Research Article

Assessing the Effects of Microphysical Scheme on Convective and Stratiform Characteristics in a Mei-Yu Rainfall Combining WRF Simulation and Field Campaign Observations

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Received 5 October 2019; Revised 15 December 2019; Accepted 22 January 2020; Published 9 March 2020

Academic Editor: Harry D. Kambezidis

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Microphysics parameterization becomes increasingly important as the model grid spacing increases toward convection-resolving scales. Using observations from a field campaign for Mei-Yu rainfall in China, four bulk cloud microphysics schemes in the Weather Research and Forecasting (WRF) model were evaluated with respect to their ability to simulate precipitation, structure, and cloud microphysical properties over convective and stratiform regimes. These are the Thompson (THOM), Morrison graupel/hail (MOR_G/H), Stony Brook University (SBU_YLIN), and WRF double-moment six-class microphysics graupel/hail (WDM6_G/H). All schemes were able to predict the rain band but underestimated the total precipitation by 23%–35%. This is mainly attributed to the underestimation of stratiform precipitation and overestimation of convective rain. For the vertical distribution of radar reflectivity, many problems remain, such as lower reflectivity values aloft in both convective and stratiform regions and higher reflectivity values at middle level. Each bulk scheme has its advantages and shortcomings for different cloud regimes. Overall, the discrepancies between model output and observations mostly exist in the midlevel to upper level, which results from the inability of the model to accurately represent the particle size distribution, ice processes, and storm dynamics. Further observations from major field campaigns and more detailed evaluation are still necessary.

1. Introduction

The representation of microphysics is of substantial importance in numerical weather prediction (NWP) models because it controls the distributions of latent heating and cooling and condensate loading that influences the dynamics [1, 2]. With the increases of computing power and NWP technology, more accurate and detailed descriptions of cloud microphysical processes are proposed and the trend has been toward prognostically calculating hydrometeor types and sizes explicitly [3–8]. However, these microphysical schemes have their own advantages in different types of cloud and weather system. Extensive and detailed validations for existing schemes are therefore needed to constrain and reduce uncertainties for different cloud types and regions.

Obvious discrepancies between models and observations are found by previous studies, such as smaller stratiform areal coverage, weaker precipitation [9, 10], and heavier precipitation from convective regions [11] in simulated storms. A recent trend in evaluating NWP models is to use remote sensing datasets such as satellites [12–14], radars [15, 16], and cloud-aerosol lidar [17, 18]. These active sensors makes it possible to evaluate the three-dimensional structure of clouds and precipitation [19], and in particular, the simulated and observational reflectivity allows one to more easily see detailed meso- and storm-scale structures forecasted by finer-resolution NWP models [20, 21].

Parameterizing microphysics remains challenging because of fundamental uncertainty in the underlying microphysical processes, especially for ice [15]. Therefore, more

hydrometeor variables need to be evaluated in addition to the macrophysical quantities just like accumulated rainfall and cloud coverage which are evaluated in previous research. Johnson et al. [22] used the observed polarimetric radar variables to evaluate the microphysics schemes in the ensemble forecasts, and they found that a hail-like rimed-ice category may be necessary to reproduce the observed hail signature. Remillard et al. [23] used cloud radar doppler spectra to evaluate stratocumulus drizzle size distributions in large-eddy simulations with size-resolved microphysics. Detailed observations from field campaigns which can reflect macro- and microphysical characteristics are also used. Naeger et al. [24] evaluated several bulk microphysical parameterizations in combination with observations from a cold season precipitation experiment of an intense warm frontal band. Taufour et al. [25] used the airborne in situ measurements and dual-polarization radar variables to evaluate a two-moment scheme. They found that improving the hydrometeor representation, focusing especially on the description of the particle size distributions for different water species, is a good way to improve microphysical scheme.

Utilizing multisource datasets from radar and field campaign to evaluate the cloud microphysical schemes has only recently begun in China. With the increases in local severe weather activities, the need for more accurate weather information has become increasingly crucial especially for Yangtze River basin where extreme precipitation occurs frequently during Mei-Yu season. Mei-Yu is one of the most significant events for the hydrological cycle in the East Asia monsoon region [26], which produces a large amount of flood disasters and substantial economic losses in the Yangtze-Huai River Valleys [27]. During Mei-Yu season, a quasi-stationary front, known as the Mei-Yu front, is formed and extends from eastern China to southern Japan [28]. At any given time, Mei-Yu front is associated with the presence of an elongated cloud band, which is usually a mixture of deep convective clouds and stratiform clouds [10]. Different microphysical and thermodynamic features are observed in two cloud regimes. In convective regions, the growth of ice is dominated by riming, whereas in stratiform regions, deposition and aggregation are the primary mechanisms [29]. The resultant latent heating profiles are quite different for the two regions [30, 31].

To provide a much needed data source concerning the formation-dissipation processes of mesoscale convective system (MCS) during the Mei-Yu season, a field campaign entitled the “Investigative Monsoon Frontal Rainfall Experiment (IMFRE) 2018” was conducted from 10 June 2018 to 10 July 2018 in the middle reaches of the Yangtze River (MRYR). The purpose of this study is to investigate the impacts of bulk cloud microphysics schemes on the simulation of different cloud regimes (stratiform and convective clouds) along the Mei-Yu front using observations from the IMFRE 2018. We will examine the differences in the evolution, horizontal, and vertical structure of MCS and determine the strengths and weaknesses of different microphysics schemes for Mei-Yu rainfall. Furthermore, the cloud microphysical properties from C-band dual-

polarization doppler weather radar (C-POL) are also evaluated. The remainder of this paper is organized as follows. Section 2.2 describes the datasets used in this study. The methods and description of the case study are presented in Section 2. The results and discussions are presented in Section 3. Finally, the main findings of this study are summarized in Section 4.

2. Data and Methods

2.1. Precipitation Data and Reanalysis. A precipitation product [32], based on the rain gauge precipitation from automatic weather stations in China and the Climate Prediction Center morphing technique (CMORPH) precipitation [33], was used in this study. This product has a $0.1^\circ \times 0.1^\circ$ spatial resolution with hourly temporal resolution. What is more, large-scale air flow and thermodynamic conditions of Mei-Yu front are analyzed with the hourly ERA-5 reanalysis [34] in uniform grid of $0.25^\circ \times 0.25^\circ$, which is the latest and fifth generation of European reanalysis produced by the European Center for Medium-Range Weather Forecasts (ECMWF). The ERA-5 reanalysis was also used as model initial and lateral boundary conditions.

2.2. Datasets from Field Campaign. Various datasets have been collected to study the mechanism of MCS during Mei-Yu season from the field campaign of IMFRE 2018. Three-dimensional structures and microphysical properties of MCS measured by IMFRE provide critical observations to examine the impacts of different bulk schemes on cloud microphysics and precipitation. The red dot (Figure 1(a)) represents the Xianning site of the field campaign, where convective systems can easily start and develop because of the impact of mesoscale topography, primarily influenced by the Mufu Mountain to the southeast of Xianning.

The primary instruments used in this study include the China New Generation Weather Radar (CINRAD) and C-POL. In the studying area, there are 15 S-band operational Doppler radars (the black circles in Figure 1(a)) operating at 10 cm wavelength and providing 9 unique elevation scans every 6 minutes). The reflectivity datasets underwent critical quality control [35, 36] and were gridded to 3 km horizontally and 0.5 km vertically in an attempt to make a comparison with model simulations. C-POL is located in Xianning site (the red dot in Figure 1(a)); the specifications of measurements from C-POL are shown in Table 1. The radar data are preprocessed by a group of algorithms [37] so as to provide hydrometeor categories. The algorithms include corrections of system biases of reflectivity and differential reflectivity, suppression of ground clutter and anomalous echoes, and filtering of differential phase shift.

2.3. Model Setup and Experiments Design. To investigate the effects of microphysical schemes on convective and stratiform characteristics in a Mei-Yu front storm, several numerical experiments were performed with the Weather Research and Forecasting (WRF version 3.6.1) model, a nonhydrostatic, compressible, three-dimensional atmospheric model. The

FIGURE 1: (a) Distribution of 15 S-band operational Doppler radars (circles), and the campaign field site of Xianning station (red dot), as well as Yangtze River (thick solid lines) and boundaries of provinces (thin solid lines); shadings represent the terrain height. Hubei Province is indicated by the blue line. (b) Simulation domain used in the WRF simulations; the black box represents the range of Figure 1(a) for domain-average analysis in this study.

TABLE 1: Main specifications of the C-POL used in the IMFRE field campaign.

Main specifications	Parameter settings
Antenna diameter	3.2 m
Beam width	1.4°
Wavelength	5.5 cm
Pulse length	1.0 μ s
Peak power	≥ 250 kW
Sensitivity in Z	-15~70 dBZ
Range resolution	75, 150 m
Temporal resolution	1~6 min

simulation domain consisted of 560 by 530 grids with a horizontal resolution of 3 km (Figure 1(b)). There were 50 layers from surface to 50-hPa. All simulations started at 0600 UTC 29 June with 30-hour run. And the model outputs were saved at a 12-min interval.

In this paper, four bulk microphysical schemes were tested in WRF to investigate their performance in simulating the structure and evolution of MCSs and cloud microphysics, with a focus on the convective-stratiform precipitation processes. The schemes are Thompson (THOM) scheme [6], the Morrison graupel/hail (MOR_G/H) scheme [7], the Stony Brook University microphysics scheme (SBU-YLIN) [38], and the WRF double-moment six-class microphysics (WDM6) graupel/hail (WDM6_G/H) scheme [8]. Each scheme is described briefly in Table 2. Other physics parameterization schemes include the Yonsei University (YSU) planetary boundary layer (PBL) scheme [39], the Rapid Radiative Transfer Model for General Circulation Models (RRTMG) scheme for longwave radiation calculations [40], the Goddard shortwave scheme for shortwave radiation calculations [41], and the Noah land surface scheme [42].

2.4. Convective-Stratiform Partitioning Algorithm. In order to analyze the convective-stratiform precipitation processes in a Mei-Yu front storm, a partitioning algorithm,

based on Steiner et al. [43], was used to separate areas of convection from stratiform regions for each synthesized radar volume. Several input parameters for the partitioning scheme are tuned to fit the midlatitude scenarios because the scheme is originally developed for tropical convection [44]. The partitioning algorithm is based on the 3 km horizontal radar reflectivity gradient, which is a background exceeding technique using a low-level 2D horizontal reflectivity field [45]. The algorithm has three steps. First, any grid points having reflectivities greater than 43 dBZ are classified as convective, according to the Z-R relationship in midlatitudes [44]. Second, Reflectivity at each radar grid is compared to its background intensity, computed using the linearly averaged reflectivity with an 11-km radius centered on the grid. Any grid point that exceeds its background reflectivity by an intensity-dependent value is classified as convective. Last, for each grid point classified as convective by either of the two tests, an intensity-dependent radius of influence is used to assign an area around the point as convective. The rest of the echoes that exceed 10 dBZ are classified as stratiform.

This algorithm is also suitable for the WRF-simulated radar reflectivity so that the model results are evaluated at the same metrics as the observations. WRF-simulated radar reflectivity is calculated assuming Rayleigh scattering following the approach of Smith [45], using the specified or predicted size distribution and particle-density parameters consistent with each scheme.

3. Results and Discussion

In this section, the simulations of the above four microphysical schemes are evaluated from rainfall among different cloud regimes, horizontal and vertical structure of MCS, and cloud microphysical properties, determining their strengths and weaknesses for Mei-Yu rainfall over the MRYS.

TABLE 2: Characteristics of the four microphysical schemes used for the WRF simulations.

Scheme (acronym)	No. of moments	Notes
Thompson (THOM)	2	The scheme prognoses the mass mixing ratios of cloud droplets, cloud ice, rain, snow, and a hybrid graupel/hail category, plus the number mixing ratios of cloud ice and rain
Morrison graupel/hail (MOR_G/H)	2	Explicit prediction of mass and number mixing ratios of rain, cloud ice, snow, and graupel/hail and mass mixing ratio of cloud droplets
Stony Brook University microphysics (SBU-YLIN)	1	The scheme prognoses mass mixing ratios of cloud droplets, rain, cloud ice, and precipitating ice
Double-moment six-class graupel/hail (WDM6_G/H)	2	The scheme prognoses mass mixing ratios of cloud droplets, rain, cloud ice, snow, and graupel and number mixing ratios of cloud droplets, rain, and cloud condensation nuclei

FIGURE 2: Large-scale air flow and thermodynamic conditions at 0000 UTC 30 June 2018 from ERA-5 reanalysis. (a) Horizontal wind vector (arrows) at 700 hPa, geopotential height at 500 hPa (thick solid lines), and pseudo-equivalent potential temperature at 850 hPa (shading). The green line in (a) indicates the winds shear line at 700 hPa. (b) Vertical cross sections along 114°E of pseudo-equivalent potential temperature (solid lines) and relative humidity (shading).

3.1. Case Description. During IMFRE field campaign 2018, a Mei-Yu front storm was initiated over the MRYR and lasted for about 19 hours from 1800 UTC 29 June to 1200 UTC 30 June. The large-scale meteorological conditions derived from ERA-5 reanalysis at 0000 UTC 30 June are presented in Figure 2. The field of air flow at 700-hPa was characterized by a northeast-southwest oriented shear line formed at 29–30°N (the green line in Figure 2(a)). South of this shear line, there was a warm and moist southwesterly low-level jet (LLJ) extending from the South China Sea to the JiangHuai Basin. The large pseudo-equivalent potential temperature gradient at 850-hPa, which is often referred to as the location of Mei-Yu front, is also near 30°N. These large-scale weather conditions are typical features of Mei-Yu front rainstorm.

Figure 3 describes the life cycle of the Mei-Yu front rainstorm via the hourly radar reflectivity at 3 km from 0000 to 0800 UTC 30 June, 2018. During the developing stage (1800 UTC 29 June–0200 UTC 30 June), two small MCSs along the northwest-southeast oriented shear line formed and strengthened when moving eastward. At the mature

stage (0300–0600 UTC 30 June), the two MCSs merged into one convective system and remained between 112 and 114°E. After 0600 UTC 30 June, the MCSs weakened and gradually dissipated, while the stratiform region remained quite extensive until 0800 UTC 30 June.

The MCSs occurred along the Mei-Yu front, causing moderate precipitation in Central Hubei Province with northwest-southeast oriented rain bands and the rain center exceeded 100 mm adjacent to Xianning site (Figure 4(a)). As shown in Figure 5, rainfall mainly occurred during 0000–1200 UTC on 30 June precipitation and the peak occurred during 0400–0600 UTC on 30 June.

3.2. Evaluation of Convective-Stratiform Precipitation. In spite of minor location errors for the rainfall as compared with the observations, all simulations captured the distribution of northwest-southeast oriented rain bands (Figure 4). Thompson scheme (Figure 4(b)) simulates precipitation centers larger than 75 mm as a little bit

FIGURE 3: Distributions of radar reflectivity (in dBZ) at 3 km altitude every 1-hr based on ground-based radar measurements obtained from 0000 to 0800 UTC 30 June 2018. The black dot indicates Xianning site.

FIGURE 4: Continued.

FIGURE 4: Longitude-latitude distribution of surface precipitation accumulated from 1800 UTC 29 June to 1200 UTC 30 June 2018 from (a) rain gauge observations and simulations of (b) THOM, (c) MOR_G/H, (d) SBU-YLIN, and (e) WDM6_G/H scheme.

FIGURE 5: Hourly surface precipitation rate averaged within the region (107–117°E, 27–35°N) from the observations (black solid curve) and the simulations of THOM (blue curve), MOR_G/H (red curve), SBU-YLIN (green curve), and WDM6_G/H (purple curve).

northwest with a larger scope, with the 15–50 mm centers being smaller than the observation (Figure 4(a)), and so do the Morrison (Figure 4(c)) and SBU-YLIN scheme (Figure 4(d)). The rain scopes less than 15 mm simulated by the first three schemes (Thompson, Morrison, and SBU-YLIN scheme) are close to the observation. In contrast, the locations of heavy precipitation (more than 50 mm) simulated by the WDM6_G/H scheme (Figure 4(e)) are scattered with a larger scope than the observation, while the rain scope less than 15 mm is smaller than the observation. To quantitatively evaluate the simulated precipitation, Figure 5 shows the time series of hourly surface rain rate from the observations and WRF simulations with 4 microphysics schemes. As shown, the tendencies of simulated curves are close to observations but all schemes

underestimate the total mean precipitation by 23%–35%. Total precipitation values from WDM6_G/H, THOM, and MOR_G/H scheme are more close to the observation than the SBU-YLIN scheme.

In order to evaluate the WRF-simulated MCS structure in those convective and stratiform regions, the classification algorithm used by Steiner et al. [43] has been applied to both radar observations and WRF simulations. Figure 6 shows the hourly rain rates which are averaged over the convective and stratiform regions from both observations and the WRF simulations. Compared with the mean observed convective rain rate (4.43 mm/h), the first three simulations (Figures 6(b)–6(d)) overestimate the convective precipitation rate ranging from 4.57 mm/h for the THOM scheme to 5.43 mm/h for MOR_G/H. We also

FIGURE 6: Hourly averaged precipitation rate over convective (red) and stratiform (blue) regions from (a) observations and (b) THOM, (c) MOR_G/H, (d) SBU-YLIN, and (e) WDM6_G/H scheme. The mean values in the upper right corner are the time- and domain-averaged rain rates over convective and stratiform regions during 00:00–12:00 UTC 30 June 2018.

found that the first three schemes have simulated less stratiform rainfall than the observation (2.19 mm/h). As a result, the ratio of convective to stratiform precipitation

is much higher than the observed one, especially in MOR_G/H and SBU-YLIN scheme. Most of the schemes underestimate the stratiform precipitation and

FIGURE 8: Comparisons of radar reflectivity (Z_e , dBZ) frequency at 3 km altitudes from observations and simulations. The analysis domain is shown in Figure 1(a). The occurrence frequency is calculated by the number of grid points falling in each Z_e range divided by the total number of the grid points of the analysis domain using output from 0000 UTC to 1200 UTC on 30 June 2018.

overestimate the convective rain except the WDM6_G/H scheme, which produces more stratiform precipitation.

3.3. Horizontal and Vertical Structure of Mei-Yu Front Rainstorm. To evaluate the horizontal distribution of simulated MCS, 3 km radar reflectivity (Z_e , dBZ) at developing (0100 UTC), mature (0400 UTC), and dissipating (0700 UTC) stage are presented in Figure 7. THOM, MOR_G/H, and SBU-YLIN schemes capture the two smaller MCSs at the developing stage, although the MCSs location is a little bit northwest than the observations. At the mature stage, the two simulated MCSs are merged into one just like the radar observations, but there is a time delay in the three schemes. The simulated centers with large Z_e ($Z_e > 40$ dBZ) are also scattered by the WDM6_G/H scheme. At the dissipation stage, the WDM6_G/H simulations are much stronger than the observations and the others are close to observations. Figure 8 shows the comparisons of Z_e frequency at 3 km altitudes from observations and simulations to further examine the horizontal distribution of Z_e . Compared to the observations, all schemes dramatically underestimate the occurrence frequency of lower Z_e ($0 < Z_e < 10$ dBZ) but overestimate the occurrence frequency of higher Z_e ($Z_e > 20$ dBZ). Except for WDM6_G/H, the other schemes also overestimate the frequency of medium Z_e ($10 < Z_e < 20$ dBZ). In general, all schemes underestimate the occurrence frequency of lower Z_e but overestimate frequency of higher Z_e , especially for the WDM6_G/H scheme.

We further examined the vertical structure of MCS between the observations and simulations. The cross sections of Z_e indicated by a black line in Figure 7 are chosen to

study the evolution of the vertical structure (Figure 9). It can be found that the large reflectivity ($Z_e > 40$ dBZ) within the deep convective cores from radar extended to about 6 km at the developing stage. The simulated heights of deep convective cores are close to observations except for MOR_G/H scheme with the large reflectivity extended to about 9 km. At the mature stage, deep convective cores of THOM and WDM6_G/H schemes extended to about 12 km which is almost the same distance that occurred in radar observations. However, all simulations underestimate radar reflectivity in the stratiform region at heights of 9–13 km during the whole lifetime of MCSs.

The Contoured Frequency by Altitude Diagrams (CFADs) of reflectivity are shown in Figure 10 from both radar observations and WRF simulations for stratiform and convective cloud, which are produced from the reflectivity volume at 12-min intervals from 03 to 05 UTC on 30 June 2018. This period corresponds exactly to the mature stage of MCS. Discrepancies in the reflectivity distribution characteristics between simulations and observations are obvious. For stratiform cloud, the simulated maximum frequency of Z_e (except SBU-YLIN) at lower levels is much smaller than the observations, which are located around 25–30 dBZ and 10 dBZ. Near 6 km, the observed maximum frequency of Z_e is located around 20–30 dBZ and decreases with height. The simulations of THOM and MOR_G/H scheme are close to this observation. The simulated Z_e ($Z_e > 10$ dBZ) frequency from all schemes at upper levels (10–14 km) is smaller than the observations. For convective cloud, the observed maximum frequency of Z_e at middle and lower levels (0–6 km) is located around 35–40 dBZ, and the simulations of THOM and SBU-YLIN are as much as the observations. The simulated frequency of Z_e around 30–50 dBZ from MOR_G/H scheme is stronger than other schemes. Simulated frequency of Z_e around 20–35 dBZ above 6 km is much weaker than the observations. This kind of vertical distributions of the simulations may cause the simulated MCS to be lower than the observed.

3.4. Microphysical Properties of Hydrometeors. In this paper, a fuzzy-logic, C-POL hydrometeor classification algorithm following the method of Dolan et al. [46] is employed to carry out the hydrometeor classification of the Mei-Yu rainfall. Five hydrometeor types are identified as IC = ice crystals, GA = graupel, DS = dry snow, WS = wet snow, and RN = rain. The vertical cross sections of hydrometeor categories derived from C-POL along 284.0° azimuth at 0925 BJT on 30 June 2018 and WRF simulations at the same position are shown in Figure 11. Due to limited C-POL datasets in this field campaign, the distributions of different hydrometers frequency are not shown in this study.

The middle and upper regions (above 6 km) of the cross section from C-POL are characterized by dry snow and regions of ice crystals. Regions of graupel are concentrated at heights from 4 to 8 km, which then transition to rain drops. For the vertical distribution of rain particles, all simulations are close to the observation, although SBU-YLIN scheme simulates greater top height of rain than the observation. The

FIGURE 9: Cross section of radar reflectivity (in dBZ) along the black lines in Figure 7 from (a), (b), (c) observations and simulations of (d), (e), (f) THOM; (g), (h), (i) MOR_G/H; (j), (k), (l) SBU-YLIN; and (m), (n), (o) WDM6_G/H during developing (the first column), mature (the second column), and dissipating (the third column) stage. The black solid lines in simulations denote the 0°C isotherm.

four simulated vertical distributions of snow are also similar to the observation. However, there are many discrepancies found in the graupel and ice vertical distribution. THOM

scheme simulates almost the same vertical graupel distribution as the observation, but fewer ice particles. MOR_G/H scheme simulates more graupel than observation. The

FIGURE 10: The Contoured Frequency by Altitude Diagrams (CFADs) of reflectivity over stratiform region (left column) and convective region (right column) for (a), (b) radar; (c), (d) THOM; (e), (f) MOR_G/H; (g), (h) SBU-YLIN; and (i), (j) WDM6_G/H. The analysis domain is shown in Figure 1(a).

FIGURE 11: Vertical cross section of hydrometeor categories derived from C-POL along 284.0° azimuth at 0925 LT on 30 June 2018 and simulations. HC categories are defined as IC = ice crystals, GA = graupel, DS = dry snow, WS = wet snow, and RN = rain. For the simulations, the blue curve represents the area where the rain mixing ratio is positive, yellow line indicates graupel distribution, pink line represents snow distribution, and grey line represents ice distribution.

MOR_G/H and WDM6_G/H schemes simulate more graupel and ice than those in the observations. Because the SBU-YLIN scheme does not distinguish between graupel and snow, only the snow distribution is shown in Figure 11. Overall, the discrepancies between model output and observations exist in the midlevel to upper level (above 6 km),

which results from the inability of the model to accurately represent the particle size distribution, ice processes, and storm dynamics.

Similar to the method of analyzing clouds and precipitation, hydrometeor mixing ratio of stratiform and convective clouds is evaluated over the same study area. Figure 12 shows

FIGURE 12: The time- and domain-averaged hydrometeor mixing ratio vertical profiles over the (a), (c), (e), (g), (i) stratiform and (b), (d), (f), (h), (j) convective regions for (a), (b) THOM; (c), (d) MOR_G/H; (e), (f) SBU-YLIN; and (g), (h) WDM6_G/H scheme from 0300 to 0500 UTC on 30 June 2018 within the region (107–117°E, 27–35°N).

TABLE 3: Temporally and domain-averaged integrated vertically mixing ratio of cloud, rain, and ice-phase hydrometeors (sum of ice, snow, and graupel) of the four microphysical schemes over stratiform and convective region.

	Stratiform			Convective		
	Cloud	Rain	Ice-phase Mixing ratio ($\text{g}\cdot\text{kg}^{-1}$)	Cloud	Rain	Ice-phase
THOM	0.483	0.497	5.803	2.181	3.630	8.407
MOR_G/H	0.515	0.584	4.197	1.974	4.393	10.441
SBU-YLIN	0.630	0.858	7.120	2.964	5.195	9.865
WDM6_G/H	0.257	1.037	2.651	0.428	5.166	5.079

FIGURE 13: The temporal evolution of domain-averaged maximum vertical air velocity of THOM, MOR_G/H, SBU-YLIN, and WDM6_G/H scheme over (a) stratiform and (b) convective regions within the region (107–117°E, 27–35°N).

the time- and domain-averaged hydrometeor mixing ratio vertical profiles over the stratiform and convective regions for different microphysical schemes. We can clearly find a common feature in different schemes: less cloud and rain are distributed in the stratiform region than in the convective region. Meanwhile, there are more snow and cloud ice particles distributed in the stratiform region than in the convective region, and less graupel is seen in the stratiform cloud regime than in the convective region. These features indicate that the convective-stratiform partitioning algorithm used in this paper is reasonable. Compared to the other three schemes, WDM6_G/H scheme produced less cloud in both cloud regions and more rain in stratiform region. In convective regions, more rain particles are also found above 2 km for WDM6_G/H scheme. This indicates a large autoconversion of cloud water to rain in the WDM6_G/H scheme than the other schemes. Table 3 shows integrated vertically mixing ratio of cloud, rain, and ice-phase hydrometeors which is the sum of ice, snow, and graupel over stratiform and convective regions. The ice-phased particles in the WDM6_G/H scheme are less than those in the other schemes especially for the snow particles in both cloud regimes. This is because the smallest maximum vertical air velocity of WDM6_G/H scheme in the convective regime, cloud, and rain particles cannot be brought to upper level air (Figure 13). The THOM and SBU-YLIN

scheme simulate less ice but more snow than the other schemes, resulting in moderate mixing ratio of ice-phase particles. The MOR_G/H scheme simulates the most ice-phase particles in convective region, corresponding to the highest radar reflectivity within 0–6 km and the strongest maximum vertical velocity in convective region, while the mixing ratio of ice-phase particles in stratiform region shows a moderate level, and this is consistent with the underestimated reflectivity above 6 km.

4. Conclusions

Based on multisource datasets from IMFRE 2018, four bulk cloud microphysics schemes in WRF model were evaluated with respect to their ability to simulate convective and stratiform precipitation, structure, and cloud microphysical properties for a Mei-Yu front rainstorm. The findings from this study can be summarized as follows.

In spite of minor location errors for the accumulated rainfall as compared with the observations, all simulations captured the distribution of northwest-southeast oriented rain bands. However, four schemes underestimate the total precipitation by 23%–35%, and this is mainly attributed to the underestimation of stratiform precipitation. We also found that THOM, MOR_G/H, and SBU-YLIN scheme underestimate the stratiform precipitation and overestimate

the convective rain, while WDM6_G/H scheme produces less convective precipitation than observation.

THOM, MOR_G/H, and SBU-YLIN schemes can successfully capture the horizontal evolution of MCSs during the whole life cycle, but there is a time delay for about 1–2 hours. For the vertical distribution of radar reflectivity, the large reflectivity (>40 dBZ) within the deep convective cores from radar extended to about 6 km at the developing stage. The simulated heights of deep convective cores are close to observations except for MOR_G/H scheme with the large reflectivity extending to about 9 km. At the mature stage, deep convective cores of THOM and WDM6_G/H schemes extended to about 12 km which is almost the same distance that occurred in radar observations. However, all simulations underestimate radar reflectivity in the stratiform region at heights of 9–13 km during the whole lifetime of MCSs.

Discrepancies in the vertical distribution characteristics between simulations and observations are obvious from the CFADs of reflectivity. For stratiform cloud, all simulated radar reflectivity values at upper levels (8–14 km) are smaller than the observations. For convective cloud, the observed maximum probability at middle and lower levels (0–6 km) is located around 35–40 dBZ, and the simulations of THOM and SBU-YLIN are as much as the observations. The simulated radar reflectivity of MOR_G/H is stronger than other schemes. Simulations of reflectivity above 6 km are much weaker than the observations.

All schemes are able to simulate well the rain distribution at low level and snow distribution above 6 km. However, there are many discrepancies between simulations and observation of graupel and ice vertical distribution. THOM and SBU-YLIN scheme simulate less ice but more snow than other schemes, resulting in moderate mixing ratio of ice-phase particles. The MOR_G/H scheme simulates the most ice-phase particles in convective region, corresponding to the strongest maximum vertical velocity in convective region, while the ice-phase particles in stratiform region show a moderate level, and this is consistent with the underestimated reflectivity above 6 km. The ice-phased particles in WDM6_G/H scheme are less than those in other schemes especially for the snow particles in both cloud regimes.

In summary, each bulk scheme evaluated in this study has its advantages and shortcomings for different cloud regimes. Overall, the discrepancies between model output and observations mostly exist in the midlevel to upper level, which probably results from the inability of the model to accurately represent the particle size distribution, ice processes, and storm dynamics. Therefore, more detailed microphysics schemes, such as higher moment schemes or complicated schemes that can describe more ice-phase particle interactions, may be needed to properly represent these evaluated features.

It is worth noting that, due to the limited Mei-Yu front rainstorm cases observed by IMFRE, the microphysical characteristics of Mei-Yu rainfall will continue to be observed and studied in the later stage. Further observations from major field campaigns and simulations are still necessary. Meanwhile, the errors caused by the nonlinear

method of the numerical sensitivity test, the uncertainties of model initials, and the limited ability of the model simulations (e.g., cumulus, land surface, or radiation schemes) all have certain influence on the simulation results.

Data Availability

The ERA-5 data are available at <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors would like to acknowledge China Meteorological Administration for providing the hourly precipitation data. This research was funded by the National Key R&D Program of China (2018YFC1507200) and the National Natural Science Foundation of China under grants 41620104009, 41830965, and 41705034.

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