Variable Raindrop Size Distributions in Different Rainbands Associated With Typhoon Fitow (2013)

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Abstract The microphysical characteristics of rain may vary in different rain regions of a tropical cyclone (TC), but few studies have demonstrated the differences in raindrop size distributions (RSDs) of convective rain in different rainbands of a specific TC. This study examines the RSD characteristics and evolution of convective rain within outer rainbands and a coastal-front-like rainband associated with Typhoon Fitow, based on observational data from a disdrometer at Shibo station in Shanghai, China, during 6–7 October 2013. Considering the fast passage of convective TC rainbands over the disdrometer and the low rain rate of stratiform rain in the outer area, this study proposes a modified rain-type classification method based on the disdrometer data. This study indicates that convective outer-rainband rain (ORR) and coastal-front rain (CFR) have different rain parameters, three parameters of the gamma model, radar reflectivity–rain rate (Z–R), and shape–slope (μ–A) relationships. The convective ORR has higher concentrations at all drop sizes than the convective CFR as well as larger spectral width, leading to the greater rainfall rate. The different Z–R relationships suggest the necessity of a variable relationship for quantitative precipitation estimation (QPE) in different rain regions of the TC. This study also demonstrates for the first time that the RSD evolution with increasing rain rate is different in various convective rainbands associated with Fitow, suggesting that different microphysical parameterization schemes may be required for different rainbands in TC models.

1. Introduction

A power law relationship between rain rate (R) and radar reflectivity (Z) has been widely used in radar- and satellite-based quantitative precipitation estimation (QPE). The power law relationship depends on the fact that the radar reflectivity and rain rate are related to each other through the raindrop size distribution (RSD; Marshall & Palmer, 1948). Based on the inherent connection between RSD characteristics and physical processes in clouds, Rosenfeld and Ulbrich (2003) introduced conceptual models of different kinds of RSD corresponding to different microphysical and dynamical processes of rain formation (e.g., raindrop coalescence and breakup, size sorting). Thus, understanding the RSD characteristics is very important in improving QPE algorithms and microphysical parameterization schemes in numerical models (Jaffrain & Berne, 2011; Milbrandt & Yau, 2005; Thompson et al., 2015; Zhang et al., 2006). The RSD varies in different climate regions and weather systems (Chen et al., 2012; Janapati et al., 2017; Jorgensen & Willis, 1982; Kumari et al., 2014; Thurai et al., 2012; Tokay & Short, 1996; Ulbrich & Lee, 2002; Vieux & Bedient, 1998; Wen et al., 2018; Wilson & Pollock, 1974). Using disdrometer instruments to measure the size and fall velocity of raindrops (Kathiravelu et al., 2016), some studies have examined the RSDs of landfalling tropical cyclones (TCs) in the western North Pacific basin (Chang et al., 2009; Wang et al., 2016; Wen et al., 2018). However, these studies only focused on the composite RSD characteristics of TC rain.

Previous studies have shown that TC rain has a larger concentration of small (drop diameter <1 mm) to midsize (1–4 mm) drops than non-TC rain (Chang et al., 2009; Deo & Walsh, 2016; Wang et al., 2016; Wen et al., 2018). Chang et al. (2009) found that the mass-weighted mean diameter in typhoon rainfall in Taiwan is larger (Dm ~ 2 mm) than that in Atlantic hurricane rainfall (Dm ~ 1.67 mm; Tokay et al., 2008), and argued that this is due to the lifting effect of the Central Mountain Range in Taiwan. Wang et al. (2016) and Wen et al. (2018) found that the concentration of small drops in typhoons that made
landfall in mainland China is much higher than those reported by previous studies (Chang et al., 2009; Deo & Walsh, 2016; Tokay et al., 2008), possibly due to a higher concentration of condensation nuclei (Liu et al., 2011; Rosenfeld et al., 2008).

In addition to the regional difference, the RSD varies with different rain types due to the different microphysical processes of rain formation (Brown et al., 2016; Krajewski et al., 2006; Lee et al., 2009; Niu et al., 2010; You et al., 2014; Zhang et al., 2001). Convective precipitation particles in active cumulus and cumulonimbus clouds grow primarily via the collection of cloud droplets (i.e., by coalescence), whereas stratiform precipitation particles in nimbostratus clouds grow by vapor deposition aggregation to generate large snowflake or graupel (Houze, 2014). A TC can contain various rain types, including the eyewall with slantwise updrafts and deep convection, spiral rainbands with strong convective cells, and upper level stratiform cloud initiating from eyewall updraft (Houze, 2010; Willoughby, 1988), which hints that the RSD of convective rain varies in different rain regions of the TC.

The classification of rain type based on disdrometer data has been widely used in RSD analysis. From consideration of the temporal variability of rain rate derived from a surface disdrometer, Testud et al. (2001) proposed that, if all 10-min adjacent rain rates from \( R_{k-5} \) to \( R_{k+5} \) (subscript \( k \) denotes each individual spectrum) are less than 10 mm/hr, the spectrum \( k \) belongs to stratiform rain. Otherwise, the spectrum is classified as convective rain. This method does not consider the existence of mixed rain type, and possibly classifies the stratiform rain within the influence radius of a convective cell as convective rain. Bringi et al. (2003) and Chen et al. (2013) took account of mixed rain type and the standard deviation of rain rate (\( \sigma_R \)). If the adjacent rain rates from \( R_{k-5} \) to \( R_{k+5} \) are higher than 0.5 mm/hr, and \( \sigma_R \) is less than 1.5 mm/hr, then the spectrum \( k \) is classified as stratiform rain; otherwise, if the adjacent values from \( R_{k-5} \) to \( R_{k+5} \) are higher than 5.0 mm/hr, and \( \sigma_R \) is more than 1.5 mm/hr, then the spectrum \( k \) is classified as convective rain; the remaining samples belong to mixed rain, which are excluded from the RSD analysis. Note that these two methods require all 10-min consecutive rain samples to be more (or less) than a certain threshold value of rain rate, and do not consider the fast passage of a TC rainband over a disdrometer, which may occur in less than 10 min. Therefore, it is necessary to evaluate previous rain-type classification methods in TC rain based on the disdrometer data.

There may be differences in rain microphysical characteristics due to different dynamical and thermodynamical mechanisms of rain formation in various rain regions of a TC, as argued by previous studies (Black & Hallett, 1999; Houze, 2010; Houze et al., 1992; Marks & Houze, 1984; Ulbrich & Lee, 2002). As a fundamental property of rain microphysics, there may be different RSD characteristics in different rain regions of the TC (Bringi et al., 2003; Bruintjes, 1999; Deo & Walsh, 2016; Houze, 2014; Rosenfeld & Ulbrich, 2003; Ulbrich, 1983; Ulbrich & Lee, 2002), but few studies have focused on this issue. Thus, this study investigates the RSD characteristics of convective rain when several rainbands associated with Typhoon Fitow (2013) passed over Shanghai, which made landfall on the border between Zhejiang and Fujian provinces in China at 1800 UTC 6 October 2013. During the following two days, four rainbands associated with the typhoon caused heavy rainfall (more than 370 mm of maximum accumulated rainfall) in Shanghai (Bao et al., 2015, hereafter Bao15), including three outward spiraling rainbands and a coastal-front rainband (Bao15), and even transit into extratropical cyclones during autumn. The whole precipitation event of Fitow was fully measured by an OTT Particle Size and Velocity (PARSIVEL; OTT Hydromet, Germany; Löffler-Mang & Joss, 2000) disdrometer in Shanghai, which provides an opportunity to examine the RSD characteristics of this rain event. Ulbrich and Lee (2002) demonstrated the difference of rainfall characteristics associated with a typical cold front and remnant of Tropical Storm Helene over the southeastern United States, while this study will investigate the RSDs of convective rain within various rainbands associated with Typhoon Fitow that developed from a tropical depression over the western North Pacific basin, as well as the RSD evolution with increasing rain rate. The RSD characteristics of TCs over different oceanic basins will thus to some extent be compared in this study.

The evolution of the rainbands associated with the precipitation process in Shanghai is described in section 2. The disdrometer data and analysis methods are introduced in section 3. Section 4 presents the composite RSDs of the rain event. In section 5, we examine the impact of previous rain-type classification methods...
on RSD analysis, and introduce a modified classification method and discuss its performance as well as $Z-R$ and $\mu-A$ relationships and the RSD evolution of convective rain in different rainbands of Typhoon Fitow. The conclusions are summarized in section 6.

2. Evolution of Rainbands Associated With the Rain Event in Shanghai

Figure 1 shows the composite Doppler radar reflectivity as used in Bao15. In general, the rainfall in Shanghai was associated with four rainbands (RB1–RB4). When Typhoon Fitow made landfall at 1800 UTC 6 October 2013, an outer rainband (RB1) approached Shanghai and then moved northward (Figures 1a and 1b). A few hours later, RB3 developed to the south of RB1 and passed over Shanghai (Figures 1b–1f). When RB3 moved to the north of Shanghai at 1200 UTC 7 October, RB4 brought convective rain to Shanghai again (Figures 1d–1e). RB1, RB3, and RB4 were the outer rainbands of Typhoon Fitow.
Although RB2 was also initiated from an outer rainband of Fitow, it finally developed into a front-like rainband, resulting in about 10 hr of heavy rain starting at 1700 UTC 7 October in Shanghai (Figure 1f). The evolution of surface dewpoint temperature and 10-m wind vectors shows a cold-air tongue extended to the border region of Zhejiang, Jiangxi, and Fujian provinces as Fitow dissipated at 1500 UTC 7 October (Figure 2). Based on the wind profiler data from Huzhou station in Zhejiang province and Shibo station in Shanghai, whose locations are indicated in Figure 2, the change of wind direction from southerly to northerly at the altitude of 2–4 km shows that the coastal front passed over Huzhou and Shibo at around 2100 UTC 7 October and 0000 UTC 8 October (Figure 3), respectively. We conclude that the rainfall in Shanghai during the night of 7 October was produced by the coastal-front-like rainband (RB2). A more detailed description can be found in Bao15.

Figure 4a shows the evolution of rain rate observed by the rain gauge and integrated from a disdrometer at Shibo station in Shanghai (black square in Figure 1), while Figure 4b is a time–height diagram of Doppler radar reflectivity over Shibo station. In general, the passages of the four rainbands (Figure 4b) are in good agreement with the peaks in rain rate observed by the rain gauge and integrated from the disdrometer at Shibo station (Figure 4a), as well as the high concentration of raindrops (Figure 4c). The radar reflectivity is characterized by a vertically oriented column (Houze, 2014) as each convective rainband passes through (Figure 4b), and shows that the three outer rainbands (RB1, RB3, and RB4) are embedded within the stratiform rain (Figure 4b). Note that the rain rate derived from the disdrometer appears to be higher than that observed by the rain gauge, possibly because of overestimation of large raindrops resulting from PARSIVEL instrument limitations, as identified by previous studies (Park et al., 2017; Wen et al., 2017). Both tumbling raindrops associated with the strong-wind effect of landfalling TCs and overlapping raindrops associated with a higher concentration of TC rain may increase the sampling of false large raindrops, leading to a higher rain rate than that observed by rain gauges (Han et al., 2012; Park et al., 2017). This issue will be discussed extensively in future work.

The satellite images indicate that Shanghai was covered all the time by the upper-level and low-rain-rate cloud (figure not shown), while convective outer rainbands or segments occasionally passed through until 1500 UTC 7 October. The backward trajectories of air particles over Shanghai (Figure 5) further demonstrate that this upper level cloud may be initiated from the eyewall updraft, as discussed by Bao15. During the second rain stage (Stage II) from 1700 UTC 7 October to 0700 UTC 8 October, in contrast, the rain was produced mainly by a coastal-front-like rainband (RB2). As indicated by the radar echo (Figure 4b) and rain gauge (Figure 4a), the convective rain occurred first and lasted about 10 hr, and then the stratiform rain closely followed. For convenience, the rain caused by RB1, RB3, and RB4 in Stage I is termed the outer-rainband rain (ORR), while the rain associated with RB2 in Stage II is termed the coastal-front rain (CFR) in this study. After 0700 UTC 8 October, the radar reflectivity top (>25 dBZ) is below 3-km height, lower than the melting layer of about 4 km (Figure 4b). Thus, the rain in the third stage (Stage III) can be classified as shallow rain, with radar echo top lower than the melting layer (Cha et al., 2009; Fabry & Zawadzki, 1995; Wen et al., 2016).

3. Data and Methods

3.1. PARSIVEL Disdrometer and Data Sets

In this study, particle size spectrum data were obtained from an OTT PARSIVEL disdrometer at Shibo station in Shanghai with 1-min temporal interval (Figure 4c). The PARSIVEL disdrometer can measure 32 nonequidistant classes of particle size ranging from 0.062 to 24.5 mm and 32 nonequidistant classes of fall speed ranging from 0.05 to 20.8 m/s, providing a 32 × 32 two-dimensional array (Battaglia et al., 2010; Yuter et al., 2006). However, the two smallest size classes are not used because of low signal-to-noise ratio, so the actual sampling diameters start at the third diameter class of 0.312 mm (Battaglia et al., 2010; Jaffrain & Berne, 2011; Löffler-Mang & Joss, 2000). A detailed description of the PARSIVEL disdrometer may be found in Löffler-Mang and Joss (2000). We also used the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model and the NCEP Global Data Assimilation System (GDAS) analysis with a resolution of 1° to calculate the back trajectories of air particles in Figure 5 (Draxler & Hess, 1998). The best track data set of Typhoon Fitow was described in Ying et al. (2014).
3.2. RSD Analysis Methods

Several data quality control (QC) procedures are first conducted to ensure the accuracy of the RSD analysis. Any 1-min sample in which either the drop number is less than 10 or the rain rate is less than 0.1 mm/hr is eliminated as noise (Tokay & Bashor, 2010). Raindrops with diameter exceeding 6.5 mm or falling velocity 60% higher or lower than the empirical fall velocity–diameter relationship of Atlas et al. (1973) for rain are eliminated (Battaglia et al., 2010; Jaffrain & Berne, 2011; Tokay et al., 2008), which accounts for about 10% of the total number. We also excluded spurious samples affected by strong wind (Friedrich et al., 2013). Consequently, there are 2,042 of the 3,420 original samples left for the RSD analysis in this study. In addition, we corrected the drop size with the equivalent spherical diameter proposed by Battaglia et al. (2010) to reduce the observational error of particle shape derived directly from the disdrometer.

Fitting a gamma model to the RSDs facilitates a quantitative comparison of the different RSDs presented in this study, since each parameter in the gamma model corresponds to physically meaningful characteristics of the rainfall (Ulbrich, 1983). The well-known gamma model can be expressed as follows:

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\text{Figure 2.} \text{ Observed winds (full barb is 10 m/s) and dewpoint temperature [units: °C; values greater (lower) than 20 °C are indicated by red (blue) numbers] from surface stations at (a) 0600 UTC 7, (b) 1500 UTC 7, and (c) 0000 UTC 8 October 2013. The typhoon symbol denotes the final position where Fitow’s track report ceased at 0600 UTC 7 October. In (b), the wind profiler locations in Huzhou and Shanghai are indicated by HZ and SH, and the green line schematically shows the cold air tongue.} 
\]
where $D$ is the equivalent raindrop diameter (mm) and $N(D)$ is the number concentration of raindrop per unit volume and per unit size interval (mm$^{-1}$μm$^{-3}$). $N_0$, $\mu$, and $\Lambda$ are the intercept (mm$^{-1}$μm$^{-3}$), shape, and slope parameters (mm), respectively (Ulbrich & Atlas, 1998; Vivekanandan et al., 2004; Zhang et al., 2003). The parameter $N_0$ is the drop concentration $N(D)$ when the raindrop diameter $D$ approaches the minimum, so larger $N_0$ denotes higher concentration of small raindrops. A shape parameter $\mu$ greater (less) than 1 indicates a concave downward (upward) shape of the RSD. A larger slope parameter $\Lambda$ denotes a narrower shape of the RSD, namely, that the RSD tail truncates at smaller $D$ (Konwar et al., 2014; Ulbrich, 1983).

The number concentration of drops at the $i$th size class $N(D_i)$ can be represented as follows:

$$N(D_i) = N_0 D_i^\mu \exp(-\Delta D)$$

Figure 3. Time–height plots of the horizontal wind (full barb is 10 m/s) observed by the wind profilers at (a) Huzhou station in Zhejiang province and (b) Shibo station in Shanghai (shown in Figure 2b) every half hour from 1200 UTC 7 Oct to 1200 UTC 8 October 2013. The gray strip denotes the time when the coastal front was passing over each station.
Based on the $N(D)$, the $n$th-order moment is defined as

$$M_n = \int_0^{D_{\text{max}}} D^n dD = \sum_{i=1}^{32} N(D_i)\Delta D_i$$  \hspace{1cm} (3)$$

In addition, several integral rainfall parameters, namely, the total concentration of raindrops (m$^{-3}$), radar reflectivity factor $Z$ (mm$^6$/m$^3$), rain rate $R$ (mm/hr), and rain water content $W$ (g/m$^3$), can be calculated directly from the measured RSD after QC as follows:

$$N_t = \sum_{i=1}^{32} N(D_i)\Delta D_i$$  \hspace{1cm} (4)$$

$$Z = \sum_{i=1}^{32} N(D_i)D_i^6\Delta D_i$$  \hspace{1cm} (5)$$

**Figure 4.** Time series of (a) the rain rates (mm/hr) observed by the rain gauge and integrated from the PARSIVEL disdrometer data after quality control (QC) at Shibo station in Shanghai, (b) the radar reflectivity (dBZ) from the Doppler radar data with 6-min temporal interval over Shibo station, and (c) the RSD obtained from the disdrometer. The gray strip highlights 2000 UTC 6 October 2013, and the blue dashed lines at 1700 UTC 7 and 0700 UTC 8 October 2013 separate the rainfall event into the three stages, respectively, corresponding to outer-rainband rain (ORR), coastal-front rain (CFR), and shallow rain.
\[ R = 6\pi \times 10^{-4} \sum_{i=1}^{32} \sum_{j=1}^{32} V_i N(D_i) D_i^2 \Delta D_i \quad (6) \]

\[ W = \frac{\pi \rho_w}{6} \sum_{i=1}^{32} N(D_i) D_i^3 \Delta D_i \quad (7) \]

where \( \rho_w \) is the density of water (1,000 kg/m\(^3\)). The mass-weighted mean diameter \( D_m \) (mm) and normalized intercept parameter \( N_w \) (mm/m\(^3\)) are two representative parameters of RSD and have often been used in previous studies to compare RSD characteristics in different climatic rain regimes regardless of the time scale and rain rate (Bringi et al., 2003; Wang et al., 2016). As the ratio of the fourth to third moment of the RSD, the mass-weighted mean diameter \( D_m \) (mm) is defined as

\[ D_m = \frac{M_4}{M_3}, \quad (8) \]

and the normalized intercept parameter \( N_w \) (mm/m\(^3\)) is calculated as follows:
Note that all integral rainfall parameters and $D_m$ and $N_w$ in the following RSD analysis are directly calculated from the disdrometer data after QC.

4. Composite RSDs in Different Rainbands

Figure 6 shows the composite RSDs of ORR, CFR, and shallow rain. Similar to previous studies (Wen et al., 2016, 2017), the spectral width of the ORR is larger than those of the CFR and the shallow rain. The shallow rain exhibits the smallest spectral width of RSD and the largest peak value of raindrop concentration (Figure 6). For drop sizes smaller than 1 mm, the ORR and the CFR have similar concentrations, but at other drop sizes the concentrations of the ORR are larger than those of the CFR. Consequently, the ORR has the smallest three parameters of the gamma model, whereas the shallow rain has the largest ones (Figure 6), similar to the findings of Wen et al. (2016).

As also shown by Table 1, the higher raindrop concentration ($N_w$) in the ORR may also increase the collision–coalescence rate to favor larger-size raindrops, as discussed by Han et al. (2012), leading to a larger value for the $D_{\text{max}}$ appearing in the ORR. However, the ORR has a smaller mass-weighted mean diameter $D_m$ than the CFR (1.13 and 1.45 mm, respectively) due to the greater number of samples of small raindrops in TC rain (Chang et al., 2009; Tokay & Short, 1996; Wang et al., 2016). Whether the convective ORR also has smaller mean raindrop diameter and mean rain rate than the convective CFR will be discussed further in the following sections.

5. RSD Analysis and Discussion Using Different Rain-Type Classification Methods

The previous classification methods of rain type were derived mainly for weather systems other than TCs. After QC there are 2,042 samples in total left in this study, of which 315 samples are classified as convective and 300 samples as stratiform rain by the classification method of Chen et al. (2013), while the other 1,427 samples (accounting for about 70% of the total) are classified as mixed rain and are excluded from the RSD analysis in this study (Figure 7a). More precisely, although the ORR has 1,044 samples after QC, only 18.1% of the samples (189) are adopted for subsequent RSD analysis, namely, 115 convective samples and 74 stratiform samples (Figure 8a). In contrast, 46.7% (333 samples) of 713 samples in the CFR after QC are selected.

| Type                | ORR during Stage I | CFR during Stage II | Shallow rain during Stage III |
|---------------------|--------------------|---------------------|------------------------------|
| Duration (min)      | 225                | 267                 | 1044                         |
| Accumulated amount (mm) | 83.7             | 5.4                 | 113.6                        |
| $R$ (mm/hr)         | 22.33              | 1.22                | 6.53                         |
| $Z$ (dBZ)           | 42.4               | 23.3                | 36.3                         |
| $N_T$ ($m^3$)       | 1016               | 399                 | 523                          |
| $D_m$ (mm)          | 1.62               | 0.89                | 1.13                         |
| $D_{\text{max}}$ (mm) | 5.500              | 2.375               | 5.500                        |
| $\log_{10} N_w$ (mm/m$^3$) | 4.05             | 4.00                | 3.93                         |

Note. The terms $R$, $Z$, $W$, $N_T$, $D_m$, $D_{\text{max}}$, and $\log_{10} N_w$ represent rain rate, radar reflectivity, rain water content, total drop concentration, mass-weighted mean diameter, maximum diameter, and normalized intercept parameter, respectively. The rainfall duration and accumulated amount are also given for the different rain types in each stage. “C,” “S,” and “T” denote the convective, stratiform, and total rainfall, respectively.
for subsequent RSD analysis (Figure 8a). Such high sample exclusion rate in RSD analysis using Chen's method has never appeared in previous studies, so it is necessary to examine the impact of high sample exclusion rate on the RSD analysis.

On the other hand, Testud's method selects 1,081 samples as convective rain and the remaining 961 samples as stratiform rain, without mixed rain samples (Figure 7a). This implies that the RSD of convective (or stratiform) rain classified by Testud's method may have mixed rain characteristics (Figure 8b). Consequently, there are 665 (379) convective (stratiform) samples in the ORR using Testud's method for subsequent RSD analysis (Figure 8b), many more than those using Chen's method. Note that the shallow rain type defined by radar echo tops lower than the melting layer also has 19 samples classified as convective rain by Testud's method (Figure 8b), which confirms the confusion between stratiform and convective rain. Therefore, it is worth investigating which classification method can present a more accurate RSD in this rain event.

Different sample adoption rates using different classification methods have an important impact on the resulting RSD. Chen's method classifies 115 samples as convective ORR (Figure 8a), far fewer than the 665 samples using Testud's method (Figure 8b). Chen's method appears to exclude more samples in the RSD analysis of convective TC rain. For example, during the 10-min episode from 2028 UTC to 2038 UTC 6 October, all 11 samples are classified as convective rain by Testud's method, but none by Chen's method (Table 2). In fact, there was a convective rainband (RB1) passing over the disdrometer during this period, as shown by the evolution of radar echoes (highlighted by the gray strip in Figure 4b). However, it cannot meet the condition in Chen's method that the rain rates of all 10-min consecutive samples are more than 5.0 mm/hr due to the fast passage of the narrow rainband (RB1) over the disdrometer, so these samples were not classified as convective rain by Chen's method. Consequently, the RSD of RB1 was not included in the composite RSD (green solid line in Figure 9a) of the convective ORR using Chen's method. Using Testud's method, in contrast, the stratiform rain within the radius of influence of a convective cell may be classified as convective rain (Figure 8b). As a result, when RB1 was passing over the disdrometer, many adjacent samples are classified as convective rain, even though the rain rate is less than 5 mm/hr (Table 2).

Figure 7. (a) Time series of rain rate $R$ (mm/hr) calculated from the disdrometer data set after QC. The red, blue, and green bars or values indicate the convective (“C”), stratiform (“S”), and mixed (“M”) rains classified as by “Ch” (Chen et al., 2013), “Te” (Testud et al. 2010), and “Mo” (the modified classification method in this study), respectively. (b) Sample percentage (%) distribution of different rain rates in ORR, CFR, and shallow rain, respectively.
For the stratiform rain, Chen's method selects 74 stratiform rain samples in the ORR (Figure 8a), also far fewer than the 379 stratiform rain samples selected by Testud's method (Figure 8b). The different lower threshold values of rain rate adopted in Chen's and Testud's methods may be responsible for the different sample adoption rates of stratiform rain. Chen's method excludes 225 (21.6%) samples of total ORR because their rain rate is less than 0.5 mm/hr, whereas most of these samples are included by Testud's method because they meet the condition of rain rate greater than 0.1 mm/hr (Figure 7b). Previous studies (Black et al., 2002; Houze, 2010) have identified that tiny ice particles initially produced in the midlevel updraft of the eyewall can be lifted to the tropopause and advected outward far from a TC center, resulting in widespread stratiform rain. In combination with Bao15 and the discussion of Figure 5, the stratiform ORR should come mainly from the upper level cloud initially from the eyewall updraft, because Shanghai is more than 300 km away from Fitow's landfall position and was covered by the low-rain-rate stratiform rain throughout Stage I (until 1700 UTC 7 October). Chen's method may be unsuitable for TC rain because it never considers the low rain rate of stratiform rain in the outer-rainband region. In contrast, the stratiform CFR followed

**Table 2**

| Minute | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 |
|--------|----|----|----|----|----|----|----|----|----|----|----|
| Rain rate (mm/hr) | 1.53 | 8.05 | 12.42 | 15.97 | 37.82 | 93.93 | 23.60 | 8.34 | 1.05 | 0.49 | 0.27 |
| Chen   | nan | nan | nan | nan | nan | nan | nan | nan | nan | nan | nan |
| Testud | C   | C   | C   | C   | C   | C   | C   | C   | C   | C   | C   |
| New    | nan | nan | nan | C   | C   | C   | C   | nan | nan | nan | nan |

*Note.* “C” denotes the convective rain, whereas “nan” denotes the mixed rain excluded in subsequent RSD analysis.
closely behind the convective CFR, similar to the formation process of nimbostratus associated with deep convection in Houze (2014), leading to higher stratiform rain rate (Figure 7a). As a result, there are only 25 (3.5%) samples less than 0.5 mm/hr in the CFR samples (Figure 7b).

The composite RSDs of convective ORR and convective CFR shown in Figure 9a indicate that the concentrations of raindrops smaller than 3.25 mm using Chen’s method are slightly higher than those using Testud’s method, but the concentrations of raindrops larger than 3.25 mm using Chen’s method are conversely lower than those using Testud’s method. For the stratiform rain, the concentrations of raindrops smaller than 1 mm and larger than 2 mm using Chen’s method are obviously lower than those using Testud’s method (Figure 9b).

1. Modification of the Rain-Type Classification Method

The performance of the previous rain-type classification methods in TC rain demonstrates that a classification method more suitable for TC rain is needed. First, the low rain rate of stratiform rain in the outer area of a TC suggests replacing the threshold value of 0.5 mm/hr with the lowest threshold value of 0.1 mm/hr in the QC procedure. This means that there is no limitation on the smallest threshold value of rain rate for the disdrometer data after QC, like Testud’s method. For the convective rain type, we require the mean rain rate to exceed 5.0 mm/hr instead of each sample exceeding 5.0 mm/hr within 10-min consecutive samples. Based on Chen’s and Testud’s methods, therefore, a modified classification method is summarized as follows: (1) if 11 adjacent rain rates from \( R_k \) to \( R_{k+5} \) are higher than 0.1 mm/hr and less than 5.0 mm/hr, and the \( \sigma_R \) of the 11 rain rates is less than 1.5 mm/hr, then the spectrum \( k \) is classified as stratiform rain; (2) if 11 adjacent rain rates from \( R_k \) to \( R_{k+5} \) are higher than 0.1 mm/hr (considering the continuity of rain), and the mean value of the 11 rain rates is higher than 5.0 mm/hr (considering the fast passage of a TC rainband over a disdrometer) and the \( \sigma_R \) of the 11 rain rates is higher than 1.5 mm/hr, and three adjacent rain rates from \( R_k \) to \( R_{k+1} \) are higher than 5.0 mm/hr, then the spectrum \( k \) is classified as convective rain. Herein there must...
be at least three consecutive 1-min periods of rain (from \(R_{k,1}\) to \(R_{k+1}\)) higher than 5.0 mm/hr to not only exclude the impact of unpredictable error at some time (Thompson et al., 2015) but also lower the false selection of stratiform rain as convective rain as happens in Testud's method; (3) otherwise, the remaining samples are classified as mixed rain.

Using the modified rain-type classification method, there are 225 (288) and 267 (174) samples for convective and stratiform rain types of the ORR (CFR), an increase of 110 (88) and 193 (41) samples compared with using Chen's method, respectively. The samples of convective and stratiform rain types are also strictly separated by the regression line reported by Bringi et al. (2003) (Figure 8a). This means that there are no stratiform samples on the left side of this regression line falsely classified as convective rain. Also, there is no sample of shallow rain classified as convective rain type (Figure 8c). Therefore, the modified classification method avoids the confusion between stratiform and convective rain that often occurs using Testud's method (Figure 8b).

In fact, the greatest discrepancy in RSD performance using the three classification methods is in the ORR. As shown in Figure 9a, the concentration of drops larger than 3.25 mm in the convective ORR may be underestimated using Chen's method, possibly due to the exclusion of some convective samples like those in RB1 (as shown in Table 2). Using the modified classification method (red solid line) modifies the possibly underestimated concentrations (green solid line in Figure 9a). In addition, the modified classification method corrects the possibly underestimated concentrations of drops smaller than 2 mm in the convective ORR using Testud's method (blue solid line), because those stratiform samples originally misclassified as convective rain by Testud's method are excluded when the modified method is used.

Figure 9b shows that the concentration of drops smaller than 1 mm may be underestimated in the stratiform ORR using Chen's method (green solid line) due to the elimination of all the samples of rain rate less than 0.5 mm/hr (see the previous section), whereas the modified method corrects this by retaining more samples of the stratiform ORR (red solid line). In contrast, Testud's method strongly overestimates the concentration of drops larger than 2 mm (blue solid line), because it likewise misclassifies many convective rain samples as stratiform rain, and the modified method also modifies this possible overestimation (red solid line).

To highlight how the modified method overcomes the shortcomings of previous methods for TC rain, Figure 9c compares the RSDs of the stratiform ORR samples classified by the modified method (red dashed line) and the ORR samples with rain rate of 0.1–0.5 mm/hr (cyan dashed line), and the RSDs of the convective ORR classified by the modified method during Stage I (red solid line) and during 2031–2034 UTC 6 October (cyan solid line) in Table 2. For the stratiform ORR, the concentrations of drops smaller than 1 mm are similar in the red and cyan dashed lines in Figure 9c, which means that retaining low-rain-rate samples (less than 0.5 mm/hr) may correct the possibly underestimated concentrations of drops smaller than 1 mm using Chen's method (green solid line in Figure 9b). In the convective ORR, the RSD during 2031–2034 UTC 6 October has the same spectral width as the composite RSD of all convective ORR samples using the modified classification method, and even presents higher concentrations at large size classes (Figure 9c), which means that retaining convective rain samples like those in RB1 corrects the possibly underestimated concentrations of drops larger than 3.25 mm using Chen's method (green solid line in Figure 9a). Therefore, the modified classification method corrects the faults of RSDs using the previous methods that were caused by their possibly inaccurate sample classification of different rain types.

2. \(Z-R\) and \(\mu-A\) Relationships of Convective Rain

The different RSDs in various rainbands can be represented by the parameters \(A\) and \(b\) in the radar or satellite precipitation estimation algorithm (\(Z = AR^b\)). The coefficient \(A\) indicates the size of raindrops (larger raindrops have larger \(A\)) and the exponent \(b\) indicates the microphysical process. Larger \(b\) (>1) implies the size-controlled case (collision and coalescence), whereas \(b–1\) implies the number-controlled case (collision, coalescence, and breakup; Rosenfeld & Ulbrich, 2003; Sharma et al., 2009).

Figure 10a shows scatterplots of \(Z\) versus \(R\) for convective ORR and convective CFR using the modified classification method developed in this study, and the composite result of seven typhoons reported by Wen et al. (2018), as well as the corresponding \(Z-R\) best fit lines. Using the least squares method, \(Z-R\) relationships of \(Z = 65.07R^{1.70}\) for the convective ORR and \(Z = 354.05R^{1.22}\) for the CFR are derived in this study, compared with \(Z = 147.28R^{1.58}\) for the composite result in Wen et al. (2018). In general, the coefficient \(A\) of the CFR
is highly consistent with that of the rain associated with the cold front \((Z = 365.5.05R^{1.38})\) reported by Ulbrich and Lee (2002), while the coefficient \(A\) of the ORR in this study is much smaller than the value of 300 for hurricane rain reported by Jorgensen and Willis (1982) and that of the rain associated with the remnant of TS Helene \((Z = 117.6R^{1.46})\) reported by Ulbrich and Lee (2002). This may be due to the higher concentration of small drops in TCs making landfall in China than in hurricanes over the Atlantic basin, as discussed in previous studies (Chen et al., 2012; Rosenfeld & Ulbrich, 2003; Wen et al., 2018). Note that the coefficient \(A\) of the convective ORR is also smaller than that in Wen et al. (2018), which means that the convective ORR should have more small raindrops. As a result, a given reflectivity value of 50 dBZ corresponds to an outer-rainband rain rate of about 70 mm/hr but a front-like rain rate of about 100 mm/hr (Figure 10a). Actually, this phenomenon of a spiral rainband developing into a frontal rainband is often seen when a TC transits into an extratropical cyclone (Klein et al., 2000; Bao15). If the differences in different typhoon rain events are excluded, the three different \(Z-R\) equations in Figure 10 imply that a single \(Z-R\) relation is not appropriate for radar or satellite QPE of TC rain, and also suggests the necessity of variable \(Z-R\) equations in different rain regions of the TC. Therefore, this study also demonstrates that there are different rain microphysical characteristics in different rain regions outward from a TC center, as argued by previous studies (Black & Hallett, 1999; Houze, 2010).

Although the gamma model has three parameters, there is an inherent correlation between \(\mu\) and \(\Lambda\) (Zhang et al., 2001). The \(\mu-\Lambda\) relationship is widely used in the retrieval of RSDs derived from polarimetric radar data. Figure 10b gives the \(\mu-\Lambda\) scatterplots of the samples with rain rate more than 5 mm/hr and total

![Figure 10](https://example.com/figure10.png)

**Figure 10.** Scatterplots and corresponding best fit lines of (a) radar reflectivity \(Z (\text{mm}^6/\text{m}^3)\) versus rain rate \(R (\text{mm/hr})\) and (b) shape parameter \(\mu\) versus slope parameter \(\Lambda (\text{mm})\) for convective ORR (red) and convective CFR (blue) using the modified classification method developed in this study, and the composite result of seven typhoons reported by Wen et al. (2018).
concentration above 1,000 m$^3$ for convective ORR and convective CFR, and the results reported by Chang et al. (2009) and Wen et al. (2018), as well as the corresponding fitting lines. Consequently, the fitting line of the convective ORR has a steeper slope (smaller quadratic coefficient) than the convective CFR, and it is also steeper than that reported by Wen et al. (2018). In general, the fitting lines for both convective ORR and CFR are closer to that reported by Chang et al. (2009). The reasons for this result need to be investigated further in future work.

3. RSDs of Convective Rain at Different Rain Rates

Using the modified classification method, the convective ORR has shorter duration of precipitation and smaller mass-weighted mean diameter as well as smaller parameters of the gamma model, but about 25% higher rain rate than the convective CFR (Table 1 and Figure 9a). As shown by the composite RSDs in Figure 11a, both the convective ORR and convective CFR have higher concentrations at all drop sizes than the total ORR and total CFR, but the discrepancy between convective and total ORRs is larger. The convective ORR has higher concentrations than the convective CFR at almost all drop sizes, leading to higher

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Figure 11. (a) Composite RSDs of total ORR (red dashed line), total CFR (blue dashed), convective ORR (red solid line), and convective CFR (blue solid line); (b) the RSDs of convective ORR (solid lines) and convective CFR (dashed lines) classified by the modified classification method at different rain rates; (c) mean concentrations and (d) mean raindrop diameters at different rain rates of convective ORR (red bars) and convective CFR (blue bars); and (e) the ratio $\left[ N(D_j) - N(D_{ic}) \right] / N(D_{ic})$ of deviation $[N(D_j) - N(D_{ic})]$ between RSD at the $j$th rain rate $[N(D_j)]$ and composite RSD $[N(D_{ic})]$ with respect to composite RSD $[N(D_{ic})]$ for convective ORR (solid lines) and convective CFR (dashed lines).
convective rain rate despite the smaller total rain rate (Table 1). It also confirms the results of previous studies (Chang et al., 2009; Chen et al., 2013; Tokay et al., 2008; Wang et al., 2016; Wen et al., 2018) that TC rain has higher raindrop concentration and smaller mass-weighted mean diameter than other weather systems. Note that this result is different from the result of Ulbrich and Lee (2002) that the rain rate associated with the cold front is much higher than that associated with the remnant of TS Helene. It is likely that the ORR in this study was measured when Fitow was making landfall, whereas TS Helene was dissipating. In addition, the CFR in this study is associated with a coastal front, which has weaker convergence than a typical cold front as identified by Bosart et al. (1972).

To investigate the evolution of RSD with increasing rain rate, Figure 11b shows the RSDs of the convective ORR and convective CFR at different rain rates. It is categorized into three rain-rate classes: (1) 5–10 mm/hr (moderate rain), (2) 10–50 mm/hr (heavy to torrential rain), and (3) >50 mm/hr (extreme rain). For the convective CFR, the concentrations at all drop sizes generally and progressively increase with increasing rain rate, as do the mean concentration (Figure 11c) and mean raindrop diameter (Figure 11d), similar to the findings of previous studies of other weather systems (Niu et al., 2010; Porcù et al., 2014; Testud et al., 2001). This means that the increase of rain rate contributes to the increase of both raindrop size and concentration. In the convective ORR, however, there are higher concentrations of raindrops near 1 mm in the first rain-rate class (5–10 mm/hr) than in the rain-rate class of 10–50 mm/hr. Compared with the case at 5–10 mm/hr (red solid line), although the mean concentration of the convective ORR remains nearly unchanged at 10–50 mm/hr, the mean raindrop diameter remarkably increases, which contributes to the increase of rain rate (blue solid line in Figure 11b).

To highlight the above differences, Figure 11e shows the ratio \([N(D_j) - N(D_k)]/N(D_k)\) of deviation \([N(D_j) - N(D_k)]\) between RSD at the \(j\)th rain rate \([N(D_j)]\) and composite RSD \([N(D_k)]\) with respect to composite RSD \([N(D_k)]\) at the \(i\)th drop size for convective ORR and convective CFR. For the convective ORR at 5–10 mm/hr, the deviation ratios are greater than zero for raindrop sizes smaller than 1 mm, indicating that the concentrations of small raindrops are very high at the low rain rate (at the initial stage of convection), even higher than those at the following stage of convection (10–50 mm/hr). At 10–50 mm/hr, the deviation ratios for small raindrop sizes are less than zero, but those for 1–2-mm raindrop sizes are greater than zero. The nearly unchanged mean concentration (Figure 11c) and increase of mean raindrop diameter (Figure 11d) indicate that the increasing rain rate of the convective ORR results mainly from the growth of near 1- to 1–2-mm raindrops in the first two rain-rate classes (Figure 11e). Once the rain rate exceeds 50 mm/hr, the largest deviation (ratio more than 1) appears at the 2–3-mm raindrop sizes, which means that the raindrops continue to grow consistent with the increasing mean raindrop diameter as shown in Figure 11d. Meanwhile, the mean concentration shows a sharp increase (Figure 11c), mainly contributed to the remarkably increasing concentrations at tiny raindrop sizes (<0.7 mm; Figure 11e). Several previous studies had indicated the occurrence of double-peak or multipeak model of RSD as the rain rate increases, and attributed this tendency to the equilibrium associated with raindrop coalescence and breakup processes (Rosenfeld & Ulbrich, 2003;
Steiner & Waldvogel, 1987; Zawadzki et al., 2001). In contrast, the RSD evolution of convective rain classified by previous methods cannot clearly demonstrate the raindrop growth process with increasing rain rate in the convective ORR, because the concentrations for raindrops smaller than 1.5 mm (larger than 2.5 mm) may be underestimated by Testud’s (Chen’s) method in the low (high) rain rate class of convective ORR (Figure 12) as discussed above.

For the convective CFR at 5–10 mm/hr, the deviation ratios at all drop sizes are less than zero, and the curve of the deviation ratio as a function of drop size is approximately parallel to the corresponding curve for 10–50 mm/hr, indicating that the concentrations at all drop sizes in the convective CFR increase monotonically with increasing rain rate. At more than 50 mm/hr, the largest deviation in the convective CFR also appears at the 2–3-mm raindrop sizes. This means that the rate of increase of midsize (2–3-mm) raindrops is the greatest at high rain rate for both CFR and ORR, which further confirms the viewpoint of Tokay et al. (2008) that the midsize drops contribute significantly to the rain rate in moderate-to-heavy rain. What then causes the different RSD evolution between convective ORR and convective CFR?

Previous studies argued that the RSD at the initial stage of convection triggering may be responsible for the subsequent evolution of the RSD with increasing rain rate in tropical rain (Testud et al., 2001; Zawadzki et al., 2001). Similar to the previous findings for other weather systems (Niu et al., 2010; Porcù et al., 2014; Testud et al., 2001), the concentrations of the convective CFR also increase monotonically with increasing rain rate in this study. A different scenario for the evolution of the convective ORR with increasing rain rate is as follows. As convection begins, a high concentration of small raindrops (near 1 mm) is first produced in the convective ORR. These grow to become larger (1–2 mm) drops, probably via the accretion of cloud water by raindrops rather than through the increase of drop concentration in the convective CFR. While the concentration of drops near 1 mm decreases and the concentration of larger than 1.3 mm drops increases (Figure 11b), the mean concentration remains nearly unchanged in the first two rain-rate classes of the convective ORR (Figure 11c). This means that the increase of TC rain rate is dominated by the increase of mean raindrop diameter (raindrop growth) rather than the increase of mean raindrop concentration in the first two rain-rate classes. Once the rain rate exceeds a certain threshold value, the mean concentration of raindrops suddenly increases due to a rapid rise in tiny drop (<0.7 mm) concentration, as characterized by the double-peak raindrop spectrum (Figure 11e).

In addition to the different RSD at the initial stage, the interaction between convective and stratiform rain may be another factor affecting the subsequent development of convective ORR. Based on the above statements, the outer rainbands are embedded beneath the upper level and widespread cloud initiating from slantwise eyewall updraft (Willoughby, 1988; Houze, 2010; Bao15), as also shown by the vertical radar echoes in Figure 4b and the backward trajectories of air particles in Figure 5. Thus, the ice crystals from upper level cloud always seed outer rainbands (Houze, 2010). When these ice crystals fall into the outer rainbands, they can rapidly grow by riming in the vertically ascending air, leading to the increase of rain rate (Fernández-González et al., 2014; Houze, 2014; Zawadzki et al., 2005). In contrast, the stratiform CFR is produced at the weakening stage of convective rain, so there is no seed-feeding process in the CFR during Stage II (Figure 9a). In summary, this study using the modified rain-type classification method demonstrates that the convective ORR has different RSD characteristics and evolution from the convective CFR. Although the RSD characteristics derived from disdrometers cannot directly represent the microphysical processes in clouds of the TC, they can be used to partly confirm the different rain microphysical characteristics or processes in different rain regions of a TC as argued by Houze (2010). This also implies that different microphysical parameterization schemes may be required for different rainbands in TC models, such as the autoconversion threshold value between cloud droplets and raindrops.

6. Summary

A heavy rain event associated with the passage of three outer rainbands of Typhoon Fitow (2013) and a coastal-front-like rainband as Fitow dissipated was fully measured by a PARSIVEL disdrometer in Shanghai. Unlike previous studies that analyzed the composite RSD of TC rain, this study investigated the RSD characteristics of convective rain in different rainbands of a TC, focusing on a quantitative comparison of the RSD characteristics and evolution of convective outer-rainband rain (ORR) and coastal-front rain (CFR) associated with Fitow.
The impact of previous rain-type classification methods on RSD analysis of TC rain was examined, and a modified rain-type classification method was proposed based on the observed disdrometer data in this study. The modified classification method was demonstrated to be more applicable in TC rain, because it takes account of the fast passage of convective TC rainbands over the disdrometer and the low rain rate of stratiform rain in the outer area.

Using the modified rain-type classification method developed in this study, it was found that the convective ORR was occasionally embedded within the widespread stratiform rain of the TC. In contrast, the convective CFR was closely followed by the stratiform CFR. In addition, analysis of the RSD characteristics indicates that the convective ORR and CFR have different rain parameters, parameters of the gamma model, radar reflectivity–rain rate (Z-R), and shape–slope (μ-A) relationships. The convective ORR has higher concentrations at almost all drop sizes than the convective CFR as well as larger spectral width, leading to the higher rainfall rate. The different Z-R relationships suggest the necessity of a variable Z-R equation for radar or satellite QPE in different rain regions outward from a TC center, based on a dense detecting network of disdrometers. In addition, this study confirms, to a certain extent, that the TCs over the western North Pacific basin have different rainfall characteristics from TCs over other oceanic basins.

This study also demonstrates for the first time that the RSD evolution of the convective ORR was different from the convective CFR as the rain rate increased. The concentrations of the convective CFR increase monotonically with increasing rain rate. In the convective ORR, however, a high concentration of small (near 1 mm) raindrops first appears at lower rain rate (at the initial stage of convection), and then the rain rate increases due to raindrop size growth, whereas the mean concentration remains nearly unchanged. Once the rain rate exceeds a certain threshold value, there is a sudden increase of tiny drops (less than 0.7 mm) as well as increase of the mean raindrop concentration. The increase of midsize raindrops is greatest at high rain rate, which confirms the previous viewpoint that the midsize drops make the dominant contribution to the rain rate of heavy rain. Different precipitation formation mechanisms for convective ORR and convective CFR were discussed that may account for their different RSD evolutions with increasing rain rate. The difference of RSD evolution in various convective rainbands associated with Typhoon Fitow suggests that different microphysical parameterization schemes may be required for different rainbands in the TC model.

In summary, this study compared RSD characteristics of convective rain in various rainbands associated with Typhoon Fitow as well as the evolution with increasing rain rate, which partly demonstrates the different rain microphysical characteristics in different rain regions outward from a TC center argued by previous studies. Note, however, that this result was only derived from the analysis of surface disdrometer data in a single TC event, and the microphysical processes in convective clouds cannot be detected directly by the surface disdrometer. Therefore, we will further investigate the RSDs in other convective rainbands (e.g., inner spiral rainbands) of TCs based on multiple observations (e.g., polarimetric radar and satellite detection) as well as the reliability of the modified rain-type classification, and use high-resolution simulations to validate the impact of microphysical parameterization schemes on rainfall rate and amount in future work.

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