

Response to Reviewer #1

Overall comments:

The authors present a well-designed study of DSD over a dense urban area. The results can advance our understanding of rainfall microphysics and improve radar QPE in urban areas. There are some places in the manuscript that need further clarification, but other than that, this is a well-written paper and can be accepted after revision. My specific comments are listed below (not necessarily in order of importance).

Response: We thank the reviewer for the kind words. We appreciate the reviewer's time and effort spent on our manuscript. We have carefully revised this manuscript based on the reviewer's comments. In the text below we quote the reviewers' comments verbatim and we follow them with our detailed responses in red.

Specific comments:

1. Please explain the meaning of $\log_{10}N_w$ and D_m on their first occurrence.

Response: We thank the reviewer for this suggestion. $\log_{10}N_w$ is the normalized intercept parameter of the Gamma model of raindrop size distribution, whereas D_m is the mass-weighted mean diameter (Bringi and Chandrasekar, 2001). We have clarified this in the revision (page 1, line 16 in the clean version): *"The mean values of the normalized intercept parameter ($\log_{10}N_w$) and the mass-weighted mean diameter (D_m) of convective rain are higher than that of stratiform rain, and there is a clear boundary between the two types of rain in terms of the scattergram of $\log_{10}N_w$ versus D_m ."*

2. The Introduction needs to be further strengthened. It seems that this study only differs from previous studies simply through using a long-term dataset, as can be inferred from the current version, which is actually not.

Response: We thank the reviewer for this great advice. We totally agree with the reviewer that this study differs from previous studies not only on the utilization of long-term raindrop size distribution data, but also the detailed analysis. For example, the impacts of urban heat island (UHI) effect on rainfall microphysical properties have never been studied in the literature. We have clarified this in the revision. Motivated by the reviewer's comment, we have also extensively revised the introduction section of this manuscript.

3. I would suggest not to mention "local microphysics" in P2, Line 4, as apparently this present study does not provide much interpretation of rainfall microphysics. The main objective is for better characterizations of DSD in urban region and potential improvement for radar QPE.

Response: We thank the reviewer for the comment. We have rewritten the introduction as suggested, although we would like to note that the characteristics of DSD are among the most important microphysical properties of local precipitation.

4. P1, Line 21, what does "UHI up stage of a day" mean? Please clarify.

Response: We thank the reviewer for pointing this out. Basically, "UHI up stage of a day" means a stage characterized by an abrupt rise of urban heat island intensity of a day (Yang et al., 2013). We have clarified this in the revision (page 1, line 21-22, in the clean version), now this sentences read: *In addition, at the stage characterized by an abrupt rise of urban heat island (UHI) intensity as well as the stage of strong UHI intensity during the day, DSD shows*

higher D_m values and lower $\log_{10}N_w$ values.”

5. Since there is a dual-pol radar collocated with the disdrometer, I wonder how the dual-pol radar fields are utilized in this study. The dual-pol fields used in this study are simulated using the T-matrix method. How accurate is the simulation?

Response: We thank the reviewer for this great comment. Unfortunately, the dual-pol radar has not been deployed during this study period. There is another dual-pol radar nearby, which is managed by Beijing Meteorological Bureau (BMB). But that radar is still suffering from signal processing and data quality issue. In this study, we meant to use the simulated dual-polarized radar fields to derive the rainfall estimators, in support of the future operational X-band radar applications. The simulation is based on real raindrop size distribution data collected by the disdrometer. In particular, the scattering properties of raindrops are computed using T-matrix method (Leinonen, 2014). The accuracy of computation is $1e-3$. In fact, the simulated fields as such are often used to calibrate and validate real radar (remote sensing) measurements since they are considered *in situ* measurements.

6. Hail contamination remains a challenge for radar QPE. However, this is how dual-pol radar can surpass conventional radar (using the KDP field). It seems strange to me that the authors remove hail from all their records, as this will degrade the significance of their study. Please justify.

Response: We thank the reviewer for this very good question. There are two main issues in radar quantitative precipitation estimation. One is the derivation of theoretical or experimental radar rainfall relations, and the other is real application of the derived relations. In general, only the liquid rain should be included in the algorithm development (since the ultimate goal is to conduct rainfall estimation). That is why the hail contaminated data are eliminated in the theoretical analysis.

In real applications, in order to get the liquid rainfall estimates especially from the rain-hail mixture (i.e., with hail contaminations), the *R-KDP* relations are suggested since they are not sensitive to hail compared to reflectivity *Z*. In such cases, reflectivity values, as a power term, are often very large (higher than 55 dBZ) due to hail contamination, which will lead to an overestimation of rain. On the contrary, *KDP*, as a phase term, is directly related to the liquid water content, and we can get more accurate rainfall rates using the *R-KDP* relationship. However, the choice of *R-KDP* in real applications does not mean we would need to include the hail contamination data in the derivation of theoretical algorithms. In addition, we would like to focus on the liquid rainfall properties in this study. Hail and/or winter precipitation such as snow will be investigated in future studies. We have clarified this in the revision.

7. The threshold of 5 mm/h for separating convective and stratiform rainfall is small compared to previous studies. Please justify.

Response: We thank the reviewer for pointing this out. To separate convective and stratiform rainfall, we use a combination of two thresholds, i.e., rain rate and the standard deviation of rain rate. This method has been widely used in previous studies. In particular, a threshold of 1.5mm/h on the standard deviation of rain rate is often used, and a threshold of 1.5 mm/h (Wen et al., 2019;Wen et al., 2016) or 5 mm/h (Brongi et al., 2003;Chen et al., 2013;Seela et al., 2017;Seela et al., 2018;Tang et al., 2014;Wen et al., 2017) or 10 mm/h (Marzano et al., 2010;Testud et al., 2001;Thurai et al., 2010) on rain rate is often used. In most studies in China,

the threshold of 5 mm/h is applied (Chen et al., 2013; Seela et al., 2017; Tang et al., 2014; Wen et al., 2017). In addition, the early and end stages of convective rain may be excluded from the dataset if a threshold of 10 mm/h is adopted, since the rain rates at the beginning or near ending of a convective storm are likely less than 10 mm/h (Chen et al., 2013). Based on this, we decide to use the threshold of 5 mm/h in the separation analysis.

8. Please remove the texts P7, Lines 9-12. They can be moved to the caption of Figure 5. Similarly for P9, Lines 4-6.

Response: We thank the reviewer for this suggestion. We totally agree with the reviewer. Changed as suggested!

9. Figure 5, caption, what does “shallow events” mean? Please explain

Response: We thank the reviewer for pointing this out. Shallow precipitation is a third type of precipitation besides convective and stratiform suggested by a few researchers, based on data from vertically pointing radar observations. “Shallow events” are typically characterized by low cloud top (below 0 °C isotherm) and weak rainfall rate (Fabry and Zawadzki, 1995; Cha et al., 2009). We have clarified this in the revision (page 26, line 9-10, in the clean version).

In the study by Wen et al. (2016), they used the vertical profile of reflectivity from Micro Rain Radar (MRR) and DSDs from the 2DVD to identify the shallow events. In that study, the top of radar echo of shallow rain is too low to reach the melting layer, which means that the precipitation forms directly in liquid form and no melting is present (Fabry and Zawadzki, 1995; Cha et al., 2009). The corresponding DSDs of this shallow rain have a relatively small maximum diameter and high concentration of raindrops with small diameters, indicating distinctions among the microphysical processes of the three precipitation types. In our study, due to the lack of vertical measurements, we focus on the convective and stratiform precipitation.

10. Figure 5 and texts, I’m not sure if it is reasonable to compare this study with previous studies, as clearly this study present climatological features of DSD, while the referenced studies seem to be event-based.

Response: We thank the reviewer for raising this concern. Although previous studies seem event-based, they essentially represent the local climatology and microphysics of different precipitation types. Therefore, we believe it is useful to conduct such comparison. In addition, this study provides new evidence from Asia (northern China) to further support the DSD analysis in the mid-latitudes.

11. I would suggest to present frequency distribution of rain rates among different UHI stages, along with DSD parameters in Figure 9. As the authors explained differences of DSD parameters for different rain rates in previous section, differences of DSD parameters among UHI stages might be simply due to rain rate differences. This suggestion also applies for the analysis of seasonal cycle in section 3.5.

Response: We thank the reviewer for this great suggestion. We have revised the manuscript as suggested. In particular, the frequency distribution of rain rates for different UHI stages and different months is supplemented. Descriptions of these two parts have been rephrased as follows: “The DSD spectra of different diurnal periods are quite similar to those of different rain rate classes, showing a unimodal shape and peak position at the diameter $D \sim 0.5$ mm.

It is notable that the DSD spectra are almost the same at small drop size bins ($D < 1$ mm) and have the same width. As the diameter becomes larger, variations in the DSD spectra start showing up. The DSD spectra of S UHI stage and UHI U stage show similar and higher concentration, whereas the DSD spectra of W UHI stage and UHI D stage have similar but lower concentration, indicating that during the UHI U stage and S UHI stage, high-intensity rainfall is more likely to occur. This is in line with the study in Yang et al. (2017), which showed that the short term high-intensity rainfall was more likely to happen at the UHI U stage and end at the late S UHI stage. The frequency and variation of rain rate for different UHI stage (see Fig. S2) can also indicate this point.”

“As shown in Fig. 11, all the DSD spectra have a peak at diameter $D \sim 0.5$ mm, which are consistent with other classifications in this study. The DSD in May has a relatively higher concentration while a relatively lower concentration in July. At small drop size bins ($D < 1$ mm), the spectra for May and September are similar, while the spectra for other four months are similar. As the diameter increases, the differences between these spectra become larger, and the DSD spectrum for July has the highest concentration and October the lowest concentration. The rainfall with higher concentration and large drops is more likely to happen in July, leading to a high rain rate intensity (see also Fig. S3). ”

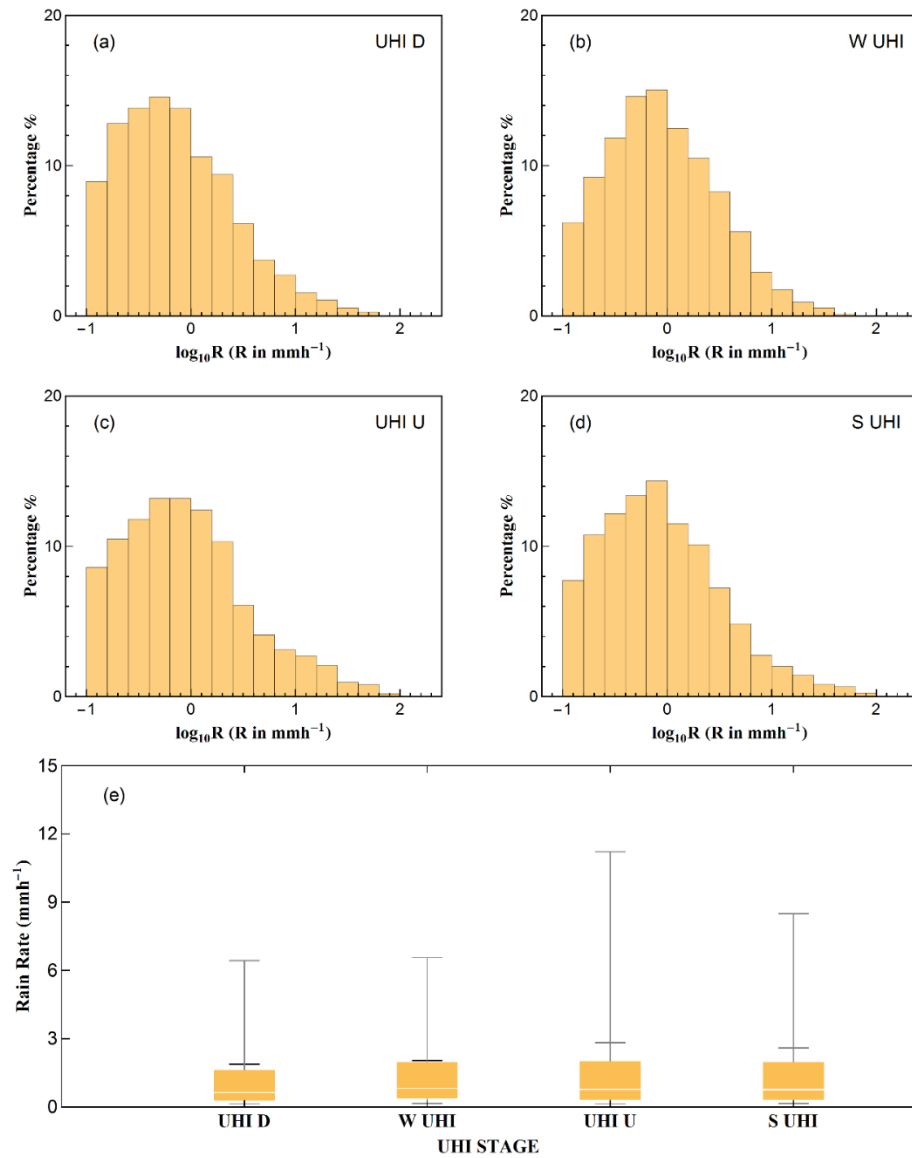


Figure S2: Histograms of rain rate $\log_{10}R$ (R in mm h^{-1}) at different UHI stages: (a) UHI down stage; (b) weak UHI stage; (c) UHI up stage; (d) strong UHI stage; (e) variation of rain rate R (mm h^{-1}) for different UHI stages. The white central lines in the boxes indicate the medians. The black central lines indicate the means, and the bottom and top lines of the box indicate the 25th and 75th percentiles, respectively. The bottom and top lines of the vertical lines out of the box indicate the 5th and 95th percentiles, respectively.

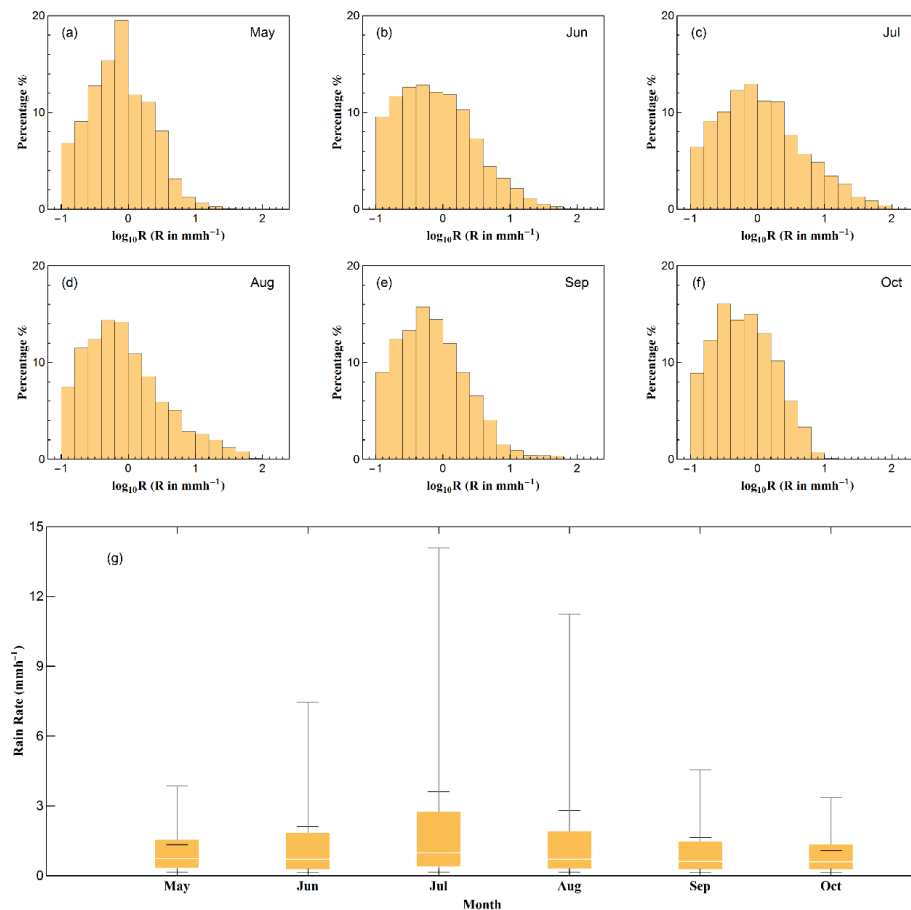


Figure S3: Same as Figure S2, but for different months.

12. Grammar and wording need double check. There are some typos throughout the manuscript, for instance, “PI, Line 34, warn should be warm”, etc

Response: We appreciate the reviewer’s careful reading of this manuscript. We have double checked the Grammar and wording issues in this manuscript. We have also asked a colleague (a native English speaker) to perform an additional internal review of this manuscript.

References:

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General Comments:

In summary, this study analyzed the statistical characteristics of raindrop size distribution (DSD) during rainy seasons (May-October) in Beijing based on a 5-year observation (2014-2018) from a Parsivel2 disdrometer deployed at Tsinghua University, compared the differences in diameter and concentration between rain types, rainfall intensity, urban heat island (UHI) stages and months, and finally explored its implications for two types of radar rainfall estimations. The manuscript is overall detailed and well written with analysis of DSD parameters and suggestions for precipitation forecast, while it has some minor problems and lacks further explanation of precipitation micro physics. Therefore, I suggest a minor revision and encourage the authors to improve this manuscript. Detailed suggestions are listed below. As I'm not working on this specific researching area, some suggestions may not be suitable for this manuscript, and the authors can decide whether or not to accept them.

Response: We thank the reviewer for the kind words. We appreciate all the valuable comments and suggestions provided by the reviewer. We have carefully revised this manuscript based on the reviewer's comments. In the text below we quote the reviewers' comments verbatim and we follow them with our detailed responses in red.

Major Comments:

1. I've noticed the authors actually show their results together with discussions in Section 3 and 4, while I personally prefer an independent Discussion Section to clarify the differences and significance of this study compared to others on DSD characteristics in Beijing (and other cities). For example, the authors derived an opposed conclusion referred to Wen and Zhang's work (P7 L10), and it would be better if the authors mark their observation locations in Fig. 1(b), explain the differences in physical mechanism and show detailed possible causes.

Response: We thank the reviewer for this great suggestion. We have mark the observation locations in Wen et al., (2017) and Ji et al., (2019) in Beijing in fig. 1. The study by Tang et al. (2014) did not detail their disdrometer position clearly, just with a description of position: "Beijing".

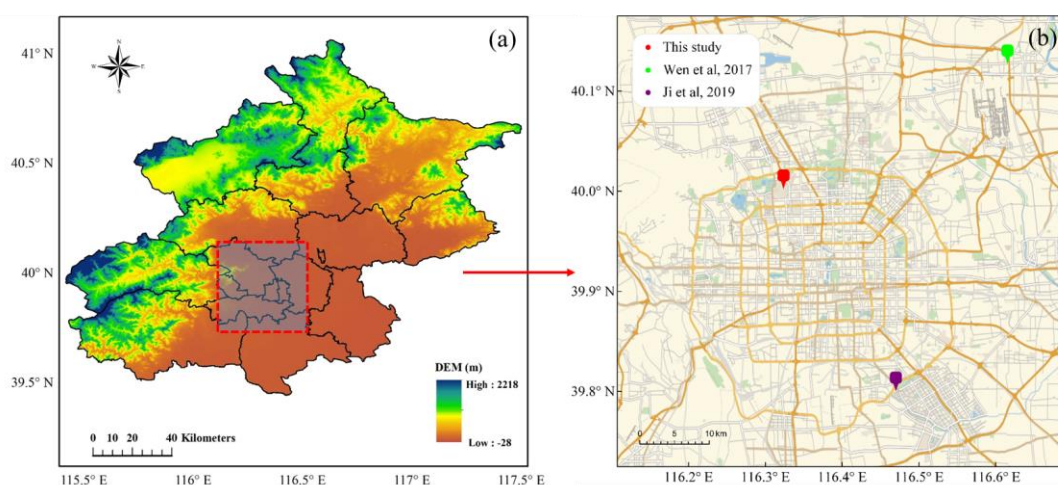


Figure 1: (a) the topography of Beijing, (b) the locations of DSD studies in Beijing area, the red mark represents the location of Parsivel² disdrometer deployed at Tsinghua University

campus in this study, the green and purple makers represent locations in the studies by Wen et al., (2017) and Ji et al., (2019), respectively.

The comparison of DSDs in different part of China (i.e., North China, East China, and South China) are indicated in Fig. 5. Even in the same region, the DSDs measured by different instruments have notable differences, such as the differences in Beijing between results from Wen et al. (2017) (2DVD, circle) and Tang et al. (2014) (Parsivel, square). In order to reduce the errors caused by different measurement instruments, in our study, only DSDs measured by Parsivel disdrometers are analyzed. It is concluded that the east part of China has the lowest mean value of $\log_{10}N_w$ (3.42) with highest mean value of D_m (1.66), while southern China has the highest mean value of $\log_{10}N_w$ (3.86) with middle value of D_m (1.46), and the north part of China has the middle value of $\log_{10}N_w$ (3.60) with lowest value of D_m (1.15). There are also differences between Beijing in this study and studies in other parts of China (Wen et al. (2016) in eastern China and Zhang et al. (2019) in southern China). These differences indicates that the DSD characteristics are highly correlated to the specific geographical locations and associated climate regimes.

For Beijing area, the results of this study and Tang et al. (2014) show great differences in convective rain and less differences in stratiform rain. These may be attributed to different convective systems during different years, and the limited measurements from only one season in the study by Tang et al. (2014), which are not sufficient to represent local DSD characteristic. However, we want to note that the detailed comparison in microphysical mechanisms of rainfall is not the main focus of this study, although results from previous studies are briefly summarized. As mentioned, this study presents more of climatological features of local DSD in Beijing, while the referenced studies seem to be event-based. More data would be required to resolve the detailed differences in physical mechanism, which can be a good future study.

2. Abstract Section. I suggest the authors should first clarify the meanings before using symbols or abbreviations such as D_m and $\lg N_w$ when showing results in Abstract Section. In addition, although P4 L15 defined N_w as “normalized intercept parameter”, I have not found its clear physical meaning which expected to be similar to N_t , the total number concentration.

Response: We thank the reviewer for this very important comment. D_m is the mass-weighted mean diameter and $\log_{10}N_w$ is the normalized intercept parameter of a Gamma model of raindrop size distribution (Bringi and Chandrasekar, 2001). We have clarified this in the Abstract Section (P1 line 16 in the clean version). In addition, N_t (m^{-3}) is the total number concentration, representing an integral of the rain drop size distribution at all diameters, and it is different for the distribution parameter N_w ($\text{m}^{-3} \text{mm}^{-1}$). The relationship of these two parameter is:

$$N_t = \int N(D)dD = \int N_w f(\mu) \left(\frac{D}{D_m}\right)^\mu \exp\left[-(4 + \mu)\frac{D}{D_m}\right] dD$$

We have clarified this in the revised manuscript (Page 5, line 4 in the clean version).

3. P6, L15, the authors use specific mean and standard derivation values of rain rate (R) as thresholds to separate convective rain from stratiform rain. However, it seems that R is only related to D spectra considering equation (10) and (3), so in my opinion this classification method is equivalent to solving nonlinear equations and will probably cause the “clear

boundary” in DSD characteristics between rain types mentioned in Abstract Section. The authors should pay attention to the classification method chosen in this study, and it would be better if they obtain more information on rain types from other data sources.

Response: We totally agree with the reviewer that the classification method may cause a “clear boundary” in the DSD characteristics since both R , $\log_{10}N_w$ and D_m are derived from the raindrop size spectra. We can get the relationship among these three parameters with a power law velocity assumption by Atlas and Ulbrich (1977),

$$v(D) = 3.78D^{0.67}; m/s$$

$$R = (0.6 \times 10^{-3}\pi)(3.78)N_w f(\mu)\Gamma(\mu + 4.67) \frac{D_m^{4.67}}{(4 + \mu)^{\mu+4.67}}; mm/h$$

As such, other data sources such as reflectivity profiles are used to classify the rain type in several studies (Cha et al., 2009; Wen et al., 2016). However, it was found that there was no significant differences compared to using R only, and using other data sources may cause different issues since they are not directly related to rainfall intensity (rain rate estimation algorithm should be applied). In addition, since $\log_{10}N_w$ and D_m are different moments of the raindrop spectra compared to the rainfall rate. The “clear boundary” is not really as sharp as one would expect. Provided the ground disdrometer data, the thresholds of mean and standard derivation values are still the most commonly used way to classify rainfall type (Brangi et al., 2003; Chen et al., 2013). Motivated by the reviewer’s comment, we have revised the manuscript by highlighting the potential of using auxiliary data in the classification of different rainfall types (last paragraph Page13 line 30-32, in the clean version): *We also want to note that combining additional observations such as the vertically-pointing profiler radar data (White et al., 2003) can further enhance the classification results of different rainfall types, which should be considered in future studies.*”

4. There is a mistake in Table 5. The correct UHI stage labels in the table should be UHI D, W UHI, UHI U and S UHI, which is consistent with Figure 9 and 10 indicating UHI W stage has the largest mean concentration and lowest D_m .

Response: We apologize for this mistake. We have corrected this in the revision. The corrected version is listed below for the reviewer’s information. Thanks again for pointing this out.

Table 5: Mean and Standard Deviation (SD) Values of R , D_m , $\log_{10}N_w$, N_t , W , μ , and Λ for different diurnal periods based on UHI intensity

	$R(mm\ h^{-1})$		$D_m\ (mm)$		$\log_{10}N_w\ (m^{-3}\ mm^{-1})$		$N_t\ (m^{-3})$		$W\ (g\ m^{-3})$		μ		Λ	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
UHI D	1.88	4.31	1.11	0.42	3.59	0.60	342.15	499.30	0.10	0.19	15.06	13.63	9.32	8.49
W UHI	2.04	4.10	1.10	0.41	3.70	0.58	378.44	398.08	0.12	0.18	15.27	14.48	9.33	8.90
UHI U	2.82	6.94	1.18	0.51	3.57	0.65	380.88	488.27	0.15	0.30	14.09	13.45	8.78	8.45
S UHI	2.60	6.79	1.18	0.46	3.56	0.64	385.00	563.30	0.14	0.30	13.97	13.95	8.61	8.43

5. Figure 13. This figure may mislead the readers as the study focused mainly on low rain rate values (less than 25 mm/h). I suggest the authors should plot it on double logarithmic coordinates, which will make it a linear relationship (i.e. convert $Z=238R^{1.57}$ to $\lg Z=1.57\lg R+\lg 238$). Besides, the derived line for total rainfall are below both convective and stratiform lines for low rain rate values, and the authors should explain this.

Response: We thank the reviewer for this very good suggestion. We agree with the reviewer that the double logarithmic plot for Z - R relationship might be better. We have revised the figure

and rephrased the related descriptions in the main manuscript (From Page 11 line 12-19 in the clean version). The revised figure is repeated here for the reviewer information.

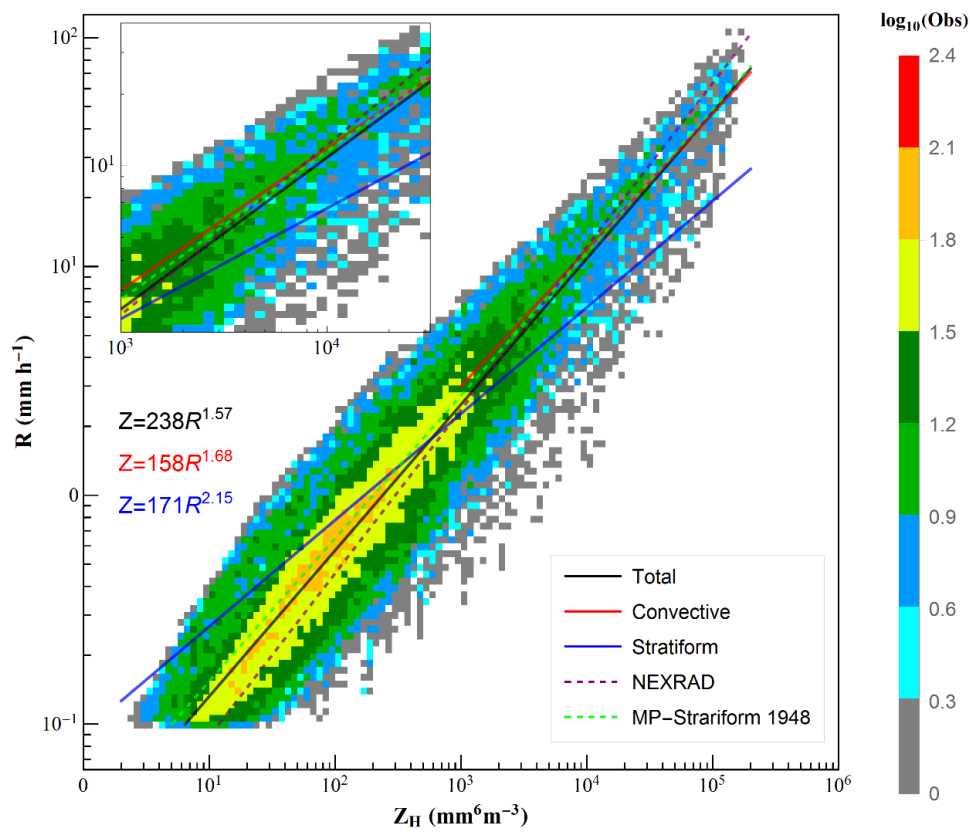


Figure 13: Scatter density plot of R (mm h^{-1}) versus Z_H ($\text{mm}^6 \text{m}^{-3}$) for all rain events. The black, red, and blue curves respectively stand for the fitted power-law relations for total rain, convective rain, and stratiform rain. The purple and green dashed lines denote the default NEXRAD $Z - R$ relation (Fulton et al., 1998) and a commonly used continental stratiform rain relation (Marshall and Palmer, 1948), respectively.

6. Section 4.1 and 4.2. How did the authors figure out the relationship equations (14)-(17)? In my opinion, it is more likely that the uncertainty in parameter values, other than suitability of algorithms, may be the main sources of normalized absolute error (NMAE).

Response: We thank the reviewer for this great comment. The relationships in equations (14)-(17) are derived through nonlinear regression using the least square method. We have clarified this in the revision (page 11, line 29 in the clean version). In the nonlinear fitting processing, we attempted to minimize the uncertainty induced by the parameter values. Such power-law relations are typically used by weather radars for quantitative precipitation estimation. Therefore, the uncertainty in the parameter values are essentially the same with the “suitability” of radar rainfall algorithms (or maybe the reviewer is referring to something else?). This type of uncertainty is also called “parameterization” error (Bringi and Chandrasekar, 2001). The values of *NMAE* can be an indicator of such parameterization error of different algorithms. We have clarified this in the revision (From page 12 line 5-10, in the clean version).

Minor Comments:

7. P2, L19-26. These sentences are weird to read with duplicate words such as “high spatial and temporal variabilities”. I guess the authors here wanted to elaborate the complexity of

measuring and modeling precipitation in Beijing due to its high urbanization (i.e. densely populated) and large heterogeneity (i.e. high spatial and temporal variabilities), and show the significance of analyzing DSD characteristics which could help us to understand urban precipitation. I suggest that the authors should rewrite this part to keep it concise and clear.

Response: We apologize for the possible confusion. We have rephrased these sentences as suggested. Now it reads: *“The rapid urbanization and complex topography have further exacerbated the high variability of precipitation in Beijing urban area, posing challenges to precipitation observations and forecast (Song et al., 2014; Yang et al., 2013a; Yang et al., 2016). This also highlights the importance of understanding local DSD characteristics to better quantify the urban precipitation.”* (page 2, lines 25-28, in the clean version)

8. P2, L21, “: : stations network de Vos et al., 2017”, add “by” after “network”. In addition, I prefer a standard usage of references in the text.

Response: We thank the reviewer for this comment. In the revision, we have added a “by” after “network”. In addition, we have standardized the references and formatting in the text.

9. P2, L22, “monitoring networks : : : have been applied”, here using “established” may be a better choice.

Response: We totally agree with the reviewer. Changed as suggested!

10. P2, L34, “warn” -> “warm”.

Response: Corrected as suggested!

11. P3, L5, “methodologies” -> “methods”.

Response: Changed as suggested!

12. P3, L7. I suggest the word “Section” should be capitalized.

Response: Changed as suggested!

13. P3, L15-17 and L25. From the manuscript, I guess these 32 non-uniform bins are set by THUD and fixed for all rainfall events, leaving the maximum observable diameter to be 24.5 mm. However, P5 L20 mentioned that the biggest raindrops ever reported are around 8 mm. The authors should clearly point it out if the latter diameter value can only represent precipitation in Beijing.

Response: We thank the reviewer for pointing this out. The 32 non-uniform bins are set by the second-generation Particle Size and Velocity (Parsivel²) disdrometer (Löffler-Mang and Joss, 2000) and are fixed for all events. The disdrometer can not only observe raindrops but also other precipitation particles such as hail and snowflakes, which are typically larger than raindrops.

The biggest raindrop ever reported is around 8 mm (Beard et al., 1986; Baumgardner and Colpitt, 1995). Therefore, the maximum diameter is often limited to 8 mm, not only in Beijing, but also other regions in the world. This is commonly recognized in the precipitation community. We have clarified this in the revision (page 5, line 26-28 in the clean version): *“In addition, to focus on rainfall, all the data contaminated by hail are removed, and raindrops at a diameter of larger than 8 mm are eliminated (Bringi and Chandrasekar, 2001) since the biggest raindrops ever reported globally in the literature are around 8 mm (Baumgardner and Colpitt, 1995; Beard et al., 1986).”*

14. P3, L24-25. How to obtain D_j if only the number of raindrops belonging to each bin was recorded? I've noticed that the maximum value of D_{\max} happened to be 7.5 mm in Table 1, so I guess there should exist a bin ranging from 7 mm to 8 mm, and the authors took its average as corresponding diameter.

Response: We thank the reviewer for this detailed question. For the second-generation Particle Size and Velocity (Parsivel²) disdrometer, the measured particles are subdivided into 32 different diameter bins. At each diameter bin, it has a specific mid-value and spread. In this study, we consider the mid-value as D_j . For example, the mid-value of the 24th bin is 7.5 mm and the bin spread is 1 mm, which means the raindrops in this category range from 7 mm to 8 mm. Then we take the mid-value of 7.5 mm as D_{24} corresponding to this particular bin. We have further clarified this in the revision (page 4, line 9-11, in the clean version): “where D_j (mm) is the mid-value of j th diameter bin, $N(D_j)$ is in $m^{-3} mm^{-1}$; A is the sampling area in m^2 ; Δt is the sampling time interval in s; A and Δt are respectively 0.0054 m^2 and 60 s in this study; ΔD_j (mm) is the diameter spread for the j th diameter bin; V_i ($m s^{-1}$) is the mid-value fall speed for the i th velocity class.”

15. P5, L30. How did the authors figure out the relationship between D_m and D_0 ?

Response: We apologize for the possible confusion. The relationship between D_m and D_0 is derived by Ulbrich (1983). For any reason, this reference was lost. We have clarified this in the revision (page 6, line 11 in the clean version): “The relationship $\Lambda D_m + 3.67 = \Lambda D_0 + 4$ (Ulbrich, 1983) may explain for such phenomenon when $\Lambda > 0$.”

16. P13, L9. I guess the authors missed “(MP-Stratiform)” after “NEXRAD”.

Response: We thank the reviewer for pointing this out. In the revision, “(MP-Stratiform)” has been added after “NEXRAD”.

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Statistical characteristics of raindrop size distribution during rainy seasons in Beijing urban area and implications for radar rainfall estimation

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Abstract. Raindrop size distribution (DSD) information is fundamental in understanding the precipitation microphysics and quantitative precipitation estimation, especially in complex terrain or urban environments which are known for its complicated rainfall mechanism and high spatial and temporal variability. In this study, the DSD characteristics of rainy seasons in Beijing urban area are extensively investigated using 5-year DSD observations from a Parsivel² disdrometer located at Tsinghua University. The results show that the DSD samples with rain rate $< 1 \text{ mm h}^{-1}$ account for more than half of total observations. The mean values of the normalized intercept parameter ($\log_{10}N_w$) and the mass-weighted mean diameter (D_m) of convective rain are higher than that of stratiform rain, and there is a clear boundary between the two types of rain in terms of the scattergram of $\log_{10}N_w$ versus D_m . The convective rain in Beijing is neither continental nor maritime owing to the particular location and local topography. As the rainfall intensity increases, the DSD spectra become higher and wider, but they still have peaks around diameter $D \sim 0.5 \text{ mm}$. The midsize drops contribute most towards accumulated rainwater. The D_m and $\log_{10}N_w$ values show-exhibit a diurnal cycle and an annual cycle. In addition, at the stage characterized by an abrupt rise of urban heat island (UHI) intensity as well as the stage of strong UHI intensity during the day, DSD shows higher D_m values and lower $\log_{10}N_w$ values, during the periods of strong urban heat island (UHI) effect and UHI up stage of a day, and the same in July and August. The localized radar reflectivity (Z) and rain rate (R) relations ($Z = aR^b$) show substantial differences compared to the commonly used NEXRAD relationships. And-and the polarimetric radar algorithms $R(K_{dp})$, $R(K_{dp}, Z_{DR})$, and $R(Z_H, Z_{DR})$ show greater potential for rainfall estimation.

1 Introduction

Raindrop size distribution (DSD) provides fundamental information on precipitation microphysics. Understanding the DSD variability is of great importance in remote sensing observations of precipitation and microphysical parameterizations in numerical weather prediction (NWP) models. For example, the DSD serves as a fundamental bridge in deriving the Z-R

relationships used by ground based weather radar (Battan, 1973; Uijlenhoet and Stricker, 1999) and space borne radar (i.e. TRMM PR: Iguchi et al., 2000; and GPM DPR: Hou et al., 2014) for quantitative precipitation estimation (QPE). The NWP systems coupled with various DSD models can capture more detailed horizontal and/or vertical rain~~fall~~ information so as to improve the accuracy of precipitation predictions (Abel and Boutle, 2012; Fadnavis et al., 2014; McFarquhar et al., 2015; Saleeby and Cotton, 2004). In addition, the DSD is highly related to the kinetic energy of rainfall that has substantial impact on the soil erosions (Angulo-Martinez and Barros, 2015; Caracciolo et al., 2011; Ellison, 1945; Kinnell, 2005; Lim et al., 2015), which is ~~critical to very useful in~~ further understanding of ~~the~~ runoff processes and mitigation of subsequent flood hazards (Angulo-Martinez and Barros, 2015; Smith et al., 2009).

Numerous studies have been devoted to the statistical characteristics of DSD worldwide. It is found that the DSD characteristics vary with geographical locations, climate regimes, seasons, rain types, and even diurnal cycles (Dolan et al., 2018; Ji et al., 2019; Seela et al., 2018; Tokay and Short, 1996; Wen et al., 2017b). Dolan et al. (2018) classified the global DSD characteristics into six groups by analyzing 12 global disdrometer datasets across three latitudes using principal component analysis. They found that the physical processes shaping the DSD characteristics were likely to vary as a function of location. The comparison of DSD in northern and southern China in Tang et al. (2014) showed that there was a clear difference in precipitation microphysical parameters between different regimes during convective rain, while the difference was less notable for stratiform events. The DSD analysis in Beijing (Wen et al., 2017a) and Taiwan (Seela et al., 2018) also indicated that there were significant differences in DSD between summer and winter rainfall, and both showed the diurnal variation. In addition, the DSD may exhibit high variability in special weather systems. For example, DSD of the tropical cyclones has a higher concentration of small and middle size drops as well as a lower mass-weighted mean diameter (i.e., D_m) in all types of rain compared with the non-tropical cyclone in Darwin (Deo and Walsh, 2016).

Beijing, the capital of China, is a very densely populated metroplex with a population higher than 21 million. It is more vulnerable to extreme weather events such as ~~torrential~~extreme rainfall and floods (Zhang et al., 2013). ~~Since the hydrology response in urban area is sensitive to the spatial and temporal variability of rainfall (Cristiano et al., 2017), Rainfall-rainfall~~ monitoring networks with high-temporal and spatial resolution (e.g., dense ~~network of~~ automatic weather stations~~network by~~ de Vos et al.; (2017); remote sensing network described by Chen and Chandrasekar (2015) and Cifelli et al.; (2018)) have been ~~applied-established in several metropolitan areas, as the hydrology response in urban area is sensitive to the spatial and temporal variability of rainfall (Cristiano et al., 2017). The precipitation in Beijing is more complex with high spatial and temporal variability due to the combined effects of high urbanization and local unique topography (Song et al., 2014; Yang et al., 2013a; Yang et al., 2016), which highlights the importance of further understanding of DSD characteristics for enhanced urban precipitation measurements and modelling. The rapid urbanization and complex topography have further exacerbated the high variability of precipitation in Beijing urban area, posing challenges to precipitation observations and forecast (Song et al., 2014; Yang et al., 2013a; Yang et al., 2016). This also highlights the importance of understanding local DSD characteristics to better quantify the urban precipitation.~~

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Several studies on DSD characteristics in Beijing area have been conducted. Tang et al. (2014) studied the DSD characteristics and the polarimetric radar parameters for convective and stratiform rain from July to October 2008 ~~in Beijing~~ and compared with other regions using a first-generation laser-based optical particle size and velocity (Parsivel¹) disdrometer ~~produced-manufactured~~ by OTT Messtechnik, Germany. Wen et al. (2017a) investigated the statistical properties of summer and winter precipitation in Beijing, including the bulk properties, raindrop fall velocity, axis ratio, and DSD, using a two-dimensional video disdrometer (2DVD) and a micro-rain radar (MRR). Ji et al. (2019) analyzed the microphysical structure of DSD using 14-month DSD measurements from a second-generation Particle Size and Velocity (Parsivel²) disdrometer in Beijing.

However, these studies are mainly focused on summer time (June-September or July-October) ~~and-or~~ with very limited measurements from one season or two, which are not sufficient to represent local DSD characteristics, especially the monthly variability, -of-Beijing during the rainy ~~or-warm~~ seasons ranging from May to October. In addition, the impacts of urban heat island (UHI) effect on rainfall microphysical properties have never been studied in the literature, as the DSD measurements used in previous studies are more likely collected in the suburban area, ~~which could not show the connections of DSD and the urbanization of Beijing.~~

This paper presents a comprehensive study of DSD properties using 5-year (2014–2018) continuous observations in Beijing urban area, aiming to advance our understanding and characterizations of DSD in urban region, as well as parameterization in remote sensing retrievals and NWP models. The DSD properties, their variabilities, as well as the potential applications in radar QPE are detailed,~~aiming to advance our understanding of local rainfall microphysics and parameterization in remote sensing retrievals and NWP models.~~

This paper is organized as follows. Section 2 describes the dataset and ~~methodologies-methods~~ for data quality control and analysis. The characteristics of DSD parameters for all rainfall events combined, different rainfall types, different ~~elassifications~~ rain rate classes, different periods of a day, and different months are detailed in ~~section-Section~~ 3. Section 4 presents the implications for radar QPE and the parameterization errors of different DSD-based radar rainfall algorithms. Summary and conclusion are given in ~~section-Section~~ 5.

2 Data and Method

2.1 Dataset

In this study, a ~~second-generation Particle Size and Velocity~~ (Parsivel²) disdrometer is used, which is deployed at Tsinghua University campus, Beijing, China (hereafter referred to as THUD). Figure 1 illustrates the specific location of THUD (40.002 N, 116.324 E; 91m above sea level), relative to the Beijing metroplex. It is an optical disdrometer with a 54 cm² horizontal sample area, and it is configured with 1 minute sampling resolution to measure the DSD and fall velocity of rain drops (Löffler-Mang and Joss, 2000). The velocity and particle sizes ~~are~~ divided into 32 non-uniform bins, varying from 0.05 to 20.8 m s⁻¹ for velocity and 0.062 to 24.5 mm for ~~drop-particle~~ diameter.

The DSD measurements are collected from June 2014 to December 2018. Lyu et al. (2018) compared the accumulated rainfall computed from the DSD data with the rainfall measurements from ~~by~~ an automatic weather station 350 m away from THUD, to cross-check the reliability of both instruments. Since most rainfall in Beijing area occurs during rainy-warm season which usually begins-starts from May to the end of October (Song et al., 2014), this study uses the data collected from May to October to analyze the DSD characteristics.

2.2 Method

The direct measurements from disdrometer are the number of raindrops at each velocity (i) and diameter (j) bin. Here, we take the mid-value of each bin as the corresponding value. Then~~From the data,~~ the maximum diameter D_{max} (mm) of raindrops can be obtained directly from the data, and the total number of rain drops T_d can be calculated:

$$T_d = \sum_{i=1}^{32} \sum_{j=1}^{32} n_{i,j}, \quad (1)$$

where $n_{i,j}$ stands for the drop number at each bin.

The number concentration of raindrops per unit volume for the j th diameter bin can be calculated as follows:

$$N(D_j) = \sum_{i=1}^{32} \frac{n_{i,j}}{A \Delta t V_i \Delta D_j}, \quad (2)$$

where D_j (mm) is the mid-value of j th diameter bin; $N(D_j)$ is in $\text{m}^{-3} \text{mm}^{-1}$; A is the sampling area in m^2 ; Δt is the sampling time interval in s; A and Δt are respectively 0.0054 m^2 and 60 s in this study; ΔD_j (mm) is the diameter interval from D_j to D_{j+1} spread for the j th diameter bin; V_i (m s^{-1}) is the mid-value fall speed for the i th velocity class.

Because of the measurement error, especially for larger size drops (Tokay et al., 2014), the empirical terminal velocity–diameter ($V - D$) relationship in Atlas et al. (1973) is adopted in this study:

$$V(D_j) = 9.65 - 10.3 \exp(-0.6 D_j), \quad (3)$$

The Gamma~~form~~ DSD model (Ulbrich, 1983) in the following form has been proved to be suitable to describe the raindrop spectra.

$$N(D) = N_0 D^\mu \exp(-\Lambda D), \quad (4)$$

where D (mm) is the rain drop diameter; $N(D)$ ($\text{mm}^{-1} \text{m}^{-3}$) is the number concentration of raindrops per unit volume ~~and~~ per diameter interval; N_0 ($\text{mm}^{-1-\mu} \text{m}^{-3}$), μ and Λ are the scale, shape and slope parameters of the Gamma distribution, and these three parameters can be derived using gamma moments (GM) (Kozu and Nakamura, 1991; Tokay and Short, 1996) or maximum likelihood methods (Montopoli et al., 2008). When $\mu=0$, the Gamma form DSD degenerates into an exponential DSD model.

In this study, we use the normalized gamma DSD described by Testud et al. (2000) which is commonly used to describe the natural variations of DSD (e.g.: Bringi and Chandrasekar 2001; Dolan et al., 2018).

$$N(D) = N_w f(\mu) \left(\frac{D}{D_m} \right)^\mu \exp \left[- (4 + \mu) \frac{D}{D_m} \right], \quad (5)$$

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where N_w ($\text{m}^{-3} \text{mm}^{-1}$) is normalized intercept parameter; D_m (mm) is the mass-weighted mean diameter. N_w , D_m , and $f(\mu)$ are calculated as follows:

$$D_m = \frac{\sum_{j=1}^{32} N(D_j) \cdot D_j^4 \cdot \Delta D_j}{\sum_{j=1}^{32} N(D_j) \cdot D_j^3 \cdot \Delta D_j}, \quad (6)$$

$$N_w = \frac{4^4}{\pi \rho_w} \left(\frac{10^3 W}{D_m^4} \right), \quad (7)$$

$$f(\mu) = \frac{6(4+\mu)^{\mu+4}}{4^4 \Gamma(\mu+4)}, \quad (8)$$

The integral parameters of total number concentration N_t (m^{-3}), rain rate R (mm h^{-1}), liquid water content W (g m^{-3}) and the mass spectrum standard deviation σ_m (mm) are also calculated in this study based on the following equations.

$$N_t = \int N(D) dD = \int N_w f(\mu) \left(\frac{D}{D_m} \right)^\mu \exp \left[-(4+\mu) \frac{D}{D_m} \right] dD = \sum_{i=t}^{32} \sum_{j=1}^{32} \frac{n_{i,j}}{A \cdot \Delta t \cdot V_j}, \quad (9)$$

$$R = \frac{6\pi}{10^4 \rho_w} \sum_{j=1}^{32} V(D_j) D_j^3 N(D_j) \Delta D_j = \sum_{j=1}^{32} R(D_j) \Delta D_j, \quad (10)$$

$$W = \frac{\pi \rho_w}{6 \times 10^3} \sum_{j=1}^{32} D_j^3 N(D_j) \Delta D_j, \quad (11)$$

$$\sigma_m = \sqrt{\frac{\sum_{j=1}^{32} (D_j - D_m)^2 N(D_j) \cdot D_j^3 \cdot \Delta D_j}{\sum_{j=1}^{32} N(D_j) \cdot D_j^3 \cdot \Delta D_j}}, \quad (12)$$

where ρ_w is the water density (1.0 g cm^{-3}); $R(D_j)$ ($\text{mm h}^{-1} \text{mm}^{-1}$) is the rain rate at the j th diameter class, and it is normalized by the total rain rate R as $R(D_j)^{norm} = \frac{R(D_j)}{R}$ in the analysis to **resolve the contribution of different raindrop sizes to the rainfall intensities, make the comparison at different rain intensities more meaningful.**

The median volume diameter D_0 (mm), defined such that drops smaller than D_0 contribute to half the total liquid water content (W), as follows:

$$\frac{\pi \rho_w}{6 \times 10^3} \int_0^{D_0} D^3 N(D) dD = \frac{1}{2} \frac{\pi \rho_w}{6 \times 10^3} \int_0^\infty D^3 N(D) dD = \frac{1}{2} (W), \quad (13)$$

is also computed and included in the analysis.

Considering that a high-resolution dual-polarization X-band radar network is being deployed in Beijing for urban hydrometeorological applications, a series of polarimetric radar variables are simulated at X-band frequency based on the DSD measurements using the T -matrix method (Waterman, 1965; Leinonen, 2014), including horizontal reflectivity Z_H ($\text{mm}^6 \text{m}^{-3}$), differential reflectivity Z_{dr} (dB), and specific differential phase K_{dp} ($^\circ \text{km}^{-1}$). The drop shape model used in the simulation is the one proposed by Thurai et al. (2007). The temperature data are obtained from an automatic weather station collocated with THUD disdrometer. In addition, various DSD-based radar QPE relations are derived and their parameterization errors are investigated for future development of Beijing urban radar rainfall system.

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2.3 Quality Control

To minimize the measurement errors and improve data reliability, several quality control procedures have been applied on the 1-minute DSD data. First, because of the low signal-to-noise ratios, the lowest two diameter bins are not used. That is, which means the raindrops less than 0.312 mm are eliminated in the analysis. Second, the 1-minute sample data with total raindrop number smaller than 10 or the derived rain rate less than 0.1 mm h^{-1} are considered as noise and removed (Sreekanth et al., 2017). Then, if the continuous data satisfying the above conditions last less than 5 minutes, they will be ignored to avoid the spurious and erratic measurements (Jash et al., 2019). In addition, to focus on rainfall, all the data contaminated by hail are removed, and raindrops at a diameter of larger than 8 mm are eliminated (Bringi and Chandrasekar, 2001) since the biggest raindrops ever reported globally in the literature are around 8 mm (Baumgardner and Colpitt, 1995; Beard et al., 1986). Also, thresholds on the simulated radar parameters (i.e., $Z_h = 10\log_{10}Z_H < 55 \text{ dBZ}$, $Z_{dr} > 0 \text{ dB}$, and $K_{dp} > 0 \text{ }^\circ\text{km}^{-1}$) are implemented to further guarantee the creditability of the measured rainfall DSD data.

3 DSD parameter characteristics

3.1 Distribution of DSD parameters

A total number of 43618 1-minute DSD spectra have been selected after data quality control, covering the wet seasons (May to October) from 2014 to 2018 except for May 2014 (no observation yet then). In this study, the raindrops below 1 mm are considered small drops; 1–3 mm are midsize drops; and large drops if larger than 3 mm (Krishna et al., 2016; Seela et al., 2017; Seela et al., 2018; Tokay et al., 2014). The distribution and statistics of the DSD parameters are shown in Fig. 2 and Table 1. D_0 and D_m have similar distributions with each other. Although D_0 has a larger range with a larger maximum and a smaller minimum value, it is more concentrated to small values, showing smaller mean and median diameter value with higher standard deviation, skewness and kurtosis values. The relationship $\Lambda D_m + 3.67 = \Lambda D_0 + 4$ (Ulbrich, 1983) may explain for such phenomenon when $\Lambda > 0$. The distribution of D_{max} shows that in during most of the rain events, the biggest drops are middle class size, indicating that most of the rainfall is potentially made up of small and moderate raindrops. The statistical characteristics of $\log_{10}N_w$ show almost equal median (3.596) and mean values (3.595), as well as a very small skewness value (0.040), indicating that $\log_{10}N_w$ follows a symmetry distribution. The mean, median and skewness values of $\log_{10}N_t$, $\log_{10}T_d$, and $\log_{10}\sigma_m$ also exhibit symmetry distributions. Moreover, the kurtosis of these three parameters are close to 3, characteristic of a normal distribution, which indicates that N_t , T_d , and σ_m obey the lognormal distribution. Since a threshold of 0.1 mm h^{-1} is applied on the rain rate field (i.e., $\log_{10}R$ is truncated by -1), the R meets a positive skew distribution. Because of this, the distributions of $\log_{10}W$ also have has a positive skew distribution. It is worth noting that DSD samples with rain rate about $0.8\text{--}1 \text{ mm h}^{-1}$ have the highest frequency and samples with rain rate less than 1 mm h^{-1} account for more than half of the total rain.

3.2 DSD properties for different rain types

There may be significant differences between the two general precipitation types (i.e., convective and stratiform), which results in variations in DSD characteristics. Previous studies in different climatic regions have shown that DSD may substantially differ in the two general precipitation types (i.e., convective and stratiform), which has differences in the two rain types have a great impact on the parameterization in both NWP models and remote sensing observations. In this study, rainfall events are separated into stratiform and convective cases using a method combining Bringi et al. (2003) and Chen et al. (2013). In particular, if the standard derivation of rain rate for a consequent 10-minute is greater than 1.5 mm h^{-1} and the rain rate is greater than 5 mm h^{-1} , it is classified as convective rain, otherwise it is classified as stratiform rain.

Figure 3 shows the histograms of D_m and $\log_{10}N_w$ for all the rainfall events and for the convective and stratiform subsets. The three key statistics parameters including mean, standard deviation (SD), and skewness are also indicted in Fig. 3, including mean, standard deviation (SD), and skewness. For the total data set (Fig.3a), the D_m histogram is highly positively skewed, while the skewness of $\log_{10}N_w$ is near to zero, suggesting that the distribution of $\log_{10}N_w$ is more symmetrical. The standard deviations of D_m and $\log_{10}N_w$ are large (0.46 mm for D_m and 0.62 for $\log_{10}N_w$), indicating a high variability of both D_m and $\log_{10}N_w$. The mean values of D_m and $\log_{10}N_w$ are 1.15 mm and 3.60, respectively. It should be noted that both mean values are slightly smaller compared with those obtained in Beijing area during the summer time of 2015 (from 30th July to 30th September) and 2016 (from 9th June to 26th September) (Wen et al., 2017a), which means that the DSD during summer time may be more concentrated than the whole rainy seasons.

Considering different rain types, it can be found that the D_m for both types are positively skewed, while the skewness of $\log_{10}N_w$ for convective exhibits negative. The spread of $\log_{10}N_w$ for convective rain is narrower compared to that of stratiform rain, and the skewness of $\log_{10}N_w$ is larger than that of stratiform rain (-0.98 versus 0.10). The spreads and skewness of D_m for these two rainfall types perform oppositely (see Figs. 3 b-c). In addition, histograms of D_m and $\log_{10}N_w$ during convective rain tend to shift toward the large values relative to stratiform rain, indicating that convective events have higher D_m and $\log_{10}N_w$ values than stratiform cases (1.91 mm and 3.66 for convective versus 1.08 mm and 3.59 for stratiform, respectively). As Fig. 4 shows, in both convective and stratiform rains, with the increase of rain rate, the D_m increases (the positive exponents of the fitted power-law relationships), but the distributions of D_m become narrowed. Note that at higher rain rate, the D_m values tend to be a stable value, indicating that the DSD may have come to an equilibrium state where the coalescence and breakup of raindrops are in near balance (Hu and Srivastava, 1995). It can be seen in Fig. 4a, that when rain rate $R > 60 \text{ mm h}^{-1}$, the D_m values reach a stable value around 2–2.5 mm; when rain rate $R > 60 \text{ mm h}^{-1}$, which means the increase of rain rate is mainly caused by an increase of concentration (Bringi and Chandrasekar, 2001). With respect to the $D_m - R$ relationship, the coefficient and exponent values of convective rain are slightly higher than stratiform, suggesting a larger D_m of convective rain than that of stratiform rain for a given rain rate, which is different from the findings in eastern China (Wen et al., 2016) or southern China (Zhang et al., 2019a) draws an opposed conclusion to Wen et al. (2016) in eastern China and Zhang et al. (2019a) in southern China.

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Figure 5 shows the distribution of $\log_{10}N_w$ versus D_m derived from the DSD data for all the rainfall events, as well as two different rain types. The statistical results from different parts of China (i.e., North China, East China, and South China) reported by Chen et al. (2013), Tang et al. (2014), Wen et al. (2016), Wen et al. (2017a), and Zhang et al. (2019a) are also indicated in Fig. 5. The two black rectangles correspond to the maritime and continental convective clusters and the dashed line corresponds to the stratiform (hereafter called “stratiform line”) case described by Bringi et al. (2003). For all the events combined, the distribution has a wide scale, but most points concentrate in the area of high $\log_{10}N_w$ with low D_m . For convective and stratiform events, the distributions are concentrated in different areas (Stratiform: 3.3–4.0 for $\log_{10}N_w$, 0.8–1.2 mm for D_m ; Convective: 3.7–4.2 for $\log_{10}N_w$, 1.4–2.0 mm for D_m). There is a rather clear boundary between the two rainfall types, even though there are several points coincided some overlaps. For convective rain, there are more points in the “Continental cluster” than the “Maritime cluster”, but most points are neither in the “Continental cluster” nor in the “Maritime cluster” and have a tendency to approach the stratiform rain. This indicates that the wet season convective rain in Beijing is neither maritime or continental as described by Bringi et al. (2003), which is likely due to the certain distance between Beijing and the nearest ocean (about 160 km). For stratiform rainfall, the points are more concentrated, even with a wide range of $\log_{10}N_w$ versus D_m . More than 85% of the stratiform points appear on the left side of the “stratiform line”. The average point of $\log_{10}N_w - D_m$ for all the rainfall events combined (magenta hollow star) also appears on the left side of the “stratiform line” due to the highest population of stratiform in the summer monsoon season (as shown in see also Table 2). These indicate the lower diameter and higher concentration characteristics of rainfall in Beijing area. The relationship of $\log_{10}N_w - D_0$ (See see Fig. S1) shows that the line to classify rain types based on $\log_{10}N_w - D_0$ proposed by (Thurai et al., 2016) would misclassify more convective rain as stratiform rain. This is probably because of due to the complex terrain of in Beijing (as shown in Fig. 1a). The where the high mountain to the west may have substantial impact on the rain evolved from west mainland.

The comparison of DSDs in different parts of China shows interesting results. Even in the same region, the DSDs measured by different instruments have notable differences, such as the differences in Beijing between results from Wen et al. (2017a) (2DVD, circle) and Tang et al. (2014) (Parsivel, square). In order to reduce the errors caused by different measurement instruments, only DSDs measured by Parsivel disdrometers are analyzed in this study. It is concluded that the east part of China has the lowest mean value of $\log_{10}N_w$ (3.42) with highest mean value of D_m (1.66), while southern China has the highest mean value of $\log_{10}N_w$ (3.86) with middle value of D_m (1.46), and the north part of China has the middle value of $\log_{10}N_w$ (3.60) with lowest value of D_m (1.15). This highlights which indicates that the DSD characteristics are highly dependent on correlated to the specific geographical locations and associated climate regimes. The results of Beijing from this study and Tang et al. (2014) Chen et al. (2013) show great differences in convective rain and less differences in stratiform rain, which is attributed to different convective systems during different years.

The DSD spectra and $R(D)$ distributions of two rain types are shown in Fig. 6. Substantial differences are observed between these two rainfall types in both DSD spectra and $R(D)$ distributions. The peaks of DSD spectra for both rainfall types are at the same diameter bin around $D \sim 0.5$ mm, while the spectrum for convective is higher than that of stratiform. The peak

of $R(D)$ distribution for stratiform rain is at the diameter around 0.9 mm while 1.9 mm for convective rain, which is much larger than where the DSD spectra peaks occur due to the D^3 dependency of $R(D)$. In addition, the distribution of $R(D)$ for convective rain is much lower and broader. The differences in DSD spectra and $R(D)$ distributions indicate that the convective rainfall has a higher concentration of moderate to large size drops, and the large drops contribute more to convective rainfall compared to stratiform rainfall.

3.3 DSD characteristics in different rain rate classes

To further understand the characteristics of DSD at different rainfall intensities in Beijing area, the DSD measurements are divided into 8 classes according to the associated rain rate (R): C1, $0.1 \leq R < 0.5$; C2, $0.5 \leq R < 1$; C3, $1 \leq R < 2$; C4, $2 \leq R < 5$; C5, $5 \leq R < 10$; C6, $10 \leq R < 25$; C7, $25 \leq R < 50$; C8, $R \geq 50 \text{ mm h}^{-1}$. Such classification is based on the fact of high frequency of low rain rates in Beijing area, as well as several previous studies including Das and Maitra (2016), Harikumar et al. (2010), Krishna et al. (2016), Sarkar et al. (2015), and Tokay and Short (1996). The DSD sample numbers and rain rate statistics for each category are summarized in Table 3. For each rain rate class, the composite DSD spectrum is shown in Fig. 7a. Note that almost for all raindrop size bins, the concentration of higher rain rate class is higher than that of a lower rain rate class. Furthermore, the breadth of DSD shape increases and the tail of DSD shifts gradually to the larger diameter with as the rainfall intensity increases of rainfall intensity, which is similar to the previous findings in Taiwan (Seela et al., 2017), south Indian (Jash et al., 2019), Palau (Krishna et al., 2016), and United Kingdom (Islam et al., 2012). All the DSD spectra only have one peak which differs from Krishna et al. (2016) where the spectrum becomes bimodal when rain rate $R > 8 \text{ mm h}^{-1}$. In addition, the peaks of all DSD spectra are at a diameter around $D \sim 0.5 \text{ mm}$, which is different from Jash et al. (2019) for India where the peak position shifts towards larger diameters as rain rate increases.

The mean normalized $R(D)$ of each rain rate class is shown in Fig. 7b, illustrating the contribution of each diameter bin to the total rainwater. The normalized rain rate distributions are unimodal, and the peaks are around $D \sim 0.9\text{--}2.5 \text{ mm}$. The peak position shifts to a larger diameter and the distribution becomes lower and broader as rain rate increases. These results are similar to those in Jash et al. (2019) for India, but different from those in Peters et al. (2002) for German where the $R(D)$ distribution has a secondary peak at lower rain rate intensity ($R < 1 \text{ mm h}^{-1}$). This analysis implies that raindrops of diameter 0.9–2.5 mm (i.e., moderate size) contribute most towards accumulated rainwater during the rainy season in Beijing area, and the size of drops contributing the most rainfall increases as the rainfall intensity increases.

Variations of normalized intercept parameter ($\log_{10} N_w$) and mass-weighted mean diameter (D_m) in each rain rate class are provided in Fig. 8 with box-whisker plot. The central white line and black line in the box represent the median and mean values and the top and bottom lines of the box represent the 75th and 25th percentiles. The top and bottom lines out of the box respectively stand for the 95th and 5th percentiles. It can be seen that D_m values are increasing with the increase of rainfall intensity, while the increasing trend of $\log_{10} N_w$ is not as clear. This could be due to the imbalance between the decrease in small drop concentration and the increase in midsize and large drop concentration at higher rain rate ($R > 10 \text{ mm h}^{-1}$, from

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C6 to C8). The means and standard deviations of D_m , $\log_{10} N_w$, N_t , W , μ , and Λ for each rain rate class are provided in Table 4. Table 4 which clearly shows that with the increase of rainfall intensity, the mean values of total number concentration (N_t) and liquid water content (W) increase, while the mean values of shape parameter (μ) and slope parameter (Λ) show a decreasing trend, which ensures resulting in a wider breadth and lower peak of DSD at high rain rates.

5 3.4 Diurnal variations of DSD characteristics

Since the 1980s, Beijing has been experiencing rapid urbanization, causing a lot of problems among which urban heat island UHI is one of the most well-known phenomena (Yang et al., 2013b). Some studies showed that extreme precipitation events are more likely to occur during the period when the urban heat island (UHI) intensity is high, usually from late afternoon to early morning in Beijing local time (LST) (Li et al., 2008; Song et al., 2014; Yang et al., 2013a; Yang et al., 2017; Zhang et al., 2019b). In order to explore the DSD variations during the day, the diurnal periods are divided into four parts based on the UHI variation described in Yang et al. (2013b): strong UHI stage (S UHI, 2100–0600 LST), weak UHI stage (W UHI, 1100–1600 LST), UHI down stage characterized by a fast decline of UHI intensity (UHI D, 0600–1100 LST) and UHI up stage characterized by an abrupt rise of UHI intensity (UHI U, 1600–2100 LST). The rain rate and DSD characteristics corresponding to these four stages are shown in Table 5. The DSD spectra and $R(D)$ distributions are shown in Fig 9.

The DSD spectra of different diurnal periods are quite similar to those of different rain rate classes, showing a unimodal shape and peak position at the diameter $D \sim 0.5$ mm. It is notable that the DSD spectra are almost the same at small drop size bins ($D < 1$ mm) and have the same width. As the diameter becomes larger, variations in the DSD spectra start showing up. The DSD spectra of S UHI stage and UHI U stage show similar and higher concentration, and whereas the DSD spectra of W UHI stage and UHI D stage have similar but lower concentration, indicating that during the UHI U stage and S UHI stage, high-intensity rainfall is more likely to occur. This is in line with the study in Yang et al. (2017), which showed that the short term high-intensity rainfall was more likely to happen at the UHI U stage and end at the late S UHI stage. The frequency and variation of rain rate for different UHI stage (see Fig. S2) can also indicate this point.

The $R(D)$ distributions for different diurnal periods in Fig. 9b show little difference between UHI U stage and S UHI stage, and the distributions at these two stages are lower and broader than the other two stages. For At the W UHI stage, the $R(D)$ distribution is the highest and the peak is at diameter around $D \sim 0.9$ mm, and the UHI D stage almost has the same peak around $D \sim 0.9$ –1 mm, while the peaks of during other two stages are at the diameter around $D \sim 1$ mm. That is, the drop size at the W UHI stage which contributes most to the accumulated rainwater is smaller than those at UHI U stage or S UHI stage. The box-whisker plots of variation of mass-weighted mean diameter (D_m) and normalized intercept parameter ($\log_{10} N_w$) for each diurnal periods show the same results (see Fig. 10). The W UHI stage has the highest mean concentration and the lowest mean D_m value, while the UHI U stage has the largest mean D_m value and the S UHI stage has the lowest mean concentration.

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3.5 DSD characteristics in different months

To ~~have obtain~~ a better understanding of the seasonal variations of DSD characteristics in Beijing urban area, rain data collected in different months are analyzed. The rain rate and DSD characteristics for different months are shown in Table 6. Figure 11 illustrates the corresponding DSD spectra and $R(D)$ distributions.

As shown in Fig. 11, all the DSD spectra have a peak at diameter $D \sim 0.5$ mm, which are consistent with other classifications in this study. The DSD in May has a relatively higher concentration while ~~a relatively lower concentration in July, that of July has a relatively lower concentration.~~ At small drop size bins ($D < 1$ mm), the spectra for May and September are similar, while the spectra for other four months are similar. As the diameter increases, the differences between these spectra become larger, and the DSD spectrum ~~uma~~ for July has the highest concentration and October ~~has~~ the lowest concentration. The rainfall with higher concentration and large drops is more likely to happen in July, leading to a high rain rate intensity (~~see also Fig. S3~~).

It is also noted that the $R(D)$ distribution for each month is different from each other. The distributions of May, October, and September have a peak at diameter around $D \sim 0.9$ mm, while ~~the~~ distributions of June and August have a peak at diameter around $D \sim 1$ mm. The $R(D)$ distribution of July has two peaks at diameter around $D \sim 1$ mm and $D \sim 1.5$ mm. In addition, the $R(D)$ distribution of July is the widest and lowest, suggesting that a wide range of moderate drops contribute mostly to the rain in July. The D_m and $\log_{10}N_w$ in Fig. 12 show an interesting ~~annual circle-of-a-year~~: the $D_m(\log_{10}N_w)$ first goes up and (~~down~~) then goes down (~~up~~), while ~~the $\log_{10}N_w$ goes oppositely, and in July $D_m(\log_{10}N_w)$ reaches the highest (lowest) value.~~

4 Implications for Radar Rainfall Estimation

4.1 Single polarized radar applications

The power-law relationship between radar reflectivity (~~in mm^6m^{-3}~~) and rain rate (~~in mmh^{-1}~~) ($Z = aR^b$) is the most widely used ~~algorithm~~ for single polarized radar QPE (including the current operational radars in Beijing). However, the coefficient a and exponent b greatly rely on the DSD variability ~~which may vary in different climate regimes, geographical locations, and rain types~~ (Bringi et al., 2003; Rosenfeld and Ulbrich, 2003; Uijlenhoet, 2001). The default $Z - R$ relationship applied for the operational Weather Surveillance Radar — 1988 Doppler (WSR-88D) systems in the United States is $Z = 300R^{1.4}$ (Fulton et al., 1998), whereas $Z = 200R^{1.6}$ is commonly used in the continental area for stratiform rain (Marshall and Palmer, ~~1948~~), hereafter referred to as MP-Stratiform relationship). The more appropriate and localized a and b are expected to improve regional radar rainfall estimation. In the following, the localized $Z - R$ relationships for different rain types are derived ~~by the nonlinear least square method~~, aiming to provide references for operational S-band radar rainfall applications in Beijing.

Figure 13 shows the scatter density plot of rain rate versus horizontal reflectivity, as well as the fitted power-law relations for different rain types. ~~The default NEXRAD algorithm and MP-Stratiform relationship for continental stratiform rain are also indicated in Fig. 13 for comparison.~~ Figure 13 shows that most of the samples are at low values where both Z_H and R are

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small, which also suggests that the DSD may be under size-controlled conditions (Steiner et al., 2004). Meanwhile, the relationship for total rainfall ($Z = 238R^{1.57}$) underestimates the rain rate at low values compared with the stratiform relationship ($Z = 171R^{2.15}$), due to the inconsistent rain rate - reflectivity structures of two rain types.

The default NEXRAD algorithm and MP-Stratiform relationship for continental stratiform rain are also indicated in Fig. 13 for comparison. The convective relationship $Z = 158R^{1.68}$ has a higher coefficient but lower exponent than the stratiform relation (i.e., $Z = 121R^{2.47}$), which is similar to previous studies. At low reflectivity values ($Z_H < 25.23$ dBZ), the curve of MP-Stratiform relationship is below that of the local stratiform relation, but at higher values, it reverses. As the mean reflectivity of stratiform rain (21 dBZ) is less than 25.23 dBZ (See Table 2), the MP-Stratiform relationship may introduce a cause underestimation of rainfall. The default NEXRAD relationship behaves similarly: underestimation at lower reflectivity values and overestimation at higher reflectivity values. Considering the mean reflectivity value of convective rain, the default NEXRAD relationship may cause overestimation of rainfall. In other words, the default relationship $Z = 300R^{1.4}$ should be used with caution for local applications in Beijing.

4.2 High frequency (X-band) polarimetric radar applications

A high-resolution dual-polarization X-band radar network is being deployed for urban hydrometeorological applications in Beijing area. To support the radar deployment and facilitate the rainfall applications, the polarimetric parameters, including differential reflectivity Z_{dr} (dB) and specific differential propagation phase shift K_{dp} ($^{\circ}\text{km}^{-1}$) are computed from the DSD measurements. Therein, the T-matrix method (Waterman, 1965) is adopted and the computations are made for at X-band frequency, radar wavelength. In addition, the polarimetric rainfall relations are derived based on the nonlinear least-squares method, including $R(K_{dp})$, $R(K_{dp}, Z_{DR})$, and $R(Z_H, Z_{DR})$. Here $Z_{DR} = 10^{Z_{dr}/10}$ is the differential reflectivity in linear scale.

Equations (14)–(17) show the derived X-band radar rainfall relations:

$$R(Z_H) = 0.0304Z_H^{0.638}, \quad (14)$$

$$R(K_{dp}) = 15.421K_{dp}^{0.817}, \quad (15)$$

$$R(K_{dp}, Z_{DR}) = 26.778K_{dp}^{0.946}Z_{DR}^{-1.249}, \quad (16)$$

$$R(Z_H, Z_{DR}) = 4.785 \times 10^{-3}Z_H^{0.978}Z_{DR}^{-3.226}, \quad (17)$$

The derived X-band radar rainfall relations are as follows:

$$R(Z_H) = 0.0576Z_H^{0.557}, \quad (14)$$

$$R(K_{dp}) = 15.421K_{dp}^{0.817}, \quad (15)$$

$$R(K_{dp}, Z_{DR}) = 26.778K_{dp}^{0.946}Z_{DR}^{-1.249}, \quad (16)$$

$$R(Z_H, Z_{DR}) = 5.886 \times 10^{-3}Z_H^{0.994}Z_{DR}^{-4.929}, \quad (17)$$

Note that there are differences in the $Z - R$ relationships between X- and S-band due to Mie scattering at higher frequency.

Previous studies showed that the parameterization errors associated with various radar rainfall relations are among the key factors affecting the derived rainfall performance (Bringi and Chandrasekar, 2001). HereHence, the parameterization errors in

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the X-band radar rainfall algorithms are investigated and quantified in this study. Figure 14 illustrates the scatter density plots of rain rates derived from $R(Z_H)$, $R(K_{dp})$, $R(K_{dp}, Z_{DR})$, and $R(Z_H, Z_{DR})$ versus the rain rates directly computed from DSD. To quantify the parameterization errors, the normalized mean absolute error (NMAE) of estimated rainfall rate is calculated, which is defined as:

$$5 \quad NMAE = \frac{\langle |R_{EP} - R_D| \rangle}{\langle R_D \rangle}, \quad (18)$$

where the angle brackets stand for sample average; R_{EP} and R_D denote the estimated rain rates derived from parameterized radar rainfall algorithms and DSD information, respectively. The $NMAE_{RR}$ is calculated for different rainfall rate intervals from 0 to 100 mm h⁻¹. Figure 15 shows the parameterization error structure of $R(Z_H)$, $R(K_{dp})$, $R(K_{dp}, Z_{DR})$, and $R(Z_H, Z_{DR})$ as a function of rainfall rate.

10 It can be seen from Figs. 14 and 15 that the algorithms based on dual polarization radar parameters can provide better ~~estimates~~ performances than $Z - R$ relationship. In addition, the dual parameter algorithms, namely $R(K_{dp}, Z_{DR})$ and $R(Z_H, Z_{DR})$, have even better performance than the single parameter based algorithm including $R(K_{dp})$. The NMAE has a decreasing trend as the rain rate increase from 1 mm h⁻¹ to 60 mm h⁻¹. The ~~fluctuation~~ opposite trend when rain rate is greater than 60 mm h⁻¹ may be due to the random errors caused by ~~a~~ few samples of large values. The parameterization errors

15 of $R(K_{dp})$, $R(K_{dp}, Z_{DR})$, and $R(Z_H, Z_{DR})$ become stable when rain rate is getting higher than 10 mm h⁻¹. It is also noted that at low rain rate (less than 10 mm h⁻¹), the NMAE of $R(Z_H, Z_{DR})$ is the smallest, while at higher rain rate (higher than 10 mm h⁻¹) the NMAE of $R(K_{dp}, Z_{DR})$ becomes the smallest. It is also noted that at low rain rate (less than 1 mm h⁻¹), the NMAE of $R(K_{dp})$ is the smallest, while at the rain rate of 1–10 mm h⁻¹, the NMAE of $R(Z_H, Z_{DR})$ is the smallest, and when rain rate is getting higher than 10 mm h⁻¹, the NMAE of $R(K_{dp}, Z_{DR})$ becomes the smallest. This again highlights the importance of

20 selecting ~~appropriate~~ proper rain rate relations for ~~specific~~ local radar applications.

5 Summary and Conclusion

In this paper, 5-year (2014–2018) observations of DSD from a disdrometer deployed at Tsinghua University are analyzed to explore the microphysical characteristics of precipitation during rainy seasons (May–October) in Beijing urban area. The main conclusions are as follows:

- 25 1. For all rain events, all the DSD parameters (D_m , D_0 , D_{max} , $\log_{10} N_w$, $\log_{10} N_t$, $\log_{10} R$, $\log_{10} \sigma_m$, $\log_{10} T_d$ and $\log_{10} W$) ~~derived from DSD~~ (except σ_m) have a positive skewness, indicating a high frequency of low values and low frequency of high values in Beijing urban area. ~~And m~~ More than half of the DSD measurements are characterized by rainfall rate less than 1 mm h⁻¹.
- 30 2. The mean values of $\log_{10} N_w$ and D_m of convective rain are higher than that of stratiform rain, indicating a higher raindrop concentration and larger drop size during convective events. This is also in line with the raindrop spectra and

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normalized $R(D)$ distribution. In addition, $\log_{10}N_w$ of convective rain is negatively skewed, which is opposite to that of stratiform rain. For both rainfall types ~~of rain~~, the D_m values are higher but the distributions are narrower at higher rainfall intensities.

3. There is a clear boundary to distinguish between convective and stratiform rain from the scatterplot of $\log_{10}N_w$ versus D_m . However, the convective rain in Beijing area is neither continental nor maritime as described by Bringi et al. (2003), due to the particular location and complex topography. Moreover, the comparison with ~~results in~~ different parts of China shows that the DSD variability is closely related to geographic location, climate regimes and study periods.
4. Stratified by rain rate, the DSD spectra become higher and wider as the rain rate increases, but all have peaks at the similar diameter size ~~same diameter~~ $D \sim 0.5$ mm. The peaks of the normalized $R(D)$ distribution ~~move shift~~ to larger diameter size (still within the midsize range) and the distribution becomes lower and wider as the rain rate increases. Meanwhile, the D_m and $\log_{10}N_w$ show an increasing trend while and the slope parameter (μ) shows a decreasing trend as the rain rate increases.
5. During the periods of strong UHI and UHI up stages, the DSD spectra trend to have a higher concentration at large size drops, and larger D_m values than other periods, indicating intense rainfall at during these periods. The DSD has similar characteristics in July and August. In addition, the D_m and $\log_{10}N_w$ values show a diurnal cycle and an annual cycle. All these findings indicate substantial ~~great~~ temporal variabilities of DSD in Beijing.
6. The ~~localized~~ $Z - R$ relationship derived from local DSD in Beijing is quite different from the operational NEXRAD algorithm (MP-Stratiform ~~which may overestimate (underestimate) rainfall at high (low) rain intensity. that may underestimate (overestimate) rainfall at low (high) rain intensity.~~). The error structures of different algorithms show that the polarimetric radar rainfall relations $R(K_{dp})$, $R(K_{dp}, Z_{DR})$, and $R(Z_H, Z_{DR})$ have greater potential than $Z - R$ methods for urban QPE.

The ~~statistical analysis of~~ DSD characteristics presented in this study not only provides a further understanding of precipitation microphysical variabilities in Beijing but also provides indications for future model development to improve local precipitation forecast. In addition, a high-resolution X-band dual polarization radar network is being deployed in Beijing. This study is expected to provide references for future development of localized radar rainfall algorithms. Nevertheless, the DSD spectra also show the limitations of Parisvel² disdrometer in measuring small raindrops. Future study should be carried out with multiple instruments including a two-dimensional video disdrometer just deployed in this area. We also want to note that combining additional observations such as the vertically-pointing profiler radar data (White et al., 2003) can further enhance the classification results of different rainfall types, which should be considered in future studies. In addition, further investigation on the spatial variability of DSD induced by the complex micro-topography in urban area should be conducted in a future study.

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Data availability.

Disdrometer data used in this study are available through contacting the authors.

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Author contributions.

YM, GN, FT and HC conceived the idea; GN and FT provided financial support and observation data; YM conducted the detailed analysis; HC and CVC provided comments on the analysis; all authors contributed to the writing and revisions.

Completing interests.

The authors declare that they have no conflict of interest.

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Supplementary Materials

Figure S1: Scatter density plot of $\log_{10} N_w$ versus D_0 : (a) the total rainfall events; (c) stratiform events; (d) convective events. (b) is the scatterplot of $\log_{10} N_w$ versus D_0 for convective (red circle dots) and stratiform (blue square dots) cases. The black dashed line is the $\log_{10} N_w - D_0$ relationship for stratiform rain reported by Thurai et al. (2016).

Figure S2: Histograms of rain rate $\log_{10} R$ (R in mm h^{-1}) at different UHI stages: (a) UHI down stage; (b) weak UHI stage; (c) UHI up stage; (d) strong UHI stage; (e) variation of rain rate R (mm h^{-1}) for different UHI stages. The white central lines in the boxes indicate the medians. The black central lines indicate the means, and the bottom and top lines of the box indicate the 25th and 75th percentiles, respectively. The bottom and top lines of the vertical lines out of the box indicate the 5th and 95th percentiles, respectively.

Figure S3: Same as Figure S2, but for different months.

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Tables:

Table 1: Statistics of DSD parameters for all observations: D_m , D_0 , D_{max} , $\log_{10}N_w$, $\log_{10}N_t$, $\log_{10}R$, $\log_{10}\sigma_m$, $\log_{10}T_d$ and $\log_{10}W$

Parameters	D_m (mm)	D_0 (mm)	D_{max} (mm)	$\log_{10}N_w$ (N_w in $\text{m}^{-3}\text{mm}^{-1}$)	$\log_{10}N_t$ (N_t in m^{-3})	$\log_{10}R$ (R in mm h^{-1})	$\log_{10}\sigma_m$ (σ_m in mm)	$\log_{10}T_d$ -	$\log_{10}W$ (W in g m^{-3})
Min	0.376	0.304	0.687	0.435	0.747	-1.000	-1.071	1.041	-2.244
Media	1.054	0.949	1.875	3.596	2.301	-0.134	-0.517	2.253	-1.277
Mean	1.148	1.037	1.987	3.595	2.311	-0.070	-0.521	2.264	-1.229
Max	5.546	6.777	7.500	5.669	3.798	2.037	0.064	3.739	0.678
SD	0.456	0.431	0.913	0.621	0.476	0.558	0.126	0.450	0.495
Skewness	1.780	2.115	1.550	0.040	0.058	0.648	-0.140	0.107	0.571
Kurtosis	9.010	12.252	6.535	4.070	2.859	3.150	3.121	2.711	3.074

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Table 2: Statistical properties of DSD parameters for convective and stratiform rain

	Number	D_m	N_w	N_t	R	σ_m	Td	W	R_H	Z_{dr}	K_{dp}
Parameters	-	(mm)	($\text{m}^{-3}\text{mm}^{-1}$)	(m^{-3})	(mm h^{-1})	(mm)	-	(g m^{-3})	(dBZ)	(dB)	($^{\circ}\text{ km}^{-1}$)
Convective	3650	1.909	4570	1042	16.2	0.385	1024	0.745	40.227	1.579	1.113
Stratiform	39968	1.078	3881	312	1.1	0.308	250	0.072	21.052	0.421	0.037
Total	43618	1.148	3938	373	2.4	0.314	315	0.128	22.656	0.518	0.128

Table 3: Number and DSD retrieved rain rate statistics of each rain rate class

	Rain Rate Threshold	No. of Samples	Mean mm h^{-1}	SD mm h^{-1}	Skewness	Kurtosis
C1	$0.1 \leq R < 0.5$	16464	0.27	0.11	0.36	1.96
C2	$0.5 \leq R < 1$	9340	0.72	0.14	0.29	1.92
C3	$1 \leq R < 2$	7466	1.43	0.29	0.29	1.90
C4	$2 \leq R < 5$	6145	3.08	0.82	0.62	2.26
C5	$5 \leq R < 10$	2141	6.93	1.41	0.47	2.06
C6	$10 \leq R < 25$	1463	15.47	4.11	0.58	2.25
C7	$25 \leq R < 50$	446	34.85	6.91	0.42	1.96
C8	$R \geq 50$	153	62.98	10.95	1.39	5.44

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Table 4: Number and DSD retrieved rain rate statistics of each rain rate class

	D_m (mm)		$\log_{10}N_w$ (m ⁻³ mm ⁻¹)		N_t (m ⁻³)		W (g m ⁻³)		μ		Λ	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C1	0.91	0.27	3.47	0.64	177.06	261.50	0.02	0.01	12.40	10.09	20.90	16.54
C2	1.06	0.32	3.62	0.63	304.90	429.05	0.05	0.02	9.05	7.90	14.63	12.87
C3	1.20	0.37	3.68	0.60	392.99	474.86	0.09	0.03	7.00	6.23	10.86	9.23
C4	1.37	0.43	3.73	0.59	547.35	514.13	0.18	0.06	5.55	5.16	8.19	6.52
C5	1.64	0.51	3.70	0.55	693.45	421.56	0.36	0.08	4.65	4.34	6.05	4.26
C6	2.01	0.56	3.62	0.50	947.33	447.56	0.71	0.19	3.06	2.59	3.93	2.18
C7	2.25	0.36	3.72	0.32	1886.51	866.64	1.50	0.30	1.46	1.53	2.51	0.91
C8	2.32	0.19	3.90	0.20	3240.38	1012.48	2.68	0.48	0.62	0.79	2.01	0.44

Table 5: Mean and Standard Deviation (SD) Values of R , D_m , $\log_{10}N_w$, N_t , W , μ , and Λ for different diurnal periods based on UHI intensity

	$R(\text{mm h}^{-1})$		D_m (mm)		$\log_{10}N_w$ (m ⁻³ mm ⁻¹)		N_t (m ⁻³)		W (g m ⁻³)		μ		Λ	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
W-UHI	1.88	4.31	1.11	0.42	3.59	0.60	342.15	499.30	0.10	0.19	15.06	13.63	9.32	8.49
UHI-U	2.04	4.10	1.10	0.41	3.70	0.58	378.44	398.08	0.12	0.18	15.27	14.48	9.33	8.90
S-UHI	2.82	6.94	1.18	0.51	3.57	0.65	380.88	488.27	0.15	0.30	14.09	13.45	8.78	8.45
UHI-D	2.60	6.79	1.18	0.46	3.56	0.64	385.00	563.30	0.14	0.30	13.97	13.95	8.61	8.43

	$R(\text{mm h}^{-1})$		D_m (mm)		$\log_{10}N_w$ (m ⁻³ mm ⁻¹)		N_t (m ⁻³)		W (g m ⁻³)		μ		Λ	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
UHI-D	1.88	4.31	1.11	0.42	3.59	0.60	342.15	499.30	0.10	0.19	15.06	13.63	9.32	8.49
W UHI	2.04	4.10	1.10	0.41	3.70	0.58	378.44	398.08	0.12	0.18	15.27	14.48	9.33	8.90
UHI U	2.82	6.94	1.18	0.51	3.57	0.65	380.88	488.27	0.15	0.30	14.09	13.45	8.78	8.45
S UHI	2.60	6.79	1.18	0.46	3.56	0.64	385.00	563.30	0.14	0.30	13.97	13.95	8.61	8.43

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Table 6: Mean and Standard Deviation (SD) Values of R , D_m , $\log_{10}N_w$, N_t , W , μ , and Λ for each month

	$R(\text{mm h}^{-1})$		D_m (mm)		$\log_{10}N_w$ (m ⁻³ mm ⁻¹)		N_t (m ⁻³)		W (g m ⁻³)		μ		Λ	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
May	1.34	2.09	1.04	0.39	3.74	0.68	440.30	602.46	0.08	0.10	9.20	8.05	16.44	16.19
Jun	2.10	4.61	1.16	0.47	3.55	0.66	363.01	464.13	0.12	0.21	8.61	8.09	13.83	12.76
Jul	3.61	8.20	1.28	0.50	3.49	0.58	358.84	507.50	0.18	0.36	8.34	9.34	12.53	12.58
Aug	2.80	6.74	1.16	0.45	3.57	0.62	375.65	476.69	0.15	0.29	9.70	9.60	15.03	14.80
Sep	1.63	4.10	1.04	0.42	3.70	0.64	418.63	612.39	0.10	0.18	10.29	9.35	17.19	15.26
Oct	1.07	1.37	1.03	0.34	3.68	0.55	307.38	312.11	0.07	0.07	7.82	6.86	14.14	12.38

Figures:

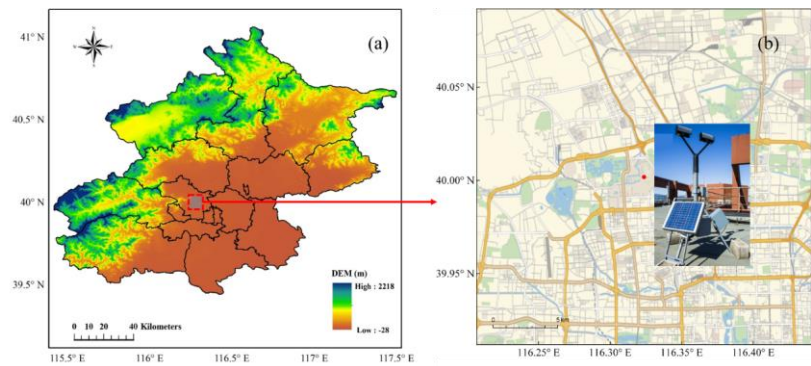


Figure 1: The topography of Beijing and the location of Parsivel² disdrometer deployed at Tsinghua University campus.

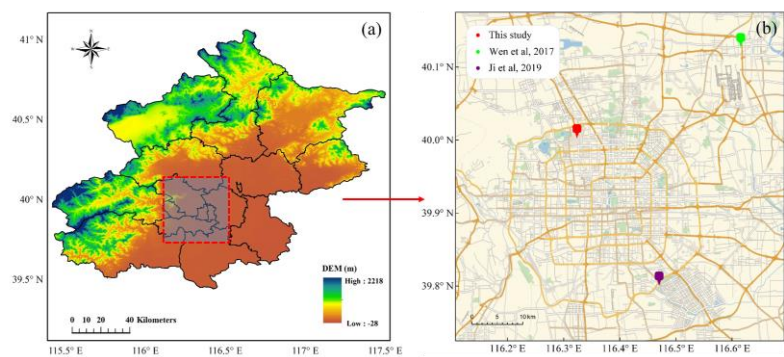


Figure 1: (a) the topography of Beijing, (b) the locations of DSD studies in Beijing area, the red mark represents the location of Parsivel² disdrometer deployed at Tsinghua University campus in this study, the green and purple makers represent locations in the studies by Wen et al. (2017) and Ji et al. (2019), respectively.

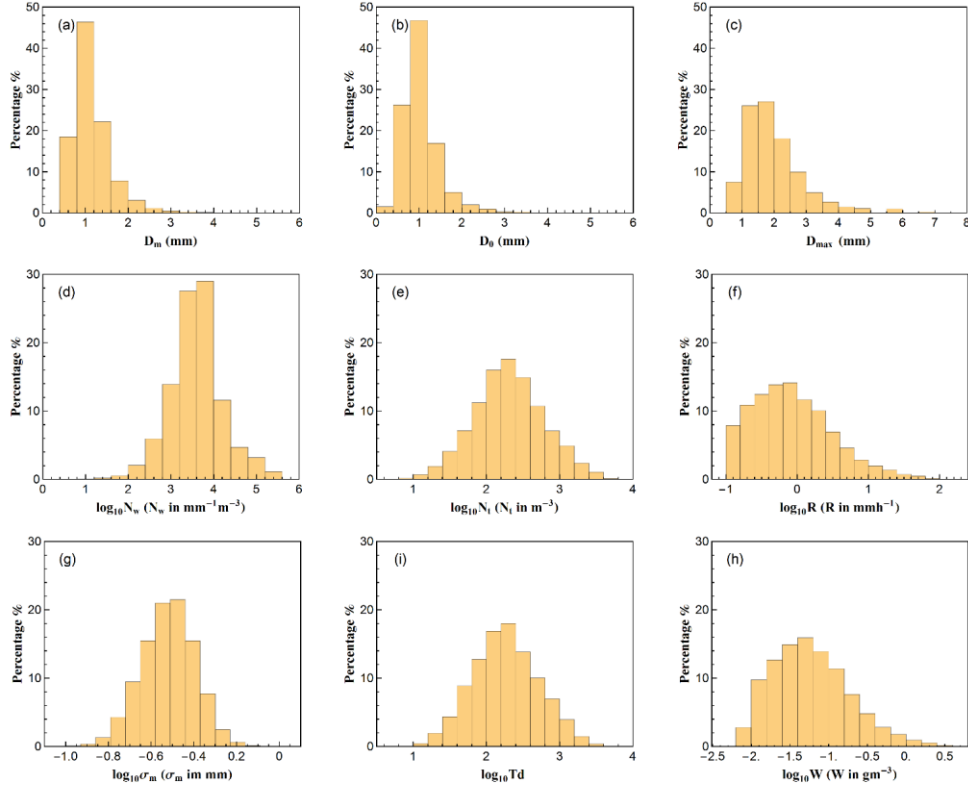


Figure 2: Histograms of different DSD parameters for all selected rainfall: (a) the mass-weighted mean diameter, D_m (mm); (b) median volume diameter D_0 (mm); (c) maximum diameter, D_{max} (mm); (d) generalized intercept parameter, $\log_{10} N_w$ (N_w in $\text{m}^{-3} \text{mm}^{-3}$); (e) total number concentration, $\log_{10} N_t$ (N_t in m^{-3}); (f) rain rate $\log_{10} R$ (R in mm h^{-1}); (g) mass spectrum standard deviation $\log_{10} \sigma_m$ (σ_m in mm); (h) total number of rain drops $\log_{10} T_d$, (i) liquid water content $\log_{10} W$ (W in g m^{-3}).

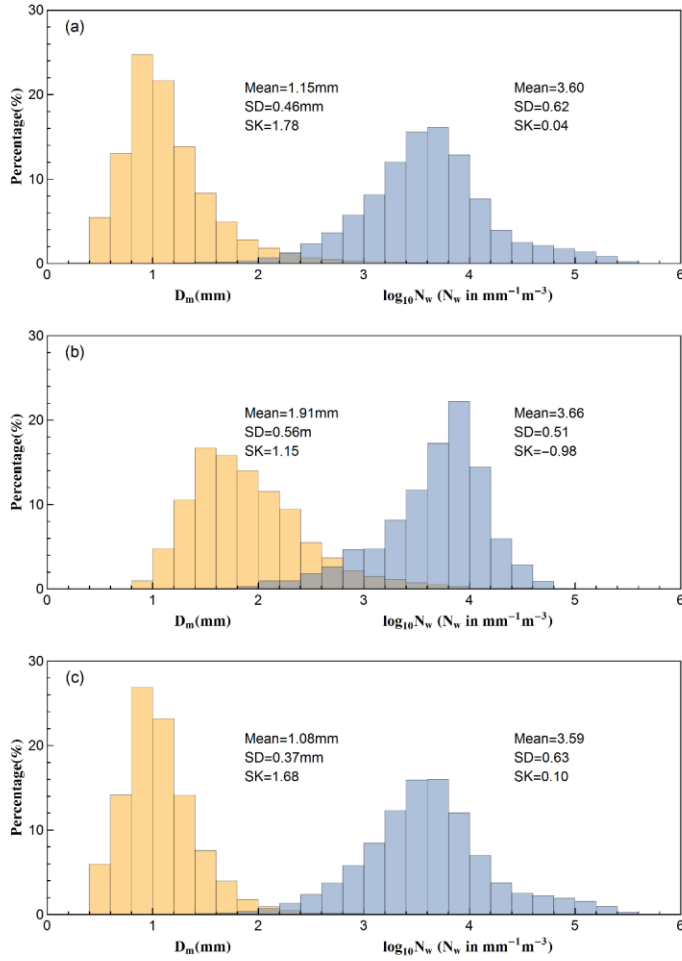


Figure 3: Histograms of D_m and $\log_{10}N_w$ for (a) all the rainfall events, (b) convective events, and (c) stratiform events. Mean values, standard deviation (SD), and skewness (SK) are also shown in the respective panels.

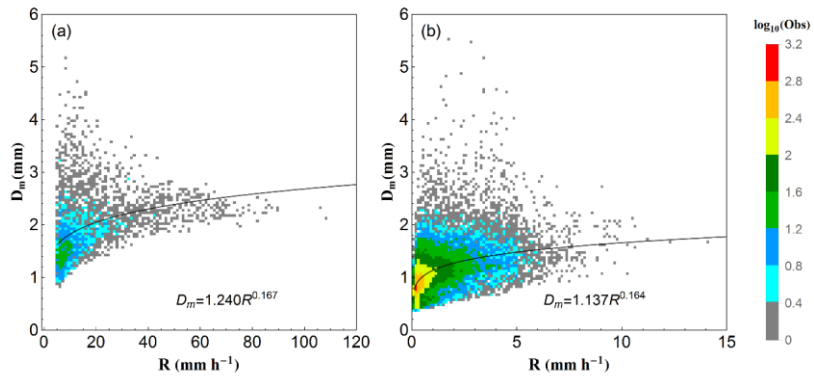
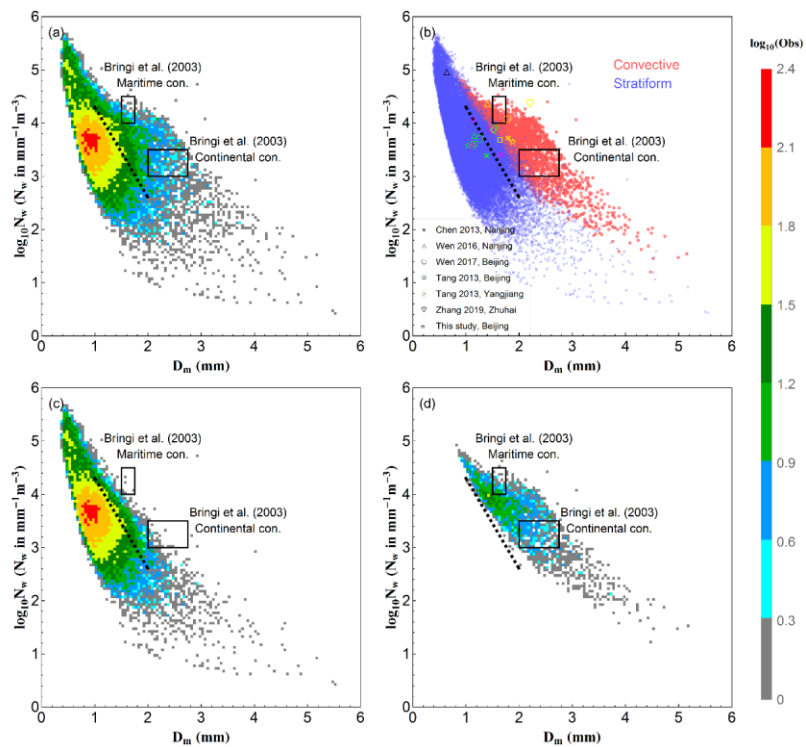


Figure 4: Scatter density plot for D_m (mm) versus R (mm h⁻¹) for (a) convective events, (b) stratiform events. The fitted power-law relationships are also provided in each panel adopting a least-squares method.



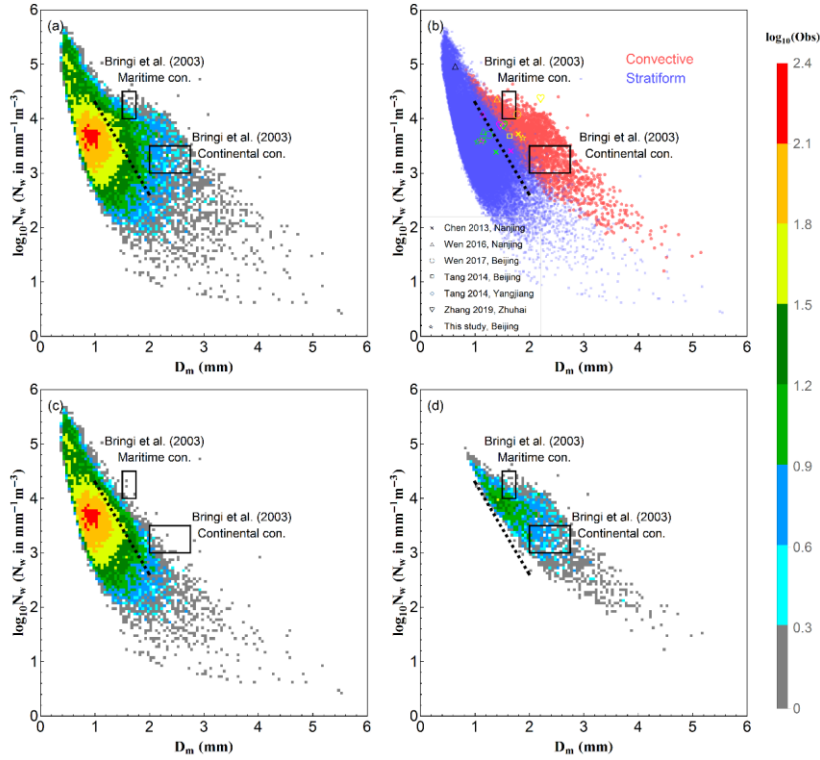


Figure 5: Scatter density plot of $\log_{10}N_w$ versus D_m : (a) the total rainfall events; (c) stratiform events; (d) convective events. (b) is the scatterplot of $\log_{10}N_w$ versus D_m for convective (red circle dots) and stratiform (blue square dots) cases. The two ~~black-grey~~ rectangles in each subplot correspond to the maritime and continental convective clusters, and the black dashed line is the $\log_{10}N_w - D_m$ relationship for stratiform rain reported by Brangi et al. (2003). The cross, hollow triangles, ~~circle~~, squares, diamonds, and hearts in (b) represent the averaged values obtained in previous studies by [Chen et al. \(2013\)](#), [Wen et al. \(2016\)](#), [Wen et al. \(2017\)](#), [Tang et al. \(2014\)](#), [Tang et al. \(2014\)](#), [Zhang et al.\(2019\)](#), for different parts of China. The colors of these symbols represent different events: magenta for total rainfall events; green for convective events, yellow for stratiform events, and black for the shallow events, a third type of precipitation besides convective and stratiform suggested by a few researchers, based on data from vertically pointing radar observations ([Fabry and Zawadzki, 1995](#); [Cha et al., 2009](#)) in the study by [Wen et al. \(2016\)](#).

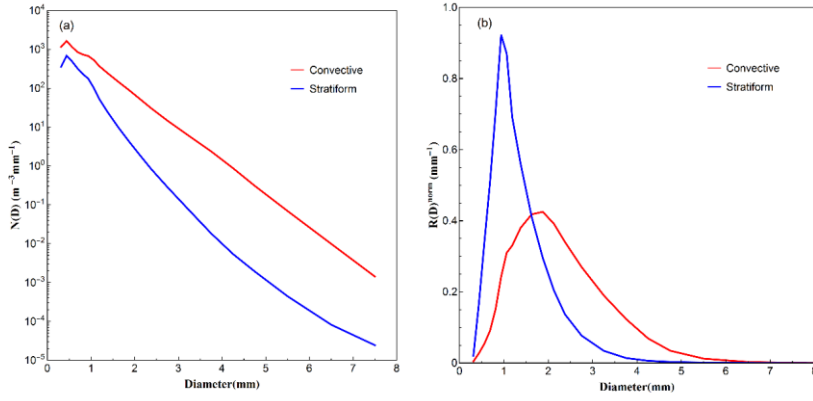


Figure 6: Composite raindrop spectra (a) and normalized $R(D)$ distributions (b) for different rain types.

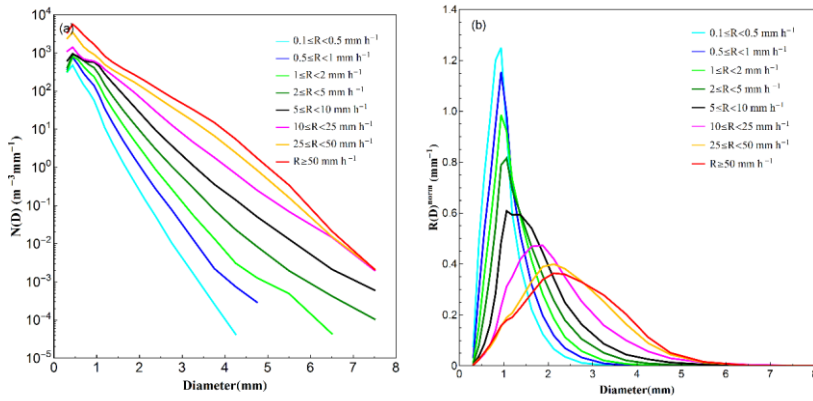


Figure 7: Same as Figure 6, but for different rain rate classes.

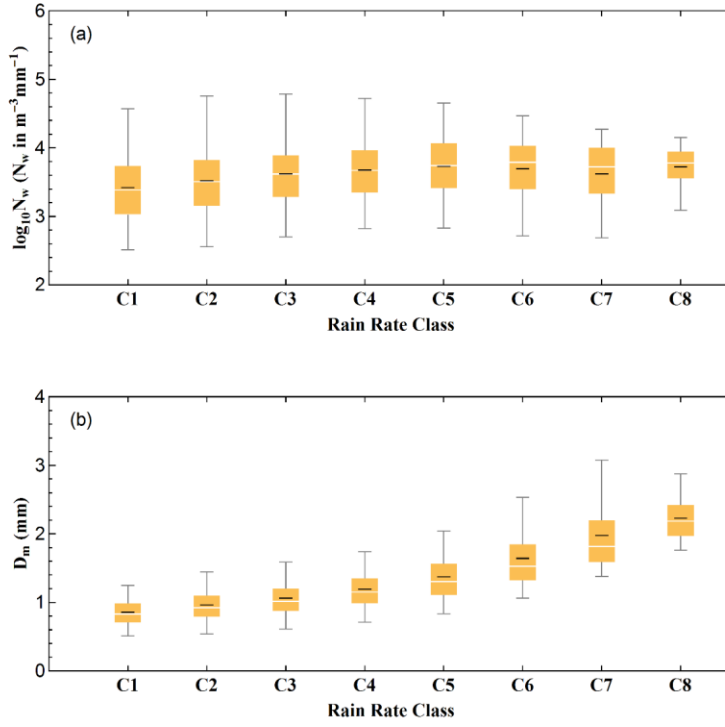


Figure 8: Variation of normalized intercept parameter, $\log_{10} N_w$ (a) and mass-weighted mean diameter, D_m (b) for different rain rate classes. The white central line of the box indicates the median, the black central line in the box indicates the mean values, and the bottom and top lines of the box indicate the 25th and 75th percentiles, respectively. The bottom and top lines of the dashed-vertical lines out of the box indicate the 5th and 95th percentiles, respectively.

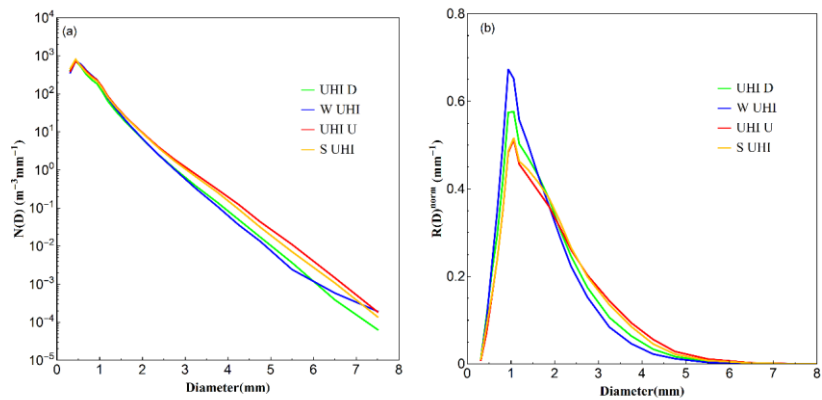
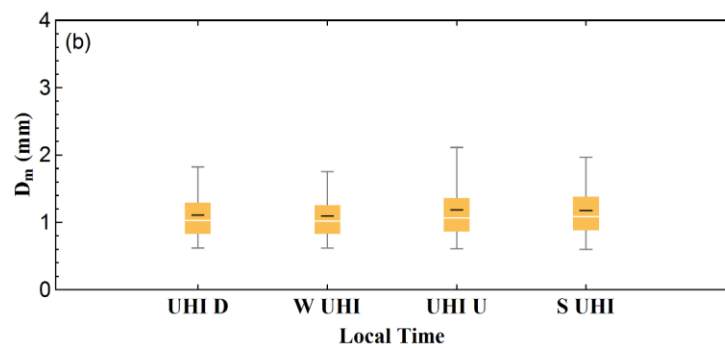
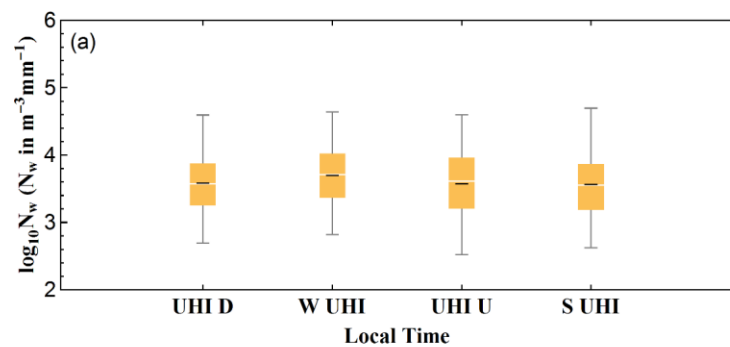


Figure 9: Same as Figure 6, but for different diurnal periods based on UHI intensity.



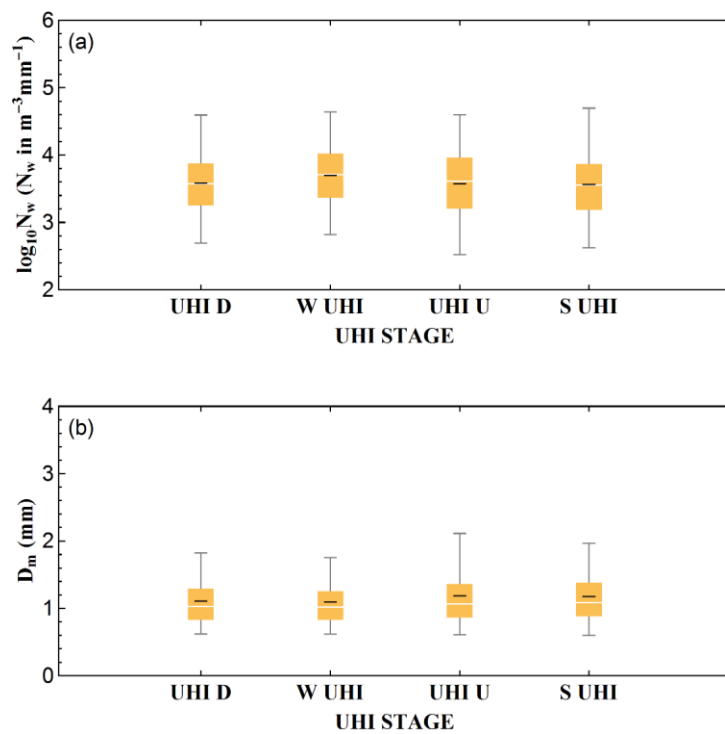


Figure 10: Same as Figure 8, but for different diurnal periods based on UHI intensity.

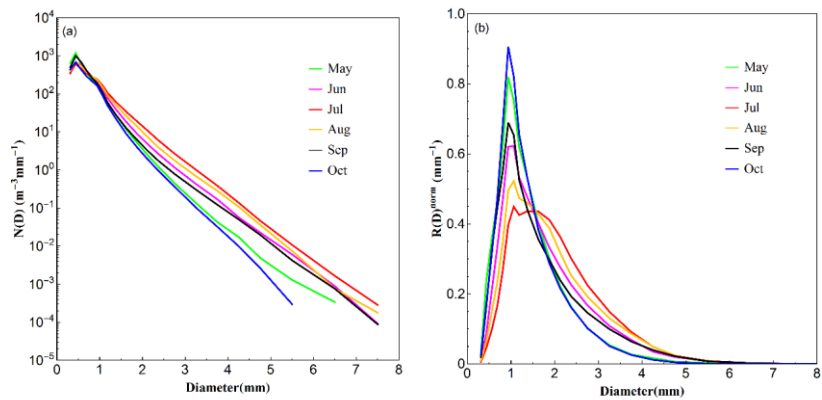


Figure 11: Same as Figure 6, but for different months.

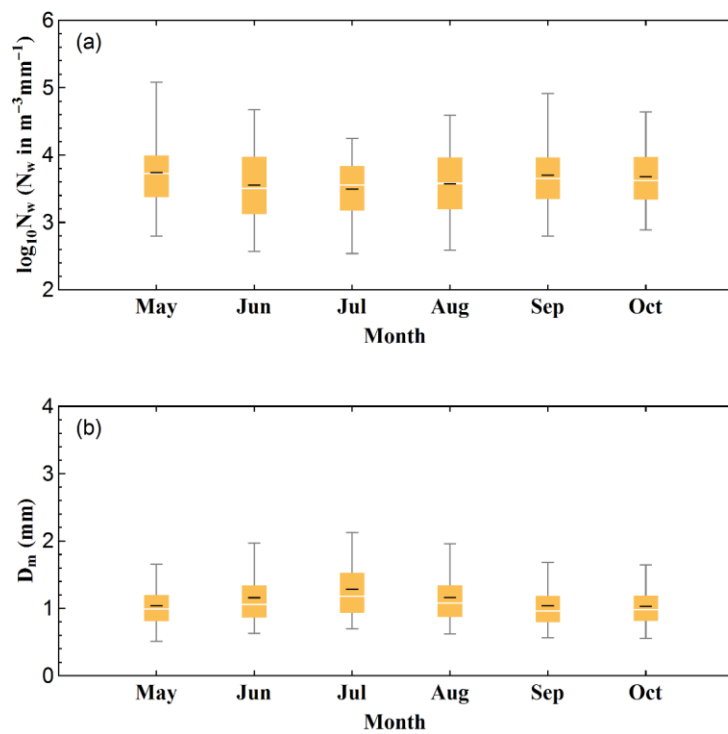
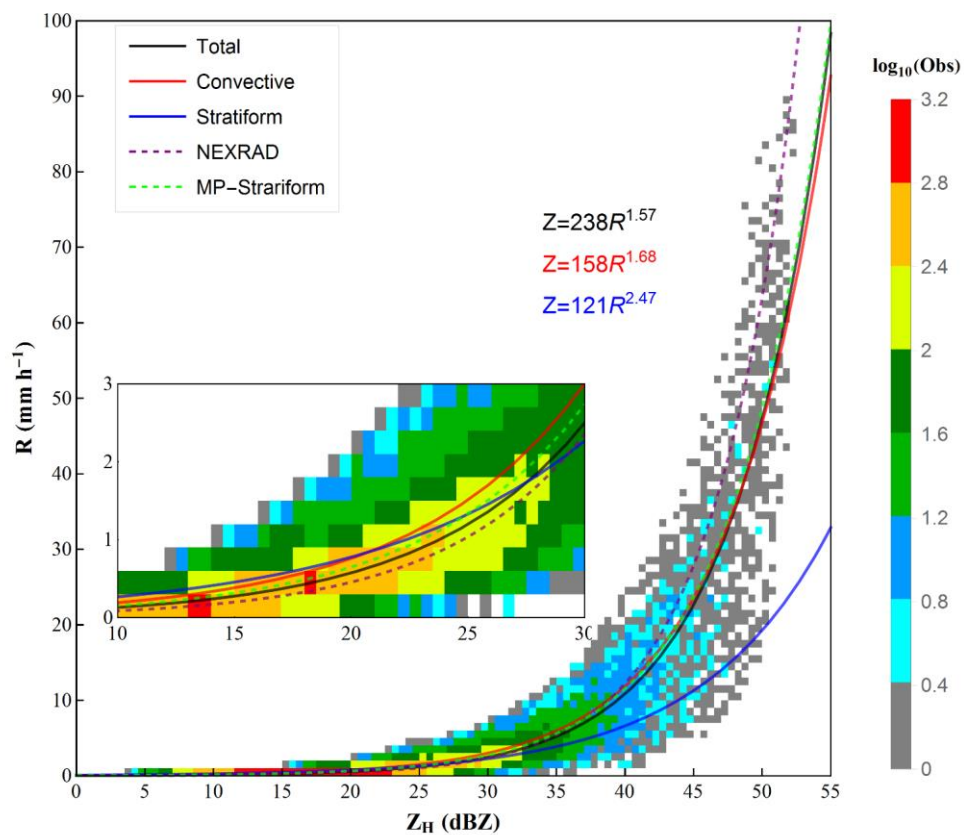


Figure 12: Same as Figure 8, but for different months.



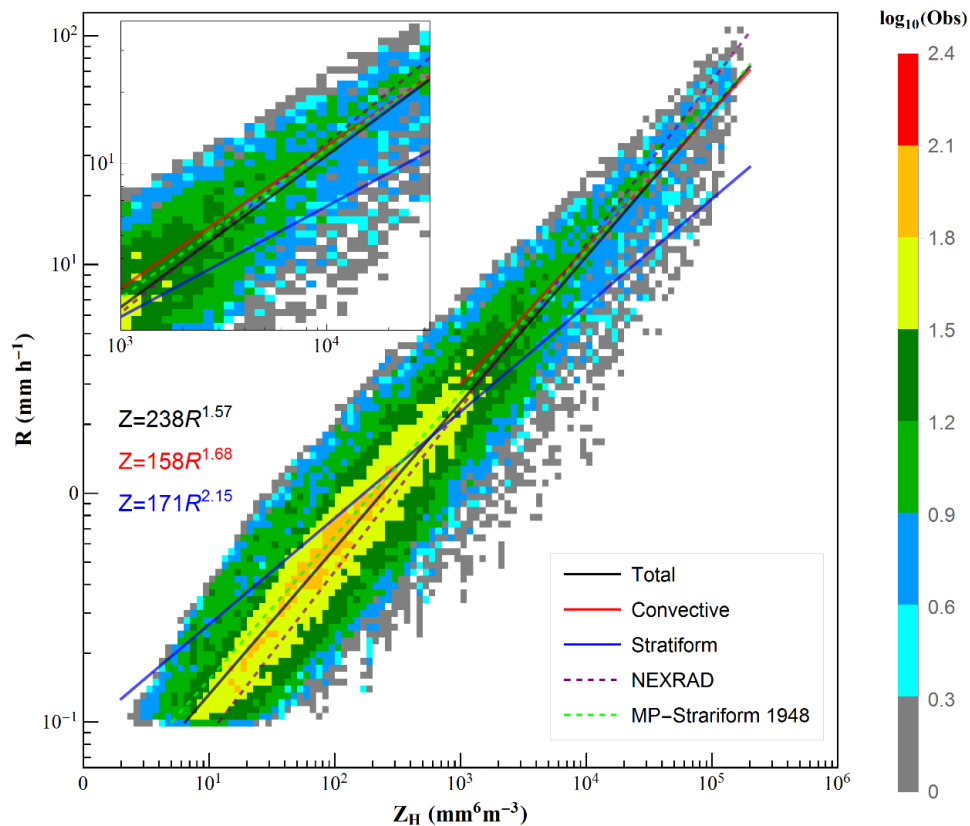
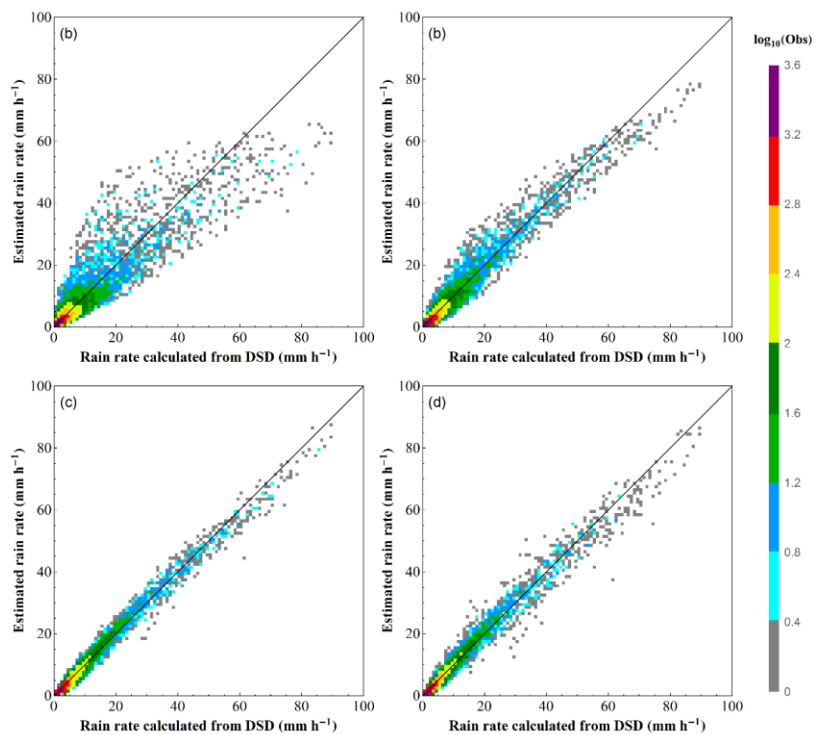


Figure 13: Scatter density plot of R (mm h^{-1}) versus Z_H ($\text{mm}^6 \text{m}^{-3}$) for all rain events. The black, red, and blue curves respectively stand for the fitted power-law relations for total rain, convective rain, and stratiform rain. The purple and green dashed lines denote the default NEXRAD $Z - R$ relation (Fulton et al., 1998) and a commonly used continental stratiform rain relation (Marshall and Palmer, 1948), respectively.

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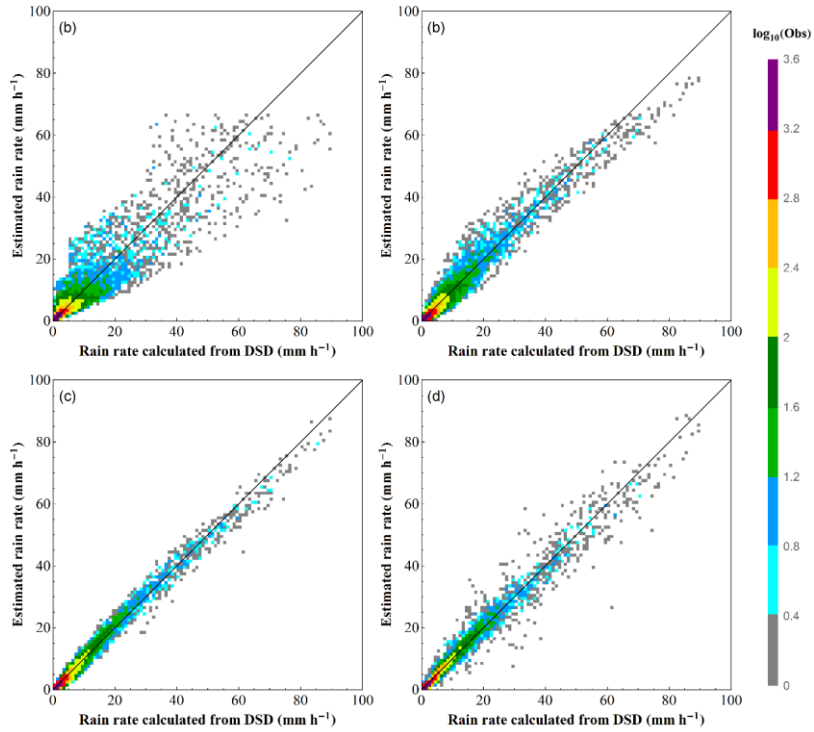
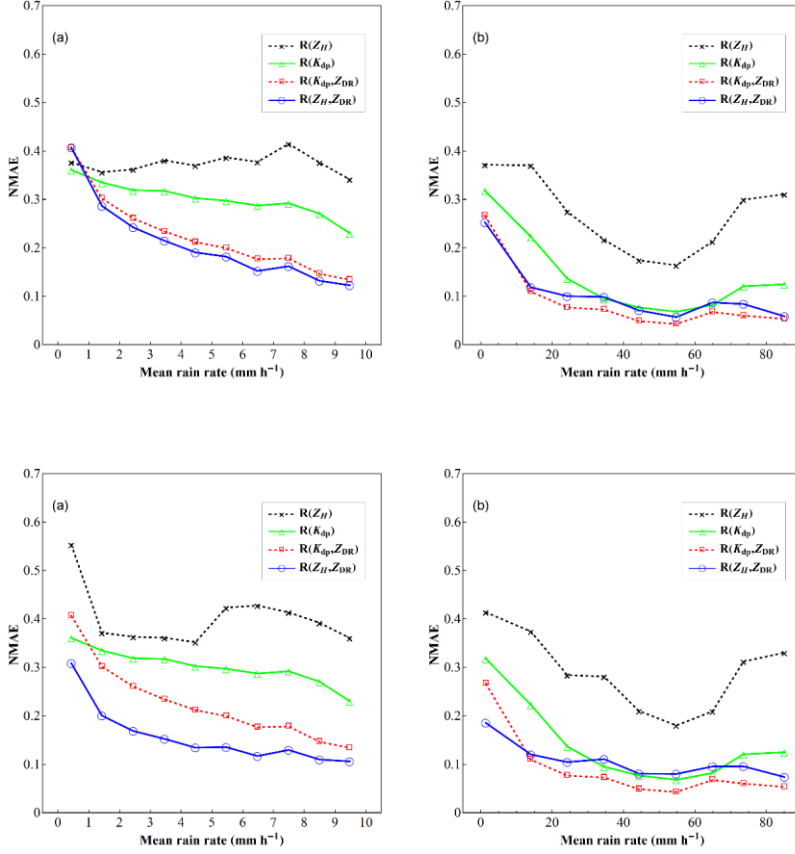


Figure 14: Scatter density plots of rainfall rates estimated from radar rainfall relations versus rain rates calculated directly from DSD: (a) $R(Z_H)$, (b) $R(K_{dp})$, (c) (K_{dp}, Z_{DR}) , and (d) $R(Z_H, Z_{DR})$. The black diagonal line in each panel represents the 1–1 relationship.



5 Figure 15: Parameterization error structure of $R(Z_H)$, $R(K_{dp})$, $R(K_{dp}, Z_{DR})$, and $R(Z_H, Z_{DR})$ as a function of rainfall rate: (a) for mean rain rate less than 10 mm h^{-1} ; (b) for rain rate of the whole dataset.

Supplement

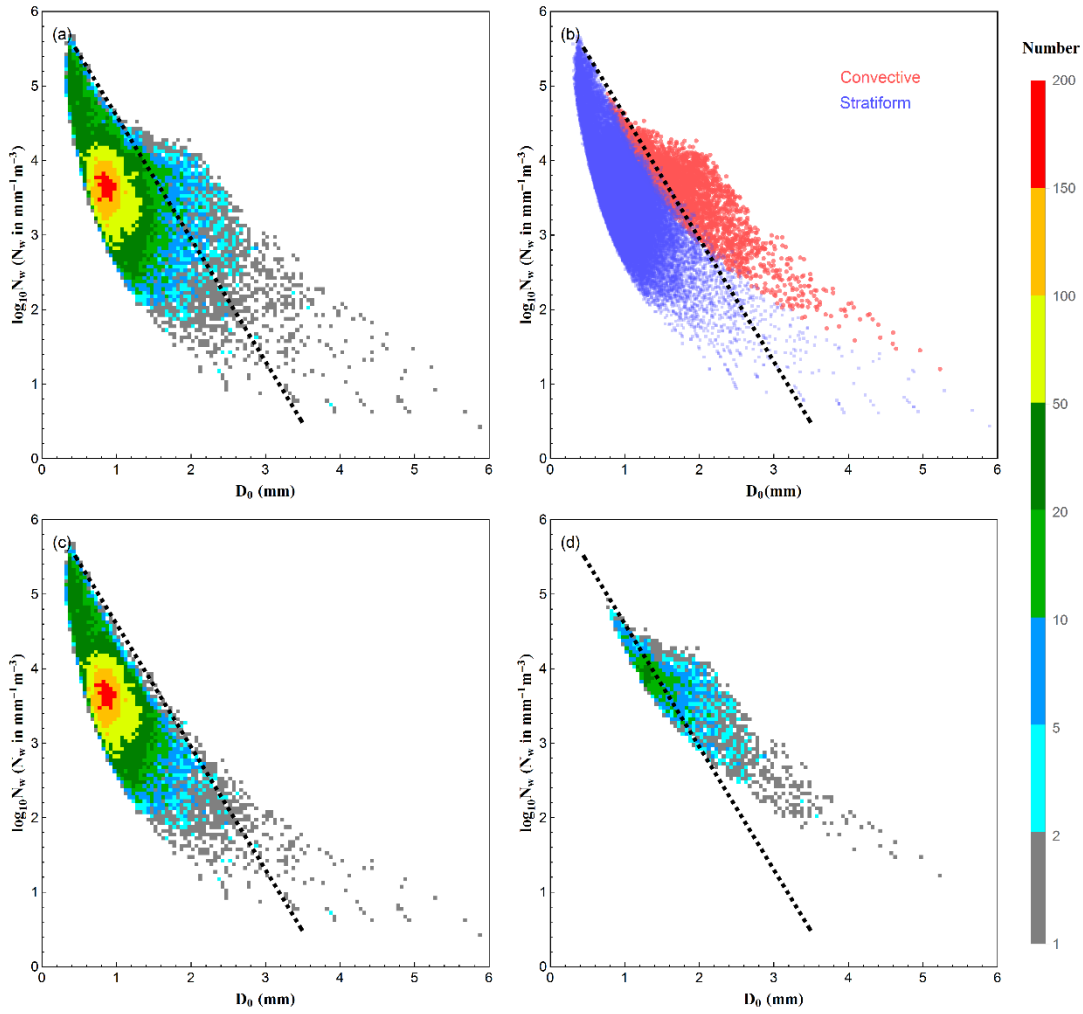


Figure S1: Scatter density plot of $\log_{10}N_w$ versus D_0 : (a) the total rainfall events; (c) stratiform events; (d) convective events. (b) is the scatterplot of $\log_{10}N_w$ versus D_0 for convective (red circle dots) and stratiform (blue square dots) cases. The black dashed line is the $\log_{10}N_w - D_0$ relationship for stratiform rain reported by Thurai et al. (2016).

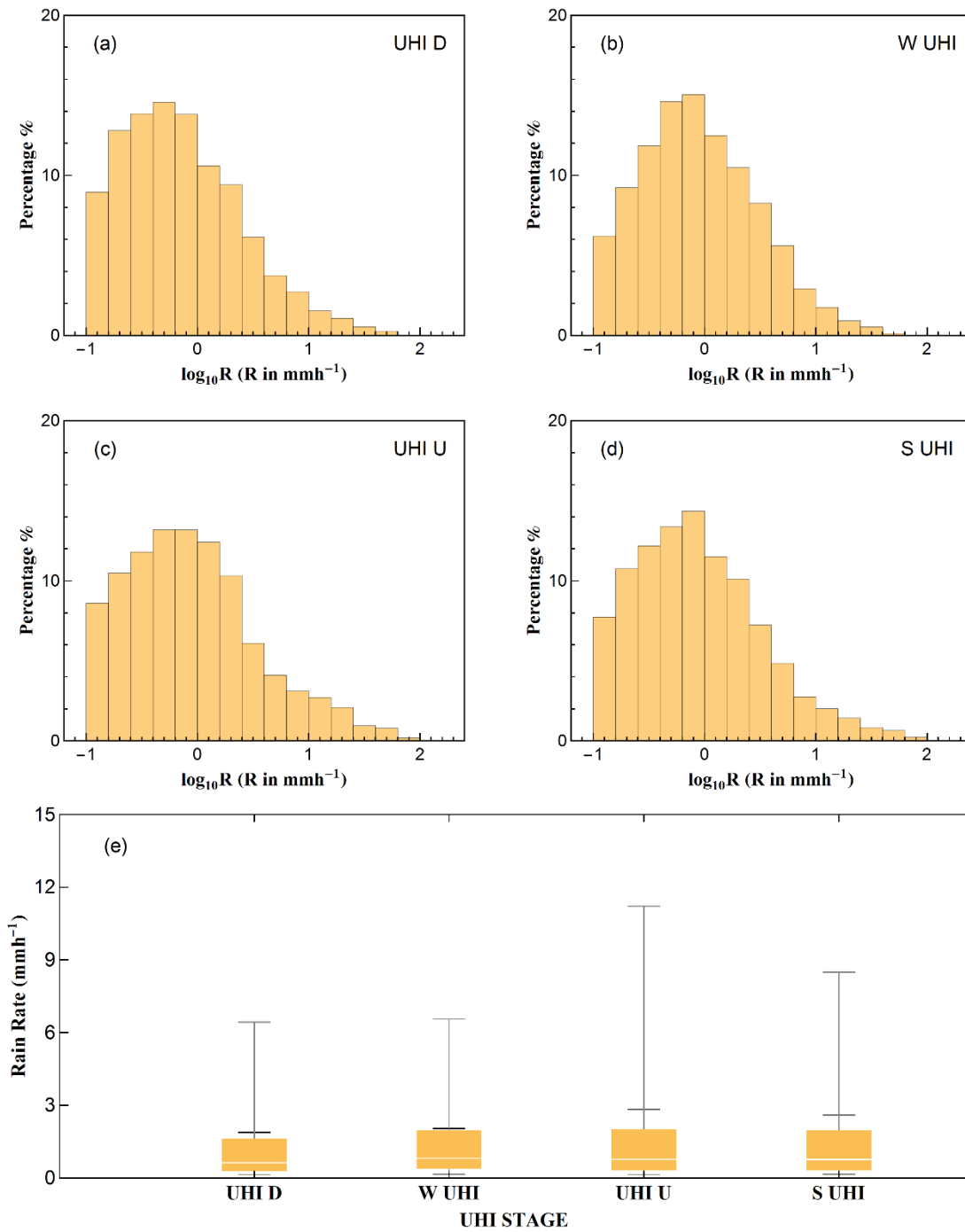


Figure S2: Histograms of rain rate $\log_{10} R$ (R in mm h^{-1}) at different UHI stages: (a) UHI down stage; (b) weak UHI stage; (c) UHI up stage; (d) strong UHI stage; (e) variation of rain rate R (mm h^{-1}) for different UHI stages. The white central lines in the boxes indicate the medians. The black central lines indicate the means, and the bottom and top lines

of the box indicate the 25th and 75th percentiles, respectively. The bottom and top lines of the vertical lines out of the box indicate the 5th and 95th percentiles, respectively.

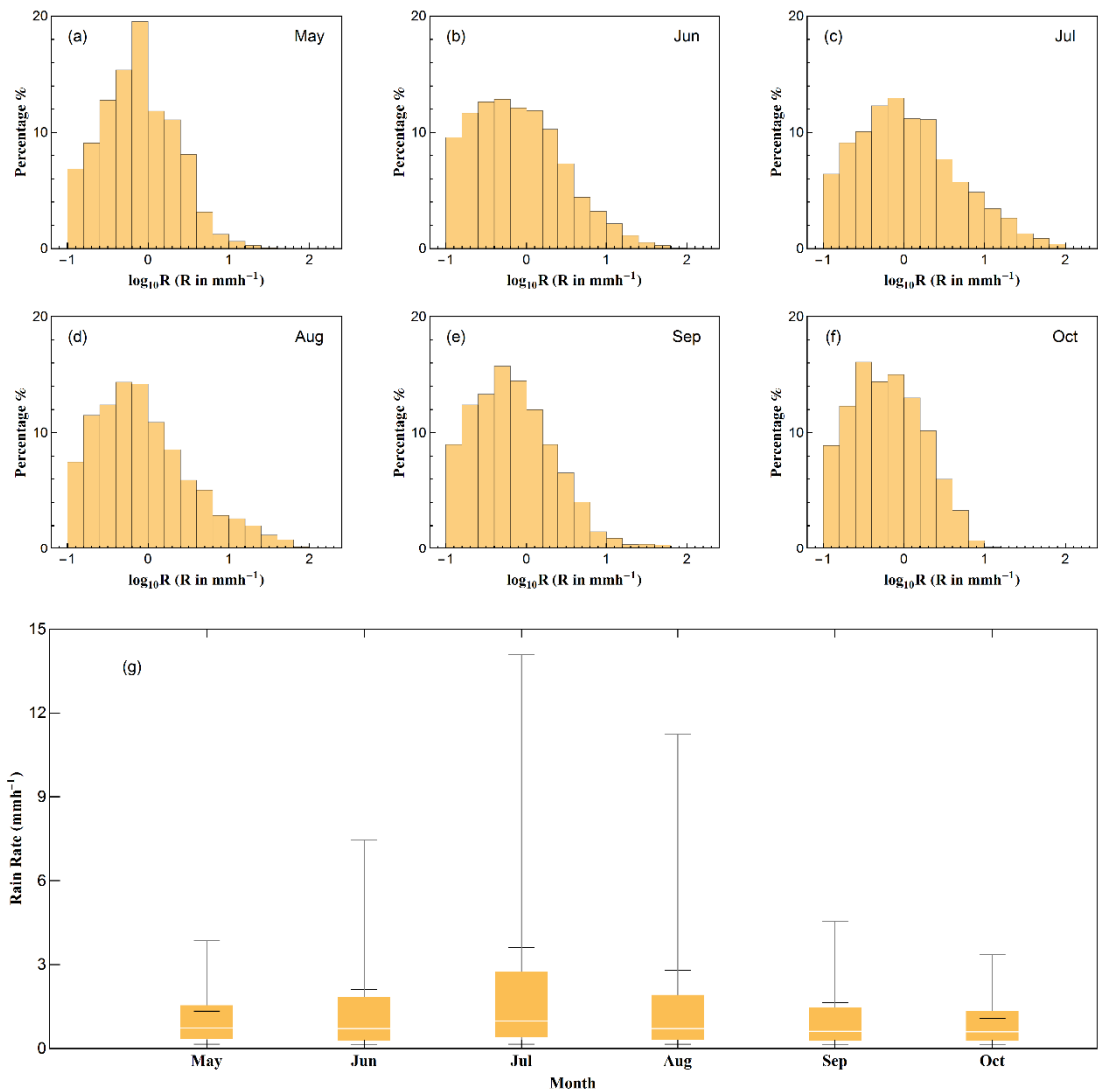


Figure S3: Same as Figure S2, but for different months.