# Evaluation and Improvements of Cloud and Precipitation Physics in the Operational Hurricane WRF Model at NOAA/EMC

US Weather Research Program/Joint Hurricane Testbed

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## OVERALL GOAL

The overall goal of this project is to evaluate and improve the cloud and precipitation physics used in the operational Hurricane Weather Research and Forecast (HWRF) model developed in the Environmental Modeling Center (EMC) at the National Centers for Environmental Prediction (NCEP) of NOAA, achieving improved prediction of hurricane structure and intensity, including the size, by the HWRF model at NCEP/EMC.

## SPECIFIC OBJECTIVES

We will first evaluate and identify possible discrepancies in the current cloud and precipitation physics used in the HWRF model and understand how these discrepancies may affect the hurricane structure and intensity. This will be done by implementing the current schemes into the hurricane model TCM4 developed by the PI and conduct sensitivity experiments that are designed with both real cases and idealized simulations. The focus is given to both grid-scale moist processes and subgrid scale convective processes in the HWRF model. Both are critical to the realistic representation of three-dimensional (3D) diabatic heating, which is believed to be the key to both the structure and intensity of hurricanes. We will then closely work with the members of the HWRF model development team at NCEP/EMC to improve the relevant aspects of the cloud and precipitation scheme used in the HWRF model at NCEP/EMC. The following four specific objectives will be achieved:

- To diagnose the discrepancies of the current cloud and precipitation physics and the interaction between grid-scale moist processes and subgrid-scale convection in the HWRF model and to understand how they affect hurricane intensity and structure, including size;

- To improve the representation of the cloud and precipitation physics in the HWRF model based on the PI and co-I's previously results and evaluate the performance of the modified schemes through model inter-comparison between the HWRF model and TCM4;

- To test and tune the modified schemes in the experimental prediction mode and to evaluate their overall improvements in predicting hurricane structure and intensity using the HWRF model hindcasts for the cases in the 2010 hurricane season;

- To document the modified schemes with both technical and scientific details and to provide training to the members of the HWRF model development team at NCEP/EMC.

## APPROACH

The approach to achieve our goal is to conduct numerical experiments using the HWRF model, the hurricane model–TCM4, and the single-column parcel model–SCPM with bulk and spectral microphysics schemes. The SCPM will be used to create a multi-dimensional lookup table for the supersaturation as a function of vertical velocity and other model parameters, refining the bulk scheme to be used operationally, and will be embedded in the convection scheme. The TCM4 will be used to diagnose the discrepancies of the current schemes used in the HWRF model in simulating hurricane intensity and size changes. We will implement the current cloud and precipitation schemes used in the HWRF model into TCM4 and perform a suite of idealized numerical experiments to help isolate the effects of individual processes and understand their combined impacts. In this regard, TCM4 can be regarded as a diagnostic tool to help identify the key physical processes. Based on the inter-model evaluation, we will modify the current relevant modules in the HWRF model or replace them with more advanced/improved schemes to better represent the cloud and precipitation physics in the HWRF model and to achieve improved prediction of hurricane intensity and structure at NCEP/EMC.

## WORKS COMPLETED

*We completed the following tasks during the period 08/01/2009-07/31/2010:*

1. *To have diagnosed the discrepancies of the current cloud microphysics physics;*
2. *To have examined the interaction between grid-scale moist processes and subgrid-scale convection in the HWRF model to understand how they affect hurricane intensity and structure, including size;*
3. *To have analyzed the potential discrepancies of the current dynamical core of the HWRF model and the improvements of precipitation physics in HWRF;*
4. *To have developed and tested the single column parcel model (SCPM).*

*We have completed the following tasks during this reporting period (08/01/2010-01/31/2011):*

5. *To have examined the potential effect of the initial vortex size on the subsequent size change in the model prediction;*

6. *To have revealed the importance of the initial radial tangential wind profile to the size change in hurricane models;*

7. *To have started to look at and diagnose/evaluate the new physics parameterization schemes in the HWRF model;*

8. *To have set up a real-time forecast system for the eastern Pacific locally in the University of Hawaii using the HWRF model so that more case studies and real-time forecasts will be performed to systematically evaluate the model discrepancies.*

### First project year (08/01/2009-07/31/2010)

As the first step, we have implemented the current cloud microphysics scheme and convective parameterization scheme used in the HWRF model into TCM4 and conducted sensitivity experiments to identify those aspects that considerably affect the spatial distribution of diabatic heating and thus on the model hurricane structure and intensity, including the storm size. The 3D distribution of diabatic heating from both subgrid cumulus convection and grid-scale moist processes are the key to the hurricane structure and intensity. We have compared the structure, intensity, and diabatic heating of the HWRF model cloud microphysics scheme with that used in TCM4. We have examined the possible effect of cumulus convective parameterization scheme in coarse model domains on the fine-resolution explicit simulations of hurricanes in TCM4. These comparisons have helped us identify the potential discrepancies of the current cloud and precipitation physics used in the HWRF model and elucidate the physical mechanisms and also provide the basis for our improvements of the HWRF cloud and precipitation physics in the coming project year.

We have also extended our diagnostics of cloud and precipitation physics to examine the possible discrepancies in the dynamical core of the HWRF model in comparison with the simulation using the WRF_ARW dynamical core with the same model physics options. It is our purpose to see whether biases in the prediction of hurricane size and intensity by HWRF are related to the dynamical core. Hurricane Katrina (2005) was selected in this comparison. Our results show that in terms of storm intensity prediction by HWRF, two aspects need to be addressed: why the initial surface wind speed and the intensity of the storm are weak and why the simulated maximum surface wind intensified much slower than the central surface pressure deepened. Although the NMM dynamical core simulated weaker hurricane intensity, it simulated the track considerably better in terms of the landfall timing and location than the ARW dynamical core for the Hurricane Katrina case. This indicates that the NMM dynamical core might capture the evolution of the large-scale environmental flow, which is the key to the accurate prediction of storm motion. However, the storm intensity is largely controlled by the inner core dynamics, which was not well represented by the numerical scheme in the NMM dynamical core and needs to be improved. The difference in the vertical structure of the simulated storm suggests that some discrepancies between the simulations with different dynamical core might be related to the difference in the vertical descretization. We also found that the dynamical core may affect the cloud microphysics to some degree. This has never been recognized. Therefore, a systematic diagnostics of the dynamical core of the NMM is required in order to improve the prediction of storm intensity and structure by HWRF.

In accordance with the work-plan of the project, during Year 1 we have also developed and tested a single-column parcel model (SCPM). The SCPM represents how the supersaturation is maintained close to water saturation by an approximate balance between the adaibatic cooling from ascent and condensation, in this mixed-phase region, while the liquid fraction is close to unity. This SCPM will have two roles for improving forecasts with the HWRF model in the second project year: (1) to provide improved parameterization of supersaturation and other microphysical quantities (e.g. liquid fraction) assumed to treat the grid-resolved clouds; (2) to embed the SCPM inside the deep convection parameterization, providing better estimates of convective heating aloft and detrainment of condensate mass.

<u>This reporting period (08/01/2010-01/31/2011)</u>

In the period, we have tried to understand what factors and physical processes that control the size change in hurricane models. This is the key to the evaluation of model cloud and precipitation physics. Without this knowledge, it is hard to place our efforts to improve the model physics. According the efforts we made in the first project year, we suspect that the initial vortex structure is the potential candidate that results in the subsequent rapid size increase in the current HWRF model. Therefore, we have done a systematic evaluation on this issue based both HWRF and TCM4. We first examined how the initial size (here we refer to size as the initial radius of maximum wind-RMW) of the model storm may affect the subsequent size change in the models. We found that the big storm (with large initial RMW) grew continuously during the model integration while the small storm (with small initial RMW) could maintain its small size. This indicates that the initial vortex in the HWRF might be too big at the initial time. In addition, the model resolution at 9 km might be a reason too since at this resolution the model could not resolve the observed RMW. As a result, higher resolution may be needed in order to improve the size prediction by the HWRF model.

Similar to the initial size of the model vortex, we found a crucial impact of the radial wind profile at the initial time on the predicted evolution of hurricane size in the models. It is found that even though the storms have the same initial RMW, those with broad radial wind profile would grow much faster than the narrow vortices that have a rapid decaying profile of tangential wind with radius at the initial time. This is mainly due to the existence of vorticity skirt for the slow decaying wind profiles, which have large inertial stability outside the eyewall, preventing the contraction of the RMW at the early stage of model integration. At later stage, the broad profile favors large surface flux and formation of outside rainbands and diabatic heating outside the eyewall. This leads to a considerable increase in storm size in the prediction. We examined the initial structure of hurricanes in HWRF and found that this is the most likely the candidate for the size increase in the current HWRF, indicating a need to improve the representation of the initial vortex structure in the operational HWRF model.

Since the new version 3.2 of the HWRF model will be released in April 2011, we have already worked on the new physics in the next version HWRF model. We have implemented the new GFS cumulus parameterization scheme into TCM4 and started to perform some initial test runs with both TCM4 and HWRF model. The PI is a member of the WRF model development team and also implemented a modified Tiedtke cumulus parameterization scheme into the whole WRF model system. This provides an opportunity to intercompare different cumulus parameterization schemes in the HWRF model version 3.2. We indeed have helped identify some bugs in the WRF system that will be released in April 2011.

To achieve our goal and have close monitoring on the model performance, we have implemented the HWRF model in a real-time forecast mode early this year. This will be a testbed for our planned improvements to the model physics in the rest of the project year. This is a milestone for this project and for follow-up possible JHT projects. We hope that some moderate bridge funds could be provided to allow us to continue our effort toward improved prediction of hurricane structure and intensity changes by the HWRF model forecasting system.

## HIGHLIGHTS OF RESULTS

To diagnose the discrepancies of the current cloud microphysics and the interaction between grid-scale moist processed and subgrid-scale convection in the HWRF model and to understand how they affect hurricane intensity and structure, we have implemented both HWRF cloud microphysics scheme and the simplified Arakawa-Schubert (SAS) cumulus convective parameterization scheme into the hurricane model TCM4 and conducted a series of numerical experiments. We have also examined the potential discrepancies in the dynamical core and the potential sensitivity of the predicted hurricane size to the initial size and structure of the model storms. We have already set up a real-time forecast system for the eastern Pacific hurricanes using the HWRF model. Here we will highlight some of our results and their implications for the rest of our project year. To have a tracking record, we kept the highlights reported in the first project year below. The highlights for the results obtained during this reporting period are given in the second half of this section.

## First project year (08/01/2009-07/31/2010)

### *a. Comparison of the Ferrier scheme in HWRF with the TCM4 mixed-phase scheme*

Currently TCM4 uses a bulk mixed-phase cloud microphysics scheme. It predicts mixing ratios of water vapor, cloud water, rainwater, cloud ice, snow and graupel, with thirty six microphysics processes. The HWRF model uses the Ferrier microphysics scheme, which considers four hydrometeors, namely, suspended cloud liquid droplets, rain, large ice, and small ice. It only calculates the horizontal and vertical advections of the total condensate, namely, the sum of all four hydrometeors and thus the scheme is relatively more economical in computation. The components of hydrometeors are then diagnosed based on some semi-empirical formulations. We have performed two idealized simulations using the two schemes in TCM4. The experimental design follows Wang (2007) except for 32 vertical levels and relatively larger nested meshes and finer finest mesh resolution (2 km) are used in this project. This aims at to see whether the HWRF cloud microphysics may result in any unexpected systematic difference from more sophisticated bulk cloud microphysics scheme, such as the mixed phase cloud microphysics scheme used in TCM4.

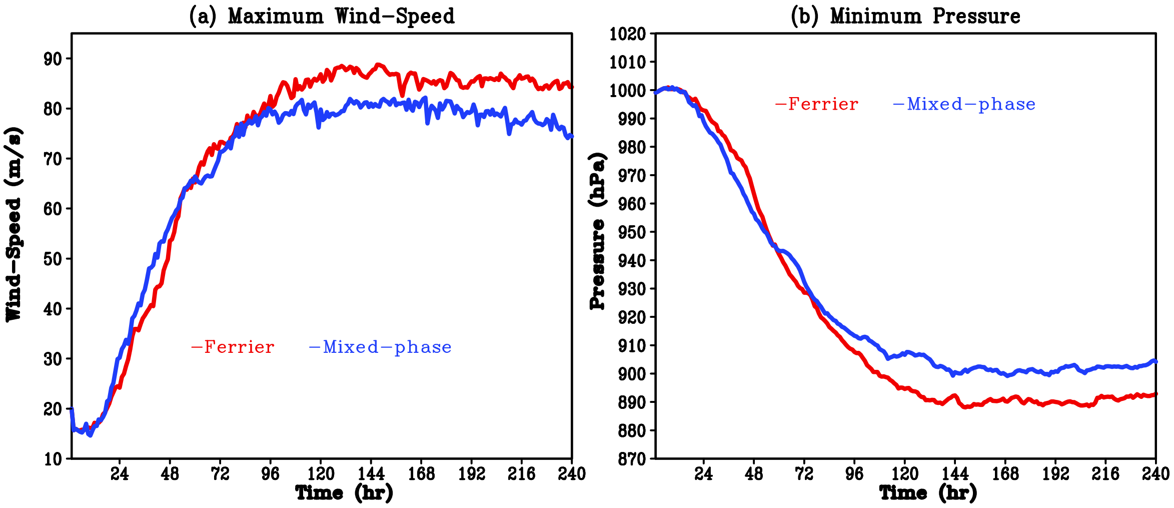


*Figure 1. (a) The maximum azimuthal mean wind speed at the lowest model level (about 35 m above sea level); (b) the minimum sea level pressure of the simulated storms using Ferrier (red) and Wang (blue) cloud microphysics schemes in TCM4.*

Figure 1 shows the time evolution of the maximum azimuthal mean wind speed at the lowest model level and the minimum sea level pressure of the simulated storm in TCM4 using the HWRF and TCM4 cloud microphysics schemes. It is interesting to see that the initial spin-up of the model storm using the Ferrier cloud microphysics scheme is slower than the TCM4 mixed phase scheme in the first 48 h of simulation. However, the subsequent intensification rate is large with the Ferrier scheme, which eventually produces a stronger storm than that with the TCM4 cloud microphysics scheme. Further the storm simulated with the Ferrier scheme does not show any increase in the radius of maximum azimuthal mean wind. This is in contrast with that simulated with the TCM4 cloud microphysics scheme (Fig. 2).

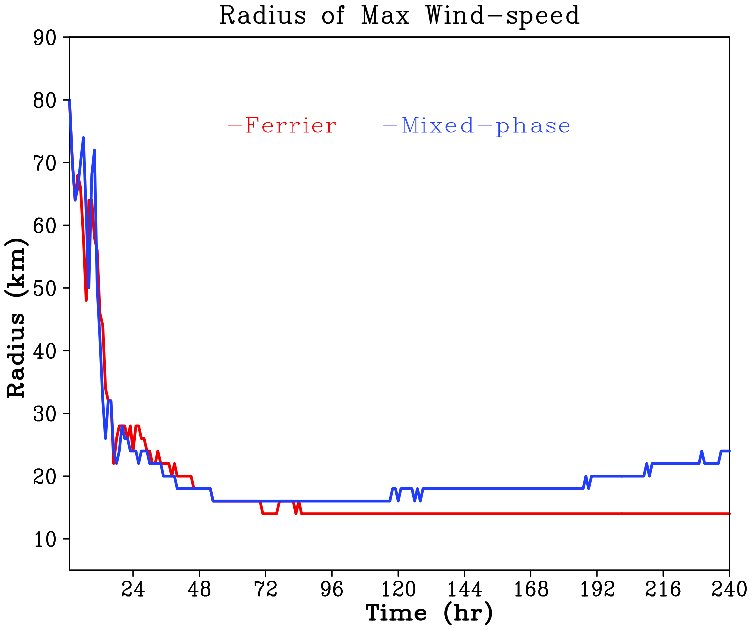


*Figure 2. Time evolution of the radius of maximum azimuthal mean wind speed of the simulated storms in TCM4 with different microphysics scheme (red: Ferrier scheme, blue: TCM4 mix-phase scheme).*

The results thus suggest that too big hurricanes predicted by HWRF model are unlikely due to the cloud microphysics scheme used. Consistent with the findings by Wang (2009), the larger storm with the TCM4 cloud microphysics corresponds to the rainfall (Fig. 3) and diabatic heating rate (Fig. 4) extending to larger radii. Further the azimuthally averaged diabatic heating rate by the TCM4 scheme tilt radially outward more than the Ferrier scheme because the latter simulated smaller radius of maximum wind (Fig. 2). Detailed examinations show that the simulated ice hydrometeors using the two schemes are quite different. For example, the Ferrier scheme produces much less stratiform clouds as well as much less anvil clouds outside the eyewall than the mixed phase scheme used in TCM4 (Fig. 5). This is also consistent with much smaller heating rate outside the eyewall and smaller radius of maximum azimuthal mean wind due to the lack of strong spiral rainbands (Figs. 3 and 4).

In summary, the Ferrier cloud microphysics scheme performs reasonably well in TCM4. Results show that the initial spin up of the model storm is slower using the Ferrier scheme than the Wang scheme used in TCM4. However, the subsequent storm is stronger in the former than in the latter. The Ferrier scheme produces much less stratiform clouds and anvil clouds outside the eyewall due to the lack of strong spiral rainbands. As a result, the diabatic heating and ice hydrometeors are concentrated mainly in the eyewall region. This is also responsible for the simulated smaller radius of maximum azimuthal mean wind. These results suggest that the slow intensification and fast growth of the storm size in the operational HWRF model may not result from the discrepancies in the cloud microphysics scheme used. However, caution needs to be taken for this statement. The results we show are based on 2 km mesh simulation. It is not clear the difference would become smaller or larger if the horizontal resolution similar to that used in the operational HWRF is used. We plan to do sensitivity experiments to learn about the resolution dependency.

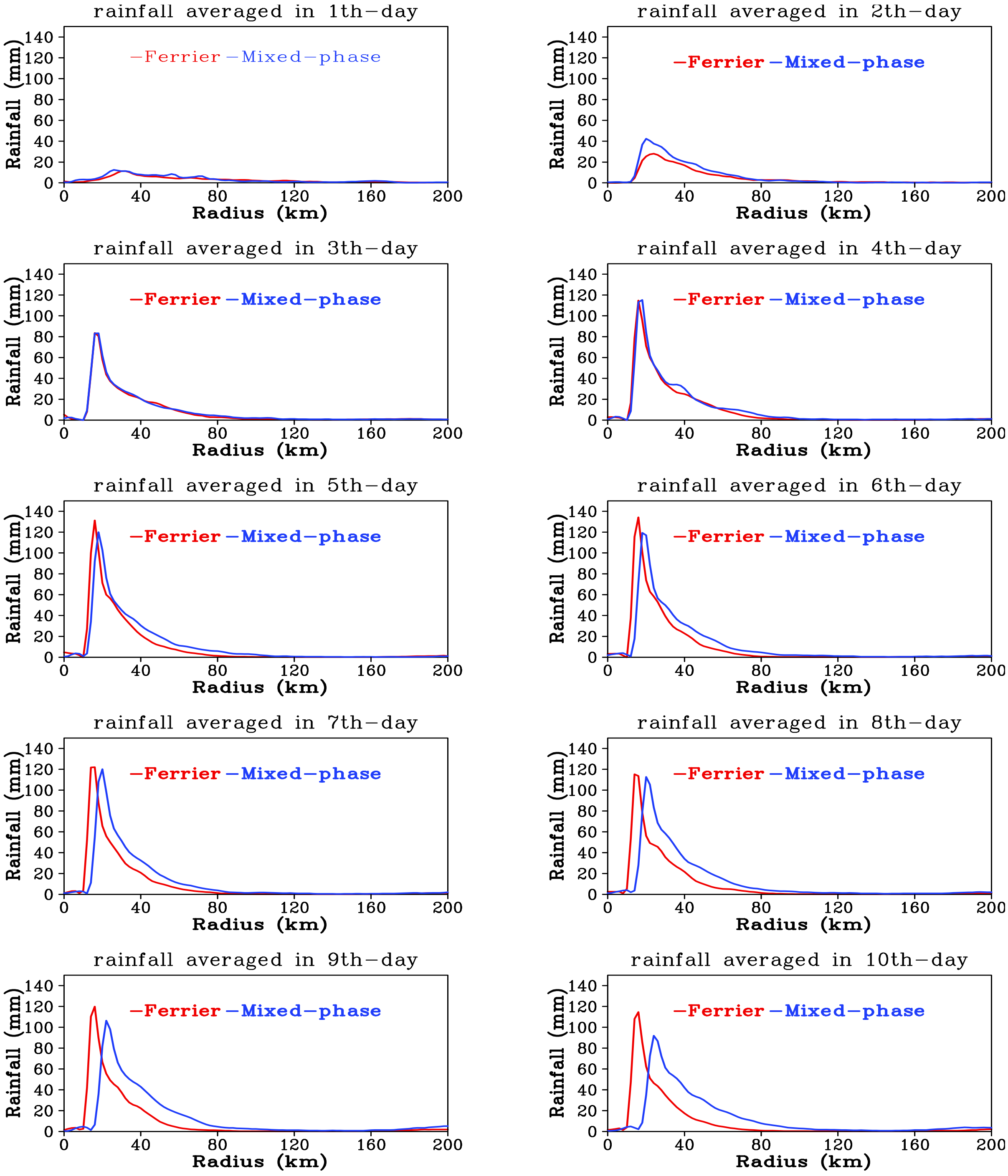


*Figure 3. The azimuthal mean rainfall averaged in each 24h of simulation (red: Ferrier, blue: TCM4 mixed-phase).*

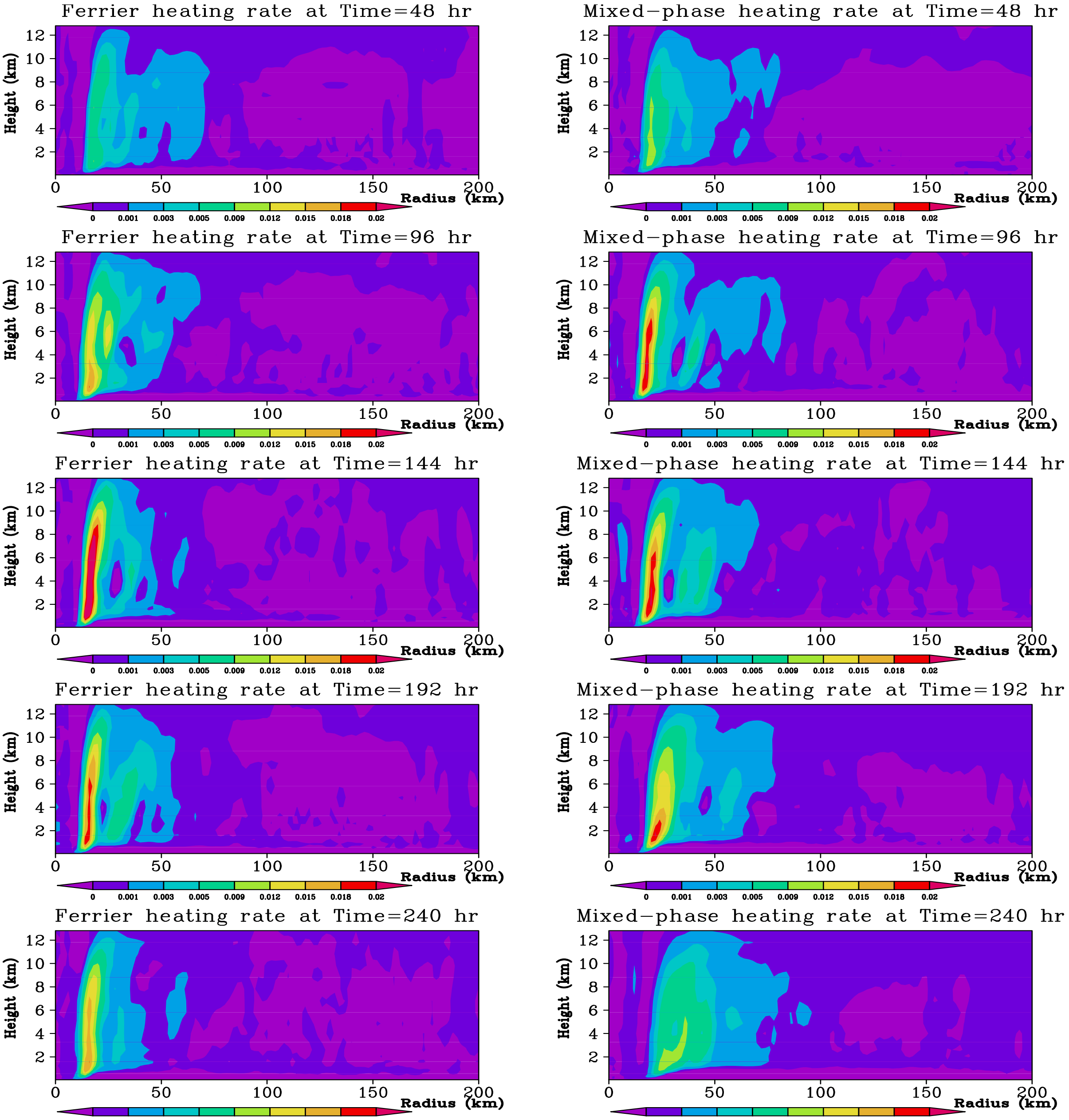
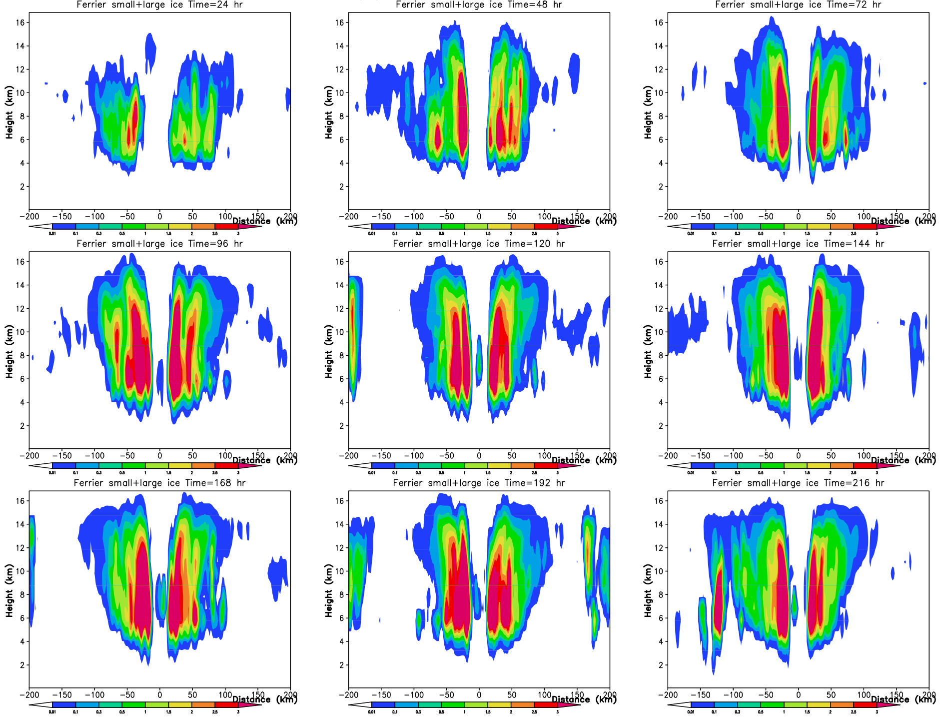


*Figure 4. Radius-height distribution of the azimuthal mean diabatic heating at given times in the simulated storm with the Ferrier (left) and TCM4 (right) cloud microphysics schemes.*

(a) Ferrier Scheme



(b) TCM4 Scheme

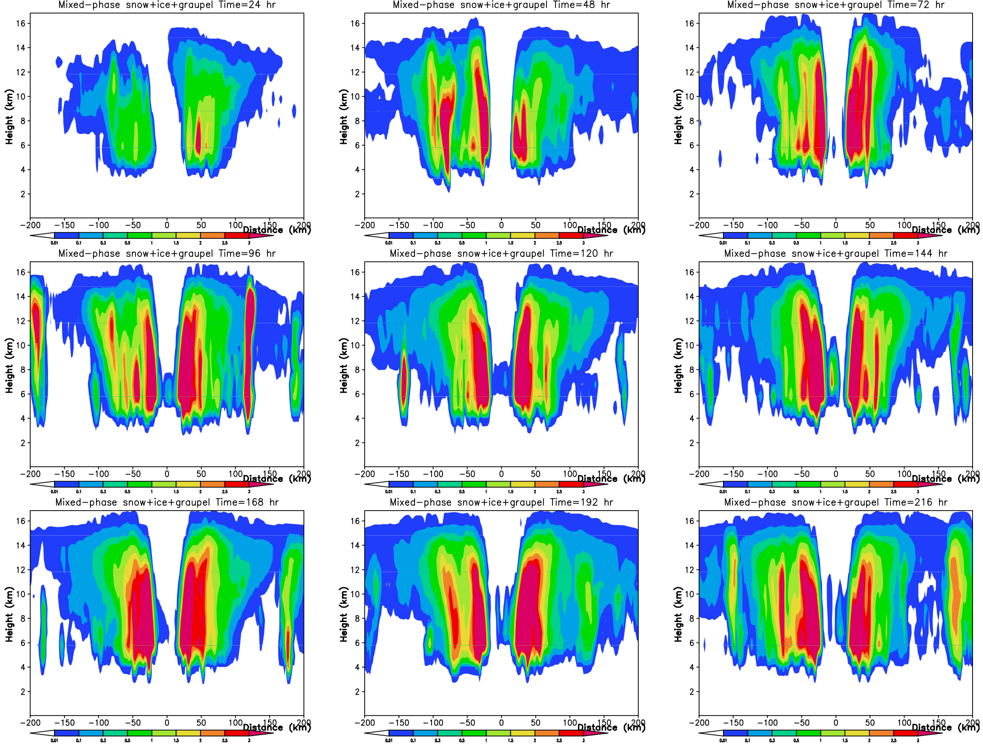


*Figure 5. vertical cross-section of total ice along the east-west across the storm center simulated by Ferrier scheme (a) and TCM4 cloud microphysics scheme (b).*

### *b. Effect of the SAS cumulus parameterization scheme in TCM4*

In order to examine the effect of the use of a convective parameterization scheme in the outer coarse meshes on the simulated hurricane structure and intensity, we have implemented the Simplified Arakawa-Schubert (SAS) cumulus parameterization scheme into TCM4 and performed two experiments using TCM4 with the finest mesh resolution of 2.5 km (note that a little bit coarser than that used for the simulations discussed above). Note that the SAS cumulus parameterization scheme is currently used in the operational HWRF model. In one experiment, the SAS cumulus parameterization scheme is used. Considering the horizontal resolution of TCM4, we only activated the SAS cumulus convection scheme in the two outer coarse meshes (with resolutions of 67.5 km and 22.5 km). In the other experiment, no any cumulus parameterization scheme is used in any model meshes.

Figure 6 shows the time evolution of the maximum azimuthal mean wind speed at the lowest model level and the minimum sea level pressure in the two simulations using TCM4. What we can see is the different evolutions of the storm intensity at some later stages while with little difference in the early intensification stage. This can be explained by the fact that the use of the cumulus parameterization in the coarse meshes takes time to affect the innermost mesh where most active convection occurs. Nevertheless, the differences still become visible and significant at later stages. In particular, the storm without the use of convective parameterization in the outer meshes becomes not only stronger and but also larger, as inferred from the radial distribution of rainfall rate shown in Fig. 7. The results from these sensitivity experiments thus demonstrated that the use of cumulus convective parameterization in the operational HWRF may need to be tested further. The interaction between the grid-scale and subgrid scale moist processes is also complicated. This is implicated further by the use of the implicit subgrid scale processes in different meshes in a nested model, such as the one used in the HWRF model.

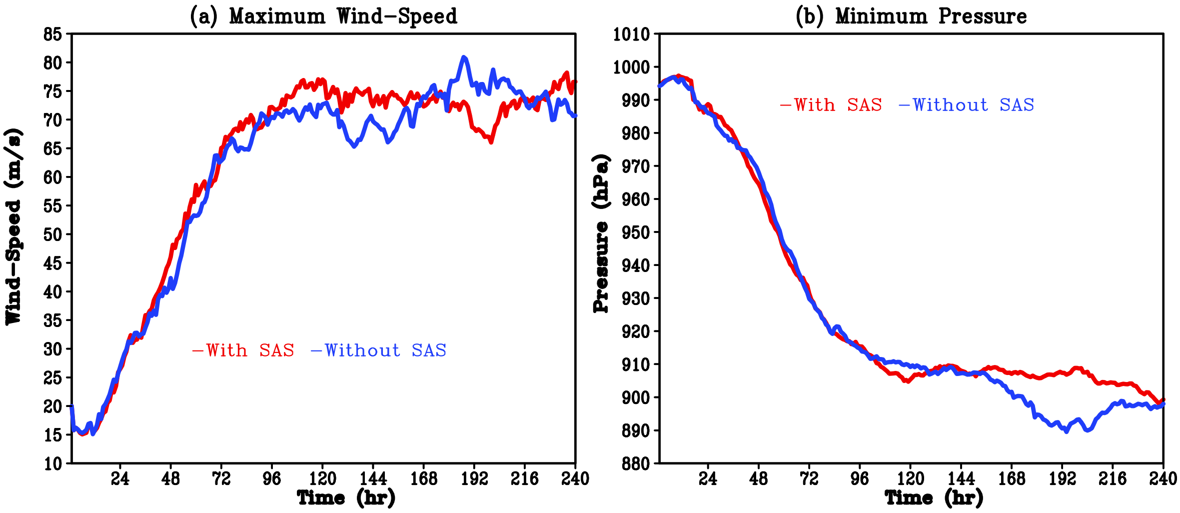


*Figure 6. (a) The maximum azimuthal mean wind speed at the lowest model level (about 35 m above sea level); (b) the minimum sea level pressure of the simulated storms using Wang cloud microphysics scheme with (red) and without (blue) the use of the SAS convective parameterization scheme in the outer coarse meshes in TCM4.*

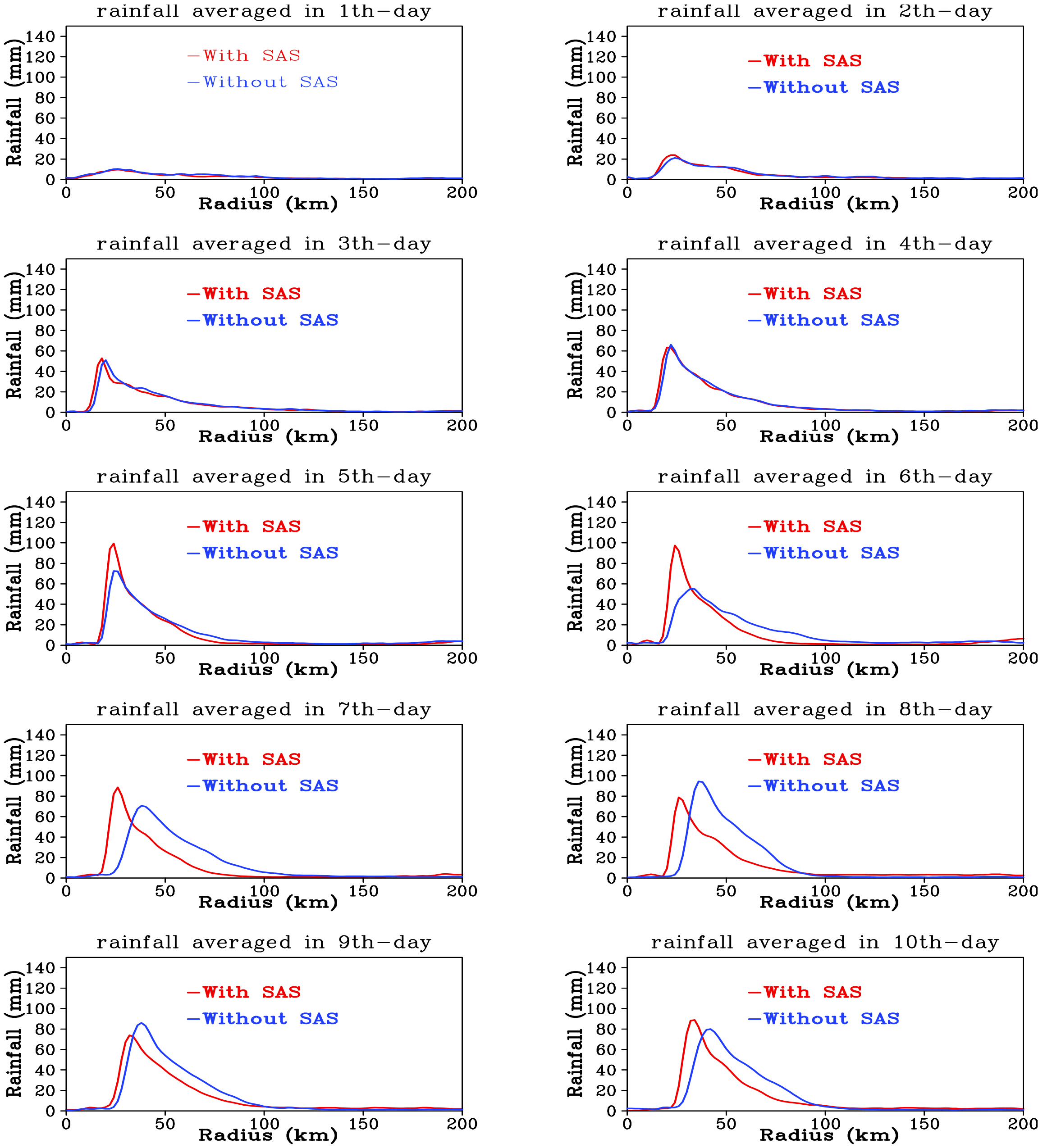


*Figure 7. The azimuthal mean rainfall averaged in each 24h of simulations (red: with, blue: without the use of SAS convective scheme in the outer coarse meshes in TCM4).*

### *c. Comparison of the NMM and ARW dynamical cores*

We have extended our diagnostics of cloud and precipitation physics to examine the possible discrepancies in the dynamical core of the HWRF model in comparison with the simulation using the WRF_ARW dynamical core with the same model physics options. HWRF model is based on the dynamical core of the nonhydrostatic mesoscale model (NMM) of NCEP. WRF ARW dynamical core is developed at NCAR and is widely used in research and modeling community. It is our purpose to see whether biases in the prediction of hurricane size and intensity by HWRF are related to the dynamical core. Hurricane Katrina (2005) was selected in this comparison since it was one of the most devastating natural disasters in the United States in the history.

The NCEP final analysis data (FNL) was used as both the initial field and boundary conditions. As we can see from Fig. 8 that hurricane intensity in FNL is generally considerably weaker, in particular during the mature stage, than that given in the NHC best track data. We therefore used a bogus scheme (Wang 2007) to enhance the initial hurricane intensity in FNL. The model domain was triply nested with grid spacings of 0.15, 0.05, 0.017 degree for NMM core and 15000, 5000, 1666.66 m for ARW core, roughly the same resolution for the two dynamical cores. The rapid intensification phase of Hurricane Katrina was covered by the finest model domain (not shown). To focus on the dynamical core, we used the same physics options in all experiments, namely, the physics schemes used in the operational HWRF at NCEP, including Ferrier scheme for grid-resolved cloud microphysics, Betts-Miller-Janjic (BMJ) scheme for cumulus convection, GFDL long/short-wave radiation scheme, Monin-Obkuhov scheme for ocean surface flux calculation, the Noah land-surface model, Mellor-Yamada-Janjic (MYJ) TKE scheme for the planetary boundary layer (PBL). Convective parameterization was used only in the outermost domain. Three sensitivity experiments were conducted, namely NMM dynamical core without and with bogus vortex, and ARW dynamical core with bogus vortex. Note that the bogus vortex was embedded in the FNL only at the initial time. Therefore, except for different dynamical core (and also the pre- and pros-processing), in the bogused experiments, the model physics and initial and boundary conditions were identical. This allows for a direct comparison of the two dynamical cores in the WRF modeling system.

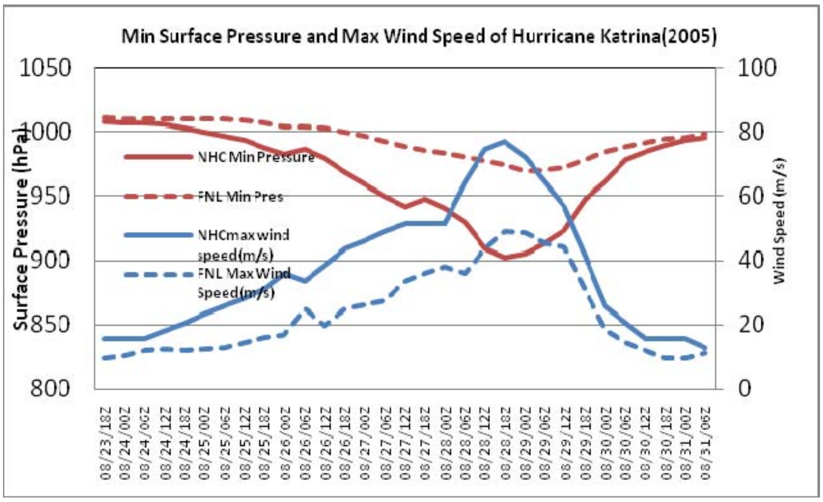


*Figure 8. Minimum sea level pressure (purple) and maximum surface wind speed (blue) in the NHC best track data and in the NCEP FNL analysis.*

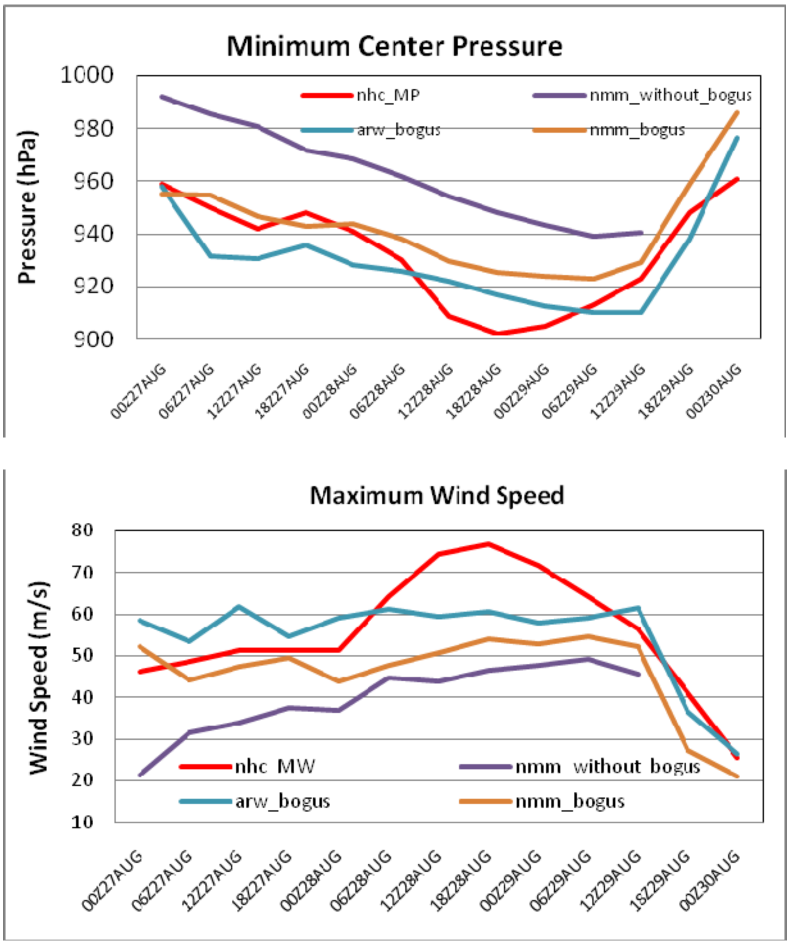


*Figure 9. Minimum sea level pressure (upper panel) and maximum surface wind speed (lower panel) in the NHC best track, and from the three numerical experiments designed to examine the effect of dynamical core on the simulated storm by HWRF.*

The initial intensity is very close to the observation in both simulations with vortex bogus (NMM_bogus and ARW_bogus in Fig. 9). Both captured the main intensity evolution of Hurricane Katrina but both failed to simulate the rapid intensification on August 28. The experiment without bogus scheme (NMM_without_bogus) also captured the intensity evolution except that the intensity is weaker than that with the bogus vortex. Note that although the same initial conditions were used in the two bogus simulations, the storm intensity immediately after the pre-processing had a higher maximum surface wind (about 10%) in the ARW dynamical core than in the NMM dynamical core. The storm simulated in the former was also considerably stronger than that in the latter. The simulation with the NMM dynamical core without bogus vortex reproduced the intensification better than that with the bogus vortex, indicating that the NMM dynamical core might not be able to simulate very strong intensity of hurricanes. Note that although we show only simulations at one initial time, experiments with different initial times gave quite similar results (not shown). Therefore, in terms of storm intensity prediction by

HWRF, two aspects need to be addressed, why the initial surface wind speed of the storm is weak and why the simulated maximum surface wind intensified much slower than the central surface pressure deepened. All three simulations captured the storm motion reasonably well (Fig. 10). Although the storm in the experiment with no bogus vortex in NMM_without_bogus is much weaker than that with the bogus vortex (NMM_bogus), the simulated tracks in the two experiments were quite similar (not shown). Further, although the NMM dynamical core simulated weaker hurricane intensity, it simulated the track considerably better in terms of the landfall timing and location than the ARW dynamical core for this case. This indicates that the NMM dynamical core might capture the evolution of the large-scale environmental flow, which is the key to the accurate prediction of storm motion. However, the storm intensity is largely controlled by the inner core dynamics, which was not well represented by the numerical scheme and needs to be improved in the NMM dynamical core.

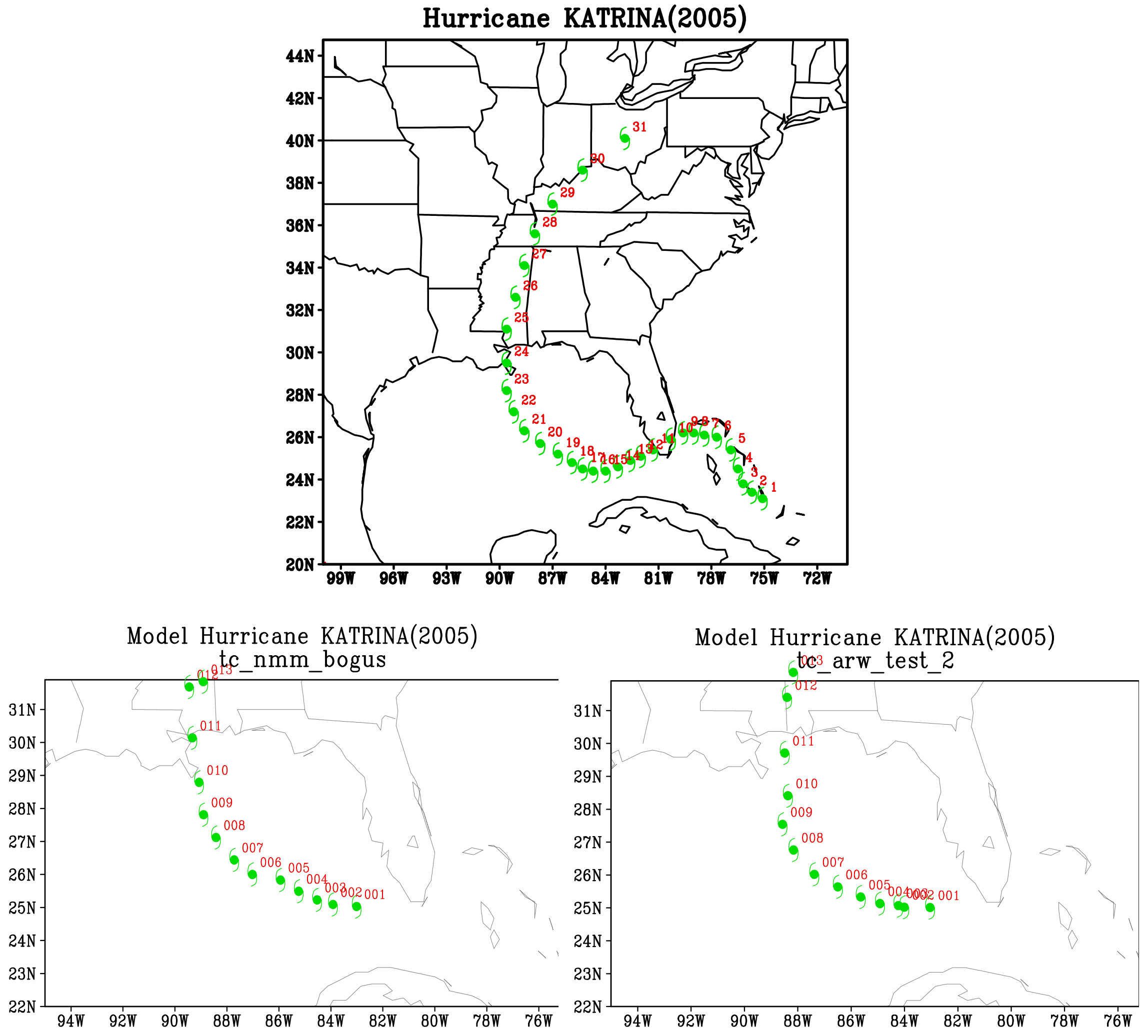


*Figure 10. The best track of Hurricane Katrina (2005) from the NHC best track data (upper panel) and that predicted by WRF model with NMM (lower left) and ARW (lower right) dynamical core.*

Figure 11 shows the height-radius cross-section of the azimuthally mean tangential wind at the initial time and after 24 h simulation from two experiments with bogus vortex. Consistent with the intensity evolution shown in Fig. 9, at the initial time, the azimuthal mean tangential wind is already weaker throughout the depth of the troposphere in the NMM dynamical core experiment. The difference at the initial time is purely a result of the different pre-processing algorithms used in the two dynamical cores. After 24 h of simulation the difference became even larger. In particular, the NMM dynamical core simulated a shallower maximum tangential wind core immediately above the boundary layer around 850 hPa while the ARW dynamical core produced a maximum tangential wind core extending to higher levels. This difference might be related to the difference in the vertical descretization of the two dynamical cores. In addition, the radius of maximum wind in the lower troposphere is also larger in the simulation with the NMM dynamical core than that with the ARW dynamical core, indicating that the dynamical core also contributes to the too large storm in the prediction of hurricanes by the HWRF. We have tested the effect of divergence damping used in the NMM dynamical core and found that it affects the simulated size of the storm but it seems not the main reason. Therefore, a systematic dynamics of dynamical core of the NMM is required in order to improve the prediction of storm intensity and structure by HWRF. Here we have only highlighted its potential impact on the model prediction.

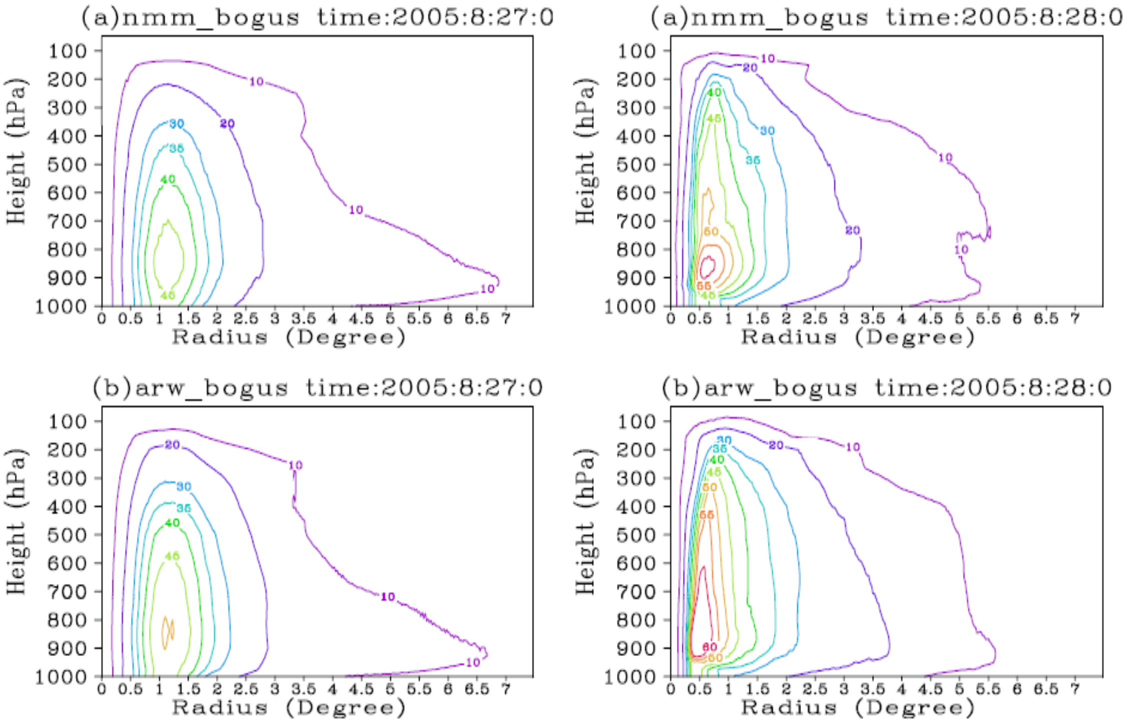
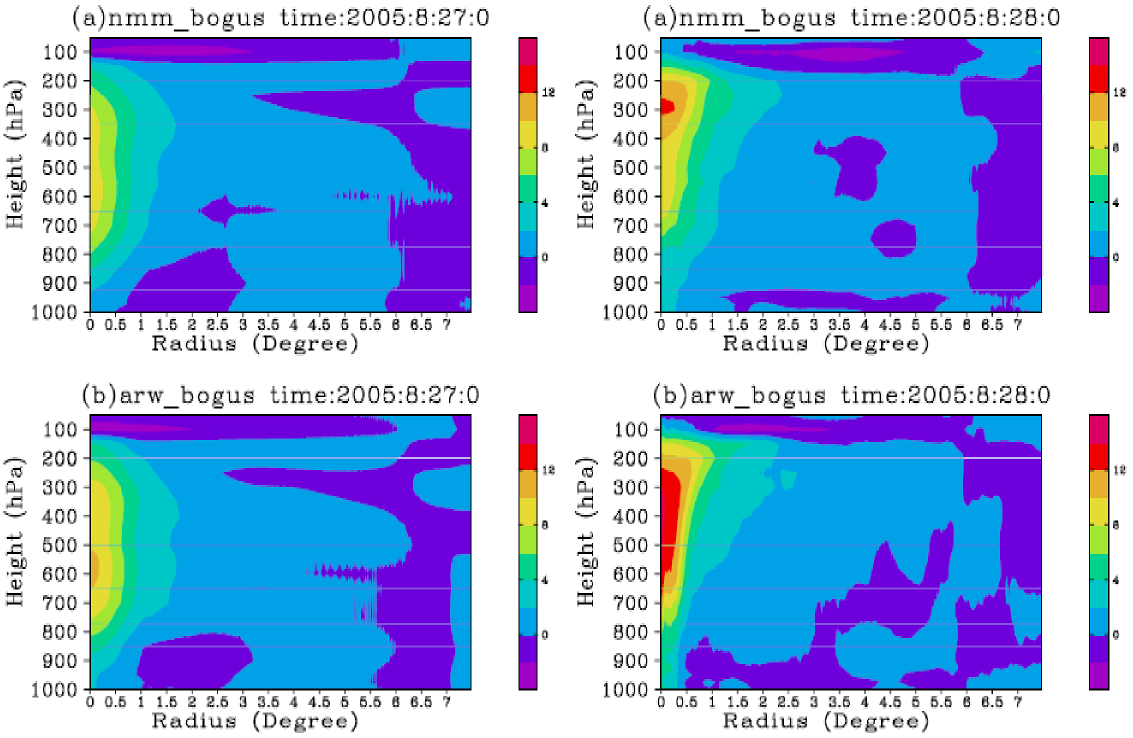


*Figure 11. Height-radius cross-section of the azimuthally mean tangential wind at the initial time and after 24h of simulation with the NMM and ARW dynamical core and the initial bogus vortex.*

Corresponding to the difference in the vertical structure of the simulated azimuthal mean tangential wind shown in Fig. 11, the warm core, defined as the temperature anomaly related to annulus mean temperature between radii of 500 km to 750 km, is similar at the initial time but became stronger in the simulation with the ARW dynamical core (Fig. 12), consistent with the stronger storm in the simulation than that in the NMM dynamical core experiment. Larger negative temperature anomalies occurred in the simulation with the ARW dynamical core than that with the NMM dynamical core, indicating that not only the physics parameterizations can affect the heating/cooling distributions but also the dynamical core may affect how the dynamics responds to the physical forcing in hurricane simulations. Furthermore, even the same cloud microphysics scheme was used in the two simulations the distribution of hydrometeors is quite different. An example of the azimuthal mean radius-height distribution of cloud water is given in Fig. 13. We can see that the cloud liquid water shows shallow clouds outside the eyewall and extends outward to large radii in the lower troposphere, indicating shallow clouds above the boundary layer. This can explain why the negative temperature anomalies are so small in the lower troposphere in the simulation with the NMM dynamical core. In addition, the cloud water also fills in the lower eye region in the simulation with the NMM dynamical core. These results suggest that the dynamical core may affect the cloud microphysics to some degree. This has never been recognized.


(a)nmm_bogus time:2005:8:27:0

(a)nmm_bogus time:2005:8:28:0

(b)arw_bogus time:2005:8:27:0

(b)arw_bogus time:2005:8:28:0

*Figure 12. Height-radius distribution of the azimuthally mean temperature anomalies at the initial time and after 24 h of simulation with the NMM and ARW dynamical cores and initial bogus vortex.*

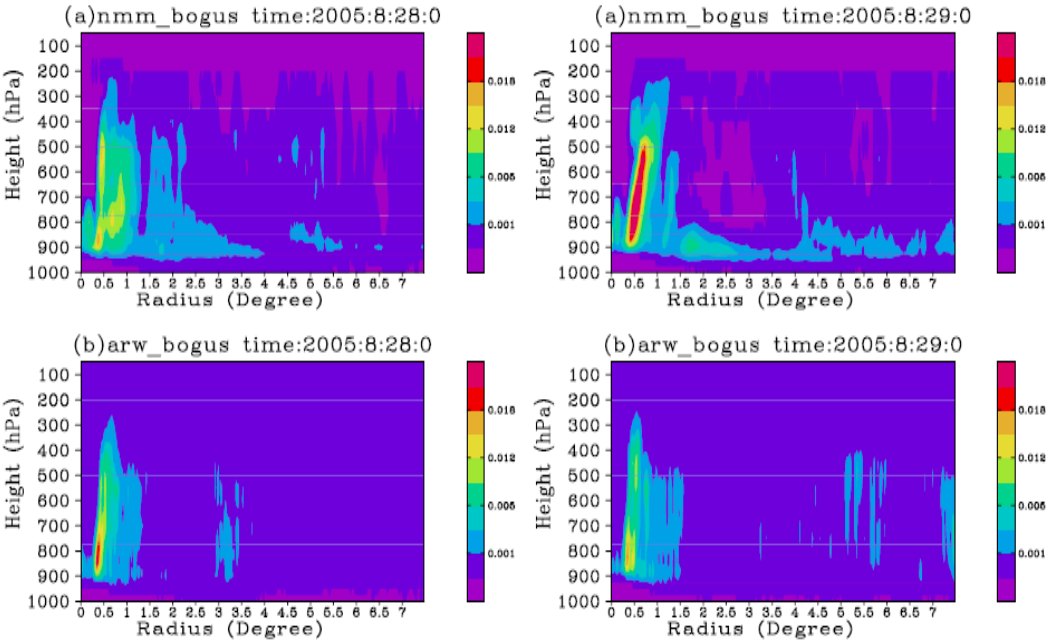


*Figure 13. Height-radius distribution of the azimuthally mean cloud water after 24 h and 48h of simulations with the NMM and ARW dynamical cores, respectively.*

### *d. Develoment and test of the SCPM*

In accordance with the work-plan of the project, during Year 1 we have developed and tested a single-column parcel model (SCPM). Later in this project, this SCPM will have two roles for improving forecasts with the HWRF model:

- Provide improved parameterization of supersaturation and other microphysical quantities (e.g. liquid fraction) assumed to treat the grid-resolved clouds;
- Embed the SCPM inside the deep convection parameterization, providing better estimates of convective heating aloft and detrainment of condensate mass.

To minimize computational expense, our SCPM represents an adiabatic parcel with a simplified cloud-microphysical framework. It treats coagulation of hydrometeors with the single-moment bulk microphysics scheme described by Phillips and Donner (2006). There are 5 classes of hydrometeor: cloud-droplets, cloud-ice, rain, snow and graupel. In the SCPM, cloud does not sediment, while precipitation does. Diffusional growth of cloudy condensate is treated by applying the formula from Korolev and Mazin (2003) for the supersaturation, as a function of cloud-liquid and cloud-ice properties. The change in supersaturation during ascent from one model level to the next determines that of all cloud condensate due to diffusional growth, which constrains the individual rates of condensation and vapor growth of cloud-liquid and cloud-ice. Cloud-droplets and cloud-ice particles are asssumed to be monodisperse, with number mixing ratios that are $10^8$ and $10^5$ $kg^{-1}$ respectively below the -36$^oC$ level, being zero and $10^8$ $kg^{-1}$ respectively above due to homogeneous freezing.

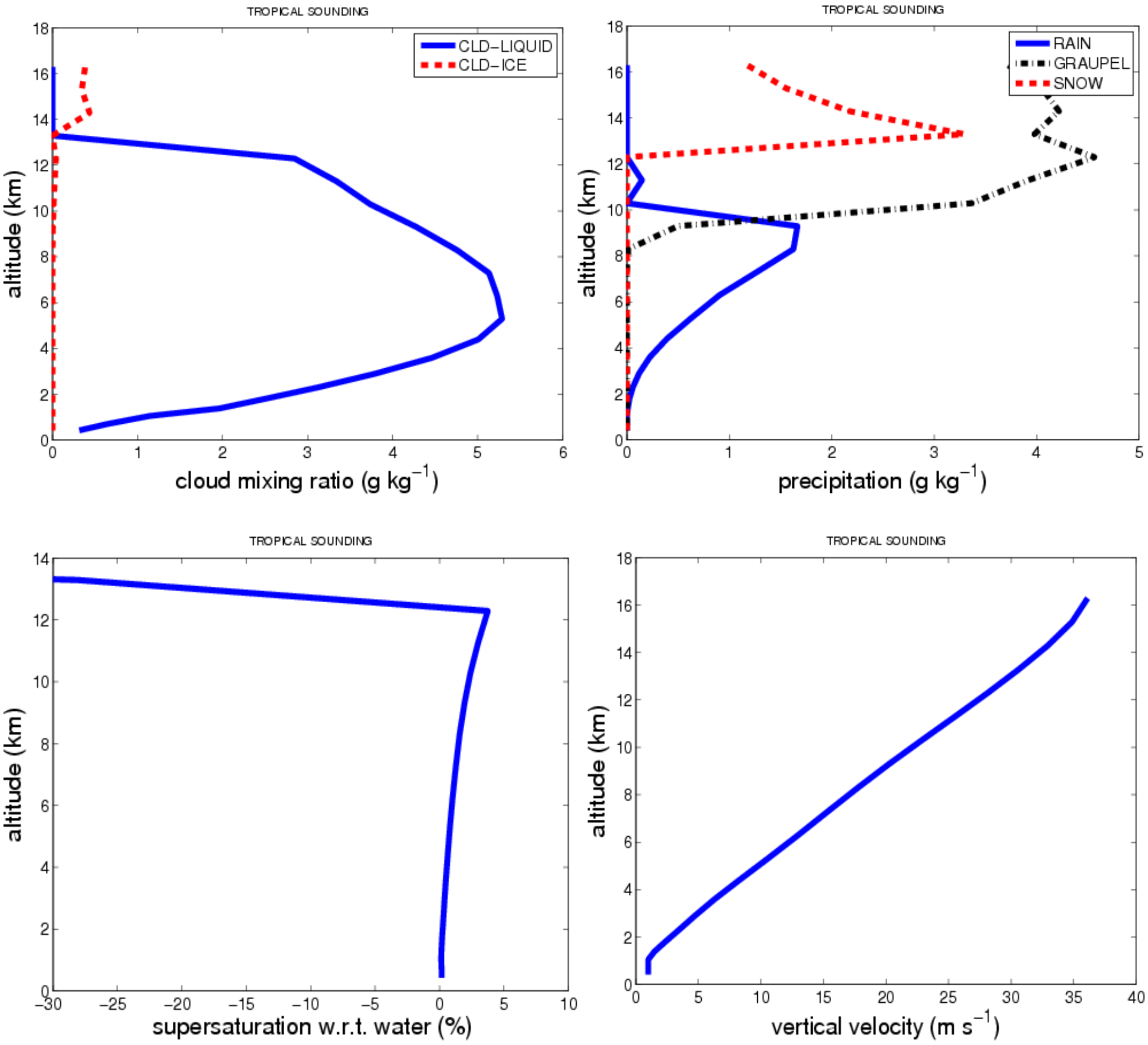


*Figure 14. Off-line simulation by the SPCM of a cloudy adiabatic parcel in a vigorous deep convective updraft, for an unstable sounding. The depth of the parcel is 1 km and the ascent is calculated from an extremely unstable tropical sounding, with a relative humidity of 86% and air temperature of 27$^{o}$ C near the surface, and a convective available potential energy (CAPE) of about 6000 J/kg. To integrate the evolution equation of parcel kinetic energy, it was assumed that 10% of the CAPE was converted to kinetic energy of the parcel, implicitly accounting for the effects of other retarding factors (e.g. gravitational burden of condensate, vertical perturbation pressure gradient force). Note the discontinuity of supersaturation at the top of the mixed phase region (about 12 km altitude). There, all supercooled cloud-liquid upwelled there must freeze, causing a collapse of humidity to ice saturation.*

First, after developing the SCPM, it was tested for a tropical case of a convective ascent in a very unstable atmosphere. Figure 14 shows off-line results from the SCPM's simulation of a real tropical sounding that has extreme instability. Much of the rain is predicted to freeze, forming copious graupel in the mixed-phase region (0 to -36 degC). Thus, the SCPM realistically captures a feature of convective updrafts found in other more detailed models, about graupel dominating the overall mass of ice precipitation. As is evident from Fig. 14, the SCPM realistically represents homogeneous freezing of all cloud-liquid at the level where the parcel reaches -36 degC (about 12 km altitude). Here, the humidity collapses during ascent towards ice saturation. The mass of cloud-ice becomes appreciable.

The SCPM represents how the supersaturation is maintained close to water saturation by an approximate balance between the adaibatic cooling from ascent and condensation, in this mixed-phase region, while the liquid fraction is close to unity. This is because of ascent is appreciable and the ice concentration is low in the mixed-phase region (see Korolev and Mazin 2003; Korolev 2007). Also apparent from Fig. 14 is the prediction by the SCPM of the inexorable increase of supersaturation with height in the deep convective updraft. This is partly due to the increasing rate of ascent and partly due to accretion of cloud-liquid. In natural convective clouds, this rise in supersaturation is an important feature, causing in-cloud droplet activation that tends to maintain the droplet number concentration at appreciable values, despite losses by accretion.

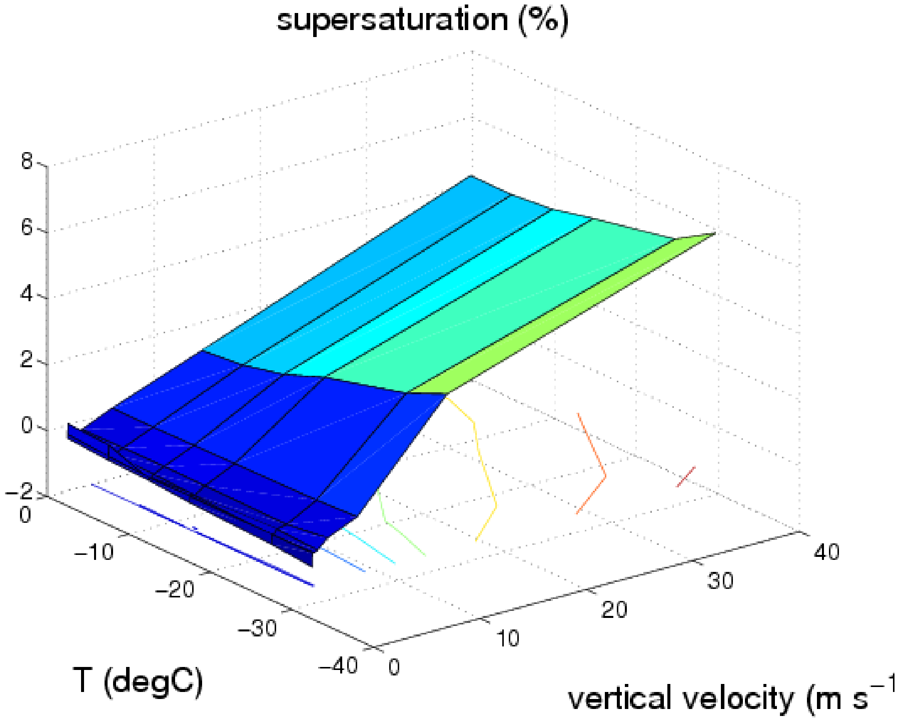


*Figure 15. In-cloud supersaturation with respect to liquid water in an adiabatic parcel, predicted by many off-line runs of the SPCM. All parcel runs begin at the surface with relative humidity of 86% and temperature of 27$^o$C. Ascent is prescribed at a constant value during each run. Note how the faster the ascent, the greater the supersaturation. Accretion of cloud by precipitation explains why the supersaturation does not decrease markedly with increasing supercooling. The absence of negative supersaturations here is consistent with findings of Korolev (2007) and Phillips et al. (2007) about the Bergeron-Findeisen process being usually restricted to weaker ascent, depending on the ice concentration.*

Next, many idealised runs were performed with the SCPM, in order to create enhanced microphysical parameterisations for the hurricane model. Vertical velocity was prescribed at a fixed, constant value in each run. Different rates of ascent were assumed in different runs. Figure 15 shows the supersaturation in the mixed-phase region, from this ensemble of idealised runs. Liquid fraction is predicted to be close to unity for most of the vertical velocities of these runs. The plotted results (Fig. 15) form a look-up table that may be applied to treatments of both large-scale stratiform and convective clouds in the hurricane WRF model.

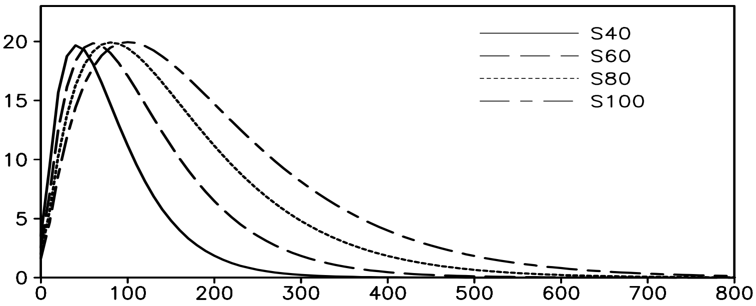
During Year 2 of the present project, in addition to applying it to improve the hurricane model, as noted above, development of the SCPM may make use of our recent codes for bulk microphysics in an aerosol-cloud model (Phillips et al. 2007, 2009). There may be improved conversion of cloud-ice to snow, sub-cycling for coagulation processes when ascent is slow, and more accurate cloud-ice numbers in the mixed-phase region. During this Year 1, this bulk microphysics code of the aerosol-cloud model has been improved with emulated bin microphysics to represent the dependency of ice morphology (shape, bulk density) on size, for graupel and snow. Simple theoretical formulae to predict cloud-droplet concentrations, due to in-cloud activation, have been derived by the Co-I, with analysis of inc-loud microphysical equilibrium. These all provide potential avenues for enhancing the SCPM during Year 2.

This reporting period (08/01/2010-01/31/2011)

*e. Effect of initial vortex size on the predicted storm inner-core size change*

The influence of the initial vortex size on the inner-core size of the simulated hurricane has been investigated using TCM4. We have focused on how the initial vortex size (the radius of maximum wind-RMW) controls the hurricane inner-core size in the mature stage. A positive feedback mechanism responsible for the hurricane inner-core size is identified (Xu and Wang 2010). Figure 16 shows the radial profiles of the tangential wind and vertical relative vorticity in the initial vortices used in our numerical experiments. Here the profiles from S40 to S100 indicate the increase in the initial RMW from 40 km to 100 km. What we can see here is that the larger vortex shows large cyclonic relative vorticity up to a radius beyond 200 km while the small vortex has cyclonic relative vorticity in a radius less than 100 km. As a result, the large vortex has its high inertial stability to extend to larger radii, which prevents the boundary layer inflow due to friction and diabatic heating in the eyewall. This leads to a slower intensification of the storm in the subsequent model simulation. In sharp contrast, the small vortex intensified faster but reached a weaker intensity at its mature stage, as we can see from Figure 17. One interesting result is that the small storm remained small throughout the integration while the large storm increased its inner core size considerably with time (see Figures. 18 and 19). To understand the model storm behavior, we have elaborated a positive feedback between the storm size and the convection outside the eyewall as documented in Xu and Wang (2010).

(a) Tangential Wind (m/s)



(b) Absolute Vertical Vorticity ($10^{-4}$ $s^{-1}$)

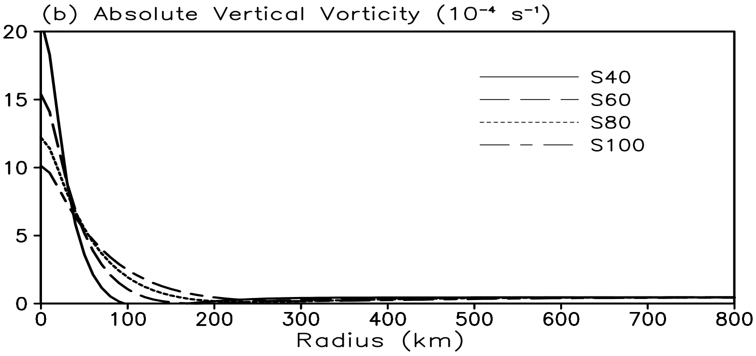
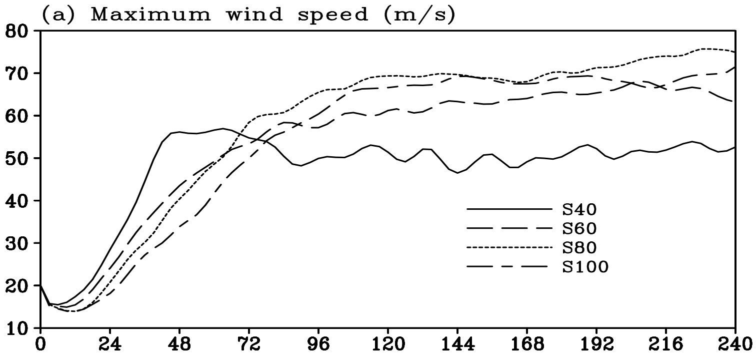


*Figure 16. The radial profiles of the tangential wind (a) and relative vorticity (b) used in the sensitivity experiments using TCM4 to understand how the size change varies with the initial vortex size.*

(a) Maximum wind speed (m/s)



(b) Minimum surface pressure(hPa)

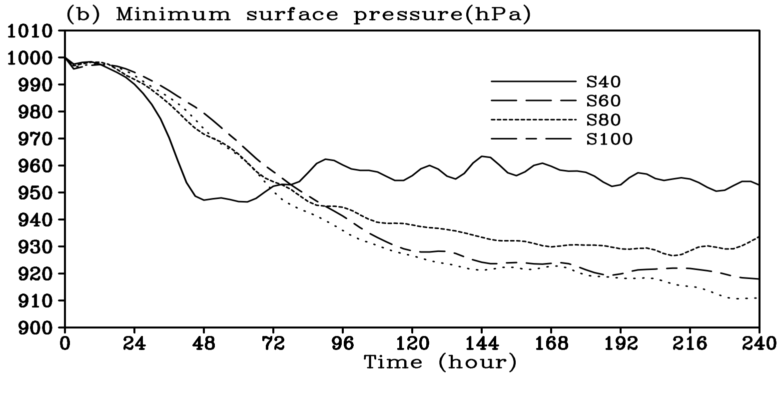


*Figure 17. Time evolution of the maximum wind at the lowest model level (a) and the minimum central sea level pressure (b) in the four experiments using TCM4.*

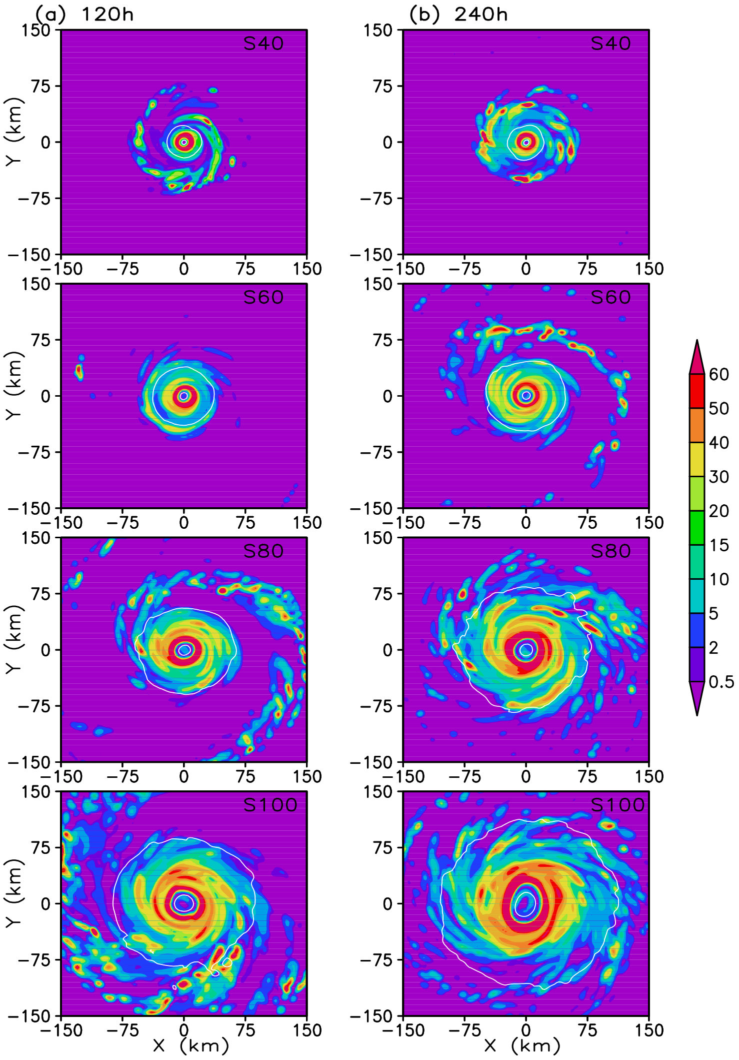
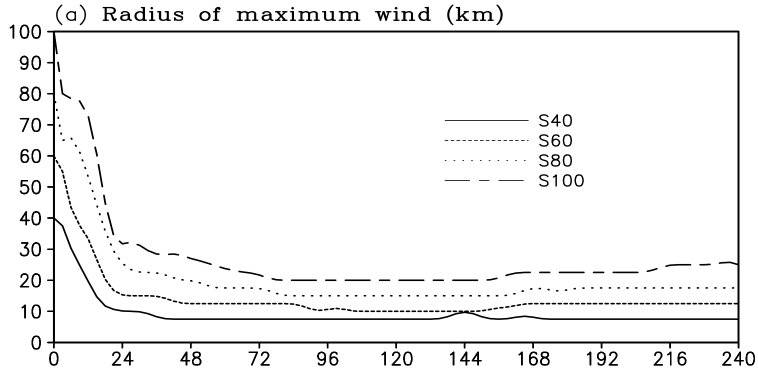


*Figure 18. The TCM4 simulated surface rain rate in 4 experiments for the four storms with different initial size as shown in Figure 17 after 120 h (left column) and 240 h (right column) of simulation.*

We found that a large initial size vortex has a broad tangential wind distribution outside the RMW, causing large surface entropy fluxes outside the eyewall and favoring the development of active spiral rainbands. Diabatic heating in spiral rainbands drives strong boundary layer inflow outside the eyewall. The latter brings high absolute angular momentum inward and thus contributes to the increase in tangential winds outside the eyewall, leading to the outward expansion of the wind field and the increase in the inner-core size of the simulated hurricane.

The broadened wind field in the initially large storm favors more surface entropy flux outside the eyewall and thus more active spiral rainbands. In addition, the large radial extent of relatively high absolute vertical vorticity (and thus the large inertial stability) in the large-size initial vortex makes the increase in tangential wind due to radial advection of absolute angular momentum effective. This is a positive feedback for the large initial size vortex to increase in its inner-core size in the simulation. On the contrary, a small initial size vortex with the same intensity has weak winds and thus small surface entropy fluxes outside the eyewall, prohibiting the development of active spiral rainbands in large radii, resulting in weak boundary layer inflow outside the eyewall and limiting the radial advection of absolute angular momentum. As a result, the increase in tangential winds outside the eyewall is suppressed, the outward expansion of the wind field is prohibited, and thus the inner-core size remains small (Figures 18 and 19). This is a positive feedback to maintain a small inner-core size storm. The positive feedback mechanism identified here can thus explain the observational results of Cocks and Gray (2002), which showed that small TCs were smaller than the medium and large TCs early on and throughout their respective composite lifecycles. The results also strongly suggest that the rapid size increase of hurricane in the HWRF model might be related partly to the initial vortex size in the initialization scheme. In addition, the model resolution at 9 km might be a reason too since at this resolution the model could not resolve the observed RMW. As a result, higher resolution may be needed in order to improve the size prediction by the HWRF model.


(a) Radius of maximum wind (km)

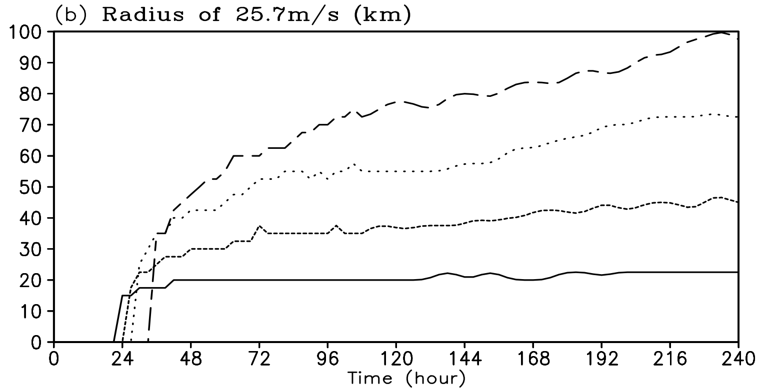

(b) Radius of 25.7m/s (km)

*Figure 19. Time evolution of the radius of maximum wind (a) and the radius of damaging wind (b) in the four experiments using TCM4 with different initial vortex size shown in Figure 17.*

### *f. Sensitivity of the predicted storm size change to the initial radial wind profile*

The above explanation as a positive feedback to lead to size change in the simulation can be further tested by using the initial vortices with the same radius of maximum wind while varying the radial decaying rate of the initial radial wind profile. We thus want to address how the radial wind profile of the initial vortex may affect the subsequent size evolution in the model integration. To address this issue, we performed three more experiments with the initial vortices having the same radius of maximum but different radial decaying rate outside the RMW as shown in Figure 20. Similar to the vortices specified in the initial size experiments, here the vortices show different extension of cyclonic relative vorticity outside the core region (Figure 20b). For the broad vortex, winds are strong outside the eyewall with relatively higher relative vorticity extending outward up to 300 km, while the compact vortex have cyclonic vorticity in about 200 km radius. This difference presents difference in inertial stability and also implies higher surface entropy flux for broad vortex as the case shown earlier for large size vortex. As a result, the mechanism and evolution of the size change for the different shapes of the initial vortex are similar to those discussed for the dependence on the initial vortex size (Figures 21 and 22).

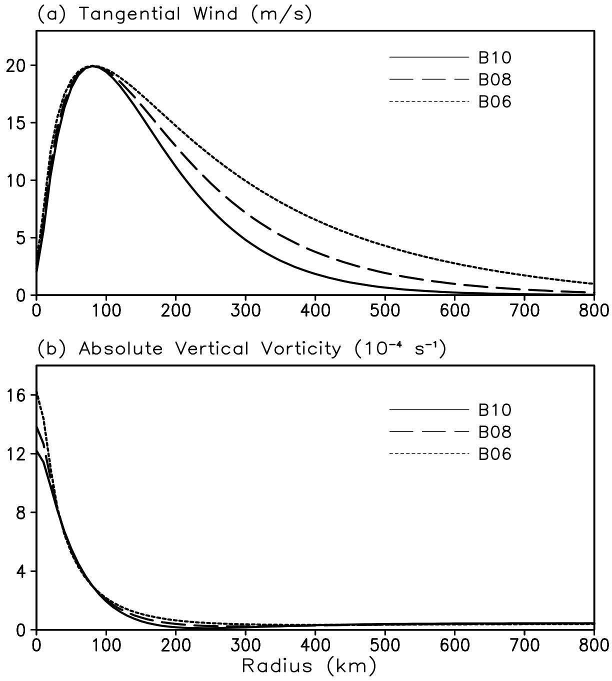


*Figure 20. The radial profiles of the tangential wind (a) and relative vorticity (b) used in the sensitivity experiments using TCM4 to understand how the size change varies with the initial vortex size.*

### *g. The setup of real-time forecast for hurricane over the eastern Pacific using HWRF*

To allow us further to evaluate the HWRF model in a quasi-operational context, we have set up the HWRF as a real-time forecast mode at University of Hawaii and configured it to the eastern North Pacific and central Pacific. Currently we are testing the system and make sure it will work properly in the hurricane season this year. Further we are constructing a bogus scheme to allow an enhancement of the initial storm in the model initialization. Since the version 3.2 we have got is the interim testing version for bug fixes, we will update the model immediately after the official new version is released in April 2011. In particular, this also allows us to test the new

GFS cumulus parameterization used in the new version of the HWRF model.

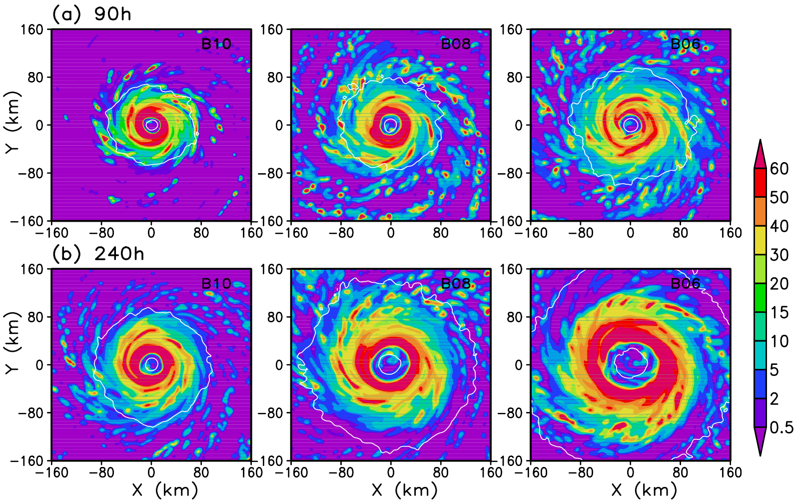


*Figure 21. The TCM4 simulated surface rain rate in the 3 experiments for the storms with different initial shape in their radial profile of tangential wind as shown in Figure 20 after 90 h (top panel) and 240 h (lower panel) of simulation*

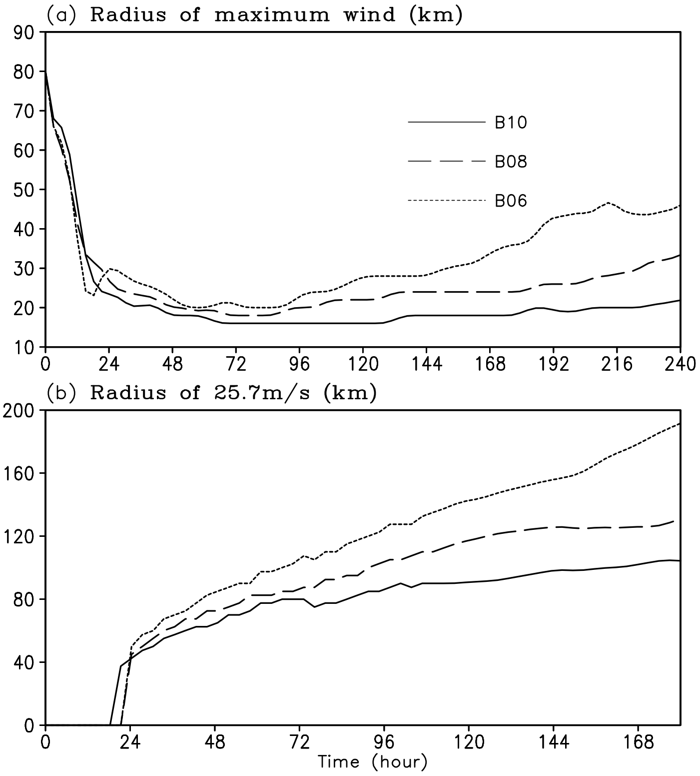


*Figure 22. Time evolution of the radius of maximum wind (a) and the radius of damaging wind (b) in the three experiments using TCM4 with different radial wind profiles in the initial vortex size shown in Figure 20.*

## WORK PLAN

Since some physics packages have been updated in the HWRF model, our originally planned implementation of some improvements to the original cloud and precipitation physics are no longer meaningful. We hope that some moderate bridge funds could be provided to allow us to continue our effort toward improved prediction of hurricane structure and intensity changes by the HWRF model forecasting system based on the latest version. We request one year bridge fund to support a postdoctoral fellow (Dr. Dong-Hyun Cha, joined the project since December 2010) to work on the project for one more year till July 31 2012 after the current support ending at July 31, 2011. I hope this can be treated as a special case for model improvements since model evaluation is so critical to the model improvements. We have made considerable progress in identifying the discrepancies in both the dynamical core and the model physics in the past 2 years. With the possible bridge fund support, we can also examine the numerics in the dynamical core in the HWRF model, which currently seems to trap moisture below the boundary layer where diabatic heating is located outside the eyewall. This is most likely a result of splitting error in the model dynamical core. The PI has extensive experience in numerics and physics and as well as hurricane dynamics. Therefore we can make sure a success of the project at the end. The total extra cost will be moderate and I can use some of the remaining fund and my other grant to cover 50% of the cost for the postdoctoral fellow As a result, I request a 50% support to the postdoctoral fellow and one month summer salary for the PI. The total amount I would request is about $48,000.

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