The Future of the Community Climate System Model: Computational and Scientific Challenges

Bill Collins
http://www.cgd.ucar.edu/~wcollins
National Center for Atmospheric Research
Boulder, Colorado

• Brief history and accomplishments of the CCSM program
• Development of a coupled chemistry-climate version of CCSM
• Computational challenges in Earth system modeling
The CCSM Program

Scientific Objectives:

- Develop a comprehensive climate model to study the Earth’s Climate.
- Investigate seasonal and interannual variability in the climate.
- Explore the history of Earth’s climate.
- Estimate the future of the environment for policy formulation.

Recent Accomplishments:

- Release of a new version (CCSM3) to the climate community.
- Studies linking SST fluctuations, droughts, and extratropical variability.
- Simulations of last 1000 years, Holocene, and Last Glacial Maximum.
- Creation of largest ensemble of simulations for the IPCC AR4.
Configuration of NCAR CCSM3

- Atmosphere (CAM 3.0)
  - 128 × 256 × 26

- Ocean (POP 1.4.3)
  - 320 × 384 × 40

- Land (CLM 2.2)
  - 128 × 256 × 10

- Sea Ice (CSIM 4)
  - 320 × 384 × 5

http://www.cccsm.ucar.edu

Collins et al, 2005
The CCSM Community

Development Group
- NCAR
- Universities
- Labs
- Physics
- Applications
- Chemistry

CCSM3
- Atmosphere (CAM 3)
- Land (CLM 3)
- Coupler (CPL 6)
- Ocean (POP 1)
- Sea Ice (CSIM 4)

Model Users
Current Users:
- Institutions: ~200
- Downloads of CCSM3: ~600

Climate Community
Publications:
- NCAR: 87
- Universities: 94
- Labs/Foreign: 48
Total: 229

Current Users:
• Institutions: ~200
• Downloads of CCSM3: ~600

Publications:
• NCAR: 87
• Universities: 94
• Labs/Foreign: 48
Total: 229
Improvements in Atmospheric Fidelity

D. Williamson, in Collins et al, 2005

JANUARY, 200 mb, NH(30N-90N)

Unconditional error
Conditional error
Phase error
Scaled Variance Ratio
Computational Characteristics of CCSM3

• CCSM3 has been climate-validated and run on:
  - IBM Power 3 and 4 systems
  - SGI Altix systems
  - SGI Origin systems
  - Cray X1 vector systems (work on XT3 and XD1 underway)
  - NEC SX vector systems
  - Specific Xeon linux systems (work on Opteron underway)

• Computational requirements for CCSM3 on Power 4s:
  - T31 land/atm $\times$ 3° ocean/ice: 62 CPU hrs/sim. year
  - T42 land/atm $\times$ 1° ocean/ice: 292 CPU hrs/sim. year
  - T85 land/atm $\times$ 1° ocean/ice: 1146 CPU hrs/sim. year
Application of CCSM3 to IPCC

**NCAR’s Bluesky Supercomputer:**
- 1600 Power 4 Processors
- Peak speed: 8.3 Teraflops

**Characteristics of NCAR CCSM3:**
- ~1 quadrillion operations/simulated year
- Rate of simulation: 3.5 sim. years/day
- Ensemble size: 11,000 simulated years
- Computation cost: ~7 million CPU hours
- Output: 10 GB/simulated year
- Data volume for IPCC: ~100 TB
<table>
<thead>
<tr>
<th>Author</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Editors</td>
<td>Preface</td>
</tr>
<tr>
<td>Drake, John</td>
<td>Overview of the Software Design and Parallel Algorithms of the CCSM</td>
</tr>
<tr>
<td>Worley, Pat</td>
<td>Software Design for Performance Portability in the Community Atmosphere Model</td>
</tr>
<tr>
<td>Mirin, Art</td>
<td>A Scalable Implementation of a Finite-Volume Dynamical Core in the Community Atmosphere Model</td>
</tr>
<tr>
<td>Putman, Bill</td>
<td>Cross-platform performance of a Portable Communications Module the NASA Finite Volume General Circulation Model</td>
</tr>
<tr>
<td>Taylor, Mark</td>
<td>High Resolution Mesh Convergence Properties and Parallel Efficiency of a Spectral Element Atmospheric Dynamical Core</td>
</tr>
<tr>
<td>Ghan, Steven</td>
<td>Load Balancing and Scalability of a Subgrid Orography Scheme in a Global Climate Model</td>
</tr>
<tr>
<td>Hoffman, Forrest</td>
<td>Vectorizing the Community Land Model (CLM)</td>
</tr>
<tr>
<td>Kerbyson, Darren</td>
<td>A Performance Model of the Parallel Ocean Program</td>
</tr>
<tr>
<td>Jacob, Rob</td>
<td>cpl6: The New Extensible, High-Performance Parallel Coupler for the Community Climate System Model.</td>
</tr>
<tr>
<td>Jacob, Rob</td>
<td>MxN communication and parallel interpolation in CCSM3 using the Model Coupling Toolkit.</td>
</tr>
<tr>
<td>Ding, Chris</td>
<td>Coupling multi-component models by MPH on distributed memory computer architectures</td>
</tr>
<tr>
<td>Buca, Cecelia</td>
<td>Design and Implementation of Earth System Modeling Framework Components</td>
</tr>
</tbody>
</table>
Scientific objectives for the near future

• **Major objective:**
  Develop, characterize, and understand the most realistic and comprehensive model of the observed climate system possible.

• **Subsidiary objectives:**
  - Simulate the interaction of chemistry, biogeochemistry, and climate with a focus on climate forcing and feedbacks.
  - Analyze and reduce the principal biases in our physical climate simulations using state-of-the-art theory and observations.
  - Simulate the observed climate record with as much fidelity as possible.
Recent evolution of climate forcing

Hansen and Sato, 2001
Simulating the chemical state of the climate system

- In the past, we have generally used offline models to predict concentrations and read these into CCSM.

- This approach is simple to implement, but
  - It cuts the feedback loops.
  - It eliminates the chemical reservoirs.

- The next CCSM will include these interactions.
Extension of CCSM3 to a 1st generation Earth system model

Coupler

Land
C/N Cycle
Dyn. Veg.

Atmosphere

Ocean

Sea Ice

C/NCycle
Dyn. Veg.

Sea Ice

Coupler

Ecosystem & BGC

Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.
Flux of CO$_2$ into the world oceans

(Ocean ecosystem model)

Moore, Doney, and Lindsay
Tropospheric Ozone

Coupler

Land
- C/N Cycle
- Dyn. Veg.

Atmosphere
- Gas chem.

Ocean
- Ecosystem & BGC

Sea Ice

Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.
Evolution of tropospheric ozone
(1890-2100, following A2 scenario)

Lamarque et al, 2005
Tropospheric Aerosols

Coupler

Land

Atmosphere

Ocean

Sea Ice

C/N Cycle

Dyn. Veg.

Gas chem.

Prognostic Aerosols

Ecosystem & BGC

Climate Forcings (W/m²): 1850-2000

Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.

Aerosol Forcing

Top of Model, Clear Sky
mean = -3.36 W/m²

Surface, Clear Sky
mean = -6.12 W/m²

Atmospheric Absorption, Clear Sky
mean = 2.75 W/m²
Solar Forcing

Coupler

Land

Atmosphere

Ocean

Sea Ice

C/N Cycle
Dyn. Veg.
Gas chem.
Prognostic Aerosols
Upper Atm.
Ecosystem & BGC

Sea Ice

Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.
Solar Cycle Studies: Model Input

Spectral composite courtesy of:

Judith Lean (NRL) and Tom Woods (CU/LASP)
Response of the upper atmosphere to solar variability

Marsh and Matthes
Historical Forcings, including CFCs and volcanic aerosols

Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.
Calculated and Observed Ozone Trends

WACCM O3 Trend: 1979–2000 (%/decade)


Rolando Garcia

- Red inset on left covers approximately same region as observations on right
- Agreement is quite good, including region of apparent “self-healing” in lower tropical stratosphere

CAS2K5 Meeting
9/2005, Annecy
Calculated and Observed Temperature Trends

Rolando Garcia

- Red inset on left covers approximately same region as observations on right
- Note comparable modeled vs. observed trend in upper stratosphere, although model trend is somewhat smaller
Agricultural land use

Coupler

Land

C/N Cycle Dyn. Veg. Land Use

Atmosphere

Gas chem. Prognostic Aerosols Upper Atm.

Ocean

Ecosystem & BGC

Sea Ice

Climate Forcings (W/m²): 1850-2000

Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.
Historical changes in agricultural land use

Johan Feddema

Anthropogenic Impacts on Land Cover
Extent of Agriculture

1870

1990

Percent
Area
Grassed

Johan Feddema

CAS2K5 Meeting
9/ 2005, Annecy
Changes in surface albedo by land use

Johan Feddema
Potential Configuration of CCSM4

Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.
Assumptions:

- It is likely that the AR5 report will be issued 6 years after AR4, in 2013.
- Following the precedent in AR4, the simulations will have to be finished three years ahead, in 2010.

- Therefore CCSM4 has to be ready for production in 2009.
- CCSM4 has to be ready for testing in 2008.
A sample budget for computing needs  
*(One of many possible configurations of CCSM4)*

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of Tracers</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosols</td>
<td>32</td>
<td>10-50% (Atm.)</td>
</tr>
<tr>
<td>Chemistry</td>
<td>94</td>
<td>400 – 500% (Atm.)</td>
</tr>
<tr>
<td>Atmos. Res. → 1°</td>
<td>× 5 (Atm.)</td>
<td></td>
</tr>
<tr>
<td>Ocean BGC</td>
<td>25</td>
<td>250 – 375% (Ocean)</td>
</tr>
<tr>
<td>Land BGC</td>
<td>40</td>
<td>&lt; 20% (Land)</td>
</tr>
<tr>
<td>Total</td>
<td>159</td>
<td>≅ 20 – 25 × Chem × Res.</td>
</tr>
</tbody>
</table>

*Note: other possible requirements could include:*
- Increased ocean resolution to eddy permitting/resolving scales
- Vertical resolution of the atmosphere for tropospheric processes
- Addition of models for stratosphere and upper atmosphere
- Execution of the land model on a separate, high resolution grid
Conclusions

• The CCSM project has succeeded in building and applying three generations of AOGCMs.

• The project is now experimenting with the elements of a 1st generation Earth system model.

• A major challenge for that model is the computational burden associated with increased resolution and with detailed chemistry and biogeochemistry.

• Projections for the required throughput (simulated years/wall-clock day) are at least 25x over today.

• If we assume persistence, projections for the required capacity (total cycles/wall-clock day) are at least 25x over today.