1.06 2.79 4.69</td>
<td>0.03 0.21 0.37</td>
</tr>
<tr>
<td>CanESM2 r3</td>
<td>396 641 1025</td>
<td>1.78 4.35 6.87</td>
<td>1.10 2.80 4.69</td>
<td>0.07 0.22 0.37</td>
</tr>
<tr>
<td>CESM1-BGC</td>
<td>407 697 1121</td>
<td>1.92 4.80 7.34</td>
<td>1.21 3.10 5.06</td>
<td>0.18 0.52 0.74</td>
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<tr>
<td>FGOALS-S2.0</td>
<td>404 636 993</td>
<td>1.89 4.31 6.70</td>
<td>1.19 2.79 4.62</td>
<td>0.16 0.21 0.30</td>
</tr>
<tr>
<td>GFDL-ESM2G</td>
<td>395 616 967</td>
<td>1.77 4.14 6.56</td>
<td>1.14 2.70 4.50</td>
<td>0.11 0.12 0.18</td>
</tr>
<tr>
<td>GFDL-ESM2M</td>
<td>400 621 964</td>
<td>1.83 4.18 6.54</td>
<td>1.18 2.74 4.50</td>
<td>0.15 0.16 0.18</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>411 636 983</td>
<td>1.98 4.31 6.64</td>
<td>1.28 2.83 4.58</td>
<td>0.25 0.25 0.26</td>
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<tr>
<td>INM-CM4</td>
<td>386 591 897</td>
<td>1.64 3.92 6.15</td>
<td>1.00 2.57 4.21</td>
<td>−0.03 −0.01 −0.11</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>375 573 908</td>
<td>1.48 3.75 6.22</td>
<td>0.93 2.40 4.22</td>
<td>−0.10 −0.18 −0.10</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>398 658 1121</td>
<td>1.81 4.50 7.35</td>
<td>1.15 2.90 5.00</td>
<td>0.12 0.32 0.68</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>383 590 948</td>
<td>1.60 3.91 6.45</td>
<td>1.04 2.51 4.39</td>
<td>0.01 −0.07 0.07</td>
</tr>
<tr>
<td>MRI-ESM1</td>
<td>361 516 778</td>
<td>1.28 3.20 5.39</td>
<td>0.81 2.05 3.63</td>
<td>−0.22 −0.53 −0.69</td>
</tr>
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<th>Radiative Forcing (W m⁻²)</th>
<th>Cumulative ∆T (°C)</th>
<th>∆T Bias (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-model Mean</td>
<td>393 621 968</td>
<td>1.74 4.19 6.56</td>
<td>1.10 2.71 4.48</td>
<td>0.07 0.13 0.16</td>
</tr>
<tr>
<td>CCTM Estimate</td>
<td>386 600 931</td>
<td>1.64 4.00 6.35</td>
<td>1.03 2.58 4.32</td>
<td>— — —</td>
</tr>
<tr>
<td>Historical + RCP 8.5</td>
<td>385 592 916</td>
<td>1.63 3.93 6.26</td>
<td>1.02 2.53 4.28</td>
<td>−0.01 −0.05 −0.04</td>
</tr>
</tbody>
</table>
Discussion and Conclusions

- Ordering among model predictions of atmospheric CO₂ persisted on the order of several decades.

- Underestimate of ocean CO₂ uptake likely contributes to a persistent and growing atmospheric CO₂ bias in most ESMs.

- Similar deficiencies in land models—including the response of GPP to CO₂ concentration, allocation to woody pools, nutrient limitation, response of heterotrophic respiration to temperature, and land use change—further contribute to an atmospheric CO₂ bias.

- Future fossil fuel emissions targets designed to stabilize CO₂ levels would be too low if estimated from the multi-model mean of ESMs.

- Value in tuning models: The CCTM projection provided a 6-fold reduction in uncertainty at 2060 and a 5-fold reduction at 2100.

- Models could be improved through extensive comparison with observations using a community benchmarking system like planned for the International Land Model Benchmarking (ILAMB) project.
Why Benchmark?

- to show the broader science community and the public that the representation of the carbon cycle in climate models is improving;
- to provide a means, in Earth System models, to quantitatively diagnose impacts of model development in related fields on carbon cycle and land surface processes;
- to guide synthesis efforts, such as the Intergovernmental Panel on Climate Change (IPCC), in the review of mechanisms of global change in models that are broadly consistent with available contemporary observations;
- to increase scrutiny of key datasets used for model evaluation;
- to identify gaps in existing observations needed for model validation;
- to provide a quantitative, application-specific set of minimum criteria for participation in model intercomparison projects (MIPs);
- to provide an optional weighting system for multi-model mean estimates of future changes in the carbon cycle.
Human capital costs of making rigorous model-data comparisons is considerable and constrains the scope of individual MIPs.

Many MIPs spend resources “reinventing the wheel” in terms of variable naming conventions, model simulation protocols, and analysis software.

**Need for ILAMB:** Each new MIP has access to the model-data comparison modules from past MIPs through ILAMB (e.g., MIPs use one common modular software system). Standardized international naming conventions also increase MIP efficiency.
International Land Model Benchmarking project and diagnostic system
What is a Benchmark?

- A benchmark is a quantitative test of model function, for which the uncertainties associated with the observations can be quantified.

- Acceptable performance on benchmarks is a necessary but not sufficient condition for a fully functioning model.

- Since all datasets have strengths and weaknesses, an effective benchmark is one that draws upon a broad set of independent observations to evaluate model performance on multiple temporal and spatial scales.

(Randerson et al., 2009)
### Example Benchmark Score Sheet from C-LAMP

<table>
<thead>
<tr>
<th>Metric</th>
<th>Metric components</th>
<th>Uncertainty of obs.</th>
<th>Scaling mismatch</th>
<th>Total score</th>
<th>Sub-score</th>
<th>CASA'</th>
<th>CN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LAI</strong></td>
<td>Matching MODIS observations</td>
<td>Low</td>
<td>Low</td>
<td>15.0</td>
<td>13.5</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>• Phase (assessed using the month of maximum LAI)</td>
<td>Low</td>
<td>Low</td>
<td>6.0</td>
<td>5.1</td>
<td>4.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Maximum (derived separately for major biome classes)</td>
<td>Moderate</td>
<td>Low</td>
<td>5.0</td>
<td>4.6</td>
<td>4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Mean (derived separately for major biome classes)</td>
<td>Moderate</td>
<td>Low</td>
<td>4.0</td>
<td>3.8</td>
<td>3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NPP</strong></td>
<td>Comparisons with field observations and satellite products</td>
<td>Moderate</td>
<td>Low</td>
<td>10.0</td>
<td>8.0</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>• Matching EMDI Net Primary Production observations</td>
<td>High</td>
<td>High</td>
<td>2.0</td>
<td>1.5</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• EMDI comparison, normalized by precipitation</td>
<td>Moderate</td>
<td>Moderate</td>
<td>4.0</td>
<td>3.0</td>
<td>3.4</td>
<td></td>
<td></td>
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<tr>
<td>• Correlation with MODIS ($r^2$)</td>
<td>High</td>
<td>Low</td>
<td>2.0</td>
<td>1.6</td>
<td>1.4</td>
<td></td>
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<tr>
<td>• Latitudinal profile comparison with MODIS ($r^2$)</td>
<td>High</td>
<td>Low</td>
<td>2.0</td>
<td>1.9</td>
<td>1.8</td>
<td></td>
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<tr>
<td><strong>CO₂ annual cycle</strong></td>
<td>Matching phase and amplitude at Globalview flash sites</td>
<td>Moderate</td>
<td>Low</td>
<td>15.0</td>
<td>10.4</td>
<td>7.7</td>
<td></td>
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<tr>
<td>• $60^\circ$–$90^\circ$N</td>
<td>Low</td>
<td>Low</td>
<td>6.0</td>
<td>4.1</td>
<td>2.8</td>
<td></td>
<td></td>
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<tr>
<td>• $30^\circ$–$60^\circ$N</td>
<td>Low</td>
<td>Low</td>
<td>6.0</td>
<td>4.2</td>
<td>3.2</td>
<td></td>
<td></td>
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<tr>
<td>• $0^\circ$–$30^\circ$N</td>
<td>Moderate</td>
<td>Low</td>
<td>3.0</td>
<td>2.1</td>
<td>1.7</td>
<td></td>
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<tr>
<td><strong>Energy &amp; CO₂ fluxes</strong></td>
<td>Matching eddy covariance monthly mean observations</td>
<td>Moderate</td>
<td>Low</td>
<td>30.0</td>
<td>17.2</td>
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<tr>
<td>• Net ecosystem exchange</td>
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<td>6.0</td>
<td>2.5</td>
<td>2.1</td>
<td></td>
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<tr>
<td>• Gross primary production</td>
<td>Moderate</td>
<td>Moderate</td>
<td>6.0</td>
<td>3.4</td>
<td>3.5</td>
<td></td>
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<tr>
<td>• Latent heat</td>
<td>Low</td>
<td>Moderate</td>
<td>9.0</td>
<td>6.4</td>
<td>6.4</td>
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<tr>
<td>• Sensible heat</td>
<td>Low</td>
<td>Moderate</td>
<td>9.0</td>
<td>4.9</td>
<td>4.6</td>
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<tr>
<td><strong>Transient dynamics</strong></td>
<td>Evaluating model processes that regulate carbon exchange on decadal to century timescales</td>
<td>Moderate</td>
<td>Low</td>
<td>30.0</td>
<td>16.8</td>
<td>13.8</td>
<td></td>
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<tr>
<td>• Aboveground live biomass within the Amazon Basin</td>
<td>Moderate</td>
<td>Moderate</td>
<td>10.0</td>
<td>5.3</td>
<td>5.0</td>
<td></td>
<td></td>
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<tr>
<td>• Sensitivity of NPP to elevated levels of CO₂: comparison to temperate forest FACE sites</td>
<td>Low</td>
<td>Moderate</td>
<td>10.0</td>
<td>7.9</td>
<td>4.1</td>
<td></td>
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<tr>
<td>• Interannual variability of global carbon fluxes: comparison with TRANSCOM</td>
<td>High</td>
<td>Low</td>
<td>5.0</td>
<td>3.6</td>
<td>3.0</td>
<td></td>
<td></td>
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<tr>
<td>• Regional and global fire emissions: comparison to GFEDv2</td>
<td>High</td>
<td>Low</td>
<td>5.0</td>
<td>0.0</td>
<td>1.7</td>
<td></td>
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</tbody>
</table>

Total: 100.0 | 65.9 | 58.3

(Randerson et al., 2009)
Meeting Co-organized by Forrest Hoffman (UC-Irvine and ORNL), Chris Jones (UK Met Office), Pierre Friedlingstein (U. Exeter and IPSL-LSCE), and Jim Randerson (UC-Irvine).

About 45 researchers participated from the United States, Canada, the United Kingdom, the Netherlands, France, Germany, Switzerland, China, Japan, and Australia.
General Benchmarking Procedure

Model aspects to be evaluated
- **Process**
  - Biophysics
  - Hydrology
  - Biogeochemistry
  - Vegetation dynamics
- **Parameter**
  - State variables
  - Rate variables
  - Responses
  - Feedback

Model improvement
- Structure
- Parameter
- Initial condition
- Input variables

Benchmarks
- Observations
- Experimental results
- Data-model products
- Relationship and patterns
- Temporal scale
- Spatial cover
- Error structure

Metrics of performance skills
- *A priori* thresholds
- Scoring systems considering weights for different processes and data sets
- To determine model’s
  - Acceptability
  - Ranking
  - Strength and deficiency

(Luo et al., 2012)
# ILAMB 1.0 Benchmarks Now Under Development

<table>
<thead>
<tr>
<th></th>
<th>Annual Mean</th>
<th>Seasonal Cycle</th>
<th>Interannual Variability</th>
<th>Trend</th>
<th>Data Source</th>
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<tbody>
<tr>
<td><strong>Atmospheric CO₂</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flask/conc. + transport</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>NOAA, SIO, CSIRO</td>
</tr>
<tr>
<td>TCCON + transport</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Caltech</td>
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<tr>
<td><strong>Fluxnet</strong></td>
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Summary

- Our international collaboration has made significant progress on development of metrics and diagnostics for ILAMB 1.0.
- As CMIP5 papers come out, we need to collect cost functions and algorithms for integration into an ILAMB 1.0 package.
- Much more work is needed on
  - diagnostics for full suite of variables and time scales,
  - combining metrics into model skill scores,
  - applying skill scores to weight models for multi-model statistics, and
  - writing papers.
- Greater participation is welcome!
- ILAMB Meeting in 2013? With ICDC-9 or GLASS/GSWP?

International Land Model Benchmarking (ILAMB) Project
http://www.ilamb.org/


