6D.4

USING VARIABLE RESOLUTION MESHES TO MODEL TROPICAL CYCLONES IN NCAR'S CAM GENERAL CIRCULATION MODEL

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1.) INTRODUCTION

Modeling of tropical cyclones in General Circulation Models (GCMs) has been historically difficult due to factors such as relatively small storm size and intense convective processes which require comprehensive physical parameterizations. Tropical cyclones are significantly under-resolved, if not completely unresolved, at traditional GCM grid spacings of 50-300 km. However, recent advances in model numerics as well as computer resources facilitate GCM modeling at grid scales more amenable to tropical cyclone development.

This paper explores a novel variable-resolution mesh approach that allows for high spatial resolutions in areas of interest, such as low-latitude ocean basins where tropical cyclones are prevalent. Such GCM designs allow for targeted use of computing resources, further improving the ability of global models to resolve tropical cyclone dynamics at horizontal resolutions previously only achievable through the use of axisymmetric or limited area models (LAMs).

2.) VARIABLE RESOLUTION IN NCAR'S CAM-SE

The National Center for Atmospheric Research's (NCAR's) Spectral Element (SE) dynamical core (Taylor *et al.*, 2007) is the newest available choice in the Community Atmosphere Model (hereafter CAM-SE). One of CAM-SE's primary benefits is the ability to scale nearly linearly to tens of thousands of processors. This feature distinguishes it on massively parallel systems from less scalable dynamical cores such as the Eulerian spectral transform (EUL) and finite volume (FV) options in CAM. As parallel computing environments continue to grow in both capability and number, CAM-SE holds massive promise in its ability to effectively utilize such architectures (Dennis *et al.*, 2011).

In addition, CAM-SE possesses the ability to run on non-uniform, refined grids built upon a cubed-sphere computational mesh. This structure allows for simulations at resolutions approaching that of limited area regional models without abandoning the global modeling framework. The refinement technique utilized by CAM-SE is conforming, meaning every grid element edge is shared by only two elements and also requires all cells be quadrilateral. It is also unstructured which eliminates the need to tile the grid in a more restrictive row/column fashion (Levy *et al.*, 2012). The grid is static and is refined only during the model initialization.

The version of CAM used for this study is v5.1.09. Time steps are varied between runs but are based on the finest scale in any refined meshes. All coarser scales are restricted to the same time step. Hyperviscosity is also varied with resolution but, unlike the time step, also varies with scale within refined runs. Resolutions of interest are shown in Table 1.

Resolution	≈ Grid Spacing (km)	Analogous to…	Dynamics time step (s)
ne15	222	2° x 2°	640
ne30	111	1° x 1°	320
ne60	55	0.5° x 0.5°	160
ne120	28	0.25° x 0.25°	80

Table 1. Descriptions of CAM-SE resolutions discussed in this paper.

3.) SHORT-TERM, SEEDED CYCLONE EXPERIMENTS

As a first-order test the model is initialized with a warm-core vortex in axisymmetric hydrostatic and gradient-wind balance in an aquaplanet configuration (Reed and Jablonowski, 2011). Sea surface temperatures (SSTs) are set to a uniform 29°C and the CAM5 physical parameterization package is used. The vortex is initialized in a quiescent environment. While there is no background steering flow, the cyclone's motion (northwesterly in Northern Hemisphere) is predictable due to the beta-effect, resulting from a differential in Coriolis forces across the cyclone.

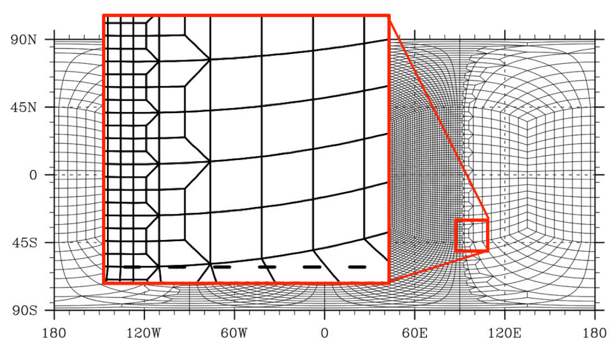

Figure 1. An ne15 mesh refined by a factor of 4 to ne60 on one half of the global domain. A portion of the transition region is magnified.

One important desirable property of a variable-resolution model used for studying tropical cyclones is satisfactory interaction of a cyclone with a grid transition region. However, it is difficult to quantify to which degree

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the storm behaves "well" in the mesh-transition region since no reference solution exists for comparison. The vast majority of tests investigating the behavior of variable-resolution models therefore involve qualitative analysis. The assessment here focuses on symmetric development of the storm, stretching or filamentation of the vortex structure during its passage from the coarse into the fine grid, and any numerical noise induced in the domain which does not exist when using uniform grids.

In these simulations, a grid of ne15 (~2°x2°, 15x15 elements per cubed-sphere face, see Table 1) refined to ne60 (~0.5°x0.5°) on one half of the globe (Figure 1) was used. This refinement is selected for three reasons. One, CAM struggles to maintain tropical cyclones at ne15 while resolving them adequately at ne60. Two, the hemispheric refinement provides a smooth longitudinal edge for the cyclone to pass through. Three, the narrow transition region used is the most aggressive width allowed for a refinement of this scale and therefore any abnormal behavior of the tropical cyclone should be most evident in this setup.

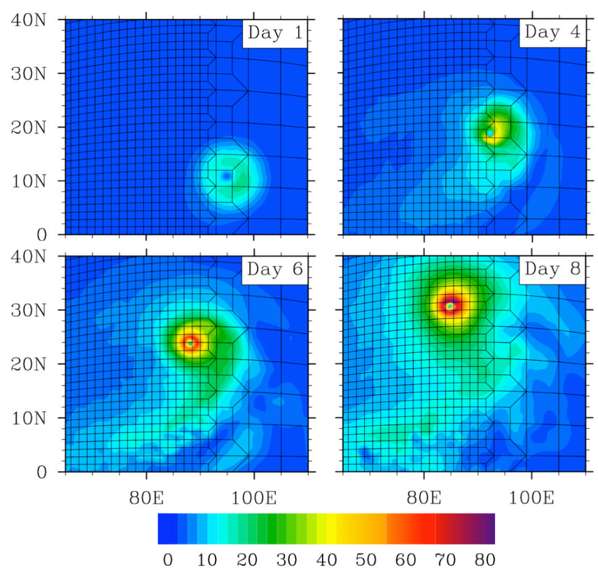

Figure 2. 850 hPa wind speed (m/s) evolution of an initial vortex seed passing through a mesh transition region from an ne15 grid to ne60 grid.

The 850 hPa wind speed evolution of the storm is plotted in Figure 2. By the end of the Day 1, the vortex seed remains closed and circular but has weakened slightly, in part due to the coarse grid. By Day 4 the storm is centered in the inner half of the transition region. It remains relatively symmetric and no spurious features in the domain containing the cyclone are evident. By Day 6 the storm enters the fine mesh and begins intensifying as the core is better resolved. This eventually results in a recognizable tropical cyclone fully embedded in the fine mesh by Day 8.

In addition, CAM-SE is tested by seeding a cyclone in a globally uniform ne60 mesh as well as in the fine grid interior of an ne15 mesh which is refined by a factor of four to ne60. Figure 3 shows the resultant 850 hPa wind field of the two cyclones after 5 and 10 days. Good agreement exists in the storm's spatial extent, size of the eyewall, and location within the storm core of the maximum winds. The intensity evolution of the cyclone as measured by either minimum surface pressure or maximum wind speed are also nearly identical between the cyclones in each model setup (not shown).

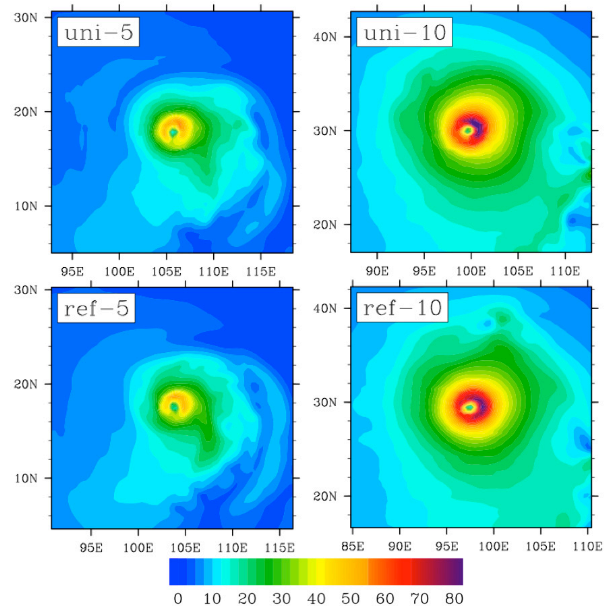

Figure 3. 850 hPa wind speed (m/s) at Days 5 (left) and 10 (right) for cyclone in globally uniform ne60 mesh (top, "uni") and an ne15 mesh refined to ne60 (bottom, "ref") in the cyclone domain.

Any discussion of cyclones in refined versus non-refined grids requires a cursory look at the computational requirements of running the model in both configurations. The primary benefit derived from such refinement is the ability to target computing resources in regions where the modeler is most interested—in this case, over the cyclone. The meshes described had 194,402 elements (uniform) and 38,666 elements (refined) in the global domain, equal to ratio of 0.199. With each simulation running on a fixed number of processors, the refined run was able to produce a nearly identical result while requiring only 20.1% of the resources of the uniform run. This outcome highlights the potential improvements that can be made in GCM modeling of tropical cyclones by utilizing variable resolution, especially for individual case studies or projects that involve regional modeling of cyclone behavior. One other major advantage of this approach is that the model does not rely on externally-forced and possibly numerically and physically inconsistent boundary conditions required by LAMs.

4.) YEAR-LONG AQUAPLANET CLIMATE EXPERIMENTS

As an additional level of complexity, longer simulations were completed on grids with a refined region analogous to an ocean basin in the Northern Hemisphere. The grid is shown in Figure 4. These aquaplanet simulations have fixed SSTs and no continents. Over long time periods such simulations evolve to a statistically steady state which shares similarities with the observed climate system. This setup represents an intermediate test between simple, short-term, deterministic test cases such as that in the previous section and more complex model setups which couple the atmospheric component of CAM to corresponding land, ocean, or sea modules.

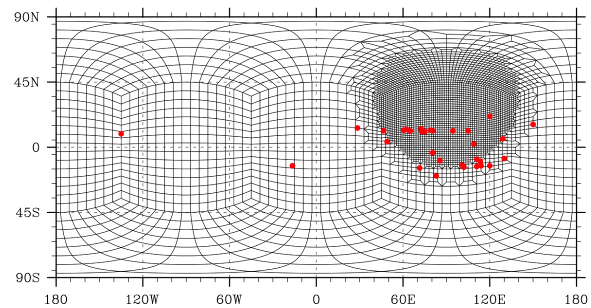

Figure 4. Mesh used for year-long aquaplanet simulations. The mesh was refined from ne15 globally to ne60 with a band of ne30 cells to smooth the transition region. Red dots indicate tropical cyclone origins during one year of the aquaplanet model run.

Simulations described here were run for approximately 14 months, with the first two being discounted from analysis as model spin-up. Unlike Section 3, the CAM4 physical parameterization package was used in these studies as the effect of the new microphysics packages in CAM5 in long-term simulations with prescribed aerosol fields (required for aquaplanet simulations) are still a topic of ongoing research. The zonally-averaged SSTs followed the distribution:

$$SST(\emptyset) = T_{max}\left(1 - \sin^4\left(\frac{2\pi\emptyset}{\emptyset_{max}}\right)\right) \quad (1)$$

where T_{max} is the temperature at the equator (35°C), ϕ is latitude, and ϕ_{max} is 60°. SSTs beyond 60° of latitude were fixed at 0°C. This profile is approximately 2°C warmer in mid-latitudes than the observed annual-mean zonal-mean SSTs in order to simulate a summer-like SST distribution in both hemispheres.

Figure 4 also shows the origin locations of tropical cyclones within the year-long aquaplanet simulation. Cyclones were detected using the commonly-used method outlined in Vitart *et al.*, (1997). The existence of a surface pressure minimum and collocated vorticity maximum, a warm core, and a threshold wind speed of 17 m/s near the ground are all required.

These results are in agreement with Walsh *et al.*, (2007) who argued that cyclone detection in GCM output is strongly dependent on model resolution. Given a threshold of 17 m/s, the coarse (ne15) grid does an insufficient job of generating storms that meet the basic definition of a tropical cyclone. However, in the regions where the resolution is increased, the ability of the model to resolve storms which surpass the minimum criteria improves greatly. These resolution-intensity/detection correlations are in good agreement with recent high-resolution tropical cyclone modeling studies (e.g. Walsh *et al.*, 2012, etc.) which have shown improved correlation of modeled cyclone intensity with increasing resolution.

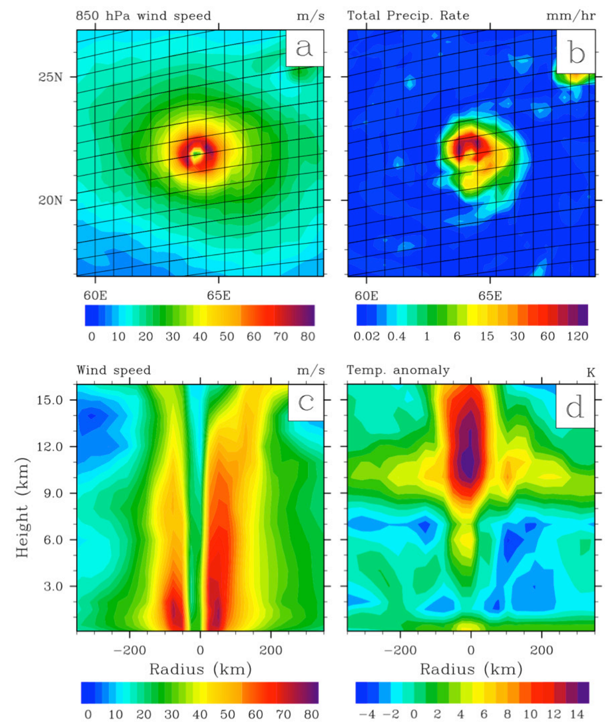

Figure 5. Example of cyclone (at maximum intensity) formed in refined nest during long-term aquaplanet simulation. Panel (a) shows 850 hPa wind speed (m/s), panel (b) shows total instantaneous precipitation rate (mm/hr), panel (c) shows a latitudinal cross section of wind speed through the core of the storm (m/s), and panel (d) shows latitudinal cross section of temperature anomaly (K).

Additional simulations were conducted with another level of refinement in the same region as shown in Figure 4. This additional refinement improved the finest scale to ne120 (~28 km or 0.25°x0.25°). Figure 5 shows a fully developed cyclone in the refined region. The modeled cyclone exhibits features such as a circular precipitation maximum in the cyclone's core region as well as spiral rainbands (5b), a tilted eyewall (5c), and an observable warm core (5d). It reaches a minimum pressure of 911 hPa with a maximum near-surface wind speed of 75 m/s (165 mph). While the ability of CAM to produce realistic cyclones at high-resolutions has been previously demonstrated, this refinement setup allows for a regional simulation of tropical activity at roughly 25 km with the same computational demand that would be required for a simulation of 50 km without refinement. As such, for a fixed computing load, a halving of the grid spacing is achieved by carefully selecting a regional area to direct resources to.

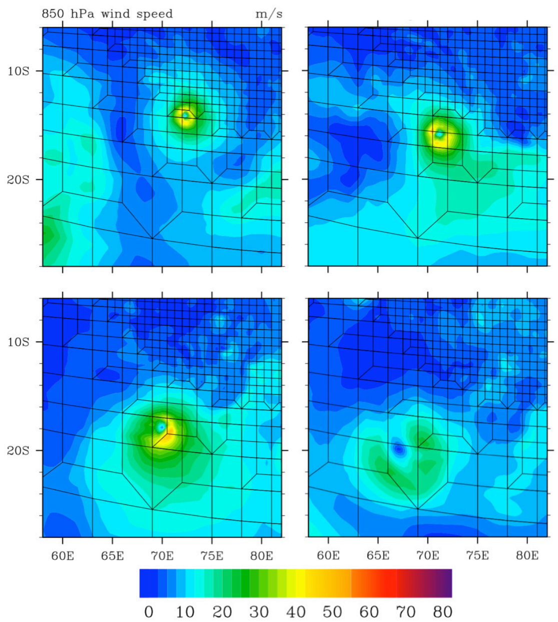

Figure 6. 850 hPa wind speed (m/s) evolution of a cyclone in the Southern Hemisphere (starting in upper left) which formed in the high resolution nest and passed southwestward into the coarser global nest (ending in the bottom right). Plots are at 18 hour increments.

The fact that the mesh is not centered on the equator allows for the generation of cyclones in the Southern Hemisphere which may exit the fine mesh as tropical cyclones (as opposed to the Northern Hemisphere where the mesh's spatial extent allows cyclones to transition to extratropical systems before leaving the refined domain). Figure 6 shows the evolution of a cyclone passing out of the refined region. As in Section 3, the model qualitatively maintains the closed, symmetric nature of the vortex structure without any noticeable numerical error at the boundary or wave reflection back into the refined region. The storm correspondingly weakens as the coarse-grid region is unable to resolve the previously intense cyclone.

5.) SUMMARY

This paper investigates the potential of using variable-resolution GCMs—in particular, NCAR's CAM-SE—to model tropical cyclones. 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. Starting with the same vortex seed, tropical cyclones in a regionally-refined mesh are nearly identical to those simulated at the corresponding (and more computationally-intensive) globally uniform resolution. Finally, more sophisticated, long-term, climate runs on an aquaplanet show that refinement supports spontaneous generation of tropical cyclones in regions of high resolution. These results are promising first steps in developing a framework which will allow variable-resolution GCMs to offer a new tool in modeling tropical cyclones at resolutions previously unavailable to the global modeler.

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