Climate, Carbon, and Ecosystem Interactions

Presented by John Dunne and Charles Stock on behalf of GFDL, Princeton University CICS, and external collaborators

Frontiers in Climate and Earth System Modeling: Advancing the Science
Geophysical Fluid Dynamics Laboratory
May 20, 2013
Recent Coupled Carbon-Climate Activities

- Led or co-authored >25 papers on interactions between climate and biogeochemistry since 2009
- Improved understanding of processes determining biogeochemical distributions and change
- Reduced uncertainty in future ocean and land carbon uptake and biogeochemical feedbacks
GFDL’s earth system model (ESM) for coupled carbon-climate interactions

**Earth System Model**

- Comprehensive land and ocean carbon dynamics
- Interactive/Prognostic CO$_2$
- Allows investigation of feedbacks.

**Key Components**

- Atmospheric circulation and radiation
- Ocean circulation
- Sea Ice
- Ocean ecology and biogeochemistry
- Land physics and hydrology
- Plant ecology and land use
- Allows Interactive CO$_2$
Earth System Modeling for Coupled Carbon-Climate

How much CO$_2$ will the land and ocean continue to take up?
What are the biogeochemical feedbacks?
What are the biogeochemical and ecological impacts?
ESM2M and ESM2G differ only in ocean physics

Goal: Comparison of implications of ocean vertical coordinate choice

$z^*$ (MOM4.1):
- Depth-based vertical coordinate
- Over 40 years of experience

$\rho$ (GOLD):
- Density-based vertical coordinate
- Easy to preserve water masses
Both ESMs represent Carbon Cycles in addition to Climate

ESM2M

<table>
<thead>
<tr>
<th>Reservoirs in PgC</th>
<th>Fluxes in PgC a⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation</td>
<td>1003</td>
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<tr>
<td>Soil</td>
<td>1339</td>
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<tr>
<td>Surface Ocean</td>
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<tr>
<td>Biota</td>
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<tr>
<td>Intermediate and Deep Ocean</td>
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<tr>
<td>Sedimentation</td>
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</table>

ESM2G

<table>
<thead>
<tr>
<th>Reservoirs in PgC</th>
<th>Fluxes in PgC a⁻¹</th>
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</thead>
<tbody>
<tr>
<td>Vegetation</td>
<td>997</td>
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<tr>
<td>Soil</td>
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<tr>
<td>Surface Ocean</td>
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<td>1.1</td>
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<td>37231</td>
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<tr>
<td>Sedimentation</td>
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</tbody>
</table>

2 PgC ≈ 1 ppm CO2

• Though similarly credible, large differences exist.
• ESM2M has 43% more surface ventilation and 21% more ocean primary production than ESM2G.

Dunne et al., 2013: J. Climate.
Robustness of Climate Change Response to Differing ESM2M and ESM2G Circulation

While large mean state differences exist ...

- ESM2G has a shallower thermocline, more Antarctic Bottom Water formation, and tropical upwelling
- ESM2M has more Southern Ocean upwelling and downwelling and thermocline ventilation

... Their climate change response is very similar.

- Both oceans respond similarly to similar atmospheric forcing.
- Slow-down in Atlantic Overturning and speed-up of Southern Ocean Overturning results in tropical and subantarctic downwelling anomalies in ocean tracers.

Winton et al., 2012; Dunne et al., in preparation
Reducing Uncertainty in Ocean CO$_2$ uptake

- Both models have stable controls
- ESM2M takes up 10% more CO$_2$ than ESM2G
- Both models saturate uptake rate by ~2080 (~700 ppm)
Rich structure in projected surface nutrient changes, largely similar between models

**ΔSurface NO$_3$ under RCP8.5**

- **ESM2M**
- **ESM2G**

- Increased stratification and decreased nutrient supply leads to 6% decrease in surface NO$_3$ globally
- 5% decrease in large phytoplankton production, but negligible change in total production with enhanced microbial loop at higher temperature
Relating large scale changes to the California Current

Rykaczewski and Dunne (2010; GRL)

- GFDL ESM’s increase NO$_3$ in the California Current
- While T and NO$_3$ are negatively correlated seasonally and interannually, they are positively correlated under climate change
Relating large-scale changes to the California Current

- Dominance of remote forcing on local California Current changes
- Interplay of changes in atmospheric winds and heat fluxes, stratification, ventilation, and watermass pathways modulating biogeochemical response

Rykaczewski R. and J. P. Dunne (2010; GRL)
Oxygen ventilation mechanisms rebalance in importance under climate change

Motivation: Observational records suggest decreasing interior $O_2$ leading to concerns about increasing volume of low $O_2$ waters (hypoxia).

Conclusions: GFDL ESMs increase weak hypoxia volume, but decrease most hypoxic volume as winter convection off of Chile becomes more robust.

Gnanadesikan, Dunne, and John, 2012: Understanding why the volume of suboxic waters does not increase over centuries of global warming in an Earth System Model
Largest Ocean Acidification Impact Not at the Surface but Rather in Tropical Mode Waters

ESM2M

Pacific Section (190E)

a) pH 2006-2016

b) rcp2.6 pH change by 2096

c) rcp8.5 pH change by 2096

Illustrates the importance of including dynamical, chemical and biogeochemical interactions

Resplandy, L. L. Bopp, J. Orr, and J. Dunne (in press)
Putting the puzzle pieces together: Mechanisms of Ocean Change in GFDL ESMs

- Warming increases stratification
  - Ventilation and nutrient supply decreases globally
  - Shift to microbial loop with little total productivity change
- Poleward expansion and slow-down of subtropical gyres
  - Shoaling nutricline in the subtropical gyres
  - Enhanced nutrients, hypoxia and acidification in some areas
  - Beginning convection off Chile ventilating Pacific low O$_2$ region
- Intensified hydrological cycle reduces North Atlantic overturning
  - Shoaling Northern Subpolar Atlantic and deepening tropical physical and biogeochemical properties
- and many more pieces…. Overall, a changing balance of processes creates intense regional structure in the net biogeochemical change.
Motivation:
• 2nd most important anthropogenic greenhouse gas
• Precursor to O₃
• Concern about positive CH₄-climate feedback under exhaustion of OH

Conclusions:
• 5% historical variation in $\tau_{CH_4}$ driven mainly by anthropogenic emissions
• CM3 projects reduced $\tau_{CH_4}$ except in RCP8.5

Arctic-Boreal Land BGC and Climate

- 500-700 PgC in peatlands - source of CO$_2$, CH$_4$, and N$_2$O
- Involves interactions between vegetation, soil, biogeochemistry, and hydrology on a landscape scale, including permafrost.
- Requires new land capabilities
Moving forward with GFDL’s ESMs

- Multi-member ensembles for detection/attribution
- Centennial-millennial scale carbon-climate coupling
- Idealized climate and carbon sensitivity

**Comprehensiveness:** beyond CO$_2$ to aerosol, Fe, CH$_4$ and N cycles, including improved hydrology and ecosystems

**Resolution:** Resolving the ocean mesoscale for carbon uptake and marine ecosystem applications
• Led or co-authored over 25 published studies of climate impacts on marine resources since 2009
• Led comprehensive synthesis on the use of IPCC-class models to assess the impact of climate on living marine resources
• Developed and applied innovative earth system models to improve ecosystem impacts assessment.
Negative impacts on endangered leatherback turtles

- Hatch and emergence success depend on temperature and precipitation
- Sex ratio depends on precipitation levels
- Returns to land for nesting depend on ocean productivity (cold, La-Nina conditions indicate more productive ecosystem)

Negative impacts on endangered leatherback turtles

- Project declining numbers due to lower hatching/emergence with increasing temperature
- Nesting further north unlikely due to extremely dry conditions in subtropics
- Potential to maintain population through irrigation and shading if projected impacts begin to manifest.

Potential increase in nutrients to California Current

Rykaczewski, R. and J. P. Dunne, 2010, GRL, 37
• Present assessments: magnitude, direction, and first-order drivers of climate-change impacts

• Priority developments:
  • Strengthen mechanistic and quantitative connections between climate drivers and ecosystem responses
  • Consider responses to multiple stressors
  • Improve resolution of local/regional impacts
  • Provide predictions and projections on time-scales from seasons to centuries.
Primary production alone is not a good indicator of fisheries yields

Connecting climate and global fisheries

Observation-based estimates of mesozooplankton production
(NOAA Copepod database, O’Brien, 2005; Hirst and Bunker, 2003; SeaWiFS)

Mesozooplankton production in GFDL’s COBALT ecosystem model
(Stock et al., 2010; Stock et al., submitted)
Impacts predictions for diverse space/time scales

Pursuing ecosystem applications and integration of ecosystem dynamics with GFDL models making physical climate predictions over the full range of these spatial and temporal scales.
Improving ecosystem models to improve carbon projections

Migrating mesozooplankton support “active” carbon fluxes from the euphotic zone, contributing ~15-40% of flux due to sinking particles.

Migration detected with ADCP

![Graph showing migration detected with ADCP](image)

Luo et al., DSR2, 2000

Modeled carbon remineralization by migrators

![Graph showing modeled carbon remineralization](image)

Bianchi, D. C. A. Stock, et al., GBC, 2013
Climate Adaptation and Mitigation:

• Improved understanding of the changing climate system through coupled climate-carbon models
• Assessments of climate change impacts to inform science, service and stewardship decisions

Healthy Oceans:

• Improved understanding of ecosystems to inform resource management decisions

Resilient coastal communities and economies:

• Resilient coastal communities that can adapt to the impacts of hazards and climate change