12A.4 How do Cloud Microphysical Processes Influence the Numerical Simulation of a Tropical Cyclone's Intensity Change?

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1. Introduction

Hurricane intensity forecast remains a challenging problem in both operational and research communities. Forecast of hurricane rapid intensification is particularly challenging as it is plagued by limited understanding of the physical processes that related to hurricane intensity change (Davis and Bosart 2002) and improper parameterization of physics processes in numerical models (Karyampudi et al. 1998).

Previous studies showed that cloud microphysics processes are important to tropical cyclone intensity forecast. Willoughby et al. (1984) demonstrated that tropical cyclone structure and intensity change were influenced by cloud microphysics processes. They found that the peak intensity of tropical cyclone produced by the warm-rain microphysics scheme was 18 hPa lower (947 hPa vs. 965 hPa) than that produced by the mixed-ice phase scheme. In a recent study, Zhu and Zhang (2006) presented pronounced sensitivity of numerical simulation of intensity and inner core structure of Hurricane Bonnie (1998) to various cloud microphysics processes with MM5 model. They indicated that the weakest storm was produced by removing all three categories of ice from cloud microphysical processes, and the most rapid development of the storm was obtained by removing evaporation of cloud water and rainwater from the model. Another study by McFarquhar et al. (2006) investigated the roles of microphysical processes on the numerical simulation of Hurricane Erin (2001). They showed that the choice of microphysics schemes, even changing of a single microphysical parameter, could cause notable differences in the simulations of the intensity and the evolution of Hurricane Erin.

In this study, we will examine the sensitivity of numerical simulations of early rapid intensification of Hurricane Emily (2005) to various cloud microphysical parameterization schemes using an advanced research version of Weather Research and Forecasting (WRF ARW) model (Skamarock et al. 2005). Several key factors, which are commonly associated with hurricane intensity changes, will be analyzed from the numerical resluts to explain how cloud microphysical processes influence the hurricane structure and intensity change.

2. Overview of Hurricane Emily (2005)

Hurricane Emily (2005) formed on 10 July and dissipated on 21 July 2005. With the maximum surface wind (MSW) of 72 m s^{-1} and minimum central sea level pressure (MCSLP) of 929 hPa, Emily is the strongest and the longest lived hurricane ever on record formed in the month of July. It is also the earliest Category-5 hurricane in the Atlantic basin and the only Category-5 hurricane formed before August. It caused

$400 million property damage, 5 direct and 9 indirect fatalities, as well as soil erosion, flooding, and landslides in northeastern Mexico.

According to Franklin and Brown (2006), Emily originated from Tropical Depression Five in the central tropical Atlantic in the evening of 10 July. During its early rapid intensification period between 1800 UTC 13 July and 0000 UTC 16 July, the observed MCSLP dropped from 1003 hPa to 958 hPa. Total decrease in storm central pressure was 45 hPa within the 54-h period. In the first 36-h between 1800 UTC 13 July and 0600 UTC 15 July, Emily intensified rapidly from a tropical storm to a category-4 hurricane on the Saffir-Simpson scale with the extreme deepening rate of 2 hPa h^{-1}. In this study, a series of numerical experiments is conducted to simulate the early rapid intensification of Emily.

3. Experiment Design

A two-way interactive, three-level nested grid technique is employed to conduct the multi-scale simulation with WRF ARW model. Figure 1 shows the model domains and Table 1 lists the specifications for the model domains. The outer domains A and B (27-km and 9-km grid spacings) are integrated from 1800 UTC 13 to 0000 UTC 16 July 2005. The inner most domain C (3-km grid spacing) is started at 12h (0600 UTC 14 July 2005) and moved with the storm center (increment from C1 to C2 as shown in Fig.1). The model vertical structure comprises 31 σ levels with the top of the model set at a pressure of 50 hPa.

For the numerical simulations, the model physics options are the same for the three domains except that no cumulus parameterization is included for the 3-km domain. RRTM longwave radiation and Dudhia shortwave radiation schemes are adopted for all three domains. For the 27-km and 9-km grid spacings, Grell-Devenyi ensemble cumulus scheme is used. In order to examine the sensitivity of numerical simulation of Hurricane Emily to cloud microphysical schemes in the WRF model, six different microphysical schemes are used in different experiments (See Table 2).

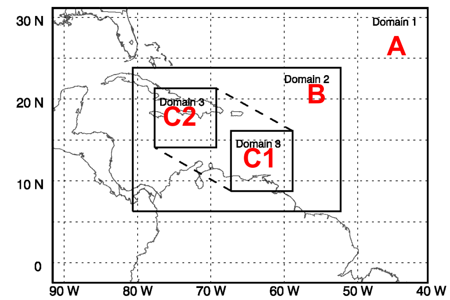

Fig.1 Location of Model domains for the numerical simulations.

Table 1. Dimension, grid spaces, and time steps for the model domains

Domain	Dimensions (x×y×z)	Grid Spacing	Time Step
A	190×140×31	27 km	120 s
B	340×220×31	9 km	40 s
C	301×271×31	3 km	13.3 s

Table 2. Microphysics options for the experiments.

Microphysics option (Exp.)	Hydrometeors Included (in addition to water vapor)
Kessler (KS)	Cloud water, and rain
Lin (LIN)	Cloud water, cloud ice, rain, snow, and graupel
WRF Single Moment 3-class (WSM3)	Cloud water/ice, rain/snow
WRF Single Moment 5-class (WSM5)	Cloud water, cloud ice, rain, snow
WRF Single Moment 6-class (WSM6)	Cloud water, cloud ice, rain, snow, and graupel
Ferrier (FERR)	Cloud water, cloud ice, rain, snow, and graupel

The model initial conditions are generated from the WRF 3-dimensional variational data assimilation (3DVAR) system (Barker et al. 2004). A 6-hourly cycled data assimilation is performed in the first 12-h of the numerical simulation (from

1800 UTC 13 to 0600 UTC 14 July). The available GOES-11 rapid scan Atmospheric Motion Vectors, QuikSCAT ocean surface vector winds, and aircraft dropsonde data (temperature, moisture, and wind profiles), collected during NASA Tropical Cloud System Processes (TCSP) mission, are assimilated into WRF model. Detailed method for data assimilation is described in Pu et al. (2007).

4. Results

To examine the influence of cloud microphysics processes on the WRF simulation of Hurricane Emily's early rapid intensification, all results discussed in this paper are from the 3-km grid spacing (domain C).

4.1 Intensity

Figure 2 compares the time series of the MCSLP and MSW from different experiments. Significant differences in storm intensity forecasts are evident in the experiments with various cloud microphysics schemes with the extreme difference ranging from 9 hPa (or 12 m s^{-1}) overdeepening to 27 hPa (or 15 m s^{-1}) underdeepening in MCSLP (or MSW) at the end of the simulations.

It is apparent from Figure 2 that the simulation with the warm rain Kessler scheme produces an earlier and quicker intensification than all other simulations. With a deepening rate of about 1.3 hPa h^{-1}, the simulated MCSLP is 949 hPa, which is 9 hPa deeper than the observed intensity, at the end of the simulation. In contrast, with WSM3 scheme, the model generates the shallowest storm and the slowest deepening rate with the MCSLP at 985 hPa at the end of the simulation. With WSM5 scheme, the WRF model produces a category-2 storm when the MCSLP reaches 967 hPa after 42-h integration. Even quicker deepening rates are produced by the experiments with WSM6 and Lin schemes. At the end of the simulation, MCSLP forecast in WSM6 is 9 hPa closer to the observed intensity than that in WSM5. In the mean time, the experiment with Lin scheme produces similar intensity as that with WSM6 scheme. The above results suggest that the numerical simulation of Hurricane Emily's intensification is very sensitive to cloud microphysical processes in WRF model.

a)

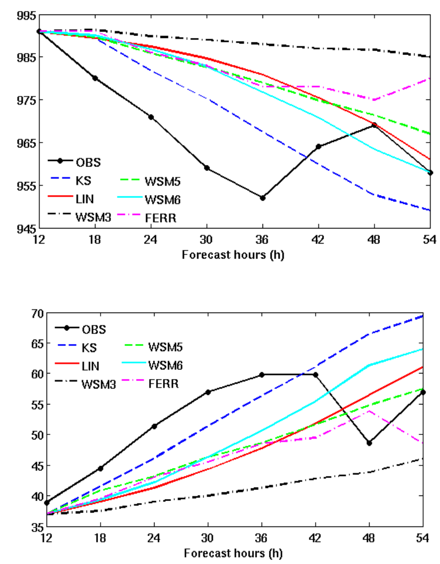

Fig. 2. Time series (6-h interval) of the storm a) MCSLP (hPa) and b) MSW (m s^{-1}) from the National Hurricane Center best track data (OBS) and numerical experiments during 0600 UTC 14 to 0000 UTC 16 July 2005.

4.2 Track

Figure 3 compares the simulated tracks from different experiments with the National Hurricane Center best track analysis. As in Fig.3, all the simulated tracks stick together in the first 18-h of the simulations and diverge in the next 24-h. All the experiments, except FERR (the experiment with Ferrier scheme), generate large northward and eastward bias in the simulated tracks during the last 24h of the model integration. However, all the experiments tend to reproduce the observed storm moving speed of 7 m s^{-1}.

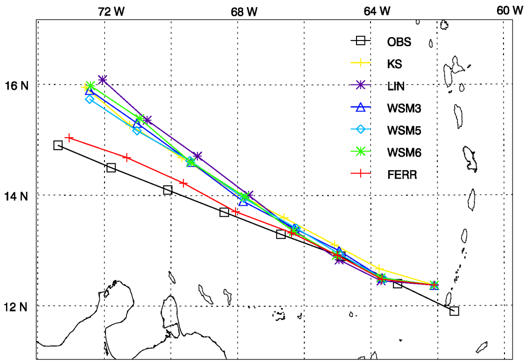

Fig. 3. The tracks of Emily (in 6-h interval) from the best track data (OBS) and model simulations during 0600 UTC 14 to 0000 UTC 16 July 2005.

4.3 Vertical structures of hydrometeors

Figure 4 shows the vertical profiles of cloud water (Fig.4a), cloud ice (Fig.4b), rain water (Fig.4c), and total water loading (summation of cloud water, cloud ice, rain water, snow, and graupel) (Fig.4d) averaged over an area within 250 km radius from the storm center at 0600 UTC 15 July 2005.

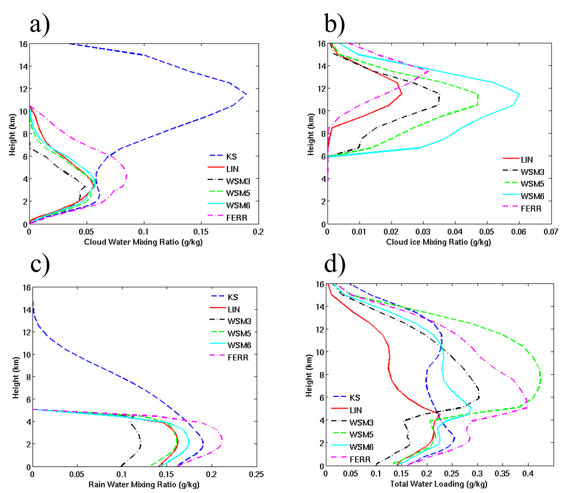

Fig. 4. Vertical distribution of area averaged (within 250 km radius from the storm center) a) cloud water, b) cloud ice, c) rain water, and d) total water loading in g kg^{-1} at 0600 UTC 15 July 2005 (at 36-h of the simulations).

The simulated cloud water is quite different in the experiment with the warm rain Kessler scheme from those with the ice-phased schemes (Figure 4a). With Kessler scheme, most of the cloud water is produced at upper troposphere, while with the ice-phased schemes, the model produce the most of cloud water at low troposphere. Overall, compared with the ice-phased schemes, the warm rain Kessler scheme generates much more cloud water at mid to high troposphere.

Figure 4b compares the cloud ice mixing ratio in different experiments. It is apparent that the experiment with Ferrier scheme produces the peak value of cloud ice at 13 km height level, which is 2 km higher than the height levels of the peak values from the other experiments. Among all the ice-phased schemes, WSM6 scheme causes the model to produce the largest amount of cloud ice, while the Lin scheme results in the smallest amount of cloud ice.

Figure 4c compares the rain water profiles from different experiments. It shows that the model produces large amount of rain water in the mid to upper troposphere when Kessler scheme is used. In all ice-phased microphysical schemes, Ferrier scheme results in more rain water and WSM3 causes less rain water at mid to low troposphere.

Figure 4d illustrates the vertical profiles of total water loading in clouds. With Kessler scheme, two maxima of total water are generated near 3-km and 12-km height levels in the forms of cloud water and rain water. With Lin scheme, the simulated total water peaks at 4-km height level in the form of rain water and cloud water. WSM3, WSM6, and Ferrier scheme cause the model to produce their maximum total water in the form of cloud water and precipitating ice at 5-km height. With WSM5 scheme, the model generates the maximum of total water at 8-km height level in the form of snow and cloud ice.

4.4 Convective heating rate

To gain deeper insight into the

sensitivity of storm intensity to cloud microphysical schemes, the vertical distribution of convective heating rate (following Zhu and Zhang (2006)) from different experiments are compared in Figure 5.

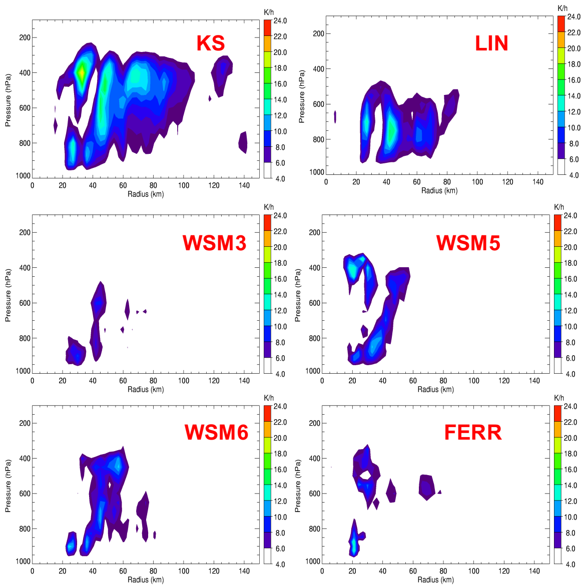

Fig. 5. Vertical distribution of heating rate (K/h) from different experiments at 0600 UTC 15 July 2005. The horizontal axis represents the radial distance from the storm center and the vertical axis denotes the pressure level.

With the warm rain Kessler scheme, the model produces much stronger convective heating rate over a large area in the storm vortex, especially at the upper troposphere. This strong heating corresponds to the deepest storm intensity at 0600 UTC 15 July 2005. In contrast, WSM3 causes the weakest heating rate, which is corresponding to the shallowest simulated storm. Lin, WSM5, and WSM6 result in similar intensity forecasts for Hurricane Emily with quite different structure of convective heating rate. With Lin scheme, the model produces the maximum heating rate at 700 hPa and large area of heating at the mid to low troposphere. These features may be related to the formation of the large amount of rain water. With WSM5 and WSM6, the model produce the peak heating rates at 400 hPa, which may be attributed to the generation of precipitating ice at 400 hPa. In addition, the experiment with Ferrier scheme generates much smaller amount of heating release, compared with the other 6-class hydrometeor microphysics schemes, such as Lin and WSM6. The above results indicate that the simulated storm intensities are highly related to the heating releases produced by the numerical experiments.

4.5 Environmental vertical wind shear

Previous studies suggested that small vertical wind shear is a necessary condition for tropical cyclone intensification. Figure 6 illustrates the time series (in 6-h interval) of environmental vertical shear between 850 and 200 hPa wind vectors averaged in the area between 200 and 800 km radius from the storm center. It is shown that the vertical wind shears vary in different experiments. In most experiments, the shears are less than 8 m s^{-1} except the experiment with Ferrier scheme. Tendencies of the vertical wind shear are different in the various experiments. Specifically, for Ferrier scheme, vertical wind shear increases rapidly from 5.7 to 12.2 m s^{-1} in the 42-h simulation. In contrast, with Kessler scheme, the vertical wind shear is lest than 6 m s^{-1} in the first 12-h, then increases slowly in the rest of simulation period as the storm intensifies very rapidly. For the experiment with Lin scheme, the vertical wind shear changes slightly in the first 18-h simulation before it decreases from 5.5 to 3.2 m s^{-1} in the next 24 hours of the simulation. WSM3, WSM5, and WSM6 all produce similar vertical wind shears with the extreme difference in 1 m s^{-1}. These results suggest that the weaker vertical wind shear does not guarantee the rapid deepening of the storm intensity. Hence, with vertical wind shear only, we are not able to explain the simulated storm intensity change.

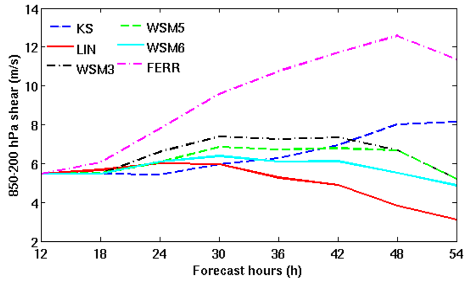

Fig. 6. Environmental vertical wind shear (m s^{-1}) between 200 hPa and 850 hPa averaged in the area between 200 and 800 km radius from the storm center during 0600 UTC 14 to 0000 UTC 16 July 2005.

5. Summary and discussion

A series of numerical simulations of Hurricane Emily (2005) is conducted with WRF model to examine the sensitivity of numerical simulations of hurricane early rapid intensification to cloud microphysics parameterization schemes. The major conclusions are the following:

1) Numerical simulation of Hurricane Emily's early rapid intensification is very sensitive to cloud microphysical schemes in the WRF model.

2) The magnitude of the environmental vertical wind shear does not correspond well with the simulated hurricane intensity in most of the cases.

3) The convective heating rates produced by experiments with various microphysical schemes are closely related to the simulated storm intensities.

Although the results from this study explain partially the sensitivity of the numerical simulation of Hurricane Emily's rapid intensification to cloud microphysical schemes, the contributions from cloud microphysics processes are not large enough to explain the differences between the observed and the model simulated intensity changes. Further investigation is reported in a poster presentation (P2.40) in the conference.

6. Acknowledgements

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