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Macro- and Micro-characteristics of Clouds and Precipitation During the 7·20 Extreme Rainstorm in Zhengzhou, China

LIU Chen-yun (刘晨云)^{1,6}, MA Zhan-shan (马占山)^{2,3}, LIU Qi-jun (刘奇俊)^{2,3}, GUAN Cheng-gong (管成功)^{2,3},
LIANG Hong (梁宏)⁴, JIAN Bi-da (简碧达)⁵, LI Zhe (李喆)^{2,3}, LIU Zhao-dong (刘兆东)^{2,3},
WANG Yong-qing (王咏青)¹, HU Zhi-qun (胡志群)³

(1. Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters/Key Laboratory of Meteorological Disasters, Ministry of Education/School of Atmospheric Sciences, Nanjing University of Information Science & Technology, Nanjing 210044 China; 2. CMA Earth System Modeling and Prediction Centre (CEMC), Beijing 100081 China; 3. State Key Laboratory of Severe Weather Meteorological Science and Technology, Beijing 100081 China; 4. CMA Meteorological Observation Center, Beijing 100081 China; 5. College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000 China; 6. Lianyungang Meteorological Bureau, Lianyungang, Jiangsu 222000 China)

Abstract: To simulate and analyze the main features and differences in rainfall and cloud macro- and micro-physical properties during an extreme rainstorm in Zhengzhou, Henan, China, that occurred on July 20, 2021, three cloud microphysics schemes—weather research and forecasting single-moment 6-class microphysics (WSM6), Thompson, and LiuMa—were applied using the China Meteorological Administration mesoscale (CMA–MESO) model. Simulations based on all three schemes successfully reproduced the 24-hour accumulated rainfall. Among them, the maximum 24-hour accumulated rainfall simulated by the WSM6 scheme was the closest to observation values. However, challenges remain in simulating the temporal evolution of precipitation intensity, particularly that of maximum hourly rainfall. The maximum hourly precipitation simulated by the LiuMa scheme was the closest to the observations in terms of spatial distribution, intensity, and radar echoes. Cold and warm cloud precipitation processes jointly dominated the entire event; however, warm cloud precipitation dominated during the period with the maximum hourly precipitation. The vertical distributions of liquid-phase hydrometeors simulated by the three schemes were relatively consistent, whereas the simulations of ice-phase hydrometeors were sensitive to the specific scheme used. During the period with the observed maximum precipitation intensity, the vertical distributions of raindrop size and terminal velocity, as modeled by the three schemes, were well-aligned.

Key words: extreme precipitation; Liu-Ma; WSM6; Thompson; Zhengzhou

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1 INTRODUCTION

Heavy rainfall is a common meteorological disaster in China during the summer, causing direct economic losses of 167.86 billion yuan every year (Li and Zhao 2022). Accurate rainstorm forecasting is of key social and economic importance for disaster prevention and mitigation (Vieux and Bedient 2004). Numerical weather prediction (NWP) is an essential method for forecasting meso- and micro-scale weather systems, such as rainstorms and typhoons, and serves as a crucial reference for forecasters. Quantitative precipitation forecasts (QPFs) have steadily improved with continuous

advancements in numerical modeling. However, extreme rainstorm forecasts remain challenging for current NWP models (Zhang et al. 2023). Many high-resolution models suffer from irrational rainfall zones and the underestimation of precipitation intensity. Uncertainties in predicting the area and intensity of extremely heavy precipitation are also considerably greater than those in predicting general precipitation (Cai et al. 1992; Tan and Chen 2008). In numerical models, precipitation is typically generated based on a combination of cumulus convection and cloud microphysics parameterization schemes. Models with high horizontal resolution can directly resolve most cloud microphysical processes and generally do not use cumulus convection schemes. In such cases, cloud microphysics schemes are crucial for determining the performance of QPF models (Xu et al. 2023). Many studies have analyzed the differences in extreme precipitation forecasts using different cloud microphysics schemes (Chen et al. 2019; Ma et al. 2021a; Xu et al. 2021) and shown that uncertainty in cloud schemes has become a major source of error in forecasting extreme heavy rainfall. Therefore, understanding the macro- and micro-characteristics of clouds, as well as the differences

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Biography: LIU Chen-yun, primarily undertaking research on cloud microphysics parameterization.

Corresponding author: MA Zhan-shan, e-mail: mazes@cma.gov.cn

between various cloud microphysics schemes for modeling extreme precipitation, is essential for improving and selecting cloud physics schemes.

From July 18–22, 2021, Henan experienced a rare extreme precipitation event, with the accumulated precipitation at 29 stations exceeding historical extremes. The maximum hourly precipitation intensity at the Zhengzhou station reached 201.9 mm, setting a record for rainfall in the mainland of China. This extreme precipitation event resulted in 339 fatalities and missing persons, and direct economic losses reached 53.2 billion yuan. In view of the severity of this event, it has been referred to as the “Zhengzhou 7·20 extreme rainstorm” (Su et al. 2021).

The Zhengzhou 7·20 extreme rainstorm has attracted widespread attention in the meteorological community. Many studies have explored the formation mechanism of this event from various perspectives, including large-scale circulation anomalies and the impact of mesoscale weather systems (Deng et al. 2022; Yin et al. 2022; Zhang et al. 2023; Zhou et al. 2024). For example, Zhang et al. (2023) identified three mesoscale systems that play important roles during rainstorms in this region. The low system formed by the southwestern inverted trough in Zhengzhou is the most critical system for triggering and enhancing rainstorms. In addition, the barrier jet and downslope gravity flow near the Taihang Mountains, north of Zhengzhou, may contribute to the local enhancement of rainstorms.

Previous studies have explored the Zhengzhou 7·20 event from the perspective of cloud physics and precipitation formation. For instance, Yin et al. (2023) found that water vapor flux convergence is a key factor affecting the efficiency of large-scale precipitation, and that the net water vapor consumption in cloud microphysical processes is critical for microphysical cloud precipitation efficiency. Yin et al. (2022) also analyzed the role of nonlocal hydrometeor advection processes in the formation of extreme precipitation and found that these processes are important in determining the maximum hourly precipitation intensity. Research based on observations and simulations has shown that warm rain processes dominate heavy rainfall events (Ding et al. 2023; Shu et al. 2023), and that high concentrations of medium-to large-sized raindrops may be generated by active ice-phase and effective collision-coalescence processes (Chen et al. 2023; Wu et al. 2023). However, there is still a lack of understanding of cloud microphysical characteristics such as mixing ratios, particle sizes, falling velocities, and number concentrations of hydrometeors in the Zhengzhou 7·20 extreme rainstorm, and the performances and differences in simulations of microphysical quantities during extreme precipitation processes across different cloud microphysics schemes remain unclear. Consequently, in this study, we simulated the Zhengzhou 7·20 extreme rainfall event and analyzed the characteristics and differences of the simulated

precipitation and cloud macro- and micro-physical fields using the weather research and forecasting single-moment 6-class microphysics (WSM6), Thompson, and LiuMa cloud microphysics schemes in the China Meteorological Administration mesoscale (CMA-MESO) model version 5.0.

2 WEATHER CONDITIONS DURING THE ZHENGZHOU 7·20 EXTREME RAINSTORM EVENT

From July 17–22, 2021, Henan experienced extraordinarily heavy precipitation. The event was characterized by heavy rainfall over a prolonged duration, significant accumulated rainfall, and extremely intense short-term rainfall. The accumulated precipitation exceeded 500 mm, with a maximum of 1122.6 mm recorded at Baizhai station. Nearly 50% of all meteorological stations in Henan recorded daily rainfall greater than 100 mm, and approximately 1/6 of the national meteorological stations broke their historical daily rainfall records. This event was especially notable for its intense short-term rainfall, with 392 stations recording hourly precipitation greater than 50 mm, and 34 recording hourly precipitation greater than 100 mm. From 00:00 UTC on July 20 to 00:00 UTC on July 21, the maximum daily rainfall at Zhengzhou station reached 624.1 mm, which was 3.4 times the maximum daily rainfall recorded since the station was established in 1954. At 09:00 UTC on July 20, 2021, the maximum hourly precipitation reached 201.9 mm, setting a record for hourly precipitation in the mainland of China. This event caused hundreds of casualties and severe economic losses.

The extreme rainstorm event in Zhengzhou formed under the joint influence of multiscale weather systems. As shown in Fig. 1, before the occurrence of precipitation, two typhoons interacted over southern and southeastern China, continuously transporting moisture toward the

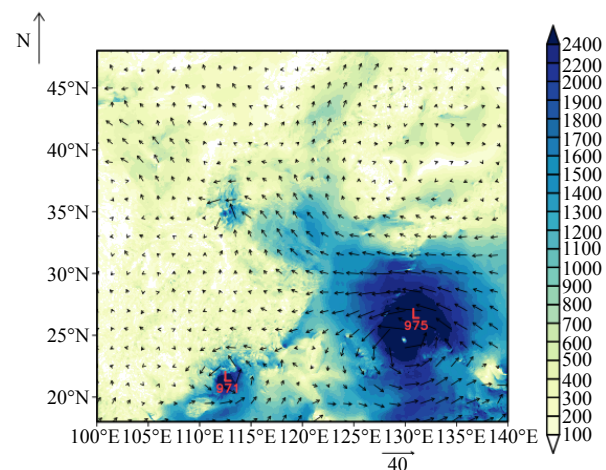


Figure 1. The 850 hPa wind field at 00:00 UTC on July 20, 2021. Shading denotes integrated water vapor transport (units: $\text{kg m}^{-1} \text{s}^{-1}$). The red “L” marks the low-pressure center, with red numbers indicating sea level pressure (units: hPa).

Zhengzhou area. This was a key factor that contributed to the occurrence of the extreme rainstorm. Moreover, under the persistent influence of the northward-shifting western Pacific subtropical high, substantial convective available potential energy accumulated around Zhengzhou. Coupled with a deep moist layer, these conditions favored the development of deep warm cloud convection with high precipitation efficiency. On the afternoon of July 19, precipitation was enhanced under the joint influence of intensified Typhoon In-Fa, the boundary layer southeasterly jet established in the Huang–Huai River region, and orographic convergence in front of the Taihang–Funiu Mountains in western Henan. From the night of July 19 to July 20, a new mesoscale vortex appeared in western Henan, which moved slowly and developed rapidly, further strengthening the convergence of low-level winds and the accumulation of environmental water vapor in Zhengzhou, and increasing the intensity and organization of meso- and micro-scale convective systems, resulting in extreme accumulated precipitation and intense short-term rainfall in Zhengzhou.

3 METHODS

3.1 CMA–MESO model

A regional operational numerical weather prediction system developed by the China Meteorological Administration (CMA–MESO v5.0) was used in this study, which included both an atmospheric model and data assimilation. The atmospheric model framework employed a fully compressible non-hydrostatic dynamical code with six independent prediction variables—potential temperature, specific humidity, three-dimensional wind field components, and dimensionless air pressure. The model discretizes the spatial variables in the staggered Arakawa C-grid and implements an off-centered two-time-level semi-implicit and semi-Lagrangian scheme for time discretization based on the latitude–longitude grid. A height-based terrain-following coordinate Charney–Phillips variable staggering was used in the vertical direction (Chen et al. 2008). A piecewise rational scalar advection scheme was employed to calculate the advection of moist variables (Su et al. 2013). CMA–MESO v5.0 uses a three-dimensional variational data assimilation system that incorporates various observations, including Radiosonde, Airep, Synop, Ships and buoys, atmospheric motion vectors, radar velocity azimuth display, wind profiles, precipitation water derived from Global Positioning System station observations, and surface observations to improve the quality of the initial fields of the model (Yang et al. 2019).

3.2 Cloud microphysics schemes

We compared the WSM6, Thompson, and LiuMa cloud microphysics schemes to investigate the characteristics and differences in cloud macro- and micro-physical fields during the Zhengzhou 7·20 extreme rainfall event. The WSM6 cloud microphysics scheme was developed by Hong et al. (2004), based on the works of

Dudhia (1989) and Rutledge and Hobbs (1983), and was improved by optimizing the parameterization of ice nuclei and ice crystal concentrations. As a single-moment scheme, it predicts only the mixing ratios of cloud water, rain, ice crystals, snow, and graupel. During its operational application in CMA–MESO v5.0, Ma et al. (2021b) optimized ice crystal deposition to enhance the simulation of supercooled liquid water. In this study, we employed such an improved WSM6 scheme.

The Thompson scheme (Thompson et al. 2004) is a double-moment cloud microphysics scheme that predicts the mixing ratios and number concentrations of raindrops and ice crystals, as well as the mixing ratios of cloud water, snow, and graupel particles. The treatment of snow particles in this scheme is unique, as it assumes that the diameter distribution of snow particles is associated with temperature and ice water content, represented as a sum of the exponential and gamma distributions. Additionally, snow particles are considered nonspherical, and their density is inversely proportional to their diameter.

The LiuMa double-moment cloud microphysics scheme (Hu and He 1988; Liu et al. 2003; Ma et al. 2022) was developed independently by the CMA. This scheme includes five types of hydrometeors—cloud water, rain, ice crystals, snow, and graupel—and predicts both their mixing ratios and the number concentrations of the latter four types. Furthermore, this scheme parameterizes the broadening function of cloud droplet spectra and the riming rates of ice crystals and snow particles, allowing for more accurate depictions of cloud microphysical processes, such as the auto-conversion of cloud water to raindrops, ice crystals to snow particles, and snow particles to graupel particles. Transformations among different types of hydrometeors occur through processes such as auto-conversion, collision, freezing, melting, and ice-particle multiplication.

3.3 Experimental setup

In this study, we simulated extreme rainstorms that occurred in Zhengzhou, from 00:00 UTC on July 20 to 00:00 UTC on July 21, 2021, using the three aforementioned cloud microphysics schemes. Simulated precipitation and radar echoes were compared with actual observations, and the differences in cloud microphysical quantities (i.e., particle size, falling velocity, hydrometeor mixing ratio, and number concentration) among the three schemes were analyzed. The 6-hour analytical field from the National Centers for Environmental Prediction's Global Forecast System (NCEP–GFS) was used as the initial and lateral boundary conditions of the simulation. The model has a time step of 30 s, a horizontal resolution of 0.03° , 2501×1671 grid points, and 50 vertical sigma levels. The top of the model is set to 10 hPa. In addition to the cloud microphysics schemes, other physical parameterization schemes used in this study are all consistent with operational applications, including the Rapid Radiative Transfer Model longwave radiation (Mlawer et al. 1997), the Dudhia shortwave radiation

(Dudhia 1993), the Noah land surface (Chen and Dudhia 2001), and the Mellor–Yamada–Rumtsev–Fairall planetary boundary layer parameterization (Hong and Pan 1996) schemes. A cumulus convection scheme was not used in this study owing to the high horizontal resolution of the model. The model integration began at 00:00 UTC on July 20, 2021, and continued for 24 h, with an output interval of 1 h.

3.4 Data

The NCEP–GFS analytical field provides an optimal physical estimate of the current global atmospheric state. It was produced by NCEP using a data assimilation system that integrates observational data worldwide. The dataset has a horizontal resolution of $0.25^\circ \times 0.25^\circ$ and consists of 127 vertical levels. In this study, it was used as an input field for model simulations. Additionally, global navigation satellite system/meteorology (GNSS/MET)-derived precipitable water vapor (PWV) retrieval data, provided by the Meteorological Observation Center of the CMA, were employed as the benchmark to select an appropriate initial field for the model. For comparison, ground-based observational precipitation data were obtained from the National Meteorological Information Center of the CMA (<https://data.cma.cn>). These precipitation data originated from national surface meteorological stations and underwent a three-tier

quality control procedure.

4 RESULTS AND DISCUSSION

4.1 Water vapor and precipitation forecasts of the initial fields

Data assimilation plays a crucial role in improving the quality of initial model fields. In addition to the assimilation of conventional observation data, the assimilation module of CMA–MESO v5.0 also includes a three-dimensional cloud analysis function for assimilating weather radar data, which can improve the assimilation quality of humidity in the initial fields, thereby enhancing the performance of model simulation of precipitation (Zhu et al. 2017). Two experiments were conducted to simulate the extreme precipitation observed in the study event. The first experiment, referred to as the control (CTRL) experiment, used the National Centers for Environmental Prediction global forecast system (NCEP–GFS) analysis data as the initial field. Based on this, the third experiment (referred to as the 3DRAD experiment) included a three-dimensional cloud analysis to assimilate the radar data. The results of these two experiments were used to analyze the differences in the water vapor of the initial fields (Fig. 2) and their impacts on extreme precipitation forecasts (Fig. 3). Fig. 1 shows the comparison of the PWV between the GNSS/MET

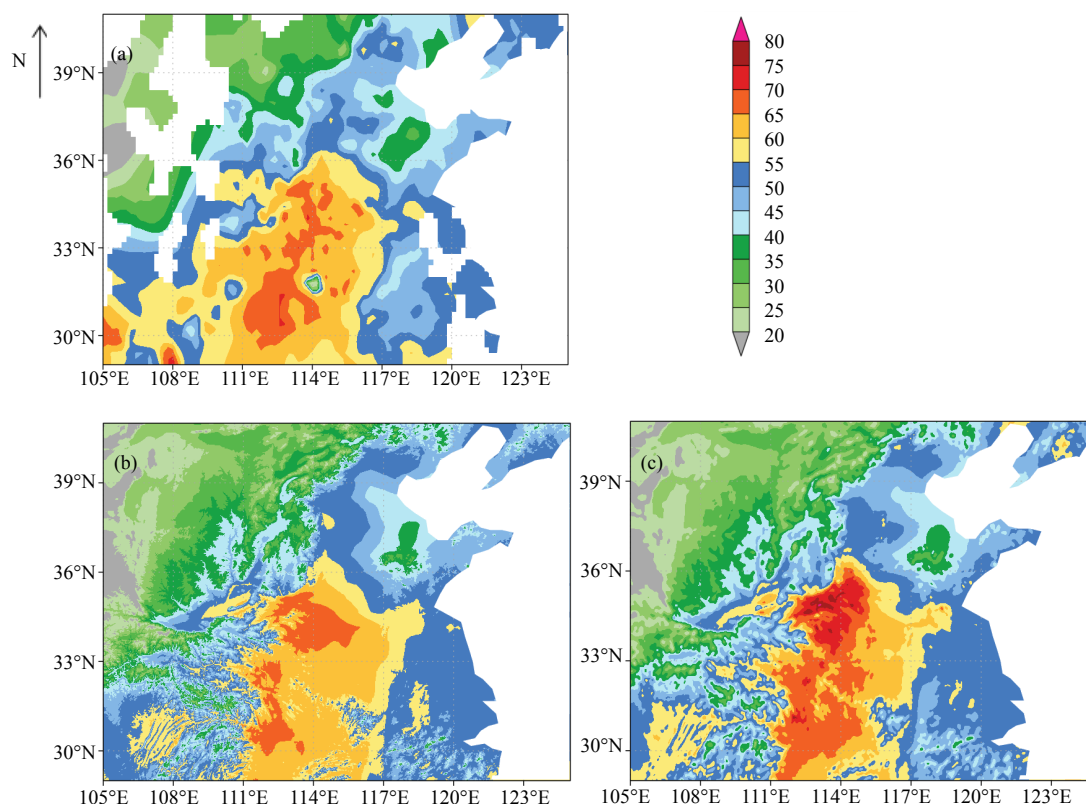


Figure 2. Distributions of precipitable water vapor (units: kg m^{-2}) at 00:00 UTC on July 20, 2021 from (a) GNSS/MET observations, (b) the initial field of the experiment based on the NCEP–GFS data (control experiment), and (c) the initial field of the experiment based on the NCEP–GFS data with the assimilation of radar data via three-dimensional cloud analysis (3DRAD experiment).

observations and the initial fields of the two experiments. Both experiments reasonably reflect the overall distributional characteristics of the PWV in the study area, though notable differences were found in regions where $PWV > 65 \text{ kg m}^{-2}$.

The large-value centers of the PWV in the initial field for the CTRL experiment ranged from 65 to 70 kg m^{-2} , and were concentrated in central Henan (Fig. 3b). However, there was considerable underestimation of the PWV in southern Henan and central Hubei. In contrast, the PWV in the initial field systematically increased in the 3DRAD experiment because water vapor was considered to be saturated in radar echo areas during cloud analysis. The distribution of high PWV values in the 3DRAD experiment was consistent with GNSS/MET observations (Fig. 3c), although the PWV was slightly overestimated, especially in northern and central Henan, with a maximum $PWV > 75 \text{ kg m}^{-2}$, with extreme rainfall.

To analyze the impacts of different initial water vapor

conditions on the forecasts of the extreme precipitation process, we simulated the 24-hour precipitation distribution using the WSM6 cloud microphysics scheme in both the CTRL (Fig. 3b) and 3DRAD experiments (Fig. 3c). Both experiments adequately simulated the location and overall distribution of the rain belt, but the CTRL experiment substantially underestimated the intensity of the precipitation center, with 24-hour accumulated precipitation below 200 mm. The center and amount of precipitation simulated by the 3DRAD experiment were closer to the observations, and the maximum precipitation of the simulations exceeded 350 mm. This result indicates that a cloud analysis that considers radar data can greatly improve precipitation forecasts. Therefore, the initial fields formed by considering the cloud analysis were used in all subsequent simulations to analyze the cloud macro- and micro-characteristics of the extreme precipitation process simulated by the three distinct cloud microphysics schemes.

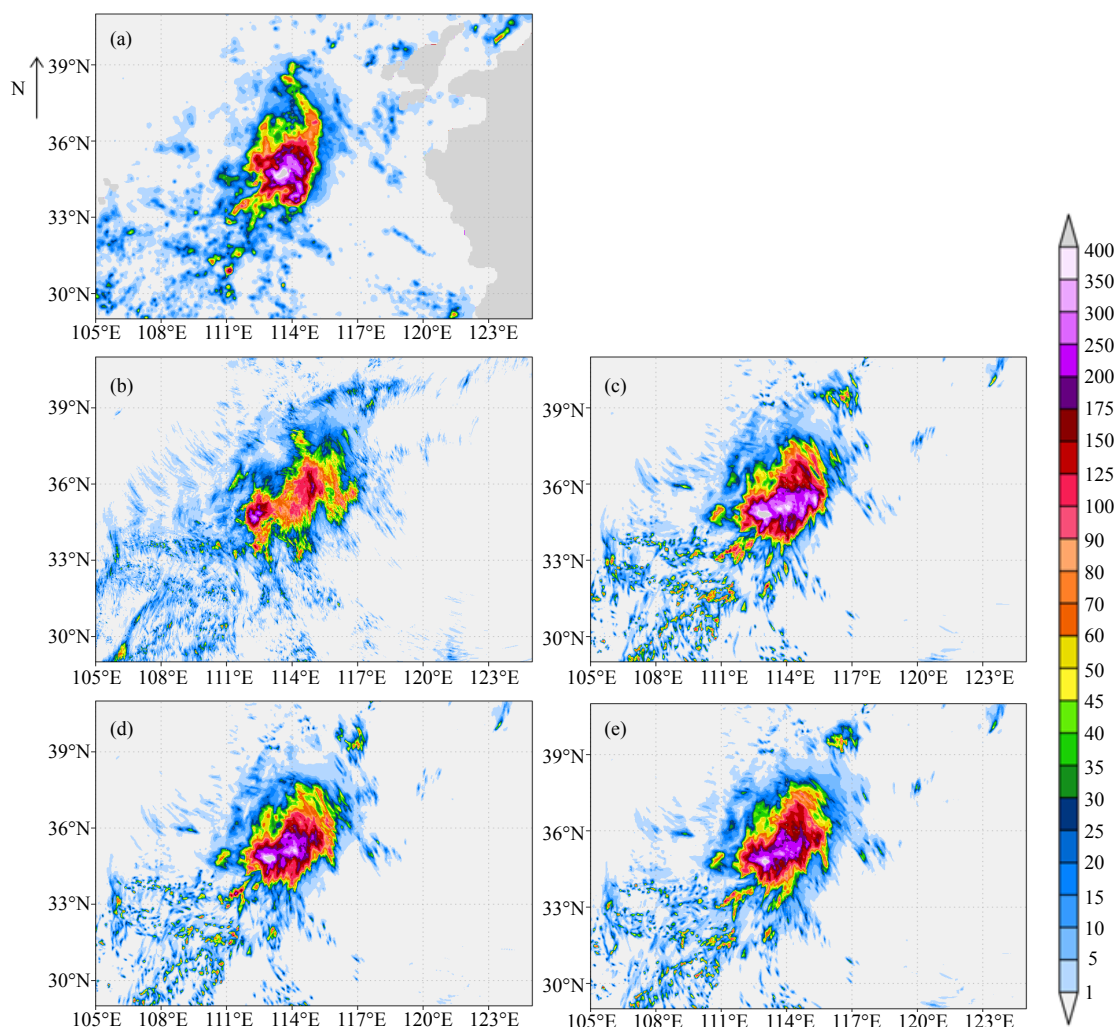


Figure 3. Spatial distribution of the 24-hour accumulated precipitation (units: mm) from 00:00 UTC on July 20 to 00:00 UTC on July 21, 2021, from (a) the observations and simulations in (b) the control experiment with the WSM6 scheme and in the 3DRAD experiment with (c) the WSM6, (d) Thompson, and (e) LiuMa schemes.

Figures 3c–3e show the 24-hour accumulated precipitation from 00:00 UTC on July 20 to 00:00 UTC on July 21, 2021, simulated using the WSM6, Thompson, and LiuMa schemes, respectively. As presented in Fig. 3a, the 24-hour accumulated precipitation is greater than 50 mm, mainly occurring in Henan. The grade of precipitation in most of central and northern Henan reached extraordinarily heavy rainfall (greater than 250 mm), with the precipitation center located in Zhengzhou, where the maximum 24-hour precipitation reached 624.1 mm. Specifically, all three simulations reproduced heavy precipitation of over 250 mm observed (Fig. 2a) in central and northern Henan. The maximum 24-hour accumulated precipitation values simulated by the WSM6, Thompson, and LiuMa schemes were 566.536, 540.919, and 536.64 mm, respectively, which are somewhat lower than the observed peak of 624.1 mm. Nonetheless, the distribution of precipitation centers that exceed 350 mm differed among the various schemes and actual observations. Simulations from the WSM6 and Thompson schemes showed multiple scattered peaks (Figs. 2c and 2d), whereas the peak simulated by the LiuMa scheme was relatively narrow and had a slightly weaker intensity (Fig. 3e).

To compare the performances of the three cloud microphysics schemes in the simulation of heavy rainfall areas, we investigated the temporal evolution of the observed and simulated hourly precipitation averaged over the region, 111°–117°E and 32°–36°N, as shown in Fig. 4. The precipitation data used in this study were obtained from station observations. To ensure consistency in the area used to calculate the mean precipitation, the observed data were first linearly interpolated to grid points before averaging. It can be seen that the observed regional mean hourly precipitation remained relatively stable (1.6–2.3 mm), except for a peak of 3 mm at 09:00 UTC on July 20, corresponding to the time when the historical maximum hourly precipitation of 201.9 mm was observed in Zhengzhou. The hourly precipitation simulated by the three cloud microphysics schemes showed a similar trend

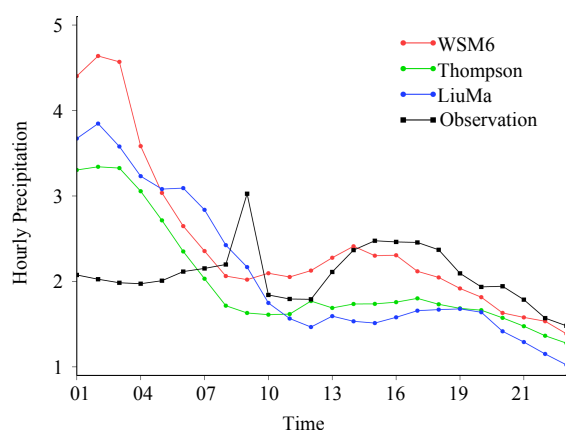


Figure 4. Time series of observed and simulated mean hourly precipitation (units: mm) across 111°–117°E, 32°–36°N from 01:00 UTC on July 20 to 00:00 UTC on July 21, 2021.

over time. From 01:00 UTC to 10:00 UTC on July 20, the precipitation intensity gradually decreased from 3.3–4.7 to 1.6–2.1 mm h⁻¹, which was noticeably larger than the observed values. The simulation from the WSM6 scheme showed the most notable overestimation, with a maximum of 4.7 mm h⁻¹, while the simulation from the Thompson scheme had the smallest overestimation. From 10:00 UTC on July 20 to 00:00 UTC on July 21, all schemes underestimated the regional mean hourly precipitation. The results of the WSM6 scheme were closer to the observations, whereas those of the Thompson and LiuMa schemes showed remarkable underestimations. Additionally, none of the schemes could simulate the peak regional mean precipitation observed at 09:00 UTC on July 20. These results indicate that, although the model with the three cloud microphysics schemes could adequately simulate the spatial distribution of 24-hour precipitation, there remain challenges in simulating the temporal evolution of hourly precipitation and the intensity of extreme precipitation. Furthermore, the simulated precipitation showed alternating strong and weak intensity characteristics, possibly related to the excessive water vapor increase in the initial fields due to cloud analysis (Fig. 2).

The spatial distribution of the hourly precipitation from the simulations and observations at the time of the observed maximum hourly precipitation intensity (08:00–09:00 UTC on July 20) is shown in Fig. 5, which demonstrates the respective abilities of different cloud microphysics schemes to simulate extreme hourly precipitation intensity. Overall, the simulations with the three schemes adequately exhibited widespread precipitation in northern Henan and extremely heavy precipitation in Zhengzhou. Observations indicate that hourly precipitation exceeding 25 mm was primarily concentrated at 113.5°–114°E, 34.5°–35°N, and most of the areas experienced hourly precipitation of >50 mm; the extreme heavy precipitation center was recorded at Zhengzhou station, reaching 201.9 mm h⁻¹. Simulations with the WSM6 and Thompson schemes showed two precipitation centers in the range of 113.5°–115°E and 34.5°–35°N, with a true center in the west and a false center in the east. As shown in Figs. 5b and 5c, both simulations considerably underestimated the maximum hourly precipitation at the western center (55.92 and 46.49 mm). The simulation from the LiuMa scheme, which showed better agreement with the location of the observed precipitation center and the simulated intensity (67.35 mm h⁻¹), was also slightly higher than that from the other two simulation schemes, but was still notably lower than the observed values. Additionally, all three schemes underestimated the scattered precipitation <10 mm in the southwest (Fig. 4a).

4.2 Cloud macro characteristics

Radar echoes serve as an essential reference for evaluating the ability of numerical models to predict cloud macro-characteristics. Fig. 6 shows the distributions of the

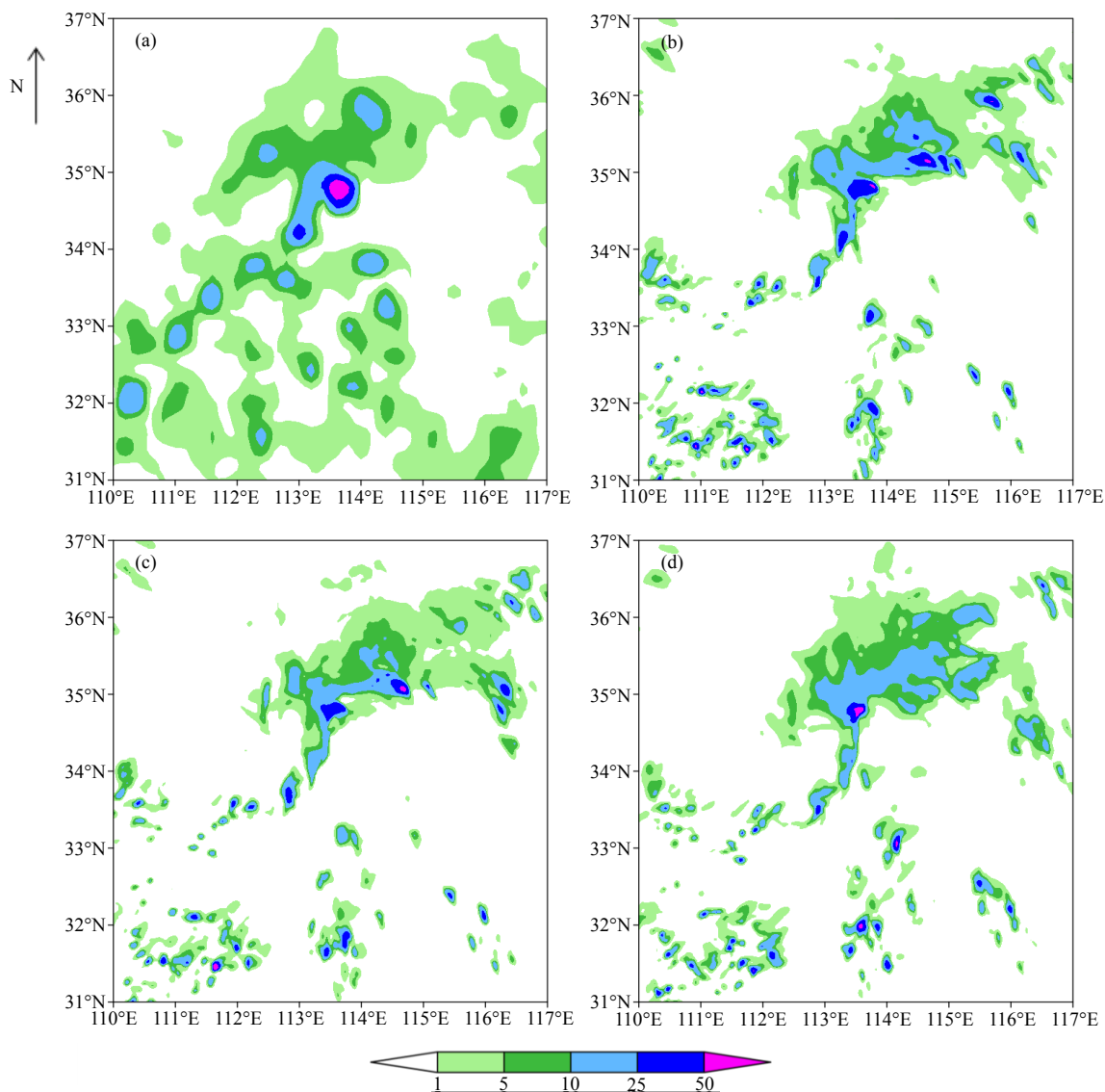


Figure 5. Spatial distribution of the hourly precipitation (units: mm) from 08:00 to 09:00 UTC on July 20, 2021, from (a) the observations and simulations under the (b) WSM6, (c) Thompson, and (d) LiuMa schemes.

observed composite reflectivity (CR) and those simulated using the three cloud microphysics schemes at the time of maximum precipitation intensity (09:00 UTC on July 20). The algorithm for calculating the CR in the model followed [Stoelinga \(2005\)](#), and observations indicated that at the time of peak precipitation, large areas of strong echoes (>30 dBZ) appeared in northern and central Henan, southern Shanxi, and southern Hebei. Moreover, the echo centers with a CR reaching 50 dBZ were mainly located in Zhengzhou and its vicinity, indicating remarkable precipitation intensity in Zhengzhou. Compared with observations, the CR values simulated by the WSM6 and Thompson schemes showed smaller coverage, with missing signals in central and southern Shanxi, central Hebei, and a notably weaker center. Comparatively, the simulation using the LiuMa scheme showed better agreement with the observations in the strong echo areas (>35 dBZ) in northern Henan, southern Hebei, and

southern Shanxi, and it successfully reproduced echoes >50 dBZ near Zhengzhou.

4.3 Hydrometeor mixing ratio

To analyze the similarities and differences in the simulated hydrometeor contents using different cloud microphysics schemes, we investigated the vertical distributions of the average simulated hydrometeor mixing ratio in the region of heavy precipitation centers ($112^{\circ}\text{--}117^{\circ}\text{E}$, $32^{\circ}\text{--}36^{\circ}\text{N}$) from July 20 to 21, 2021, as shown in [Fig. 7](#). The results demonstrated that the simulated total hydrometeor content and ice-phase hydrometeor composition of the three schemes were significantly different, whereas the simulated cloud water and rainwater contents were more consistent. In terms of the total hydrometeor content, although all three simulated maximum mixing ratios occurred at heights of 400–600 hPa, the simulation with the WSM6 scheme exhibited the smallest total hydrometeor content, with a maximum value

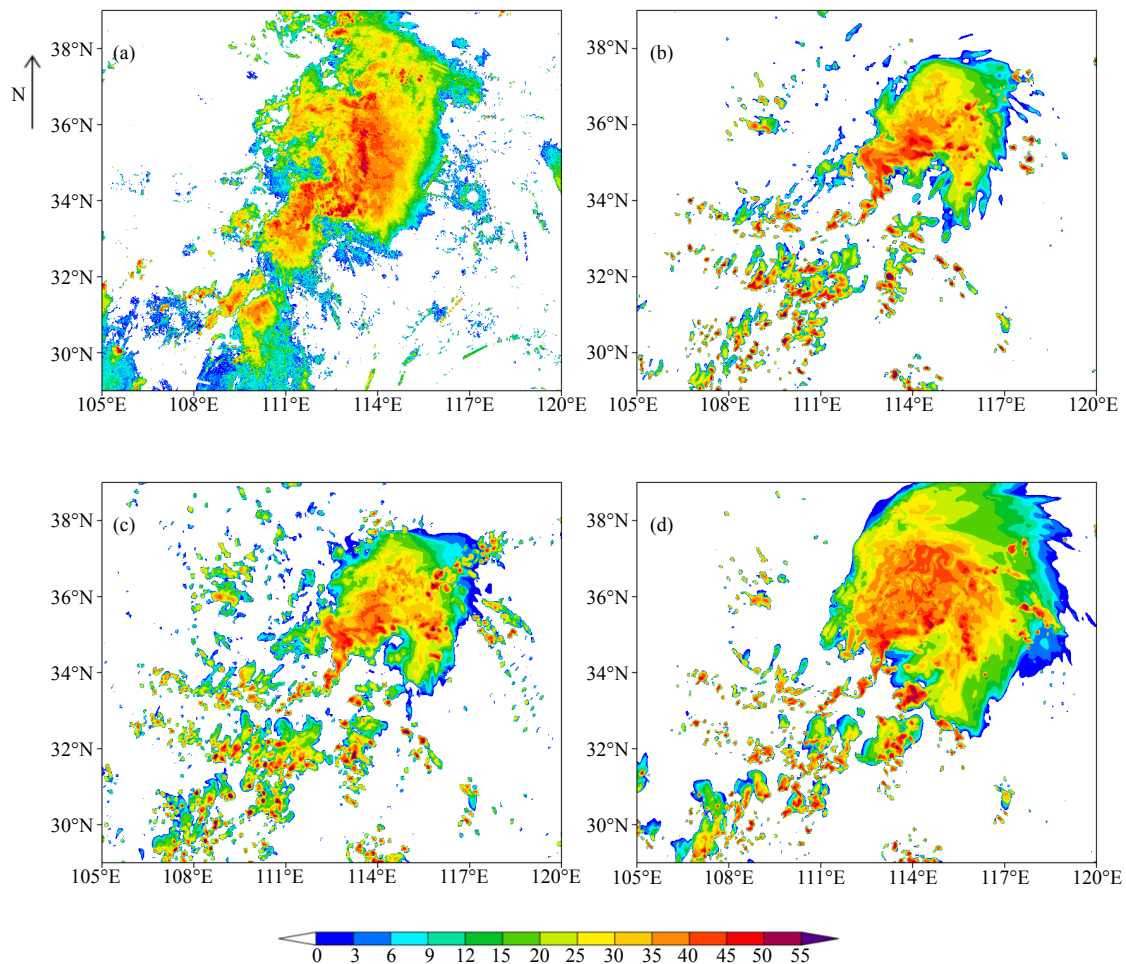


Figure 6. Composite reflectivity (units: dBZ) distributions at 09:00 UTC on July 20, 2021, from (a) the observations and the simulations under the (b) WSM6, (c) Thompson, and (d) LiuMa cloud microphysics schemes.

of 0.26 g kg^{-1} at 600 hPa. The simulations with the LiuMa and Thompson schemes had maximum total hydrometeor contents at 500 hPa, with peaks of 0.46 and 0.34 g kg^{-1} , respectively. Combined with the simulations of the mean rainfall (Fig. 4), it was found that, although the WSM6 cloud microphysics scheme simulated the smallest total hydrometeor content, the near-surface rainwater content was slightly higher than that of the Thompson and LiuMa schemes. This result indicates that WSM6 simulates more ice-phase hydrometeors that contribute to surface rainfall through rapid settling and melting processes, leading to a higher precipitation efficiency. In contrast, the simulation with the LiuMa scheme had less near-surface rainwater, despite the higher ice-phase hydrometeor content, suggesting relatively weaker cold cloud settling and melting processes in this scheme. The differences in the total hydrometeor content simulated by the three schemes were primarily caused by differences in the simulated ice-phase hydrometeor content. The maximum simulated solid hydrometeor contents were 0.19 g kg^{-1} for the WSM6 scheme, 0.32 g kg^{-1} for the Thompson scheme, and 0.43 g kg^{-1} for the LiuMa scheme, which were all quite

close to the observed maximum total hydrometeor content. Additionally, the solid hydrometeor composition simulated using the Thompson scheme differed from that simulated using the WSM6 and LiuMa schemes. Simulations involving the latter two schemes included ice crystals, snow particles, and graupel particles, whereas the simulation using the Thompson scheme included only snow particles and a very small number of graupel particles. The simulated ice crystal and graupel particle contents from the Thompson scheme were thus considerably lower than those from the other two schemes, indicating notable differences in the treatment of the ice phase processes. This phenomenon was also observed in previous studies (Chen et al. 2019).

The maximum hydrometeor contents simulated by different cloud microphysics schemes were further analyzed in the case of hourly precipitation intensity exceeding historical records. The period of the strongest hourly precipitation (from 08:00 UTC to 09:00 UTC on July 20) and the $1^\circ \times 1^\circ$ area near Zhengzhou station (113.66°E , 34.71°N), where the maximum rainfall intensity was observed, were selected to determine the

maximum total hydrometeor mixing ratio at different heights, as shown in Table 1. It can be seen that the maximum values in the heavy precipitation center were mainly distributed in the lower troposphere. The total hydrometeor contents simulated by the three schemes at the same level were close to each other, with most of them above 3.3 g kg^{-1} at altitudes below 800 hPa. The maximum total hydrometeor contents from the Thompson, WSM6, and LiuMa schemes appeared at 925, 900, and 850 hPa, respectively, with values of 4.15, 4.21, and 4.08 g kg^{-1} . For the cold levels at 300 and 400 hPa, the maximum total hydrometeor content simulated by the three schemes exceeded 1.33 g kg^{-1} , and the maximum from the Thompson scheme reached 2.73 g kg^{-1} at 400 hPa. While the hourly precipitation intensity simulated by the three schemes was still notably underestimated compared with observations, the maximum values of

hydrometeor contents exceeded 4 g kg^{-1} (Fig. 4).

4.4 Latent heat

Precipitation involves transformation between different phases of water substances, in which evaporation, melting, and sublimation absorb heat, whereas condensation, freezing, and deposition release latent heat. These thermal changes greatly alter atmospheric temperature and humidity stratification, as well as the thermodynamic fields of clouds. Consequently, they exert a profound influence on the evolution and progression of cloud systems and the precipitation they generate.

Figure 8 shows the vertical characteristics of the regional average rates of latent heating simulated using the WSM6, Thompson, and LiuMa schemes over a 24 h period in the main precipitation region (112° – 117°E , 32° – 36°N , i.e., Henan) and over a 1 h period in the region of

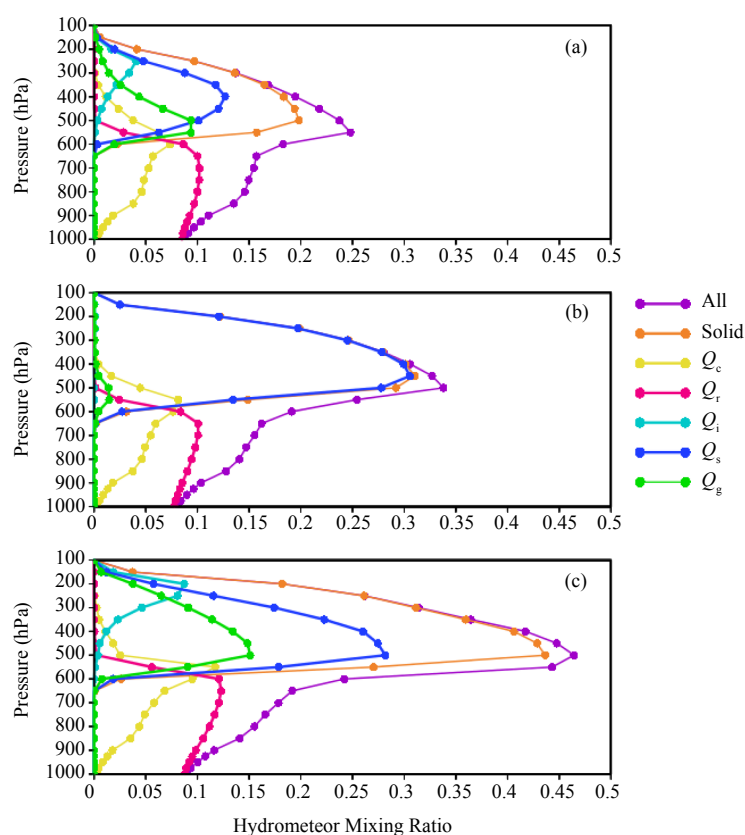


Figure 7. Vertical distributions of the simulated hydrometeor mixing ratio (units: g kg^{-1}) averaged across 112° – 117°E , 32° – 36°N from 00:00 UTC on July 20 to 00:00 UTC on July 21, 2021, from the (a) WSM6, (b) Thompson, and (c) LiuMa cloud microphysics schemes. In the figure, Q_c , Q_r , Q_i , Q_s , and Q_g represent the mixing ratios of cloud droplets, raindrops, ice crystals, snow, and graupel, respectively. Solid and All denote the mixing ratio of solid hydrometeors and total hydrometeors, respectively.

Table 1. Maximum hydrometeor contents (units: g kg^{-1}) at different heights near Zhengzhou (113° – 114°E , 34° – 35°N) at 09:00 UTC on July 20, 2021.

Cloud microphysics schemes	1000 hPa	975 hPa	950 hPa	925 hPa	900 hPa	850 hPa	800 hPa	700 hPa	600 hPa	500 hPa	400 hPa	300 hPa	200 hPa
WSM6	3.44	3.43	3.49	3.90	4.21	4.02	3.39	2.51	1.90	1.68	1.37	1.46	0.78
Thompson	3.97	3.98	3.99	4.15	3.87	3.79	3.27	2.16	2.19	2.05	2.73	1.96	1.13
LiuMa	3.27	3.31	3.47	3.66	3.84	4.08	3.54	3.05	1.91	1.50	1.61	1.33	0.45

maximum hourly precipitation intensity (112.5° – 113.5° E, 34.5° – 35° N, i.e., Zhengzhou). The vertical distributions of the regional average heating rates showed consistent patterns in the same region across all schemes; however, the values and distribution heights of the maximum rates differed noticeably between the two regions. For the 24 h average latent heating rates in Henan, simulations revealed two peaks at 500 and 700 hPa, with values of 25–28 and 19–21 K d^{-1} , respectively. High heating rates were mainly located at 400–800 hPa, indicating that precipitation in Henan was dominated by both cold and warm cloud processes. During the period of maximum precipitation intensity from 08:00 UTC to 09:00 UTC, the regional average heating rates simulated by the three schemes in Zhengzhou were mainly distributed in the lower and middle troposphere below 600 hPa. Maximum heating rate values occurred near 700 hPa, all exceeding 180 K d^{-1} , which was considerably higher than those in Henan. These results suggest that extreme hourly precipitation was primarily dominated by warm cloud condensation (Fig. 8b). Meanwhile, the simulated maximum latent heat heating rates varied among the schemes. Specifically, the

WSM6 and LiuMa schemes predicted maximum values of $\sim 220 \text{ K d}^{-1}$ in Zhengzhou, whereas the Thompson scheme yielded a relatively subdued peak at 180 K d^{-1} .

Based on the consensus that the horizontal distribution of vertically integrated atmospheric latent heat generally coincides with surface precipitation rates (Li et al. 2021), the smaller hourly precipitation amount simulated by the Thompson scheme in Zhengzhou (Fig. 5c) is attributable to the lower rate of latent heating; that is, cloud condensation in the Thompson scheme was the weakest at that time. Overall, precipitation in Henan is jointly driven by high-level ice-phase deposition and low-level cloud–water condensation. In Zhengzhou, where extreme precipitation occurred, low-level water vapor condensation was extremely intense and much stronger than the various latent heat release processes in Henan, being primarily driven by warm cloud precipitation.

4.5 Raindrop diameter and falling velocity

Figure 9 illustrates the vertical distributions of the mass-weighted average diameter (D_m) and average terminal velocity of raindrops in Zhengzhou during the period of maximum hourly precipitation intensity from 08:00 to 09:00 UTC on July 20. These were simulated using the three cloud microphysics schemes and provided every 5 min. Compared with the results from the Thompson scheme (Fig. 9c), it can be seen that the vertical distributions of the maximum, minimum, and average values of the D_m simulated by the WSM6 (Fig. 9a) and LiuMa (Fig. 9e) schemes are more similar, except at altitudes $>6 \text{ km}$. At altitudes of 4–6 km, the ranges of D_m values simulated by the WSM6 and LiuMa schemes are relatively wide, with maximum values appearing at 5.6 km, reaching 3.3 and 3.8 mm, respectively. The D_m values also peak near this altitude, with values of 2.7 and 2.8 mm, respectively. The larger overall size of raindrops near the 5.6-km altitude can be attributed to the rapid melting of ice-phase hydrometeors as they descend to this level and transition into raindrops. Within the near-surface layer below 1.0 km, the WSM6 and LiuMa schemes simulated a range of D_m values between 2.0 and 2.6 mm. Notably, the LiuMa scheme yielded higher average D_m values that were better aligned with the maximum values, suggesting that it simulated larger raindrops in the near-surface region more accurately than the WSM6 scheme. Although the vertical distributions of the maximum and minimum D_m values in the Thompson scheme are similar to those of the other two schemes, the average D_m is notably lower, skewing closer to the minimum threshold. This suggests that the Thompson scheme simulation was dominated by a larger proportion of smaller raindrops. Overall, the average D_m values indicated that the simulation from the LiuMa scheme had the largest raindrops, followed by that simulated by the WSM6 scheme, whereas the simulation by the Thompson scheme had the smallest raindrops.

The falling velocity of raindrops is related to their size and directly affects precipitation intensity. Figs. 9b,

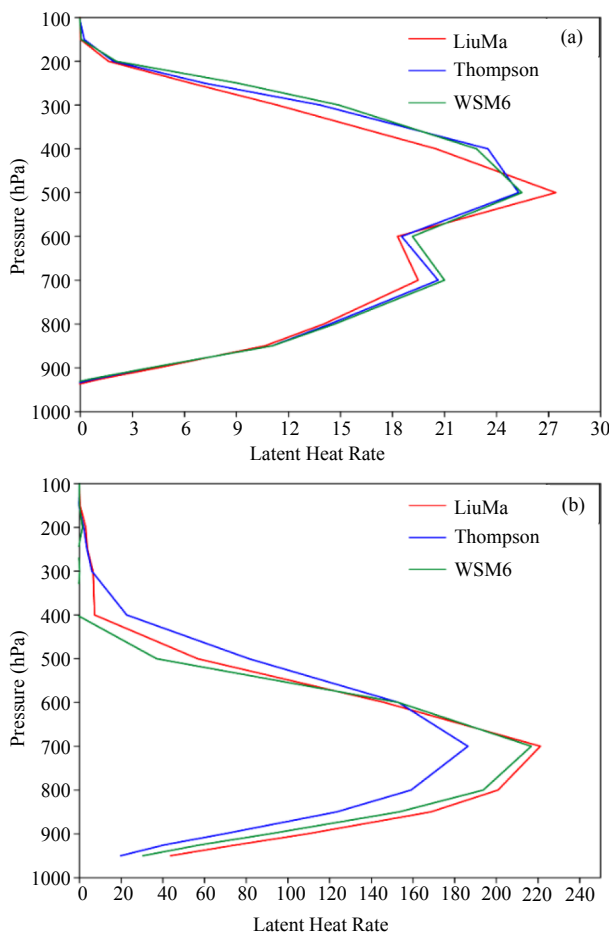


Figure 8. Vertical distributions of average latent heating rates (units: K d^{-1}) simulated under the three schemes at (a) 112° – 117° E, 32° – 36° N (Henan) from 00:00 UTC on July 20 to 00:00 UTC on July 21, 2021, and (b) 112.5° – 113.5° E, 34.5° – 35° N (Zhengzhou) from 08:00 UTC to 09:00 UTC on July 20, 2021.

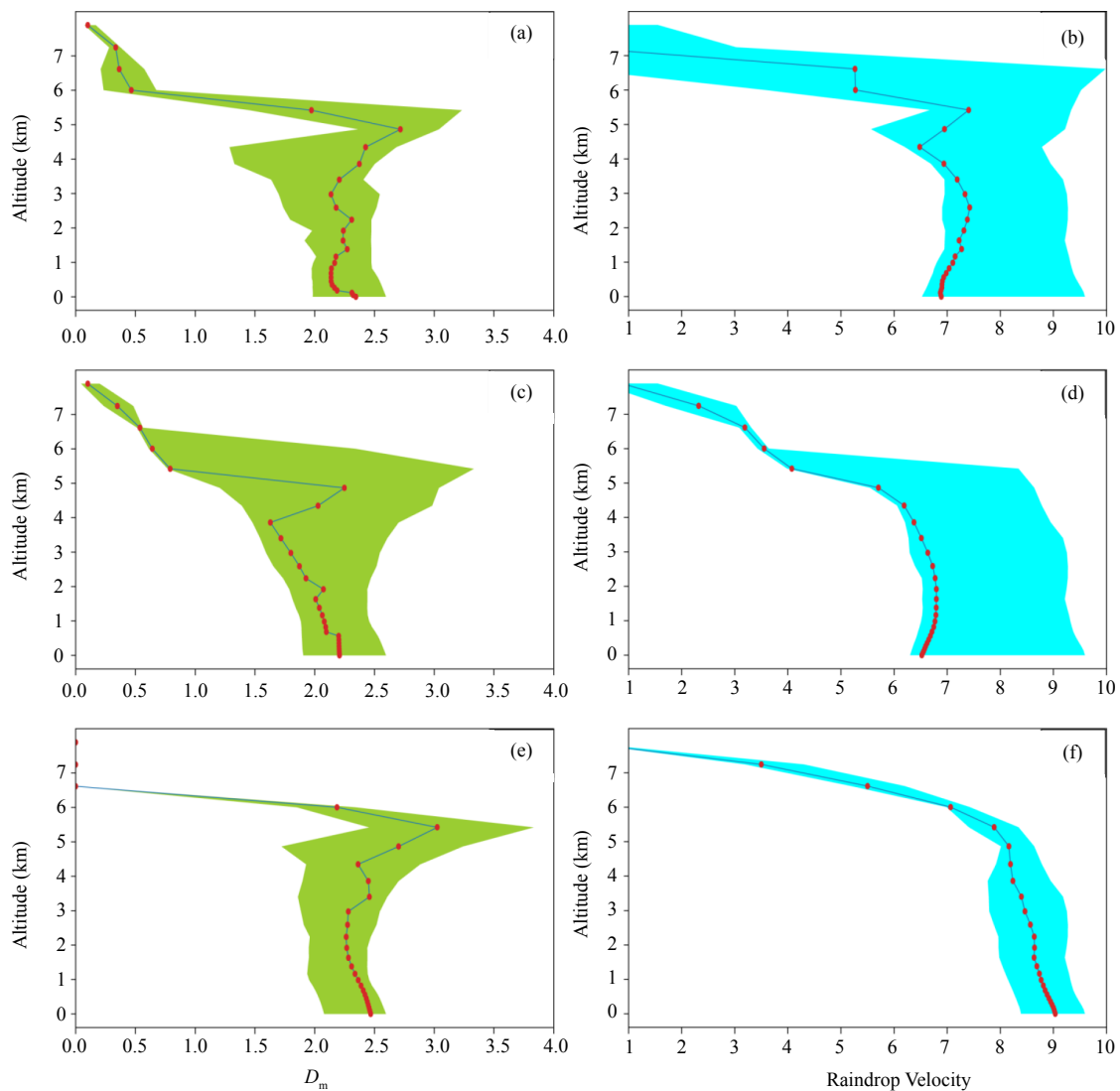


Figure 9. Vertical distributions of the (a, c, e) 5-minute mean mass-weighted diameter (D_m ; units: mm) and (b, d, f) 5-minute mean falling velocity (units: m s^{-1}) of raindrops from 08:00 UTC to 09:00 UTC on July 20, 2021, simulated by the (a, b) WSM6, (c, d) Thompson, and (e, f) LiuMa schemes. Shaded regions represent the ranges of the D_m (falling velocity) of raindrops, with the left (right) boundaries denoting the profiles of minimum (maximum) values, and red dots indicating their means.

9d, and 9f show the vertical distribution characteristics of the falling raindrop velocities simulated using the three schemes. Above 6 km, the mean falling velocities of the raindrops were substantially lower than those at lower altitudes because of the smaller D_m values. Below 6 km, the falling velocities of raindrops simulated using the WSM6 and Thompson schemes initially increased and then decreased with decreasing height. The range of velocities is broader, spanning from 6.3 to 9.5 m s^{-1} , with the mean velocities tending to align with the minimum values of the velocity spectrum. The simulated falling velocity with the LiuMa scheme shows a narrower range, mainly from 8.0 to 9.5 m s^{-1} , which increases as they approach the ground. Near the surface, the average raindrop falling velocity simulated by the LiuMa scheme is $\sim 9.0 \text{ m s}^{-1}$, that simulated by the WSM6 scheme is 7.0 m s^{-1} , and the velocity simulated by the Thompson scheme is the smallest (6.7 m s^{-1}). The larger hourly

precipitation intensity simulated by the LiuMa scheme, shown in Fig. 4d, is related to a larger simulated raindrop falling velocity.

Combining the vertical distributions of D_m and raindrop falling velocity simulated by the three cloud microphysics schemes, it is evident that the raindrops in this extreme rainfall event exhibited a positive correlation between falling velocity and diameter (Gunn and Kinzer 1949). Furthermore, the three schemes uniformly demonstrated pronounced variations in the raindrop size and velocity at different altitudes. Smaller, slower-falling raindrops are concentrated in the upper troposphere (above 6 km) because it is difficult to form large raindrops at colder altitudes. In the mid-troposphere, raindrop sizes vary dramatically, with remarkably increased falling velocities; this is associated with the rapid melting of ice-phase hydrometeors. Near the ground surface, raindrops exhibited minimal fluctuations in both

diameter and falling velocity, with relatively large values. In summary, the simulation from the LiuMa scheme had the largest D_m and fastest raindrop falling velocity, followed by the simulation from the WSM6 scheme, whereas the raindrops simulated by the Thompson scheme were the smallest and slowest.

4.6 Number concentration

We investigated the characteristics of hydrometeor number concentrations during the period of observed maximum hourly precipitation intensity. Because the WSM6 scheme is a single-moment microphysics scheme, and the Thompson scheme is an incomplete double-moment microphysics scheme, only the simulation results from the LiuMa scheme are relevant to this analysis. Fig. 10 shows the vertical profiles of the 5-minute average number concentrations of ice crystals (N_i), snow particles (N_s), graupel particles (N_g), and raindrops (N_r). The distribution of ice-phase hydrometeors is deep, reaching up to 15 km in height, and indicating a strong convective process. N_i , N_s , and N_g varied significantly in magnitude and vertical distribution. The number concentration of ice crystals is far higher than that of snow and graupel particles and primarily distributed from 8 to 15 km, with a maximum value of $1.3 \times 10^6 \text{ num kg}^{-1}$ at $\sim 12 \text{ km}$. The number concentration of snow is two orders of magnitude smaller than that of ice crystals and mainly distributed from 5 to 14 km, with a maximum value of $1.0 \times 10^4 \text{ num kg}^{-1}$ at $\sim 9 \text{ km}$. N_g is the smallest, being concentrated from 5 to 7 km, with a maximum value of $2.7 \times 10^3 \text{ num kg}^{-1}$. From 5.5 km down to 4 km, the melting of ice-phase hydrometeors led to a rapid increase in N_r . Between 2 and 4 km, N_r increases slowly, maintaining at $\sim 7.5 \times 10^3 \text{ num kg}^{-1}$. At altitudes below 2 km, N_r continually decreases, which is

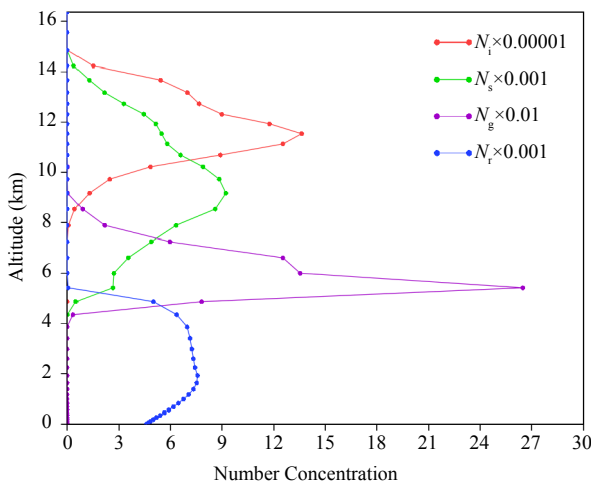


Figure 10. Vertical profiles of the 5-minute mean number concentrations (units: num kg^{-1}) of the hydrometeors (ice crystals, snow particles, graupel, and raindrops) near the Zhengzhou station ($112^\circ\text{--}117^\circ\text{E}$, $32^\circ\text{--}36^\circ\text{N}$) from 08:00 UTC to 09:00 UTC on July 20, 2021, as simulated by the LiuMa microphysics scheme. In the figure, N_i , N_s , N_g , and N_r represent the number concentration of ice crystals, snow, graupel, and raindrops, respectively.

associated with raindrop coalescence. During this process, there was an increase in the concentration of heavy raindrops, as reflected by the rising mass-weighted D_m of the raindrops near the ground surface, as shown in Fig. 9e.

5 CONCLUSION

In this study, we evaluated the performance of three cloud microphysics schemes (WSM6, Thompson, and LiuMa) using the CMA-MESO v5.0 model in simulating the extreme rainfall events in Henan, China, from July 20 to 21, 2021. The main conclusions are as follows.

(1) Using cloud analysis, assimilation substantially improved moisture initialization and precipitation forecasts. All schemes reasonably captured the spatial distribution and extremity of 24-hour accumulated precipitation, although simulating hourly intensity evolution remains challenging. The WSM6 scheme yielded 24-hour accumulations closest to the observations, whereas the LiuMa scheme better reproduced the hourly peak intensity.

(2) During peak precipitation, the LiuMa scheme simulated composite reflectivity closest to the observations, particularly in high-reflectivity regions, whereas WSM6 and Thompson showed narrower and weaker echoes.

(3) Although the vertical distributions of liquid-phase hydrometeors were consistent across schemes, ice-phase hydrometeors were scheme-sensitive. The LiuMa scheme produced the highest ice-phase content, whereas WSM6 had the lowest. Snow dominated ice-phase hydrometeors in the Thompson scheme. Snow content was the highest in the WSM6 and LiuMa schemes, followed by raindrops, cloud water, graupel, and ice crystals. Most hydrometeor mixing ratios peaked in the mid-troposphere (400–600 hPa) except for ice crystals, which peaked at higher altitudes. The total hydrometeor mixing ratio exceeded 4 g kg^{-1} in the lower troposphere during peak hourly rainfall.

(4) Latent heating rates were consistent among the schemes, with both warm and cold cloud processes contributing to the event. However, warm cloud processes dominated during peak rainfall hours.

(5) Trends in raindrop evolution were similar across schemes—small, slow-falling drops in the upper troposphere; variable sizes and faster falls in the mid-troposphere; large, stable drops in the lower troposphere. The LiuMa scheme produced the largest and fastest-falling drops.

(6) The LiuMa scheme realistically simulated the hydrometeor number concentrations, with ice crystals being the highest, followed by snow, rain, and graupel.

In this study, the simulation capabilities of three cloud microphysical schemes were assessed for the Zhengzhou 7·20 extreme rainfall event based on the CMA-GFS model, and their cloud macro- and micro-physical characteristics were compared. Consistent with the findings of Shi et al. (2021), simulations also indicated that global models generally underestimate the

precipitation intensity of the 7-20 event, which can be attributed to its inherently extreme nature. Furthermore, simulation performance varied among different schemes. In particular, the WSM6 scheme outperformed the Thompson scheme in capturing precipitation intensity, which is consistent with the conclusions of Huang et al. (2020) based on an extreme rainfall event in Guangzhou. Meanwhile, the LiuMa scheme demonstrated the best performance in terms of cumulative rainfall and the spatial distribution of precipitation. However, compared to the heavy rainfall in North China reported by Kang et al. (2016), the more abundant solid hydrometeor content in this Zhengzhou event may be a key microphysical factor contributing to its greater total precipitation and intensity. Additionally, systematic comparisons of the WSM6, Thompson, and LiuMa schemes within the same extreme event remain rare. Although this study preliminarily reveals the potential of the LiuMa scheme, its conclusions are based on a single case. Future work will involve aggregating more extreme weather events for comprehensive statistical analysis, with the aim of providing more reliable guidance for scheme selection in operational forecasting.

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