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Impact of Multiphysics Ensemble on Typhoon Mujigae (2015) Simulation in WRF Model

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Abstract: Typhoons, characterized by their high destructive potential, significantly impact coastal residents' lives and property safety. To optimize numerical models' typhoon simulation, carefully selecting appropriate physical parameterization schemes is crucial, offering robust support for disaster prevention and reduction efforts. This study focuses on Typhoon Mujigae, conducting a comparative analysis of different physical parameterization schemes (microphysics, cumulus parameterization, shortwave radiation, and longwave radiation) in WRF simulations. The key findings are as follows: cumulus and microphysics parameterization schemes notably influence the simulation of typhoon tracks and intensity, while the impact of longwave and shortwave radiation schemes is relatively minor. Typhoon intensity is more sensitive to the choice of parameterization schemes than track. Together, the Kain-Fritsch cumulus convection scheme, WRF Single Moment 5-class scheme, and Dudhia/RTM radiation scheme yield the best intensity simulation results. Compared with the Betts-Miller-Janjić and Grell 3D scheme, the use of the Kain-Fritsch scheme results in a clearer, taller eyewall and more symmetric deep convection, enhancing precipitation and latent heat release, and consequently improving the simulated typhoon intensity. More complex microphysics schemes like Purdue Lin, WRF Single Moment 5-class, and WRF Double Moment 6-class perform better in simulations, while simpler schemes like Kessler and WSM3 exhibit significant deviations in typhoon simulations. Particularly, the large amount of supercooled water clouds simulated by the Kessler scheme is a major source of bias. Furthermore, a coupling effect exists between cumulus convection and microphysics parameterization schemes, and only a reasonable combination of both can achieve optimal simulation results.

Key words: WRF; typhoon simulation; cumulus parameterization; microphysics parameterization; deep convection

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1 INTRODUCTION

Typhoons, characterized by their intense cyclonic vortices and warm-core structure, typically originate over warm sea surfaces in tropical or subtropical regions (Kepert^[1]). Guided by steering winds and influenced by the beta effect, they commonly follow a northwestward trajectory (Chan^[2]), making landfall along the

southeastern coast of China. Typhoon events are frequently accompanied by strong gusts and heavy precipitation, posing significant threats to life and property safety in coastal regions of China (Zhang and Chen^[3]; Ren et al.^[4]). Accurately forecasting the trajectory and intensity of typhoons is essential for providing robust scientific support for disaster preparedness and mitigation in meteorological contexts.

At present, the accuracy of typhoon forecasting heavily relies on numerical models. While recent advancements have significantly improved the prediction of typhoon tracks, forecasting their intensity remains a challenge, resulting in notable discrepancies (Wang^[5]; Tan et al.^[6]). Processes such as boundary layer dynamics, cumulus convection, cloud microphysics, and longwave and shortwave radiation are crucial in influencing typhoon intensity. However, models often use parameterization methods to approximate these sub-grid processes, serving as a major source of simulation errors (Liu et al.^[7]; Chan and Chan^[8]; Baki et al.^[9]). Extensive research has been conducted on the optimization of different physical parameterization schemes within the mesoscale

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numerical weather prediction model, Weather Research and Forecasting (WRF). However, for different individual typhoon cases, consistent results regarding the preferred combinations of these schemes have yet to be achieved (Raju et al. [10]; Wannawong et al. [11]). Determining the optimal parameterization scheme combination for achieving the best simulation of typhoon intensity remains a central focus of inquiry.

The latent heat released during convective and precipitation processes constitutes the primary energy source for typhoons (Briegel and Frank [12]), directly influencing intensity. In numerical simulations, such a process is closely linked with physical parameterization schemes, including cumulus convection, cloud microphysics, and longwave and shortwave radiation. Scholars have highlighted the substantial impact of cumulus parameterization schemes (CPs) on simulating typhoon intensity (Islam et al. [13]). Moreover, microphysics schemes (MPs) cover various phase descriptions of water, including vapor, ice crystals, rainwater, and snow, directly influencing the forecast of typhoon intensity (Tao et al. [14]). Furthermore, research suggests that longwave and shortwave radiation processes also play a role in typhoon intensity simulation (Tao et al. [14]; Bu et al. [15]; Yang and Tan [16]). Therefore, it is crucial to explore the individual and combined impacts of different types of parameterization schemes on typhoon intensity simulation. Moreover, within the same type of parameterization scheme, multiple choices may lead to variations in simulation results (Wang [17]; Tan et al. [6]). Analyzing the variations caused by different parameterization schemes, identifying associated issues with each scheme, and providing practical usage recommendations are essential for advancing our understanding and prediction of typhoon intensity in meteorological contexts.

Typhoon Mujigae (2015) made landfall in Zhanjiang, Guangdong, causing severe loss of life and property. This study focused on the optimization of parameterization schemes related to cumulus convection, microphysics, and radiation for Mujigae. The aim was to achieve the best simulation results for typhoon intensity and to explore potential mechanisms behind the differences in simulation outcomes resulting from different parameterization schemes. The second section introduced Mujigae and detailed the configuration of sensitivity experiments. In the third section, we analyzed the differences in simulated Mujigae's intensity and track based on various parameterization scheme combinations. The fourth section explored potential mechanisms for generating simulation differences by analyzing convective and precipitation conditions. Finally, the paper concluded with a summary and discussion.

2 MODEL EXPERIMENT AND METHODOLOGY

2.1 Case description

Typhoon Mujigae, the strongest typhoon to make landfall in China in 2015, resulted in 27 fatalities and

caused direct economic losses exceeding 3.66 billion USD (Tang et al. [18]). According to the Joint Typhoon Warning Center (JTWC) records, Mujigae developed into a tropical depression over the ocean at 1200 UTC on October 1, 2015, located at 122.7°E and 15.2°N. It then moved northwestward into the South China Sea, rapidly intensifying into a strong typhoon by 1000 UTC on October 3. At 0600 UTC on October 4, it made landfall along the coastal area of Potou, Zhanjiang City. The maximum near-center surface wind speed (MSWS) was more than 50 m s^{-1} , and the central minimum sea level pressure (MSLP) reached 950 hPa (Pang et al. [19]).

2.2 Model description and configuration

The non-hydrostatic mesoscale model Weather Research and Forecasting (ARW) Version 4.0 (WRF) was employed as the numerical model for this study. The initial fields were generated using ERA5 reanalysis data provided by the ECMWF, with a horizontal resolution of 0.25° . The International Best Track Archive for Climate Stewardship (IBTrACS) data (Knapp et al. [20]) were employed to validate typhoon simulation results. Additionally, to compare and analyze the differences in the model's capability to simulate typhoon eyewall precipitation and convective activity under different parameterization schemes, the Integrated Multi-satellite Retrievals for Global Precipitation Measurement (IMERG) data were used. This dataset includes precipitation information with a temporal resolution of 30 minutes and a spatial horizontal resolution of 0.1° (Huffman et al. [21]).

The simulation domain center was located at (19.1°N, 115.2°E), and the grid points in the simulation domain were 436×349 (Fig. 1). The simulation period covered from 0000 UTC on October 2, 2015, to 0000 UTC on October 5, 2015, encompassing the entire process of Mujigae intensifying from a tropical storm to a strong typhoon and ultimately making landfall. The model's time integration time step was set at 30 seconds, with a horizontal resolution of 6 km. The vertical configuration included a top at 50 hPa and 40 layers. The layer

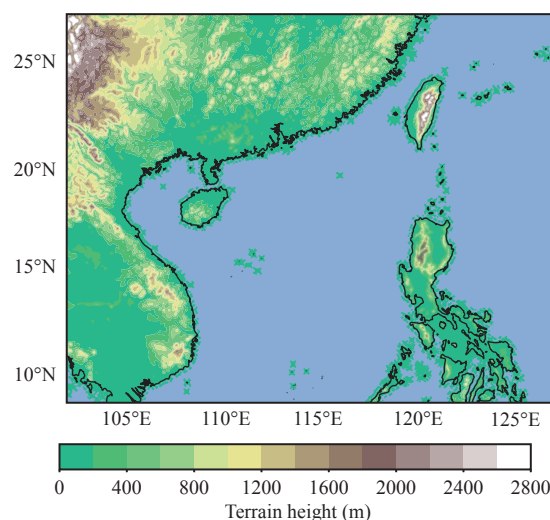


Figure 1. Model domain configurations.

distribution followed the default settings. The planetary boundary layer scheme and land surface scheme employed were the Yonsei University boundary layer scheme (YSU) (Hong et al. [22]) and the Noah land surface model (Noah), respectively. All the detailed information described above is listed in Table 1.

Table 1. Module configuration of WRF.

Module	Configuration
Period	20151002_00:00:00– 20151005_00:00:00
Time step	30 seconds
Domain	10°–30°N, 100°–130°E (436×349)
Horizontal resolution	6 km
Vertical resolution	Module top set to 50 hPa, 40 layers
Map projection	Mercator
Planetary boundary layer	Yonsei University Scheme
Land surface	Noah Land Surface Model

2.3 Experiment design

This study conducted a suite of sensitivity experiments involving parameterization schemes, including those related to cumulus convection, microphysics, and shortwave and longwave radiation. The CPs involve an implicit calculation method to describe the development, evolution, and precipitation generation of sub-grid-scale convective clouds. In this study, sensitivity experiments were conducted with the Kain-Fritsch (KF) scheme, Betts-Miller-Janjić (BMJ) scheme, and Grell 3D (G3) scheme.

The KF scheme calculates moisture tendencies for four categories of variables (cloud water, cloud ice, rain, and snow) and includes a representation of shallow convection processes. The KF scheme, based on the Lagrangian parcel method and vertical momentum dynamics, is capable of discerning convective triggering and cloud properties (Kain and Fritsch [23]; Kain [24]). The BMJ scheme falls into the category of adjustment-type schemes, utilizing reference profiles to adjust the vertical profiles of temperature and humidity. It considers the impact of both deep and shallow convection on environmental instability (Janjić [25]). The G3 scheme is an improvement derived from the Grell-Devenyi ensemble scheme. Both of them employ an ensemble approach to handle convective triggering, with ensemble-averaged results fed back into the main model (Grell [26]; Grell and Dévényi [27]).

The role of MPs is explored in simulating the processes of precipitation particle aggregation, accretion, growth, and fallout. Based on the complexity of MPs, the following five schemes were selected for experimentation: Kessler, Purdue Lin (Lin), WRF Single Moment 3-class (WSM3), WRF Single Moment 5-class (WSM5), and WRF Double Moment 6-class (WDM6). The Kessler scheme is the simplest when only warm cloud precipitation

processes and calculating clouds and raindrops are considered (Kessler [28]). The Lin scheme considers five categories of mass variables (cloud water, cloud ice, rain, snow, and graupel) and accounts for non-hydrostatic effects, entrainment, cloud microphysics, lateral mixing, and vertical mixing processes (Chen and Sun [29]). WSM3 considers mass variables for cloud water particles and raindrops. WSM5 calculates variables for four categories (cloud water, cloud ice, rain, and snow). At the same time, WSM6 is a double-moment scheme, calculating variables for five precipitation particles (cloud water, cloud ice, rain, snow, and graupel), and it also considers the number density of ice crystals, cloud water, and raindrops (Hong et al. [30]).

Shortwave radiation schemes (SRs) and Longwave radiation schemes (LRs) are employed in the main model to compute atmospheric temperature tendency profiles and surface radiation fluxes, playing a crucial role in the accuracy of simulation results. SRs calculate solar radiation under clear-sky and cloudy atmospheric conditions, considering diurnal variations. The SRs used in the experiments include Dudhia, RRTMG, and CAM, while LR schemes include RRTM, CAM, and RRTMG. The Dudhia scheme does not consider the impact of ozone, so when selecting it, the model's top layer needs to be set below the stratosphere (Dudhia [31]). RRTMG scheme is a modification of RRTM and is applied in general circulation models (GCM). RRTMG considers atmospheric components consistent with RRTM, including water vapor, ozone, and other long-lived greenhouse gases (Iacono et al. [32]). The CAM scheme is part of the NCAR Community Atmosphere Model (CAM 3.0) and comprises both shortwave and longwave radiation components. The CAM model integrates multispectral radiation transmission, parameterized radiation schemes, and cloud radiation parameterization (Collins et al. [33]).

For sensitivity numerical experiments related to Mujigae, the study involved four CPs (including the option to disable cumulus convection parameterization), five MPs, and three radiation schemes (Table 2). The notation CxMxRx will be used in the text to represent various combinations of parameterization schemes.

2.4 Method

The statistical metrics used in this paper to analyze the experimental results are the root mean square error (RMSE) and the coefficient of variation (C_v), and their calculation formulas are as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (x_i - o_i)^2}{n}} \quad (1)$$

$$C_v = \frac{\sigma}{\mu} \quad (2)$$

In Eq. 1, x_i represents the simulated value, o_i represents the observed value, and n represents the sample size. In Eq. 2, σ stands for standard deviation, and μ stands for mean value.

Table 2. MPs (5 types), CPs (4 types, including the case with no parameterization), SRs, and LR (3 types) were used in the ensemble experiments.

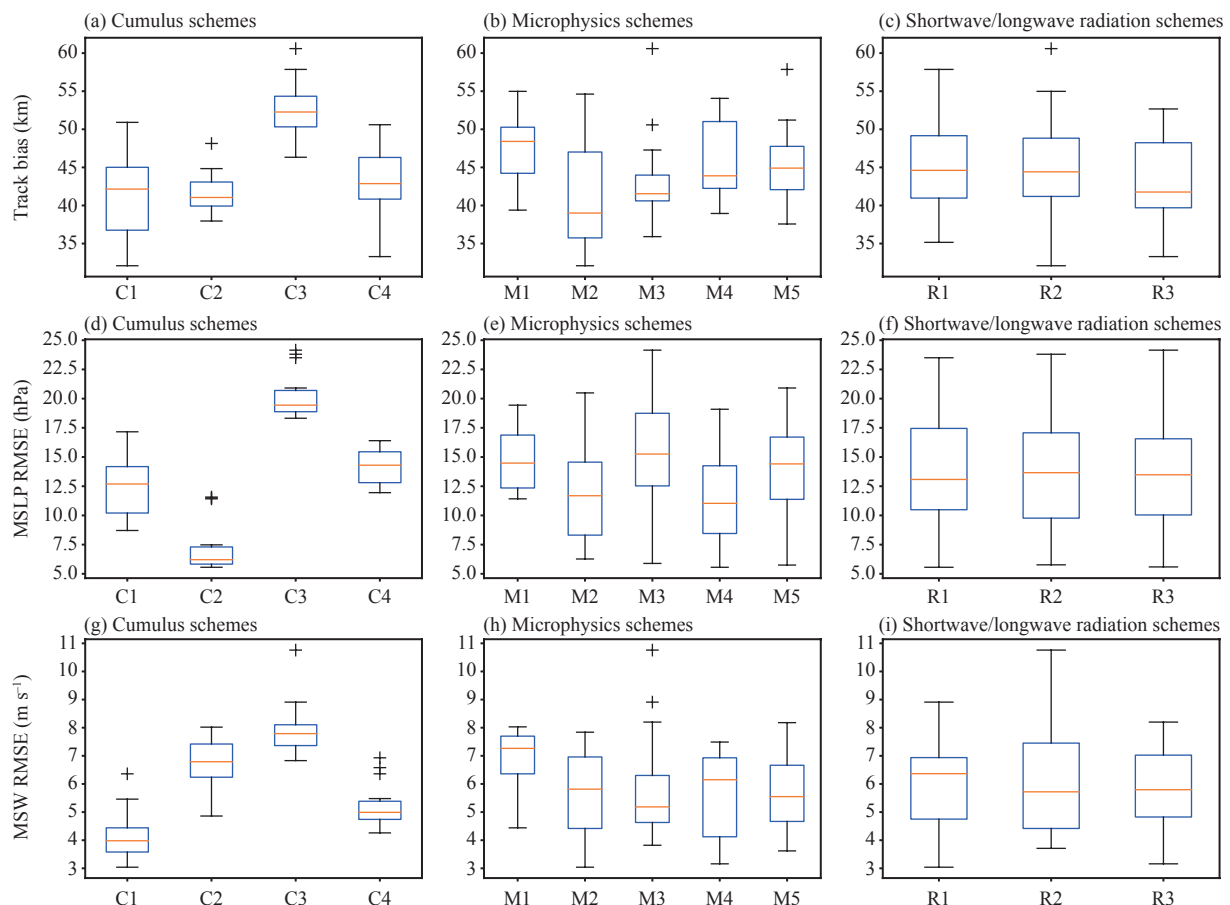
Number	Cumulus (CU)	Number	Microphysics (MP)	Number	Shortwave/longwave radiation physics
C1	None (0)	M1	Kessler (1)	R1	Dudhia/RRTM (1/1)
C2	KF (1)	M2	Lin (2)	R2	CAM/CAM (3/3)
C3	BMJ (2)	M3	WSM3 (3)		
		M4	WSM5 (4)	R3	RRTMG/RRTMG (4/4)
C4	G3 (5)	M5	WDM6 (16)		

3 TRACK AND INTENSITY

The RMSE of track bias and intensities simulated by the four CPs are shown in Figs. 2a, 2d, and 2g. The experiments utilizing the KF scheme exhibit excellent performance in path simulation, with the C2 group demonstrating the smallest average track bias. Conversely, the experiments adopting the BMJ scheme exhibit the largest path deviation, particularly the C3 group, which shows the largest average track bias (Fig. 2a). The impact of the five MPs on Mujigae's track simulation is illustrated in Fig. 2b. The track bias exhibits a close resemblance with minimal discrepancies attributed to each scheme. Specifically, the Lin scheme demonstrates the smallest median and minimum track bias, while the Kessler scheme yields the maximum track bias. The

use of two combinations of SRs and LR causes the smallest differences in typhoon tracks among the three parameterization schemes, with the CAM/CAM combination showing relatively good track simulation (Fig. 2c). Among all experiments, the ensemble member with the smallest track bias is C1M1R3. This experiment involves deactivating the CPs and using the Lin scheme along with the RRTMG/RRTMG radiation scheme (see Table A1 in the Appendix).

In terms of typhoon intensity, the model generally overestimates the MSWS and underestimates the MSLP of Mujigae. There is a significant bias in the simulation of the wind-pressure relationship. Concerning the CPs, the KF scheme performs best in simulating the MSLP of the typhoon, with smaller median, maximum, and minimum

**Figure 2.** Box plots of (a), (b), and (c) simulated track bias, (d), (e), and (f) RMSE in simulated MSLP, and (g), (h), and (i) RMSE in MSWS.

RMSE compared with other schemes. However, the use of CPs increases the RMSE in simulating the MSWS, with the BMJ scheme causing the highest RMSE. Regarding MPs, the Lin and WSM5 schemes show relatively small RMSE in simulating the MSLP, while the Kessler and WSM3 schemes exhibit larger errors (Fig. 2e). In simulating the MSWS, the Kessler scheme overall shows higher RMSE, and, in terms of the median RMSE, the WSM3 scheme performs the best (Fig. 2h). Concerning radiation schemes, the CMA/CMA combination demonstrates smaller RMSE in intensity simulation (Figs. 2f and 2i). The C2M4R1 has the smallest RMSE in simulating the MSLP, using the KF scheme, WSM5 scheme, and Dudhia/RRTM radiation scheme. The C0M1R1 has the smallest RMSE in simulating the MSWS, deactivating the CPs, using the Lin scheme, and employing the Dudhia/RRTM scheme (see Table A1 in the Appendix). The coefficient of variation can characterize the degree of dispersion in data. The C_v for track error is only 0.14, while the C_v for RMSE_MSWS and RMSE_MSLP is 0.28 and 0.37, respectively (calculated based on the data in Table A1 in the Appendix). Thus, in the comparison of typhoon track simulation, the selection of different parameterization schemes is more sensitive to typhoon intensity simulation.

Based on the above analysis, compared with SRs/LRs, CPs and MPs have a greater impact on typhoon

simulations. Fig. 3 further demonstrates the typhoon intensity and path simulation results for selected experimental members from the ensemble experiments. By comparing the combinations of C1, C2, C3, and C4 with M2R2, we can analyze the effects of different CPs on typhoon simulations. Similarly, contrasting the combinations of M1, M2, M3, M4, and M5 with C2R2 allows us to assess the influence of various MPs on typhoon simulations. In terms of track simulation, each experiment fit well with observations, and there are relatively small differences among the experiments. Regarding intensity simulation, within the CPs groups, the order of intensity from smallest to largest is C3M2R2, C4M2R2, C1M2R2, and C2M2R2. It is evident that the use of the KF results in the greatest intensity, while the BMJ produces the lowest. Among the MPs groups, C2M1R2 exhibits the lowest intensity, followed by C2M3R2. The remaining experiments demonstrate higher simulated intensities with relatively small differences. The use of the Kessler results in the lowest typhoon intensity, while the Lin, WSM5, or WDM6 schemes perform well in simulating typhoon intensity. The detailed information of simulation bias and RMSE for these eight selected ensemble members is listed in Table 3.

In summary, CPs and MPs have a significant impact on the simulation of Mujigae's track and intensity, while radiation schemes have a relatively minor impact.

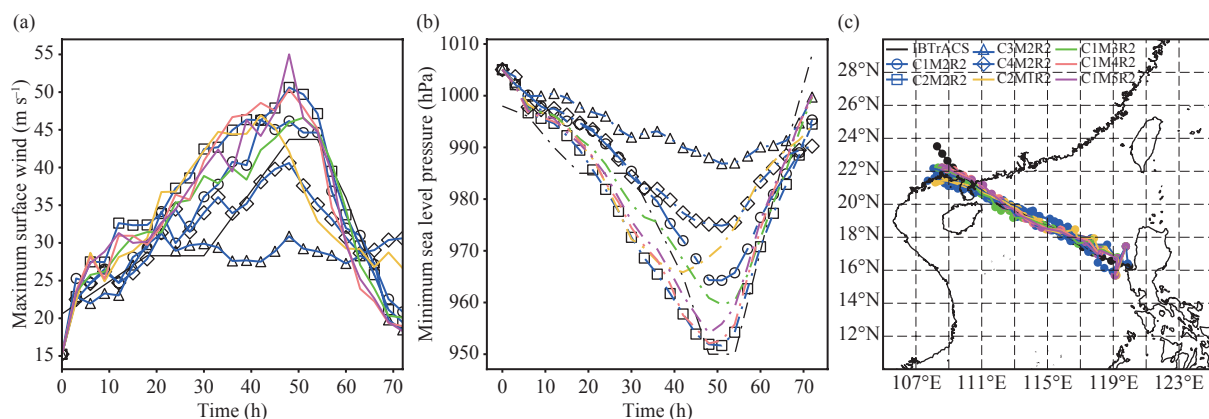


Figure 3. Temporal variations of (a) the MSLP in hPa, (b) the MSWS in m s^{-1} , and (c) the tracks among selected ensemble members are compared with the IBTrACS.

Table 3. Simulation bias and RMSE in typhoon track and intensity for selected ensemble members.

Name	Bias_track (km)	Bias_MSWS (m s^{-1})	Bias_MSLP (hPa)	RMSE_MSWS (m s^{-1})	RMSE_MSLP (hPa)	MSLP (hPa)
C1M2R2	32.09	1.80	4.91	4.44	8.71	964.28
C2M2R2	37.96	5.03	-2.24	7.35	7.09	951.68
C3M2R2	47.85	-4.77	14.11	7.44	19.10	986.86
C4M2R2	37.86	-0.60	7.36	4.35	13.08	974.86
C2M1R2	48.14	2.37	3.38	7.60	11.42	965.87
C2M3R2	42.89	2.61	2.47	4.86	6.21	959.61
C2M4R2	43.27	4.10	-0.49	7.49	5.94	952.08
C2M5R2	40.61	3.21	0.83	6.44	5.77	954.03

Moreover, the variations in simulated typhoon intensity among different scheme combinations are much larger than those in typhoon tracks, indicating that the choice of parameterization schemes has a more pronounced effect on typhoon intensity simulation. Among the CPs, the KF scheme enhances typhoon intensity, while the BMJ scheme reduces it. In terms of MP, schemes that consider both solid and liquid precipitation particles simulate higher typhoon intensity compared with those considering only cloud droplets and raindrops, with the Lin scheme performing optimally and the Kessler scheme the least. Among the radiation schemes, CAM/CAM exhibits good performance. As the ensemble members generally overestimate the MSWS of Mujigae while underestimating the MSLP, the use of the KF, WSM5 scheme, and Dudhia/RRTM scheme yields better intensity simulation results.

4 CONVECTIVE PROCESSES AND PRECIPITATION

The latent heat released during convective and precipitation processes is the primary energy source for typhoon growth and has a significant impact on the warm core structure and the maximum potential intensity (MPI) of typhoons (Emanuel ^[34]; Bister and Emanuel ^[35]). This section will compare the simulation of convective and precipitation processes among different parameterization scheme ensemble members and discuss the impact of CPs and MPs on typhoon intensity simulation.

4.1 Typhoon core precipitation

Approximately 60% of the upward motion in a typhoon occurs in the core region, where intense convective activity releases latent heat, providing energy for the typhoon's growth (Jorgensen et al. ^[36]). The total precipitation simulated in WRF consists of cumulus precipitation and grid-scale precipitation, which are calculated by CPs and MPs, respectively. If the CPs are disabled, the cumulus precipitation will be zero. Fig. 4 presents the differences in cumulus precipitation, grid-scale precipitation, and vertical velocity simulated by various experiments within the typhoon core. In terms of convective cloud parameterization, group C2, which uses the KF scheme, exhibits the largest vertical velocity and the strongest convective intensity within the typhoon core (Fig. 4g). Moreover, the KF scheme generates the highest cumulus precipitation (Fig. 4a), while the grid-scale precipitation decreases when no CPs is used (Fig. 4d), but it is still higher than other schemes. Conversely, group C3 using the BMJ scheme and group C4 using the G3 scheme show suppressed convection and reduced total precipitation. However, despite generally overestimating typhoon core precipitation in other schemes, the C3M2R2 using the BMJ scheme provides simulation results for typhoon core precipitation that closely align with IMERG data. Especially during the strengthening phase of the typhoon, from the 15th to the 50th hour, the precipitation simulated by C3M2R2 is the least (Fig. 4i). In terms of

MPs, the Kessler results in a slight reduction in cumulus precipitation, while the differences among the other schemes are relatively minor. Compared with cumulus precipitation, there are greater differences in grid-scale precipitation among these various schemes. Specifically, the Lin scheme produces the highest amount of grid-scale precipitation, while WSM3 generates the least. The differences among the remaining schemes are relatively small. The Lin scheme also exhibits greater vertical velocity and convective intensity, while the convective activities in WSM3 and the Kessler scheme are weaker.

In terms of SRs and LR, the three combinations of radiation schemes yield similar results in simulating the total precipitation and vertical motion speed within the typhoon core. However, the results from the Dudhia/RRTM group are slightly higher than those from the other experiments (Figs. 4c, 4f, and 4i). Additionally, the experimental results reveal a strong correlation between convective intensity and precipitation within the typhoon's core. Groups that exhibit greater vertical velocities also demonstrate stronger precipitation intensities within the typhoon's core.

The intensity of typhoons exhibits a robust correlation with core precipitation. During their developmental stage, an increase in core precipitation is often indicative of enhanced typhoon strength. This is attributed to the substantial release of latent heat during the condensation of water vapor, which effectively warms the typhoon's core, thereby facilitating its intensification (Jorgensen et al. ^[36]). The findings of this study corroborate this perspective. Specifically, the C3M2R2 model demonstrated a marked reduction in core precipitation from hours 10 to 60 of the simulation (Fig. 4j), concomitant with a significant decrease in typhoon intensity from the 10th hour of the simulation (Figs. 3a and 3b). Conversely, the cases characterized by higher core precipitation, namely C2M2R2, C2M4R2, and C2M5R2, yield simulated typhoon intensities that were comparatively greater.

Overall, the CPs has a greater impact on precipitation simulation. Regardless of whether it is cumulus precipitation or grid-scale precipitation, the differences caused by using different CPs are significant. On the other hand, the MPs has a more pronounced effect on grid-scale precipitation.

In Fig. 5, the regions of high reflectivity (exceeding 10 dBZ) within the eyewall are indicative of the height of convective clouds, with greater convective heights often corresponding to stronger typhoon intensities (Jiang ^[37]). The C3M2R2 simulation exhibits the lowest eyewall height, which is consistent with its lowest maximum simulated typhoon intensity. In contrast, the simulations with greater typhoon intensities, namely C2M2R2, C2M4R2, and C2M5R2, demonstrate higher eyewall heights, generally reaching close to the 200 hPa level, which is near the tropopause.

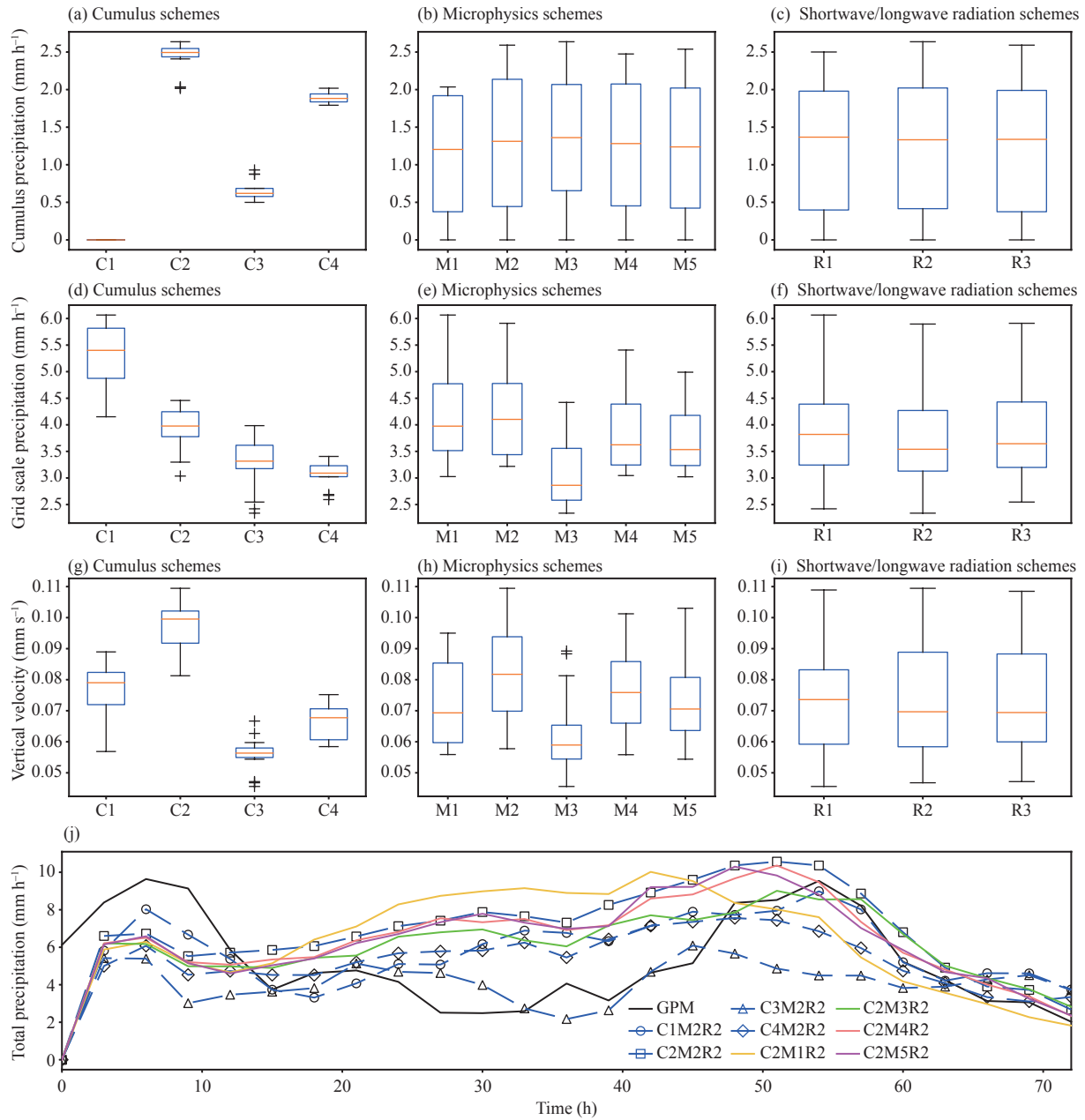


Figure 4. Average cumulus precipitation within a 200 km radius of the typhoon core during the simulation period. (a–c) represent CPs, MPs, SRs, and LR, respectively; (d–f) average grid scale precipitation; (g–i) average vertical velocity within the typhoon core; (j) time series of core rainfall rate for selected ensemble members.

4.2 Typhoon eyewall

Previous studies have indicated that the morphology of the eyewall is crucial for maintaining and enhancing the warm core structure, and is also associated with the intensification and sustenance of typhoon strength (Kepert^[1]). CPs significantly influence the simulation of the typhoon eyewall's morphology and height. The eyewall simulated by the KF scheme is relatively high, extending to around 200 hPa near the top of the troposphere, with greater reflectivity and convective intensity in the eyewall center (Fig. 5e). In contrast, the eyewalls simulated by the G3 (Fig. 5f) and BMJ (Fig. 5b) schemes are weaker, with BMJ particularly showing significant weakening of the eyewall. The choice of MPs

also affects the height of the eyewall. The eyewall simulated by the Kessler scheme is relatively low, with an average height only around 500 hPa (Fig. 5c). The eyewall in the Lin scheme exhibits the highest average reflectivity (Fig. 5e). It is evident that schemes considering both solid and liquid precipitation particles produce clearer and taller eyewalls compared to those considering only cloud droplets and raindrops. For example, the eyewalls in Lin, WSM5, and WDM6 are generally more prominent with stronger reflectivity and greater convective intensity compared to WSM3 and Kessler at the eyewall region.

4.3 Deep convection

Rapid intensification (RI) of typhoons is closely related to deep convection, and a vigorous deep convection

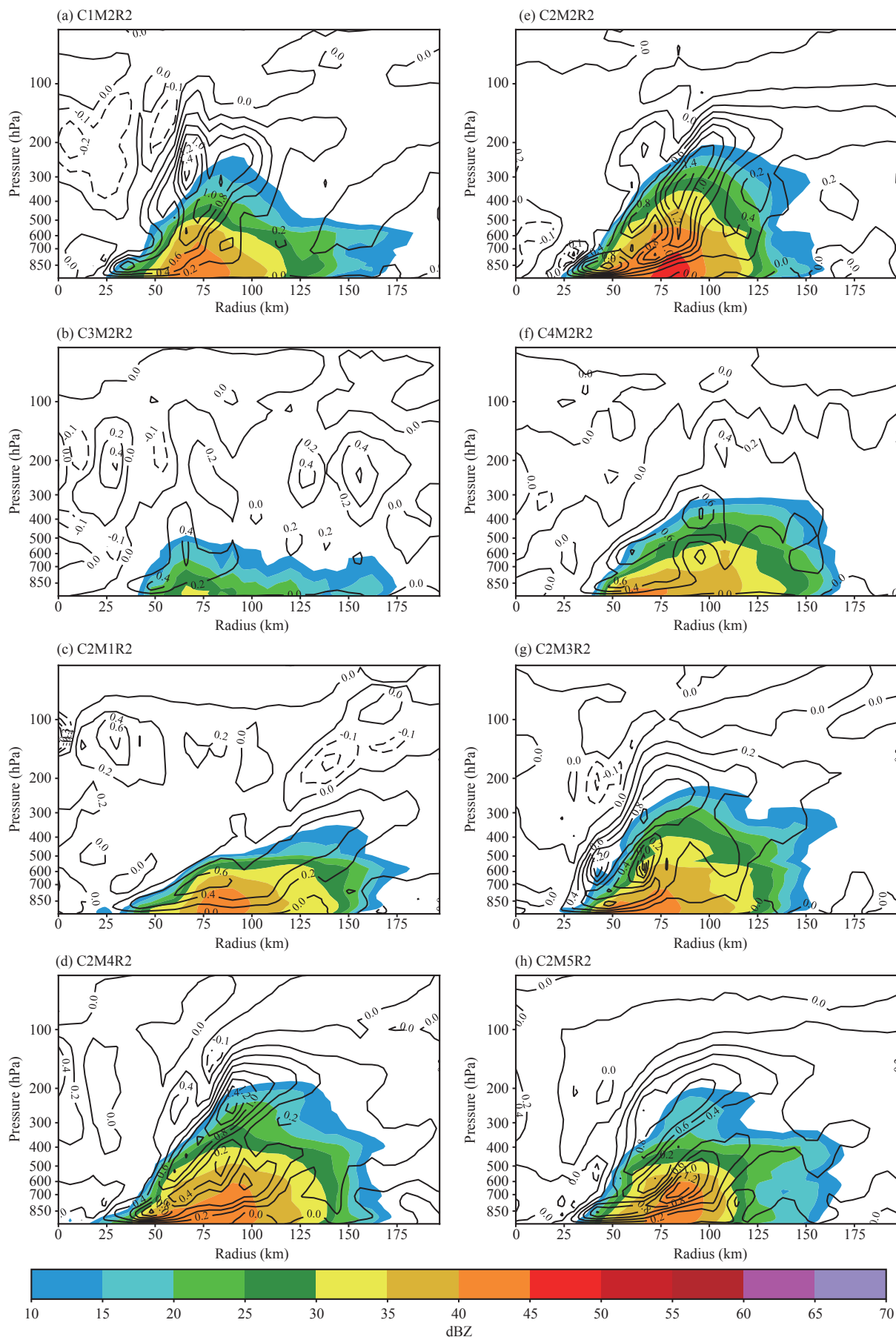


Figure 5. Vertical velocity and reflectivity profiles of selected ensemble members at 03:00 on October 4, 2015 within the typhoon eyewall.

within the typhoon eyewall often indicates the potential for the typhoon to reach greater intensity (Tao and Jiang [38]; Liu et al. [39]). Generally, stronger deep convection leads to lower cloud-top temperatures. Therefore, cloud-top temperature is commonly used to characterize the intensity of deep convection.

In the suite of CPs, the KF scheme exhibits the lowest average cloud-top temperature, suggesting higher simulated heights of deep convection within the typhoon eyewall (Fig. 6a). The G3 scheme and experiments with the CPs turned off have similar average cloud-top temperatures, while the BMJ scheme generally produces higher cloud-top temperatures compared to experiments without CPs. The BMJ scheme suppresses deep convection activity within the typhoon, especially during the simulated hours 10 to 40. The C3M2R2 experiment using the BMJ scheme shows the highest average cloud-top temperature during this period (Fig. 6d). The distribution of differences in cloud-top temperatures among CPs groups is similar to the differences in vertical velocity and precipitation distribution mentioned above. The KF group, which exhibits greater convective intensity, also has lower cloud-top temperatures, while BMJ shows the opposite trend.

Regarding MPs, the limitations of the Kessler scheme, which only considers warm cloud precipitation processes, result in abnormally high cloud-top heights (Fig. 6b). This indicates an inability to accurately reflect the depth of convection. In other MPs, the WSM5 scheme exhibits slightly lower cloud-top temperatures, suggesting better performance in simulating deep convection. The impact of radiation schemes on cloud-top temperature is minimal, with only the CAM/CAM scheme showing

slightly lower cloud-top temperatures than the other schemes (Fig. 6c).

In the typhoon eyewall, convective symmetry and greater depth are favorable for typhoon intensification (Hack and Schubert [40]; Jiang and Ramirez [41]). Typhoons simulated using the KF scheme typically exhibit a more symmetric distribution of deep convection (Fig. 7c) and a more circular eyewall. Concerning MPs, the Kessler scheme shows an unusually low cloud-top temperature (Fig. 7g), while the eyewall cloud-top temperature distributions in the remaining experiments are similar. The WSM3 showing slightly higher cloud-top temperatures, indicating shallower convection compared with other experiments (Fig. 7b).

Weaker typhoons tend to have lower convective heights. During the intensification phase (hours 10 to 40 of the simulation), the typhoon with the lowest intensity, C3M2R2, corresponds to the lowest cloud top heights. Conversely, the simulations with greater typhoon intensities, C2M2R2, C2M4R2, and C2M5R2, exhibit higher cloud top heights. Moreover, Fig. 7 illustrates that the deep convection distribution of the less intense typhoons, C3M2R2 and C4M2R2, exhibits lower asymmetry.

The cloud amount at various altitudes can also reflect the depth of convection and the vertical structure of the typhoon. The cloud amounts at 2000 meters in Kessler and WSM3 schemes, which consider only cloud water and raindrops, are lower than those in other MPs (Fig. 8b). This reflects the relatively smaller convective depth of the typhoons simulated by them, which corresponds to the weaker convective intensity and lower eyewall height as analyzed previously. Additionally, the Kessler scheme

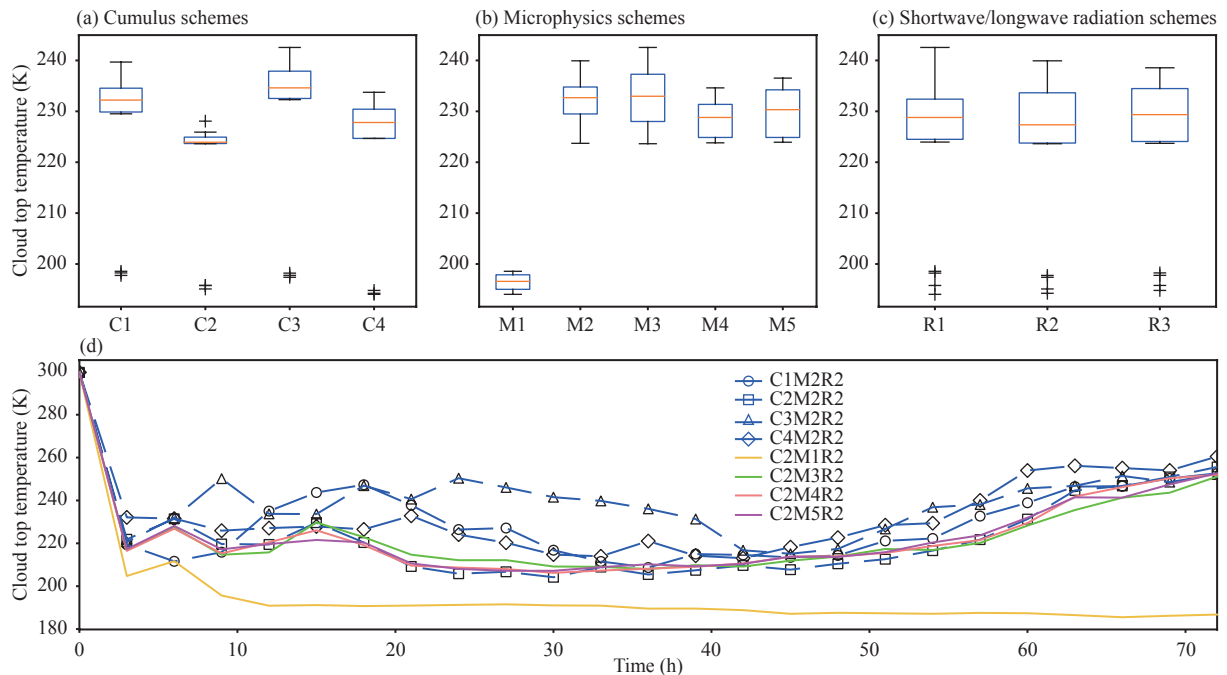


Figure 6. (a–c) Box plots of the average cloud-top temperatures during the simulated period for the typhoon eyewall; (d) time series of the selected ensemble members' average cloud-top temperatures within the eyewall.

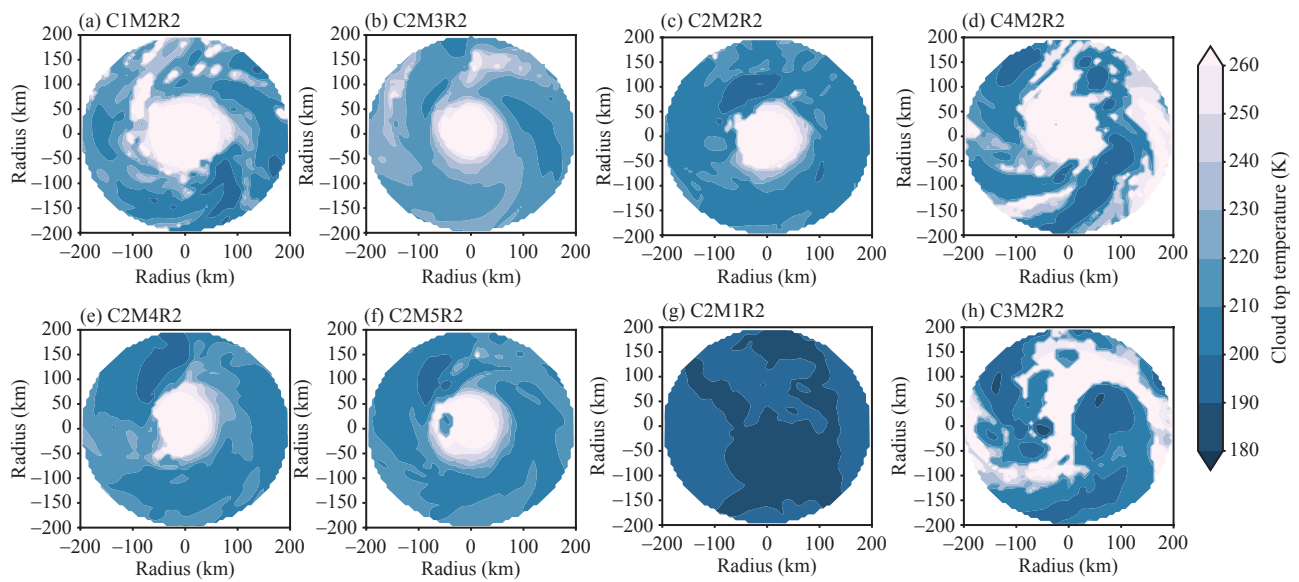


Figure 7. Selected ensemble members: distribution of average cloud-top temperature in the eyewall at 03:00 UTC on October 4, 2023.

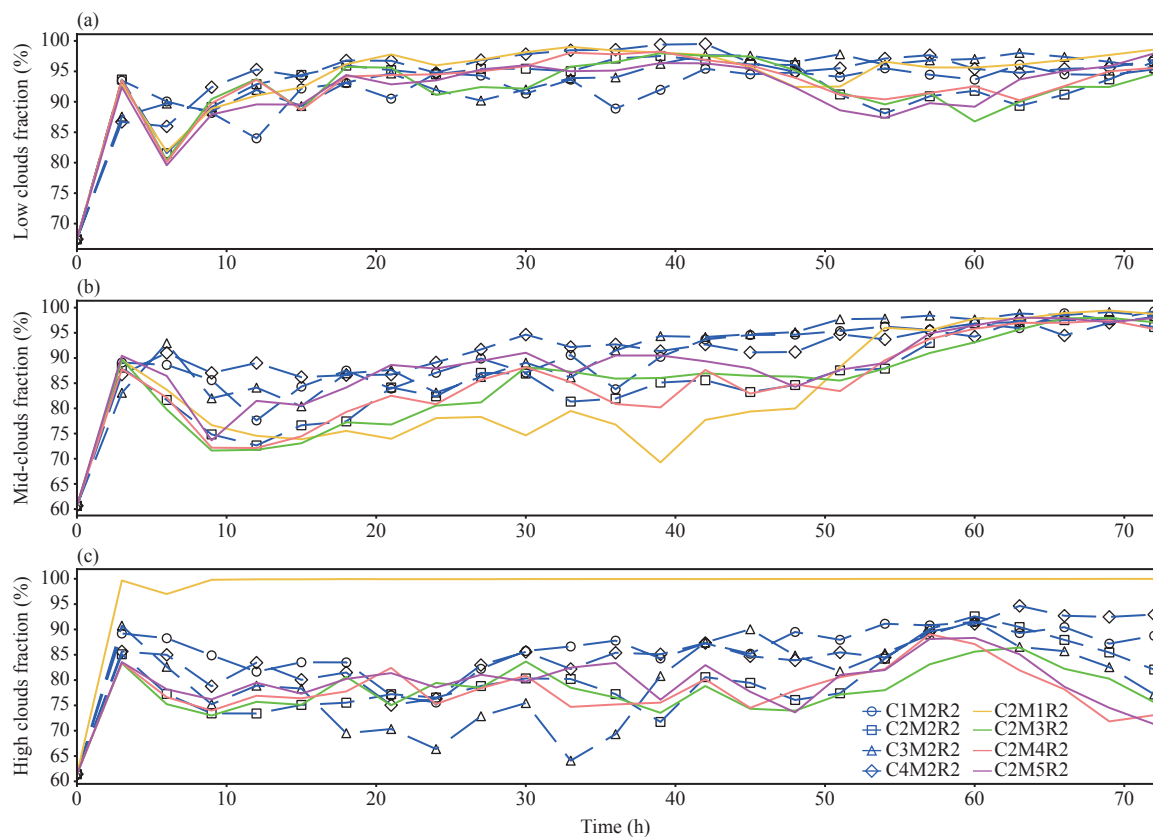


Figure 8. Temporal variations in low (300 m), mid- (2000 m), and high (6000 m) cloud cover among selected ensemble members.

simulates a significant amount of high-level supercooled water clouds, resulting in an unusually high cloud coverage at elevated altitudes (Fig. 8c), consequently reducing the simulated intensity of Mujigae.

4.4 Cloud precipitation particles

For the CPs, the cloud droplet concentration is lower in the KF scheme, while the G3 and BMJ schemes exhibit cloud droplet concentrations similar to the experiments

without CPs (Fig. 9a). Regarding raindrop concentration, CPs tend to down-regulate raindrop concentration, with G3 and BMJ schemes showing the most significant reduction (Fig. 9b). In terms of ice particle concentration, the KF scheme has the highest ice particle concentration, G3 scheme approaches the cases without CPs, and the BMJ scheme has the lowest ice particle concentration (Fig. 9c). Snow particle concentration follows a similar pattern, with

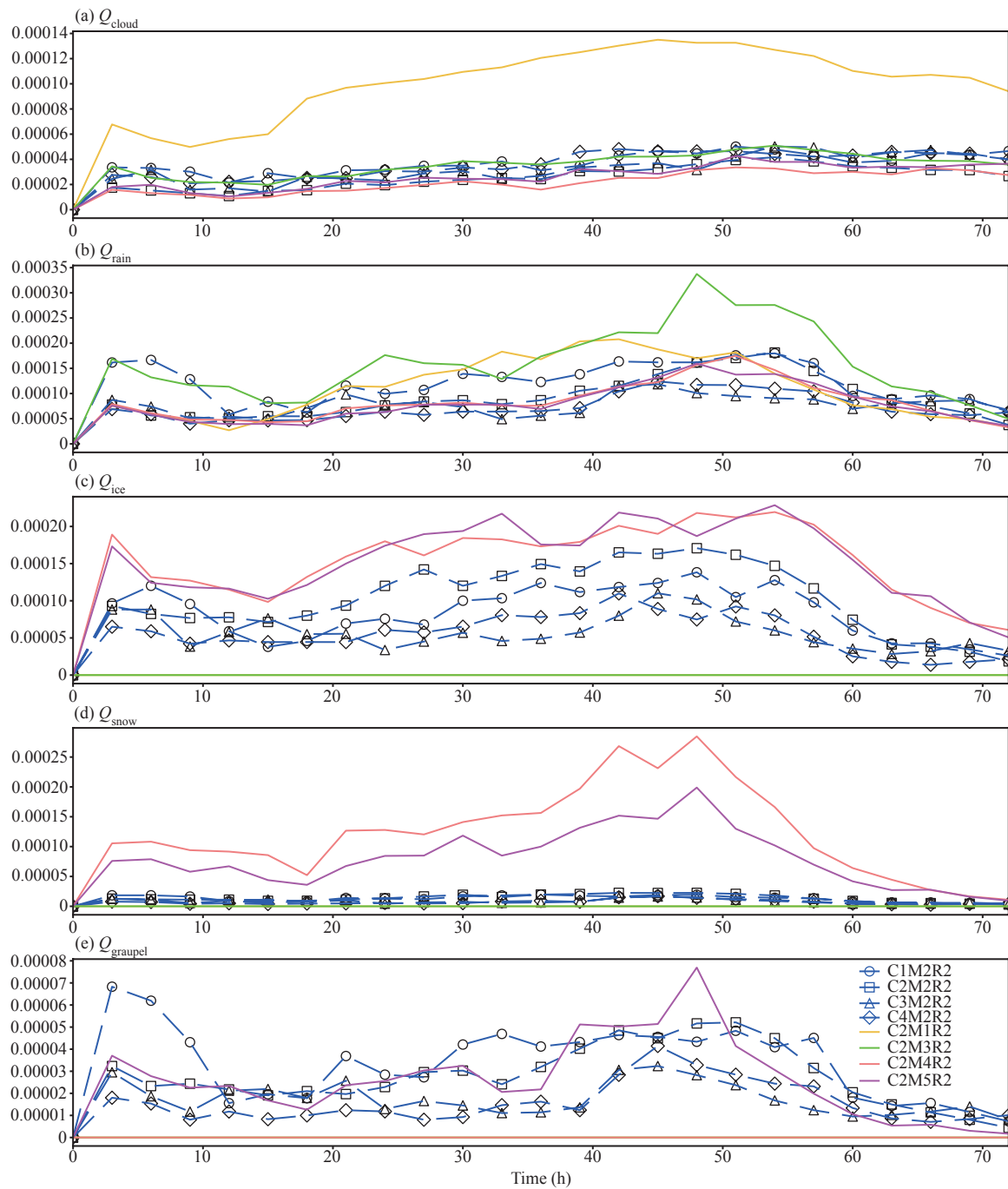


Figure 9. Temporal variations of concentrations of solid and liquid precipitation particles (units: kg kg^{-1}) among selected ensemble members. (a) cloud droplet mixing ratio, (b) raindrop mixing ratio, (c) ice particle mixing ratio, (d) snow particle mixing ratio, and (e) graupel particle mixing ratio.

the KF scheme having the highest concentration, G3 scheme approaching the cases without CPs, and the BMJ scheme having the lowest snow particle concentration. Regarding graupel particle concentration, the KF scheme has the highest concentration, followed by the G3 scheme, and the BMJ scheme has the lowest concentration.

For the MPs, the Kessler scheme produces cloud droplet concentrations far exceeding other experiments (Fig. 9a), but raindrop concentrations are similar to other schemes. This reflects the limitation of the Kessler scheme, which does not consider other solid precipitation

particles and lacks processes for cold cloud precipitation, resulting in an excessive amount of high-level cold clouds. Similarly, the WSM3 scheme, which only considers cloud droplets and raindrop concentrations, does not show an excessive increase in cloud droplets as in the Kessler scheme. However, raindrop concentrations are significantly higher than those in other experiments, especially after 40 hours of simulation, corresponding to the mature stage of Mujigae's intensity and structure development (Fig. 9b). On the other hand, the WSM5 and WDM6 schemes have significantly higher concentrations of solid precipitation

particles than other experiments (Fig. 9d), which may lead to an increase in small raindrops and a decrease in large raindrops (Duda et al. ^[42]). The Lin scheme exhibits a balanced concentration of the five types of precipitation particles compared to other experiments, without any particularly prominent situations.

5 DISCUSSION

CPs focus on the generation of clouds and the triggering of convection, and a robust cloud convection parameterization is crucial for improving the model ability to simulate clouds, especially for the simulation of typhoon intensity. Compared to the BMJ scheme, the KF scheme is capable of simulating stronger typhoon convection and cumulus precipitation intensity. In terms of deep convection simulation, it exhibits more vigorous deep convective activity, and the distribution of deep convection is more symmetrical. In simulating the eyewall structure, the KF scheme can produce a clearer and taller eyewall structure.

MPs focus on the generation and development of precipitation particles, processes crucial for the release of latent heat in typhoon convection and have a significant impact on grid-scale precipitation. Experimental results show that more complex microphysical models, such as Lin, WSM5, and WDM6, perform better in simulating typhoon intensity. These models exhibit a more reasonable distribution of various precipitation particle concentrations. The simpler schemes like Kessler and WSM3 only consider the concentrations of cloud droplets and raindrops, and are unable to describe deep convective processes. In particular, the Kessler scheme has some limitations in simulating warm cloud precipitation, which weakens convective intensity and significantly affects the simulation of typhoon intensity.

Furthermore, different categories of parameterization schemes are subject to coupling processes (Li et al. ^[43]), as reflected in the coupling between CPs and MPs. CPs address the occurrence and development of convective processes, while MPs affect the phase transition of water vapor. The coupling of these two processes has a significant impact on the simulation of typhoon intensity. When the KF scheme, which promotes the occurrence and development of convection, is coupled with MPs that can calculate solid precipitation particles such as the Lin scheme, the simulated typhoon intensity is greater, and the eyewall structure is clearer and taller. Conversely, when the KF scheme is used with the Kessler scheme, there is a significant simulation bias due to a lack of cold cloud precipitation processes.

6 CONCLUSION

This study conducted a sensitivity analysis on the parameterization scheme combinations for simulating Mujigae, evaluating the impacts of three CPs (KF, BMJ, and G3), five MPs (Kessler, Lin, WSM3, WSM5, and WDM6), and three radiation parameterization schemes

(Dudhia/RRTM, CMA/CMA, and RRTMG/RRTMG) on the simulation. The conclusions drawn are as follows:

(1) In terms of the simulation of track and intensity, CPs and MPs have a significant impact on the simulation of the track and intensity of Mujigae. Different scheme combinations simulate typhoon intensity differences far greater than track differences, making the choice of parameterization schemes more critical for intensity simulation. For the track, the combination of turning off CPs and using the Lin scheme and RRTMG/RRTMG scheme yields the optimal simulation track. For intensity, using the KF scheme, WSM5 scheme, and Dudhia/RRTM scheme produces better intensity simulation.

(2) In the CPs, the KF scheme promotes typhoon convection and cumulus precipitation, with more latent heat release favoring typhoon development. Therefore, this scheme simulates a stronger typhoon with a clearer and taller eyewall and a more symmetric distribution of deep convection. In contrast, the BMJ convection scheme suppresses the development of convective activity, resulting in a weaker typhoon with a lower eyewall.

(3) In terms of MPs, those capable of simulating both liquid and solid precipitation particles, such as Lin, WSM5, and WDM6, can simulate a larger typhoon intensity and stronger grid-scale precipitation. Kessler and WSM3, which only calculate cloud droplet and raindrop concentrations and can not describe deep convective processes, simulate weaker typhoon intensity. In particular, the Kessler scheme simulates a large amount of supercooled water clouds, leading to significant deficiencies in typhoon structure simulation, making it not recommended for use in typhoon simulations.

(4) CPs focuses on the evolution of convective activity, while MPs focuses on simulating phase changes in water vapor. These two schemes are not often independent when simulating typhoons but exhibit a certain degree of coupling. The KF scheme, which promotes convective development, when used in conjunction with complex MPs such as Lin, can further improve the model ability to simulate clouds and increase latent heat release, thus simulating a larger typhoon intensity.

It should be noted that the analysis results presented in this paper are primarily based on the experiments conducted using Typhoon Mujigae. To further enhance the credibility of the recommendations regarding the selection of parameterization schemes for typhoon simulations, sensitivity experiments have also been conducted for Typhoon Lekima (2019) (see Figs. A1 and A2, and Table A2 in the Appendix). The experimental results of Lekima also indicate that the KF in CPs, along with the Lin, WSM5, or WDM6 schemes in MPs, yield superior simulation outcomes. These additional experiments lend further credibility to the findings of this paper. However, it remains necessary to conduct further experiments to assess the applicability of these findings across different regions or typhoons of varying intensities. Additionally, it is

important to note that boundary layer parameterization schemes also play a crucial role in simulating typhoon intensity (Keller^[44]; Smith and Thomsen^[45]). This study primarily explores the impact of CPs and MPs on typhoon convection and precipitation processes, using the fixed YSU boundary layer parameterization scheme in the experiments. In future research, it would be beneficial to expand the scope of the study by incorporating multiple boundary layer parameterization schemes to comprehensively investigate the impact of physical parameterization schemes on typhoon simulations.

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Appendix

Table A1. Simulation bias and RMSE in typhoon track and intensity for Mujigae. The bolded parts show the selected examples mentioned in the main text.

Name	Bias_track (km)	Bias_MSWS (m s ⁻¹)	Bias_MSLP (hPa)	RMSE_MSWS (m s ⁻¹)	RMSE_MSLP (hPa)	MSLP (hPa)
C1M1R1	48.68	-0.04	8.76	6.36	13.04	973.32
C1M1R2	50.91	-1.21	9.06	4.44	12.61	973.69
C1M1R3	48.86	-1.88	8.82	5.46	12.69	973.81
C1M2R1	35.16	0.37	6.39	3.04	10.77	970.37
C1M2R2	32.09	1.8	4.91	4.44	8.71	964.28
C1M2R3	35.94	0.61	6	3.54	10.29	968.47
C1M3R1	42.15	-2.25	13.56	3.98	17.16	981.6
C1M3R2	40.53	-2.29	12.02	4.15	16.05	978.69
C1M3R3	35.91	-2.5	11.89	3.82	15.74	977.49
C1M4R1	43.01	0.52	6.04	3.37	9.64	967.09
C1M4R2	44.52	0.51	7.39	3.71	10.12	968.46
C1M4R3	40.37	-0.38	5.91	3.16	9.29	965.28
C1M5R1	37.57	-2.12	9.39	3.62	13.12	974.63
C1M5R2	45.5	-1.33	10.62	4.12	14.24	975.4
C1M5R3	42.39	-1.29	10.43	4.6	14.12	974.98
C2M1R1	44.84	2.35	3.81	8.02	11.57	964.41
C2M1R2	48.14	2.37	3.38	7.6	11.42	965.87
C2M1R3	43.75	2.13	2.93	7.67	11.5	964.83
C2M2R1	41.05	4.46	-0.53	6.73	7.12	956.42
C2M2R2	37.96	5.03	-2.24	7.35	7.09	951.68
C2M2R3	40.05	4.22	-0.97	6.79	6.27	953.33
C2M3R1	40.63	1.22	4.36	5.67	7.48	961.77
C2M3R2	42.89	2.61	2.47	4.86	6.21	959.61
C2M3R3	38.32	2.24	2.45	5.35	5.89	959.05
C2M4R1	38.95	3.61	0.23	6.96	5.56	953.03
C2M4R2	43.27	4.1	-0.49	7.49	5.94	952.08
C2M4R3	39.8	3.32	0.97	6.82	5.59	954.82
C2M5R1	42.48	3	0.77	6.37	6.14	955.97
C2M5R2	40.61	3.21	0.83	6.44	5.77	954.03
C2M5R3	41.14	2.66	1.32	6.11	5.75	955.41
C3M1R1	53.02	-4.92	13.38	7.79	18.32	985.48
C3M1R2	54.98	-4.78	13.73	7.67	19.44	986.62
C3M1R3	50.06	-4.57	13.46	8.03	18.5	985.9
C3M2R1	54.62	-3.97	12.89	6.83	19.01	984.44
C3M2R2	47.85	-4.77	14.11	7.44	19.1	986.86
C3M2R3	52.23	-4.94	14.48	7.84	20.49	988.92
C3M3R1	47.28	-6.68	17.79	8.91	23.5	992.41
C3M3R2	60.59	-7.49	17.68	10.76	23.8	993.84
C3M3R3	50.58	-5.72	18.11	8.2	24.15	995.07
C3M4R1	52.27	-3.99	12.81	6.91	18.75	983.93
C3M4R2	54.06	-4.61	13.7	7.39	19.09	982.67
C3M4R3	52.67	-4.74	13.48	6.92	18.49	983.32
C3M5R1	57.86	-4.91	14.74	7.94	20.16	986.77
C3M5R2	51.21	-5.01	14.82	8.18	20.91	987.68
C3M5R3	46.33	-5.36	15.13	7.34	20.06	986.77
C4M1R1	44.38	-3.12	9.69	6.93	15.99	981.38
C4M1R2	41.38	-3.09	10.51	6.36	16.4	981.5

(Continued from the preceding table)

Name	Bias_track (km)	Bias_MSWS (m s ⁻¹)	Bias_MSLP (hPa)	RMSE_MSWS (m s ⁻¹)	RMSE_MSLP (hPa)	MSLP (hPa)
C4M1R3	39.39	-3.09	9.7	6.58	15.92	981.17
C4M2R1	46.74	-0.64	6.73	4.9	12.6	973.88
C4M2R2	37.86	-0.6	7.36	4.35	13.08	974.86
C4M2R3	33.29	-0.92	6.93	4.87	12.77	973.89
C4M3R1	40.73	-2.32	10.54	4.79	14.21	976.81
C4M3R2	42.51	-1.62	9.09	5.08	14.77	977.66
C4M3R3	40.94	-1.73	9.16	5.29	14.3	977.43
C4M4R1	50.6	-0.95	6	4.63	11.95	970.86
C4M4R2	45.87	-0.65	7.03	4.26	12.22	971.88
C4M4R3	42.87	-1.35	7.82	5.48	12.84	973.55
C4M5R1	47.67	-1.22	8.24	4.99	14.58	976.94
C4M5R2	44.31	-1.74	10.05	4.99	15.59	979.37
C4M5R3	48.03	-1.32	9.51	4.69	15.31	978.76

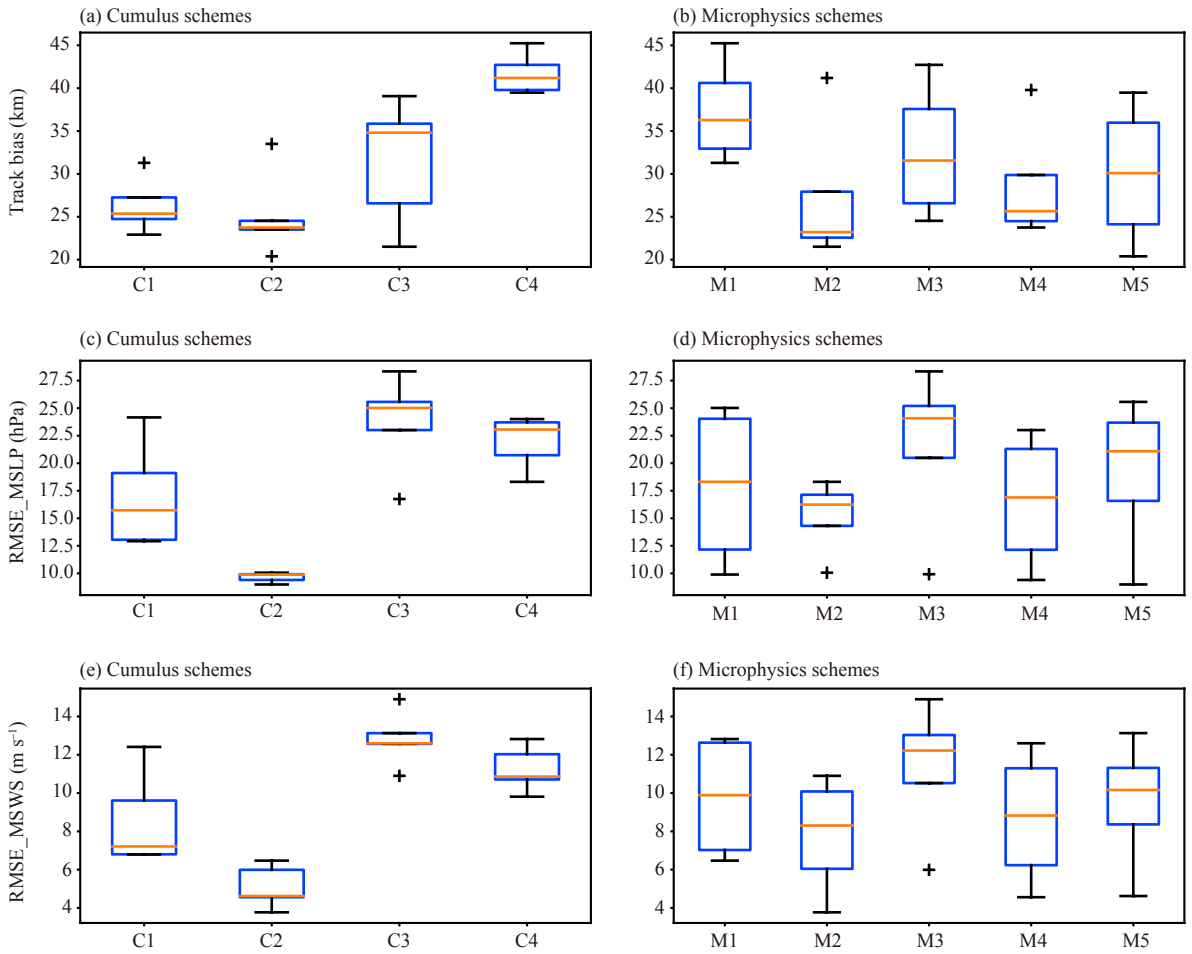


Figure A1. Temporal variations of (a) the MSLP (hPa), (b) the MSWS (m s⁻¹), and (c) the tracks among selected ensemble members are compared with the IBTrACS for Lekima. C2M2R3 has the smallest path deviation, while C2M5R3 has the strongest simulation strength.

Table A2. Simulation bias and RMSE in typhoon track and intensity for Lekima. The bolded parts show C2M2R3 with the lowest simulation strength and C2M5R3 with the lowest path deviation.

Name	Bias_track(km)	Bias_MSWS (m s ⁻¹)	Bias_MSLP (hPa)	RMSE_MSWS (m s ⁻¹)	RMSE_MSLP (hPa)	MSLP (hPa)
C1M1R3	31.29	-5.55	11.27	7.21	12.92	942.32
C1M2R3	22.92	-2.49	5.79	6.8	15.73	927.68
C1M3R3	27.26	-10.36	19.55	12.41	24.16	952.58
C1M4R3	24.74	-4.62	5.98	6.79	13.05	935.78
C1M5R3	25.37	-7.14	14.48	9.61	19.11	945.82
C2M1R3	33.5	-4.4	7.96	6.47	9.89	935.18
C2M2R3	23.51	0.95	-4.35	3.77	10.06	920.95
C2M3R3	24.53	-2.9	1.62	5.99	9.92	929.31
C2M4R3	23.75	-1.05	-2.24	4.56	9.4	923.22
C2M5R3	20.39	-1.45	-1.09	4.62	8.99	925.17
C3M1R3	39.07	-11.83	22.86	12.57	25.02	958.18
C3M2R3	21.51	-8.07	11.15	10.9	16.75	937.23
C3M3R3	35.86	-13.03	24.52	14.9	28.34	960.45
C3M4R3	26.57	-10.65	19.06	12.6	23.01	951.38
C3M5R3	34.81	-10.61	21.72	13.13	25.57	957
C4M1R3	45.24	-11.68	21.1	12.82	23.71	954.78
C4M2R3	41.19	-8.74	16.18	9.81	18.31	950.76
C4M3R3	42.72	-11.22	21.53	12.03	24.01	958.77
C4M4R3	39.79	-9.94	18.45	10.86	20.73	954.37
C4M5R3	39.48	-9.67	20.54	10.71	23.06	958.68

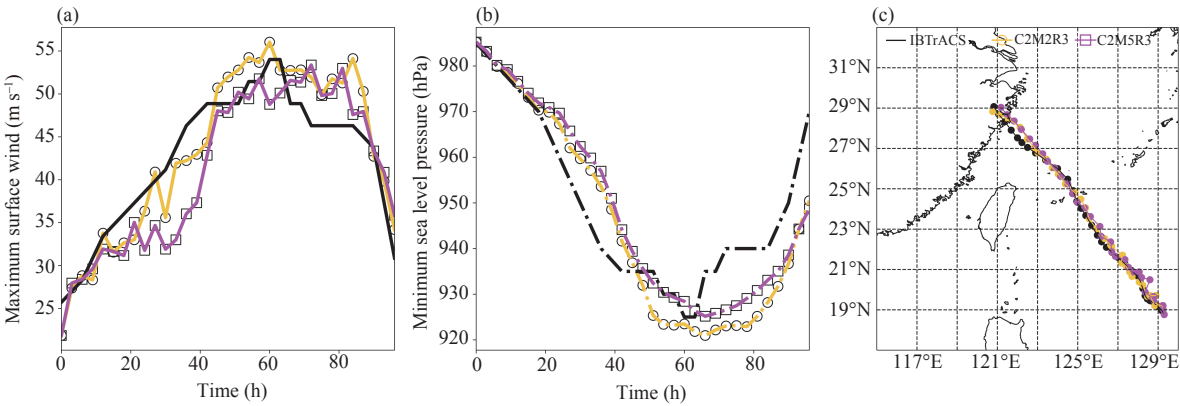


Figure A2. Temporal variations of (a) the MSLP (hPa), (b) the MSWS (m s⁻¹), and (c) the tracks among selected ensemble members are compared with the IBTrACS for Lekima. C2M2R3 has the smallest path deviation, while C2M5R3 has the strongest simulation strength.