**12A.4 Real-Time High-Resolution MM5 and WRF Forecasts during RAINEX**

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## 1. INTRODUCTION

Hurricane intensity forecasts continue to be a challenging problem. The Hurricane Rainband and Intensity Change Experiment (RAINEX) aimed to better understand the evolution of the storm inner core structure and its interaction with its rainbands, which is one of the factors controlling the storm intensity change. RAINEX includes an aircraft component with three P3 aircrafts simultaneously flying into the rainbands and inner core region of a hurricane and a real-time high-resolution modeling component that helps with the mission planning during the field program. RAINEX flew several successful missions into Hurricanes Katrina, Ophelia and Rita (2005). Fig 1 shows the best track of these hurricanes. During RAINEX, from 15 August-30 September 2005, an experimental real-time high-resolution "mini ensemble" was conducted using the 5th generation Pennsylvania State University-NCAR non hydrostatic Mesoscale Model (MM5) and the Weather Research and Forecasting (WRF) model. The main objective of this study is to compare and validate the RAINEX high-resolution mini-ensemble and global model forecasts of the storm track, intensity, structure, and rainfall for Hurricanes Katrina, Ophelia and Rita. One of the challenges in RAINEX and the 2005 hurricane season in general, is that the development of many tropical cyclones (TCs) occurred in the western Atlantic, the Caribbean Sea and the Gulf of Mexico regions. Forecasting TC genesis becomes very important for the RAINEX mission planning; therefore, this study will also attempt to validate and compare the model skill on TC genesis.

## 2. MODEL AND DATA

During the months of August and September in 2005, 3-5 day model forecasts were conducted on a daily basis at 0000 UTC using four different initial and lateral boundary conditions from the large-scale and global models including the Global Forecasting System (GFS), the Geophysical Fluid Dynamic Lab (GFDL), the Naval Operational Global Atmosphere Prediction System (NOGAPS), and the Canadian Meteorological Center (CMC). The outer MM5 and WRF model domains cover a region of the Gulf of Mexico, the Caribbean Sea, and the Atlantic Ocean west of 50°W and south of 37°N with 15 km grid resolution. A multi-nested, vortex-following model grid is used when the National Hurricane Center (NHC) declared a tropical depression, tropical storm or hurricane; the RAINEX models ensemble included 3 nested domain simulations with resolutions of 15, 5 and 1.67 km grids, respectively. The second domain size is 121 x 121 grid points and the third domain is 151 x 151 grid points. All of the domains have 30 vertical sigma levels with 11 sigma levels within the planetary boundary layer (PBL). The second and third domains are centered on the hurricane and follow the vortex as it moves (Tenerelli and Chen, 2001). One of the problems using global model forecast fields to initialize a high-resolution model is that the initial vortex is usually much weaker than the observations. We use a procedure developed at the University of Miami, relocating a vortex spun up in MM5 to the actual position of the storm. This technique significantly improves the intensity of the simulations of major hurricanes. The model forecasts are compared and validated using the RAINEX observations, which include airborne radars, dropsondes and flight level data, in addition to remote sensing and satellite imagery, ground radar and conventional best track data.

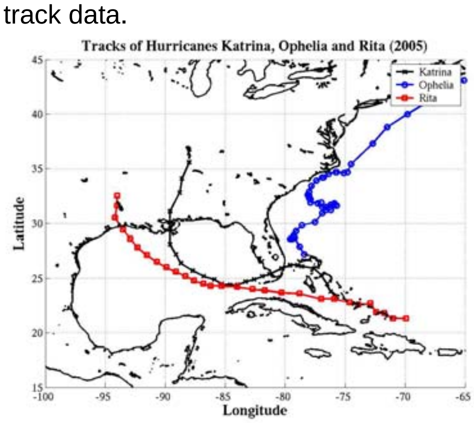


**Fig 1: Best tracks of Hurricane Katrina, Ophelia and Rita (2005).**

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## 3. RESULTS

### 3.1 Track and Intensity

To understand if high resolution numerical models have significant skill in predicting storm track and intensity, comparisons are made between the RAINEX mini-ensemble and the global models and validated with the best track data. In the cases of Hurricane Katrina and Ophelia, the MM5 and WRF models showed slight improvements over the global models in predicting the motion and timing of the hurricanes. Larger improvements were observed for Hurricane Rita in the western Gulf. Overall the track improvements over the global models were not very significant. This is likely because the steering flows of a hurricane (troughs and ridges) are fairly broad features that can be resolved by the global model grid scale. However, in terms of storm intensity, high resolution is needed to resolve the hurricane's inner core, rainbands and small-scale features. In nearly all of the cases, MM5 and WRF produced a deeper and more realistic storm compared to the global models. The largest improvement was for Hurricane Katrina. Fig 2 shows a time series of maximum sustained wind speed (kt) of all the model runs analyzed and the best track data from 00 UTC August 27, when Katrina was in the Gulf of Mexico. From this figure, it is evident that the MM5 simulations predicted the intensity evolution and the maximum wind speed the best. In addition, the MM5 model intensity forecasts improve with increasing resolution. Many of the global models missed the maximum wind by greater than 50 kt. The GFDL model did perform much better but it was not superior to MM5 and WRF.

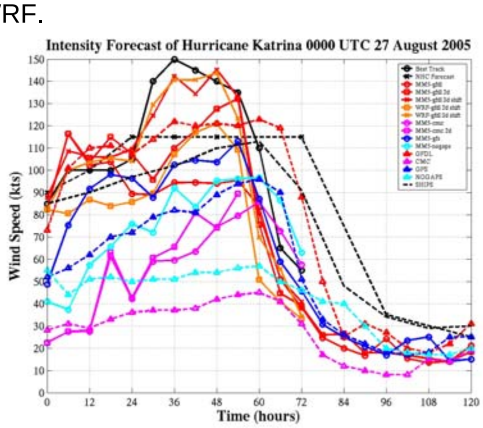



**Fig 2: 5 day forecast of maximum sustained wind speed (kt) from all models analyzed for Hurricane Katrina at 00 UTC Aug27.**

### 3.2. Storm Structure

One of the most beneficial aspects of high resolution models is the ability to capture fine details of the hurricane structure. The testing of these models in operational mode has shown that high-resolution MM5 and WRF models display considerable skill in predicting the size, shape, and structure of the storm. Fig 3a and b display the rain rate of Hurricane Rita from the TRMM Precipitation Radar and a 1.67 km MM5 simulation around 12 UTC 23 September. The model amazingly captured the development of Rita's concentric eyewall. In addition, the timing and duration of the eyewall replacement cycle and the general shape and size of the storm were all well captured. Internal dynamics of hurricanes, such as eye-wall replacements cycles, are known to be erratic and not easily forecast, so it striking that a model can predict it.

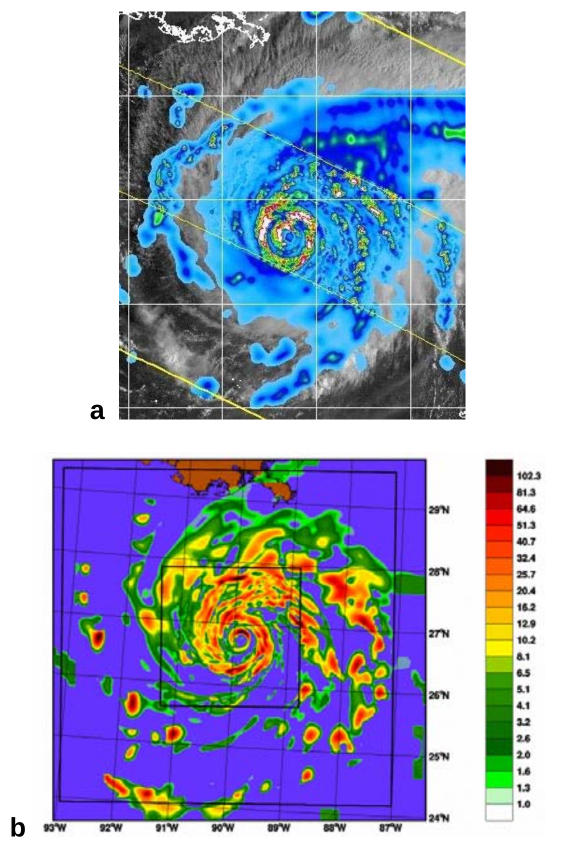
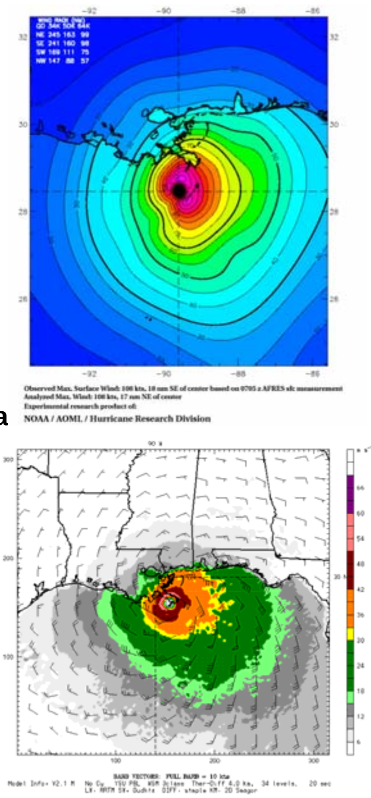


**Fig 3: (a) Rain rate from the TRMM Precipitation Radar at 12 UTC 23 Sept of Hurricane Rita and (b) a 36-h forecast of rain rate from an MM5 simulation valid at 12 UTC 23 Sept.**

Unlike Hurricane Rita, Katrina did not go through eye-wall replacement cycles. Fig 4a displays the Hurricane Research Division's surface wind analysis (HWIND) of Hurricane Katrina at 0730 UTC Aug 29th. Just prior to landfall, hurricane force winds spread as far as 100 nm away from the center with tropical storm conditions up to 245 nm from the center. Fig4b is the NCAR/MMM WRF moving nest 2 domain 4km 37-h forecast for Katrina valid at 0700 UTC Aug 29th. This WRF forecast correctly captured the rather large size and shape of Katrina's wind field. In addition, the magnitude of the wind speed is also well captured. After analyzing several numerical simulations of hurricanes, it appears that the high-resolution MM5 and WRF simulations have a grasp on the storm and environmental processes that are necessary for a mature hurricane to undergo secondary eyewall replacement cycles. These models can provide very valuable information to further study and eventually forecast eyewall replacement cycles and their associated intensity oscillations.




a

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**Fig 4: (a) HWIND of Hurricane Katrina at 0730 UTC Aug 29th. (b) WRF 4km 37-h forecast valid at 0700 UTC Aug 29th.**

### 3.3 Tropical Cyclone Genesis

Even though the RAINEX mission objectives did not include understanding when and if tropical cyclone genesis will occur, it became a very important component for the mission planning, especially since much of the TC development occurred close to land in the western Atlantic and Caribbean. Unexpectedly, some of the high-resolution models proved to be very valuable in forecasting TC development. The MM5 model initialized off the CMC initial conditions (MM5-cmc) proved to be the most sensitive to TC genesis. This model had only a few "false alarms" overall and was most often the first model to indicate development. Fig 5 shows an illustration of the model performance for the development of Hurricane Katrina in the Bahamas. Fig 5a and b is the 72 h forecast from the 00 UTC 22 August MM5-cmc and MM5-gfs simulations, respectively. The MM5-cmc spins up a category 1 hurricane near South Florida from a tropical wave in about 3 days, which verifies very well with the observed evolution, while all other models indicated slow or no development like the MM5-gfs model. The MM5-cmc was also superior to the other models in depicting the early stages of development of Hurricanes Maria, Nate and Ophelia. This model also predicted the development of all of the storms and compares very well with satellite imagery (Fig 5). At the conference, a detailed statistical analysis will be presented to report which models proved to have the most skill in predicting TC genesis.

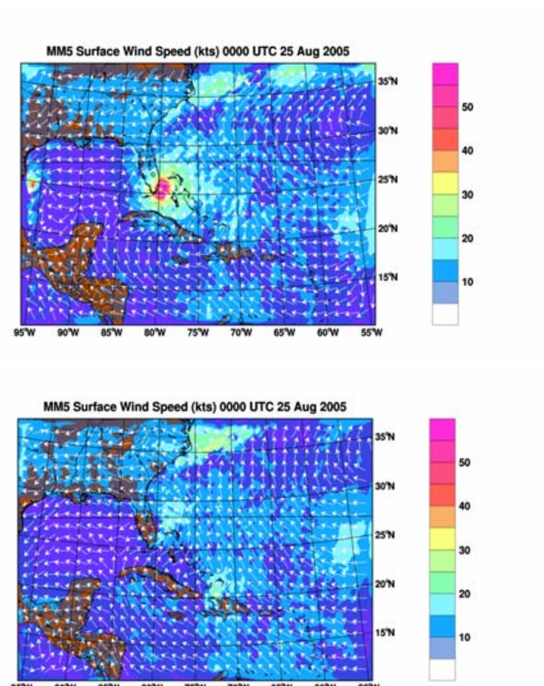


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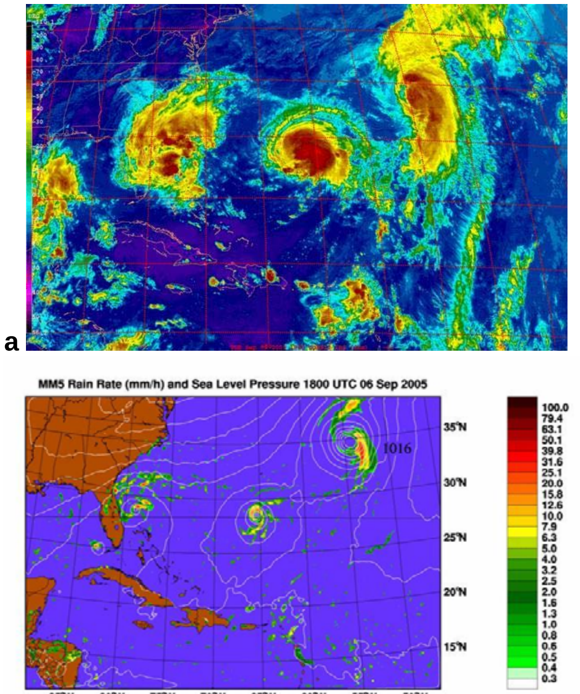
**Fig 5: 72 h forecast of wind speed (kt) valid at 00 UTC 25 August from the (a) MM5-cmc and (b) MM5-gfs simulations.**




**b**

**Fig 6: (a) Infrared satellite image of Hurricane Maria, Nate and Ophelia at 1800 UTC 06 Sept and (b) an MM5 42-h forecast of rain rate valid at 1800 UTC 06 Sept.**

## 4. SUMMARY

The RAINEX mini-ensemble was a very valuable tool during RAINEX operational forecasts and mission planning. The high-resolution simulations have displayed considerable skill over the global models in forecasting TC intensity, structure and even in predicting TC development. Increasing grid scale resolution is essential to resolve realistic storm structure and intensity. More elaborate comparisons will be made and presented at the conference.

## 5. REFERENCES

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