

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 have completed the following tasks during this report period (01/01/2009-01/31/2010):

- (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).*

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 discretization. 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 adiabatic 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.

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. Here we will highlight some of our results and their implications for the rest of our project years.

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.

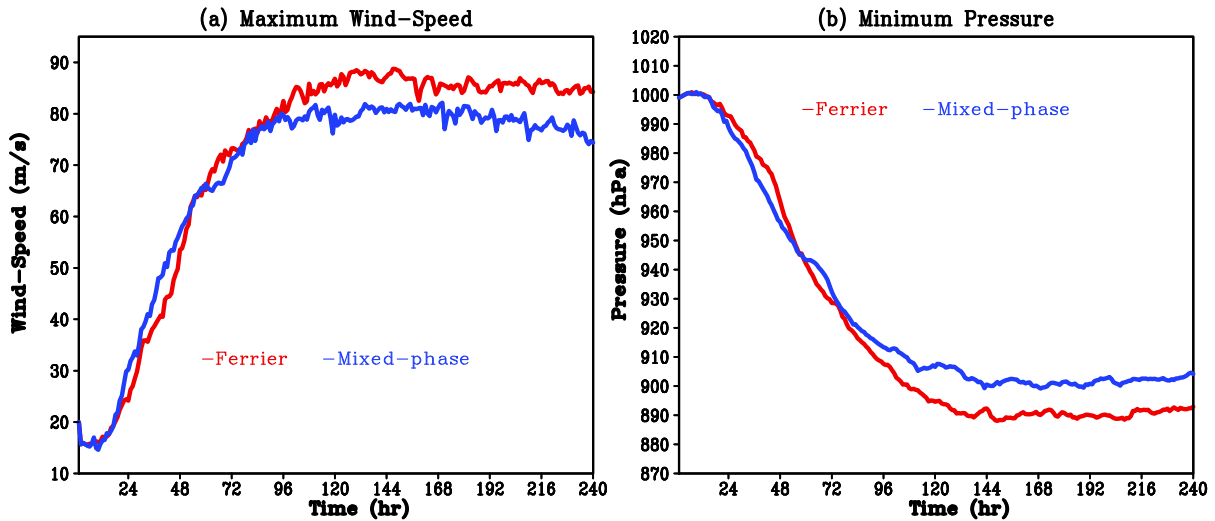


Figure 1. (a) The maximum azimuthal mean wind speed at the lowest model level (about 35 m above sea level); (b) the minimum sea level pressure of the simulated storms using Ferrier (red) and Wang (blue) cloud microphysics schemes in TCM4.

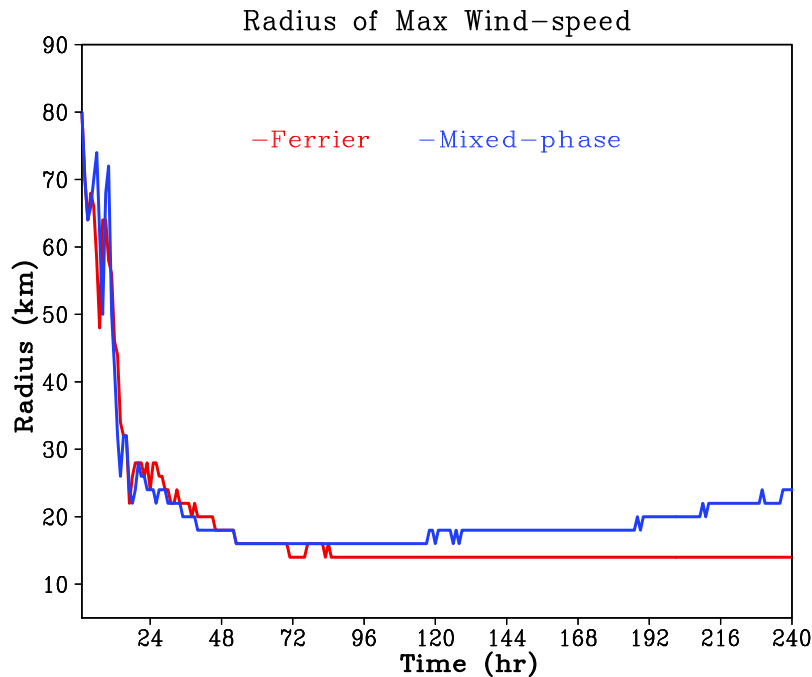


Figure 2. Time evolution of the radius of maximum azimuthal mean wind speed of the simulated storms in TCM4 with different microphysics scheme (red: Ferrier scheme, blue: TCM4 mix-phase scheme).

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).

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.

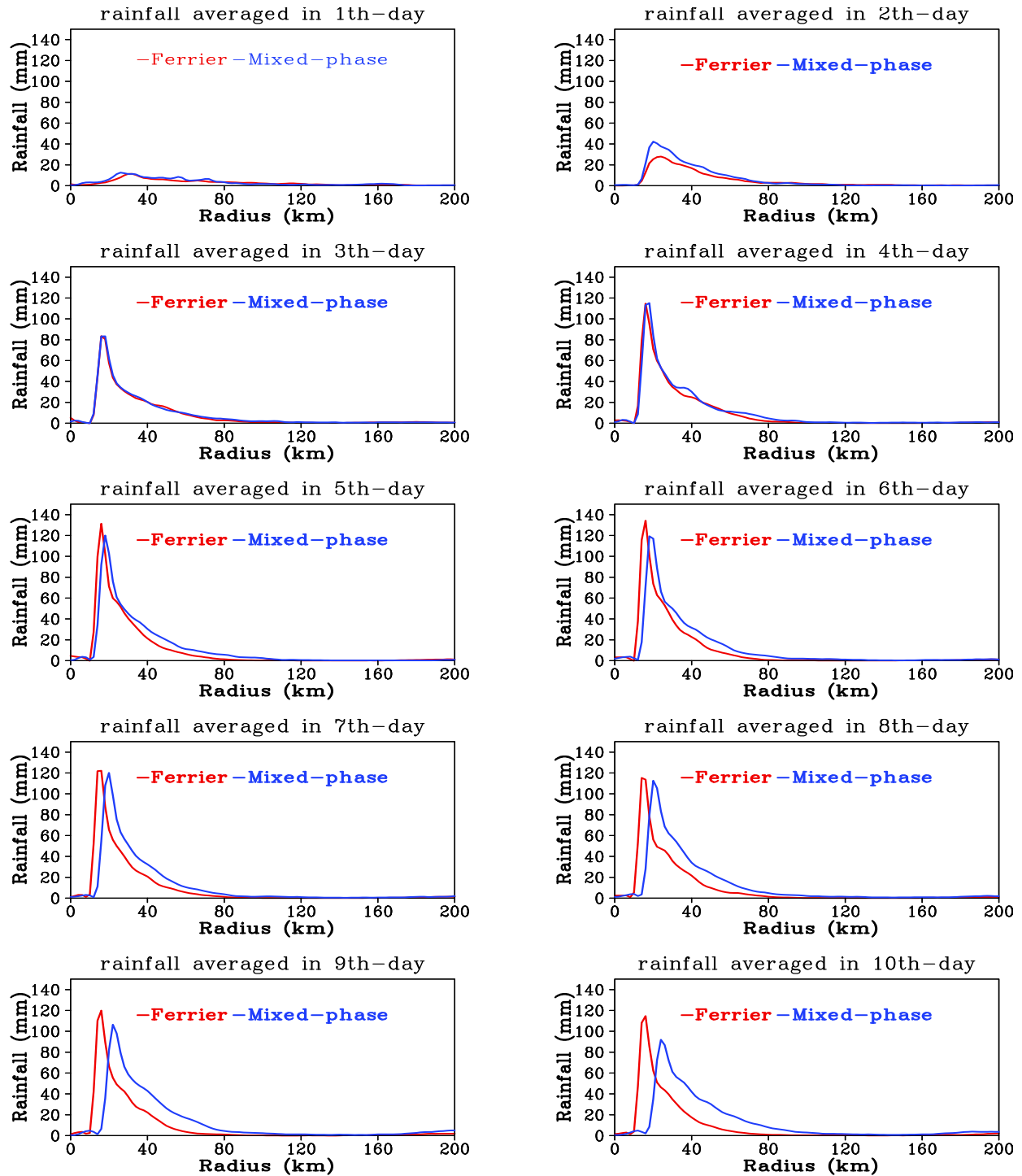


Figure 3. The azimuthal mean rainfall averaged in each 24h of simulation (red: Ferrier, blue: TCM4 mixed-phase).

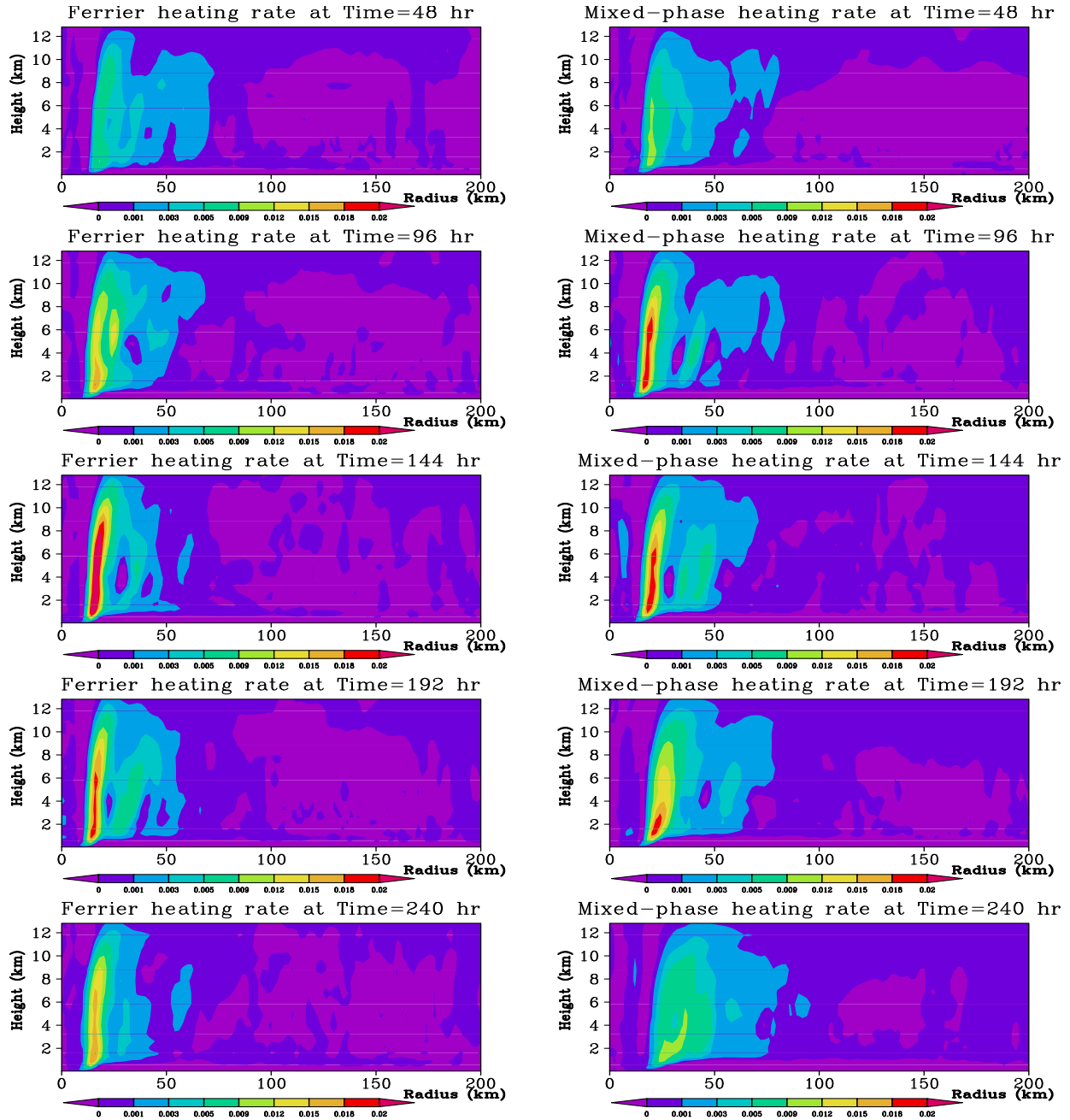


Figure 4. Radius-height distribution of the azimuthal mean diabatic heating at given times in the simulated storm with the Ferrier (left) and TCM4 (right) cloud microphysics schemes.

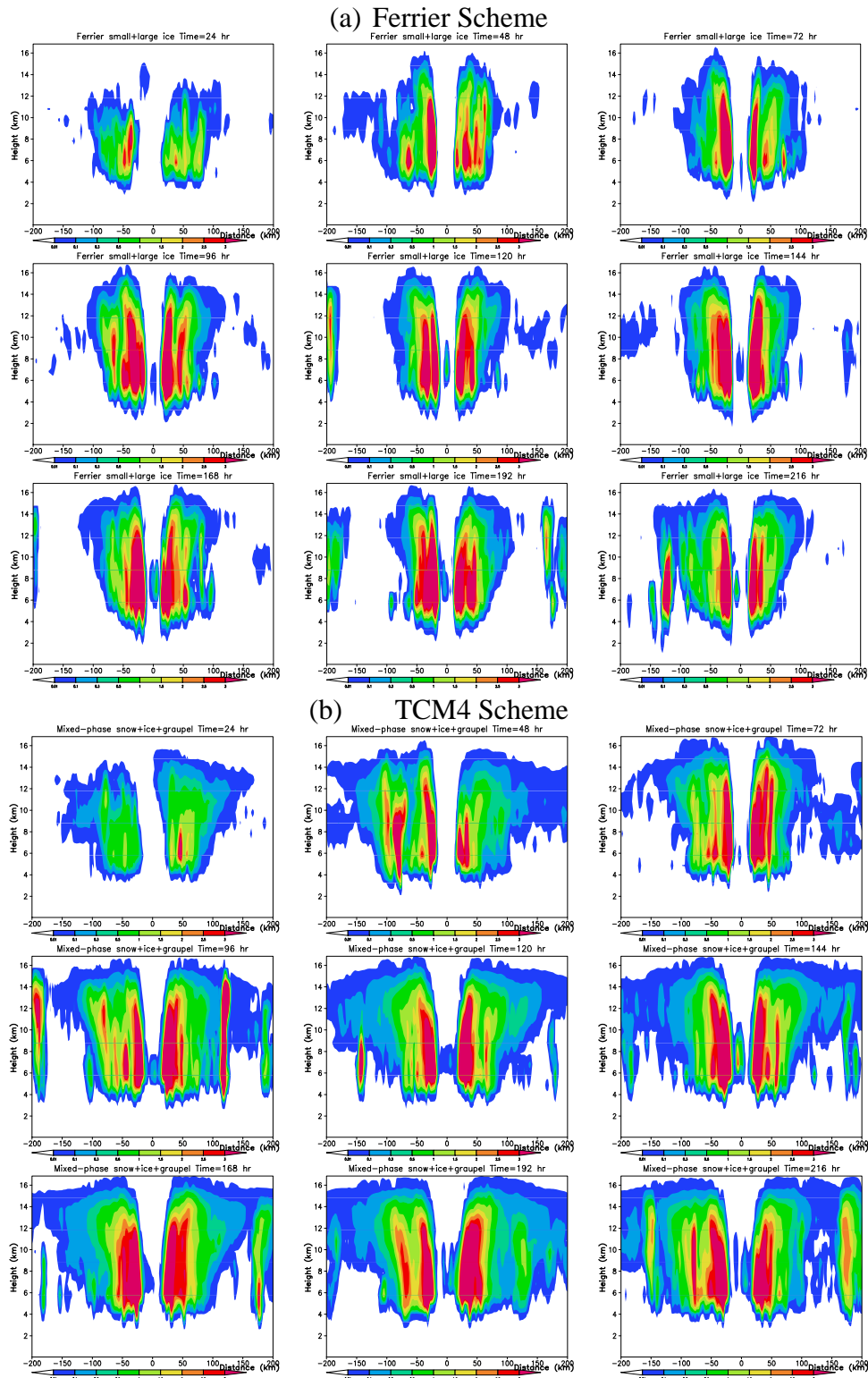


Figure 5. vertical cross-section of total ice along the east-west across the storm center simulated by Ferrier scheme (a) and TCM4 cloud microphysics scheme (b).

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.

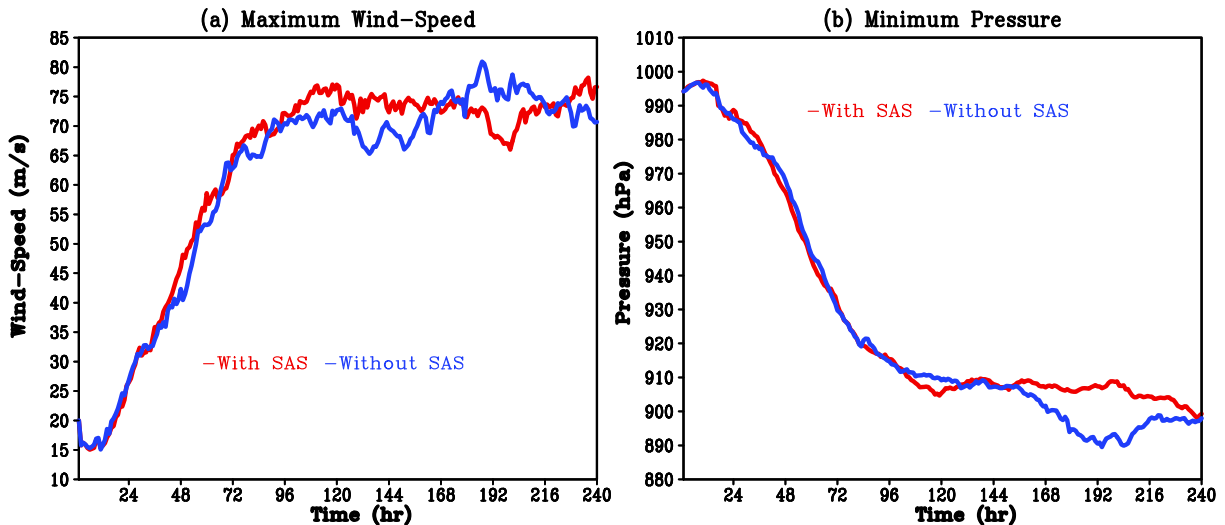


Figure 6. (a) The maximum azimuthal mean wind speed at the lowest model level (about 35 m above sea level); (b) the minimum sea level pressure of the simulated storms using Wang cloud microphysics scheme with (red) and without (blue) the use of the SAS convective parameterization scheme in the outer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

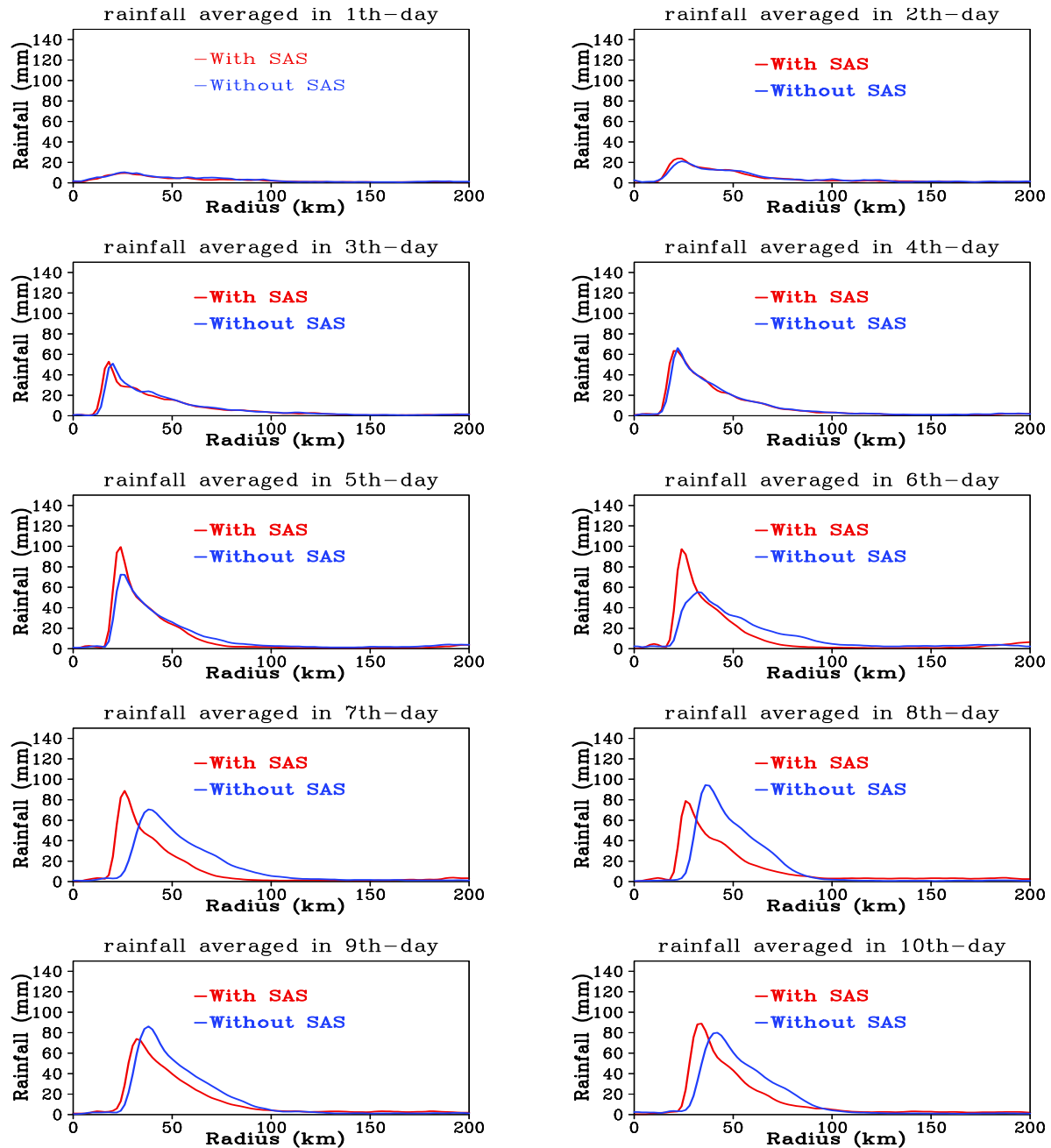


Figure 7. The azimuthal mean rainfall averaged in each 24h of simulations (red: with, blue: without the use of SAS convective scheme in the outer coarse meshes in TCM4).

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 post-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.

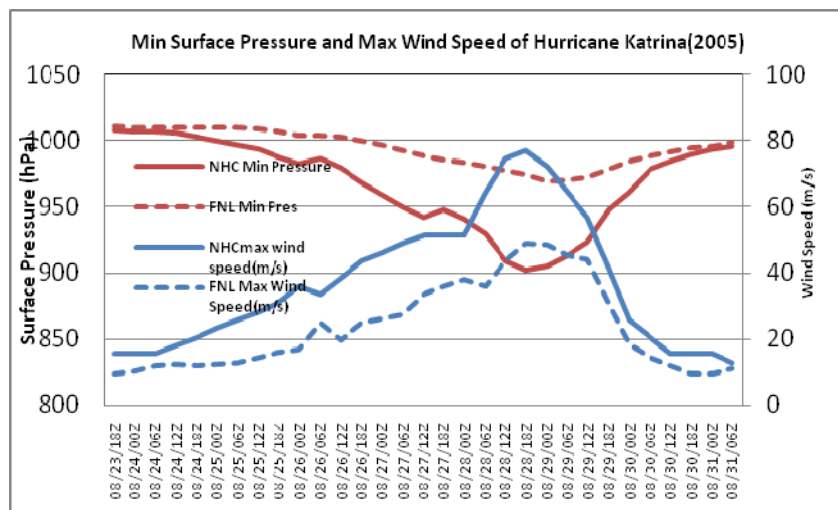


Figure 8. Minimum sea level pressure (purple) and maximum surface wind speed (blue) in the NHC best track data and in the NCEP FNL analysis.

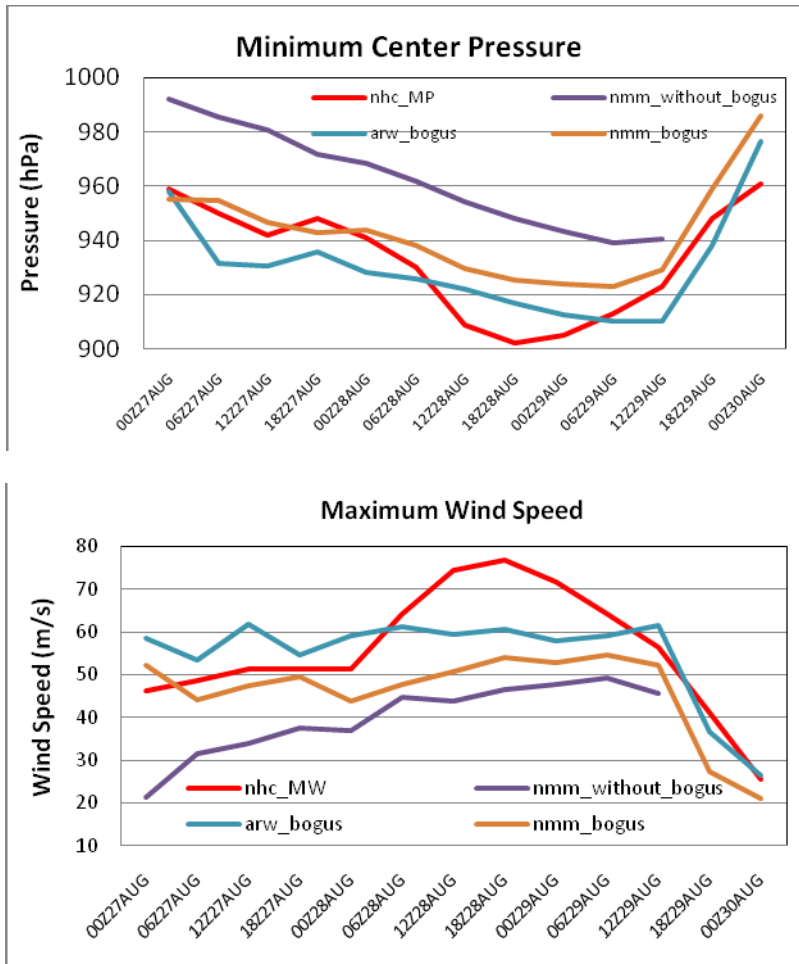


Figure 9. Minimum sea level pressure (upper panel) and maximum surface wind speed (lower panel) in the NHC best track, and from the three numerical experiments designed to examine the effect of dynamical core on the simulated storm by HWRF.

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.

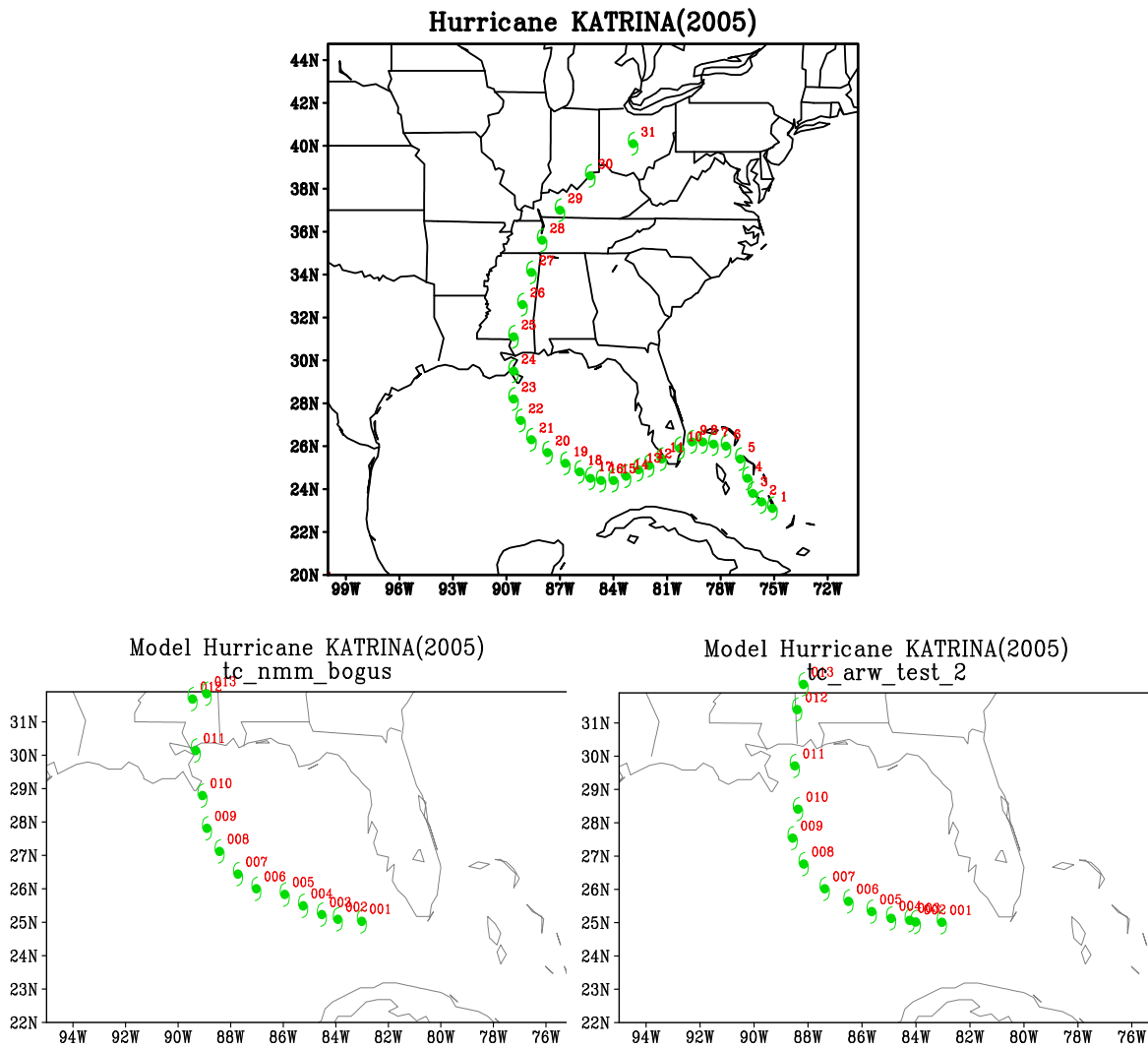


Figure 10. The best track of Hurricane Katrina (2005) from the NHC best track data (upper panel) and that predicted by WRF model with NMM (lower left) and ARW (lower right) dynamical core.

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 discretization 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.

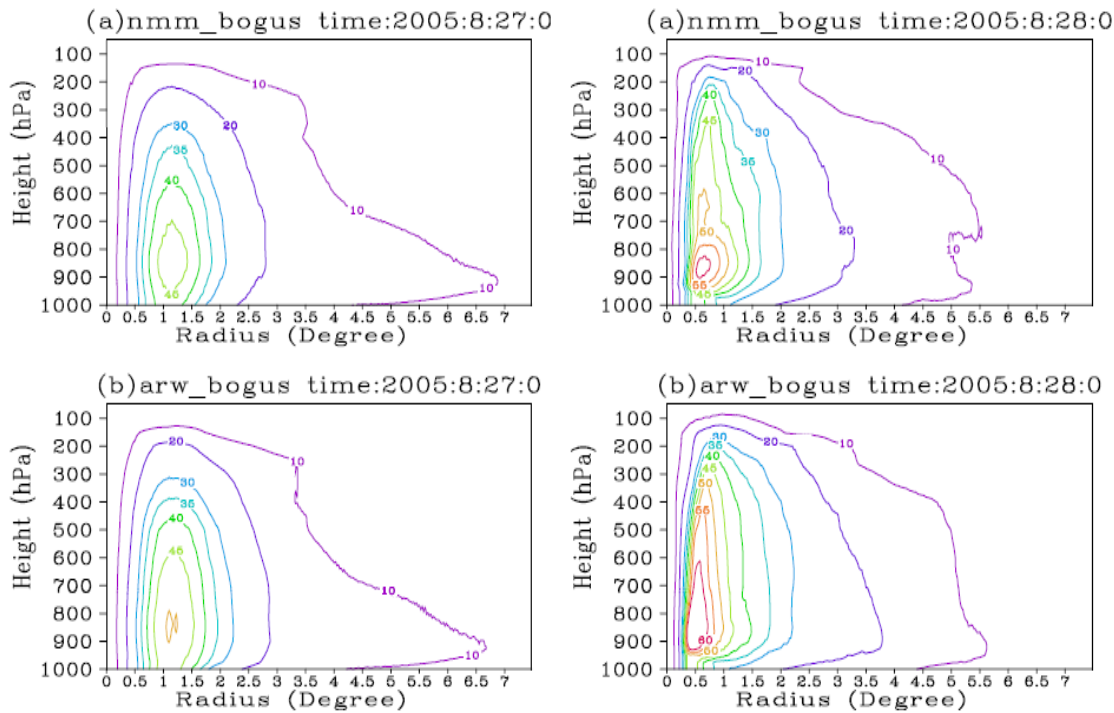


Figure 11. Height-radius cross-section of the azimuthally mean tangential wind at the initial time and after 24h of simulation with the NMM and ARW dynamical core and the initial bogus vortex.

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.

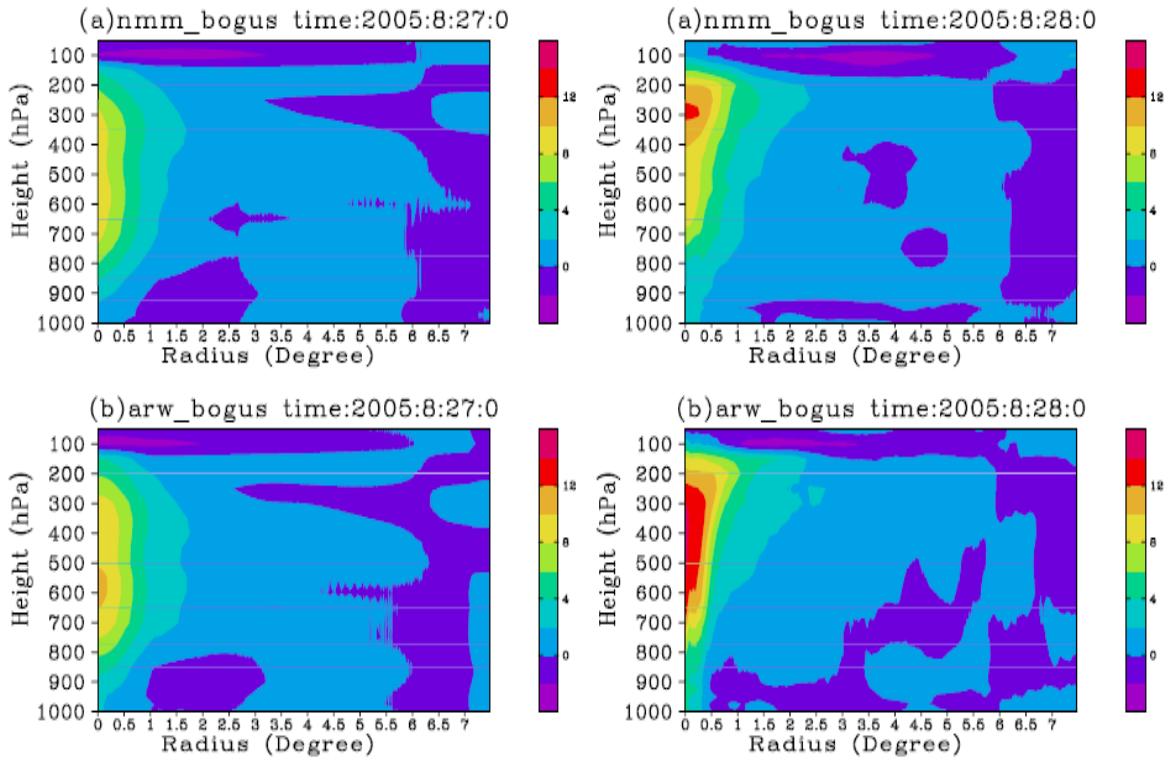


Figure 12. Height-radius distribution of the azimuthally mean temperature anomalies at the initial time and after 24 h of simulation with the NMM and ARW dynamical cores and initial bogus vortex.

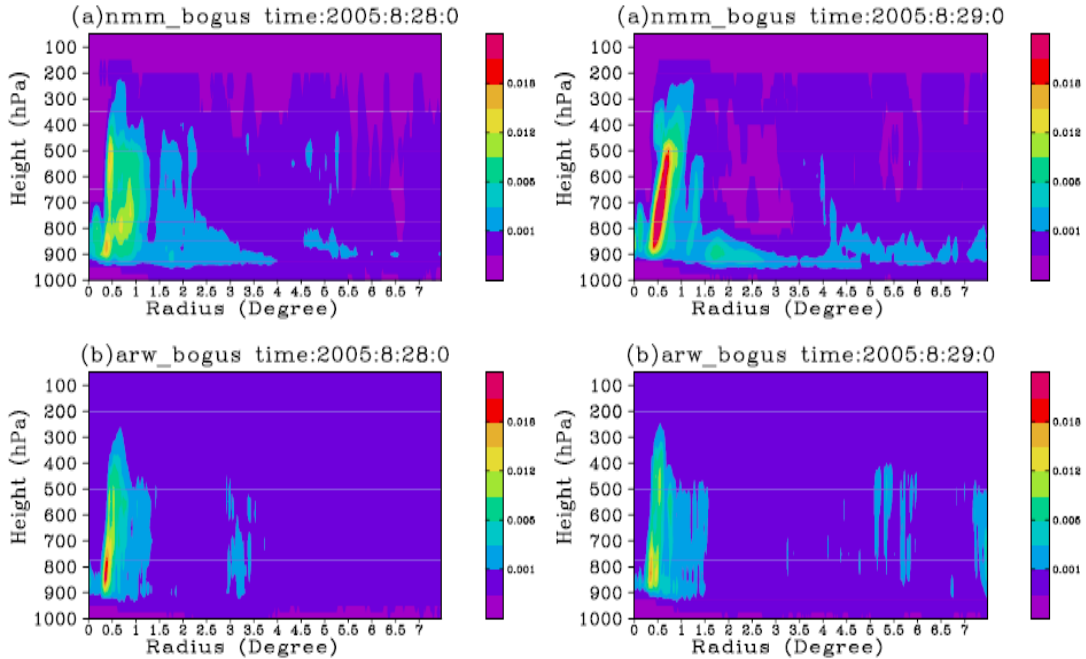


Figure 13. Height-radius distribution of the azimuthally mean cloud water after 24 h and 48h of simulations with the NMM and ARW dynamical cores, respectively.

d. Development 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 assumed to be monodisperse, with number mixing ratios that are 10^8 and 10^5 kg^{-1} respectively below the -36°C level, being zero and 10^8 kg^{-1} respectively above due to homogeneous freezing.

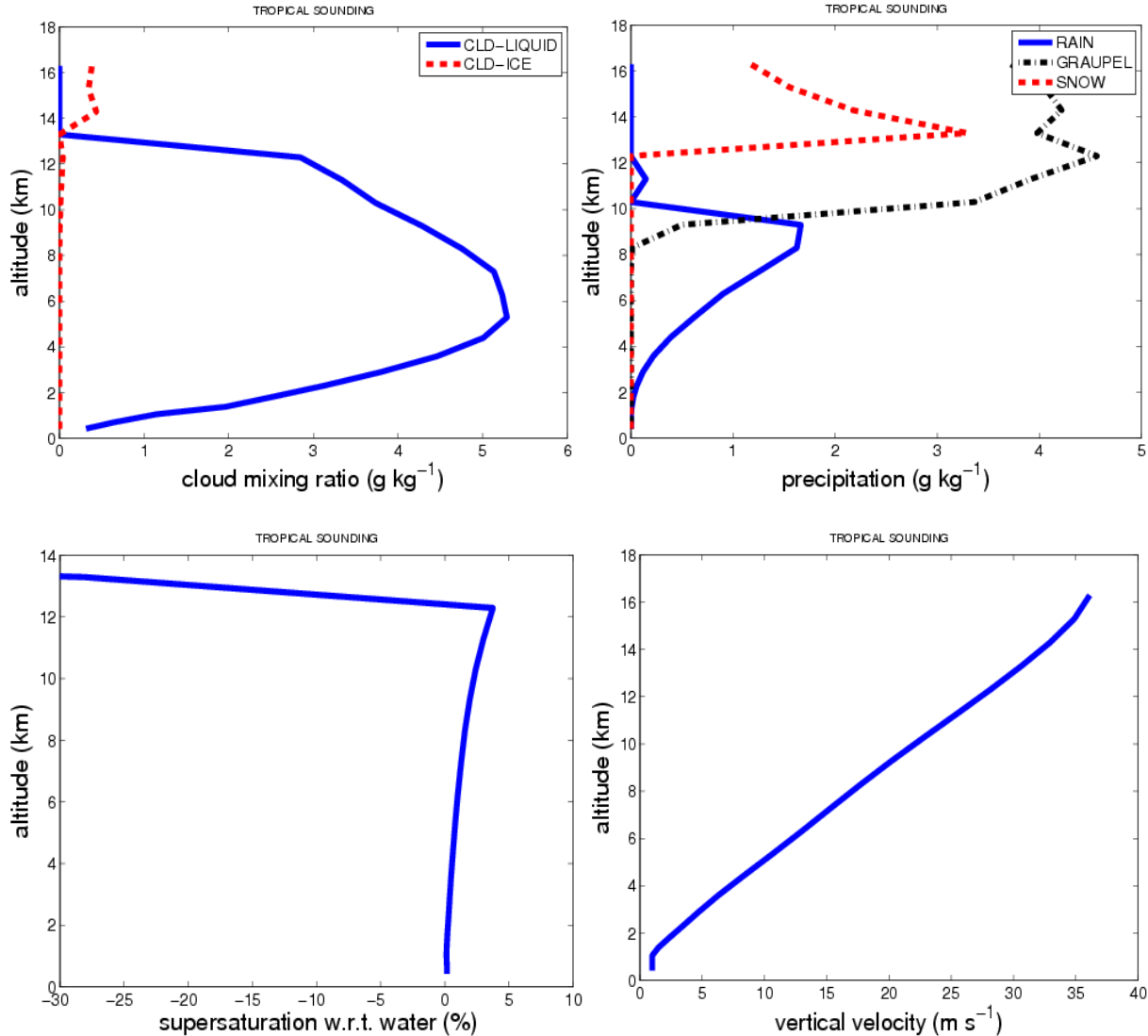


Figure 14. Off-line simulation by the SCPM of a cloudy adiabatic parcel in a vigorous deep convective updraft, for an unstable sounding. The depth of the parcel is 1 km and the ascent is calculated from an extremely unstable tropical sounding, with a relative humidity of 86% and air temperature of 27 degC 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 adiabatic 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.

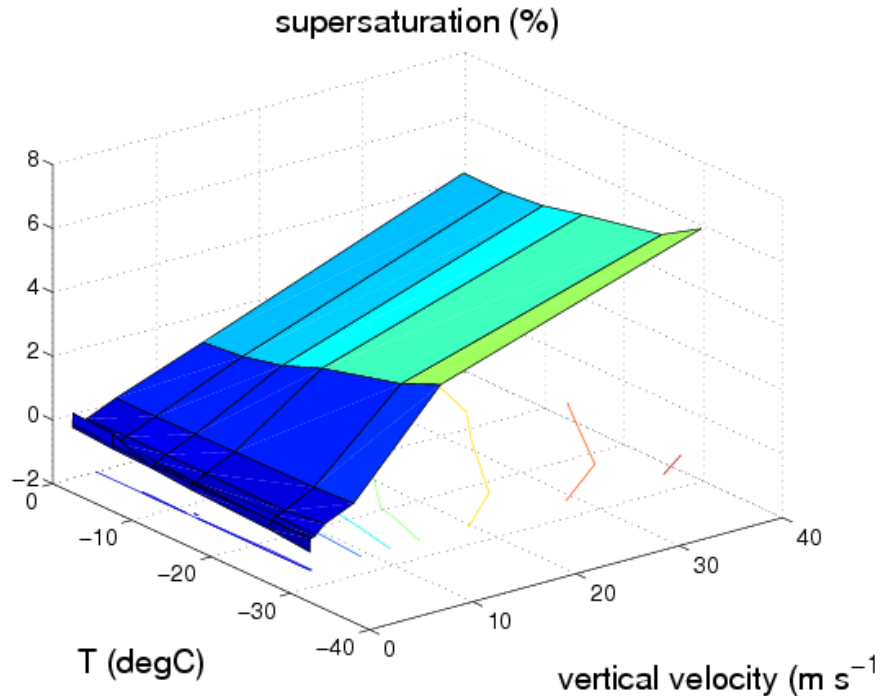


Figure 15. In-cloud supersaturation with respect to liquid water in an adiabatic parcel, predicted by many off-line runs of the SCPM. All parcel runs begin at the surface with relative humidity of 86% and temperature of 27°C . Ascent is prescribed at a constant value during each run. Note how the faster 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 in-cloud microphysical equilibrium. These all provide potential avenues for enhancing the SCPM during Year 2.

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