A Comparison of Convective Raindrop Size Distributions in the Eyewall and Spiral Rainbands of Typhoon Lekima (2019)

Xuwei Bao1, Liguang Wu2, Shuai Zhang1, Huizhen Yuan3, and Huihui Wang4

1Key Laboratory of Numerical Modeling for Tropical Cyclones and Shanghai Typhoon Institute, China Meteorological Administration, Shanghai, China, 2Department of Atmospheric and Oceanic Sciences and Institute of Atmospheric Sciences, Fudan University, Shanghai, China, 3Wenzhou Meteorological Bureau, China Meteorological Administration, Wenzhou, China, 4Taizhou Meteorological Bureau, China Meteorological Administration, Taizhou, China

Abstract A reliable shape-slope (μ-A) relationship for polarimetric retrieval in tropical cyclones (TCs) is unavailable due to the lack of raindrop size distribution (RSD) measurements within the TC eyewall. This study presents an analysis of the convective RSDs in the eyewall and spiral rainbands, based on ~26 hr of measurement from 17 Thies disdrometers during the landfall of Typhoon Lekima (2019) in eastern China. A μ-A relationship for polarimetric retrieval in the eyewall is derived, which is different from those in spiral rainbands of Lekima. The average raindrop diameter parameter $D_m$ (concentration parameter $N_w$) is found to generally decrease (increase) radially from the TC center, but note that most rain samples with intense rain rate >50 mm hr$^{-1}$ occur in the convection-dominated portion of inner rainbands. To explain why, an equilibrium RSD is proposed as a constraint on the growth of $D_m$ and $\log_{10} N_w$ with increasing rain rate.

1. Introduction

The extreme precipitation of tropical cyclones (TCs) is associated mainly with the convective rain in their eyewall, spiral rainbands, and other rainbands caused by the interaction between the TC circulation and other weather systems (Chen et al., 2013; Czajkowski et al., 2013; Houze, 2010; Rappaport, 2014; Zhang et al., 2009). Previous studies have identified various formation mechanisms for convection in different rain regions of a TC, resulting in different cloud structures and microphysical processes (Bao et al., 2019, 2020; Didlake et al., 2017; Hence & Houze, 2008; Houze, 2010; Li & Wang, 2012; Montgomery & Kallenbach, 1997; Moon & Nolan, 2015; Willoughby, 1988). Conversely, microphysical processes (e.g., release of latent heat) play a critical role in the convection development and eventual precipitation in TCs (Chan & Chan, 2016; Khain et al., 2016; Li et al., 2013; Wang, 2009; Williams, 2019). As a fundamental property of precipitation observed directly by surface disdrometers, raindrop size distributions (RSDs) have been analyzed extensively to understand microphysical processes in TCs and improve microphysical parameterization schemes in TC models, as well as final quantitative precipitation forecast (QPF) or estimation (QPE; Bringi et al., 2003; Chang et al., 2009; Deo & Walsh, 2016; Janapati et al., 2017; Marshall & Palmer, 1948; Milbrandt & Yau, 2005; Thompson et al., 2015; Tokay et al., 2008; Wen et al., 2018). So far, however, the differences among RSDs in various rain regions of a TC have not been well investigated because of the lack of RSD measurements within the TC eyewall, which usually decays rapidly after landfall.

The different RSD characteristics in various spiral rainbands of a TC have been discussed in previous studies (Bao et al., 2019, 2020; Chen et al., 2012; Ulbrich & Lee, 2002; Wang et al., 2016; Wen et al., 2018). In recent years, more and more Doppler weather radars are being (or have been) upgraded with dual-polarization capability, and then used to observe TCs (Zhang et al., 2019). Different shape-slope (μ-A) relationships, which can reflect physical characteristics of actual rain, have been used widely in the retrieval of polarimetric radar observations in different rain regions (Brawn & Upton, 2008; Chang et al., 2009; Chen et al., 2012; Zhang, 2015; Zhang et al., 2003). Thus, different μ-A relationships derived from RSDs have been suggested for the polarimetric retrieval in various spiral rainbands of a TC by Bao et al. (2019, 2020). In contrast, the RSD within a mature TC eyewall has not been well observed, although Chen et al. (2012) argued that a few rain samples were collected by a single disdrometer close to the center of Typhoon Morakot (2009). However, the
eyewall of Morakot had been substantially destroyed and filled during its passage over Taiwan. To date, it has not yet been determined whether there are also different RSD characteristics along with a distinctive $\mu$–$\Lambda$ relationship in the TC eyewall from those in spiral rainbands.

In order to measure the RSD characteristics simultaneously in different rain regions of a TC, a number of disdrometers have been deployed in eastern China by the China Meteorological Administration (CMA) since 2017 (Bao et al., 2020). Super Typhoon Lekima made landfall in this area in 2019, with a wind speed of 52 m s$^{-1}$, before moving over this observational network (Figure 1). The mature concentric eyewalls of Lekima persisted for at least 15 hr until the typhoon made landfall in eastern China (Figure 1). Thus, the convective rain in the eyewalls and spiral rainbands of Lekima was collected by this observational network, providing an opportunity to compare the RSD characteristics as well as $\mu$–$\Lambda$ relationships among the TC eye-wall and various spiral rainbands.

In combination with different kinematic and thermodynamical structures in the eyewall and inner and outer rainbands of a TC as noted in previous studies (Houze, 2010; Li & Wang, 2012; Montgomery & Kallenbach, 1997; Moon & Nolan, 2015), this study focuses on investigating whether the RSD characteristics of convective rain differ in the different rain regions of Lekima, especially between the eyewall and various spiral rainbands. We examine whether a variable $\mu$–$\Lambda$ relationship derived from the different RSDs should be

![Figure 1](image-url)
applied for polarimetric retrieval in different rain regions of a TC in the future. Data and methods are introduced in section 2. Section 3 presents the results of RSD analysis and relevant discussion. Finally, conclusions are summarized in section 4.

2. Data and Methods

2.1. Data

Each of the 17 Thies laser-optical disdrometers is collocated with a CMA national automatic weather station (AWS) along the eastern coast of Zhejiang Province (Figure 1a). The detailed open access of disdrometer data and information is given in the Acknowledgments section of this study. The CMA best track shows that Typhoon Lekima made landfall at Wenling in Zhejiang Province, with super typhoon strength (52 m s⁻¹, 930 hPa), around 0145 local standard time (LST) 10 August 2019. Lekima then continued to move northwestward over the observational network (Figure 1). Thus, the heavy rain produced by Lekima before and during landfall was measured comprehensively by this dense disdrometer network.

The Thies disdrometer uses a laser beam 228 mm long, 20 mm wide (sampling area 45.6 cm²), and 0.75 mm thick to measure drop diameter and fall velocity. If rain occurs, the Thies disdrometer outputs a 22 × 20 matrix at 1-min sampling interval, with 22 diameter classes (20 fall velocity classes) ranging from 0.125 to 9.0 mm (0 to 12.0 m s⁻¹). A more detailed description of the Thies instrument, as well as its assessment, may be found in previous literatures (Angulo-Martínez et al., 2018; Frasson et al., 2011; Thies Clima, 2007). All disdrometers in this observational network started simultaneously to measure the rain around 0000 LST 9 August 2019, so this is defined as the sampling start time of disdrometers in this study.

As in Bao et al. (2020, hereafter Bao20), the China New Generation Doppler Weather Radar (CINRAD/SA) data from Wenzhou station (black triangle in Figure 1a) are also utilized by this study. The radar reflectivity shows that Lekima maintained a structure of concentric eyewalls for at least 15 hr prior to landfall (Figure 1). Thus, the sampling end time of disdrometers was chosen at 0200 LST 10 August 2019, which ensures the convective rain produced in the eyewalls and spiral rainbands of Lekima (with an approximately mature structure) were observed simultaneously by the observational network.

2.2. Methods

Before RSD analysis, the quality control (QC) procedures and calculation methods of integral rain parameters used in Bao20 are also adopted by this study (Atlas et al., 1973; Friedrich et al., 2013; Jaffrain & Berne, 2011). However, each sample of disdrometer data in this study is a 22 × 20 matrix, unlike the 32 × 32 matrix in Bao20, so the number concentration \( N(D_i) \) of the \( i \)th size class \( (D_i) \) in the three-parameter gamma model (Ulbrich, 1983) is modified as follows:

\[
N(D_i) = \sum_{j=1}^{20} \frac{n_{ij}}{A_{\text{eff}}(D_i) \cdot \Delta t \cdot V_j \cdot \Delta D_i},
\]

(1)

where \( A_{\text{eff}}(D_i) \) (mm²) is the effective sampling area of the Thies disdrometer for the \( i \)th size class and \( \Delta t \) (60 s) is the sampling time; \( n_{ij} \) denotes the raindrop count for the \( i \)th size class and the \( j \)th velocity class; \( V_j \) (m s⁻¹) is the measured fall velocity of the \( j \)th velocity class, while \( \Delta D_i \) is the diameter interval of the \( i \)th size class (Angulo-Martínez et al., 2018; Frasson et al., 2011; Thies Clima, 2007). In addition, all integral rain variables and the three parameters of the gamma model in this study are calculated directly from the observed disdrometer data after QC; the detailed formulas for their calculation may be found in Bao20. A classification method of TC rain types modified by Bao et al. (2019) is utilized to discriminate convective and stratiform rain types in this study.

As a part of the CINRAD/SA network, the S-band radar in Wenzhou has a three-dimensional volume scan within a radius of 230 km every 6 min, and each volume scan consists of nine sweeps ranging from 0.5° to 19° (Chu et al., 2013; Kim et al., 2014). This study also adopts similar QC procedures for the radar data to those in Bao20 (Wang et al., 2011; Wu et al., 2013). The radar reflectivity data after QC are interpolated onto a Cartesian grid with a horizontal (vertical) resolution of 1 km (500 m). As in Bao20, the wind field data are
also retrieved using the TC tracking radar echoes by correlation (T-TREC) technique of Wang et al. (2011), when the center of Lekima moved inside a detection range of 100 km from the Wenzhou radar. The radius of maximum wind (RMW) can then be derived from the retrieved wind field; the RMW oscillates around ~60 km (±10 km) for about 10 hr prior to landfall (not shown). Therefore, 60 km is defined as the reference RMW in this study.

3. Results
3.1. Structure
Figure 1a shows the structure of concentric eyewalls in Lekima at 1331 LST 9 August 2019. Although the intensity decreased slowly as Lekima moved toward the eastern coast of China, the concentric eyewalls were maintained until it made landfall at Wenling in Zhejiang Province around 0145 LST 10 August 2019 (Figures 1b and 1c). Figure 1d shows the average radius-height cross section of radar reflectivity transecting the rainbands of Lekima in the northwest quadrant at 2259 LST 9 August 2019. The eyewalls generally have higher convection-top height than spiral rainbands, indicative of stronger convection in the eyewalls (Houze, 2010; Rogers et al., 2013). The secondary eyewall has a larger outward tilt than the primary eyewall, consistent with previous studies (Black & Willoughby, 1992; Houze et al., 2007). In this study, the convection-dominated portion (outer or upwind end) of the inner rainbands, as defined by Didlake and Houze (2013a, 2013b), has slightly higher convection-top height (especially near 150 km from the TC center) than its downwind part (about 90–120 km from the TC center). This confirms the stronger convective activity on the upwind end of inner rainbands found in previous studies (Didlake & Houze, 2013a, 2013b; Houze, 2010). Because the innermost (stratiform-dominated) portion of inner rainbands (about 60–90 km from the TC center) is just beneath the slantwise secondary eyewall, its convection-top height is difficult to be obtained herein. The closer the rainbands are to the TC center, the larger the peak value of radar reflectivity, which is associated with larger mean raindrop diameter as indicated by previous studies (Kumjian & Ryzhkov, 2012). Moreover, the reflectivities in the two eyewalls and the convection-dominated portion (90–180 km from the TC center) of the inner rainbands appear to increase with decreasing height below the melting layer, dominated by the collision-coalescence process (Seela et al., 2018), whereas those in the outer rainbands (normally outside 3 RMW) and the stratiform-dominated portion (downwind end) of the inner rainbands remain nearly unchanged, due to the lack of collision-coalescence process as discussed by Bao20. Didlake and Houze (2013b) identified the dominance of stratiform features in the stratiform-dominated portion of inner rainbands, where convective activity is suppressed by the compensating downdraft beneath the strong radial outflow of the eyewall.

3.2. Radial features of RSD
Figure 2 displays the radial distribution of integral rain rate $R$ (mm hr$^{-1}$), mass-weighted diameter $D_m$ (mm), normalized intercept parameter $\log_{10} N_w$ (mm$^{-1}$ m$^{-3}$) and RSD (mm$^{-1}$ m$^{-3}$) of all samples derived from the disdrometer data set after QC. The samples with larger rain rate ($\geq$30 mm hr$^{-1}$) are mainly concentrated in three regions: the eyewall, the convection-dominated portion of the inner rainbands, and the region affected by the outer rainbands (Figure 2a). In general, the percentage of convective rain (CR) in total rain decreases gradually with increasing radius within a distance of ~5 RMW from the TC center. It is interesting that in the eyewall there are no samples categorized as stratiform rain (SR) by the classification method modified by Bao et al. (2019). Note moreover that the percentage of SR is much higher than that of CR within an annular region between 3 and 5 RMW from the TC center, which supports the suggestion that the SR samples in this region result mainly from the upper-level cloud initiated from the eyewall updraft, characterized by a high concentration of small raindrops and low rain rate (Bao et al., 2019). These results may explain why TC rain mainly consists of a high concentration of small raindrops (Tokay et al., 2008; Wang et al., 2016; Wen et al., 2018), but sometimes has a large concentration of medium-to-large-sized raindrops within some convective rainbands (Brauer et al., 2020; Wolff et al., 2019).

Figure 2b shows that the rain samples within the RMW generally have larger $D_m$ than those in other rain regions of Lekima because they collected more midsize and large raindrops $\geq$2 mm (Figure 2d), but smaller normalized concentration $\log_{10} N_w$ as expected (Figure 2c). These midsize and large raindrops are likely...
associated with the melting of hail and graupel produced by stronger convection within the eyewall (Black et al., 1996; May et al., 2008; Zhang et al., 2001), or the growth of raindrops via a collision-coalescence process below the melting layer as they fall (Seela et al., 2018), or even a combination of the two. In agreement with the findings in Bao20, the CR in the inner rainbands also has larger $D_m$ (smaller $\log_{10} N_w$) than that in the outer rainbands in this study. Note that the rain in the stratiform-dominated portion of the inner rainbands has larger $D_m$ than that in the convection-dominated portion. In addition to the discussion in Bao20, there may be another reason for this phenomenon: Larger raindrops produced within the strong outward tilting updraft in the secondary eyewall fall directly into the stratiform-dominated region of the inner rainbands, especially within 1.5 RMW (~90 km herein; Houze, 2010). Figure 3a shows scatterplots of average $\log_{10} N_w$ versus average $D_m$ for the CR in each 20-km distance bin from the TC center. The CR within the RMW has larger $D_m$ ($\geq 2.5$ mm) and smaller $\log_{10} N_w$ ($\leq 3.8$ mm$^{-1}$ m$^{-3}$), whereas the CR in the outer rainbands has smaller $D_m$ ($\leq 2.0$ mm) and larger $\log_{10} N_w$ ($\geq 4.0$ mm$^{-1}$ m$^{-3}$). The CR in the inner rainbands has intermediate values. The RSD at about 60–90 km (in the stratiform-dominated portion of the inner rainbands) looks more like that within the RMW ($\leq 60$ km), which is in agreement with the analysis and discussion in Figure 2. The RSD characteristics of the CR at about 90–240 km from the TC center are similar, while the RSD characteristics of the CR outside 240 km form another cluster. The total rain samples also show a similar distribution (Figure 3a). The rain samples within 90 km (outside 240 km) from the TC center are thus classified as eyewall (outer-rainband) rain, whereas those between 90 and 240 km are classified as inner-rainband rain in this study.
The composite RSDs demonstrate more explicitly that the eyewall (outer-rainband) CR has the highest (smallest) concentration of raindrops ≥2.0 mm, whereas the inner-rainband CR is in between (Figure 3b). In contrast, the outer-rainband CR has the highest concentration of raindrops ≤2.0 mm. The concentrations of tiny raindrops (<0.7 mm) in the eyewall CR are slightly higher than those in the inner-rainband CR, possibly due to breakup of more large raindrops in the eyewall CR, as characterized by the sudden reduction of concentrations at large raindrop classes (>4 mm). If this is not an artifact associated with the coarse diameter bin of the Thies disdrometer, the sharp rise in concentration at a diameter near 2 mm may be related to actual microphysical features of raindrop growth, which will be discussed in section 3.4.

3.3. Z-R and μ-Λ relationships

Figure 3c shows the scatterplots and corresponding best fit lines of radar reflectivity $Z$ (mm$^6$ m$^{-3}$) versus rain rate $R$ (mm hr$^{-1}$) for the eyewall (black line), inner-rainband (red line), and outer-rainband (blue line) CR, as well as the best fit lines in Wen et al. (2018) and Bao et al. (2019). The coefficient $A$ in the power law relationship ($Z = AR^B$) generally increases as the radius decreases, due to increasing average $D_m$ (Figure 2a), so the eyewall (outer-rainband) CR has the largest (smallest) $A$. The $Z-R$ relationship of outer-rainband CR in this study is in close agreement with the result in Bao et al. (2019), whereas the $A$ of inner-rainband CR in this study is smaller than that in...
Bao20. This may be because CR samples (with large \(D_m\)) between RMW and 1.5 RMW are not included in the inner-rainband CR in this study (Figure 2a). Note that this is the first report of such a large value of coefficient \(A\) in the eyewall CR. Thus, the composite \(Z-R\) relationship derived from climatological RSD characteristics might smooth the different \(Z-R\) relationships in various rain regions of a TC. If a composite \(Z-R\) relationship is used to quantitatively estimate rain in a TC like Lekima, it is therefore likely to result in considerable QPE errors.

Corresponding to the different RSD characteristics in the eyewalls and spiral rainbands of Lekima (Figure 2), different \(\mu-A\) relationships are demonstrated by Figure 3d. The best fit curve for the eyewall CR not only has greater slope, but the slope also increases slightly with \(A\), which has not been presented in previous studies. The increasing slope means the eyewall CR has a larger \(\mu\) for a given \(A\) as \(A\) increases (Figure 3d), related to a higher concentration of large raindrops. Thus, it is strongly suggested that a variable \(\mu-A\) relationship should be utilized to retrieve polarimetric variables in different rain regions of a TC in future when using CINRAD/SA radars that are being (or have been) upgraded with dual-polarization capability (Zhang et al., 2019).

### 3.4. Impact of RSD on Rain Rate

The calculation of integral rain rate depends on both raindrop diameter and concentration. Figures 4a and 4b demonstrates that the average \(D_m\) and \(\log_{10}N_w\) increase generally with increasing rain rate in all three rain regions of Lekima. The average \(D_m\) appears to decrease with increasing radius; the eyewall CR has the largest average \(D_m\) for each rain rate class (Figure 4a). The average \(\log_{10}N_w\) is largest in the
outer-rainband CR in all rain rate classes (Figure 4b). The values of inner-rainband CR lies mostly between those of the eyewall and outer-rainband CR.

In agreement with the viewpoint of Bao20 that the growth of raindrop concentration makes the dominant contribution to the increase of rain rate for convection with low raindrop concentration at the initial stage, the growth rate of average log$_{10}$N$_w$ ($D_m$) with increasing rain rate in the eyewall CR is larger (smaller) than that in the outer-rainband CR (Figures 4a and 4b). Particularly from 20–30 to 30–40 mm hr$^{-1}$, the average log$_{10}$N$_w$ in the eyewall CR increases notably, and also from 30–40 to 40–50 mm hr$^{-1}$ in the inner-rainband CR (Figure 4b). Once the rain rate exceeds 50 mm hr$^{-1}$, however, the log$_{10}$N$_w$ almost no longer increases, and even decreases.

Figure 4c shows many samples with large log$_{10}$N$_w$ and small $D_m$ (small log$_{10}$N$_w$ and large $D_m$) in the outer-rainband (eyewall) CR at 30–50 mm hr$^{-1}$. Once the rain rate exceeds 50 mm hr$^{-1}$, however, most samples are concentrated in the inner rainbands, and in a range of $D_m$ of 2.0–3.5 mm and log$_{10}$N$_w$ of 3.7–4.3 mm$^{-1}$ m$^{-3}$ (Figures 2a and 4c). This suggests that neither log$_{10}$N$_w$ nor $D_m$ in the outer-rainband and eyewall CR can be too large or too small for the production of intense rain rate (>50 mm hr$^{-1}$), because the occurrence of intense rain rate requires appropriate raindrop diameter and corresponding concentration as noted by Bao20.

The raindrops with 2–3 mm diameter make the maximum contribution to each rain rate class, whereas the contribution of small raindrops (<1 mm) is minimal (Figure 4d). This confirms major contribution of mid-size drops to the rain rate in moderate-to-heavy rain (Tokay et al., 2008). The lack of low-level and midlevel updraft over the outer-rainband region as noted by previous studies (Li & Wang, 2012; Wang, 2012) allows small raindrops to fall directly to the ground to yield high raindrop concentration of outer-rainband CR (Figure 3b), but their contribution to the rain rate is relatively small (Figure 4d). Raindrops with 1–2 mm diameter appear to make almost the same contribution as those with 2–3 mm diameter at 20–30 mm hr$^{-1}$ in the outer-rainband CR. As the rain rate increases, however, the contribution of raindrops ≥2 mm increases, which skews the peak contribution toward larger raindrop diameter.

In the eyewall CR, the contribution of raindrops ≤2 mm at 20–30 mm hr$^{-1}$ is markedly smaller than that in the outer-rainband CR (Figure 4d), because there are more raindrops ≥2 mm (Figure 3b). Although the contribution of raindrops ≥3 mm to each rain rate in the eyewall CR is greater than that in the outer-rainband CR, it still does not exceed the contribution of raindrops with 2–3 mm diameter. The effect of the RSD in the inner-rainband CR lies between that in the eyewall and outer-rainband CR. The dominant contribution of raindrops with 2–3 mm diameter in all three rain regions may also be associated with a balance between raindrop coalescence (increasing raindrop size and decreasing concentration) and breakup (decreasing raindrop size and increasing concentration) as proposed by previous studies (D’Adderio et al., 2018; Low & List, 1982; Schlottke et al., 2010), characterized by a bimodal RSD with peaks at <0.5 and 2–3 mm.

In summary, neither log$_{10}$N$_w$ nor $D_m$ can be too large or too small for intense TC rain rate. Once the raindrops reach a large enough size through coalescence growth, they will break up to give a large concentration of tiny raindrops that make a relatively small contribution to the rain rate. This ultimately leads to a decrease in the concentration of large raindrops, and increase in concentration of small raindrops. Meanwhile, the increase or maintenance of large raindrops in convection requires a certain magnitude of updraft (Kumjian & Ryzhkov, 2012), which will lift small raindrops upward or hold them aloft to be collected by falling large raindrops through collision-coalescence process. Collision-coalescence growth, collisional breakup and size sorting by updraft produce an equilibrium RSD, which eventually constrains the unlimited growth of raindrop diameter and concentration in TCs. This also explains why the distribution of $D_m$ (or log$_{10}$N$_w$) narrowed with increasing rain rate in previous studies (Chang et al., 2009; Wen et al., 2018) and why the concentration rises sharply at a diameter near 2 mm in Figure 3b.

4. Summary

Based on ~26 hr of measurement from 17 Thies disdrometers before Super Typhoon Lekima (2019) made landfall in eastern China, this study has presented different convective RSD characteristics in the eyewalls and various spiral (inner and outer) rainbands of Lekima. Distinctive shape-slope ($\mu$-A) and
reflectivity-rain rate (Z-R) relationships have, for the first time, been derived from the unique convective RSD of the eyewall.

In general, the average mass-weighted diameter $D_m$ (mm) in each of the eyewall, inner-rainband and outer-rainband convective rain (CR) decreases radially from the TC center, whereas the average normalized concentration $\log_{10}N_m$ (mm$^{-1}$ m$^{-3}$) increases. Explicitly, the eyewall CR has larger average $D_m$ and smaller average $\log_{10}N_m$ than the outer-rainband CR, due to higher concentrations of raindrops ≥ 3 mm and lower concentrations of raindrops ≤ 1 mm, while the values of the inner-rainband CR lie in between.

Note, however, that most rain samples with an intense rain rate >50 mm hr$^{-1}$ are concentrated in the convection-dominated portion (upwind end) of inner rainbands, in a range of $D_m$ of 2.0–3.5 mm and $\log_{10}N_m$ of 3.7–4.3 mm$^{-1}$ m$^{-3}$ in this study. To explain why, an equilibrium RSD associated with collision-coalescence growth, collisional breakup and size sorting is proposed as a constraint on the growth of $D_m$ and $\log_{10}N_m$ with increasing rain rate. This means the production of intense rain rate requires appropriate raindrop diameter and corresponding concentration, namely, neither of them can be too large or too small (like in the eyewall or outer-rainband CR).

Many results in this study are from surface disdrometer data, so additional verification is required using additional observations in future work, for example, dual-polarization radar observations. However, inevitable retrieval errors will be introduced when using a uniform µ-A relationship derived from a composite climatological RSD for dual-polarization radar observation in TCs like previous studies. Thus, a variable µ-A relationship is strongly suggested to be used for polarimetric retrieval in various rain regions of a TC in the future.

**Data Availability Statement**

The radar CAPPI and disdrometer data are available online (https://pan.stc.org.cn/f/a044804c9e2c4e1c8ba0/).

**References**

Angulo-Martínez, M., Beguería, S., Latorre, B., & Fernández-Raga, M. (2018). Comparison of precipitation measurements by OTT Parsivel2 and Thies LPM optical disdrometers. *Hydrology and Earth System Sciences*, 22, 1–37.

Atlas, D., Srivastava, R. C., & Seshadri, R. S. (1973). Doppler radar characteristics of precipitation at vertical incidence. *Reviews of Geophysics*, 11, 1–35.

Bao, X., Wu, L., Tang, B., Ma, L., Wu, D., Tang, J., et al. (2019). Variable raindrop size distributions in different rainbands associated with Typhoon Flovo (2013). *Journal of Geophysical Research: Atmospheres*, 124, 12,626–12,631. https://doi.org/10.1029/2019JD036268

Bao, X., Wu, L., Zhang, S., Li, Q., Lin, L., Zhao, B., et al. (2020). Distinct raindrop size distributions of convective inner- and outer-rainband rain in Typhoon Maria (2018). *Journal of Geophysical Research: Atmospheres*, 125, e2020JD032482. https://doi.org/10.1029/2020JD032482

Black, M. L., Burpee, R. W., & Marks, F. D. Jr. (1996). Vertical motion characteristics of tropical cyclones determined with airborne Doppler radial velocities. *Journal of the Atmospheric Sciences*, 53, 1887–1909.

Black, M. L., & Willoughby, H. E. (1992). The concentric eyewall cycle of Hurricane Gilbert. *Monthly Weather Review*, 120, 947–957.

Brauer, N. S., Basara, J. B., Homeyer, C. R., McFarquhar, G. M., & Kirstetter, P. E. (2020). Quantifying precipitation efficiency and drivers of excessive precipitation in post-landfall Hurricane Harvey. *Journal of Hydrometeorology*, 21, 433–452.

Brawn, D., & Upton, G. (2008). On the measurement of atmospheric gamma drop-size distributions. *Atmospheric Science Letters*, 9, 245–247.

Bringi, V. N., Chandrasekar, V., Hubbert, J., Gorgucci, E., Randeu, W. L., & Schoenhuber, M. (2003). Raindrop size distribution in different climatic regimes from disdrometer and dual-polarized radar analysis. *Journal of the Atmospheric Sciences*, 60, 354–365.

Chan, K. T. F., & Chan, J. C. L. (2016). Sensitivity of the simulation of tropical cyclone size to microphysics schemes. *Advances in Atmospheric Sciences*, 33, 1024–1035.

Chang, W.-Y., Wang, T.-C. C., & Lin, P.-L. (2009). Characteristics of the raindrop size distribution and drop shape relation in typhoon systems in the Western Pacific from the 2D video disdrometer and NCU C-band polarimetric radar. *Journal of Atmospheric and Oceanic Technology*, 26, 1973–1993.

Chen, B., Wang, Y., & Ming, J. (2012). Microphysical characteristics of the raindrop size distribution in Typhoon Morakot (2009). *Journal of Tropical Meteorology*, 18, 162–171.

Chen, Y.-C., Chang, K.-T., Chiu, Y.-J., Lau, S.-M., & Lee, H.-Y. (2013). Quantifying rainfall controls on catchment-scale landslide erosion in Taiwan. *Earth Surface Processes and Landforms*, 38, 372–382.

Chu, Z., Yin, Y., & Gu, S. (2013). Characteristics of velocity ambiguity for CINRAD-SA Doppler weather radars. *Asia-Pacific Journal of Atmospheric Sciences*, 49, 1–7.

Czajkowski, J., Villarini, G., Michel-Kerjan, E., & Smith, J. A. (2013). Determining tropical cyclone inland flooding loss on a large scale through a new flood peak ratio-based methodology. *Environmental Research Letters*, 8, 044056. https://doi.org/10.1088/1748-9326/8/4/044056

D’Adderio, L. P., Porcu, F., & Tokay, A. (2018). Evolution of drop size distribution in natural rain. *Atmospheric Research*, 200, 70–76.
Deo, A., & Walsh, K. J. E. (2016). Contrasting tropical cyclone and non-tropical cyclone related rainfall drop size distribution at Darwin, Australia. *Atmospheric Research, 181*, 81–94.

Didlake, A. C. Jr., Heymsfield, G. M., Reasor, P. D., & Guimond, S. R. (2017). Concentric eyewall asymmetries in Hurricane Gonzalo (2014) observed by airborne radar. *Monthly Weather Review, 145*, 729–749.

Didlake, A. C. Jr., & Houze, R. A. Jr. (2013a). Convective-scale variations in the inner-core rainbands of a tropical cyclone. *Journal of the Atmospheric Sciences, 70*, 504–523.

Didlake, A. C. Jr., & Houze, R. A. Jr. (2013b). Dynamics of the stratiform sector of a tropical cyclone rainband. *Journal of the Atmospheric Sciences, 70*, 1891–1911.

Frasson, R. P. M., da Cunha, L. K., & Krajewski, W. F. (2011). Assessment of the Thies optical disdrometer performance. *Atmospheric Research, 101*, 237–255.

Friedrich, K., Higgins, S., Masters, F. J., & Lopez, C. R. (2013). Articulating and stationary PARSIVEL disdrometers. *Journal of Hydrometeorology, 14*, 352–370.

Janapati, J., Seela, B. K., Reddy, M. V., Reddy, K. K., Lin, P.-L., Rao, T. N., & Liu, C.-Y. (2017). A study on raindrop size distribution variability in before and after landfall precipitation of tropical cyclones observed over southern India. *Journal of Atmospheric and Solar-Terrestrial Physics, 159*, 23–40.

Khain, A., Lynn, B., & Shpund, J. (2016). High resolution WRF simulations of Hurricane Irene: Sensitivity to aerosols and choice of microphysical schemes. *Atmospheric Research, 167*, 129–145.

Kim, J.-H., Ou, M.-L., Park, J.-D., Morris, K. R., Schwaller, M. R., & Wolff, D. B. (2014). Global precipitation measurement (GPM) ground validation (GV) prototype in the Korean Peninsula. *Journal of Atmospheric and Oceanic Technology, 31*, 1902–1921.

Kumjian, M. R., & Rythkov, A. V. (2012). The impact of size sorting on the polarimetric radar variables. *Journal of the Atmospheric Sciences, 69*, 2042–2060.

Li, J., Wang, G., Lin, W., He, Q., Feng, Y., & Mao, J. (2013). Cloud-size simulation study of TC Hagupit (2008). Part II: Impact of cloud microphysical latent heat processes on TC intensity. *Atmospheric Research, 120*, 202–215.

Li, Q., & Wang, Y. (2012). A comparison of inner and outer spiral rainbands in a numerically simulated tropical cyclone. *Monthly Weather Review, 140*, 2782–2805.

Low, T. B., & List, R. (1982). Collision, coalescence and breakup of raindrops. Part I: Experimentally established coalescence efficiencies and fragment size distributions in breakup. *Journal of the Atmospheric Sciences, 39*, 1591–1606.

Marshall, J. S., & Palmer, W. M. (1948). The distribution of raindrops with size. *Journal of Meteorology, 5*, 165–166.

May, P. T., Kepert, J. D., & Keenan, T. D. (2008). Polarimetric radar observations of the 873 persistently asymmetric structure of Tropical Cyclone Ingrid. *Monthly Weather Review, 136*, 616–630.

Milbrandt, J., & Yau, M. (2005). A multimoment bulk microphysics parameterization. Part II: A proposed three-moment closure and scheme description. *Journal of the Atmospheric Sciences, 62*, 3065–3081.

Montgomery, M. T., & Killenbach, R. J. (1997). A theory for vortex Rossby-waves and its application to spiral bands and intensity changes in hurricanes. *Quarterly Journal of the Royal Meteorological Society, 123*, 435–465.

Moon, Y., & Nolan, D. S. (2015). Spiral rainbands in a numerical simulation of Hurricane Bill (2009). Part I: Structures and comparisons to observations. *Journal of the Atmospheric Sciences, 72*, 164–190.

Rappaport, E. N. (2014). Fatalities in the United States from Atlantic tropical cyclones: New data and interpretation. *Bulletin of the American Meteorological Society, 95*, 341–346.

Rogers, R., Reasor, P., & Lorsolo, S. (2013). Airborne Doppler observations of the inner-core differences between intensifying and steady-state tropical cyclones. *Monthly Weather Review, 141*, 2970–2991.

Schlottke, J., Straub, W., Beheng, K., Gomaa, H., & Weigand, B. (2010). Numerical investigation of collision-induced breakup of raindrops. Part I: Methodology and dependencies on collision energy and eccentricity. *Journal of the Atmospheric Sciences, 67*, 557–575.

Seela, B. K., Janapati, J., Lin, P.-L., Wang, P. K., & Lee, M.-T. (2018). Raindrop size distribution characteristics of summer and winter season rainfall over north Taiwan. *Journal of Geophysical Research: Atmospheres, 123*, 11,602–11,624. https://doi.org/10.1029/2018JD028307

Thies Clima (2007). Instructions for use: Laser precipitation monitor 5.4110.xx.x00 V2.4x STD. Adolph Thies GmbH and Co., 64 p.

Tokay, A., Bashor, P. G., Habib, E., & Kasparis, T. (2008). Raindrop size distribution measurements in tropical cyclones. *Monthly Weather Review, 136*, 1669–1685.

Ulbrich, C. W. (1983). Natural variations in the analytical form of the raindrop size distribution. *Journal of Climate and Applied Meteorology, 22*, 1764–1775.

Ulbrich, C. W., & Lee, L. G. (2002). Rainfall characteristics associated with the remnants of tropical storm Helene in upstate South Carolina. *Weather and Forecasting, 17*, 1257–1267.

Wang, M., Zhao, K., & Wu, D. (2011). The T-TREC technique for retrieving the winds of landfalling typhoons in China. *Acta Meteorologica Sinica, 25*, 91–103.

Wang, M., Zhao, K., Xue, M., Zhang, G., Liu, S., Wang, L., & Chen, G. (2016). Precipitation microphysics characteristics of a Typhoon Matmo (2014) rainband after landfall over eastern China based on polarimetric radar observations. *Journal of Geophysical Research: Atmospheres, 121*, 12,415–12,433. https://doi.org/10.1002/2016JD025307

Wang, Y. (2009). Do outer spiral rainbands affect tropical cyclone structure and intensity? *Journal of the Atmospheric Sciences, 66*, 1250–1273.

Wang, Z. (2012). Thermodynamic aspects of tropical cyclone formation. *Journal of the Atmospheric Sciences, 69*, 2433–2451.

Wen, L., Zhao, K., Chen, G., Wang, M., Zhou, B., Huang, H., et al. (2018). Drop size distribution characteristics of seven typhoons in China. *Journal of Geophysical Research: Atmospheres, 123*, 6529–6548. https://doi.org/10.1029/2017JD027950
Williams, G. J. (2019). The effects of ice microphysics on the inner core thermal structure of the hurricane boundary layer. *Meteorology and Atmospheric Physics, 131*, 987–1003.

Willoughby, H. E. (1988). The dynamics of the tropical hurricane core. *Australian Meteorological Magazine, 36*, 183–191.

Wolff, D. B., Petersen, W. A., Tokay, A., Marks, D. A., & Pippitt, J. L. (2019). Assessing dual confidential polarization radar estimates of extreme rainfall during Hurricane Harvey. *Journal of Atmospheric and Oceanic Technology, 36*, 2501–2520.

Wu, T., Wan, Y., Wo, W., & Leng, L. (2013). Design and application of radar reflectivity quality control algorithm in SWAN. *Meteorological Science and Technology, 41*, 809–817. (in Chinese with an English abstract)

Zhang, D., Liu, Y., & Yau, M. K. (2001). A multiscale numerical study of Hurricane Andrew (1992). Part IV: Unbalanced flows. *Monthly Weather Review, 129*, 92–107.

Zhang, G. (2015). Comments on “Describing the Shape of Raindrop Size Distributions Using Uncorrelated Raindrop Mass Spectrum Parameters”. *Journal of Applied Meteorology and Climatology, 54*, 1970–1976.

Zhang, G., Vivekanandan, J., Brandes, E. A., Meneghini, R., & Kozu, T. (2003). The shape-slope relation in Gamma raindrop size distribution: Statistical error or useful information? *Journal of Atmospheric and Oceanic Technology*, 20, 1106–1119.

Zhang, G. F., Mahale, V. N., Putnam, B. J., Qi, Y., Cao, Q., Byrd, A. D., et al. (2019). Current status and future challenges of weather radar polarimetry: Bridging the gap between radar meteorology/hydrology/engineering and numerical weather prediction. *Advances in Atmospheric Sciences, 36*(6), 571–588. https://doi.org/10.1007/s00376-019-8172-4

Zhang, Q., Liu, Q., & Wu, L. (2009). Tropical cyclone damages in China 1983–2006. *Bulletin of the American Meteorological Society, 90*, 489–495.