The Brief History and Future Development of Earth System Models: Resolution and Complexity

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NERSC Lecture Series at Berkeley Lab
May, 2014
Overview

• Brief history of climate modeling
• Brief discussion of computational methods
• Environmental Justice connected to climate change
• Behind the scenes White House origin of the U. S. Global Change Research Program (USGCRP)
• The future of the USGCRP and National Climate Assessment
The next two NASA satellite videos give insight to how the climate is changing and the interaction of vegetation on the carbon cycle.

Credit to the NASA Aqua instrument: Tom Pagano and colleagues at JPL
The atmospheric carbon dioxide and vegetation connection!
The Climate and Earth System Modeling Story
Laws of Physics, Chemistry, and Biology

• Equations govern the dynamics of atmosphere, ocean, vegetation, and sea ice

• Equations put into a form that can be solved on modern computer systems

• Physical processes such as precipitation, radiation (solar and terrestrial), vegetation, boundary transfers of heat, momentum, and moisture at earth’s surface are included

• Forcings: GHGs, Volcanic, Solar variations
Mathematical equations (known since 1904)

Eqs. of Momentum

\[
\frac{du}{dt} - \left( f + u \frac{\tan \phi}{a} \right) v = -\frac{1}{a \cos \phi} \frac{1}{\rho} \frac{\partial p}{\partial \lambda} + F_\lambda
\]

\[
\frac{dv}{dt} + \left( f + u \frac{\tan \phi}{a} \right) u = -\frac{1}{\rho a} \frac{\partial p}{\partial \phi} + F_\phi
\]

Hydrostatic

\[
g = -\frac{1}{\rho} \frac{\partial p}{\partial z}
\]

Conservation of mass

\[
\frac{\partial \rho}{\partial t} = -\frac{1}{a \cos \phi} \left[ \frac{\partial}{\partial \lambda} (\rho u) + \frac{\partial}{\partial \phi} (\rho v \cos \phi) \right] - \frac{\partial}{\partial z} (\rho w)
\]

First law of thermodynamics

\[
C_p \frac{dT}{dt} - \frac{1}{\rho} \frac{dp}{dt} = Q
\]

Gas law

\[
p = \rho RT
\]

\[(u, v, w, \rho, p, \text{and } T),\]
The Community Earth System Model (CESM) is becoming more complete

A DOE and NSF supported activity
Timeline of Climate Model Development

- **Mid-1960s**
  - Atmosphere/Land Surface
  - Ocean
  - Sea Ice
  - Coupled Climate Model

- **Mid 1970s-1980s**
  - Atmosphere/Land Surface/vegetation
  - Ocean
  - Sea Ice
  - Coupled Climate Model

- **1990s**
  - Atmosphere/Land Surface/vegetation
  - Ocean
  - Sea Ice
  - Coupled Climate Model
  - Sulfate Aerosol
  - Carbon Cycle

- **Present Day**
  - Atmosphere/Land Surface/vegetation
  - Ocean
  - Sea Ice
  - Coupled Climate Model
  - Sulfate Aerosol
  - Carbon Cycle
  - Dust/Sea Spray/Carbon Aerosols
  - Interactive Vegetation
  - Biogeochemical Cycles

- **2000-2010**
  - Atmosphere/Land Surface/vegetation
  - Ocean
  - Sea Ice
  - Coupled Climate Model
  - Sulfate Aerosol
  - Carbon Cycle
  - Dust/Sea Spray/Carbon Aerosols
  - Interactive Vegetation
  - Biogeochemical Cycles
  - Ice Sheet

Small teams
Atmospheric Grids

Problem near the poles where longitudes converge

Regional focus

Figure V.1. A variable resolution grid based on a Spherical Centroidal Voronoi Tessellation.

From C. Hannay, NCAR
Part of the global grid (25 km) for the next IPCC simulations
**Vertical Grid**

- Vertical resolution is also important for quality of simulations.

- Levels are not equally spaced (levels are closer near surface and near tropopause where rapid changes occur).

- In CAM: “hybrid” coordinate
  - bottom: sigma coordinate (follows topography)
  - top: pressure coordinate
  - middle: hybrid sigma-pressure

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**Diagram: Vertical Level Structure of CAM 4.0**

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<th>Level Index</th>
<th>Interface Index</th>
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- Pure pressure region
- Hybrid sigma-pressure region
- Pure sigma region

Surface ~ 1000 mbar

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Tropical storms, hurricanes, and intense hurricanes for high resolution (25 km) atmospheric model (CAM5) M. Wehner, DOE LBL
Leading Mode of Global SST Variability Seasonal Capability (Neale, NCAR)

Observations

CCSM4
Velocities

Price, Lipscomb et al, DOE/LANL, 2010
Examples of NERSC Use

- 20\textsuperscript{th} and 21\textsuperscript{st} century simulations for IPCC
- Single forcing simulations
- Hurricane changes
- Closing Bering strait
- Heat waves, etc.
- Model development
Probability of US heat Waves Affected by a Subseasonal Planetary Wave Pattern: Prediction 15-20 days in Advance

Role of the Bering Strait on the hysteresis of the ocean conveyor belt circulation and glacial climate stability

Objective
Study the influence of the Bering Strait opening/closure on the hysteresis of the Atlantic meridional overturning circulation (AMOC) and abrupt climate change.

Approach
• CCSM3 is used as the primary tool.
• Two simulations have been done under present-day climate boundary conditions with everything being identical except one with an open Bering Strait and the other with a closed one.
• Freshwater is slowly added into the North Atlantic until the AMOC collapses, then freshwater water is slowly reduced until the AMOC restarts again. The simulations run 4400 years each at NERSC.

Impact
• Our results suggest that AMOC hysteresis only exists when Bering Strait is closed. Thus abrupt climate changes occur only in glacial time.
• This could have broad impact on both past and future climate studies.

The Pacific-Atlantic Seesaw and the Bering Strait

Objective

Study the influence of the Bering Strait opening/closure on the Pacific-Atlantic climate response to a collapse of the Atlantic meridional overturning circulation (AMOC)

Approach

- CCSM3 is used as the primary tool.
- Two simulations have been done under present-day climate boundary conditions with everything identical except one with an open Bering Strait and the other with a closed one.
- Freshwater is slowly added into the North Atlantic until the AMOC collapses, then freshwater water is slowly reduced until the AMOC restarts again.

Impact

- Our results suggest that a seesaw-like climate change due to an AMOC collapse can only occur with a closed Bering Strait.
- This could have broad impact on both past and future climate studies.

We are here

RCP2.6 requires negative emission

Old and New Scenarios

CO₂ concentrations

ppm

2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200 2220 2240 2260 2280 2300

SRES: A1FI  A2  A1B  B1
RCP:  RCP8.5  RCP6  RCP4.5  RCP2.6

G. Strand, NCAR
Climate and Earth System models have and continue to contribute to understanding and predicting the climate system. They allow the science community to determine objectively the possible impacts of climate change on food production, flooding, drought, sea level rise, and health as well as decision support. Higher resolution and more complete models will help.
Professions: Public Trust

Debate in Congress about the President’s Climate Action Plan

From National Science Board S & E Indicators (2012)
Genesis of U.S. Global Change Program
White House Cabinet meeting on climate change in 1990

President George H. W. Bush

John Sununu, Chief of Staff
We installed a climate model in The White House!

Allan Bromley, President's Science Advisor
Convinced the cabinet about climate change.
We have lost the bipartisan approach.
U.S. Global Change Research Program

$2.7 Billion over 12 agencies

Thomas R. Armstrong, PhD
Executive Director, USGCRP
Office of Science and Technology Policy
Executive Office of the President
Washington, DC

www.globalchange.gov

I chaired the Review Committee for the National Academies

Slides provided by Thomas Armstrong
Global Change Research Act

Global Change Research Act of 1190 (P.L. 101-606)
Act at http://www.globalchange.gov/about/program-structure/global-change-research-act

Called for a “comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change”

OMB/OSTP FY 14 S&T Memo: Guidance to the Agencies

“Emphasize research that advances understanding of vulnerabilities in human and natural systems and their relationships to climate extremes, thresholds, and tipping points”

Passed by bipartisan Congress
National Climate Assessment released on May 6, 2014 at the White House
The End

Special thanks to the
Department of Energy, Office of Science (BER),
the National Science Foundation (NSF), and OSTP
USGCRP Research Enterprise

Create new knowledge

- Advance Science of Earth and Human System: Integrated

Translate, provide and assess knowledge for societal use

- Inform Decisions (including GCIS and Adaptation)
- Conduct Sustained Assessment (including NCA)
- Communicate and Educate

Identify needs to inform science planning

Science and Stakeholder Communities
USGCRP in the Federal Context

Principals: http://globalchange.gov/about/program-structure/officials

CENRS Sub-Committees, WG, & Task Forces

- Air Quality Research (AQRS)
- Critical and Strategic Mineral Supply Chains (CSMSC)
- Interagency Arctic Research Policy Committee Interagency Working Group (IARPC)
- Integration of Science and Technology for Sustainability Task Force
- National Earth Observations Task Force (NEO)
- Disaster Reduction (SDR)
- Ecological Services (SES)
- Global Change Research (SGCR)
- Ocean Science & Technology (SOST)
- Water Availability & Quality (SWAQ)
- Toxics & Risks (T&R)
- US Group on Earth Observations (USGEO)
Research Goals
U.S. Global Change Research Program

- **Goal 1.** Advance science: Earth system understanding, science of adaptation and mitigation, observations, modeling, sharing information
- **Goal 2.** Inform decisions: Scientific basis to inform, adaptation and mitigation decisions
- **Goal 3.** Conduct sustained assessments: build capacity that improves Nation’s ability to understand, anticipate, and respond
- **Goal 4.** Communicate and educate: Advance communication and educate the public, improve the understanding of global change, develop future scientific workforce
The USGCRP Strategic Plan
Outcomes and Priorities Activities

**Outcomes**
- Providing Knowledge on Scales Appropriate for Decision Making
- Incorporating Social and Biological Sciences
- Enabling Responses to Global Change via Iterative Risk Management

**Priorities Activities**
- Enhance Information Management and Sharing
- Enable new capabilities for Integrated Observations and Modeling
- Increase Proactive Engagement and Partnerships
- Leverage International Investments & Leadership
- Develop the Scientific Workforce for the Future