A CO$_2$-climate sensitivity study with a mathematical model of the global climate

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An increase in the CO$_2$-content of the atmosphere resulting from man’s activity could have a significant effect on the climate in the near future. We describe here some new results from a study of the response of a mathematical model of the climate to an increase in the CO$_2$-content of the air.

The mathematical model consists of (1) a general circulation model of the atmosphere and (2) a simple mixed layer ocean model with uniform thickness. The atmospheric model predicts the changes of the vertical component of vorticity, divergence, temperature, moisture and surface pressure based on the same...
Transient Responses of a Coupled Ocean–Atmosphere Model to Gradual Changes of Atmospheric CO₂. Part I: Annual Mean Response
S. Manabe, R. J. Stouffer, M. J. Spelman and K. Bryan

Fig. 1. Schematic diagram of the G, S, and D integrations. The abscissa denotes time in years and the ordinate is the logarithm of the ratio of atmospheric carbon dioxide at time t to its initial value. The period chosen for detailed analysis is indicated by shading.

Fig. 8. The temporal variation of the differences in area-averaged, decadal-mean surface air temperature (°C) between the integrations (a) G and S, and (b) D and S. Solid, dashed, and dotted lines indicate the differences over the globe, and Northern and Southern Hemispheres, respectively.

Fig. 12. (a) The transient response of the surface air temperature of the coupled ocean–atmosphere model to the 1% per year increase of atmospheric carbon dioxide. The response (°C) is the difference between the 30-year (60th to 90th year) mean surface air temperature from the G integration and 100-year mean temperature from the S integration. (b) The equilibrium response of surface air temperature to the doubling of atmospheric carbon dioxide. The response is the difference between the two 10-year mean states of the E3x and E5 integrations. (c) The ratio of the transient to equilibrium responses.
How is this ‘Carbon Cycle’ work?
How is this ‘Carbon Cycle’ work?

1. The focus is climate sensitivity to changing CO$_2$

2. Reasonable so long as the experimental design approximates the net carbon cycle response to plausible fossil fuel projections.

... but is it?


Early GFDL Ocean BGC and Coupled Carbon-Climate


Carbon Sensitivity to Climate with Sarmiento

Figure 1 Time series of model boundary conditions and predictions. a, Atmospheric CO$_2$ based on observations before 1990 and the IPCC IS92a model thereafter. b, Annual ocean uptake of carbon by the biology model. Four simulations are shown: the constant-biota control model (thin solid line), the constant-biota GW model (thick solid line), the constant-phosphate control model (thin dotted line) and the constant-phosphate GW model (thick dotted line). c, Annual ocean uptake of carbon by the ‘solubility’ model. d, Maximum value of overturning in the thermohaline cell of the North Atlantic in units of Sverdrups (1 Sv = 10$^6$ m$^3$ s$^{-1}$). e, Global mean of the air–sea heat flux. f, Global mean vertical density gradient at the base of the first layer of the model (50.9 m) for latitudes polewards of 30° in both hemispheres.

Simulated response of the ocean carbon cycle to anthropogenic climate warming

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### Carbon Sensitivity to Climate with Sarmiento

**Table 1: Oceanic uptake of anthropogenic CO₂ in constant-biota model**

<table>
<thead>
<tr>
<th></th>
<th>Cumulative uptake (Pg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1765–1990</td>
</tr>
<tr>
<td><strong>A. Constant-biota baseline</strong></td>
<td>112</td>
</tr>
<tr>
<td><strong>B. Change due to variation in transport processes in absence of biological pump</strong></td>
<td>-5</td>
</tr>
<tr>
<td><strong>C. Change due to warming in absence of biological pump</strong></td>
<td>-23</td>
</tr>
<tr>
<td><strong>D. Change due to biological pump</strong></td>
<td>+39</td>
</tr>
<tr>
<td><strong>E. Global warming constant-biota model</strong></td>
<td>123</td>
</tr>
</tbody>
</table>


**Graphs**

- **a** ∆Air-Sea CO₂ Flux due to physics (Pg C °-1 yr⁻¹)
- **b** ∆Air-Sea CO₂ Flux due to biology (Pg C °-1 yr⁻¹)
...Meanwhile, other groups were building coupled carbon-climate models, e.g.:


... and GFDL struggled to define how to contribute.
Coupled Carbon Cycle Climate Model Inter-comparison (C⁴MIP) Project showed large uncertainties in land and ocean uptake under SRES-A2

• 200-400 PgC (100-200 ppm CO₂) feedbacks in both land and ocean
• Coarse/simple climate models
• Rudimentary ecosystem models

Source: Friedlingstein et al. (2006; J. Climate)
Coupled Carbon Cycle Climate Model Inter-comparison (C^4MIP) Project showed large uncertainties in land and ocean uptake under SRES-A2.

GFDL was not able to participate

- 200-400 PgC (100-200 ppm CO_2) feedbacks in both land and ocean
- Coarse/simple climate models
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Source: Friedlingstein et al. (2006; J. Climate)
Recommendations of the Earth System Modeling Task Force

Challenge: How can we produce a decadal-centennial scale Earth System Model for GFDL?
Creation of GFDL’s ESMDT (04/22/2004)

Status of Component Models

Climate Model
- ESM2 (1000 yrs in 500 days; 180pa; 130K cpu hrs/mo)
  - Currently minimally acceptable for Dec-Cen
  - Intensive efforts to improve both speed and realism
- ESM1p5 (1000 yrs in 120 days; 40pa; 29K cpu hrs/mo)
  - Unacceptable for Dec-Cen
  - No support for development

Dynamic Land Biogeochemistry Model
- Preliminary LM3vp1-AM2p12 runs (code and FRE in 2 mo)
- Coupled Carbon code is in testing
- Continuing development on N45 grid

Prognostic Ocean Biogeochemistry Model
- Prototype available in FRE
- Coupled version in a matter of weeks
- Continuing development on OM1p5 grid

Atmospheric Transport Model — prototype available

Component Integration Steps

- Code to pass CO₂ between model components is ongoing

- Propose to develop individual components:
  - Land dynamics and BGC at N45 resolution in stand-alone, AM2 and CM2 (within LMDT in collaboration with AMDT and CMDT)
  - Ocean BGC in OMIP configurations

- Propose to develop ESM through:
  - Including ESM components in Khartoum city release
  - Developing prototype ESM1p5
  - Incorporating ESM into Regression Test Suite as soon as components are ready for long spin-up
  - Switching resolution to ESM2p1 if/when available

Example Spin-up Strategy

- CO₂ roles: Atm. tracer, land/ocean BGC, radiative forcing
- Reminder: Carbon inventory adjusts to climate
- Spin-up Goal: find CO₂ in equilibrium with climate
- Challenge: fickle models and climate

Roles of collaborators

Sarmiento Lab. (AOS) - Contributed ocean tracer infrastructure, C system components, preliminary prognostic BGC code and plans to evaluate and apply ESM for C cycle studies

Pacala Lab. (EEB) - Implemented LM3v and are evaluating biophysical feedbacks, vegetation dynamics and terrestrial carbon cycle

UNH - Contributed historical land use forcing and may contribute C and N river transport and water management models

Hedin Lab. (EEB; with Pacala Lab) - Plans to develop land N model

USGS - Plans to evaluate hydrology in ESM

Wood Lab. (CEE) - Plans to contribute to evaluation of LM3 hydrology

...for a minimum 1800 yr integration in ESM1p5 taking 4 months
GFDL ESMs for Coupled Carbon-Climate and Chemistry

- Comprehensive land and ocean carbon dynamics
- Interactive/prognostic CO$_2$
- Forced by either concentrations or anthropogenic fluxes
- Allows investigation of feedbacks
- Amenable to inter-disciplinary impacts studies
CMIP5 scenarios of land use change (Hurtt et al 2011)

Unique features of GFDL land model:
- wood harvesting of primary and secondary forests
- secondary forests re-growth and shifting cultivation
- explicit treatment of above and below ground physical and biogeochemical states for LU categories
- vegetation and soil fluxes as well as harvests for all land use types
- for LM4: improving croplands phenology and diversity
- Management: fertilizer seasonality, products management
Unparalleled Biogeochemical Comprehensiveness in GFDLs CMIP5 ESMs (Tracers of Phytoplankton with Allometric Zooplankton; TOPAZ)

Diatoms and Other Large Phytoplankton
Flexible N:P:Si:Fe:Chl
Aragonite and Calcite

Biogeochemistry

DOM cycling
Particle sinking
Atm. Deposition
Gas exchange
River Input
Removal
Sediment Input
Scavenging

Phytoplankton ecology

Recycled nutrients
Small phyto.
Large phyto.
N$_2$-fixer
Protist
Filter feeder
Detritus
semilabile
semireflect.
DOM

New nutrients

Carbon
Oxygen
Nitrogen
Phosphorus
Iron
Alkalinity
Silicon
Lithogenic

Dunne et al. (2005;2013)
NOAA's First Earth System Models reduce uncertainty in heat and carbon uptake under climate warming.

- Depth-based vertical coordinate
- Over 40 years of experience

\[ z^* \text{ (MOM4.1)}: \]

\[ \rho \text{ (GOLD)}: \]

- Density-based vertical coordinate
- Easy to preserve water masses

Dunne et al. (2012, 2013); Winton et al. (2013); Hallberg et al. (2013)
Twenty-First-Century Compatible CO₂ Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models under Four Representative Concentration Pathways

Scenario Uncertainty Dominance

Structural Uncertainty Dominance
Overall good agreement between IAMs and ESMs in Compatible CO₂ Emissions for each Scenario
Hoffman et al., 2014

- Land competitive even including both dynamic vegetation and land use with secondary forests
- Ocean-atmospheric partitioning among the best
- While overestimating contemporary CO$_2$ (not enough land uptake), they give median uptake at 2100.
LULCC affects atmospheric CO$_2$ and thus climate

- Land-use (in blue) emissions contributed ~30 ppm to the 2005 atmospheric CO$_2$ increase.
- Without land use over historical period:
  - Global surface temperature would be 0.16±0.06°C lower (similar to other ESMs);
  - Land would be a sink of C;
- Larger LU source requires a larger enhanced sink

Simulations with NOAA/GFDL FF-emissions forced ESM2G model, Shevliakova et al. 2013
Difference in summer climate from LU

1986-2005, surface air temperature

Malyshev et al 2015
Global reversibility of Community Composition (John et al., GRL, 2015)

Scenario: Ramp-up/Ramp-down

RCP8.5 2006-2100 (Riahi et al., 2007), followed by reversal of RCP8.5 from 2101-2195.
Amplification of ocean productivity changes

% change, primary prod  % change, mesozoo prod

- PROJECTED PERCENT CHANGES IN MESOZOOPLANKTON PRODUCTIVITY ARE 2X PRIMARY PRODUCTIVITY CHANGES
- LARGE REGIONAL CHANGES
- QUANTITATIVE ATTRIBUTION TO THE SAME PLANKTONIC FOOD WEB CHARACTERISTICS THAT DRIVE SPATIAL GRADIENTS

Perfect Plasticity Approximation (PPA) Vegetation Dynamics

- Challenges for global PPA
  - capturing plant diversity
  - phenology and mortality
  - evaluating succession

Willow Creek, WI

Z*

Tree cohorts with multiple individuals (stems)

Weng et al., 2015
Strigul et al. 2008
Nitrogen Biogeochemistry

- Fixed C:N vegetation pools
- Prognostic biological N fixation
- 4 competing sinks of mineral N
  - plant uptake, immobilization, sorption to particles, denitrification
- Organic removal of N
  - leaching, ecosystem losses through fire
- Riverine N Biogeochemistry

Gerber et al. 2010, 2013; Lee 2014
Land-use specific fire models => LU-specific datasets to estimate these parameters, *Magi et al 2011*

*New daily fire model to enable prognostic biomass burning aerosols in CM4/ESM4*
Carbon, Organisms, Respiration, and Protection in the Soil Environment (LM3-CORPSE) model

- Vertical structure
- Explicit above and below ground litter
- DOC leaching
- Dynamic microbial activity
- Protected carbon pools
- Root exudates
- Implemented in water-tiled version (LM3-TiHy)

- Currently adding N
- P is next

Key uncertainty: the sensitivity of soil Carbon to changing climate
Carbon Cycle Research After IPCC AR6

1.5°C Threshold Closer Than We Think?
Adjust the IPCC temperature baseline to address COP21 targets

Temperature Baseline:
- COP21: 1881-1910
- Original: 1986-2005

- 2025-2030
  - we cross 1.5°C

2022
IPCC AR6
Partitioning Climate Change Uncertainty into its Structural, Scenario and Internal Components

Hawkins and Sutton, 2009, BAMS
If the COP21 momentum continues to drive policy, the climate modeling community will shift projections from change under future warming to ongoing equilibrium to current climate.

With the 1.5C threshold met and 2C threshold approaching, the focus on scenarios should narrow towards net emissions near zero – “Climate Change” research will become “Climate sustainability” research”

Carbon Cycle research should transition from rudimentary structural description focused on scenario uncertainty towards Structural and Internal variability Uncertainty

Under ‘sustainable’ (net zero) emissions, climate services provided by land and ocean carbon cycles re-equilibrating to changed climate will largely determine allowable energy trajectories.

These challenges requiring more comprehensive Earth System Modeling include:
• Blue Carbon – Identification of climate services of carbon storage in marine environments
• Comprehensive Biofuels and other land use
• Tipping Points like AMOC, biodiversity change, permafrost CO₂ and CH₄
• Detection and attribution of carbon change
• Climate carbon feedbacks and trajectories like the Southern Ocean, Soils, biogeochemistry
Future GFDL Carbon Cycle Research

- **Application**: Multi-member ensembles for detection and attribution, centennial-millennial scales, idealized sensitivity, diverse impacts

- **Comprehensiveness**: Comprehensive and robust ecosystem, biogeochemistry and human interaction models and self consistent representation of aerosol, Fe, CH₄ and N cycles

- **Resolution**: Regional atmosphere-land interactions, the ocean mesoscale and boundaries, and the human and marine applications

- **Prediction**: Integration with seasonal-decadal climate effort, exploring opportunities for biogeochemistry predictability