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Key Points:

- The near-surface rain and drop size distributions retrieved from GPM-DPR are reliable across the Yangtze-Huai River Valley in central China
- Three cases were selected during IMFRE to represent the developing, mature, and dissipating stages of Meiyu precipitation systems
- Coalescence slightly overwhelms breakup and/or evaporation in stratiform region but it is dominant in convective region as raindrops fall

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Vertical Structures of Typical Meiyu Precipitation Events Retrieved From GPM-DPR

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Abstract This work for the first time analyzed the vertical structures of the different stages of Meiyu precipitation systems over the Yangtze-Huai River Valley in central China using measurements and retrievals from the Global Precipitation Measurement Mission Dual-Frequency Precipitation Radar (GPM-DPR) and Feng Yun satellites. GPM-DPR-retrieved near-surface rain and drop size distributions were first validated against the surface disdrometer measurements and showed good agreement. Then we analyzed three cases from the Integrative Monsoon Frontal Rainfall Experiment to demonstrate the different characteristics of convective precipitation and stratiform precipitation (SP) in the developing, mature, and dissipating stages of the Meiyu precipitation systems, respectively. For statistical analysis, all Meiyu cases during the period 2016–2018 detected by GPM-DPR were collected and classified into different types and stages. In the stratiform regions of Meiyu precipitation systems, coalescence slightly overwhelms breakup and/or evaporation processes, but it was dominant in the convective regions when raindrops fall. There were large numbers of large ice particles during the developing stage due to strong updrafts and abundant moisture, whereas there were both large ice and liquid particles in the mature stage. The vertical structures of the SP examined in this study were similar to those over the ocean regions due to high relative humidity but different to the mountainous west regions of the USA. The findings of the stage-dependent SP vertical structures provide better understanding of the evolution of monsoon frontal precipitation, as well as the associated microphysical properties, and provide insights to improve microphysical parameterization in future models.

1. Introduction

The climate in central China is strongly influenced by the East Asian monsoon. The primary physical manifestation of the summer monsoon is persistent, heavy precipitation occurring as a coherent, well-defined rainband. Generally, the rainband is characterized by a stepwise poleward movement from south China to north China (Ding, 1992; Lau et al., 1988; Lau & Yang, 1996). In early summer, a quasi-stationary rainband extends from the Yangtze-Huai River Valley (YHRV) in central China (Figure 1) to Japan; it is accompanied by characteristic frontal structures and known as Meiyu in China and Baiu in Japan (Tao & Chen, 1987). Within this rainband, mesoscale convective systems (MCSs) develop successively and thus trigger local heavy rainfall (Ding & Chan, 2005; Yu & Li, 2012). Heavy rain events often lead to local flooding and debris flows that can cause severe property damage and loss of life (Cui et al., 2015; Gao et al., 2016). Accurate forecasting of Meiyu rain is crucial to avoid such natural disasters.

The vertical structure of precipitation and the vertical distribution of the associated hydrometeors play important roles in the amount of Meiyu rain. The vertical structure of precipitation can be used to characterize the cloud dynamics and microphysical processes involved in hydrometeor growth and decay (Geerts & Dejene, 2005; Houze, 1981; Liu & Fu, 2001; Saikranthi et al., 2014; Wu et al., 2013). These microphysical and thermodynamic processes strongly affect precipitation efficiency, and by extension rainfall rate, at the surface (Biggerstaff & Houze, 1993; Chang et al., 2014).

Operational forecasting of Meiyu rainfall relies on numerical models. However, there is still a lack of available cloud parameterization schemes for simulating and accurately predicting Meiyu rainfall (Lim & Hong, 2005; Yang et al., 2000). One of the major reasons for the poor representation of cloud physical processes in numerical models is a lack of knowledge regarding the vertical distribution and internal structure of

Figure 1. The Global Precipitation Measurement Mission Dual-Frequency Precipitation Radar (GPM-DPR) data were analyzed to understand Meiyu precipitation over the Yangtze-Huai River Valley (YHRV) in China (27–34°N, 110–123°E). The 18 one-dimensional (1-D) laser-optical particle size velocity (PARSIVEL) disdrometers (black dots) were used to validate the GPM-DPR results. The background contour is the elevation map drawn using the ETOPO1 data set (<https://www.ngdc.noaa.gov/mgg/global/global.html>). The inset shows the location of the study area, with a 13° by 7° box indicating the area shown in the figure.

hydrometeor layers. Therefore, accurate representations of the vertical profiles of Meiyu hydrometeors are needed to improve cloud parameterization schemes.

A few recent studies have focused on the vertical structures of Meiyu or summer precipitation in central China. Fu et al. (2007, 2003) investigated the precipitation structures of two heavy rain events over the YHRV in central China during the Meiyu period using the Tropical Rainfall Measuring Mission (TRMM) precipitation radar. They found distinct differences between stratiform precipitation (SP) and convective precipitation (CP) profiles, with four or three layers, and also that the coalescence process was dominant for CP but not for SP. In contrast, Cao and Qi (2014) reported that the radar reflectivity values below the freezing level (FL; i.e., the altitude in which the temperature is at 0 °C) for moderate and heavy SP and CP systems increase with height. Consistent with the findings of Cao and Qi (2014), Liu and Zipser (2013) reported that radar reflectivity values below FL generally increase downward toward the ocean surface while decreasing downward toward the land surface. The results over monsoon regions, such as more moderate convection but high humidity, are similar to those over the ocean regions. Wen et al. (2016) suggested that the raindrop evaporation and coalescence processes are largely canceled out in the SP regions based on the results of the Micro Rain Radar during two Meiyu seasons.

The Global Precipitation Measurement Mission Dual-frequency Precipitation Radar (GPM-DPR) data have been available since 2014. Using the GPM-DPR data, Zhang and Fu (2018) investigated the effects of life cycle on the vertical structure of precipitation in east China by comparison of the cloud microphysical properties among three life stages of MCSs, that is, the developing, mature, and dissipating stages. They found that the cloud microphysical properties in the CP region differ among the stages, for example, cloud droplets are large but sparse in the developing system, large and dense in the mature system, and small but relatively dense in the dissipating system. However, Chen (2013) used the CloudSat Cloud Profiling Radar retrievals and reported slightly different results from Zhang and Fu (2018), who used GPM-DPR. They indicated that in the development stage, number concentration is larger than those in other two stages in the CP region. Xu (2017) tracked a convective entity along the Meiyu front through the ground-based C-band polarimetric radar and reported small amounts of large ice particles in the initiation stage but large amounts of small- and medium-sized ice particles in the mature stage.

These previous studies were limited to exploring individual cases, and some involved all precipitation events throughout the summer or Meiyu season rather than just the events occurred on the Meiyu rainband. This study will focus on the precipitation events occurred on Meiyu rainbands and will integrate the information collected during a field campaign (named Integrative Monsoon Frontal Rainfall Experiment [IMFRE]) and the GPM-DPR data to give a more thorough picture of Meiyu precipitation systems. To provide a much-needed data set to investigate the vertical structure of Meiyu precipitation systems, the field campaign of IMFRE was conducted during the period from 10 June 2018 to 10 July 2018, in the middle reaches of the YHRV in central China. Figure 1 shows the locations of a total of 18 one-dimensional (1-D) laser-optical particle size velocity (PARSIVEL) disdrometers over the YHRV in central China (27–34°N, 110–123°E). These results have been used to validate the GPM-DPR results over the YHRV. Finally, the validated DPR-derived drop size distributions (DSDs) are used to analyze the vertical structure and microphysical properties of three Meiyu cases selected from the IMFRE. These three selected cases represent the developing, mature, and dissipating stages. To obtain statistical information about Meiyu precipitation, all Meiyu precipitation events during the period 2016–2018 have been collected and analyzed according to the three stages of SP and CP in this study.

This paper is organized as follows. Section 2 presents a description of the data used herein, the Meiyu precipitation identification scheme, and the precipitation classification. Section 3 presents an assessment of GPM-DPR-retrieved DSDs based on 1-D disdrometer measurements, the synoptic conditions and structures of three Meiyu cases during the IMFRE, and statistical analysis of the vertical structures of typical Meiyu precipitation at different stages during the 2016–2018 Meiyu seasons. Finally, section 4 summarizes our findings and conclusions.

2. Data and Methodology

2.1. Instruments and Data Set

The GPM-DPR instrument constructs three-dimensional precipitation and DSD maps consisting of both Ku-band precipitation radar (KuPR) and Ka-band precipitation radar (KaPR) data, which provide coaligned 5-km resolution images at the Earth's surface with cross-track swath widths of 245 and 125 km, respectively (Hou et al., 2013). Both radars have a nominal scan mode with a minimum detectable signal of ≥ 18 dBZ (or 0.5 mm/h). The high-sensitivity mode of KaPR has a minimum detectable signal of ~ 12 dBZ (or 0.2 mm/h) (Hou et al., 2013). By combining radar echoes from the same scattering volume at two different frequencies, the GPM provides a dual-frequency precipitation product, 2ADPR (Liao et al., 2014; Seto et al., 2013). The 2ADPR products have been validated by other data sets and used in previous studies (e.g., Hamada & Takayabu, 2015; Kotsuki et al., 2014; Zhang & Fu, 2018). The version 6 of the 2ADPR products is used in this study, including instantaneous profiles of the attenuation-corrected radar reflectivity (Z_e in dBZ), rain rate (RR in mm/h), precipitation type, and DSD, as well as profiles of the mass-weighted mean diameter (D_m in mm) and normalized DSD scaling parameter for concentration (N_w in $\text{mm}^{-1}/\text{m}^3$). Due to the sensitivity of the DPR ($Z_e > 18$ dBZ) and the limitations of dual-frequency retrieval, the 2ADPR retrievals with either $D_m < 1$ mm or $RR < 0.5$ mm/h were discarded from this study. The 2ADPR data were collected over the YHRV during the 2018 IMFRE and Meiyu seasons in 2016 and 2017. The Meiyu periods in the YHRV range from 18 June to 21 July 2016 and 9 June to 11 July 2017 as determined by the China Meteorological Administration (CMA).

The GPM-DPR results were used to study Meiyu precipitation over the YHRV of China (27–34°N, 110–123°E). To validate the GPM-DPR results, the surface DSD, rain rate, and corresponding Z_e measurements from a total of 18 PARSIVEL disdrometers during the 2018 IMFRE were collected and processed. Considering the smaller sample number associated with the matched satellite-gauge observations during IMFRE, the disdrometer measurements from the 2016–2017 Meiyu seasons, in addition to GPM DPR results, were also collected and processed to provide a statistical result of Meiyu precipitation characteristics. The 18 surface disdrometers, managed by the Institute of Heavy Rain, CMA, are illustrated in the red box in Figure 1.

Considering the discontinuity of GPM microwave imager brightness temperature (TB) in the instantaneous field of view, we used other geostationary satellite observations to determine the life stages of the Meiyu frontal precipitation systems detected by the DPR instrument. FengYun-2G (FY-2G) and FengYun-2E (FY-2E) are geostationary meteorological satellites operated by the CNSMC (National Satellite Meteorological

Center) of the CMA. FY-2G has a better field of view to observe Meiyu systems over the YHRV because it is located at a longitude of 105°E over the equator. It replaced the FY-2E satellite in July 2015 and FY-2E was shifted to 86.5°E. To identify the precipitation stages, additional TBs measured by both the FY-2G and FY-2E satellites were used in this study, providing a spatial resolution of $0.1^\circ \times 0.1^\circ$ and 1-h interval satellite TBs, but starting at different times (e.g., 00:00 and 00:30 UTC).

2.2. Identifying the Stages of Meiyu Precipitation Systems

The Meiyu-Baiu rainband is characterized by a frontal structure in the lower troposphere, called the Meiyu-Baiu front, and appears as a sharp gradient under specific humidity and equivalent potential temperature (Ninomiya, 1984) conditions, together with a horizontal wind shear line (Akiyama, 1973).

In this study, the Meiyu precipitation events were identified using a two-step procedure. First, the method of Liu and Zipser (2015) and Zhang and Fu (2018) is used to identify precipitation systems from the DPR retrievals during the Meiyu period. A precipitation system consists of an array of contiguous DPR rainfall pixels (Liu & Zipser, 2015; Zhang & Fu, 2018). That is, a precipitation system is defined by grouping contiguous area greater than 100 DPR pixels ($> 2,000 \text{ km}^2$) with near-surface $RR > 0.5 \text{ mm/h}$, as detected by the GPM KuPR (Hou et al., 2013). The second step is to check whether the precipitation system identified in Step 1 occurs on the Meiyu front. The equivalent potential temperature (θ_e) at 850 hPa is calculated following Ninomiya (1984) for Meiyu front identification. Specifically, if the largest θ_e gradient appears along the north side of the precipitation system, it is recognized as Meiyu rain. Figure 2 shows a Meiyu precipitation system occurring over the YHRV on 2 July 2016, which contains a total of 2,776 precipitating pixels, including 294 CP and 2,482 SP pixels defined and provided in the 2ADPR products (will discuss in section 2.3).

As different stages of a precipitation system have different kinematic effects, it is necessary to identify the life stage of each Meiyu precipitation system with available GPM observations. Following Byers and Braham (1949) and Houze (1982), the life cycle of an MCS can be described in terms of three stages: developing, mature, and dissipating. The methods developed previously use different criteria to identify the life stages of cloud systems and track them using temporally continuous geosynchronous satellite and/or ground-based radar data (Feng et al., 2012; Feng et al., 2018; Futyan & Del Genio, 2007; Machado et al., 1998; Mathon & Laurent, 2001; Williams & Houze, 1987). Most of these criteria are based on MCS size, duration, and depth thresholds. However, Futyan and Del Genio (2007) argued that the precise choice of threshold value is somewhat arbitrary and suggested using the evolution of the MCS radius and minimum TB to define the life stage.

Feng et al. (2012) briefly summarized the method used for life cycle stage definition by Futyan and Del Genio (2007). Three stages (developing, mature, and dissipating) are defined according to the evolution of the MCS equivalent radius and infrared temperature. A detected and tracked system is considered to be growing vertically, and is defined as “developing,” before it reaches the minimum TB. The subsequent period is considered as the “mature” stage, during which the system reaches the minimum TB and continues to grow in size until reaching its maximum. The “dissipating” stage is defined as that occurring after the mature stage, during which the system decreases in size. Following these definitions, tracking was performed on successive hourly FY-2G TB images before and after the Meiyu precipitation event captured by the GPM-DPR. By comparing manually the changes of FY-2G TB, we identified a developing precipitation system as demonstrated in Figure 2.

2.3. Classification of Precipitation Types

In the 2ADPR products, the retrieved precipitation at each pixel is classified into one of three types: SP, CP, or other (Awaka et al., 2016). As shallow rain is archived in the CP type, we removed it from the CP type in this study. An example of the snapshots of CP and SP pixels, after excluding shallow rain, is shown in Figure 2a. For CP/SP classification, the algorithm in the GPM 2ADPR determines whether the echo is convective or stratiform based on the horizontal variability of the echo and the vertical profile of reflectivity (VPR), from which the bright band (i.e., radar signature of the melting layer just below the 0°C level), echo-top height, and maximum reflectivity in the vertical profile can be identified. This algorithm is not appropriate for rain measured by the disdrometer; however, several disdrometer-based classification schemes have been developed to separate CP from SP (Bringi et al., 2003; Testud et al., 2001; Tokay & Short, 1996). The widely used classification scheme proposed by Bringi et al. (2003) was adopted in this study. According to these classification criteria, $RR \geq 0.5 \text{ mm/h}$ and $\sigma_R \leq 1.5 \text{ mm/h}$ for SP, and $RR \geq 5.0 \text{ mm/h}$ and $\sigma_R > 1.5 \text{ mm/h}$ for CP, where

Figure 2. Example identification of a precipitation system. The distributions of (a) rainfall pixels and rain types excluding shallow and (b) column maximum reflectivity, as measured by the GPM-DPR instrument. The bottom panel shows the FengYun-2G (FY-2G) brightness temperatures (TBs) at different times close to this precipitation system. The diagonal lines represent the edges of the DPR swath.

σ_R is the standard deviation of the RR over 10 consecutive 1-min DSD samplings. To match the classification thresholds in the disdrometer-based scheme, the samples in the GPM-DPR with $RR < 0.5$ mm/h and $RR < 5$ mm/h were excluded from stratiform and convective pixels, respectively.

3. Results

3.1. Assessment of GPM-DPR Retrieved DSDs

Before analyzing the vertical structure of the Meiyu precipitation, the collected GPM-DPR results are validated against surface PARSIVEL disdrometer measurements. As the PARSIVEL disdrometer provides continuous temporal measurements at a single location, while GPM-DPR data are instantaneous but with spatial continuity, matching the two data sets at both temporal and spatial scales is a challenge. To check the reliability of the GPM-DPR results, we statistically compared the GPM-DPR retrievals with surface disdrometer measurements during the period 2016–2018.

Figure 3 shows the probability density functions of D_m , $\log_{10}N_w$, RR , and Z_e derived from PARSIVEL and 2ADPR (red box in Figure 1) for CP and SP, as well as the two key parameters of mean and skewness. As shown in Figure 3a, the rain rate for SP has almost the same mean value for both PARSIVEL and 2ADPR, and nearly normal distributions (small skewness). In contrast, the RR values for CP derived from 2ADPR were much lower than those for PARSIVEL, with mean values of 23.2 and 28.06 mm/h, respectively. The probability density function of RR values from PARSIVEL showed a nearly normal distribution (skewness = 1.35), while RR values from 2ADPR had a large positive skewness of 3.65. The difference in CP RR between the two data sets may due to a nonuniform precipitation classification or to an inaccurate attenuation correction in Ka-band during heavy precipitation events.

Regarding to other parameters, Z_e , D_m , and $\log_{10}N_w$ showed excellent agreement between the data sets over both the CP and SP regions. For example, all had normal distributions with near-zero skewness (< 0.9); the mean Z_e differences were 0.82 and 1.4 for CP and SP, while the mean D_m differences were 0.01 and 0.01, and mean $\log_{10}N_w$ differed by 0.04 and 0.08, all of which were statistically insignificant differences. These results, such as larger RR , Z_e , D_m , and $\log_{10}N_w$ for CP than SP, were similar to the two-dimensional video disdrometer measurements reported in Wen et al. (2016).

Figure 3. Probability distribution functions (PDFs) of surface PARSIVEL disdrometers and near-surface DPR measurements and retrievals (red box in Figure 1) for the convective (> 5 mm/h) and stratiform (< 5 mm/h) regions. (a) Near-surface radar equivalent reflectivity (Z_e), (b) near-surface rain rate, (c) mass-weighted mean raindrop diameter, D_m , and (d) $\log_{10}N_w$. Disdrometer data with D_m values < 1 mm were discarded. The mean values (skewness) are also shown in the legend of each panel. All biases in mean values are not significant at 95% confidence interval with a two-tailed Student t test, except that of the CP RR .

A statistical analysis is also performed on the instantaneously colocated DPR and surface disdrometer measurements at 18 surface sites (indicated by black dots in Figure 1). Although there are relatively small number of matched samples (28) in all four scatterplots (Figure 4), both the (DPR-identified) convective and stratiform cases are in good agreement with the disdrometer measurements, particularly for RR (Figure 4a) and Z_e (Figure 4b), having a range of correlation coefficients from 0.7 to 0.9 (with a confidence level exceeding 95%). Correlations of D_m are also relatively high (> 0.6) for both SP and CP types, while the $\log_{10}N_w$ values have correlations around 0.4, which is still significant statistically for the SP. For the CP $\log_{10}N_w$, the scatter of points seems to be greater due to limitations in sample size. In terms of bias, all the parameters from the 2ADPR product have a quite steady performance across the whole data set, that is, the mean values of all parameters do not differ significantly between the two products with a two-tailed Student t test, which supports the results sampled in the entire red box in Figure 3, except for the CP RR values.

Overall, the GPM 2ADPR retrievals agreed well with the PARSIVEL measurements, although there were some discrepancies in CP RR . We used the GPM 2ADPR retrievals in the following analysis.

3.2. Three Cases Selected From the IMFRE

3.2.1. Environmental Background

Three Meiyu cases from the IMFRE were selected and analyzed in this study: 12:03 UTC 5 July (Case I), 14:15 UTC 27 June (Case II), and 03:30 UTC 30 June (Case III). All three selected cases exhibited multiple Meiyu front precipitation system characteristics, as described by Ninomiya and Shibagaki (2007). More importantly, the three cases represent the developing, mature, and dissipating stages, which will be discussed in the following section. Each case is indicated by a red box in Figure 5. In FY-2G TB, each Meiyu

Figure 4. Scatterplot (instantaneously colocated matching samples) of near-surface DPR retrievals and PARSIVEL disdrometer measurements for the (a) RR , (b) Z_e , (c) D_m , and (d) $\log_{10}N_w$. Blue dots indicate stratiform type and red dots indicate convective type, as identified by the DPR algorithm. Correlation coefficient (Corr), mean difference (Bias), and number of samples (N) for all available samples of each parameter are also shown in each panel, as well as the correlations for the stratiform subset (blue) and the convective subset (red). All biases are not significant at 95% confidence interval with a two-tailed Student t test, and all correlations are statistically significant at 95%, except those marked with +.

system occurred in the zone with low TB values, corresponding to the Meiyu rainband. According to the National Centers for Environmental Prediction Final Analysis (FNL) data, these three systems also appeared in front of the trough at 500 hPa and in an area with a very large θ_e at 850 hPa. The largest θ_e values were in the range of 352–356 K in Case I versus > 356 K in Case II and 344–348 K in Case III, associated with the moist tongue. The largest θ_e gradient, of ~ 16 K/200 km, was observed along the north side of the Meiyu rainband. For all three cases, although the Northwest Pacific subtropical high ridge was not seen at 22–25°N, which was the climatological location reported (e.g., Sampe & Xie, 2010), the southwesterly low level flow transported moisture to maintain the rainband. North of the Meiyu rainband, horizontal wind shear at 850 hPa was observed for Cases I and III, whereas a convergence line at 850 hPa was seen along the Meiyu rainband for Case II. These results indicated that all three selected cases from the IMFRE were indeed Meiyu front precipitation systems.

3.2.2. Identification of Precipitation Stage

Figures 6a, 6e, and 6i show the instantaneous DPR column maximum reflectivity of Cases I to III, which represent the three stages of Meiyu frontal precipitation systems, that is, developing, mature, and dissipating stages. Case I was located near the junction of Hubei and Anhui provinces, which is in the center of the study area, at 12:03 UTC 5 July 2018 (Figure 6a). The corresponding TBs observed by the FY-2G satellite within ± 1 h of the precipitation event (11:00–13:00 UTC at 1-h intervals) are depicted in Figures 6b–6d. Analysis of the TBs from 11:00 UTC to 13:00 UTC indicated that the cold regions with $TB < 230$ K gradually increased, corresponding to the definition of the developing stage of Meiyu frontal systems.

Figure 5. Synoptic map based on the National Centers for Environmental Prediction Final Analysis (FNL) global analysis data and the FY-2G TB data, showing geopotential height at 500 hPa (black solid line; unit: dagpm), equivalent potential temperature at 850 hPa (orange solid line; unit: K), wind fields (arrows) at 850 hPa, and TB (shaded) for (a) Meiyu Case I, (b) Meiyu Case II, and (c) Meiyu Case III during the Integrative Monsoon Frontal Rainfall Experiment (IMFRE). The red boxes indicate the locations of the Meiyu cases captured by the DPR.

Case II was located in the northeast of the YHRV at 14:15 UTC on 27 June 2018 (Figure 6e). The cold regions with $TB < 230$ K from 13:00 to 15:00 UTC increased slightly (Figures 6g and 6h) with the highest radar reflectivity observed by GPM-DPR. In addition, the presence of anvil clouds at 10–12 km, as illustrated in Figure 7 e, signifies a Meiyu precipitation system in its mature stage. For Case III, in contrast to Case I, the cold regions with $TB < 230$ K became progressively smaller from 02:30 to 04:30 UTC, and the DPR reflectivity values were much smaller than those in Cases I and II. Therefore, Case III was defined as the dissipating stage in this study.

3.2.3. Vertical Structure of DPR Reflectivity

To investigate the near-surface rain rates and vertical distributions of radar reflectivity for the three Meiyu precipitation systems, we plotted Figure 7. The dissipating stage (Case III) consisted mostly of light-to-moderate precipitation with $RR < 10$ mm/h (Figures 7c and 7f), while the mature and developing stages both consisted of two parts, that is, heavier rain in the central region surrounded by light rain, as shown in

Figure 6. (a, e, i) Spatial distributions of column maximum reflectivities measured by the GPM-DPR instrument for the three selected cases during the IMFRE. (b–d, f–h, and j–l) The corresponding TBs observed by FY-2G/FY-2E satellites from 1 h before to 1 h after the occurrence (within ± 1 h) of precipitation in the (top) developing stage, (middle) mature stage, and (bottom) dissipating stage. The diagonal lines represent the edges of the DPR swaths.

Figure 7. (a–c) Near-surface precipitation rates for the three selected Meiyu cases during the 2018 IMFRE. (d–f) Vertical cross sections of the attenuation-corrected reflectivity for precipitation systems in the (left) developing (Case I), (middle) mature (Case II), and (right) dissipating (Case III) stages. Cross sections are shown as black solid lines for each stage in Figures 7a–7c.

Figures 7a and 7b. Figures 7d–7f show vertical cross sections of radar reflectivity along or perpendicular to the DPR tracks that correspond to the black lines outlined in Figures 7a–7c. Most of the radar echoes were below 10 km for Cases I and III with maximum radar reflectivity ~40–50 dBZ below 6 km (Figures 7d and 7f), whereas for Case II, the radar echoes reached up to 17 km with peak radar reflectivity > 50 dBZ; anvil clouds were noted at 10–12 km on the southeastern side of the cross section.

The contoured-frequency-with-altitude diagrams (CFADs) of radar reflectivity for CP and SP regions of the three selected cases were generated and are shown in Figure 8. The CFADs explain the joint probability distribution function of height and reflectivity and represent the frequency distribution in a coordinate system of reflectivity bins (x axis) and altitude (y axis). In each CFAD, the distribution was normalized by dividing the observed frequency by the maximum frequency of any height-reflectivity bin, to compare the CFADs of the different cases. The median lines of reflectivity and FLs for the CP and SP regions of these cases were also included in the CFADs.

The SP CFADs of radar reflectivity are shown in Figures 8a–8c, where clear bright bands occurred at approximately 5 km, especially for Case III, representing melting ice-snow particles and raindrops. From 10 to 6.5 km, the reflectivity increased monotonically toward FL, which is associated with depositional growth of ice particles (Houze, 2014). Around FL, there was a sharp increase in Z_e , which was thought to be the result of both partial melting and aggregation of the hydrometeors. As aggregation resulted in the production of very large particles (Houze, 2014), according to the dependence of Z_e on the sixth power of the particle size, these large particles strongly increased the Z_e values near FLs. Second, the partially melted particles in the bright band had a liquid surface but maintained their size, which gave a higher reflectivity than the ice particles just above FL due to the higher dielectric constant of water (0.93 for liquid water drops but 0.197 for ice particles; Houze, 2014). Below bright bands, the maximum frequency of radar reflectivity and median values in Cases I and II (Figures 8a and 8b) were nearly constant or increased slightly toward the surface. These results indicate that breakup, evaporation, and coalescence processes play equally important roles (Case I), or coalescence process slightly overwhelms breakup and/or evaporation processes (Case II) when raindrops fall toward the surface. In Case III (Figure 8c), the maximum frequency and median values decreased slightly toward ~2 km below the bright band, which was associated with the partial evaporation of raindrops (Houze, 2014).

Figure 8. Normalized contoured frequency by altitude diagrams (CFADs) of stratiform (a–c) and convective (d–f) reflectivity for Meiyu precipitation systems during the IMFRE in the (left) developing (Case I), (middle) mature (Case II), and (right) dissipating (Case III) stages. In each CFAD, the frequency is normalized, that is, it is the occurrence frequency per 1 dBZ per 1 km, divided by the maximum frequency of any height–reflectivity bin. The solid and dashed lines represent the median line and freezing level (FL), respectively.

Compared to the SP CFADs, most of the CP Z_e values below FL ranged from 35 to 50 dBZ (that was around 10 dBZ larger than the SP Z_e) for all three stages (Figures 8d–8f). Compared to the nearly constant median values below FL for Cases II (Figure 8e) and III (Figure 8f), the median values of Case I (Figure 8d) increase toward ~3 km below FL, suggesting that the collision-coalescence process is dominant at this height. In addition, the bright bands in SP are not obvious in CP. Similar to the SP CFADs, the Z_e values above FLs (Figures 8d–8f) decrease sharply with height. Moreover, the CP radar echo top height (at which the 18-dBZ frequency equals zero) is 1–5 km higher than the SP, which could be attributed to the strong updraft in the convective regions suspending large ice particles at higher levels (e.g., Zipser, 1994). Among the three cases, Case II in the mature stage had the highest (up to ~17 km) echo top and the largest Z_e value above FL in the convective region (Figure 8e) and the largest θ_e (> 356 K), as mentioned earlier (Figure 5b), thus manifesting more active convection and moisture. The stronger updraft in the active convective region can lift more liquid and ice particles into the upper levels of the atmosphere and rapidly produce considerably higher concentrations of precipitable particles (Houze, 2014). When these larger, faster-falling ice particles descended, the associated radar echoes formed well-defined vertical cores of maximum reflectivity below 7 km (shown in Figure 7e).

3.3. Composite Vertical Structure

For statistical analysis, all Meiyu precipitation systems during the period 2016–2018 were collected and classified into different types and stages (Table 1) based on the methods introduced in sections 2.2 and 2.3. Regarding the contributions of SP and CP to the total amount of rainfall, CP was the dominant contributor during the developing (54.9%) and mature (58.3%) stages of the system evolution, despite that they only account for 17.6% and 19.9% of the total samples, respectively. In contrast, SP, representing 74.4% of the total samples, was the dominant contributor of total rainfall amounts (62.9%) as the systems dissipated. For all three stages, despite the larger proportions of SP samples (60.6%–74.4%), they contributed only 41.7–62.9% of the total rainfall amount, while the CP samples (only 10.5–19.9%) contributed 37.0–58.3% of total rainfall amount. These results are consistent with previous studies (e.g., Feng et al., 2012; Fuyuan & Del Genio, 2007). In terms of rain intensity, the mean rain rates in these three stages were, respectively, 10.92, 14.83, and 11.91 mm/h for CP and 2.43, 3.08, and 2.42 mm/h for SP. Extreme values were also found for CP in three stages,

Table 1

Total, SP, and CP Samples, Percentages of SP and CP Samples Relative to Total Sample, Their Contributions to Total Rainfall Amounts, and Mean Near-Surface Rain Rate, CP Samples of Over the 95% Percentile Value, in Three Stages of Meiyu Precipitation Systems During the Period 2016–2018

	Developing	Mature	Dissipating
Number of precipitation systems	10	11	13
Total pixel samples	12,310	13,396	17,875
Stratiform pixel samples (SP; %)	8,193 (66.6%)	8,115 (60.6%)	13,304 (74.4%)
Convective pixel samples (CP; %)	2,171 (17.6%)	2,669 (19.9%)	1,874 (10.5%)
Contribution of SP	45.0%	41.7%	62.9%
Contribution of CP	54.9%	58.3%	37.0%
Mean rain rate of SP (mm/h)	2.43	3.08	2.42
Mean rain rate of CP (mm/h)	10.92	14.83	11.91
Upper 5.0% CP samples (>52.4 mm/h)	78	145	78

which was identified by the top 5% rain rate (over 52.4 mm/h). Consistent with the means, the occurrence frequencies for these extreme values were higher in the mature stage than in the other two stages but were still very low. Therefore, the extremes are not of particular concern in this study.

3.3.1. Reflectivity and Precipitation Rate

The vertical structures of three stages of the Meiyu precipitation systems, based on 3 years of DPR data, are shown in Figure 9 in the form of normalized CFADs for radar reflectivity. As illustrated in Figures 9a–9c, the composite SP CFADs for all three stages are similar to the case studies shown in Figure 8, with clear bright bands and sharp increases in radar reflectivity nearby. Below the bright bands, the composite SP CFADs are slightly different from the three IMFRE cases, mostly tilting to the right toward the surface, where the CFADs increase from ~26 dBZ at 4 km to ~27 dBZ in both the developing and dissipating stages and increase from ~28 to ~29 dBZ in the mature stage. Only the frequency contours at the reflectivity thresholds of 25 to 30 dBZ in the dissipating stage (Figure 9c) tilt to the left below the bright band, be interpreted as a consequence of the evaporation and/or breakup of raindrops due to less moisture, which is consistent with Case III.

Based on these results, we concluded that the coalescence process overwhelmed the evaporation and/or breakup processes as raindrops fell, especially in the first two stages; there were no significant differences in the reflectivity values between the developing and dissipating stages, while the radar reflectivity values at the mature stage were ~2-dBZ higher than at the other two stages. The normalized radar reflectivity distribution at each level was examined using the box-whisker plots illustrated in Figure 10. Below the bright bands, the quartile and extreme values at different altitudes were also larger in the mature stage than in the other two stages (Figure 10a). That is slightly different from the findings of Zhang and Fu (2018), where they found that the difference in stratiform reflectivity values corresponding to the three life stages is small. Caution is required in interpreting CFADs below 1 km due to the sharp decrease in sample size (Figure 9g), which may have been affected by signal attenuation and ground clutter (Watters et al., 2018). Therefore, the results below 1 km are not shown in Figures 11 and 12. Figure 11 shows the composite precipitation profiles and the interquartile range. The vertical precipitation profiles of the SP (Figure 11a) were similar to their Z_e counterparts (Figures 9a–9c) where SP rain rates increased significantly from ~0.5 mm/h at an altitude of 10 km to ~2.0 mm/h at bright bands (~5 km) for all three stages and then increased slightly toward the surface for the developing and mature stages but remained constant for the dissipating stage. The rain rates in the mature stage were slightly higher than those in the developing and dissipating stages, consistent with their Z_e values. The weak growth trends in both Z_e and RR below bright bands toward the surface in the developing and mature stages were similar to those over wet regions reported elsewhere (e.g., Cao & Qi, 2014; Geerts & Dejene, 2005; Liu & Zipser, 2013). This was evident in the slightly increased $\log_{10}N_w$ and constant D_m shown in Figures 11a and 11c, respectively. In contrast, in the dissipating stage, the dominant process was unclear and dependent of the meteorological context (e.g., evaporation or without compensation by moisture convergence; Houze, 2014).

Without a clear bright band in the CFADs denoting convective reflectivity, the most distinct features were the monotonic increases in the median lines and frequency contours of convective reflectivity from the radar echo top to an altitude of 1 km (Figures 9d–9f). The rates of increase were not as large as in the fast ice-snow

Figure 9. Normalized CFADs of the attenuation-corrected reflectivity data from 34 typical Meiyu cases during the period 2016–2018 (summarized in Table 1). Three stages of (a–c) stratiform and (d–f) convective rain of the Meiyu precipitation systems. In each CFAD, the frequency is normalized, that is, it is the occurrence frequency per 1 dBZ per 1 km, divided by the maximum frequency of any height-reflectivity bin. To help identify median changes with the life stages of clouds, the solid lines represent the median lines for the current stage, and the dashed lines in a different color repeat the positions of the median lines for the other two stages. The black dashed lines in Figures 9a–9f represent the FL; the number of samples for each panel is shown in Figure 9g, where the convective (stratiform) sample number is less (greater) than 3,000.

Figure 10. The box-whisker plots for the stratiform (left) and convective (right) CFADs of radar reflectivity (in Figure 9) are normalized at each individual height level. The center of the box represents the 50% percentile value, the lower quartile (25%) and the upper quartile (75%) are the left and right boundaries of the box, and whiskers correspond to the 5% and 95% values.

Figure 11. Three stages of median precipitation rate profiles (thick lines) for (a) stratiform and (b) convective rain of the Meiyu precipitation systems derived from the GPM 2ADPR product during the period 2016–2018. Shaded areas show the interquartile range.

aggregation region (within 1 km above FL shown in Figures 9a–9c) of the SP VPRs. Similar to the case results, statistics of the CP Z_e values below FL in each stage (e.g., ~37–38 dBZ at 1 km as seen from the median lines in Figures 9d–9f) were approximately 10 dBZ greater than their corresponding SP Z_e values

Figure 12. Same as Figure 11 except for $\log_{10}N_w$ (a–b) and D_m (c–d).

(e.g., ~27–29 dBZ at 1 km in Figures 9a–9c). The interquartile ranges also increased sharply from 25–30 dBZ in the SP regions (Figure 10a) to 35–40 dBZ in the SP regions (Figure 10b). Below FL, the CP Z_e values increased by about 5 dBZ from FLs to 1 km (Figures 9d–9f). The RR profiles in Figure 11b also show slight increase between FL and 1 km in both the developing and dissipating stages, with much greater increase in the mature stage. Below 1 km the median and quartile values of the CP RR both decrease sharply (not shown), especially for the upper quartile, due to the loss of samples near the ground (Figure 9g). This may be one source for negative bias of surface CP RR when validating against the disdrometer measurements in section 3.1. The growth trends in Z_e and RR from FL to 1 km are associated with increase in both $\log_{10}N_w$ and D_m as raindrops fell (Figures 12b and 12d), which further supports the conclusion based on Figure 8d that coalescence is the dominant process in the growth of CP raindrops.

Among the three stages, the CP Z_e and RR at the mature stage were the largest at various heights (Figures 9e and 11b), due to the greater numbers of large ice particles and raindrops (as shown in Figures 12b and 12d) caused by the vigorous convection at this stage. The CP Z_e and RR values above 6 km in the developing stage were similar to those in the mature stage, while those below 5 km were the lowest because the strong upward flow in the developing stage brings large amounts of moisture from the lower layer to the upper layer (Byers & Braham, 1949; Houze, 1993). The Z_e values below 5 km in the developing and dissipating stages became indistinguishable. Zhang and Fu (2018) reported similar findings in the liquid water path and ice water path, indicating that a CP system has both more ice-phase and liquid-phase precipitation at the mature stage, whereas there is also a large amount of ice precipitation (above the FL) due to the strong upward flow in the developing stage.

3.3.2. Drop Size Distribution

To gain further insight into the microphysical structure of precipitation, the profiles of the DSD parameters for SP and CP in each stage, including D_m and $\log_{10}N_w$, are plotted in Figure 12. For SP (Figures 12a and 12c), the $\log_{10}N_w$ values of the three stages were identical except for higher values above 8 km in the mature stage. The higher $\log_{10}N_w$ values indicated that more ice particles in the mature stage might be advected from convective regions by divergent air motions (Cui et al., 2019; Herzegh & Hobbs, 1980). Their D_m profiles were consistent with the order of the stratiform vertical precipitation profiles (Figure 11a), with the smallest being in the developing stage and the largest in the mature stage. As shown in Figures 12c and 10a, the largest D_m resulted in the highest precipitation rate in the mature stage, and the lowest precipitation rate in the developing stage was attributable to the smallest D_m . These results were similar to the findings in the lower reaches of the YHRV in eastern China (Zhang & Fu, 2018).

In contrast, the life stage had a greater influence on the DSD parameters of CP (Figures 12b and 12d). In the developing stage, CP had the lowest concentration but largest particle diameter, which was even larger than D_m in the mature stage. The particle diameter is normally linked to the strong convective updrafts that are commonly observed in the developing and mature stages (Byers & Braham, 1949; Wu et al., 2018; Yuter & Houze, 1995). As the strong updrafts can carry greater numbers of large particles (regardless of whether they are liquid or ice) upward, they can readily grow by accretion of cloud liquid water in the rising parcels of air (Houze, 1993). Aircraft in situ measurements of ice particles in convective clouds have confirmed that the particles in the updrafts grow largely due to riming (Houze, 1993). Due to the presence of sufficient moisture in the mature stage, as shown in Case II and as also reported by Houze (2018), stronger vertical motions can produce more precipitable particles relatively quickly, because large concentrations of water are condensed; thus, the efficiency of riming and aggregation increases rapidly (Houze, 1993; Szumowski et al., 1997; Szumowski et al., 1998). As the Meiyu systems gradually dissipate, strong upward motions cease and particles no longer grow readily. Consequently, CP consists of large but sparse particles in the developing stage, and of both large and dense particles in the mature stage. In the dissipating stage, CP consists of small but dense particles.

The results presented in Figures 9–12 indicated that the dominant microphysical processes and vertical structures of the two precipitation types are different in terms of the life stages of Meiyu systems. For SP, below the bright bands, the Z_e and RR values in the developing and mature stages increased slightly toward the surface due to the coalescence process overwhelming the evaporation and/or breakup processes. In the dissipating stage, however, they were somewhat different, with nearly constant for RR but partly decreasing for Z_e , because the evaporation and/or breakup processes became more competitive. For CP, the growth

trends in both the Z_e and RR values below FL were associated with increases in raindrop diameter and concentration, indicating that coalescence is the dominant process in CP when raindrops fall.

Note that the height of the bright band, and the slope of VPRs below the bright band, varies by region (e.g., Cao et al., 2012; Geerts & Dejene, 2005) and season (e.g., Cao & Qi, 2014) and can strongly influence quantitative precipitation estimation. In the SP of Meiyu, as outlined earlier, the VPR has a stage-dependent slope below the bright band (negative slope for the developing and the mature stages but an absence of explicit tilt for the dissipating stage) and a higher bright band layer than in the mountainous west region of the United States (Cao et al., 2012). The stage-dependent SP VPRs revealed in this study provide insight that should allow improvement in quantitative precipitation estimations of monsoon frontal rain over the YHRV in China.

4. Summary and Conclusions

This study analyzes the vertical structures of typical Meiyu precipitation events over the YHRV based on measurements and retrievals from the GPM-DPR. To check the reliability of the GPM-DPR results, the surface PARSIVEL disdrometer measurements during the period 2016–2018 were used for validation. Three cases during the IMFRE, representing the developing, mature, and dissipating stages of Meiyu precipitation systems, were selected and classified into CP and SP. To extend our study from a statistical perspective, all Meiyu cases during the period 2016–2018 detected by DPR were also collected and classified into different types and stages. The major conclusions of this study can be summarized as follows.

1. The GPM-DPR-retrieved near-surface rain and DSDs over both the CP and SP regions were similar to the PARSIVEL measurements across the YHRV in terms of frequency distributions, with relatively small biases in the means and near-zero skewness values. Good agreement was found between matched GPM DPR and PARSIVEL samples with correlations greater than 0.7 for RR and Z_e , around 0.68 for D_m , and around 0.42 for $\log_{10}N_w$ (with a confidence level exceeding 95%). The comparison showed that the variables retrieved from GPM-DPR are reliable for use in further analyses.
2. The selected three IMFRE cases represent the different precipitation characteristics in the developing (Case I), mature (Case II), and dissipating (Case III) stages of Meiyu precipitation systems. For SP, the VPR shows a layered structure, which is most prominent in the dissipating stage (clear bright bands at ~ 5 km, with sharp increases in Z_e nearby, and almost-constant Z_e values below bright bands). For CP, the Z_e values in the developing stage increase slightly toward ~ 3 km below FL, which is not seen in the other two stages. The mature stage (Case II) is dominated by CP and has the largest Z_e value above FL and the highest echo top, indicating that the greater amounts of large ice particles in the upper levels are due to the uplift of more moisture by stronger updrafts in active convection.
3. Below the bright bands, the composite SP CFADs and RR values for all three stages during the 2016–2018 Meiyu seasons are marginally different from the selected three IMFRE cases, mostly tilting slightly to the right toward the surface, except a few reflectivity frequency contours that were in dissipating stage, although they are similar above the bright bands. Based on these statistical results, we concluded that the coalescence process slightly overwhelms the breakup and/or evaporation processes as raindrops fall. There are no significant differences between the developing and dissipating stages, while the Z_e and RR values in the mature stage are higher than those in the other two stages.
4. The growth trends in both composite CP Z_e and RR values below FLs are associated with increases in raindrop diameter and concentration, indicating that coalescence is the dominant process in CP when raindrops fall. Among the three stages, the CP Z_e and RR in the mature stage are the largest at various heights, indicating both more ice-phase and liquid-phase precipitation. The CP Z_e and RR values above 6 km in the developing stage are similar to those in the mature stage; those below 5 km are the smallest because the strong upward flow in the developing stage brings large amounts of moisture from the lower layer to the upper layer. This suggests that there is more ice water, but less liquid water, in the developing stage. Comparison of DSD profiles reveals that CP consists of large but sparse particles in the developing stage but both large and dense particles in the mature stage. In the dissipating stage, CP consists of small but dense particles.

Furthermore, the vertical structures of the SP examined in this study were similar to those over the ocean region due to high relative humidity but different to the mountainous west regions of the United States.

The fact that the SP VPR has a stage-dependent slope below the bright band has not been found before for general summer precipitation events in China (e.g., Wen et al., 2016; Zhang & Fu, 2018). One obvious possibility that could account for the differences between Meiyu and general summer precipitation is that humidity is often higher on Meiyu rainbands, and that just for the dissipating system evaporation is more likely to become competitive with the coalescence process. These findings improve our understanding of the evolution in vertical structures of monsoon frontal precipitation, as well as the associated microphysical properties, and subsequently provide insights that could improve microphysical parameterization in future models. Although the findings were obtained using 3 years of data from the GPM-DPR, the results are not necessarily conclusive due to the small sample of Meiyu episodes. Long-term integrated observations are required. The uncertainties in the estimated RR , D_m , and N_w profiles from the GPM-DPR are difficult to quantify, as there are no spatially and temporally well-matched aircraft in situ measurements or other reliable retrievals that could be used as references. With further validations of techniques for retrieving and processing dual-wavelength radar measurements, the accuracy of the DPR profiling algorithms will improve, thus increasing confidence in analyses of monsoon frontal precipitation.

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