Earth System Modeling at GFDL:

Goals, strategies and early results for the carbon system

John Dunne
In coordination with researchers at GFDL and PU
Background
The CO₂ Climate Forcing Question

CCSP Strategic Plan, 2003
Climate Forcing and Feedbacks

CCSP Strategic Plan, 2003
As a “natural progression” of IPCC style assessments, The US Climate Change Science Program’s Strategic Plan has called for the next generation of climate simulations to include explicit carbon cycling.

This task involves a daunting synthesis of climate models, terrestrial ecology models and ocean biogeochemistry models.
Climate Objectives:
• Simulate the past, present and future climate with dynamic carbon cycles
• Identify modes of variability and key susceptibilities.
• Predict biospheric response to human-induced change.
• Quantify biosphere – climate feedbacks

Biogeochemical Objective:
• Identify biospheric and biogeochemical controls
• Explore relationships between biospheric components
• Quantify the degree to which the biosphere maintains optimal conditions for itself (i.e. the GAIA hypothesis)
Timeline of Model development

CCSP Strategic Plan, 2003
Current Challenges

• The complexity and computational intensity of these models have grown beyond the scope of individual investigators.

• The large climate modeling centers are all involved in incorporating explicit carbon cycling into their models.

• This is a monumental task – no one group has yet succeeded without making large concessions and dubious assumptions.
Centers developing these models

Hadley Centre (UK)
IPSL (France)
NCAR (USA)
GFDL (USA)
MPI (Germany)
JMA-MRI (Japan)
CCSR (Japan)
CCMA (Canada)
BMRC/CSIRO (Australia)
others???
Strategy

Simulate global elemental cycles within the atm-ocean-land-ice-river system:

- Carbon (both CO$_2$ and CH$_4$)
- Nitrogen
- Dust/Iron
- Sulfur

Include important biospheric processes effecting climate and feedbacks:

- Ocean radiative bio-feedbacks through Chlorophyll absorption
- Ice radiative bio-feedbacks and gas exchange effects
- Iron transport deposition
- Eutrophication (anoxia and red tide)
- Ecological variability and change
- Atmospheric chemistry and pollution
- Glacial-interglacial cycles
- Human activities such as land use, marine resources
Schematic of an Earth System Model

**Climate Model**
- Atmospheric GCM
- Ocean GCM
- Land physics and hydrology

**Earth System Model**
- Tracer transport and chemistry
- Ocean ecology and biogeochemistry
- Dynamic vegetation and land use
- Land physics and hydrology
Current GFDL climate model
GFDL Climate Model Description

• Coupled model referred to as “CM2.0” and “CM2.1”.
  – AM2 atmosphere (2° horizontal, 24 levels)
    • Version CM2.0 uses b-grid
    • Version CM2.1 uses finite volume grid
  – MOM4 ocean model, 1° horizontal, 0.3° at Equator, 50 levels)
  – Sea ice, land, river routing models

• A complete suite of experiments has been conducted for the IPCC 2007 report.

• Detailed descriptions of these models available at:
  http://data1.gfdl.noaa.gov/nomads/forms/deccen/CM2.X/references

• Model output available at:
  http://data1.gfdl.noaa.gov
Model SST Errors

Courtesy of Tom Delworth
Global Mean Surface Temperature: CM2.1 vs. Observed

version: scenarios minus long-term trends; combined sst/t_ref; masked; 1881-1920 ref

Observed (CRU)
CM2.1 Ensemble Mean (n=5)

Courtesy of Tom Delworth
CM2.1 ocean sensitivity to forcing

Global Ocean (0–3000 m)

Temperature (K)

Heat Content (10**22 J)

ΔCO₂ from solubility (Pg)

1860 1880 1900 1920 1940 1960 1980 2000

ALL
ANTHRO
NATURAL
AEROSOL
WMGGO3

Observations

Courtesy of Tom Delworth
GFDL Ocean Biogeochemistry Description
Ocean Biogeochemical Model

- Carbon
- Oxygen
- Phosphorus
- Nitrogen
- Iron
- SiO₂ and CaCO₃

- Dissolved organic matter cycling
- Particle sinking and respiration
- Air-Sea gas flux
- Solubility pump
- Deposition
- Mineral pump
- Loss from system
Ocean Ecosystem Model

- Recycled nutrients
- New Nutrients
- N₂-fix. Phyto.
- Small Phyto.
- Protists
- DOM
- Large Phyto.
- Detritus
- Fish
- Filter Feeder
Uptake Components

N-uptake is based on Geider et al. (1997), except for the treatment of iron:

\[ \frac{Q_{\text{Fe:N}}}{\phi} = \frac{\text{Fe:N}}{(\text{Fe:N}_{\text{lim}} + \text{Fe:N})} \]

\[ \phi = \frac{\phi_{\text{max}}}{1 + \phi_{\text{max}} \alpha I_z / (2 \text{PC}_m)} \]

\[ \mu_N = \text{PC}_m / (1 + z) (1 - \exp(-\alpha I_z \phi/\text{PC}_m)) \]

Fe-uptake is proportional to dissolved Fe:

\[ \text{Uptake}_{\text{Fe}} = \text{V}_{\text{Fe}} \text{Lim}_{\text{Fe}} \exp(kT) \text{P}_N (1 - Q_{\text{Fe:N}}) \]

Diazotrophs have slow growth and high N:P.

The Si:N uptake ratio is:

\[ \text{Si:N} = (\text{Si:N}_{\text{max}} - \text{Si:N}_{\text{min}}) \text{Si:N}_{\lim}/(\text{Si:N}_{\text{max}} + \text{Si:N}_{\text{lim}}) + \text{Si:N}_{\text{min}} \]

CaCO\(_3\) production is a fraction of small Phytoplankton production.

Model fit to Sunda and Huntsman (1997) for \( T.\) Pseudonana under high (open) and low light (filled):
Recycling Components

- Grazing of $P_S \propto P_S^2$
- Grazing of $P_L$ and $P_{Di} \propto P^{4/3}$
- Detritus production a function of $P_S$, $P_L$, and $P_{Di}$ grazing and $T$
- Grazing threshold prevents phytoplankton extinction
- Dissolved Fe adsorbs onto sinking organic particles
- Sinking detritus protected from remineralization by mineral after Klaas and Archer (2002)
- Semilabile DON ($t_{remin} = 18$ yr), Semilabile DOP ($t_{remin} = 4$ yr; Abell et al., 2000), and Labile DOM ($t_{remin} = 3$ mo) produced as constant fractions of grazing.
GFDL Ocean Biogeochemistry Results (NCAR/NCEP Reanalysis)
Global variability in Nitrogen Cycling

- Water Column Denitrification
- Sediment Denitrification
- \( N_2 \) Fixation

Percent of anoxic waters (by volume)
Global Sea-Air CO$_2$ Flux
Global Sea-Air CO₂ Flux Variability

Sea – Air CO₂ Flux (mol m⁻² yr⁻¹)

CO₂ Flux Inter-annual Std (mol m⁻² yr⁻¹)

CO₂ Flux Std (mol m⁻² yr⁻¹)

CO₂ Flux % Inter-annual
Summary of reanalysis results

- Large scale WOA01 and SeaWiFS patterns are reproduced though the Southern Ocean is too low in surface nutrients.
- Many areas of improvement remain:
  - Eq. Pacific HNLC region larger than observations
  - Eq. Pacific chlorophyll and production also in excess.
  - North Atlantic subtropical gyre is too far south
  - North Atlantic spring bloom terminates too early
- Global Sea-Air variability in CO$_2$ fluxes consistent with expectations from radiative forcing
- Intermittently ice-covered regions do not out-gas significant levels of CO$_2$ in this model.
- Water column denitrification varies significantly on inter-annual time-scales.
Current Challenges
Practical development issues

Model Complexity:
• Composed of $10^6$ lines of code and scripts
• Includes $10^3$ parameter options
• Includes $10^2$ restart and initialization files
• Written by $10^1$-$10^2$ people
• Incomplete documentation
• Code is constantly changing

Model speed:
• Code retrieval and compilation takes 3 hours
• Input retrieval for short runs takes up to 2 hours
• Model runs 6 years per day on 126 processors
• Output retrieval of model year takes 2 hours
• Computer system glitches increase time by 1.2-2

Model size:
• Monthly output for a model year is 16Gb
How to initialize the carbon system?

Fossil Fuels

Atmosphere
560 PgC (280 ppmv) + FF

Ocean BGC
37400 Pg C + FF

Land BGC
2000 Pg C

~90 PgC
~60 PgC

Turnover Time
10^0-10^3 yr

Turnover Time
10^{-1}-10^2 yr

Turnover Time ~4 yr

...equilibrium takes 10^3-10^4 yrs...

...running 1000 years takes >6 months
Options to initialize the carbon system

- Run the model out for a very long time
- Perform short runs with drift and always reference to a control
- Run until the drift becomes small relative to the anthropogenic increase
- Run until the drift becomes smaller than the natural variability
- Accelerate the carbon system towards equilibrium
  - Correction via drift extrapolation
  - Inverse methods
  - Correction via solubility and biological pump separation
Is a steady state ever achieved?

- Short term solar and volcanic forcings vary on the order of 5W m\(^{-2}\):
  \[ \text{CO}_2 \text{ solubility variability} \approx 1 \text{ Pg C yr}^{-1} \]
- Long term radiative budget has \(~1\text{W m}^{-2}\) heat uptake in standard climate run:
  \[ \text{CO}_2 \text{ solubility outgassing} \approx 2 \text{ Pg C decade}^{-1} \]
- Nitrogen cycle has long time-scale variability
When is the model “good enough”?

• Is the model constructed robustly?
  – Nitrate, Silicate and Fe at mode water formation
  – Timing of blooms relative to sea ice cover

• How does one assess model fidelity?
  – Cruise data is sparse, both temporally and geographically
  – Data information can seem contradictory

• What to do when biospheric dynamics degrades climate?
  – Example: Current run turns the Amazon to a desert.
When is the model “good enough”?

• Analogy with GFDL’s CM2 development:
  – SST < 10° C away from Levitus
  – NADW > 10 Sv
  – El Nino (1 yr < trop. osc. < 5yr)

• Examples of ESM options:
  – Control run $dCO_{2\text{atm}}/dt$ less than 2 Pg C/decade?
  – Vegetation type (Rainforest/desert/savanna/etc) agreement with observations?
  – Surface nutrient agreement with observations?
  – Surface CO$_2$ flux agreement with observations?
  – Land NPP, Ocean NPP?
  – Others?
Which processes must be simulated?

• Physical pathways are simplified – e.g. no explicit rivers, estuaries or sediments.
  – Are these neglected processes important to CO$_2$ radiative feedbacks?

• Biogeochemistry has long time scales that cannot be simulated.
  – What do we need to know about longer timescales?
  – How is our lack of information affecting our understanding?

• Biology is far more complex than we can simulate computationally.
  – What susceptibilities need to be represented?
Can the Earth be modeled as a single system, or do different goals require different models?

• Hard: Climate goals only require processes with climate feedbacks:
  – “Importance” defined radiatively in W m^{-2}
  – Land albedo, transpiration and CO_2 exchange
  – Ocean CO_2 exchange (and perhaps Chl)
  – CH_4 cycle?

• Harder: Biogeochemical goals require ecosystem complexity:
  – Terrestrial Ecology
  – Ocean Ecosystems
  – Rivers, sediments, sea ice

• Hardest: Human impact goals require getting all the rest right:
  – Human health
  – Water supplies
  – Agriculture
  – Fisheries
  – Susceptibility to Catastrophe
How to address ecologically-forced degradation in physical simulation?

• Until very recently, global climate models had to an artificial “flux adjustment” at the air-sea interface to keep the climate stable and representative…

• What types ESM tunings are advisable?
  – Should CO$_2$ fluxes be adjusted to reproduce atmospheric concentrations over time?
  – Should ecological feedbacks be tuned to compensate for poor-physics (Amazon example).
Short-term Earth System Modeling Plans

- Code synchronization with climate group
- Address current issue of Amazon fidelity degradation
- Spinup to quasi steady state.
- Run IPCC scenarios of 1860-2100 to quantify:
  - Ecosystem feedbacks on atmospheric CO$_2$
  - Climate feedbacks on ecosystems
- Assess CO$_2$ fluxes under various CO$_2$ emissions, land use and mitigation scenarios.
How can data “improve models”?

• Provide boundary and initial conditions
  – WOCE, NCEP, GLODAP, etc.

• Data synthesis => Improved theory => implementation
  – Effect of mineral on organic flux

• Data - Model comparison => flaws in models => refutation of model => new theory => implementation
  – HNLC – EqPac - IronEx I – IronEx II – Fe in models