16A.1 Sensitivity of numerical simulations of Hurricane Emily (2005) to cumulus and microphysical parameterizations in the WRF model

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1. Introduction

Hurricane intensity forecast remains a great challenge in numerical weather prediction till now. Thus, understanding of the environmental, physical, and thermodynamic conditions that control the hurricane intensity change become an urgent problem. There were some recent studies dedicated to investigate the environmental control of the hurricane intensity (e.g., Emanuel 2004), while other studies made progresses to understand the physical and microphysical processes that largely impact on hurricane intensity forecast. In most recent study, Zhu and Zhang (2006) examined the effects of various cloud microphysics processes on the hurricane intensity, precipitation and inner-core structure with a series of 5-day explicit simulations of Hurricane Bonnie (1998) using MM5 model. The results indicated that varying cloud microphysics processes produced little sensitivity in hurricane track but resulted pronounced departures in hurricane intensity and inner-core structures. McFarquhar et al. (2006) investigated the effects of three different microphysical schemes in the MM5 model on high resolution simulation (2km) of Hurricane Erin (2001). They found that the different microphysical schemes caused only marginal differences in the hurricane track forecast but reproduced notable differences in the intensity forecast, although at the same time they also found that the representation of boundary layer processes is crucial in determining the strength of the simulated intensity.

In this study, we use the NCAR developed advanced research version of Weather Research and Forecasting (WRF ARW) model to further study the sensitivity of various cumulus and microphysical parameterization schemes to numerical simulations of hurricanes. The early rapid intensification period of Hurricane Emily (2005) is chosen for the study. It is our purpose to make a first snapshot to 1) examine whether the sensitivity of cumulus and microphysical processes could explain the early rapid intensification of Hurricane Emily; and 2) understand the role of microphysical processes in this rapid intensification period.

2. Overview of Hurricane Emily(2005)

Hurricane Emily(2005) formed in July 10 and dissipated in July 21 with the highest wind of 155mph(250 km/h) and minimum pressure of 929mb. Emily is the strongest and longest lived hurricane ever on record formed in the month of July. It caused $400 million property damage, 5 direct and 9 indirect fatalities. It also caused soil erosion, flooding, and landslides in northeastern Mexico.

Hurricane Emily originated from a Tropical Depression 5 in the central tropical Atlantic in the evening of July 10. It strengthened and developed into Tropical Storm Emily on the late of July 11. Rapidly strengthened during its westward moving, on July 14 Emily became a hurricane and reached category 4 in the eastern Caribbean later that day. The storm continued west-northwestward moving over the next few days and made landfall on July 18 near Cozumel, Mexico, on the Yucatan Peninsula with sustained winds of 135 mph (230 km/h). Passage over land weakened its intensity. But it strengthened and became a major hurricane again when it crossed the warm water in the southwest Gulf of Mexico. On July 20th, Emily made landfall in northeastern Mexico with sustained winds of 125 mph (205 km/h), Category 3 on the Saffir-Simpson Hurricane Scale. Then it headed over northeast Mexico, and dissipated over the Sierra Madre Oriental on July 21.

During its early intensification period between 1800UTC 13 July 2005 to 0000UTC 16 July 2005, the observed minimum central sea-level pressure (SLP) for Emily decreased from 1003mb to 958mb. The total SLP

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decrease is about 45mb during the 54 hours period! In this study, a series of numerical simulations are performed for this rapid intensification period.

3. Model and experimental design

The NCAR developed advanced research version of weather research and forecasting (WRF ARW) model (Skamarock et al. 2005) is used in this study. The WRF ARW model is a fully compressible, nonhydrostatic, terrain-following hydrostatic pressure vertical coordinate model designed to simulate mesoscale atmospheric circulations. Two way interactive, triple nested domains are adopted to achieve the numerical simulations. The model domains are shown as Fig.1. For the experiment, three horizontal resolutions are set at 27-km, 9-km and 4.5-km grid spacings, respectively. The dimensions, grid spaces, and time steps for each domain are listed in Table 1. The model vertical structure is composed of 31 sigma levels with the top of the model set at a pressure of 50hPa.

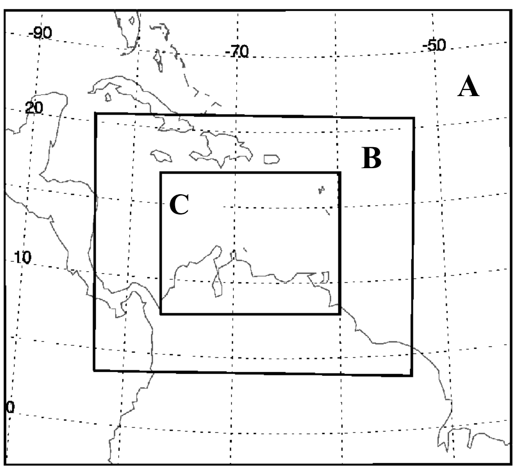


Fig. 1 Map of model domains.

Initial time for simulations is set at 18000 UTC 13 July 2005. Initial conditions for 27-km grid resolution derived from the global final analysis (FNL, 6-h interval) at 1.0x1.0 degree grids generated by National Centers for Environmental Predictions (NCEP)'s global forecast system (GFS). 54-hour simulation is conducted for domain A and B (27-km and 9-km grid spacings). The numerical simulation for domain C (4.5-km resolution) starts from 0900UTC 14 July 2005 and is initialized by interpolation of all prognostic variables from domain B.

Domain	Dimension $X \times Y \times Z$	Grid Space	Time step	Integration hours
A	190x140x31	27km	120s	0-54h
B	367x214x31	9km	40s	0-54h
C	415x235x31	4.5km	20s	15-54h

Table 1. The dimensions, grid spaces, and time steps for each domain

Since cumulus parameterization is commonly not used in fine mesh numerical simulation. Two groups of numerical experiments are designed. The first group of experiments is applied to test the sensitivity of both cumulus and microphysical schemes to the Emily intensity forecast at coarse meshes (domain A and B), while the second group of experiments is set to test the sensitivity of microphysical processes on Emily's intensity forecast at fine mesh (domain C). The detailed experimental design is listed in Table 2.

Exp.	Cumulus and microphysical schemes		
	Domain A	Domain B	Domain C
FB	BMJ+FERR	BMJ+FERR	N/A
WK	KF+WSM3	KF+WSM3	N/A
LIN	KF+WSM3	KF+WSM3	LIN
W3	KF+WSM3	KF+WSM3	WSM3
FER	KF+WSM3	KF+WSM3	FERR
W6	KF+WSM3	KF+WSM3	WSM6

Table 2. Designations used for different cumulus and microphysical configurations on coarse and fine domains. (BMJ --- Betts-Miller-Janjic cumulus parameterization; KF--- Kain-Fritch cumulus parameterization; FERR--- Ferrier microphysical scheme; WSM3 – WRF single-moment 3-class microphysical scheme; WRM6-- WRF single-moment 6-class microphysical scheme; LIN—Purdue Lin microphysical scheme.)

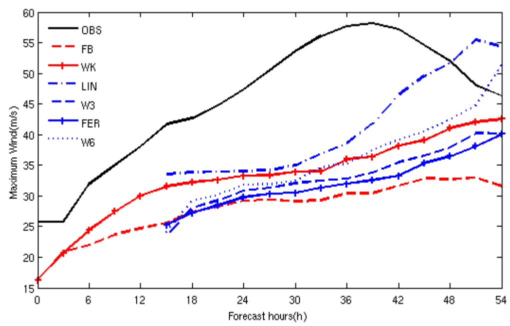
For all simulations, YSU planetary boundary layer parameterization scheme and the RRTM longwave and Dudhia shortwave radiation schemes are used.

4. Results and Discussion

4.1 Intensity

Significant differences in the hurricane intensity forecast are found between two coarse resolution simulations (27-km and 9-km grid spacings). With Kain-Fritcsh cumulus and WSM3 microphysical schemes, the model produced much better intensity forecast, compared with the forecast with Betts-Miller-Janjic cumulus and Ferrier microphysical schemes (Fig.2a and b). Then, all the high resolution numerical simulations at 4.5-km grid spacing are nested inside of the experiment WK (with WSM3 microphysics and Kain-Fritcsh cumulus parameterization) with different microphysical schemes. These high resolution simulations are started from the 0900UTC 14 July 2005. The impact of microphysical and cumulus scheme to the intensity of Emily is shown in Fig.2.

a)



b)

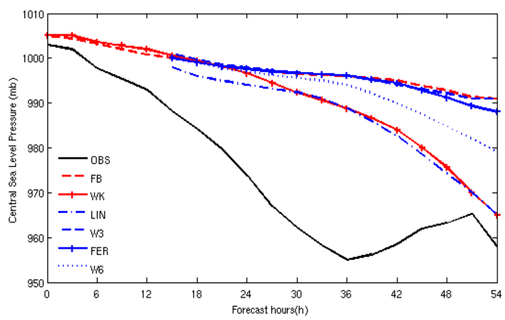


Fig.2. The series of (a) maximum surface winds (m s^{-1}) and b) minimum central SLP (hPa) for various experiments listed in Table 2.

The simulated results show obviously the impact of different microphysical schemes on Emily's intensity forecasts. Specifically, the Purdue Lin microphysics (Exp. LIN) result the best intensity forecast in 4.5km resolution although the hurricane continuously intensified near the end of simulation. The benefit of high-resolution forecast is also clearly showed when compared with the intensity produced from the Experiment WK at 9-km resolution. However, all other microphysical schemes (WSM6, Ferrier and WSM3) produced worse intensity forecasts if compared with the results generated by 9-km resolution run from Experiment WK, except the WSM6 scheme tends to produce slightly better winds near the end of forecast.

4.2 Track

The track forecasts produced by different experiments are displayed in Fig.3 a and b. The figures show that the track errors from different experiments are quite significant, especially at near the end of the simulations.

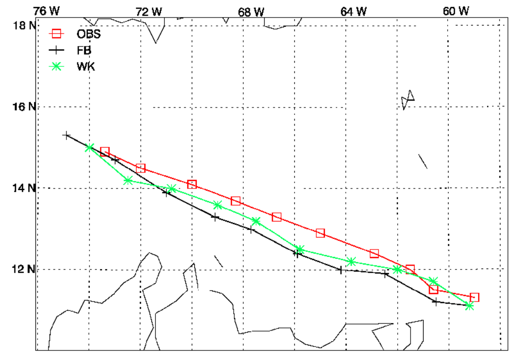


Fig.3a. Forecasts of hurricane track for the coarser resolution (9-km grid spacing) experiments with different cumulus and microphysical schemes between 1800 UTC 13 July 2005 and 0000UTC 16 July 2005. Center locations along the track are indicated every 6 h).

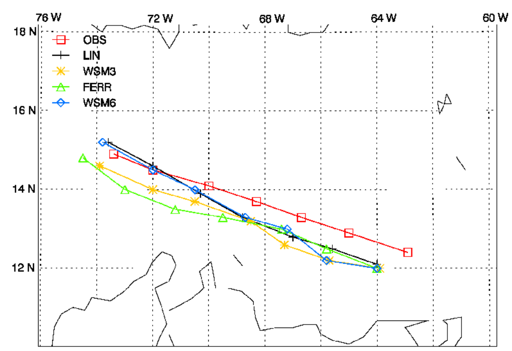
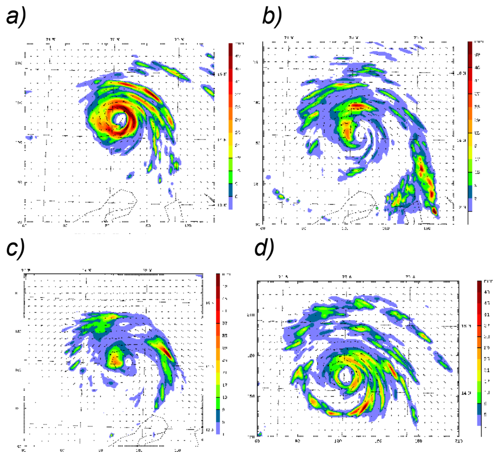


Fig.3b. Forecasts of hurricane track for the high resolution (4.5-km grid spacing) experiments with different cumulus and microphysical schemes between 1200 UTC 14 July 2005 and 0000UTC 16 July 2005. Center locations along the track are indicated every 6 h).

4.3 Precipitation structures

Figure 4 shows the hourly precipitation produced by the forecast from the Domain 3 with different microphysical schemes. Notable differences are found among different experiments. With Purdue Lin scheme the model produced the major observed rainband features, but the magnitudes of the total rainfall are larger than observations. This strong rainfall may reflect the stronger hurricane intensity the model predicted with this scheme. WSM3 cause a better rainfall amounts and features when compared with the Purdue Lin scheme although the intensity forecast is much worse. With Ferrier microphysical scheme, the model predicted a much weak rainfall in terms of both coverage and intensity. When WSM6 scheme is used, the model generated a much reasonable structure and amount of the rainfall.



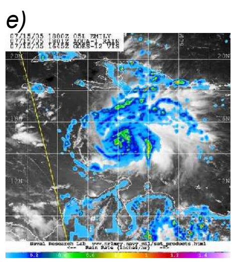


Fig4. Hourly precipitation (mm/h) at 33h forecast from 4.5-km grid spacing (Domain C), valid at 1800UTC 15 July 2005. a) LIN, b)W3, c)FER, d) W6. 2) hourly rainfall derived from Aqua satellite (inch/h).

4.4 Eyewall structure and vertical motion

The figure 5 and 6 illustrate the east-west cross sections of horizontal and vertical wind speeds along the center of the hurricane Emily from different experiments. The eyewall sizes are clearly displayed with the cross sections of the horizontal wind speed. The Purdue Lin microphysical scheme causes the strongest horizontal wind speed and smallest eye. The Ferrier scheme results the weakest horizontal wind speed, while the WSM6 scheme produces a much larger eye than any others.

Corresponding to the different eyewall structures, the eyewall vertical motions are much stronger with Purdue Lin scheme but much weaker with Ferrier and WSM3 microphysical schemes.

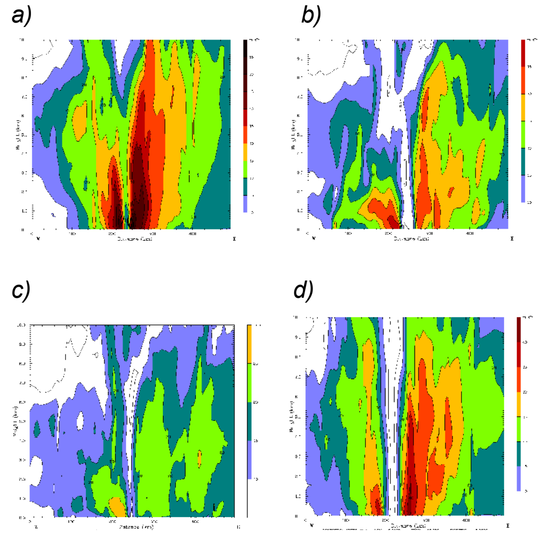


Fig.5. East-west cross sections of horizontal wind speed (ms^{-1}) through the center of Hurricane Emily at 1800UTC 15, July, 2005. The horizontal axis denotes the distance (km). a) LIN, b) W3, c)FER, d)W6.

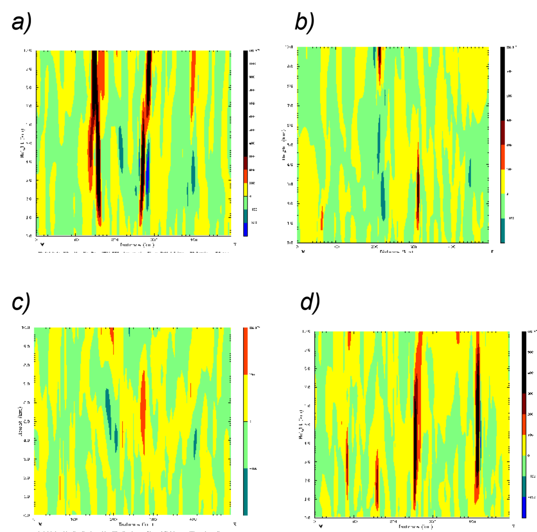


Fig.6. East-west cross sections of vertical wind speed (cms^{-1}) through the center of Hurricane Emily at 1800UTC 15, July,2005. The horizontal axis denotes the distance (km). a) LIN, b) W3, c) FER, d) W6.

Fig.7 shows the warm-core structures of the simulated hurricane Emily as represented by the potential temperature. Obviously, the experiments with Purdue Lin and WSM6 reproduced reasonable warm-cores in the central of hurricane, while the Ferrier and WSM3 microphysical schemes generated relatively weaker warm-cores.

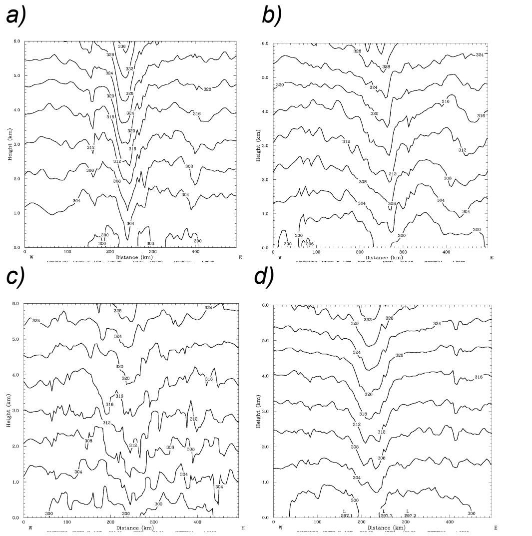


Fig.7. East-west cross sections of potential temperature (K) through the center of Hurricane Emily at 1800UTC 15, July, 2005. The horizontal axis denotes the distance (km). a) LIN, b) W3, c) FER, d) W6.

4.5. Microphysical properties

The different inner core structures and vertical motions inside of the hurricane may link with the different microphysics in the hurricane.

Figure 8 and 9 demonstrate the east-west cross sections of cloud ice mixing ratio and cloud water mixing ratio along the center of the Hurricane Emily from different experiments. Significant differences are found in the microphysical properties. With Purdue Lin microphysical schemes, the model produced less ice mixing ratio but relatively more cloud water in the upper troposphere when compared with other experiments. This fact may reflect to the relatively strong warm-core in the eyewall. With WSM3 scheme, the model generated relatively more ice but less cloud water.

In addition, the Ferrier microphysical scheme result much more cloud ice and cloud water (most in the low level of troposphere). This fact may link with the weak vertical motion near the eyewall (Fig.6). With WSM6 the model generated moderate ice mixing ratio and cloud water in the low-level troposphere.

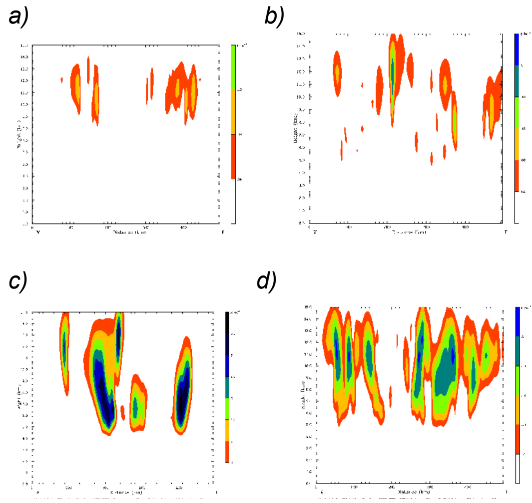


Fig.8. East-west cross sections of cloud ice mixing ratio (g kg^{-1}) through the center of Hurricane Emily at 1800UTC 15, July, 2005. The horizontal axis denotes the distance (km). a) LIN, b) W3, c) FER, d) W6.

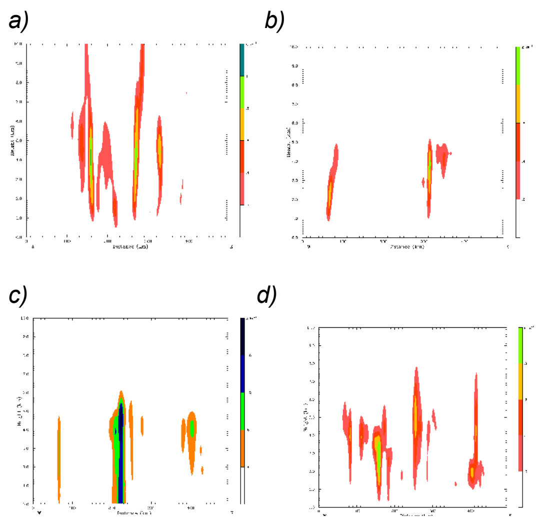


Fig.9. East-west cross sections of cloud water mixing ratio (g kg^{-1}) through the center of Hurricane Emily at 1800UTC 15, July, 2005. The horizontal axis denotes the distance (km). a) LIN, b) W3, c) FER, d) W6.

5. Summary and on-going work

As expected, the intensity forecast of Hurricane Emily is sensitive to the cumulus and microphysical parameterizations in the WRF ARW model. Overall, Kain-Fritcsh cumulus and WSM3 microphysical schemes result a better intensity forecast in coarse resolution domains. In the high-resolution simulations with different microphysics, the Purdue Lin microphysical scheme reproduces the best intensity forecast, while the WSM6 scheme generates the best precipitation forecast.

In addition to the intensity of the hurricane, the track, eyewall structures and motions, as well as the microphysical properties of the hurricane are all affected by the choices of the microphysical schemes. The different structures of the microphysical properties may have implication to the storm intensity. Further analysis and study will be continued.

Results from this study also show that the high-resolution simulations not always guarantee the better performance in hurricane intensity forecasts. The cloud microphysics play a critical role in the high resolution forecast.

The on-going studies with this case are in the following three directions: 1) continue the similar studies with even higher resolution (~1km); 2) test the sensitivity of various PBL schemes to Emily's intensity forecast; and 3) use data assimilation technique for the best possible environmental and vortex initial conditions. Additional results will be presented in the conference.

6. Acknowledgement

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7. References

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