Modeling The Earth System

Critical Computational Technologies To Enable Us To Predict Our Planet’s Future

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Requirements For Earth System Modeling

State of the Art Today

- Fairly accurate short term (3 day) weather forecasts over the continents
- Moderately accurate predictions of the major climate “states” such as the El Nino-Southern Oscillations (ENSO), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO) and the Madden-Julian Oscillation (MJO)

These are the result of:

- Thousand-fold increase in computational capability over the last 20 years applied to models
- Almost a Gigabyte/day of observational data ingested into models
- 3 decades of model development and process parameterization refinements

Requirements for Future Progress

- Development process for complex models needs to be easier
- Computing throughput must continue its exponential increase
Evolving Towards Predictive System Models

The Earth System
Unifying the Models

Water Cycle
Carbon Cycle

Atmosphere Models
Ocean Models
Land Surface Models
Terrestrial Biosphere Models
Hydrology Process Models

The Predictive Earth System
Natural Hazard

Megaflops
Gigaflops
Teraflops
Petaflops
Computational Technology Requirements

NASA Earth Science Enterprise Computational Technology Requirements Workshop - May 2002

• 150 Modeling Researchers from the US convened to assess computational technology capabilities needed for modeling Weather, Climate, and Solid Earth Panels

• Panels asked to define needed capabilities - not specific technology requirements

• Prediction capability goals for 2010 were used to frame the discussion

  5-day weather forecast at > 90% confidence
  3-day rainfall forecast
  Hurricane landfall ±180 km 2 days in advance
  Regional Air quality forecast 2 days in advance
  6-12 month seasonal climate prediction routine
  Improved temporal dimension of earthquake & volcanic eruption forecasts

  ...

• See paper for workshop report URL
Weather Prediction Requirements were the most computationally stressing
- Climate, Solid Earth within a factor of 10
- Programming coupled models identified as major challenge
- Frameworks, tools needed to increase productivity
- Algorithms for high end computing systems require continued development
  - Scaling to 1000s of processors

Computational Requirements Growth to Achieve a 5 Day Weather Forecast at 90% Confidence

<table>
<thead>
<tr>
<th></th>
<th>2002 System</th>
<th>2010+ System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>100 km</td>
<td>10 km</td>
</tr>
<tr>
<td>Vertical levels</td>
<td>55</td>
<td>100</td>
</tr>
<tr>
<td>Time step</td>
<td>30 minutes</td>
<td>6 minutes</td>
</tr>
<tr>
<td>Observations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ingested</td>
<td>$10^7$ / day</td>
<td>$10^{11}$ / day</td>
</tr>
<tr>
<td>Assimilated</td>
<td>$10^5$ / day</td>
<td>$10^8$ / day</td>
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<tr>
<td>System Components:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmosphere</td>
<td></td>
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<tr>
<td>Land-surface</td>
<td></td>
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<tr>
<td>Data assimilation</td>
<td></td>
<td></td>
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<tr>
<td>Computing:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Model</td>
<td>10 GFLOPS</td>
<td>50 TFLOPS</td>
</tr>
<tr>
<td>Total System</td>
<td>100 GFLOPS</td>
<td>1 PFLOPS</td>
</tr>
<tr>
<td>Data Volume:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input (observations)</td>
<td>400 MB / day</td>
<td>1 TB / day</td>
</tr>
<tr>
<td>Output (gridded)</td>
<td>2 TB / day</td>
<td>10 PB / day</td>
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<tr>
<td>Networking/Storage</td>
<td></td>
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<tr>
<td>Data movement</td>
<td></td>
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<tr>
<td>Internal</td>
<td>4 TB / day</td>
<td>20 PB / day</td>
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<tr>
<td>External</td>
<td>5 GB / day</td>
<td>10 TB / day</td>
</tr>
<tr>
<td>Archival</td>
<td>1 TB / day</td>
<td>10 PB / day</td>
</tr>
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Japan Earth Simulator - The First Step

40 Teraflop NEC system built specifically to do quantitative prediction and assessment of variations of the atmosphere, ocean and solid earth

- Most realistic mesoscale resolving climate model to date

Twin typhoons evolving over the Philippine Sea simulated by the Super High Resolution Global Atmospheric Simulation (AFES)

Winner of the 2002 Gordon Bell award for performance
OGCM at .1 Degree
• threshold for a good representation of the western boundary currents and of the mesoscale eddy kinetic energy

Spectral Global Atmosphere (AFES) at 10 km
• Resolving mesoscale features in a global model
• Humidity/Precipitation predictions resolving cyclone features

Coupled atmosphere-ocean-sea ice model
• Simulations reproduce satellite imagery of regression of ice at both poles

Seismic wave propagation
• Simulation of wave propagation in the Tokyo earthquake from 50 years ago

Other examples
• Thermal conductivity of carbon-nano-tube and fullerene dynamics
• Biopolymers
• Propulsion dynamics
Managing Model Complexity

Programming burden for developing coupled multi-disciplinary models is high

- Current Models are not scientifically or technically interoperable - impeding collaborations among model developers
- Incorporating new models or algorithms requires substantial code modification
- No interoperability standards exist for high end modeling

Achieving the Earth system modeling vision will require new approaches to complex modeling applications development

- National and international collaborations to bring models together and benefit from the scientific diversity of the community
- Modeling environments that make it easy to collaborate
- Standard methods for assembling collections of models into an application to address specific science problems
- Standard underlying representations of basic modeling entities (e.g., grids, fields, partitions, transformations, data movement, etc.)

PRISM & ESMF are the beginning of such environments
Program for Integrated Earth System Modeling

EC funded project to
• develop a framework for seamlessly coupling climate model components
• Promote standard interfaces for model components to a coupler that manages data exchange and synchronization

Prism Key Objectives
• Provide Software Infrastructure to
  Easily Assemble Earth System model components
  Launch/monitor complex/ensembles Earth system models
  Access, analyze and share results across a wide community
• Share development and maintenance burdens
• Let scientists spend more time on science
• Define and promote community standards
  Increase scientific and technical modularity
  Ensure high performance across a variety of platforms
The Earth System Modeling Framework

NASA funded project to
- Develop a framework to enable a common standard architecture for Earth System Models
- Simplify future development and evolution
- Enable interoperability of model components in climate, weather and data assimilation applications

Key ESMF Development Objectives
- Component based modeling architecture
- Robust, flexible tools to enhance ease of use, performance portability, interoperability, and code reuse
- Standardized representations of fields and grids
- Common low level utilities tool box
Complementary Approaches

Initial Focus

- ESMF is focusing on the infrastructure (Grids, Fields, Partitions, Utilities)
- PRISM is focusing on the coupling superstructure and the associated runtime and analysis environment

Coordination is Increasing

- Regular interactions between efforts has started
- Collaboration to ensure compatibility of key standards and interfaces
- Expectation is that each project will leverage the other’s work
Summary

- Achieving a unified earth system modeling capability will require sustained growth in computing capability
- Enabling the science will require continued development of modeling frameworks to ease the programming burden

<table>
<thead>
<tr>
<th>Progression of Modeling Capability and Complexity and the Computing Performance Required to Sustain It</th>
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<tbody>
<tr>
<td>Models</td>
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<tr>
<td>Today</td>
</tr>
<tr>
<td>Single Discipline Models</td>
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<tr>
<td>Coupled Ocean-Atmosphere Models for Climate Prediction</td>
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<tr>
<td>Single Discipline Data assimilation</td>
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<tr>
<td>Performance</td>
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<tr>
<td>Dedicated Networks</td>
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<td>Memory (RAM)</td>
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