

The Impact of Microphysical Schemes on Intensity and Track of Hurricane

W.-K. Tao¹, J. J. Shi^{1,2}, S. S. Chen³, S. Lang^{1,4}, P.-L. Lin⁵, S.-Y. Hong⁶,
C. Peters-Lidard⁷ and A. Hou⁸

¹*Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt,
Maryland, USA*

²*Goddard Earth Sciences and Technology Center, University of Maryland at Baltimore
County, Maryland, USA*

³*Rosentiel School of Marine and Atmospheric Science, University of Miami, Miami,
Florida, USA*

⁴*Science Systems and Applications, Inc., Lanham, Maryland, USA*

⁵*National Central University, Chung-Li, Taiwan, R.O.C.*

⁶*Department of Atmospheric Sciences and Global Environment Laboratory, Yonsei
University, Seoul, South Korea*

⁷*Hydrological Sciences Branch
NASA Goddard Space Flight Center
Greenbelt, Maryland, USA*

⁸*Goddard Modeling Assimilation Office
NASA Goddard Space Flight Center
Greenbelt, Maryland, USA*

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Abstract

During the past decade, both research and operational numerical weather prediction models [e.g. Weather Research and Forecasting Model (WRF)] have started using more complex microphysical schemes originally developed for high-resolution cloud resolving models (CRMs) with a 1-2 km or less horizontal resolutions. The WRF is a next-generation meso-scale forecast model and assimilation system that has incorporated a modern software framework, advanced dynamics, numeric and data assimilation techniques, a multiple moveable nesting capability, and improved physical packages. The WRF model can be used for a wide range of applications, from idealized research to operational forecasting, with an emphasis on horizontal grid sizes in the range of 1-10 km. The current WRF includes several different microphysics options.

At Goddard, four different cloud microphysics schemes (warm rain only, two-class of ice, two three-class of ice with either graupel or hail) are implemented into the WRF. The performances of these schemes have been compared to those from other WRF microphysics scheme options for an Atlantic hurricane case. In addition, a brief review and comparison on the previous modeling studies on the impact of microphysics schemes and microphysical processes on intensity and track of hurricane will be presented. Generally, almost all modeling studies found that the microphysics schemes did not have major impacts on track forecast, but did have more effect on the intensity. All modeling studies found that the simulated hurricane has rapid deepening and/or intensification for the warm rain-only case. It is because all hydrometeors were very large raindrops, and they fell out quickly at and near the eye-wall region. This would hydrostatically produce the lowest pressure. In addition, these modeling studies suggested that the simulated hurricane becomes unrealistically strong by removing the evaporative cooling of cloud droplets and melting of ice particles. This is due to the much weaker downdraft simulated. However, there are many differences between different modeling studies and these differences were identified and discussed.

1. Introduction

Advances in computing power allow atmospheric prediction models to be run at progressively finer scales of resolution, using increasingly more sophisticated physical parameterizations and numerical methods. The representation of cloud microphysical processes is a key component of these models. Over the past decade both research and operational numerical weather prediction (NWP) models [i.e., the Fifth-generation National Center for Atmospheric Research (NCAR)/Penn State University Mesoscale Model (MM5), the National Centers for Environmental Prediction (NCEP) Eta, and the Weather Research and Forecasting Model (WRF)] have started using more complex microphysical schemes that were originally developed for high-resolution cloud-resolving models (CRMs). CRMs, which are run at horizontal resolutions on the order of 1-2 km or finer, can simulate explicitly complex dynamical and microphysical processes associated with deep, precipitating atmospheric convection. A recent report to the United States Weather Research Program (USWRP) Science Steering Committee specifically calls for the replacement of implicit cumulus parameterization schemes with explicit bulk schemes in NWP as part of a community effort to improve quantitative precipitation forecasts (QPF, Fritsch and Carbone 2002).

There is no doubt that cloud microphysics play an important role in non-hydrostatic high-resolution simulations as evidenced by the extensive amount of research devoted to the development and improvement of cloud microphysical schemes and their application to the study of precipitation processes, hurricanes and other severe weather events over the past two and a half decades (see Table 1). Many different approaches have been used to examine the impact of microphysics on precipitation processes associated with convective systems¹. For example, ice phase schemes were developed in the 80's (Lin *et al.* 1983; Cotton *et al.* 1982, 1986; Rutledge and Hobbs 1984), and the impact of those ice processes on precipitation processes associated with deep convection were investigated (Yoshizaki 1986; Nicholls 1987; Fovell and Ogura 1988; Tao and Simpson

¹ The effects of aerosols (see a brief review by Tao *et al.* 2007) on microphysical (processes) schemes have also been studied.

1989; and others). The results suggested that the propagation speed and cold outflow structure were similar between runs with and without ice-phase processes. This is because evaporative cooling and the vertical shear of the horizontal wind in the lower troposphere largely determine the outflow structure. However, ice phase microphysical processes are crucial for developing a realistic stratiform structure and precipitation statistics. The sensitivity of the different types of microphysical schemes and processes on precipitation was also investigated (i.e., McCumber *et al.* 1991; Ferrier *et al.* 1995; Wu *et al.* 1999; Tao *et al.* 2003a; and others). Those results indicated that the use of three ice classes is superior to using just two and that for tropical cumuli, the optimal mix of bulk ice hydrometeors is cloud ice, snow and graupel (i.e., McCumber *et al.* 1991). Ice microphysical processes also play an important role in the long-term simulation of cloud and cloud-radiative properties (i.e., Wu *et al.* 1999; Zeng *et al.* 2008). Additionally, water budgets and process diagrams (see Fig. 7 in Tao *et al.* 1991 and Fig. 10 in Colle and Zeng 2004) were analyzed to determine the dominant cloud and precipitation processes (i.e., Fovell and Ogura 1988; Tao *et al.* 1991; Colle and Zeng 2004; and Colle *et al.* 2005). For example, Fovell and Ogura (1988) found that the melting of hail was the primary source of rain for a long lasting mid-latitude squall line. Tao *et al.* (1990) showed that the dominant microphysical processes were quite different between the convective and stratiform regions and between the mature and decaying stages. Condensation, collection (accretion) of cloud water by rain, and melting of graupel dominated in the convective region, while deposition, evaporation, melting and accretion associated with the ice phase dominated during the mature phase of a tropical squall line. However, melting and sublimation became important during the dissipating stage in the stratiform region. Colle *et al.* (2005) determined that condensation, snow deposition, accretion of cloud water by rain and melting are important processes associated with orographic precipitation events.

Many new and improved microphysical parameterization schemes were developed in the past decade (i.e., Ferrier 1994; Meyers *et al.* 1997; Resiner *et al.* 1998; Hong *et al.* 2004; Walko *et al.* 1995; Morrison *et al.* 2005; Straka and Mansell 2005; Milbrandt and Yau 2005; Morrison and Grabowski 2008; Thompson *et al.* 2004, 2008; Dudhia *et al.* 2008

and many others²). These schemes range from one-moment bulk with three ice classes to one-moment bulk with multiple ice classes to two-moment two, three and four classes of ice. Different approaches have been used to examine the performance of a new scheme. One approach is to examine the sensitivity of precipitation processes to different microphysical schemes. This approach can help to identify the strength(s) and/or weakness(es) of each scheme in an effort to improve their overall performance (i.e., Ferrier *et al.* 1995; Straka and Mansell 2005; Milbrandt and Yau 2005). Idealized simulations have also been used to test new microphysical schemes by showing their behavior in a setting that is open to simpler interpretation. In addition, another approach has been to examine specific microphysical processes (i.e., turning melting/evaporation on or off, reducing the auto-conversion rate from cloud water to rain, etc.) within one particular microphysical scheme. This approach can help to identify the dominant microphysical processes within a particular scheme (i.e., evaporation, melting of large precipitating ice particles, etc.) responsible for determining the organization and structure of convective systems (i.e., Tao *et al.* 1995; Wang 2002; Colle *et al.* 2005; Zhu and Zhang 2006(a); and many others).

An improved Goddard bulk microphysics parameterization (Tao *et al.* 2003a; Lang *et al.* 2007) has recently been implemented into WRF (Version 2.2.1 and V3 and see Appendix A). The major objective of this paper is to test the performance of the Goddard microphysics in WRF at very high-resolution. In addition, the performance of the Goddard schemes will be compared with three other 3ICE bulk microphysical schemes in WRF: WSM6, Purdue-Lin and Thompson. Numerical experiments will be performed to investigate the impact of the microphysical parameterizations on the intensity and major characteristics associated with Hurricane Katrina (2005). Also the paper will present a review on previous modeling studies on the impact of microphysical processes on other hurricanes.

² Please see Levin and Cotton (2008) and Tao and Moncrieff (2009) for a review of microphysics used in cloud system resolving models.

The paper is organized as follows. Section 2 gives a brief review of previous modeling study and section 3 present the results form Hurricane Katrina (2005). The summary will be presented in section 4.

2. Review Previous Modeling Studies

Only five modeling studies have investigated microphysics in tropical cyclones and hurricanes using high-resolution (i.e., less than 5 km) numerical models. Their results will be briefly reviewed in this section.

(a) Willoughby *et al.* (1984)

Lord *et al.* (1984) and Willoughby *et al.* (1984) examined the impact of cloud microphysics on tropical cyclone structure and intensity using a two-dimensional axis-symmetric non-hydrostatic model with 2 km grid size. Figure 1 shows the time series of minimum surface level pressure (MSLP) and maximum tangential winds at 3.1 km for the case with warm rain only and three-class ice (cloud ice, snow and graupel). The results show that the ice-phase microphysical scheme can produce lower [minimum surface pressure](#) (about 20 hPa at the end of simulation) compared to the case without ice-phase. The results also showed that the maximum tangential wind at 3.1 km increased gradually corresponding well with the lower minimum surface pressure. The greater variability of the tangential wind the ice-phase case is due to the presence of multiple convective rings throughout this case (Willoughby *et al.* (1984). In the contrast, the maximum tangential wind at 3.1 km remains relative constant in strength after 40 h model integration for the warm – rain case. One interesting feature is that the case without ice-phase produced lower minimum surface pressure for the first 40 h model integration. There is no discussion/explanation, however.

Their results suggested that ice processes are important for simulating tropical cyclone evolution, intensity, and structure. Including the ice-phase case resulted in more realistic downdrafts and convective rings compared to using warm-rain only. Lord *et al.* (1984) and Willoughby *et al.* (1994) also suggested the importance of mesoscale organization on hurricane growth and structure. The mesoscale organization (especially the mesoscale

downdrafts) was mainly initiated and maintained by cooling and melting. These results were obtained without conducting numerical simulations as those in later section.

(b) Wang (2002)

The three-dimensional numerical model used in Wang (2002) is a triply nested, movable mesh, hydrostatic primitive equation model (called TCM3). The nested domains were constructed with grid resolutions of 45, 15 and 5 km with corresponding numbers of grid points 181 x 141 x 21, 109 x 109 x 21, and 109 x 109 x 21, respectively. Wang conducted five numerical experiments to test the effects of variations in cloud microphysics parameterization on the intensification, structure, and intensity of an idealized hurricane. These experiments are (1) three-class ice with graupel (as done by McCumber *et al.* 1991, named CTRL), (2) warm rain processes only (named WMRN), (3) three-class with hail (as Lin *et al.* 1983 and named HAIL), (4) without cooling from evaporation of rain and melting of snow and graupel (named NMLT), and (5) without cooling from evaporation of rain the warm rain processes only (named NEVP).

Figure 2 shows the maximum wind speed at model lowest level and minimum sea level pressure (MSLP) from these microphysics parameterization sensitivity tests. The results indicated that the intensification rate and final intensity are not sensitive to microphysics (with only a few hPa difference between the runs with WMRN, CTRL and HAIL due to the similarities in the vertical profiles and magnitudes of latent heat release. The result is mainly due to that the insensitivity occurred because these schemes produced similar levels of downdrafts and spiral rain-bands, both being negative to rapid intensification and final intensity of the model tropical cyclones.

The vertical heating profiles are quite similar between WMRN, CTRL and HAIL case (see Fig. 3). Maximum heating in the eye-wall occurred in the mid-upper troposphere (5–8 km) in the three experiments with the maximum heating level being slightly higher in both WMRN and HAIL. There is a cooling near the sea surface with a cooling rate larger than 5 K h^{-1} . This cooling results from evaporation of falling rain in the sub-cloud layer. This can explain the similar intensity of the model tropical cyclones during this

period (Fig. 2). Wang (2002) suggested that the overall vertical heating profile is not very sensitive to the details of cloud microphysics parameterization while the peak intensity and area coverage in precipitation can be very sensitive. However, the vertical profiles of cloud hydrometeors (i.e., snow and rain) and horizontal distribution of rain bands can be affected by the microphysics. For example, wider rain bands are simulated in CTRL case compared to those using WMRN and HAIL case. This result is similar to other modeling results in simulating tropical convective lines (i.e., McCumber *et al.* 1991; Ferrier *et al.* 1995).

Also note that the case without ice-phase (WMRN) produced lower minimum surface pressure for the total 168 h model integration. The early intensification for warm rain processes only is in good agreement with Willoughby *et al.* (1984). The vertical profiles of cloud hydrometeors (i.e., snow and rain) and horizontal distribution of rain bands can be affected by the microphysics. For example, wider rain bands are simulated using 3ICE with graupel compared to those using warm-rain only and 3ICE with hail.

The experiments, NEVP and NMLT, were aimed to evaluate the effect of downdrafts on both the intensification and intensity of the simulated tropical cyclone. Removing the evaporation of rain in NEVP from WMRN almost removed the downdrafts in the simulated tropical cyclone; thus, both the intensification rate and final intensity of the storm were increased greatly (Fig. 2). Wang (2002) suggest that this may be the reason why some earlier numerical models that did not include the evaporation of rain in the simple warm rain-only parameterizations produced model tropical cyclones that went straight to their local thermodynamic limit (Holland 1997). The model tropical cyclone reached its quasi-steady state in about 3 days with a final intensity close to the minimum pressure intensity determined by the thermodynamic limit calculated by Holland's (1997) approach, which did not include the effect of cooling due to evaporation of rain. The other sensitivity case is NMLT in which the melting of snow and graupel and the evaporation of rain were removed from CTRL. As in NEVP, the downdrafts in NMLT was also significant reduced and the intensification rate and final intensity of the tropical cyclone increased dramatically as NEVP case (Fig. 2). These two experiments suggested

that without the evaporative cooling and melting by snow and graupel, weaker downdrafts were generated and it is not a favorable factor for intensification and wider rain bands.

(c) Yang and Ching (2005)

Yang and Ching (2005) used the Pennsylvania State University – National Center for Atmospheric Research (PSU-NCAR) Mesoscale model (MM5; Dudhia 1993; Grell *et al.* 1995) with two-way interactive nested domains to study the impact microphysical schemes on a real typhoon case (Typhoon Toraji 2001). The nested domains were constructed with grid resolutions of 60, 20 and 6.667 km with corresponding numbers of grid points 65 x 71 x 23, 109 x 109 x 23, and 199 x 163 x 23, respectively. Yang and Ching (2005) conducted five numerical experiments to test the effects of variations in cloud microphysics parameterization on track, and intensity of Typhoon Toraji (2001). These experiments are (1) warm rain scheme (Kessler 1969), (2) the simple scheme (Dudhia 1989), (3) the mixed phase scheme (Resinser *et al.* 1998), (4) the Goddard graupel scheme (Tao and Simpson 1989), and (5) the Schultz scheme (Schultz 1995). A Rankine vortex is applied to improve the representation of Toraji's initial condition/structure.

In all experiments, the minimum sea level pressure (MSLP) is underestimated compared to observation (Fig. 4). Yang and Ching (2005) suggested that this underestimation might be due to imperfectly balanced initial state, coarse grid resolution, and deficiency of model representation of physical processes. Nevertheless, all experiments captured the pressure filling during the landfall period. The results (Fig. 4) also showed that there are differences in the simulated minimum central pressure. Specially, the warm rain processes alone produced the strongest storm as Wang (2002) and Willoughby *et al.* (1984). Yang and Ching (2005) suggested that the reason for lowest pressure in the warm rain case is because all hydrometeors were very large raindrops (as compared to small ice particles and snow flakes in those experiments with ice microphysics), and falling out quickly at and near eye-wall region. This would hydrostatically produce the

lowest pressure. However, the difference in the MSLP is quite small for all experiments with ice processes (Goddard graupel, Resiner *et al.* and Schultz scheme).

Their results also indicated that the simulated track moved slower than observed before landfall in all experiments. But all simulated track were very close to each other. After landfall, all simulated tracks moved faster than the observed after landfall and were quite different from each other (see Table 2). Yang and Ching (2005) also indicated that the Goddard scheme (Tao and Simpson 1993) slightly produced the best track (track error is 38 km compared to 43 to 59 km in other schemes; see Table 2b in Yang and Ching). Note that the similarity in minimum central pressure and track in the first 24 hours in all experiments might be caused by the imposed Rankine vortex at initial time.

(d) Zhu and Zhang (2006b)

Zhu and Zhang (2006b) also used PSU-NCAR MM5 with two-way interactive nested domains to study the effects of various/specific microphysical processes (i.e., evaporation and the melting of large precipitating ice particles) on intensity, precipitation and structure of Hurricane Bonnie (1998). The nested domains were constructed with grid resolutions of 36, 12 and 4 km with corresponding numbers of grid points 180 x 142 x 24, 184 x 202 x 24, and 163 x 163 x 24, respectively. Six sensitivity experiments, (1) the Goddard three-ice with graupel scheme (Tao and Simpson 1993; Control run, or CTL), (2) without evaporation of rain and cloud water (NEVP), (3) without the melting of ice, snow and graupel (NMELT), (4) without graupel phase (two-class ice; NGP), (5) without ice microphysics variables (NICE; warm rain only) and (6) warm rain only but with the addition of latent heat of fusion for phase change above the melting level (NICE2), were conducted. Note these sensitivity tests were based on one specific microphysical scheme (i.e., the Goddard scheme, Tao and Simpson 1993) whereas the sensitivity tests in this study are conducted using a variety of microphysical schemes. The initial condition was enhanced by both rawinsondes and surface observations. In addition, an observed-based vortex is incorporated into model initial condition. Please see Zhu *et al.* (2004) for more information on the procedure in implementing the observed vortex into model initial condition.

Figure 5 showed the time series of simulated minimum sea level pressure (MSLP) from the sensitivity tests. Significant differences were found in intensity from these tests. The cases without evaporation of rain and cloud water (NEVP) and without melting of ice particles (NMELT) produced the strongest hurricane. These results are in good agreement with an idealized case shown in Wang (2002). In both NEVP and NMELT case, updrafts are stronger than the control (CTL) case. Zhu and Zhang (2006b) suggested that the enhanced updrafts in the NEVP and NMELT appear to result from a positive feedback between low-level convergence of relatively warmer and moister air, the latent heating release in the eye wall, and surface pressure. For both NICE and NGP case, weaker hurricane is simulated compared to control case. By adding heating of fusion into NICE (NICE2 case), the simulated storm is about 18 -hPa deeper than the NICE case, and even 8-hPa deeper than the CTL case. This result suggested the added heating release above melting layer has an impact on storm intensity. The results showed that all sensitivity - simulated tracks resembled the observed, except for the NICE case that does not make landfall (Fig. 6). In addition, the results also showed that the variations in cloud microphysics were found to have a significant impact on inner core structure (Figs. 3 and 10 in Zhu and Zhang). Stronger storms tend to show more compact eye-walls with heavier precipitation and more symmetric structures in the warm cored eye and in the eye-wall.

There is a major difference between Zhu and Zhang (2006) and previous modeling studies in warm rain only case [weaker (deep) storm in Zhu and Zhang (Wang; Yang and Ching; Willoughby *et al.*; and Li and Pu 2008 – see next subsection)]. Zhu and Zhang suggested that the difference may be contributed to the different physical processes incorporated in these models, if not to the different (shear) environments in which storm are embedded. They also suggested a model inter-comparison study is needed in order to understand how these differences arise.

(e) Li and Pu (2008)

Li and Pi (2008) used the advanced research version of Weather Research Forecasting [Advanced Research WRF (ARW)] Model (version 2.0) with two-way interactive nested domains to study the effects of microphysics schemes on early rapid intensification of Hurricane Emily (2005). The nested domains were constructed with grid resolutions of 27, 9 and 3 km with corresponding numbers of grid points 190 x 140 x 31, 340 x 270 x 31, and 301 x 271 x 31, respectively. Six sensitivity experiments, (1) Kessler warm-rain (Kessler 1969; KS), (2) Purdue Lin scheme (Lin *et al.* 1983; LIN), (3) WSM three-class simple ice scheme (Hong *et al.* 2004; WSM3), (4) WSM five class mixed phase scheme (Hong *et al.* 2004; WSM5, a two-class ice scheme), (5) WSM six-class mixed phase scheme (Hong and Lin 2006; WSM6, a three-class ice scheme) and (6) Eta Ferrier scheme (Roger *et al.* 2001; FERR, a simple three-class ice scheme), were conducted. The initial condition was enhanced by incorporation of satellite data through WRF three-dimensional variational data assimilation (3DVAR) system. Please see Pu *et al.* (2008) for more information on the data assimilation procedure. A 30-hours model integration is performed.

Figure 7 shows the track forecasts from different sensitivity-experiments and one from National Hurricane Center (NHC) best track. All simulated tracks captured observed west-northwestward movement. Overall, the track forecast, except FERR case, of Hurricane Emily is not very sensitive to the microphysics schemes in this case. For FERR produce the best-track forecast (43 km compared to 62 to 97 km in other cases, see Table 3 in Li and Pu 2008).

The result show that the difference in MSLP between these sensitivity-simulations could be up to 29 hPa (Fig. 8). The result also showed that all sensitivity-simulated intensities are weaker (under-estimated) than observed. In addition, none of simulations captured the real rapid deepening rate during the first 24-h forecast. The microphysical scheme without ice produced the earliest and quickest intensification as well as the strongest hurricane among all the simulated cases. This result is in good agreement with Wang (2002), Yang and Ching (2005) and Willoughby *et al.* (1984). In the warm rain case, much more cloud and raindrops (as well as precipitation – an indication of large raindrops

falling out quickly) are simulated compared to other schemes during whole integration. Also the including of graupel in three-class ice scheme (WSM6 and Purdue-LIN) can produce stronger intensity compared to that of two-class ice scheme (WSM5). This result is consistent with that of Zhu and Zhang (2006). However, WSM6 generated large amount of column integrated cloud ice and graupel than FERR and LIN.

3. Hurricane Katrina (2005)

(a) Model set-up and cases

Hurricane Katrina was among the most significant, costliest, and deadliest storms to ever strike the United States (Knabb *et al.* 2005). It is the sixth most intense Atlantic hurricane on record (fourth at the time of occurrence) with a minimum observed central pressure of 902 hPa (see Knabb *et al.* 2005 for more details). In this numerical study, ARW Model (version 2.1) with two-way interactive nested is used to study the effects of microphysics schemes on track and intensity of Hurricane Emily (2005). Three multiple nested domains were constructed with grid resolutions of 15, 5 and 1.667 km with corresponding numbers of grid points 300 x 200 x 31, 418 x 427 x 31, and 373 x 382 x 31, respectively. The innermost domain moved with the center of the storm. The model was integrated for 72 h from 0000 UTC 27 August to 0000 UTC 30 August 2005. A large inner domain was necessary for the Hurricane Katrina simulations because it was both an intense Category 5 hurricane and a large storm. A moving nested domain was also necessary because Hurricane Katrina moved quickly. Time steps of 30, 10 and 3.333 seconds were used in the nested grids, respectively. The model was initialized from NOAA/NCEP/GFS global analyses (1.0° by 1.0°). Time-varying lateral boundary conditions were provided at 6-h intervals.

The Grell-Devenyi (2002) cumulus parameterization scheme was used for the outer grid (15 km) only. For the inner two domains (5 and 1.667 km), the Grell-Devenyi parameterization scheme was turned off. The Goddard broadband two-stream (upward and downward fluxes) approach was used for the shortwave radiative flux calculations (Chou and Suarez 1999). The longwave scheme was based on Mlawer *et al.* (1997). The

planetary boundary layer parameterization and the surface heat and moisture fluxes (from both ocean and land).

(b) Results

Figures 9 and 10 show the simulated MSLP and track, respectively, from WRF using the six different microphysical schemes/options (Goddard 3ICE-hail, Goddard 3ICE-graupel, Goddard 2ICE, Goddard warm rain only, WSM6, Lin and Thompson). The simulated hurricane is stronger than was observed (i.e., the 48-hour simulated MSLP was too low) in all runs. However, this over-estimate in the intensity forecast after the first 24 hours may have resulted from an inaccurate forecast in the SSTs (or prescribed SSTs). For example, Zhu and Zhang (2006a) showed that simulated hurricane intensity could be weakened by 25 hPa by including storm-induced SST cooling. Simulated MSLP using the Goddard 2ICE configuration (16.92 hPa root mean square error or RMSE) and Thompson scheme (16.88 hPa RMSE) are the closest to the observations (from 24 to 48 hours into the forecast). Note that both of those schemes simulated less (or no) graupel compared to the other schemes⁴. Minimum sea surface pressures from the Goddard 3ICE and WSM6 schemes are quite similar to each other (~19-20 hPa RMSE). The Purdue-Lin scheme, however, results in an MSLP 15-20 hPa lower than the other schemes (32 hPa RMSE). Nevertheless, the simulated temporal variation of MSLP agrees well with observations (i.e., intensification prior to landfall followed by weakening).

The sensitivity tests show no significant difference (or sensitivity) in track among the different microphysical schemes (Fig. 10 and Table 3). The simulated tracks are very similar prior to landfall (the first 48 hours of model integration time). The track error ranges from 76 km (Goddard 2ICE scheme) to 95 km (Thompson scheme). After landfall, the simulated tracks remain closely packed with the storm center propagating to the north-northeast. All the simulations result in landfall farther west than was observed. The exaggerated storm intensities in the model may have affected the storm track (e.g., Fovell and Su 2007). Similar track errors were found in Shen *et al.* (2006), who used a general circulation model to assess the impact of cumulus parameterization on hurricane predictability at 0.125° resolution. Track errors were even larger (3~4 degree) in the

WRF simulations (30 km resolution) by Rosenfeld *et al.* (2007) used to study the impact of sub-micron aerosols via warm rain suppression.

Table 4 gives the relative fraction of liquid (cloud water and rain) and solid (cloud ice, snow and graupel or hail) water contents based on time-domain averages for each scheme. The main differences between the Goddard, Thompson, Purdue-Lin and WSM6 microphysical schemes are in the solid phase of water species at middle and upper levels. Graupel is the dominant ice species in Purdue-Lin and WSM6, while very little cloud ice is simulated by the Thompson scheme. Purdue-Lin and WSM6 produce very little snow (similar results were also found for another hurricane simulated by WRF) and a higher liquid fraction than the other schemes (see Table 4). Purdue-Lin has more than a 15% increase in liquid hydrometeor fraction compared to about 8% on average for the other schemes, suggesting the Purdue-Lin scheme is more sensitive to environmental conditions than the other schemes. The Thompson scheme has a solid ice fraction similar to the Goddard 3ICE-graupel due to a relatively deep layer of high average snow contents. The Goddard 2ICE simulation has the lowest liquid fraction of all the schemes.

The simulations presented in this study have similarities and differences compared to the previous modeling studies. For example, the current simulations, Yang and Ching (2005) and Li and Pu (2008) all show that warm rain only produces the quickest intensification and the strongest hurricanes for the first 24 h of integration. These results are also in agreement with idealized simulations (Wang 2002; Lord *et al.* 1984). The dominant liquid phase in the Purdue-Lin scheme (Table 4) could explain the lower MSLP compared to the other ice schemes. In addition, the current study as well as Yang and Ching (2005), Zhu and Zhang (2006b) and Li and Pu (2008) all show that the simulated track is not sensitive to the ice microphysical scheme. Li and Pu (2008) indicated that the WSM5 (2ICE) scheme produced the weakest intensity compared to other 3ICE schemes. In this study, however, the Purdue-Lin scheme produced the strongest hurricane after 24 hours of integration and was still 20 hPa stronger than the others after 48 hours of integration. Note that all of the ice microphysical schemes produced weak hurricanes compared to the observations in Li and Pu (2008). On the other hand, all of the schemes over-predict

intensity in this study. In addition, wider rain bands are simulated in all cases. The differences could be attributed to differences in model set-up (i.e., grid size, initialization) and/or cases and hurricane embedded environment.

4. Summary

The Goddard one-moment bulk liquid-ice microphysical scheme with four different options was implemented into WRF. The options are the warm rain only, 2ICE (cloud ice and snow), 3ICE-graupel (cloud ice, snow and graupel) and 3ICE-hail (cloud ice, snow and hail) configuration. These microphysical options also include rain processes with two classes of liquid phase (cloud water and rain). The Goddard bulk scheme also includes three different options for saturation adjustment. The Goddard bulk scheme's performance was tested and compared with three other WRF one-moment bulk microphysical schemes (i.e., Purdue-Lin, WSM6 and Thompson) for an Atlantic hurricane case. The present model results also compared with those previous modeling results for studying the impact of microphysics on track and intensity of hurricane. The major highlights are as follows:

- The microphysical schemes did not have a major impact on hurricane track; however, they did affect the MSLP noticeably for Katrina case. The simulated hurricanes were consistently stronger than was observed in all of the WRF runs regardless of the microphysical schemes. Nevertheless, the simulated temporal variation (intensification rate) of MSLP agreed well with observations (i.e., intensification prior to landfall followed by weakening). The simulated hurricane is strongest prior to landfall and starts to weaken after landfall, which is in good agreement with observations. Other previous model studies also found that the microphysics schemes did not have major impact on track forecast, but did have more affect on the intensity.
- The Purdue-Lin scheme resulted in an MSLP for the Katrina case that was 15-20 hPa lower than the other five schemes. One characteristic of the Purdue-Lin and WSM6 schemes is that both simulated much less snow and more rain than the other schemes for the hurricane case.

- Both Wang (2002) and Zhu and Zhang (2006b) suggested that the simulated hurricane becomes unrealistic strong by removing the evaporative cooling of cloud droplets and melting of ice particles. This is due to much weaker downdraft is simulated.
- All results (except Zhu and Zhang, 2006b) indicated the rapid deepening and/or intensification of hurricane for the warm rain only case. It is because all hydrometeors were very large raindrops, and falling out quickly at and near eye-wall region. This would hydrostatically produce the lowest pressure.
- The results also showed that the variations in cloud microphysics were found to have a significant impact on inner core structure. Stronger storms tend to show more compact eye-walls with heavier precipitation and more symmetric structures in the warm cored eye and in the eye-wall.
- The vertical profiles of cloud hydrometeors (i.e., snow and rain) and horizontal distribution of rain bands can be affected by the microphysics. For example, wider rain bands are simulated in three-class ice case with graupel compared to those using warm rain only, three-class ice with hail or two-class ice case (Wang 2002; Zhu and Zhang 2006b).
- The model inter-comparison study is needed in order to understand how these differences arise. We would suggest that a major computing center in Asian country could be in charge by collecting models as well as microphysics schemes to conducting comprehensive comparison studies.

The sensitivity Goddard microphysical scheme was only tested for one case comparisons with observations only focused on track and intensity. Additional case studies to address microphysical processes, including more comprehensive microphysical sensitivity testing (e.g., turning off certain conversion processes from one cloud species to another and testing more cases as Wang 2002 and Zhu and Zhang 2006), will be considered in future research. Finally, further sensitivity tests with the improved WSM6 scheme by Dudhia *et al.* (2008) as well as other microphysical schemes (i.e., Morrison *et al.* 2005; Li *et al.* 2009) are needed.

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APPENDIX

Description of the Improved Goddard Microphysical Scheme

(a) Saturation adjustment

When supersaturated conditions are brought about, condensation or deposition is required to remove any surplus of water vapor. Likewise, evaporation or sublimation is required to balance any vapor deficit when sub-saturated conditions are made to occur in the presence of cloud. As the saturation vapor pressure is a function of temperature, and the latent heat released due to condensation, evaporation, deposition, and sublimation modifies the temperature, one approach has been to solve for the saturation adjustment iteratively. Soong and Ogura (1973), however, put forth a method that did not require iteration but for the water-phase only.

Tao *et al.* (1989) adopted the approach of Soong and Ogura (1973) and modified it to include the ice-phase. For temperatures over T_0 (0 °C), the saturation vapor mixing ratio is the saturation value over liquid water. For temperatures below T_{00} , which typically ranges from -30 to -40 °C (-35 °C is used in this paper), the saturation vapor mixing ratio is the saturation value over ice. The saturation water vapor mixing ratio between the temperature range of T_0 and T_{00} is taken to be a mass-weighted combination of water and ice saturation values depending on the amounts of cloud water and cloud ice present. Condensation/deposition or evaporation/sublimation then occurs in proportion to the temperature. Another approach is based on a method put forth by Lord *et al.* (1984), which weights the saturation vapor mixing ratio according to temperature between 0C and T_{00} . Condensation/deposition or evaporation/sublimation is then still proportional to temperature. One other technique treats condensation and deposition or evaporation and sublimation sequentially. Saturation adjustment with respect to water is allowed first for a specified range of temperatures followed by an adjustment with respect to ice over a specified range of temperatures. The temperature is allowed to change after the water phase before the ice phase is treated. Please refer to Tao *et al.* (2003a) for the performance of these three different adjustment schemes. All three approaches are

available in the Goddard microphysical schemes. In this paper, the last technique (sequential method) is selected.

These adjustment schemes will almost guarantee that the cloudy region (defined as the area which contains cloud water and/or cloud ice) is always saturated (100% relative humidity). This permits sub-saturated downdrafts with rain and hail/graupel particles but not cloud-sized particles. This feature is similar in many other microphysical schemes that apply saturation adjustment.

(b) Conversion of cloud particles to precipitation-sized ice

Lang *et al.* (2007) have simulated two types of convective cloud systems that formed in two distinctly different environments observed during the Tropical Rainfall Measuring Mission Large-Scale Biosphere–Atmosphere (TRMM LBA) experiment in Brazil. Model results showed that eliminating the dry growth of graupel in the Goddard 3ICE bulk microphysics scheme effectively reduced the unrealistic presence of high-density ice in the simulated anvil. However, comparisons with radar reflectivity data using contoured-frequency-with-altitude diagrams (CFADs, see Yuter and Houze 1995) revealed that the resulting snow contents were too large. The excessive snow was reduced primarily by lowering the collection efficiency of cloud water by snow and resulted in further agreement with the radar observations (see Fig. 7 in Lang *et al.* 2007). The transfer of cloud-sized particles to precipitation-sized ice appears to be too efficient in the original scheme. Overall, these changes to the microphysics lead to more realistic precipitation ice contents in the model. The improved precipitation-sized ice signature in the model simulations lead to better latent heating retrievals as a result of both better convective-stratiform separation within the model as well as more physically realistic hydrometeor structures for radiance calculations. However, there appeared to be additional room for improvement in that simulated brightness temperatures showed that there was still too much precipitation-sized ice aloft. This indicates that despite the improvement, the overall transfer rate of cloud-sized particles to precipitation-sized particles was still too efficient. Lang *et al.* (2007) felt that the Bergeron process could be a contributing factor.

(c) *The Bergeron process*

An important process in the budget for cloud ice is the conversion of cloud ice to snow as the ice crystals grow by vapor deposition in the presence of cloud water, usually referred to as the Bergeron process and designated PSFI (production of snow from ice) by Lin *et al.* (1983). The formulation generally used in the parameterization is independent of relative humidity, which causes ice to be converted to snow even when the air is sub-saturated with respect to ice. One alternative formulation is to simply multiply the original formula by a relative-humidity dependent factor so that PSFI diminishes as the relative humidity approaches the ice saturation value. A second alternative formulation can be derived directly from the equation for depositional growth of cloud ice (Rutledge and Hobbs 1984) used in the model. This formulation also causes PSFI to diminish as the relative humidity approaches the ice saturation value and is physically consistent with the parameterization for depositional growth of cloud ice. The two alternative formulations produce relatively similar results since simulated ice clouds over tropical oceans often have vapor mixing ratios near the ice saturation value so that PSFI is very small. The new formulation for PSFI based on the simple relative-humidity correction factor was adopted and results in an increase in cloud-top height and a substantial increase in the cloud ice mixing ratios, particularly at upper levels in the cloud.

Table A1 shows the list of microphysical processes that parameterize the transfer between water vapor, cloud water, rain, cloud ice, snow and graupel/hail in the Goddard scheme implemented into WRF. The formula in each process can be found in Lin *et al.* (1983), Rutledge and Hobbs (1984), Tao and Simpson (1993), Tao *et al.* (2003a), and Lang *et al.* (2007).

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Table Captions

Table 1 Key papers using high-resolution numerical cloud models (including those that developed new improved microphysical schemes) to study the impact of microphysical schemes on precipitation. Model type (2D or 3D), microphysical scheme (one moment or multi-moment bulk), resolution (km), number of vertical layers, time step (seconds), case and integration time (hours) are all listed. Papers with a “*” are used for comparison with the present study, papers with a “#” denote development of a new scheme, papers with a “\$” modify/improve existing schemes, papers with a “&” compare different schemes, and papers with a “%” indicate process (budget) studies. TCM3 stands for the “Tropical Cyclone Model with triple nested movable mesh”. Also only papers with bulk schemes are listed. MM5 stands for the Penn State/NCAR Mesoscale Model Version 5.

Table 2 Simulated track error (in km) of the microphysics parameterization experiments. Note that the simulated landfall is around 24 h after model integration.

Table 3 Simulated track error (in degree) of the microphysics parameterization experiments.

Table 4 Domain- and 72-h time-average accumulated liquid (warm rain) and solid (ice) water species for the Hurricane Katrina case.

	<i>Model</i>	<i>Microphysics</i>	<i>Resolutions Vertical Layers</i>	<i>Integration Time</i>	<i>Case</i>
Lin <i>et al.</i> (1983)	2D	3-ICE	200 m/95	48 min	Hail Event Montana
Cotton <i>et al.</i> (1982, 1986)	2D	3-ICE & Ni	500 m/31	5 hours	Orographic Snow
Rutledge and Hobbs (1984)	2D Kinematics	3-ICE	600 m/20	Steady State	Narrow Cold Front
Lord <i>et al.</i> (1984) *	2D axisymmetric	3-ICE vs Warm Rain	2 km/20	4.5 days	Idealized
Yoshizaki (1986)#	2D slab-symmetric	3-ICE scheme vs Warm Rain	0.5 km/32	4.5 hours	12 September GATE Squall Line
Nicholls (1987)	2D slab-symmetric	3-ICE vs Warm Rain	0.5 km/25	5 hours	12 September GATE Squall Line
Fovell and Ogura (1988)#%	2D slab-symmetric	3-ICE vs Warm Rain	1 km/31	10 hours	Mid-latitude Squall Line
Tao and Simpson (1989, 1993)#	2D and 3D	3-ICE vs Warm Rain	1 km/31	12 hours	GATE Squall Line
Tao <i>et al.</i> (1990)	2D	3-ICE	1 km/31	12 hours	GATE Squall Line
McCumber <i>et al.</i> (1991)%\$	2D and 3D	3-ICE scheme (graupel vs hail, 2ICE vs 3ICE)	1 km/31	12 hours	GATE Squall Line
Wu <i>et al.</i> (1999)	2D slab-symmetric	2 ICE	3 km/52	39 days	TOGA COARE
Ferrier (1994), Ferrier <i>et al.</i> (1995)#	2D slab-symmetric	2-moment 4-ICE	1 km/31	12 hours	COHMEX, GATE Squall Line
Tao <i>et al.</i> (1995)	2D slab-symmetric	3-ICE	0.75 and 1 km/31	12 hours	EMEX, PRESTORM
Walko <i>et al.</i> (1995)#	2D	4-ICE	0.3 km/80	30 min	Idealized
Meyers <i>et al.</i> (1997)#\$	2D	2-moment 4-ICE	0.5 km/80	30 min	Idealized
Straka and Mansell (2005)#	3D	10-ICE	0.5 km/30?	~2 hours	Idealized
Lang <i>et al.</i> (2007)\$	3D	3-ICE	.25 to 1km /41	8 hours	LBA
Zeng <i>et al.</i> (2008)\$	2D and 3D	3-ICE	1 km/41	40 days	SCSMEX, KWJEX
Milbrandt and Yau (2005)#	1D	Three-moment	/51	50 minutes	Idealized Hail Storm
Morrison <i>et al.</i> (2005)#	Single column model	Two moments and 2-ICE	Single column model 27 layers	3 days	SHEBA FIRE-FACE
Morrison and Grabowski (2008)#	2D	Two-moment ICE	50 m/60	90 minutes	Idealized
Reisner <i>et al.</i> (1998)#	MM5 Non-hydrostatic	3-ICE and 2-moment for ICE	2.2 km/27	6 hours (2.2 km grid)	Winter Storms
Thompson <i>et al.</i> (2004)#	MM5 2D	3-ICE	10 km/39	3 hours	Idealized
Thompson <i>et al.</i> (2008)\$	WRF 2D	3-ICE	10 km/39	6 hours	Idealized
Colle and Mass (2000)	MM5 Non-hydrostatic	3-ICE	1.33 km/38	96 hours	Orographic Flooding
Colle and Zeng (2004)%	2-D MM5 Non-hydrostatic	3-ICE	1.33 km/39	12 hours	Orographic
Colle <i>et al.</i> (2005)%	MM5 Non-hydrostatic	3-ICE	1.33 km/320	36 hours	IMPROVE
Yang and Ching (2005)*	MM5 Non-hydrostatic	3-ICE	6.67 km/23	2.5 days	Typhoon Toraji (2001)
Zhu and Zhang (2006b)*	MM5 Non-hydrostatic	3-ICE	4 km/24	5 days	Bonnie (1998)
Wang (2002)*	TCM3-hydrostatic	3-ICE	5 km/21	5 days	Idealized
Hong <i>et al.</i> (2004)#	WRF Non-hydrostatic	3-ICE	45 km/23	48 hours	Korean Heavy Rainfall event
Li and Pu (2008)*	WRF Non-hydrostatic	2-ICE and 3-ICE	3 km/31	1.25 days	Hurricane Emily (2005)
Jankov <i>et al.</i> (2005; 2007)*	WRF Non-hydrostatic	2-ICE and 3ICE	12 km/31	1 day	IHOP
Dudhia <i>et al.</i> (2008)***	WRF Non-hydrostatic	3-ICE	5 km/31	1.5 days	Korean Heavy Snow event
Tao <i>et al.</i> (2009) – Present study	WRF Non-hydrostatic	2-ICE and 3ICE	1 km/31 1.667 km/31	1.5 days 3 days	IHOP and Hurricane Katrina (2005)

Table 1 Key papers using high-resolution numerical cloud models (including those that developed new improved microphysical schemes) to study the impact of microphysical schemes on precipitation. Model type (2D or 3D), microphysical scheme (one moment or multi-moment bulk), resolution (km), number of vertical layers, time step (seconds), case and integration time (hours) are all listed. Papers with a “*” are used for comparison with the present study, papers with a “#” denote development of a new scheme, papers with a “\$” modify/improve existing schemes, papers with a “&” compare different schemes, and papers with a “%” indicate process (budget) studies. TCM3 stands for the “Tropical Cyclone Model with triple nested

movable mesh". Also only papers with bulk schemes are listed. MM5 stands for the Penn State/NCAR Mesoscale Model Version 5.

Time (hr)	6	12	18	24	30	36	42	48	54	60	Ave
WR	56	49	62	65	64	15	54	72	72	76	59
ICE	58	65	52	48	42	91	53	32	41	44	53
MP	63	61	50	57	60	41	64	25	38	8	43
GG	59	56	50	47	23	54	2	25	38	26	38
SCH	52	45	47	52	68	33	22	36	68	44	47

Table 2 Simulated track error (in km) of the microphysics parameterization experiments. Note that the simulated landfall is around 24 h after model integration.

	RMS	ME
3ICE with graupel	1.16	1.02
3ICE with hail	1.25	1.09
2ICE	1.07	0.93
Purdue - Lin	1.27	1.10
WSM6	1.17	1.01
Thompson	1.20	1.06

Table 3 Simulated track error (in degree) of the microphysics parameterization experiments.

	3ICE-Hail	3ICE-Graupel	2ICE	WSM6	Lin	Thompson
Liquid hydrometeor	46.6%	36.4%	24.8%	50.4%	65.3%	34.2%
Solid Hydrometeor	53.4%	63.6%	75.2%	49.6%	34.7%	65.8%

Table 4 Domain- and 72-h time-average accumulated liquid (warm rain) and solid (ice) water species for the Hurricane Katrina case.

Figure Captions

- Fig. 1 Time series of minimum surface level pressure (MSLP) and maximum tangential winds at 3.1 km in water (W) and ice (I) models.
- Fig. 2 Time series of (a) the maximum wind speed (m s^{-1}) at the lowest model level (about 25 m from the sea surface) and (b) the minimum central sea surface pressure (hPa) in the sensitivity tests of microphysics. The horizontal line shows the MPI at the given sea surface temperature and the environmental sounding used as the initial conditions in all the numerical experiments calculated by the method of Holland (1997). Note that DSHT is the same as CTRL but it includes the dissipative heating and this case was not presented in Wang (2002).
- Fig. 3 Vertical profiles of 6-hourly mean (between 126 and 132 h) condensational heating rate in CTRL, WMRN, and HAIL: (a) azimuthally averaged between 15- and 35-km radii and (b) azimuthally averaged within a radius of 100 km from the cyclone center
- Fig. 4 Time series of observed and simulated minimum central pressure (in hPa). CWB is for observed based on JTWC observation. WR is for warm rain scheme (Kessler 1969), ICE is for simple ice (Dudhia 1989), MP is for mixed phase scheme (Resinser *et al.* 1998), GG is for Goddard Graupel scheme (Tao and Simpson 1989), and SCH is for Schultz 1995).
- Fig. 5 Three-hourly time series of the minimum central pressure (P_{\min} , hPa) for all the model simulations.
- Fig. 6 Six-hourly tracks of Hurricane Bonnie from the best analyses (thick solid) and the model simulations.

- Fig. 7 Forecasts of the hurricane track from model simulations during 0600 UTC 14 Jul–1200 UTC 15 Jul 2005, compared with the National Hurricane Center best-track data. Center locations along the tracks are indicated every 6 h.
- Fig. 8 Time series of MSLP (hPa) from the National Hurricane Center best-track data and the numerical simulations during 0600 UTC 14 Jul–1200 UTC 15 Jul 2005.
- Fig. 9 Minimum sea level pressure (hPa) obtained from WRF forecasts of Hurricane Katrina using six different microphysical schemes: Thompson, Purdue-Lin, WSM6, 3ICE-graupel, 3ICE-hail and 2ICE from 0000 UTC 27 August to 0000 UTC 30 August 2005. The observed minimum sea level pressure (solid black line) is also shown for comparison.
- Fig. 10 The corresponding hurricane tracks for the data shown in Fig. 9. The best track is shown in black for comparison and was obtained from the National Hurricane Center.

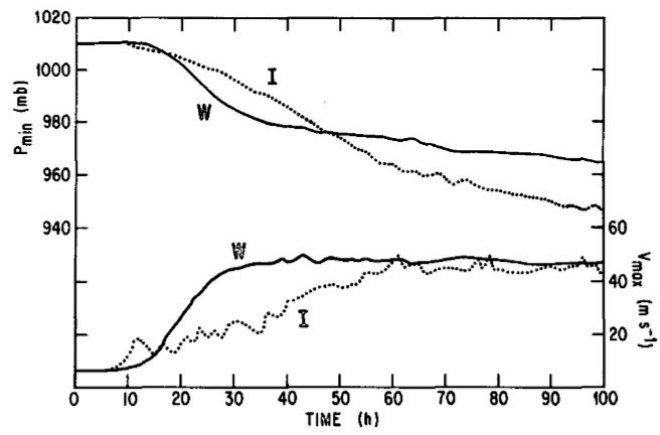


Fig. 1 Time series of minimum surface pressure and maximum tangential winds at 3.1 km in water (W) and ice (I) models.

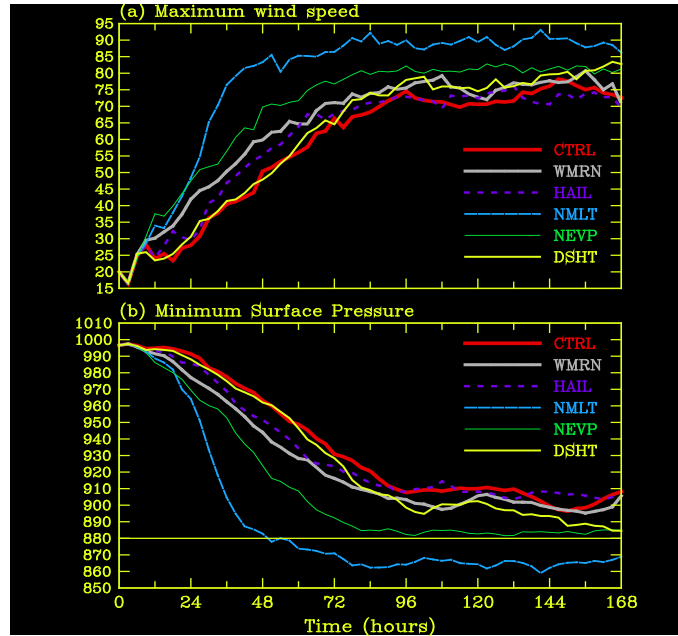


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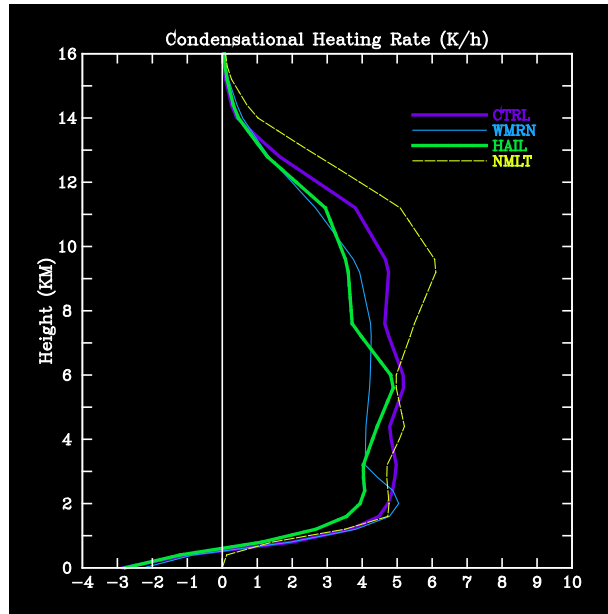


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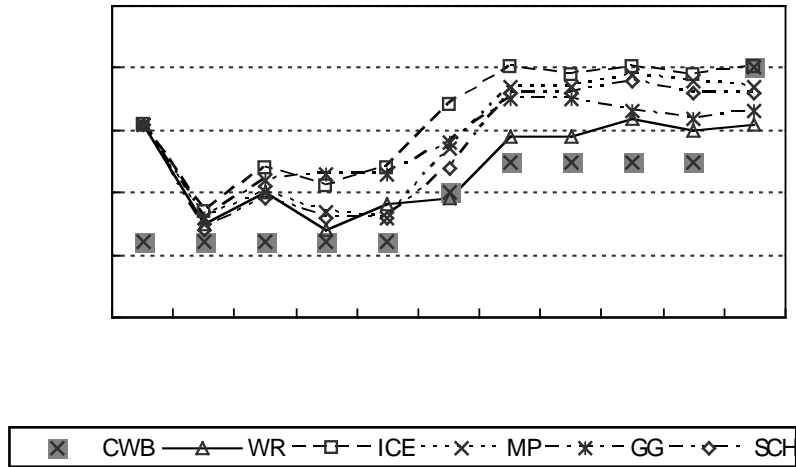


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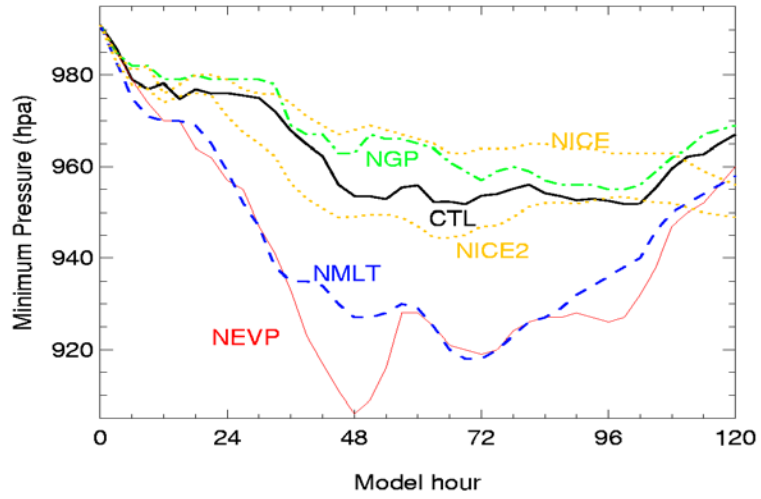


Fig. 5 Three-hourly time series of the minimum central pressure (P_{\min} , hPa) for all the model simulations.

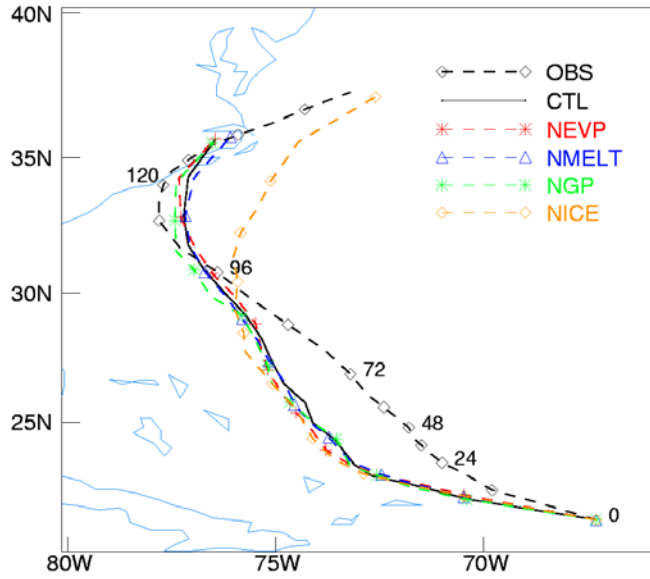


Fig. 6 Six-hourly tracks of Hurricane Bonnie from the best analyses (thick solid) and the model simulations.

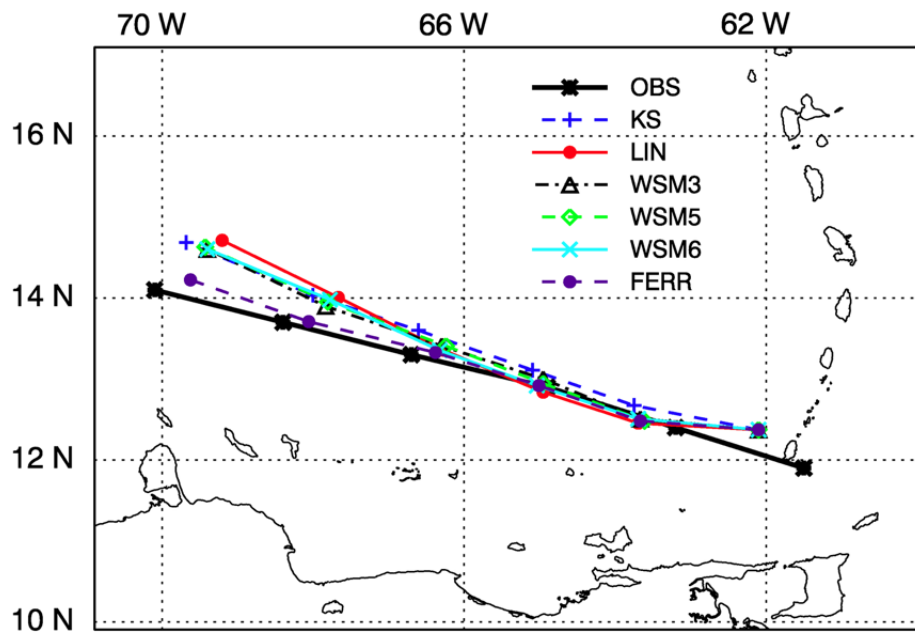


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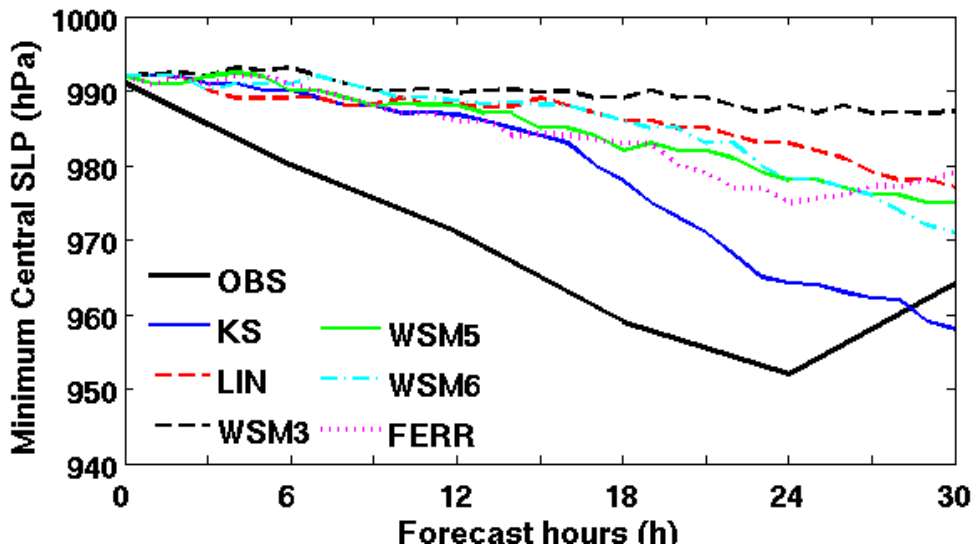


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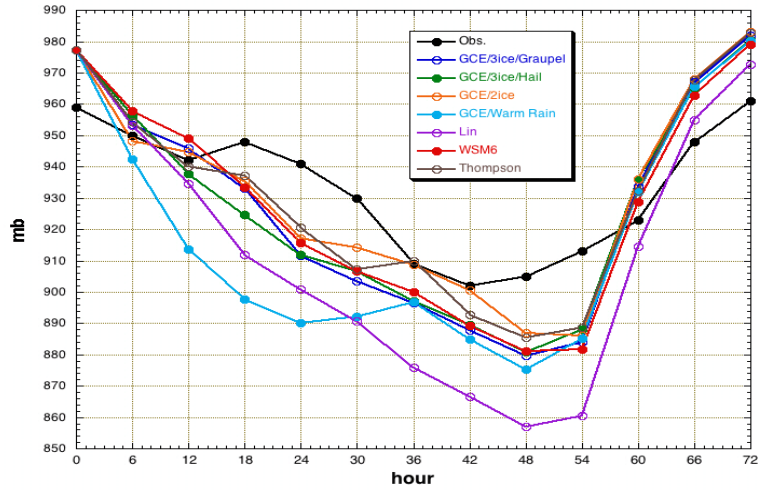


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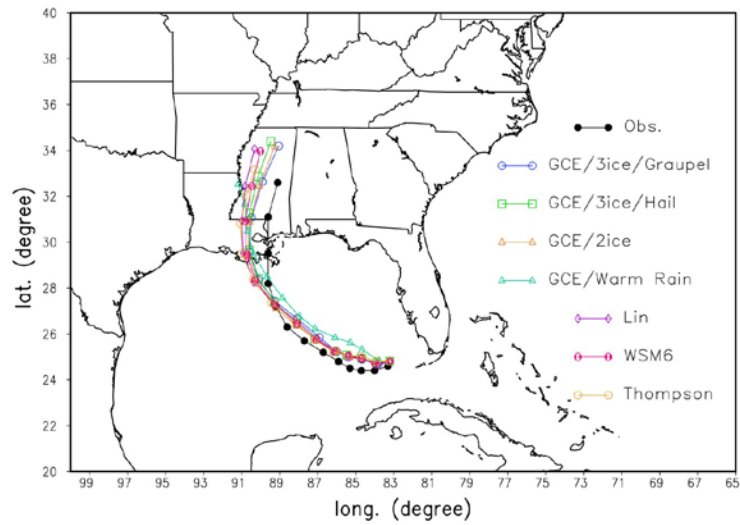


Fig. 10 The corresponding hurricane tracks for the data shown in Fig. 9. The best track is shown in black for comparison and was obtained from the National Hurricane Center.

The Impact of Microphysical Schemes on Intensity and Track of Hurricane

W.-K. Tao, J. Shi, S. S. Chen, S. Lang, P.-L. Lin, S.-Y. Hong, C. Peters-Lidard, and A. Hou,

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Popular Summary

During the past decade, both research and operational numerical weather prediction models [e.g. Weather Research and Forecasting Model (WRF)] have started using more complex microphysical schemes originally developed for high-resolution cloud resolving models (CRMs) with a 1-2 km or less horizontal resolutions. The WRF is a next-generation meso-scale forecast model and assimilation system that has incorporated a modern software framework, advanced dynamics, numeric and data assimilation techniques, a multiple moveable nesting capability, and improved physical packages. The WRF model can be used for a wide range of applications, from idealized research to operational forecasting, with an emphasis on horizontal grid sizes in the range of 1-10 km. The current WRF includes several different microphysics options.

At Goddard, four different cloud microphysics schemes (warm rain only, two-class of ice, two three-class of ice with either graupel or hail) are implemented into the WRF. The performances of these schemes have been compared to those from other WRF microphysics scheme options for an Atlantic hurricane case. In addition, a brief review and comparison on the previous modeling studies on the impact of microphysics schemes and microphysical processes on intensity and track of hurricane will be presented. Generally, almost all modeling studies found that the microphysics schemes did not have major impacts on track forecast, but did have more effect on the intensity. All modeling studies found that the simulated hurricane has rapid deepening and/or intensification for the warm rain-only case. It is because all hydrometeors were very large raindrops, and they fell out quickly at and near the eye-wall region. This would hydrostatically produce the lowest pressure. In addition, these modeling studies suggested that the simulated hurricane becomes unrealistically strong by removing the evaporative cooling of cloud droplets and melting of ice particles. This is due to the much weaker downdraft simulated. However, there are many differences between different modeling studies and these differences were identified and discussed.