Sensitivity of Hurricane Charley Simulations to Changes in the WRF Model

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1. INTRODUCTION

This study focuses on numerical simulations of Hurricane Charley (2004) performed to investigate the role that explicit and implicit moisture parameterization play in governing the track, intensity, and rainfall distribution of Charley during and around its landfall on the central Gulf Coast of Florida. The three dimensional, fully nonlinear, nonhydrostatic Weather Research and Forecasting (WRF) model, version 2.0, was used to simulate the tropical cyclone over a 24-hour time period.

The main purpose of this research is to document the effect of varying microphysics and convection parameterizations on simulations of a land-falling tropical cyclone at both coarse and fine horizontal model resolutions. Included in this objective is the comparison of simulated features with the observed track, intensity, and precipitation data. Section 2 contains a brief overview of Hurricane Charley. Section 3 contains a description of the model used, while section 4 presents the results of the simulation. Section 5 discusses the likely mechanisms driving the cyclone track, intensity, and precipitation distribution and section 6 provides a summary and concluding remarks.

2. MODEL DESCRIPTION AND DETAILS

The version of WRF used in this research has been documented in a variety of applications, including tropical cyclone simulations. The 24-hour simulation utilized in this research uses two domains, a coarser domain with a 25 km grid length and a finer domain with a 10 km grid length. These domains are not nested and both cover roughly the same horizontal area. The coarse domain size is 68 x 56 grid points while the fine domain is 144 x 144 grid points. Both domains have 31 vertical levels. The initial fields are obtained from National Centers for Environmental Prediction (NCEP) analyses taken from the Eta model. The NCEP Eta model is also used for lateral boundary conditions. The simulations begin at 1200 UTC 13 August 2004, which is 7-8 hours before Charley's landfall, and end at 1200 UTC 14 August 2004 when Charley at a position off the coast of the GA/FL border.

Precipitation processes on the grid scale are represented with three varying explicit moisture schemes. The first scheme includes predictive equations for cloud water, cloud vapor, cloud ice, rain, snow, and graupel (Lin et. al 1983). The second scheme does not include a predictive equation for graupel and is based upon the NCEP class-5 scheme. The third scheme is the scheme used in the operational NCEP Eta model (Ferrier). To represent deep, moist convection in the model, two varying convective parameterizations are employed. The first scheme used is the Kain–Fritsch (KF) parameterization (Kain and Fritsch 1993). This scheme removes Convective Available Potential Energy (CAPE, calculated using the traditional, undiluted parcel-ascent method) through vertical reorganization of mass. The scheme consists of a convective trigger function (based on grid-resolved vertical velocity), a mass flux formulation, and closure assumptions. The second scheme used is the Betts-Miller-Janjic (BMJ) parameterization (Betts and Miller 1986; Janjic 1994). The BMJ is an adjustment-type scheme that forces soundings at each point toward a reference profile of temperature and specific humidity. The scheme's structure favors activation in cases with substantial amounts of moisture in low and midlevels and positive CAPE.

The KF and BMJ schemes are known to differ in some features of their predicted rainfall (Gallus and Segal 2004) and in the response to background conditions of the atmosphere. Previous research (Gallus and Segal 2001) found large differences in the KF and BMJ bias scores (bias = f/o, where f is the number of points forecast to have rainfall above a specified threshold and o is the number of points observed to exceed that threshold) as a function of rainfall amount. Additionally, the spread ratios (Wandishin et al. 2001), or equivalently the inverse of correspondence ratios (Strensrud and Wandishin 2000), defined as the union of all grid points at which rainfall in N ensemble members exceeds a specified threshold divided by the intersection of points where the same is true, were found to be large with runs where the KF and BMJ schemes (N=2) were compared. Therefore, simulations with the

KF and BMJ schemes are considered to be reasonably independent and thus useful for sensitivity simulations conducted in our research. Additionally, the KF and BMJ convective schemes have been widely used, providing further support for their adoption in this research.

A high-resolution planetary boundary layer (PBL) parameterization (Hong and Pan 1996) is used to simulate the vertical mixing of temperature, water vapor, momentum, and cloud water. Sea surface temperatures are based on the initial analysis fields from NCEP and are held constant throughout the simulation. While it would be preferable to vary sea surface temperature to allow for an oceanic response to the strong winds at the surface, such an atmosphere–ocean–wave coupled model is not presently available. Both short- and longwave radiative effects are accounted for where clouds are explicitly represented in the model. Surface radiative fluxes are provided by the scheme used here (Dudhia 1989).

Based upon the combinations of implicit and explicit moisture schemes examined in this research, there are six basic configurations used for simulations. The control (CNTL) simulation used the Lin et. al. microphysics scheme (MPS) and the Kain-Fritsch convective parameterization scheme (CPS). At the coarse resolution of 25 km, all six combinations were carried out in independent simulations with a computational time step of 150 seconds. After careful examination of the six initial simulations, two simulations were isolated for further modification. The CNTL simulation, using Lin et. al MPS and KF CPS and a second simulation, using the Lin et. al. MPS and BMJ CPS. For each of these two runs, two additional time steps were used, 75 s and 25 s. These same two configurations were used for the 10 km simulations, each utilizing three different time steps of 60 s, 30 s, and 10 s.

Since preliminary findings in the 25 km simulations indicated little variability as a result of changes in microphysics schemes (see section 4), the Lin et. al. scheme was isolated for further simulations using varying convective parameterizations in order to provide a more narrow focus for the research. The Lin et. al. was chosen over the WSM-5 and Ferrier schemes as it is the only MPS that uses six hydrometeors.

3. OBSERVED CHARACTERISTICS OF HURRICANE CHARLEY

a. Synoptic evolution

The origin of Charley can be traced to a tropical wave that emerged from western Africa on August 4. Satellite imagery at this time revealed only a small area of associated deep convection, however, as the wave progressed quickly westward across the Atlantic, the cloud pattern slowly became better organized. The first center position estimates were given by the Tropical Analysis and Forecast Branch (TAFB) and Satellite Forecast Branch (SAB) in the vicinity of 9-10 deg N, 47 deg W at 2345 UTC 7 August. The first Dvorak T-numbers were assigned 24 hours later and 12 hours later the curved banding of deep convection became more defined, with surface observations from the southern Windward Islands indicating that a tropical depression had formed by 1200 UTC 9 August, centered about 100 nautical miles south-southeast of Barbados (Figure 1 depicts the "best track" of the tropical cyclone path). Wind and pressure histories are shown in Figure 2 and Figure 3, respectively, while Table 1 lists the best track positions and intensities.

Late on 9 August, the depression moved into the Caribbean Sea. A strong, deep-layered high pressure center to the north of the depression induced a swift west-northwestward motion at 20-24 kt. Given the low vertical shear and well-established upper-level outflow, the depression strengthened into a tropical storm early on 10 August. Relatively steady strengthening continued as the storm moved into the central Caribbean Sea and Charley reached hurricane status by 1800 UTC 11 August as he approached Jamaica. Charley's center remained offshore of Jamaica, passing about 35 nm southwest of the southwest island coast around 1500 UTC 12 August. Charley then turned northwestward toward the Cayman Islands and western Cuba. The hurricane reached Category 2 status (83-95 kts) around 1500 UTC 12 August, after passing 15 nm northeast of Grand Cayman. As Charley neared the periphery of a mid-tropospheric ridge, he turned to the north-northwest, passing 20 nm east of the east coast of the Isle of Youth at 0000 UTC 12 August. The eye of Charley crossed the southern coast of western Cuba, near Playa del Cajio, around 0430 UTC 13 August, strengthening to 105 kts just before hitting western Cuba. Cuban radar data suggested a decrease in the diameter of the eye at this time. By 0600 UTC, the eye was emerging from the north coast of Cuba, approximately 12 nm west of Havana. Turning northward and slightly weakening, Charley passed over the Dry Tortugas around 1200 UTC 13 August with maximum winds near 95 kts and a minimum central pressure of 969 mb.

By the time of our simulation initialization, Charley had come under the influence of an unseasonably strong mid-tropospheric trough, extending from the east-central United States into the eastern Gulf of Mexico (see Figure 4). In response to the steering flow on the southeast side of this trough, Charley turned north-northeastward and accelerated toward the southwest coast of Florida. At this time Charley also underwent a rapid period of intensification. By 1400 UTC 13 August, the maximum winds had increased to 110 kt and just three hours later, Charley's maximum winds reached Category 4 strength (125 kt). Due to a decrease in the eye diameter, these extreme winds were confined to an area of only 6 nm within the center. Moving north-northeastward at 18 kt, Charley made landfall on the southwest coast of Florida near Cayo Costa around 1945 13 August with maximum sustained winds near 130 kt. Charley's eye passed over Punta Gorda at 2045 UTC and continued north-northeastward across the central Florida peninsula. The center passed near Kissimmee and Orlando around 0130 UTC 14 August, with a decreased intensity of 75 kt. Charley was still a hurricane, with maximum sustained winds of 65-70 kt when the center moved off the northeast coast of Florida near Daytona Beach around 0330 UTC 14 August.

After moving back over the waters of the Atlantic, Charley slightly re-strengthened as it accelerated northeastward toward the coast of South Carolina. This re-intensification proved to be temporary and Charley came ashore again near Cape Romain, SC at 1400 UTC 14 August as a weak hurricane with maximum sustained winds of 70 kt.

b. Precipitation characteristics

Rainfall totals of up to about 5 inches were reported in western Cuba. Maximum rainfall totals from gauges in Florida ranged up to a little over 5 inches, but radar-estimated storm total precipitation over central Florida were as high as 6 to 8 inches. A 28 hour radar rainfall estimate during the period from 0500 UTC 13 August to 0900 UTC 14 August (Figure 5) indicates a 1-3 inch swath through central Florida, which corresponds fairly well to precipitation indicated during our model simulation. Figure 7 shows a base reflectivity radar image of Hurricane Charley just after landfall at 1956 UTC 13 August.

c. Damage

There were nine tornadoes reported across the Florida peninsula in association with Charley, all of which occurred on 13 August. The strongest tornado was in south Daytona Beach. This tornado struck around 2326 UTC, and produced a quarter mile long track of F1 damage. A storm surge of 4.2 feet was measured by a tide gauge in Estero Bay, near Horseshoe Key in the vicinity of Fort Myers Beach. Storm surges of 3.4 and 3.6 feet were measured on tide gauges on the Caloosahatchee River, near Fort Myers. There were also visual estimates of storm surges of 6 to 7 feet on Sanibel and Estero Islands.

Charley was directly responsible for 10 deaths in the United States. There were also 4 deaths in Cuba and 1 in Jamaica. Therefore, the direct death toll due to Charley stands at 15. An additional 20 U.S. deaths, all in Florida, were indirectly caused by Charley. There are two estimates of insured damages in the United States from Hurricane Charley. The Property Claims Service reports insured damages of 6.755 billion dollars in Florida, 25 million dollars in North Carolina and 20 million dollars in South Carolina, making a total of 6.8 billion dollars in insured losses. The Insurance Information Institute reports an estimated total of 7.4 billion dollars in insured losses. Using a two to one ratio of total damages to these two insured damage amounts, a rough preliminary estimate of the total damage is 14 billion dollars. This would make Charley the second costliest hurricane in U.S. history after Hurricane Andrew.

4. RESULTS OF SENSITIVITY SIMULATIONS

The following section will begin with a description of the simulated tropical cyclone and its environment and a comparison with the observations. The emphasis is not on the model's reproduction of the life cycle of the storm. Common deficiencies in current models, such as the initial vortex structure and uncertainties in the physical parameterizations of surface fluxes and microphysics, make the simulation imperfect (Rogers et. al 2002). The emphasis here will be on gaining useful insight into the physical processes occurring in the model that are responsible for producing the distribution of precipitation, track, and intensity characteristics of the storm. Special emphasis will be paid to the influence of the aforementioned explicit and implicit moisture schemes utilized in the simulations. Therefore, subsequent sections will constitute the majority of the results discussion and will focus extensively on the response in precipitation distribution to changes in the microphysics and convective parameterizations, given that precipitation is most notably affected by changes in these schemes and is one of the primary concerns in the forecasting and modeling of tropical cyclones. Concluding sections will focus briefly on position and intensity changes in the simulations.

a. Description of simulated storm and comparison with observations

The initial position of the simulated storm matches closely with observations, however by 1200 UTC 14 August, the simulated track is generally 150 km to the southwest of the actual position. A time series of simulated sea level pressure versus observed intensity (Figure 6) shows that the initial vortex (obtained from the NCEP global analysis) is much weaker than the observed vortex.

b. Precipitation distribution and structure

Figure 8 shows 24-hour total accumulated precipitation plots from each of the initial six runs at 25 km resolution. The most notable findings from these initial simulations are the significant response in the precipitation field to changes in the convective parameterization scheme (CPS). There is little variation between changes in microphysics schemes when the convective parameterization is held constant. Thus, for the 10 km simulations, only the Lin et. al. microphysics scheme (MPS) was used in sensitivity comparisons of the KF and BMJ convective parameterizations.

As such, both differences between the handling of precipitation by the KF and BMJ schemes overall and differences within each scheme as a result of changes in horizontal resolution, will be examined.

In examining the total accumulated precipitation at 25 km, the simulation using the KF CPS captures the general 2-4 inch swath of rainfall extending across the central Florida peninsula (Figure 9) with two maxima of >4 in. near Marco and Naples, FL on the southern Gulf coast and about 100 km offshore of Georgia. There is also a narrow band of >2 in. totals extending to the southwest of the maximum near Naples. Figure 10 shows total convective precipitation, which isolates the rainfall generated exclusively by the KF CPS. The two maxima of >4 in. portrayed on the total accumulated precipitation plot are nearly completely generated by the CPS, however, over central interior Florida, the CPS is only responsible for 0.75 to 1.5 in. of the total accumulated precipitation, indicating that the MPS generates the majority of the rainfall over this inland area.

Figure 11 reveals that the 25 km simulation using the BMJ CPS has a more uniform and lesser total accumulated precipitation field than the simulation using the KF CPS. There is a broad area of 1-2 in. rainfall across the entire Florida peninsula, with >2 in. maxima south off the coast of Naples and near Sarasota and a fairly narrow and elongated >2 in. band extending from northern Florida northeastward along the Georgia and South Carolina coasts with a bullseye of >3 in. 25-50 km off the southern SC coast. Examining the contribution from the BMJ CPS alone in Figure 12 indicates that nearly the entire precipitation field is generated by the BMJ CPS.

Figure 13 shows total accumulated precipitation from the simulation using the KF CPS at a finer resolution of 10 km. At this resolution, a banding structure is clearly evident in the precipitation field, with a narrow band of maximum totals of 4-8 in. displaced slightly to the north and east of the maximum indicated by the 25 km KF run. There is also a small >8 in. bullseye evident near Cape Coral. There is also a narrow band of 2-4 in. totals extending north-northeastward from Fort Lauderdale. Examining the total convective precipitation in Figure 14 once again suggests that the majority of the rainfall generated over the coastal and ocean areas is a result of the KF CPS, while the MPS seems to contribute more substantially to rainfall totals over the land mass.

The simulation using the BMJ CPS at 10 km fails to resolve the banding structure of precipitation and displays little variation from the 25 km BMJ CPS run (Figure 15). There is slightly more total accumulated rainfall forecasted at 10 km, but the distribution remains almost identical to the 25 km run. The total convective precipitation plot in Figure 16 suggests that like the 25 km run, the 10 km run indicates that most of the precipitation generated is by the BMJ CPS, unlike the runs utilizing the KF CPS. In addition, Figure 16 clearly indicates a slight shift westward in the precipitation elements.

c. Track and intensity

Like the precipitation forecasts, analysis of the initial 25 km simulations indicated little variability in the mean sea level pressure (MSLP) field as a consequence of changes in the microphysics schemes, yet noticeable variability when the convective parameterization was changed. Thus, for further study, Lin et. al. was fixed as the MPS and sensitivity studies were conduced with the KF and BMJ schemes are varying horizontal resolutions and computational time steps.

Figures 17 and 18 show a comparison of the 12-hour forecasted MSLP valid 0000 UTC 14 August by simulations utilizing the KF and BMJ CPS at 25 km (75 s time step). The BMJ run has the storm 4 mb weaker and 75 km further to the northeast at this time. 12 hours later at 1200 UTC 14 August the differences are more pronounced with the BMJ run placing the storm center 150 km to the north-northeast of the placement by the KF run and the BMJ run has the storm 8 mb weaker than the KF run (Figures 19 and 20). In examining how changes in the computational time step affect the minimum MSLP of the storm at 1200 UTC 14 August, table 2 shows that at a time step of 150 s (double that of the initial run), the simulation using the KF CPS forecasts the minimum MSLP to be 4 mb lower than the identical run with a time step of 75 s with a slight displacement in position to the northeast.

Decreasing the time step from 75 s to 25 s weakens the storm an additional 2 mb. Likewise, in the simulation using the BMJ CPS, increasing the time step to 150 s also results in a lower MSLP, but of only 2 mb. There is also a displacement to the southeast in the position of the storm center.

The increased model resolution of 10 km results in a slight increase in intensity at 1200 UTC 14 August, but of only 2 mb in both the KF and BMJ runs. Otherwise, at the previous forecast hours, there is little noticeable change in the storm intensity or position in the 10 km simulations.

5. DISCUSSION

In the history of numerical modeling, approaches for incorporating cumulus convection into mesoscale models have been divided into three groups. The traditional approach utilizes convective parameterization at convectively unstable points and explicit (nonparameterized) condensation at convectively stable points. The fully explicit approach uses explicit methods regardless of stability. The hybrid approach parameterizes convective scale updrafts and downdrafts, but “detrains” a fraction of parameterized cloud and precipitation particles to the grid scale. This allows the path and phase changes of such particles to be explicitly predicted over subsequent time steps (Molinari and Dudek 1992).

For the purposes of this research, the hybrid approach was used because of its known benefits in its potential for realistic simulation of mesoscale organization. It allows convective updrafts and downdrafts (which are parameterized) to coexist with stratiform rain (which is explicit). The hybrid approach accomplishes this by directly incorporating the processes that occur in nature: detrainment of hydrometeors and subsequent phase changes of such hydrometeors.

It is clear from the results that the highest variability in rainfall and storm intensity are a result of changes in the convective (implicit moisture) parameterization, rather than changes in the explicit moisture parameterization, and the convective parameterization is largely responsive to changes in grid resolution. Although the physical justification for use of convective parameterization is generally only valid at a particular range of model grid resolutions (Molinari and Dudek 1992), often no lower than 20 km, several studies have found that adequate simulation of precipitation may require the use of such parameterizations at grid spacings as fine as 5-10 km. In this particular research, it is evident that the Kain-Fritsch parameterization reponds noticeably to an increase in the model resolution, whereas the Betts-Miller-Janjic parameterization produces nearly identical precipitation output regardless of a 25 km or 10 km model grid resolution.

The Kain-Fritsch appears to be the most accurate CPS choice when simulating precipitation intensity and distribution in Hurricane Charley. Not only does the Kain-Fritsch capture the general distribution of precipitation at 25 km, but at 10 km the Kain-Fritsch CPS accurately and realistically represents the banding nature of tropical cyclone precipitation, whereas the Betts-Miller-Janjic scheme does not respond to the increased resolution and fails to capture both the banding structure of the precipitation as well as the overall rainfall distribution, especially across central Florida.

The WRF model poorly initialized the mean sea level pressure (MSLP) of Hurricane Charley, likely because of the use of coarse (40 km) Eta fields for the WRF initial fields, but also reflecting limitations of the model initialization and parameterization of surface fluxes, ocean feedback, and microphysics. Along with the inaccurate representation of Charley's initial intensity, the model poorly handled intensity changes during the 24-hour simulation period. Observations indicate that Hurricane Charley's intensity decreased by 19 mb over the 24-hour period from 1200 UTC 13 August to 1200 UTC 14 August, however all runs of the WRF model indicate an overall increase in intensity, most noticeable in the Kain-Fritsch simulations, with a 24-hour increase in central sea level pressure by 10 mb, while the Betts-Miller-Janjic simulations are less dramatic with an overall increase in 24-hour central sea level pressure by 2-4 mb. Both of these results are fairly unsatisfying, but also expected given the limitations of the model initialization.

6. CONCLUSION

Overall, the WRF simulations of Hurricane Charley, though of varying accuracy, provided successful and useful in many regards. The high-resolution numerical model reproduced the storm track and evolution of the precipitation features reasonably well. Although the simulated storm was stronger than observed, model biases are common in numerical simulations of tropical cyclones and reflect the limitations of the model initialization and parameterization of surface fluxes, ocean feedback, and microphysics. While the model did not accurately reproduce the intensity evolution of Charley, the track and synoptic-scale environment were reasonably well represented. Thus, the precipitation distribution generally followed the observations, and the simulation reproduced reality well enough to justify a detailed examination of the physical processes in the model.

Results from the sensitivity generally simulations show that 1) tropical cyclone intensity and precipitation features are largely responsive to changes in the cumulus parameterization, 2) the use of smaller computational time steps at coarser resolution results in a weaker cyclone, 3) there is a strong sensitivity of precipitation to the horizontal resolution and the 10 km runs capture the banding structure of the precipitation that the 25 km runs fail to resolve, and 4) the explicit moisture scheme makes a more significant contribution to precipitation amounts over land.

Future research regarding Hurricane Charley at landfall may benefit from modifications in the convective parameterizations and experimentation with various methods of model initialization.

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References

Betts, A. K., and Miller M. J., 1986: A new convective adjustment scheme. Part II: Single column tests using GATE wave, BOMEX, and arctic air-mass data sets. *Quart J. Roy. Meteor. Soc.*, 112, 693–709.

Dudhia, J., 1989: Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.*, 46, 3077–3107.

Gallus, W. A. Jr., and Segal M., 2001: Impact of improved initialization of mesoscale features on convective system rainfall in 10-km Eta simulations. *Wea. Forecasting.*, 16, 680–696.

Gallus, W.A. Jr.,. and Segal M., 2004: Does Increased Predicted Warm-Season Rainfall Indicate Enhanced Likelihood of Rain Occurrence?. *Weather and Forecasting*: Vol. 19, No. 6, pp. 1127–1135.

Janjić, Z. I., 1994: The step-mountain Eta coordinate model: Further developments of the convection closure schemes. *Mon. Wea. Rev.*, 122, 927–945.

Kain, J. S., and Fritsch J. M., 1993: Convective parameterization for mesoscale models: The Kain–Fritsch scheme. *The Representation of Cumulus Convection in Numerical Models, Meteor. Monogr.*, No. 46, Amer. Meteor. Soc., 165–170.

Lin, Yuh-Lang, Richard D. Farley and Harold D. Orville., 1983: Bulk Parameterization of the Snow Field in a Cloud Model. *Journal of Applied Meteorology*: Vol. 22, No. 6, pp. 1065–1092.

Molinari, J., and M. Dudek, 1992: Parameterization of convective precipitation in mesoscale models: A critical review. *Mon. Wea. Rev*., 120, 326-344.

Rogers, Robert., Aberson, Sim., Kaplan, John., and Goldenburg, Stan., 2002: A Pronounced Upper-Tropospheric Warm Anomaly Encountered by the NOAA G-IV Aircraft in the Vicinity of Deep Convection. *Monthly Weather Review*: Vol. 130, No. 1, pp. 180–187.

Stensrud, D. J., and Wandishin M. S., 2000: The correspondence ratios in forecast evaluation. *Wea. Forecasting.*, 15, 593–602.

Wandishin, M. S., Mullen S. L., Stensrud D. J., and Brooks H. E., 2001: Evaluation of a short-range multimodel ensemble system. *Mon. Wea. Rev.*, 129, 729–747.