Benefits and Challenges of High Spatial Resolution in Climate Models

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Motivation

- Improving the fidelity of climate models is difficult
- Numerical weather prediction has advanced by taking advantage of $10^6\times$ increase in computing capability since 1980 through:
  - Increasing spatial resolution
  - Improving understanding of physical processes
  - Improving data assimilation methods
- Climate models have improved, primarily through the inclusion of more processes that are relevant to climate variability and change
- There is evidence that enhanced spatial resolution improves climate model fidelity (and may change our understanding of climate dynamics both qualitatively and quantitatively)

using global atmospheric models that are comparable to the atmospheric component of climate models
Origins of Project Athena

- 2008 World Modeling Summit: dedicate petascale supercomputers to climate modeling
- U.S. National Science Foundation offered to dedicate the Athena supercomputer for 6 months in 2009-2010 as a pilot study
- An international collaboration (Project Athena) was formed by groups in the U.S., Japan and the U.K. to use Athena to take up the challenge
Project Athena

Collaborating Groups

COLA - Center for Ocean-Land-Atmosphere Studies, USA (NSF-funded)
ECMWF - European Center for Medium-range Weather Forecasts, UK
JAMSTEC - Japan Agency for Marine-Earth Science and Technology, Research Institute for Global Change, Japan
University of Tokyo, Japan
NICS - National Institute for Computational Sciences, USA (NSF-funded)
Cray Inc.

Codes

NICAM: Nonhydrostatic Icosahedral Atmospheric Model
IFS: ECMWF Integrated Forecast System
## Project Athena Experiments

<table>
<thead>
<tr>
<th>Model/Exp.</th>
<th>Resolution</th>
<th># Cases</th>
<th>Period</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>NICAM / Hindcasts</td>
<td>7 km</td>
<td>8</td>
<td>103 days</td>
<td>21 May - 30 Aug 2001 - 2009</td>
</tr>
<tr>
<td>IFS / Hindcasts</td>
<td>125 km, 39 km, 16 km</td>
<td>48</td>
<td>395 days</td>
<td>1 Nov - 30 Nov (following year) 1960 - 2007</td>
</tr>
<tr>
<td>IFS / Hindcasts</td>
<td>10 km</td>
<td>20</td>
<td></td>
<td>1 Nov - 30 Nov (following year) 1989 - 2007</td>
</tr>
<tr>
<td>IFS / Hindcasts</td>
<td>125 km, 39 km, 16 km, 10 km</td>
<td>9</td>
<td>103 days</td>
<td>21 May - 30 Aug 2001 - 2009 NICAM analogs</td>
</tr>
<tr>
<td>IFS / Summer Ensembles</td>
<td>39 km, 16 km</td>
<td>6</td>
<td>132 days</td>
<td>21 May - 30 Sep selected years</td>
</tr>
<tr>
<td>IFS / Winter Ensembles</td>
<td>39 km, 16 km</td>
<td>6</td>
<td>151 days</td>
<td>1 Nov - 31 Mar selected years</td>
</tr>
<tr>
<td>IFS / AMIP</td>
<td>39 km, 16 km</td>
<td>1</td>
<td>47 years</td>
<td>1961 - 2007</td>
</tr>
<tr>
<td>IFS / Time Slice</td>
<td>39 km, 16 km</td>
<td>1</td>
<td>47 years</td>
<td>2071 - 2117</td>
</tr>
</tbody>
</table>

[http://wxmaps.org/athena/home/](http://wxmaps.org/athena/home/)

Project Athena Publications

Sample Results

- Large-scale atmospheric circulation variability
- South Asian monsoon
- Resolution dependence of snow
- Diurnal cycle of precipitation
- Projection of climate change
- Tropical cyclones
- Tornadoes in climate simulation
Atmospheric Blocking

Geopotential height and vector wind on 500 hPa isobaric surface
Atmospheric Blocking

Tibaldi and Molteni (1990) index: At each longitude, compute:

\[
Z_{GS} = \left[ \frac{Z(\phi_0) - Z(\phi_s)}{\phi_0 - \phi_s} \right] \\
Z_{GN} = \left[ \frac{Z(\phi_n) - Z(\phi_0)}{\phi_n - \phi_0} \right]
\]

where \( Z \) = 5-day running mean geopotential height (m) at 500 hPa

\( \Phi_n = 80^\circ N + \delta \)
\( \Phi_0 = 60^\circ N + \delta \)
\( \Phi_s = 40^\circ N + \delta \)
\( \delta = -5^\circ, 0^\circ, \text{or} +5^\circ \)

Blocking is occurring where, for at least one value of \( \delta \),

1. \( Z_{GS} > 0 \)
2. \( Z_{GN} < -10 \text{ m} / (^\circ \text{ latitude}) \)
Regime Structures

ERA-I

T159

T1279

Dawson et al. 2012
Sample Results

- Large-scale atmospheric circulation variability
- South Asian monsoon
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- Diurnal cycle of precipitation
- Projection of climate change
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- Tornadoes in climate simulation
North Atlantic track densities as number density per season per unit area equivalent to a 5° spherical cap for IBTrACS (OBS) and IFS simulations, May-November season of 1990-2008.

Mean TC frequency

<table>
<thead>
<tr>
<th></th>
<th>OBS</th>
<th>T2047</th>
<th>T1279</th>
<th>T511</th>
<th>T159</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>12.5</td>
<td>10.7</td>
<td>9.2</td>
<td>7.2</td>
<td>5.3</td>
</tr>
</tbody>
</table>

- Units are numbers per MJJASON season.
- Model values in bold are significantly different from the OBS (at 95% confidence level).

Manganello et al. 2012
Intensity Distribution

Maximum Surface Wind Speed

NH

NW Pac

NE Pac

N Atl

Most intense TC at T2047: 56.6 m/s (CAT 4)

Manganello et al. 2012
Horizontal Structure of the most intense TCs

- Radius is 2° from the storm center
### 21st Century vs. 20th Century: Change in the TC Statistics for the NW Pacific

**MJJASON, 47 years**

<table>
<thead>
<tr>
<th></th>
<th>IFS T1279</th>
<th>IFS T159</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TS</td>
<td>CAT 1-2</td>
</tr>
<tr>
<td><strong>TC Frequency,</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>counts/year</td>
<td></td>
<td>+2.2 (+7%)</td>
</tr>
<tr>
<td></td>
<td>-2.4</td>
<td>+1.3</td>
</tr>
<tr>
<td><strong>Power Dissipation</strong></td>
<td></td>
<td>+1.8 (+51%)</td>
</tr>
<tr>
<td>Index, <em>10^{11} m^3/s^2</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean Peak Intensity,</strong></td>
<td></td>
<td>+3.4 (+12%)</td>
</tr>
<tr>
<td>m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean Lifetime,</strong></td>
<td></td>
<td>+0.3 (+0.1%)</td>
</tr>
<tr>
<td>hours</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Values in bold indicate statistically significant differences from the AMIP.*
Project Athena: Summary

• **Good news:** Extreme spatial resolution improves many of the qualitative features of large-scale climate simulation

• **As expected:** High spatial resolution provides higher fidelity representation of features sensitive to orography or geography

• **Unexpected:** Nonlinear dynamical effects can alter simulation changes due to spatial resolution improvements much more and possibly in different ways than we might have expected

• **Scientific Challenge:** Large biases remain in hard-to-simulate fields like tropical precipitation → still need to understand and properly represent the effects of subgrid-scale physical processes
Challenges and Tensions

- Using large allocations – takes a village
- **Exaflood of data**
- Resolution vs. parameterization
- Sampling (e.g. extreme events)
- Tensions

<table>
<thead>
<tr>
<th>HEC capability</th>
<th>Data analysis capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automation/abstraction</td>
<td>Human control</td>
</tr>
<tr>
<td>Data-driven development</td>
<td>Science-driven development</td>
</tr>
</tbody>
</table>

Climate scientists are being forced to think about data issues

<table>
<thead>
<tr>
<th>Small, portable code</th>
<th>End-to-end tools</th>
</tr>
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<tbody>
<tr>
<td>Tight, local control of data</td>
<td>Distributed data</td>
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Exaflood: Challenge and Opportunity

- In January 2007, Bret Swanson of the Discovery Institute coined the term **exaflood** for the **impending flood of exabytes** that would cause the Internet's congestive collapse.

- Hay et al., 2010: *The Fourth Paradigm* →
Athena Data Volume

• The total data volume on spinning disk at COLA for Project Athena is capped at 50 TB (for now)

• The total data volume generated and resident at NICS is 1.2 PB (~500 TB unique)

• That much data breaks everything: H/W, systems management policies, networks, apps S/W, tools, and shared archive space
Athena: Harbinger of the Exaflood

- Need to transform Ad hoc solutions → systematic, repeatable solutions
  
  (transform Noah’s Ark → Shipping Industry)
- Familiar diagnostics are hard to do at very high resolution
- Have we wrung all the “science” out of the data sets, given that we have only a small percentage of the total data volume on spinning disk? How can we tell?
- “We need exaflood insurance.”

  - Jennifer Adams