7A.3: **NCEP's Two-way-Interactive-Moving-Nest NMM-WRF modeling system for Hurricane Forecasting**

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1. Introduction:

A Hurricane is an intense atmospheric circulation characterized by strong multi-scale interactions between convective clouds, typically on the order of few kilometers, and larger scale environment, typically on the order of several hundred to thousand kilometers. In order to forecast such a system both high resolution and a huge domain are the basic requirements. However, at this time, it is not practical to operate models at regional scales, and larger, with uniform resolution on the order of 1-10 km over such huge domains. Nevertheless, moving nested grid and, more complex, adaptive grid models (Gopalakrishnan et al., 2002) may be used as efficient forecasting tools for the hurricane problem. At NCEP, a preliminary version of the moving, two-way interactive nested grid NMM-WRF modeling system is now being evaluated and tested for the hurricane predictions. This system is planned to replace the existing NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) moving nested grid regional-scale model in 2007.

Two different approaches have been adopted in the design of a movable nested mesh, especially for hurricane forecasting. In one approach two non-overlapping adjacent meshes may be dynamically coupled when the time integration for the grid points near the mesh interface is performed on each side with the use of the information in the other mesh domain (e.g., Kurihara et al., 1979). A fairly easier method is to transfer meteorological information from a fine to a course mesh and vice versa over the region of coinciding grid points (e.g., Phillips and Shukla, 1973). The nested grid NMM-WRF modeling system is broadly based on the latter approach. The coincidence of grid points between the parent and nested domain eliminates the need for more complex, generalized remapping calculations in the WRF Advanced Software Framework (Michalakes, 2002) and is expected to aid better distributed memory performance and portability of the modeling system. In this work we briefly explain the nesting technique, nest motion algorithm and finally present few results from the tracking of hurricane vortex for ideal and real cases.

2. The NMM-WRF nesting system:

A novel approach (Janjic et al., 2001; Janjic, 2003) was applied in the NCEP Nonhydrostatic Meso Model (NMM) that is currently a dynamical core option within the Weather Research and Forecasting (WRF) model initiative. With this approach instead of extending cloud models to larger spatial and temporal scales, the hydrostatic approximation is now relaxed in a hydrostatic system of equations so as to extend the applicability of the model to non-hydrostatic motions, and at the same time the favorable features of the hydrostatic formulation are preserved within the range of validity of the hydrostatic approximation. The NMM-WRF, non-hydrostatic system of equations are formulated on a rotated latitude-longitude, Arakawa E-grid and in the vertical, pressure-sigma hybrid coordinate is used. The latitude-longitude coordinate is simply transformed in such a way that the coordinate origin is located in the center of the integration domain. This kind of transformation provides a more uniform grid size all over the domain, and consequently avoids the need for excessively small time step as we approach the northern/southern latitudes. The dynamical system of equations and the numerical techniques are described for a uniform domain in Janjic et al., 2001 and Janjic, 2003. In order to deal with multi-scale forecasting, a horizontal mesh refinement capability was developed for this dynamical core and is currently being tested for the hurricane forecasting problem. The refinement capability commonly referred to as telescopic mesh supports one and two way interaction between a lower-resolution parent domain and one or more higher-resolution nests and also controls grid motion of the higher-resolution nests (Fig 1).

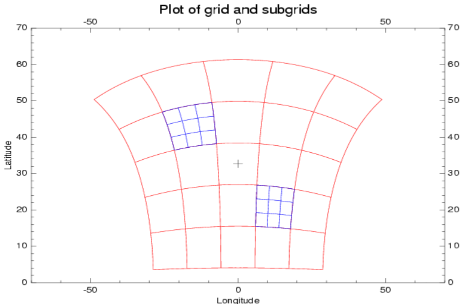

Fig 1: The NMM telescopic nest as it appears on a true latitude-longitude coordinate system.

All interpolations from the parent to the nested domain are done on a rotated latitude-longitude E-grid with the reference latitude-longitude located at the centre of the

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parent domain (Fig. 1). Consequently the nested domain can be freely moved anywhere within the grid points of the parent domain, yet the nested domain latitude-longitude lines will coincide with the latitude-longitude lines of the parent domain at integer parent-to-nest grid-size ratio (Fig. 2). All meteorological fields (except mass and moisture) are bi-linearly interpolated along the horizontal direction from the "diamond-shaped" parent grid points on to the grid points of the nested domain. Nearest neighbor approach is adopted for prescribing most of the land state variables. High-resolution topography and land-sea mask are redefined over the nested domain using the NMM-WRF Standard Initialization (NMM-WRFSI) dataset. To be consistent with the NMM model numerics, quasi-hydrostatic mass balancing is carried out after introducing the high-resolution topography. Cubic spline interpolation is used to interpolate data back and forth from standard pressure surfaces on to the hybrid surfaces. More recently, we have extended the conservation principles to tracer fields as well.

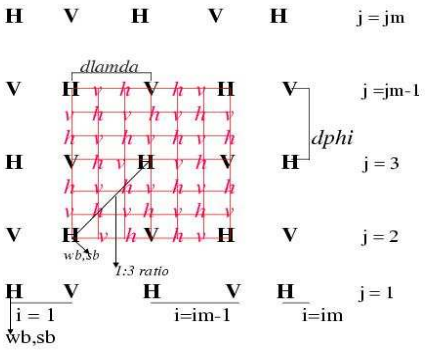

Fig 2: Nested E-grid configuration for 3:1 parent to nest ratio. wb and sb are the western and southern boundaries. The NMM grid indexing is also shown for the parent domain.

Figure 3 illustrates a sample E-grid structure with outermost rows and columns representing the input interface. External data is prescribed at this interface. Model integration starts from the third internal column/row that we will call the dynamic interface. The data in the penultimate rows and columns are a blend of the input and dynamic interface. Because of the E-grid structure and the fact that the input interface is well separated from dynamic interface, nested boundaries are updated at every time step of the parent domain exactly the same way as the parent domain is updated from the external data source. This approach seems to be simple, and yet produces an effective way of updating the interface without excessive distortion or noise. However, Bi-linear interpolation from the parent on to the nested domain is used to prescribe the wind, moisture and condensate on hybrid pressure surfaces, while the geopotential height fields is interpolated on pressure levels.

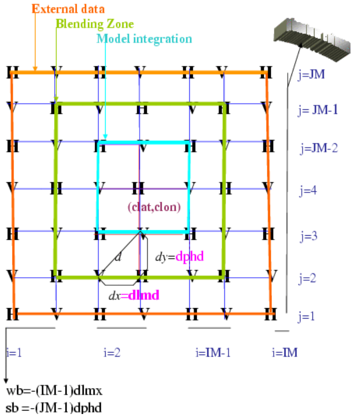

Fig 3: Nested boundary conditions.

Using interpolated information of the height fields from the parent domain, and high resolution topography over the nested domain, pseudo hydrostatic mass balancing is carried out to prescribe boundary conditions at each time step in the outermost rows and columns of the nested domain. The surface pressure, the interface pressure, the hydrostatic surface pressure and the temperature are recovered on the hybrid surfaces using cubic spline interpolation. The approach seem to be simple yet, as seen later, produces an effective way of updating the interface without much distortion or noise even while moving the teslesopic nest. The feedback, i.e., the two-way interactive nesting is a more recent feature that is being tested and constantly upgraded. For the two-way interactive technique, a 13-point averaged mass, momentum and scalar fields from the high resolution nest are weighed and fed-back into the parent domain. Currently, the weighting factor is 0.5.

3. Movement of a nest:

The nest motion for hurricanes (and tropical depressions) is based on the concept of dynamic pressure (Gopalakrishnan et al., 2002). For instance, Fig.4 shows the variation of dynamic pressure within the nested domain. The

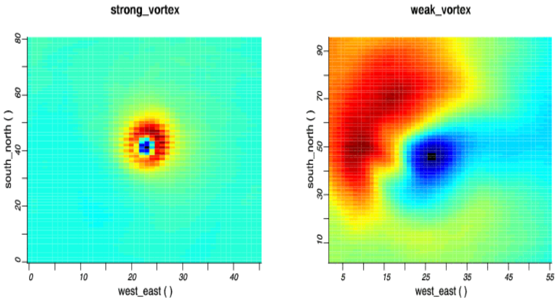

Fig 4: dynamic pressure over the nested domain for strong and weak vortex.

so called "stagnation point" is chosen as the center of the storm. At the end of every time step of the nested domain, the dynamic pressure within this domain is determined. Some filtering is done to isolate the storm center (not shown in figure 4). If the storm center is advected beyond one grid point of the parent domain (3 grid points from the center of the nested domain for a 3:1 parent to nest grid ratio) the nested domain is moved to a new position so as to maintain the storm at the center of the nested domain. Also, if the pressure difference between the center and the point of maximum dynamic pressure is lesser than 2 mb, the grid motion is terminated. It should be noted that while data is exchanged at a given time step before and after the grid motion in most part of the domain, the interpolation and pseudo hydrostatic balancing discussed earlier are still applied, but now in the masked region of the leading edge of the moving nest (where there is no data to exchange). The nest motion algorithm was tested on a semi-operational basis for the 2005 hurricane season that included a range of storms and some tropical depressions. If a storm is successfully located initially (i.e., at the start of a forecast) somewhere within the nested domain, the algorithm is sufficiently robust to provide automatic grid motion at subsequent times.

4. Results:

The NMM-WRF nested grid system discussed above has been tested and evaluated for performance. The WRF modeling infrastructure provides a suite of physics options, including the more recently available Global Forecasting System (GFS) physics. It should be emphasized that although we are constantly upgrading the physics with our eventual goal to transition to the complete suite of GFDL physics, before a fully functional prototype is established, nevertheless, we have gone ahead on evaluating the nested grid system with the available physics option during different stages of this work. Several of those results will be presented. Here we only illustrate a few of them.

(a) Idealized Case: An idealized, NMM-WRFSI-initialized GFDL hurricane-like vortex (Knutson and Tuleya, 2004) embedded in a uniform 5 m/s easterly background flow was tracked by moving the one-way nest using a simple criteria based on variations in dynamic pressure. In order to maintain the circulations, we retained the default NMM-WRF physics options on for this ideal case. Three simulations were carried out. One was with a static one-way nest, the second with a dynamic one-way nest and third was a run with high-resolution over the entire domain. Fig 5a describes the time-trace of the maximum wind speed at about 850 mb (model level 10) for a 3-day-forecast on the parent domain approximately 60^{o}x 60^{o} in size at about 36-km-resolution; static, one-way nested domain approximately 20^{o}x 20^{o} in size at about 12 km resolution; moving nest with a domain size of approximately 7^{o}x 7^{o} at 12 km resolution and, finally, a domain of uniform resolution of about 12 km.

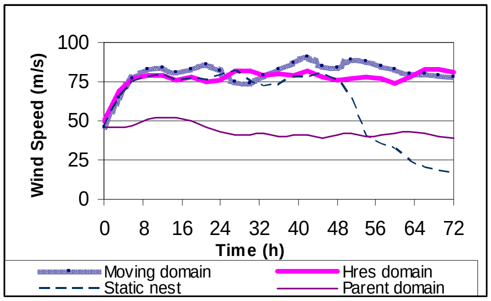

Fig. 5a: Time trace of the maximum wind speed plotted over various domains for an idealized moving vortex.

The hurricane moved out of the static nest and that explains the filling up of the mass and the consequent dissipation of the wind within the nest beyond about 2 days. Obviously, the best result is expected to be obtained from the simulation set up with high, uniform resolution of 12 km. However, because of the intensive computational requirements, this domain may only be used for a comparative evaluation. While 3 days of forecast using 108 processors took 3 hours of cpu time, the same 3 days of forecast was obtained with a moving domain using less than half the number of processors in about 25 minutes. Also, clearly the results from the one-way moving nest are comparable with a uniform high resolution domain. Finally, these preliminary results indicate satisfactory behavior of the static and the dynamic nests in simulating a multi-scale system.

(b) Semi-Operational forecasting System: An end-to-end, automated system of the NMM-WRF with the one-way moving nest initialized from real-time storm positions was run nearly for one full season in 2005, twice a day. Each forecast was worth 5 days. The grib files from the GFDL forecast was used as an input to the NMM-WRFSI. The initial and boundary conditions along with the static, land surface data for the parent domain was obtained by running the WRFSI. The only external input required for the nested domain, of course, apart from the initial position of the storm, is the static, land use data and this was generated by simply running the grid generator of the WRFSI at a higher resolution (one third of the parent domain for 3:1 parent to nest ratio) for the entire parent domain. This way, high resolution static data (like the terrain) is made available anywhere within the parent domain where the nest may move. The parent domain was set to about 60^{o}x 60^{o} at about 27-km-resolution and the one-way moving nest was set to a domain size of approximately 7^{o}x 7^{o} at 9 km resolution. The SAS convection, GFS surface, GFS boundary layer, NOAH-LSM scheme, Ferrier microphysics, GFDL radiation for the physics options were used. The aim here was to test the robustness of the one-way moving nest dynamics and algorithm related to the nest motion. There were very few failures noticed in the end to end system and each of the NMM-WRF runs (excluding the wrfsi initialization) for a five-day-forecast took about 50 minutes using 72 processors. Some of these results will be presented. Fig. 5b, for instance, shows the position of the moving nest for one of the forecasts from Hurricane Wilma.

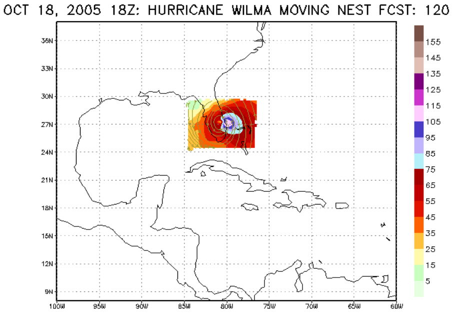

Fig 5b: semi-operational moving nest forecast of *Hurricane Wilma, 2005.*

(C) Two-way interactive, 4-Km moving nested grid simulation of Katrina: Some high resolution simulations for Hurricane Katrina was carried out. In this case the parent domain was set to about 40^ox 40^o at about 12-km-resolution and the two-way moving nest was set to a domain size of approximately 7^ox 7^o at 4 km resolution. The physics option is the same as those discussed above, except, the GFDL surface layer physics was used. Fig. 7, for instance, shows the isosurface of cloud liquid water. Clearly, the 4-km simulation is able to produce the structure of the storm quite well.

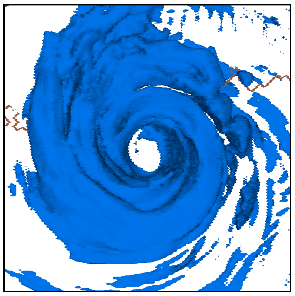

Fig 5c: Isosurface of cloud liquid water obtained from a 4km, two-way moving nested simulation of Hurricane Katrina before land-fall.

5. Future work:

It has long been recognized that hurricane models are sensitive to surface energy fluxes, momentum drag and both resolvable and parameterized convective schemes. Recent generation research models such as MM5 and WRF (Weather Research and Forecasting Model) have physical schemes more advanced than the present operational GFDL hurricane model. Despite this fact it hasn't been shown that these new generation models lead to improved forecasts of track and intensity on an operational basis. In transitioning to NCEP's next generational Hurricane WRF model, the benchmark physics will be the physics package presently used in the GFDL model. This physics package includes the Simplified Arakawa convective scheme (SAS), a Monin-Obukov surface layer scheme and the GFS boundary layer scheme, and a simple GFDL-SLAB model for land-surface. Nevertheless, despite constant upgrades to physics, we have been testing the robustness of the nested grid system. Most of the testing, until recently was on the one-way interactive nest. Some tests were more recently done by including the two-way interactive option. We will demonstrate a suite of tests including some idealized cases at the presentation. We are in the process of evaluating the two-way interactive grid system.

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