A Comparison of Spectral Bin Microphysics versus Bulk Parameterization in Forecasting Typhoon In-Fa (2021) before, during, and after Its Landfall

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THE OBJECTIVE OF THIS RESEARCH

Performance evaluation of various microphysical schemes in the mesoscale numerical models is of crucial significance for improving typhoon forecasts. Although in recent years Asian scholars have made considerable efforts on typhoon simulation and evaluation, there are relatively fewer studies focusing on the simulation differences of typhoons during their different landfall periods (e.g., before, during, and after landfall). The main objective herein is to evaluate the performances of various microphysical models in forecasting typhoon hydrometeors during the different periods of their landfall.

TWO TYPES OF MICROPHYSICAL REPRESENTATIONS ARE STUDIED

Parameterization of microphysical processes is instrumental for the accurate modeling of landfalling typhoons. There remain significant sensitivities of the models to the use of different mixing and cloud parameterizations, whether or not the numerical core can simulate the dynamics of the atmosphere correctly. So far, there have been many ways to parameterize the precipitation microphysics, wherein the bulk parameterization (hereinafter BULK) and the spectral bin microphysics (hereinafter BIN) are still the two most popular ones. BIN scheme possesses the most sophisticated representations of microphysical processes, which generally performs better than BULK scheme in simulating realistic cloud properties and surface precipitation. Hence, BIN scheme used to be treated as a benchmark for calibration and improvement of the BULK scheme. However useful, BIN scheme is not perfect as compared to long-term Tropical Rainfall Measurement Mission (TRMM) satellite observations.

Table 1. BIN versus BULK: different description of microphysics.

Description	**BIN**	**BULK**
DSD	Solving a system of kinetic equations for DSD	The DSD is prescribed in the form of exponential distribution or gamma distribution
Aerosols	Aerosol budget, transport of aerosols, size distribution of CCN, cloud–aerosol interaction	Fractional aerosol budget, transport of aerosols, size distribution of CCN, cloud–aerosol interaction
Condensation/ evaporation	The diffusion growth/evaporation equations are used	No equation for diffusion growth or evaporation; the strategy of saturation adjustment is utilized
Collisions	Stochastic collision equations are used	Simplified equations are used
Sedimentation	Differential fall velocity depending on particle size, shape, and air density	The bulk fall velocity for the same type of particles
Melting/ freezing	The shape of DSD changes during these nonlinear processes	The shape of DSD remains fixed during the highly nonlinear processes

ADVANCED MICROWAVE SATELLITE OBSERVATIONS ARE USED

GPM satellite happened to see Typhoon In-Fa before (2021/0722/2202 UTC), during (2021/0725/1144 UTC), and after (2021/0727/1105 UTC) its landfall at eastern China, which enabled us to verify the model performances of BIN and BULK schemes in simulating the severe storm during its different landfall periods. There are two important microwave sensors onboard the core observatory of GPM. One is the passive microwave imager named GPM Microwave Imager (GMI), and another is the active microwave radar named Dual-frequency Precipitation Radar (DPR). To evaluate the simulation of typhoon hydrometeors, the 89 GHz brightness temperature product (version 5) of GMI is used. As one of the most advanced Microwave Imager available, GMI takes advantage of coincident data at seven frequencies with both vertical and horizontal polarization channels: 10.6, 18.7, 23, 37, 89, 166, and 183 GHz. The swath width of GMI is approximately 885 km with a footprint of 7.2×4.4 km for 89 GHz channel, making it well-suited for model evaluation due to the wide sampling range. In addition, three-dimensional attenuation-corrected reflectivity product (version 6) measured from the DPR is also used for typhoon hydrometeors evaluation. DPR is the very first spaceborne radar with double frequencies (Ku and Ka), wherein Ku-band radar reflectivity has a wider swath width of approximately 245 km and a horizontal resolution of about 5 km, and thus is used for our analysis.

The famous G-SDSU model is a widely used fast model for comparison between GPM satellite observations and simulated data in signal space. It represents the emission and scattering of microwave radiation or radar reflectivity from hydrometeors based on their mass, composition (potentially including water, ice, and air), shape, internal structure, and orientation. We set the same microphysical assumptions in G-SDSU code as in the WRF microphysical schemes, and it was then configured to simulate radiances or backscattering signals fields of GPM satellite at the WRF horizontal resolution of the inner domain (3 km) and next spatially-averaged to match the resolution of GMI (7.2 × 4.4 km) or DPR (5 km) instruments.

THE HORIZONTAL DISTRIBUTION OF PRECIPITATION HYDROMETEORS IS ASSESSED

Figure 1 shows the WRF-simulated 89-GHz brightness temperature based on G-SDSU simulator. As shown in Figure 1, WRF simulations generally overestimate the radiance intensity in comparison to observations, which could be related to the considerations of more abundant solid particles (ice, snow, graupel, and hail) in the two microphysical schemes. Comparing different landfall periods, the features and locations of simulated typhoon rainbands could basically capture the trends represented in the observation before and after typhoon landfall, while during typhoon landfall, the simulation performances show large discrepancy as compared to observations. Comparing BIN and BULK schemes, it seems that the BIN scheme shows better performances than BULK scheme in simulating Typhoon In-Fa before its landfall (Figure 1a). Although both schemes overestimate the radiance intensity near typhoon center, the simulation with BIN scheme shows less overestimation than the simulation with BULK scheme. Besides, BULK scheme seems to underestimate the radiance intensity in the outermost region of the storm. However, BULK scheme appears to have better performances than BIN scheme in simulating Typhoon In-Fa after its landfall (Figure 1c). In contrast with BIN scheme, the typhoon rainband's structure and location are better captured by BULK scheme, especially for the inner rainbands located at 30°N–33°N and outer rainbands located at 27°N–28°N. Both schemes show similar performances in simulating Typhoon In-Fa during its landfall (Figure 1b).

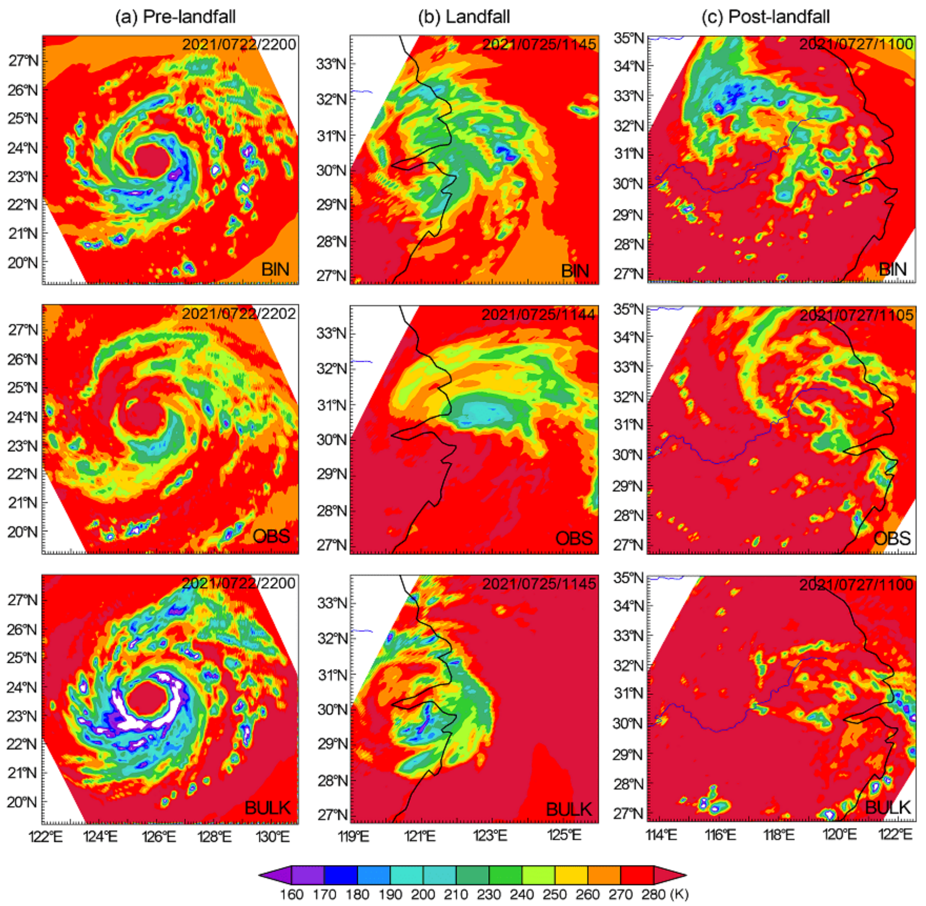


Figure 1. GMI satellite observation and WRF model simulation of brightness temperature (K) for Typhoon In-Fa (2021) during three different landfall periods.

In this section, we first utilize the GMI observed and WRF simulated 89 GHz brightness temperatures to examine the azimuthal structure of the forecast typhoon cloud and precipitation for BIN and BULK schemes. Figure 2 presents the azimuthal mean brightness temperature distributions within a radius of 500 km from the typhoon center at different periods of landfall. The observed typhoon center was obtained from the CMA BST data, while the simulated typhoon center was determined by the grid point with the minimum central pressure.

As shown in Figure 2a, the observed brightness temperature before typhoon landfall presents a curve of double peaks, with the primary peak occurring near a radius of 100 km and the secondary peak occurring near a radius of 200 km. The simulated curves of brightness temperature for both BIN and BULK schemes also exhibit the double-peak structure, but BIN scheme simulates closer brightness temperature values to observations as compared to BULK scheme. During typhoon landfall (Figure 2b), the observed curve of brightness temperature shows a single peak near a radius of 70 km, while both simulated curves of brightness temperature show multi-peak structure, indicating a relatively poor performance in typhoon structure forecast during landfall, and in agreement with the analysis of horizontal distribution of brightness temperature in Figure 4. After typhoon landfall (Figure 2c), the observed curve of brightness temperature shows weak fluctuation characteristics. The simulation with BULK scheme well resembles such characteristics, while BIN scheme simulates too much fluctuation. Besides, the simulated brightness temperature of BIN scheme (with a peak value close to 240 K) is significantly colder as compared to that of BULK scheme (with values generally greater than 270 K), indicating less forward scattering of radiation due to more abundant ice-phase particles in simulation with BIN scheme. This implies that for typhoon landing, BULK scheme appears to possess greater advantages than BIN scheme in simulating ice-phase particles and cold rain processes, which could be closely related to their different configuration of microphysical assumptions as already suggested in Table 1.

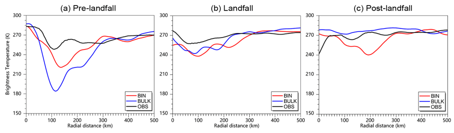


Figure 2. Azimuthal mean brightness temperature (K) distributions of GMI satellite observation and WRF simulations for Typhoon In-Fa (2021) during three different landfall periods.

Overall, the forecast skill of typhoon outer rainband is the best, the eyewall prediction comes second, and the prediction performance of inner rainband is the worst. The results suggest that the cloud microphysics schemes had the largest impact on the typhoon inner rainband forecast, which could stem from the complicated microphysical processes observed in inner rainband area.

THE VERTICAL STRUCTURE OF PRECIPITATION HYDROMETEORS IS ASSESSED

Compared with BULK scheme, BIN scheme is likely able to simulate more liquid-phase particles (mainly raindrops) after typhoon landfall, which quickly fall out and hydrostatically produce the lower pressure (Figure 2a) [5]. To confirm that, Figure 4 further presents the vertical profiles of domain-averaged mixing ratio for different hydrometeor species. It is notable in Figures 4a and 4b that BULK scheme simulates much more super-cooled cloud water while relatively fewer snow crystals than BIN scheme, and especially after typhoon landfall, the snow crystal simulated by BIN scheme is almost twice as much as that simulated by BULK scheme. Meanwhile, both schemes simulate scarce amounts of graupels ($\leq$ 0.05 g kg−1, not shown here). This explains why BIN scheme simulates stronger radar reflectivity than BULK scheme in the upper troposphere, especially during the post-landfall period (Figure 3c), hence resulting in an overestimation of cold rain processes. In the lower troposphere, however, the situation reverses. As the storm lands, the rainwater simulated by BULK scheme is gradually reduced and even less than that simulated by BIN scheme (Figure 4c), leading to a lower reflectivity in the lower troposphere (Figure 3c) and possibly an underestimation of warm rain processes. In general, BULK scheme shows potential advantages in simulating solid-phase particles (mainly snow crystals) as well as cold rain processes in the upper troposphere, which is believed to be closely associated with the much larger amount of hail simulated by BULK scheme than BIN scheme (Figure 4d). As reported in Wu et al. [10], the hail category contributes to the prevention of excessive amounts of snow crystals. In contrast, BIN scheme can be better at simulating warm rain processes and liquid-phase particles in the lower troposphere, especially after typhoon landfall, making it superior to BULK scheme in simulating typhoon intensity. However, BIN scheme is not perfect, as when compared to GPM-DPR we observed vertical reflectivity profiles (Figure 3), and it can be further improved by weakening (strengthening) the cold (warm) rain processes. Both this study and Wu et al. [10] suggest that the simulation of warm rain processes by BULK scheme needs essential improvement, and BIN scheme may help to improve BULK scheme.

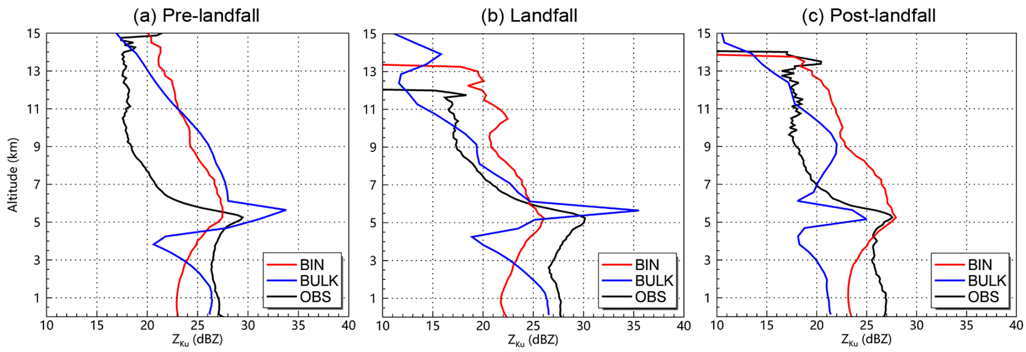
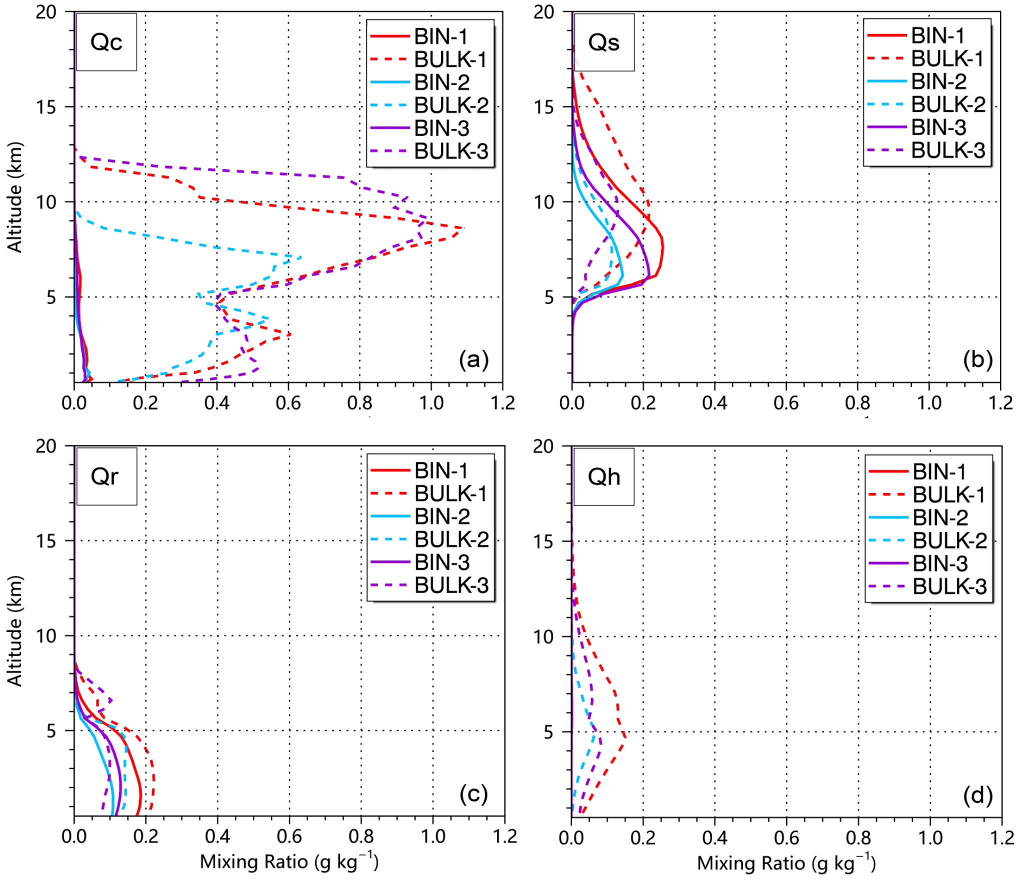


Figure 3. Domain-averaged vertical profiles of attenuation-corrected radar reflectivity (Zku) derived from both GPM DPR observation and WRF model simulation for Typhoon In-Fa (2021) during three different landfall periods.

However, BULK scheme needs essential improvement in the simulation of warm rain processes as we've analyzed earlier. In addition, it is also notable in the vertical reflectivity profiles (Figure 3) that BULK scheme shows abnormally lower simulated values than the observed near the melting level, which can partially explain its poorer performances than BIN scheme in simulating warm rain processes. As reported in Lei et al. [53], BULK scheme (WDM6 scheme) has systematic bias in the prediction of warm rain hydrometeors, and high concentration of small raindrops tends to appear near the 0 °C layer as validated against airborne observations. To confirm that, we give the number concentration of warm rain hydrometeors in typhoon simulations as shown in Figure 5. One can notice that BULK scheme (WDM7 scheme) produces abnormally high raindrop number concentrations at an altitude around the melting level (Figure 5a), possibly due to the fast melting processes of snow, graupel, and hail [53]. Meanwhile, the cloud drop number concentrations of BULK scheme are significantly higher than that of BIN scheme (Figure 5b), probably because of the saturation adjustment strategy in BULK scheme. Khain et al. [17] also revealed that the saturation adjustment applied in computing condensation/evaporation in bulk schemes is largely responsible for the major discrepancies in simulating cloud water content. Other reasons might include the differences in aerosol activation and cloud drop evaporation between the two schemes. BIN scheme implements more complex descriptions of aerosol distribution and aerosol-cloud interaction (Table 1), making it superior to BULK scheme in simulating warm rain hydrometeors. Overall, to further improve the prediction of warm rain hydrometeors by BULK scheme, we need to modify the melting process of solid-phase particles, the condensation/evaporation process of liquid-phase particles, and the aerosol-related processes based on direct cloud microphysics observations.



CaptionFigure 4. Domain-averaged vertical profiles of (a) cloud water, (b) snow, (c) rainwater, and (d) hail mixing ratio (g kg−1) during three different periods of typhoon landfall. The symbol Qx (x = c, s, r, h) represents the mixing ratio of each hydrometeor species, and the appending digits -1, -2, and -3 in the legend represent the periods before, during, and after landfall, respectively.

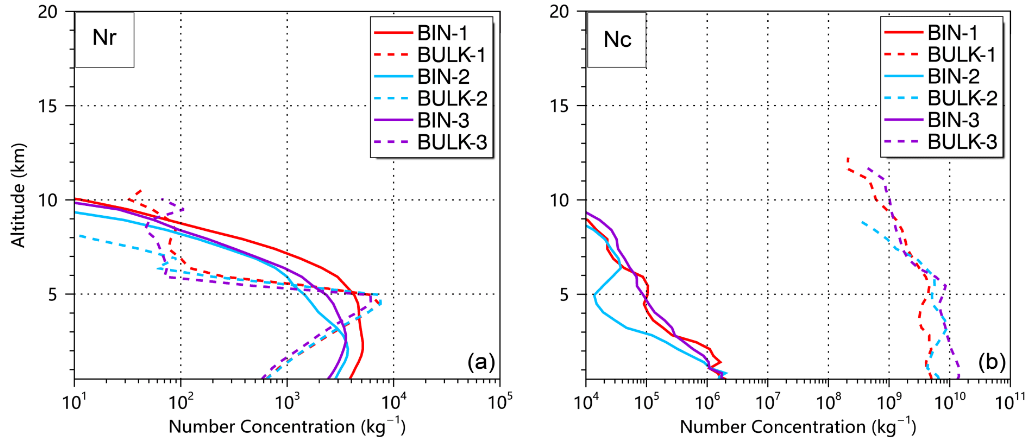


Figure 5. Domain-averaged vertical profiles of (a) raindrop and (b) cloud droplet number concentration (kg−1) during three different periods of typhoon landfall. The symbol Nx (x = r, c) represents the number concentration of each hydrometeor species, and the appending digits -1, -2, and -3 in the legend represent the periods before, during, and after landfall, respectively.

SEVERAL IMPORTANT CONCLUSIONS ARE OBTAINED

1. Simulations of the azimuthal profile of brightness temperature are validated against the corresponding GMI observations, and it is indicated that the forecast skill of typhoon inner (outer) rainbands is worst (best). Meanwhile, BIN (BULK) scheme better simulates the azimuthal structure of typhoon hydrometeors before (after) landfall, and it is relatively more difficult for both schemes to simulate the azimuthal structure of hydrometeors during typhoon landfall.

2. Simulations of the vertical profile of radar reflectivity are validated against the corresponding DPR observations, and it is indicated that, with the storm landing, BULK scheme shows worse performance than BIN scheme in simulating warm rain processes. This is because BULK scheme simulates less rainwater with lower humidity than BIN scheme after typhoon landfall, which possibly leads to stronger evaporation of rainwater. However, the BULK scheme is more advantageous in simulating cold rain processes after typhoon landfall, possibly due to its ability in simulating more hailstones that effectively consume the excessive amount of snow crystals.

3. BIN scheme might overestimate the cold rain processes while underestimate the warm rain processes in typhoon simulation, and BULK scheme shows limitations in simulating the warm rain processes, such as melting of ice particles and evaporation of liquid particles. Meanwhile, BULK scheme is noted to simulate more cloud water and larger convective updraft than BIN scheme, probably due to the widespread application of saturation adjustment in bulk parameterizations, and similar conclusions have also been reported in many model studies comparing BIN and BULK schemes.

AUTHOR INFORMATION

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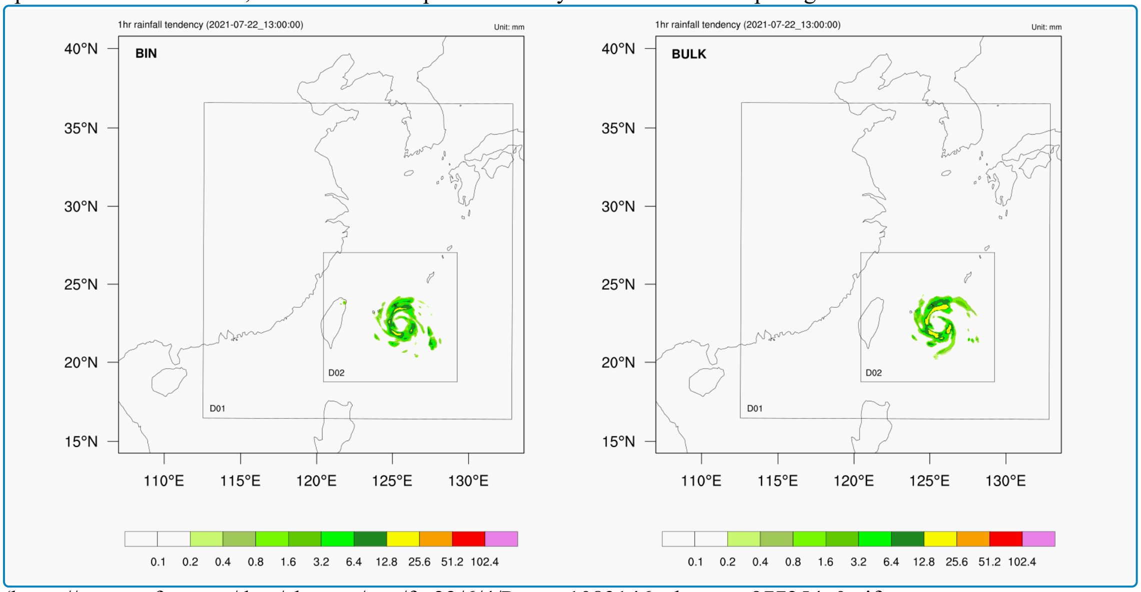
ABSTRACT

Typhoon In-Fa hit continental China in July 2021 and caused an unprecedented rainfall amount, making it a typical case to examine the ability of numerical models in forecasting landfalling typhoons. The record-breaking storm was simulated using a 3-km-resolution weather research and forecast (WRF) model with spectral bin microphysics scheme (BIN) and two-moment seven-class bulk parameterization scheme (BULK). The simulations were then separated into three different typhoon landfall periods (i.e., pre-landfall, landfall, and post-landfall). At present, the ability of WRF and other mesoscale models to accurately simulate the typhoon precipitation hydrometeors is still limited. To evaluate the performances of BIN and BULK schemes of WRF model in simulating the condensed water in Typhoon In-Fa, the observed microwave brightness temperature and radar reflectivity from the core observatory of Global Precipitation Mission (GPM) satellite are directly used for validation with the help of a satellite simulator. It is suggested that BIN scheme has better performance in estimating the spatial structure, overall amplitude, and precise location of the condensed water in typhoons before landfall. During typhoon landfall, the performance of BIN scheme in simulating the structure and location of the condensate is close to that of BULK scheme, but the condensate intensity prediction by BIN scheme is still better; BULK scheme performs even better than BIN scheme in the prediction of condensate structure and location after typhoon landfall. Both schemes seem to have poorer performances in simulating the spatial structure of precipitation hydrometeors during typhoon landfall than before/after typhoon landfall. Moreover, BIN scheme simulates more (less) realistic warm (cold) rain processes than BULK scheme, especially after typhoon landfall. BULK scheme simulates more cloud water and larger convective updraft than BIN scheme, and this is also reported in many model studies comparing BIN and BULK schemes.



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