E3SMv1.1 Biogeochemistry simulation campaign – overview of configuration and historical simulations (JAMES, 2020)

Motivation: There is large uncertainty in future changes in terrestrial and ocean carbon.

- Changes in carbon varied dramatically across models in CMIP5.
- Land models that included nitrogen limitations tended to have weaker terrestrial carbon uptake.
- These results suggest that model structure and nutrient limits matter for prediction of future climate.

Source: Jones et al. (2013)
Two pathways for carbon cycle-climate feedbacks

Progressive nutrient limitation hypothesis:

Nutrient limitations reduce the response of ecosystem growth and carbon uptake to increases in atmospheric CO$_2$ (Luo et al., 2003)
Simulation Plan

• V1 Science Question: What are the effects of nitrogen and phosphorous on climate-biogeochemistry interactions, and how sensitive are these interactions to model structural uncertainty?
The E3SMv1.1 BGC model configuration

- **Terrestrial:**
  - Two approaches to soil biogeochemistry (CTC and ECA), both including N and P limits on C uptake

- **Ocean/ice:**
  - Based on the Biogeochemical Elemental Cycling model (BEC), including N, P, Si, Fe
  - Includes ocean-ice biogeochemical interactions
## Simulation plan

<table>
<thead>
<tr>
<th></th>
<th>CO₂ input to radiation (greenhouse effect)</th>
<th>CO₂ input to carbon cycle (fertilization effects)</th>
<th>Non-CO₂ climate forcings (LULCC, aerosols...)</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully-coupled (BDRD-hist)</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td>historical</td>
<td>Simulates the fully-coupled system</td>
</tr>
<tr>
<td>Biogeochemically-coupled (BDRC-hist)</td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
<td>historical</td>
<td>Isolates the carbon-cycle response to CO₂ (fertilization)</td>
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<tr>
<td>Radiatively-coupled (BCRD-hist)</td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
<td>historical</td>
<td>Isolates carbon-cycle response to climate change</td>
</tr>
<tr>
<td>CO₂ constant (BCRC-hist)</td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
<td>historical</td>
<td>Isolates effect of non-CO₂ historical forcings</td>
</tr>
<tr>
<td>All forcings constant (CNST-forcing)</td>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Diagram" /></td>
<td>constant</td>
<td>Control for model drift in absence of forcings</td>
</tr>
</tbody>
</table>
Land biogeochemistry: high-level results
ILAMB global benchmarking for land model

- Overall, both CTC and ECA simulations perform better than most CMIP5 models across a range of metrics.

- Link to interactive output: https://doi.org/10.6084/m9.figshare.11097356.v2
Response of plant growth (GPP) to carbon fertilization effect is similar in CTC and ECA

Anomalies in globally-integrated Gross Primary Productivity (GPP)

Red and blue lines show the signal of carbon fertilization, causing increased plant growth and increased CO₂ uptake.
Impacts of CO$_2$ increase on GPP

- GPP is highest in tropical forest ecosystems (as expected)
Total loss of carbon from land since 1850 is comparable to observational estimates in default (CTC) configuration.

- **Purple, orange**: Land carbon declines over the 20th century due primarily to deforestation.
- **Blue, red**: In biogeochemically-coupled simulations, increased plant growth partly compensates.
- Arrows indicate approximate range of observationally-based estimates (Khatiwala et al., 2013).
- Total loss of carbon is much lower in ECA, due to stronger phosphorus limitation.
Ocean / sea ice BGC: high-level results
Net $\text{CO}_2$ flux from ocean to atmosphere (mmol/m$^2$/yr), present-day

- Red colors are fluxes out of ocean (outgassing)
- Blue colors are fluxes into ocean (uptake / sink)

Total ocean carbon uptake since 1850:
- Benchmark: $150 \pm 20$ PgC/yr (Le Quéré et al., 2018)
- E3SMv1.1-BGC: $\sim93$ PgC/yr
Ocean surface Chl-a – too little biomass

MODEL (BDRD-hist, 1977-2006)  OBS (SeaWIFS satellite, 1997-2010)

Possible sources of bias:
- Lack of parameterized lateral mixing along isopycnal surfaces (Redi mixing).
- Biases in riverine nutrient inputs.
- Ocean mixed-layer depth biases, which lead to too-little overturning of nutrients in regions like the North Atlantic.
- Coastal underprediction is partly a resolution issue.

These issues are being addressed in v2 developments.
Carbon cycle – Climate feedback analysis
E3SM land CO$_2$ – climate feedbacks are comparatively weak (~expected)

Beta (Response of CO$_2$ uptake to CO$_2$ concentration, PgC/ppmv)

Differences:
- Different physical climate
- Different land model
  - Physics and BGC
  - Active P cycle
- E3SM is using dynamic LULCC

Plotted on data from Thornton et al. 2009
E3SM v1 BGC estimate

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Gamma (Response of CO₂ uptake to temperature, PgC/K)

E3SM land CO₂ – climate feedbacks are comparatively weak (~expected)
Summary / Outlook

• Conducted E3SMv1.1-BGC historical simulations with two land model configurations.
  – Both perform well on ILAMB land model observational benchmarks
  – Structural differences occur in nutrient limitation and nutrient pools
  – Both configurations have comparatively weak carbon-climate feedbacks, supporting the hypothesis that such feedbacks are weaker in models where nutrient limitations are represented

• Ocean carbon cycle: several sources of bias were identified, which are being addressed for v2.

• Additional papers published / in progress will describe responses to future scenarios, land nutrient limitations and structural uncertainties, sea ice biogeochemistry, and feedbacks on atmospheric dynamics
Thank you!