Using Variable Resolution Meshes to Model Tropical Cyclones in NCAR’s CAM General Circulation Model

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Outline

Motivation

Model setup and overview

Short-term, seeded cyclone experiments

Year-long, aquaplanet climate runs

Summary
Tropical cyclones in GCMs

• Modeling of tropical cyclones in General Circulation Models (GCMs) historically difficult
  • Computing constraints -> low resolutions
  • Significant parameterization of sub-grid scale processes
    • Convection
    • Fluxes
• Higher resolution studies becoming more prevalent in hurricane research community
  • Many great examples during this week’s talks
Variable resolution feature recently implemented in NCAR Community Atmosphere Model (CAM) Spectral Element (SE) dynamical core.

CAM-SE scheduled to be default in next CESM.

Conforming refinement
- Every edge shared by only two elements.

Unstructured
- Domain not tiled in (i,j) fashion.

Static refinement
- Grid refined during initialization, does not follow atmospheric features.
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Variable resolution used for tropical cyclone studies in limited area models (LAMs), now apply this construct to GCMs.

-- Setup eliminates need for externally-forced and possibly numerically and physically inconsistent boundary conditions.
Short-term, seeded simulations

- **Analytically-derived, axisymmetric, weak, warm-core vortex** in hydrostatic and gradient wind balance on an aquaplanet ($T = 29^\circ C$) [{Reed and Jablonowski, 2011}]

- **CAM version 5.1.09, default CAM5 physics** (*parameterization scalability caveats apply!*)

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Grid spacing (equator) (km)</th>
<th>Analogous to...</th>
<th>Physics timestep (s)</th>
<th>Dynamics timestep (s)</th>
<th>Diff. coefficient (m$^4$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ne15</td>
<td>222</td>
<td>2° x 2°</td>
<td>3200</td>
<td>640</td>
<td>1e16</td>
</tr>
<tr>
<td>ne30</td>
<td>111</td>
<td>1° x 1°</td>
<td>1600</td>
<td>320</td>
<td>1e15</td>
</tr>
<tr>
<td>ne60</td>
<td>55</td>
<td>0.5° x 0.5°</td>
<td>800</td>
<td>160</td>
<td>1e14</td>
</tr>
<tr>
<td>ne120</td>
<td>28</td>
<td>0.25° x 0.25°</td>
<td>400</td>
<td>80</td>
<td>1e13</td>
</tr>
</tbody>
</table>
Cyclone transition: coarse -> fine

- Important desirable property -> *satisfactory interaction of cyclone with transition region between different resolutions*
- Set up -> start with global ne15 (~2°) and refine x4 (fine = ne60 = ~0.5°) -> refine entire hemisphere
- Why? Simple refinement, transitioning along cubed sphere edges -> “aggressive” width
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![Diagram showing grid transitions]
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Initial vortex:
\( v = 20 \text{ m/s} \)
\( \text{RMW} = 250 \text{ km} \)

Difficulties: Ideally we’d compare cyclone vs. “control” -> virtually impossible given time scales used / lack of mesh transition analogs

850 mb wind speed (m/s)

Latitudinal cross section wind speed (m/s)
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Comparing “uniform” to “refined” meshes

• Compare idealized cyclone in A) traditional **uniform** ne60 (~0.5°) mesh to a B) ne15 mesh (~2°) with a 4x **refined** area (ne60, ~0.5°)

• Smaller refined region than hemisphere: analogous to size of north Pacific ocean
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Day 10 - 850 mb wind speed (m/s)
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• In reality? If full uniform mesh is equivalent to 1.0 “work units,” refined mesh produces essentially identical results with 0.201 “work units”
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Year-long aquaplanet climate

- Use same refined mesh (~2° to ~0.5°) -> year-long aquaplanet climate
- Zonally-averaged SSTs, run for 14 months, discard first 2 as “spin-up”
- Simulation reaches steady state with features similar to observed climate system
- Provides **intermediate test** between short-term, deterministic studies (last few slides) and full-scale weather/climate simulations
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Spontaneous generation of cyclones in high resolution mesh
Aquaplanet cyclone in refined mesh

- Further refinement from ne15 -> ne120 (~0.25°)
- Example of one storm formed in northern hemisphere
- Category 4/5 equivalent cyclone - MSP: 911 hPa, max near surface wind speed: ~75 m/s
- ~25 km resolution w/ computing power of globally-uniform 50 km model
Cyclone transition fine -> coarse

- Asymmetric mesh allows for development of TCs in southern hemisphere as well
- Pass out of mesh transition region as TCs, not extratropical systems
- No numerical error or wave reflection back into refined domain
- Cyclone expectedly weakens as grid spacing becomes larger
Summary

• Cyclones passing both in and out of mesh transition regions are well-maintained and expected storm intensity increases/decreases are observed when cyclones move into/out of refined areas.

• Identically-initialized ideal TCs can be simulated significantly more efficiently in a refined grid when compared to a globally-uniform grid of the same resolution.

• High resolution nests produce realistic TC structure and simulations are able to generate TCs without vortex seeds on an aquaplanet with regionally-refined nest.

• Careful refinement selection can provide a doubling (or more) of regional resolution for the same computational cost when compared to a globally-uniform model.

Thank you!