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 (Bringi 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 ~ 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). "

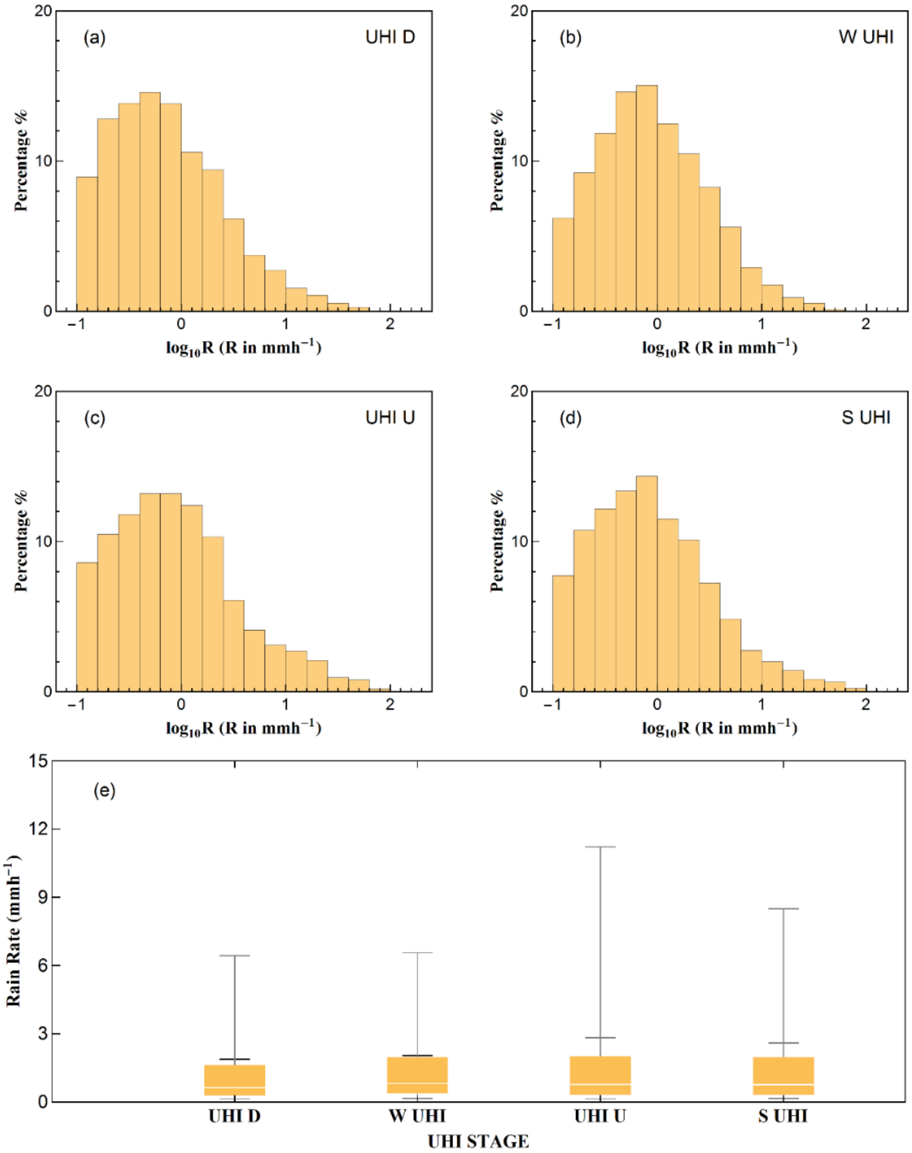

Figure S2: Histograms of rain rate $\log_{10}R$ (R in mm h^{-1}) at different UHI stages: (a) UHI down stage; (b) weak UHI stage; (c) UHI up stage; (d) strong UHI stage; (e) variation of rain rate R (mm h^{-1}) for different UHI stages. The white central lines in the boxes indicate the medians. The black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

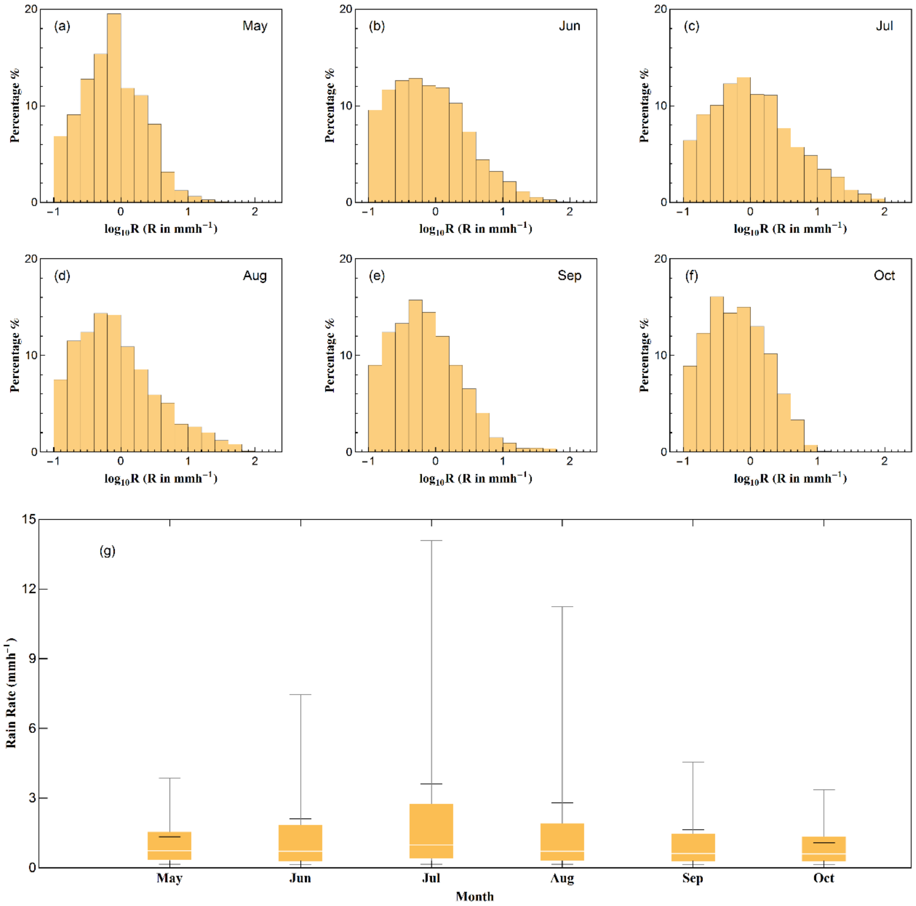

Figure S3: Same as Figure S2, but for different months.

12. Grammar and wording need double check. There are some typos throughout the manuscript, for instance, "P1,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:

Bringi, V.N. and Chandrasekar, V., 2001. Polarimetric Doppler weather radar: principles and applications. Cambridge university press, PP410.

Bringi, V. N., Chandrasekar, V., Hubbert, J., Gorgucci, E., Randeu, W. L., and Schoenhuber, M.: Raindrop size distribution in different climatic regimes from disdrometer and dual-polarized radar analysis, J. Atmos. Sci., 60, 354-365, Doi 10.1175/1520-0469(2003)060<0354:Rsdidc>2.0.Co;2, 2003.

Cha, J.-W., Chang, K.-H., Yum, S. S., and Choi, Y.-J. J. A. i. A. S.: Comparison of the bright band characteristics measured by Micro Rain Radar (MRR) at a mountain and a coastal site in South Korea, 26, 211-221, 2009.

Chen, B. J., Yang, J., and Pu, J. P.: Statistical Characteristics of Raindrop Size Distribution in the Meiyu Season Observed in Eastern China, J. Meteorolog. Soc. Jpn., 91, 215-227, 10.2151/jmsj.2013-208, 2013.

Fabry, F., and Zawadzki, I.: Long-term radar observations of the melting layer of precipitation

and their interpretation, J. Atmos. Sci., 52, 838-851, 1995.
Leinonen, J.: High-level interface to T-matrix scattering calculations: architecture, capabilities and limitations, Opt. Express, 22,1655–1660, doi:10.1364/OE.22.001655, 2014.
Marzano, F. S., Cimini, D., and Montopoli, M. J. A. R.: Investigating precipitation microphysics using ground-based microwave remote sensors and disdrometer data, 97, 583-600, 2010.
Seela, B. K., Janapati, J., Lin, P. L., Reddy, K. K., Shirooka, R., and Wang, P. K.: A Comparison Study of Summer Season Raindrop Size Distribution Between Palau and Taiwan, Two Islands in Western Pacific, J. Geophys. Res-Atmos., 122, 11787-11805, 10.1002/2017jd026816, 2017.
Seela, B. K., Janapati, J., Lin, P. L., Wang, P. K., and Lee, M. T.: Raindrop Size Distribution Characteristics of Summer and Winter Season Rainfall Over North Taiwan, J. Geophys. Res-Atmos., 123, 11602-11624, 10.1029/2018jd028307, 2018.
Tang, Q., Xiao, H., Guo, C. W., and Feng, L.: Characteristics of the raindrop size distributions and their retrieved polarimetric radar parameters in northern and southern China, Atmos. Res., 135, 59-75, 10.1016/j.atmosres.2013.08.003, 2014.
Testud, J., Oury, S., Black, R. A., Amayenc, P., and Dou, X. J. J. o. A. M.: The concept of "normalized" distribution to describe raindrop spectra: A tool for cloud physics and cloud remote sensing, 40, 1118-1140, 2001.
Thurai, M., Bringi, V., May, P. J. J. o. A., and Technology, O.: CPOL radar-derived drop size distribution statistics of stratiform and convective rain for two regimes in Darwin, Australia, 27, 932-942, 2010.
Wen, G., Xiao, H., Yang, H. L., Bi, Y. H., and Xu, W. J.: Characteristics of summer and winter precipitation over northern China, Atmos. Res., 197, 390-406, 10.1016/j.atmosres.2017.07.023, 2017.
Wen, L., Zhao, K., Zhang, G. F., Xue, M., Zhou, B. W., Liu, S., and Chen, X. C.: Statistical characteristics of raindrop size distributions observed in East China during the Asian summer monsoon season using 2-D video disdrometer and Micro Rain Radar data, J. Geophys. Res-Atmos., 121, 2265-2282, 10.1002/2015jd024160, 2016.
Wen, L., Zhao, K., Wang, M., and Zhang, G. J. A. i. A. S.: Seasonal Variations of Observed Raindrop Size Distribution in East China, 36, 346-362, 2019.
Yang, P., Ren, G. Y., and Liu, W. D.: Spatial and Temporal Characteristics of Beijing Urban Heat Island Intensity, J. Appl. Meteorol. Climatol., 52, 1803-1816, 10.1175/Jamc-D-12-0125.1, 2013.