Statistical characteristics of raindrop size distribution during rainy seasons in Complicated Mountain Terrain

Wenqian Mao1,2,3, Wenyu Zhang1,2,3,4, Menggang Kou1,2,4

1. College of Resources and Environmental Sciences, Gansu Agricultural University, Lanzhou, 730070, China
2. School of Geoscience and Technology, Zhengzhou University, Zhengzhou, 450001, China
3. Key Laboratory for Cloud Physics, Chinese Academy of Meteorological Sciences, Beijing, 100081, China
4. College of Atmospheric Sciences, Lanzhou University, Lanzhou, 730000, China

Correspondence to: Wenyu Wenzhi Mao (zhangwy@zzu.edu.cn)

Abstract: In order to improve understanding of the characteristics differences of raindrop size distribution (DSD) in over complex mountainous terrain, the differences characteristics of DSD were analyzed by using the six-months observation data at over the southern slopes, northern slopes and interior of the mountain Qilian Mountains were analyzed using six months of observations. For all rainfall events, the number concentrations of small and large raindrops are greater than that on the northern slopes, but midsize raindrops are less. The DSD spectrum of the interior inside mountains are more variable and differ significantly from that of the northern slopes. The differences in the normalized intercept parameters of the DSD for stratiform and convective rainfall are 8.3% and 10.4%, respectively, and those of the mass-weighted diameters are 10.0% and 23.4%, respectively, while the standard deviations of DSD parameters at interior inside sites are larger. The differences in the coefficient and exponent of the Z-R relationship are 2.5% and 10.7%, respectively, with an increasing value of the coefficient from the southern slope to the northern slope in for stratiform rainfall, but the opposite in for convective rainfall. In addition, the DSD characteristics and Z-R relationships are more similar at the ipsilateral sites and have smaller differences between the southern slope and interior inside mountains.

Keywords: Raindrop size distribution; Complicated mountain terrain; spatial variation; characteristic difference
1 Introduction

Raindrop size distribution (DSD), the number of raindrops per drop size per unit volume, is an important parameter to statistically describe the microstructure of precipitation (Brungi et al., 2003; Ma et al., 2019). The measurement of DSD can provide some fundamental information such as raindrop size (D), liquid water content (W), rain rate (R), radar reflectivity factor (Z) and so on, which has an essential contribution to improving quantitative precipitation estimation (QPE) using weather radar and satellite observations (Adirosi et al., 2018; Jash et al., 2019). The parameterization of DSD can obtain the distribution model parameters of DSD in different rain types, which is significant in advancing microphysics parameterization in numerical weather prediction (NWP) models (Wainwright et al., 2014; McFarquhar et al., 2015; Zhao et al., 2019). In addition, understanding the DSD is crucial in many fields concerning hydrology, agriculture, soil erosion and microwave communication (Rincon et al., 2002; Smith et al., 2009; Angulo-Martinez et al., 2015; Lim et al., 2015; Yang et al., 2016).

Numerous studies have been carried out on the statistical characteristics of DSD in different regions (Campos et al., 2006; Seela et al., 2017; Dolan et al., 2018; Protat et al., 2019; Loh et al., 2019; Jash et al., 2019). It has been shown that the number concentration and size of raindrops increase with rain rate and so the DSD becomes higher and wider. The characteristics in different rain types demonstrate that the mass-weighted mean diameter (i.e., $D_m$) and normalized intercept parameter (i.e., $N_a$) of convective rainfall (CR) are larger than those of stratiform rainfall (SR).

Furthermore, these studies also reveal that there are more differences in the characteristics of DSD. Dolan et al. (2018) divided global DSD characteristics into 6 types by using 12 datasets across three latitudes and found that the centralized regions and DSD parameters of the 6 types varied in location. The average number of raindrops in central Korea was usually greater than that in the southeast under three rainfall systems, especially drops in the 0.31–0.81 mm diameter range (Loh et al., 2019). According to the DSD measurements in results from the Tibetan Plateau (TP) region, it showed the eastern areas have regions had higher raindrop number concentration in the diameter range of raindrops on 0.437–1.625 mm diameters and more variation in different diameters than that in central regions (Wang et al., 2020). Compared to eastern China and northern China, the DSD in southern China demonstrated shows a higher number concentration of relatively small-sized drops, respectively (Zhang et al., 2019). The comparison of the $Z$-$R$ relationship (defined as $Z=AR^b$) indicates that the coefficient decreases with increasing $R$ in the southern Tibetan Plateau (TP), which is opposite in to the case in South China (Wu et al., 2017). For the DSD parameters of stratiform (SR) and convective rainfall (CR), there are various changes between the lower reaches and middle reaches of the Yangtze River (Fu et al., 2020).

As reported in the above studies, DSD characteristics significantly vary significantly with factors such as geographical location, climatic region and rain types. Pu et al. (2020) analyzed the DSD characteristics of five sites in Nanjing city and found the $N_m$ of DSD to be largest at site near industrial areas, but the $D_m$ of DSD was
largest at sites near the city’s center. In other words, even at the urban scale, there
are still differences in the microphysical characteristics reflected by the DSD, which
is due to the influence of the surrounding environment. How then do the
characteristics of DSD vary from location to location over the complicated mountain
terrain? Rao et al. (2006) suggested that the obvious variation in DSD with altitude
were related to evaporation and breakup by comparing the DSD parameters at different
altitudes, suggested that the obvious variation in DSD with altitude is related to the
processes of evaporation and breakup. Using aircraft observations, Geoffroy et al.
(2014) concluded that the total concentration of raindrops decreased while the average
drop size increased as with decreasing altitude, which used aircraft observations. Then
But how large would-might-be the differences in DSD be at different altitudes in
mountainous regions? And then how significant would-might-be the effects be of these
differences?
The Qilian Mountains, a series of marginal mountains in the
northeastern part of the Tibetan Plateau, are a vitally important ecological
protection barrier in the northwest arid areas of the region, which block the connection between of deserts and wilderness in the northwest (shown as Figure 1a).
The mountains form several inland rivers that are important water sources for the
northwest arid areas and have therefore made a considerable contribution to regional economic development (Gou et al., 2005; Tian et al., 2014; Qin et al., 2016). In this paper, we choose the Qilian Mountains as the
research object and selected six sites with different backgrounds representing the
southern slopes, northern slopes and inside-interior of Qilian mountains. To
thoroughly investigate the discrepancies in the this complex complicated mountain
terrain, the DSD characteristics and Z-R relationships were comprehensively
analyzed according to different rain types based on continuous disdrometer
observations in the rainy season. The primary goal is to obtain a deeper
understanding and characteristic differences of DSD over the finer precipitation of
Qilian Mountains and improve the accuracy of QPE, which would-could then be used as a research foundation for developing cloud water resources in
mountainous areas.

2  Data and method
2.1 Sites and instruments
The eastern and middle sections of the Qilian Mountains were chosen as the main
study area, taking into account that several important inland rivers originate from these areas of Qilian Mountains (Li et al., 2019). Six disdrometers were deployed
on the southern slopes, northern slopes and interior (close to the ridge) of Qilian mountains, with three sites in the eastern section which called Taola (TL), Huangchengshiguansha (HS), and Liuba (LB), from south to north, and with
another three sites in the middle section which called Daladong (DLD), Boligou (BLG),
and Shandan (SD), from south to north. The background of the Qilian Mountains is
shown on the satellite map in Figure 1a, and the six sites are marked on the
topographical map, also in Figure 1b. The distances between the six sites are listed in
Table 1. The sites on the south, north and interior of the mountains are basically parallel to the orientation trend of the mountains, and the sections formed by the sites in the east and interior are basically perpendicular to the trend of the mountains. Through an historical weather review and rain gauge observations, the rainy season at the six sites is concentrated in May to October, with more precipitation in July, August and September.
Figure 1. The (a) Geographical overview of the Qian Mountains; and (b) the disdrometer sites; the (circles); or triangles represent the location of the sites (c) the observation device at TL site. Source: The map above is from Google Earth © Google Earth YEAR.

Table 1. Site details: Location between every two sites (latitude, longitude, sea level height) and distances (km) between pairs of sites and distance information.

<table>
<thead>
<tr>
<th>Six sites distance (km)</th>
<th>LB (38.16°N, 102.14°E, 1926m)</th>
<th>HS (37.83°N, 102.01°E, 2342m)</th>
<th>TL (37.33°N, 102.00°E, 2910m)</th>
<th>SD (38.80°N, 101.08°E, 1765m)</th>
<th>BLG (38.4°N, 100.69°E, 2455m)</th>
<th>DLD (38.18°N, 100.3°E, 2957m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LB</td>
<td>-</td>
<td>39.6</td>
<td>94.3</td>
<td>116.0</td>
<td>129.6</td>
<td>161.1</td>
</tr>
<tr>
<td>HS</td>
<td>-</td>
<td>-</td>
<td>55.6</td>
<td>135.1</td>
<td>132.8</td>
<td>154.9</td>
</tr>
<tr>
<td>TL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>182.4</td>
<td>167.3</td>
<td>177.0</td>
</tr>
<tr>
<td>SD</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>54.2</td>
<td>96.8</td>
</tr>
<tr>
<td>BLG</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>43.3</td>
</tr>
<tr>
<td>DLD</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

This experiment studied an optical, laser-based device to measure the DSD, called a DSG4 disdrometer (Figure 1c), which meets the assessment of Functional Specification Requirements for Disdrometer issued by the China Meteorological Administration. The disdrometer has an HSC-OTT Parsivel2 sensor as the...
observation part manufactured by OTT Messtechnik (Germany) and Huatron (China). When raindrops pass through the horizontal flat laser beam generated by the transmitting part of the instrument, it causes a signal attenuation in the laser observation area. The raindrop size is determined by the degree of signal attenuation and the falling speed is recorded by the transit time. The sampling time is 60s and the velocity and drop sizes are divided into 32 non-equally spaced bins, varying from 0.05 to 20.8 m s\(^{-1}\) for velocity and 0.062 to 24.5 mm for drop diameter.

2.2 Quality control of the data

It was necessary to carry out quality control on the data because of potential instrument error. Every minute of DSD data has been carefully processed, which collected by the six DSG4 disdrometers from May to October 2020 was carefully processed. Specifically, the following criteria have been employed in choosing data for analysis (Jaffrain et al., 2011; Guyot et al., 2019; Pu et al., 2020): (1) If the first two size bins were ignored because of low signal-to-noise ratio; (2) samples with 1-min total of raindrop number of raindrops less than 10, or a rain rate at the moment of discontinuous observation less than 0.1 mm h\(^{-1}\) were regarded as noise; (3) raindrops with a terminal velocity \(v(D_i)\) that deviated from the empirical terminal velocity \(v_{emp}(D_i)\) by more than 40% were removed (Kruger and Krajewski, 2002); and (4) raindrops with diameters of more than 8 mm were eliminated; (4) raindrops with falling velocity deviated more than 5% from the empirical velocity were deleted because in their DSDs couldn’t be determined with too few bins. The fourth criterion can be expressed by the formula:

\[
|V(D_i) - V_{emp}(D_i)| < 0.4V_{emp}(D_i)
\]  

where \(V_{emp}(D_i) = 9.65 - 10.3\exp(-0.6D_i)\) \((D_i\) is the mean volume-equivalent diameter of the \(i\)th size category), as derived from the formula given in Atlas et al. (1973).

After data quality control, the sample statistics of key steps are shown in Table 2. The number of 1-min DSD spectra selected from the six sites (LB, HS, TL, SD, BLG, DLD) after data quality control covering the rainy season (May–October) in the Qilian Mountains region in 2020 were 11103, 17619, 14814, 10736, 18861 and 13230, respectively, which accounted for 87.9%, 85.8%, 84.5%, 91.2%, 80.6% and 86.5% of the total number of samples.

<table>
<thead>
<tr>
<th>Samples</th>
<th>LB</th>
<th>HS</th>
<th>TL</th>
<th>SD</th>
<th>BLG</th>
<th>DLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total minutes (min)</td>
<td>12625</td>
<td>20536</td>
<td>17526</td>
<td>11770</td>
<td>23401</td>
<td>15289</td>
</tr>
<tr>
<td>Total minutes without noise (min)</td>
<td>12602</td>
<td>20509</td>
<td>17494</td>
<td>11756</td>
<td>23371</td>
<td>15267</td>
</tr>
<tr>
<td>After quality control (min)</td>
<td>11103</td>
<td>17619</td>
<td>14814</td>
<td>10736</td>
<td>18861</td>
<td>13230</td>
</tr>
<tr>
<td>Available rain minutes (%)</td>
<td>87.9%</td>
<td>85.8%</td>
<td>84.5%</td>
<td>91.2%</td>
<td>80.6%</td>
<td>86.5%</td>
</tr>
</tbody>
</table>

2.3 Integral parameters of rainfall

The basic observations obtained by the disdrometer were their counts of raindrops
at each diameter and velocity. Also, the diameters given by the disdrometers were the mid value of two adjacent bins, which we take the diameters as the corresponding endpoint bin values. The velocities were the weighted average velocity class over the corresponding disdrometer. The raindrop number concentration $N(D)$ (m$^{-3}$ mm$^{-1}$) in the $i$th size bin per unit volume per unit size interval for diameter $D$ is was calculated by the following equation:

$$N(D_i) = \sum_{i,j=1}^{32} \frac{n_{ij}}{A \cdot \Delta t \cdot V_j \cdot \Delta D_i}$$  \hspace{1cm} (2)

where $n_{ij}$ denotes the counts of raindrops measured by the disdrometer within the size bin $i$ and velocity bin $j$ during the sampling time $\Delta t$; $A$ and $\Delta A$ are the sampling area (0.0054 m$^2$) and sampling time (60 s), respectively; $V_i$ (m s$^{-1}$) is the mid-value falling speed for velocity bin $j$; and $\Delta D_i$ is the diameter spread for the $i$th diameter bin.

Some integral rainfall parameters, such as the total number concentration $N$ (m$^{-3}$ mm$^{-1}$), rain rate $R$ (mm h$^{-1}$), radar reflectivity factor $Z$ (mm$^6$ m$^{-3}$) and liquid water content $W$ (g cm$^{-3}$), can be derived by the following equations:

$$N_t = \sum_{i=1}^{32} N(D_i) \Delta D$$ \hspace{1cm} (3)

$$R = \frac{6\pi}{10^4 \rho_w} \sum_{i=1}^{32} V(D_i) D_i^3 N(D_i) \Delta D_i$$ \hspace{1cm} (4)

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

$$W = \frac{\pi \rho_w}{6 \times 10^5} \sum_{i=1}^{32} D_i^3 N(D_i) \Delta D_i$$ \hspace{1cm} (6)

where $\rho_w$ is the water density (1.0 g cm$^{-3}$); and $V(D_i)$ is the falling speed measurements from the disdrometer. In this study, when calculating the rain rate we use $V_{\text{emp}}(D_i)$ to replace $V(D_i)$ because of measurement error, particularly at larger bins and faster falling speeds.

The DSD characteristics of DSD can be described by a three-parameter gamma distribution in following the form introduced by Ulbrich (1983). Also, it has better fitting capability than the M-P distribution on the broader variation of DSD fluctuations, including the middle rain drops, especially on small and large rain scales. And it has better capability than M-P distribution to describe the broader variation of DSD fluctuations, which has been proven to be well fitted the main part of spectra and reduce the fitting error on small and large scale. The three-parameter gamma distribution can be expressed by the following formula:

$$N(D) = N_0 D^\mu \exp(-AD)$$ \hspace{1cm} (7)

where $N(D)$ is the raindrop number concentration; $D$ is the raindrop bins with unit mm; and $N_0$, $\mu$ and $A$ are the intercept, shape and slope parameter from the three parameters of the gamma model, which can be derived from gamma moments or the least-
Although, the gamma distribution is commonly accepted, the normalized gamma distribution has also been widely adopted with its independent parameters and clear physical meaning as follows (Dolan et al., 2018; Ma et al., 2019). Although, three-parameter gamma distribution is commonly accepted model, the normalized gamma model has been widely adopted with its independent parameters and clear physical meaning as follows:

\[ N(D) = \frac{3}{128} \frac{d}{\mu(4+\mu)} (\frac{D}{D_m})^{-\mu} \exp\left(\frac{-(4+\mu)D}{D_m}\right) \]  

(8)

Where \( \mu \) is the shape parameter, which is in dimensionless; \( D_m \) (mm) is the mass-weighted mean diameter, and \( N_w \) (m\(^{-3} \) mm\(^{-1} \)) is the normalized intercept parameter computed from \( D_m \). The form is as follows:

\[ D_m = \frac{\sum_{i=1}^{32} N(D_i)D_i^4\Delta D_i}{\sum_{i=1}^{32} N(D_i)D_i^3\Delta D_i} \]  

(9)

\[ N_w = \frac{4^4}{\pi \rho_w} \left(10^3 W\right) \left(\frac{D_m^4}{D_m^3}\right) \]  

(10)

3 DSD parameter characteristics

3.1 Characteristics of DSD

The number of 1 min DSD spectra from six sites have been selected after data quality control covering the rainy season (May-October) in the Qilian Mountains region in 2020, which are accounted for 87.9%, 85.8%, 84.5%, 91.2%, 80.6%, 86.5% of the total number of samples to LB, HS, TL, SD, BLG, DLD, respectively. Figure 2a shows the mean DSDs for the six districts sites during the rainy season in the Qilian Mountains. The maximum concentration of raindrops was around in diameter and the maximum number concentration values of sites were order as follows: BLG > TL > DLD > HS > SD > LB. As the increasing diameter, the number concentration values decreased and the concentration values followed the order of LB > SD > DLD > TL > BLG > HS at around 2 mm in diameter. When the diameter was larger than 4 mm, the concentration at TL, BLG and HS were relatively high. In this study, the data were roughly divided into small raindrops (less than 1 mm in diameter), midsize raindrops (1–3 mm) and large raindrops (greater than 3 mm) to easily describe the difference in DSDs (Ma et al., 2019b; Pu et al., 2020). To highlight the DSD differences caused by the background environment, Figure 2b shows the mean DSDs normalized with the \( N_w \) and \( D_m \) results for the sites. Compared with Figure 2a, the raindrop characteristics of the raindrops are more consistent across sizes, while the differences between the above sites were more pronounced, especially in the midsizedual and large raindrops, which truly reflect the DSD differences caused by the location variability. Combining the characteristics of the geographical environment of the six sites, we can analyze some differences in DSD characteristics in
the Qilian Mountains. For small raindrops, the number concentrations on the interior and southern slopes sites were greater than that on the northern slope sites; for midsize raindrops, the number concentrations decreased sequentially on the northern, southern, and interior sites inside districts; and for large raindrops, the number concentrations on the interior sites were inside larger. In addition, the number concentrations of raindrops in the middle section of this mountainous area were slightly greater than those in the eastern section.

![Figure 2](image-url)

**Figure 2.** (a) Mean-measured DSDs and (b) Normalized DSDs at six sites of the Qilian Mountains in the rainy season.

### 3.2 Distribution of DSD parameters

In order to study the differences in DSDs, we selected six integral rainfall parameters for discussion — namely, the intercept parameter ($N_0$), mass-weighted mean diameter ($D_m$), shape parameter ($\mu$), total mass concentration ($N_0$), rain rate ($R$), and radar reflectivity factor ($Z$). Figure 3 and Table 2 show the distributions and statistics of these six DSD parameters (the distribution of each parameter was normalized using the uniform method). On average, $D_m$ was more concentrated on smaller values at HS and BLG, which showed smaller mean values than TL and DLD, while significantly more values greater than 1 mm at LB and SD; log$_10$($N_0$) was more centralized on larger values at TL and DLD, with relatively smaller values at LB and SD; and the distribution patterns for $\mu$ and log$_10$($N_0$) were similar to those for log$_10$($N_0$). The density curves of $R$ and $Z$ were similar, but there were differences among the six sites, which would be discussed in detail in subsequent content later in the paper. It is noteworthy that the frequency of samples with $R$ around 0.6–1.0 mm h$^{-1}$ was highest, and samples with $R$ less than 1 mm h$^{-1}$ accounted for more than half of the total rainfall.
Figure 3. Probability density distribution of integral DSD parameters at six sites (LB, HS, TL, SD, BLG, DLD): (a) normalized intercept parameter log$\log N_o$ (m$^{-3}$mm$^{-1}$); (b) mass-weighted mean diameter $D_m$ (mm); (c) shape parameter $\mu$; (d) total number concentration log$N_i$ (m$^{-3}$); (e) rain rate $R$ (mm h$^{-1}$); (f) radar reflectivity factor $Z_{DBZ}$.

Table 3-1. Statistical of several integral DSD parameters for all observations at six sites (LB, HS, TL, SD, BLG, DLD).

<table>
<thead>
<tr>
<th>Sites</th>
<th>log$\log N_o$ (m$^{-3}$mm$^{-1}$)</th>
<th>$D_m$ (mm)</th>
<th>$\mu$</th>
<th>log$N_i$ (m$^{-3}$)</th>
<th>$R$ (mm h$^{-1}$)</th>
<th>$Z_{DBZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LB</td>
<td>3.43</td>
<td>0.47</td>
<td>0.25</td>
<td>0.99</td>
<td>2.68</td>
<td>10.92</td>
</tr>
<tr>
<td>HS</td>
<td>3.49</td>
<td>0.48</td>
<td>0.29</td>
<td>0.89</td>
<td>3.35</td>
<td>11.12</td>
</tr>
<tr>
<td>TL</td>
<td>3.69</td>
<td>0.48</td>
<td>0.55</td>
<td>0.90</td>
<td>4.40</td>
<td>11.37</td>
</tr>
<tr>
<td>SD</td>
<td>3.48</td>
<td>0.48</td>
<td>0.17</td>
<td>0.96</td>
<td>2.12</td>
<td>10.62</td>
</tr>
<tr>
<td>BLG</td>
<td>3.72</td>
<td>0.54</td>
<td>0.15</td>
<td>0.89</td>
<td>5.17</td>
<td>11.71</td>
</tr>
<tr>
<td>DLD</td>
<td>3.69</td>
<td>0.45</td>
<td>0.50</td>
<td>0.90</td>
<td>2.66</td>
<td>11.52</td>
</tr>
</tbody>
</table>

Note: ME is mean; SD is standard deviation; SK is skewness.

3.3 Characteristics of DSD characteristics in different rain rate classes

To further understand the characteristics of DSDs at the six sites, the samples were divided into six classes according to the associated rain rates ($R$): C1, $R<0.5$; C2, $0.5 \leq R<2$; C3, $2 \leq R<4$; C4, $4 \leq R<6$; C5, $6 \leq R<10$; C6, $R>10$ mm h$^{-1}$. Such classification was based on two considerations: firstly, the number of observation samples in different rainfall rates roughly conformed to a normal distribution; and secondly, the mean maximum diameter interval of different rainfall rates gradually increased increased (Li et al., 2019). Of course, other studies about classification studies were referenced and the fact that the rain rate in this area is smaller than that in the southern China was taken into account (Ma et al., 2019b; Zeng et al., 2021). Figure 4 shows the mean DSDs at each rainfall rate class for the six sites. Table 3-1 lists contains...
the number of samples and statistical values of the DSD parameters for the six classes.

Clearly, obviously, as the rainfall rate increased, with the rain rate class increasing, the number concentration of almost all rainfall sizes and the width of DSD shapes increased, and thus the tail of the DSD shape gradually moved gradually towards a larger diameter, which are similar to the previous findings studies such as those of Ma et al. (2019b) and Pu et al. (2020). Taking a number concentration of 0.01 m$^{-3}$, the mean maximum diameter of DSD in each class was ordered as follows: in order, 2.3–2.5, 3.2–3.4, 3.9–4.5, 4.3–5.0, 5.0–5.6 and 6.0–7.0 mm (the sixth class diameter range is not fully shown in the figure). In class C1, the number concentrations were relatively similar in at different sites; starting from class C2, the differences of in number concentration increased when the diameter was greater than 2 mm for the six sites; and the differences of in number concentration were gradually reflected on in each rainfall size bin as the rainfall rate class increased. Observationally, Observingly, the DSDs of BLG, HS and TL have had larger number concentrations in different rainfall rate classes, and the DSD parameters and standard deviations (SDs) were larger, especially for BLG.

Table 3–4. Statistics of several integral DSD parameters for six rain rate classes at six sites.

<table>
<thead>
<tr>
<th>Class</th>
<th>Site</th>
<th>Samples (m$^{-3}$ mm$^{-1}$)</th>
<th>$D_m$ (mm)</th>
<th>$\mu$</th>
<th>log$_{10}N_d$ (m$^{-3}$)</th>
<th>$R$ (mm h$^{-1}$)</th>
<th>log$_{10}N_e$ (m$^{-3}$)</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 (&lt;0.5 mm h$^{-1}$)</td>
<td>LB</td>
<td>6520</td>
<td>3.25</td>
<td>0.41</td>
<td>0.88</td>
<td>0.18</td>
<td>12.36</td>
<td>7.09</td>
</tr>
<tr>
<td></td>
<td>HS</td>
<td>10753</td>
<td>3.43</td>
<td>0.44</td>
<td>0.81</td>
<td>0.17</td>
<td>12.01</td>
<td>7.03</td>
</tr>
<tr>
<td></td>
<td>TL</td>
<td>7858</td>
<td>3.52</td>
<td>0.44</td>
<td>0.79</td>
<td>0.16</td>
<td>12.91</td>
<td>7.12</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>5772</td>
<td>3.34</td>
<td>0.43</td>
<td>0.85</td>
<td>0.18</td>
<td>11.72</td>
<td>6.99</td>
</tr>
<tr>
<td></td>
<td>BL</td>
<td>10073</td>
<td>3.50</td>
<td>0.48</td>
<td>0.79</td>
<td>0.17</td>
<td>12.94</td>
<td>7.28</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>8689</td>
<td>3.51</td>
<td>0.43</td>
<td>0.79</td>
<td>0.15</td>
<td>13.04</td>
<td>6.92</td>
</tr>
<tr>
<td>C2 (0.5–2 mm h$^{-1}$)</td>
<td>LB</td>
<td>3318</td>
<td>3.66</td>
<td>0.41</td>
<td>1.06</td>
<td>0.24</td>
<td>9.93</td>
<td>5.75</td>
</tr>
<tr>
<td></td>
<td>HS</td>
<td>5000</td>
<td>3.82</td>
<td>0.39</td>
<td>0.97</td>
<td>0.21</td>
<td>10.21</td>
<td>5.88</td>
</tr>
<tr>
<td></td>
<td>TL</td>
<td>5368</td>
<td>3.87</td>
<td>0.42</td>
<td>0.98</td>
<td>0.23</td>
<td>10.35</td>
<td>6.15</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>3778</td>
<td>3.73</td>
<td>0.41</td>
<td>1.03</td>
<td>0.23</td>
<td>9.94</td>
<td>6.14</td>
</tr>
<tr>
<td></td>
<td>BL</td>
<td>6411</td>
<td>3.97</td>
<td>0.47</td>
<td>0.94</td>
<td>0.25</td>
<td>11.24</td>
<td>6.72</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>4778</td>
<td>3.88</td>
<td>0.37</td>
<td>0.95</td>
<td>0.20</td>
<td>10.91</td>
<td>6.02</td>
</tr>
<tr>
<td>C3 (2–4 mm h$^{-1}$)</td>
<td>LB</td>
<td>782</td>
<td>3.71</td>
<td>0.47</td>
<td>1.13</td>
<td>0.37</td>
<td>7.33</td>
<td>4.28</td>
</tr>
<tr>
<td></td>
<td>HS</td>
<td>884</td>
<td>3.96</td>
<td>0.50</td>
<td>1.16</td>
<td>0.34</td>
<td>8.42</td>
<td>5.22</td>
</tr>
<tr>
<td></td>
<td>TL</td>
<td>1232</td>
<td>4.00</td>
<td>0.47</td>
<td>1.13</td>
<td>0.33</td>
<td>8.70</td>
<td>5.93</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>812</td>
<td>3.89</td>
<td>0.44</td>
<td>1.19</td>
<td>0.27</td>
<td>8.57</td>
<td>5.53</td>
</tr>
<tr>
<td></td>
<td>BL</td>
<td>1865</td>
<td>4.05</td>
<td>0.49</td>
<td>1.11</td>
<td>0.30</td>
<td>8.62</td>
<td>5.75</td>
</tr>
</tbody>
</table>
C4 (4–6 mm h−1): 0.47, 0.40, 0.33, 0.29, 0.26, 0.23, 0.20, 0.13, 0.10
C6 (6–10 mm h−1): 0.47, 0.40, 0.33, 0.29, 0.26, 0.23, 0.20, 0.13, 0.10
C5 (6–10 mm h−1): 0.47, 0.40, 0.33, 0.29, 0.26, 0.23, 0.20, 0.13, 0.10
C6 (>10 mm h−1): 0.47, 0.40, 0.33, 0.29, 0.26, 0.23, 0.20, 0.13, 0.10

Figure 4: Distribution of mean measured DSD for different rain rate classes at 6–six
Figure 5 shows box-and-whisker plots of the normalized intercept parameter $\log_{10} N_w$ and mass-weighted mean diameter $D_m$ for six sites at each rain rate class. The middle line in the box indicates the median. The left and right lines in the box indicate the 25th and 75th percentiles. The left and right ends of whiskers indicate the most extreme data points between the 5th and 95th percentiles, except outliers. The median of $D_m$ gradually increased with a larger value range when the rain rate class increased, particularly for HS and BLG at class C5 and C6. The median of $\log_{10} N_w$ increased at class C1 to C3 and then tended to decrease at class C5 to C6, for which the reduction was obvious at sites with a larger value range, such as HS and BLG. Ma et al. (2019b) also obtained similar conclusions about $D_m$ and $\log_{10} N_w$. The indication was indicated that the increase of rain rate was mainly due to the growth in raindrop size. And also, the change of number concentration may have been caused by the imbalance between the loss of number concentration at small raindrop size and the addition at large raindrop size, which implies in a sense a relationship of between the collision–coalescence and break-up of raindrops. It is worth noting that the microphysical processes were quite different among the sites, which were being greatly influenced by the surrounding environment. Because HS and BLG were located on the interior of the mountain and close to the ridge, thus their dynamics and thermodynamics as well underlying surfaces were thus different from those of other districts.
Figure 5. Variation of the normalized intercept parameter $\log_{10} N_w$ (a) and the mass-weighted mean diameter $D_m$ (b) for different rain rate classes at six sites. The three lines in the boxes are the 25th, 50th and 75th percentiles, from left to right, respectively. The whiskers at the left and right ends are the 5th and 95th percentiles, respectively. The colors represent the six sites same as in other figures.

Figure 6 displays the contribution of different rain rate classes to the total rainfall at different sites. It is clear that C2 makes the most contribution to the total rainfall of all sites, followed by C3, and the sum of the two classes' contribution could reach 60% of the total rainfall. Compared with the interior districts on the inside and southern slopes, C2 and C3 contributed slightly less to sites LB and SD.
(i.e., the northern slopes), while C5 and C6 contributed relatively more to sites LB and SD, indicating that there is a greater probability of heavy precipitation events on the northern slopes. The DSD parameters in Table 3 provide a more detailed representation of the rainfall differences between the three geographical sections/locations of the Qilian Mountains, i.e., namely the interior, southern slopes and northern slopes. Meanwhile, it also reflects the characteristics of rainfall in the eastern and interior sections, such as the eastern section has had larger \( Z \) and \( D_m \) and smaller \( \log_{10} V_{c} \) and \( \log_{10} V \) compared to the interior section. It is possible that there is a certain spatial connection between precipitation at the sites, which is related to the factors like such as the source of precipitation vapor, weather system and so on.

**Figure 6.** Proportion of rainfall with different rain rate classes to rain amount at six sites.

### 3.4 DSD properties for different rain types

Previous studies on DSD have shown that there are significant differences in the DSD of convective and stratiform rainfall in the same climatic region, which has a substantial impact on the parameterization of NWP and remote sensing observations (Bringi et al., 2003; Penide et al., 2013). Due to the different physical mechanisms of convective and stratiform rainfall, it is possible to discuss the differences in microphysical structures for rainfall types through their DSD. In some studies, there have been many different classification methods for rainfall types. For example, Testud et al. (2001) used the rain rate; Chen et al. (2013) combined the rain rate and its standard deviation (SD); and the findings of Das et al. (2018) were based on the rain rate and radar reflectivity factor. Among these, the method from of Chen et al. (2013) has commonly been used to establish samples of convective and stratiform rainfall, but mainly in which the studies' area were concentrated in semi-humid or humid regions with relatively high rain rate and rainfall. However, the Qilian Mountains are located in the semi-arid regions of China and far from the sea, which where the average rainfall rain and rainfall are quite
different from the semi-humid regions. Therefore, this paper proposes a new classification method for precipitation applicable to the arid and semi-arid regions of Northwest China based on the classification ideas of Chen et al. (2013) and Das et al. (2018).

Firstly, the sequences of DSD with continuous 1-min samples more than 10 minutes are determined, and $R_t$ is defined to denote the rain rate at time $t$. The In the first cases, the $R$ of samples from $R_{t,5}$ to $R_{t,5}$ are all less than 5 mm h$^{-1}$ and their standard deviation (SD) is less than 1.5 mm h$^{-1}$; in the second cases, the $R$ of samples from $R_{t,5}$ to $R_{t,5}$ are greater than or equal to 5 mm h$^{-1}$ with more than 99 samples and their SD is greater than 1.5 mm h$^{-1}$; and in the third case, the situation is the same as the second case but their SD is less 1.5 mm h$^{-1}$. Secondly, samples satisfying $Z<20$ and $W<0.08$ in the second case are removed (Thurai et al., 2016; Das et al., 2018). And then, samples with $R_t$ greater than or equal to 5 mm h$^{-1}$ in the second case are regarded as convective rainfall and samples with $R_t$ less than 5 mm h$^{-1}$ in the second case are regarded as transitional rainfall (the rainfall stage in which convective precipitation develops and declines). Samples in the first case are regarded as stratiform rainfall.

Through experiments, the third case does not exist. The log$_{10} N_a$ and $D_a$ of different rainfall types are different, which were taken as the main research objects. Figure 7 shows the variation of log$_{10} N_a$ with $D_a$ at different sites. The blue, red, and yellow scattered points represent stratiform, convective and transitional rainfall, respectively. Obviously, there are fairly clear boundaries between the scatter points for the different precipitation type events, and the same dividing line can be used to distinguish between the different rainfall types at different sites. The black solid lines were drawn based on visual examination of the data with a slope of approximately $-1.60$ and intercept of 6.008 to represent the split between stratiform, transitional and convective rainfall in all subplots. The black dashed line can distinguish transitional rainfall (transitional and stratiform rainfall have an overlap area) with a slope of approximately $-3.338$ and intercept of 6.847. Note that the dividing line between stratiform and convective rainfall has the same slope as that obtained by Bringi et al. (2003) (solid green line with a slope of $-1.6$ and intercept of 6.33) who fitted the composite results based on disdrometer data and from radar retrievals covering many climate conditions from near the equator to plateau. The log$_{10} N_a$ and $D_a$ from the figures for stratiform, convective and transitional rainfall are respectively concentrated in the ranges of 3.1–3.9 m$^{-2}$mm$^{-1}$, 0.75–1.1 mm; 3.8–4.2 m$^{-2}$mm$^{-1}$, 1.4–1.6 mm; 3.6–4.0 m$^{-2}$mm$^{-1}$, 1.05–1.2 mm. Compared to the maritime-like cluster and continental-like cluster of convective rainfall proposed by Bringi et al. (2003), the convective events in the Qilian Mountains are more consistent with the continental-like cluster (the gray rectangle with smaller log$_{10} N_a$ and larger $D_a$ in Figure 7). There are isolated convective events in the maritime-like cluster, but it is difficult to have more events from the trend between log$_{10} N_a$ and $D_a$. This is also consistent with the features of the geographical location of the Qilian Mountains.
Figure 7. Scatter plot of $\log_{10} N_w$ versus $D_m$ for different rain types at (a) LB, (b) HS, (c) TL, (d) SD, (e) BLG, and (f) DLD. The stratiform cases, convective cases and transitional cases are represented by blue, red and yellow scatter points, circle dots, respectively. The black dashed lines are the $\log_{10} N_w - D_m$ relationship for stratiform versus convective cases and stratiform versus transitional case.

Figure 8 shows the mean DSDs for stratiform, convective and transitional rainfall at the six sites. The range of number concentrations and corresponding raindrop diameters for the three types are were significantly different, matching the basic characteristics of DSD. The mean DSDs of stratiform rainfall differed slightly among the sites; convective rainfall had had big differences at among the sites; and transitional rainfall presented appears more differences beginning at larger than 2.2 mm in diameter,
which were the expected results. Stratiform rainfall usually has a large horizontal extent and an homogeneous cloud distribution, which makes the DSD characteristics basically the same under the influence of the same cloud system in the mountainous areas. However, convective rainfall is related to the local thermal and dynamical factors, which could lead to differences in the DSD at different sites adding when considering the complex topography and diverse underlying surfaces in mountainous areas. For example, in-for convective rainfall, there was a significant increase in the number concentration of raindrops larger than 2.2 mm in diameter at BLG, HS and TL, indicating that these districts sites are conducive to the development of convective precipitation. Also, the number concentration of small raindrops at BLG and HS were higher than that in TL (the southern slope), which may be due to the higher altitude of the interior inside sites reducing the falling distance of raindrops after exiting the cloud and decreasing the impact of collision on the raindrop evolution. In other words, even in-for the same rainfall type, the microphysical process of rainfall at different sites is still different, depending on the topography and position of the observation point relative to the cloud base.

Figure 8: Distribution of mean measured DSD for (a) stratiform rainfall, (b) convective rainfall and (c) transitional rainfall at six sites.

Figure 9 shows box-and-whisker plots of log$_{10}N_a$ and $D_a$ for different rain types. The log$_{10}N_a$ and $D_a$ of stratiform rainfall were smaller than those of convective rainfall but larger than those of transitional rainfall. Sites with a large log$_{10}N_a$ value range have had a larger values range for $D_a$, and sites with a large median for log$_{10}N_a$ have had a smaller median for $D_a$, especially at sites HS and BLG for sites in convective rainfall. Based on the mean values of the six sites in Table 45, the DSD characteristics in the Qilian Mountains consists of a larger $N_a$ and a smaller $D_a$ due to the melting of tiny, compact graupel, and rimed ice particles (relative to large, low-density snowflakes). Compared with transitional rainfall, the $D_a$ of convective rainfall was obviously larger, indicating that the increase in rain rate in this area is mainly due to the growth in raindrop size. Moreover, on the northern slopes one should consider the increase of number concentration, because the log$_{10}N_a$ of convective rainfall also have increased. Note that the number of convective samples on the northern slope was higher than that of other sites, which corresponds to the speculation in regarding the contribution of different rain rate classes. On average, for stratiform rainfall, the dispersion degree of log$_{10}N_a$ and $D_a$ at different sites was 8.3% and 10.0%, respectively; and for convective rainfall it was 10.4% and 23.4%, respectively. The standard deviation of DSD parameters at sites HS and BLG sites
are relatively large.

Table 4.5 Statistical of several integral DSD parameters for six sites with stratiform rainfall, convective rainfall and transitional rainfall

<table>
<thead>
<tr>
<th>Type</th>
<th>Sites</th>
<th>No. samples</th>
<th>$\log_{10} N_o$ (m$^{-2}$mm$^{-3}$)</th>
<th>$D_m$ (mm)</th>
<th>$\mu$ (m$^{-3}$)</th>
<th>$\log_{10} N_r$ (mm$^{-3}$h$^{-1}$)</th>
<th>$R$ (mm)</th>
<th>Z (dBZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>LB</td>
<td>7123</td>
<td>3.42 0.42 0.96 0.21 11.48 7.98 1.98 0.38 0.54 0.60 16.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HS</td>
<td>12694</td>
<td>3.60 0.44 0.88 0.21 11.24 7.89 2.14 0.40 0.54 0.58 16.17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TL</td>
<td>10091</td>
<td>3.71 0.43 0.87 0.20 11.90 8.01 2.23 0.39 0.65 0.67 16.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>7175</td>
<td>3.51 0.44 0.95 0.22 11.15 8.03 2.07 0.39 0.62 0.64 17.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BLG</td>
<td>12467</td>
<td>3.72 0.49 0.88 0.23 12.24 8.50 2.25 0.44 0.70 0.74 17.11 6.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DLD</td>
<td>9685</td>
<td>3.70 0.42 0.88 0.21 11.91 7.91 2.23 0.38 0.67 0.69 17.18 6.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>LB</td>
<td>292</td>
<td>3.91 0.35 1.49 0.35 6.50 3.30 2.81 0.23 9.28 5.56 35.88 3.59</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HS</td>
<td>100</td>
<td>3.85 0.67 1.71 0.84 6.33 4.33 2.95 0.30 12.55 13.75 37.32 6.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TL</td>
<td>159</td>
<td>3.54 0.59 1.87 0.74 5.21 4.97 2.72 0.30 9.48 6.91 37.96 5.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>219</td>
<td>3.91 0.37 1.54 0.47 6.61 4.68 2.85 0.19 10.75 7.68 36.24 5.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BLG</td>
<td>198</td>
<td>3.91 0.74 1.64 0.97 8.00 7.37 3.06 0.27 10.57 15.49 36.29 6.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DLD</td>
<td>203</td>
<td>3.94 0.48 1.50 0.43 6.96 5.24 2.87 0.27 9.41 6.04 35.89 4.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>LB</td>
<td>787</td>
<td>3.76 0.39 1.15 0.21 8.37 4.35 2.47 0.31 2.16 1.25 26.42 3.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HS</td>
<td>541</td>
<td>3.89 0.49 1.05 0.29 8.98 6.74 2.59 0.33 1.81 1.15 24.79 3.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TL</td>
<td>465</td>
<td>3.77 0.70 1.22 0.49 8.81 6.91 2.56 0.44 2.30 1.21 27.10 4.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>819</td>
<td>3.87 0.41 1.12 0.26 8.23 5.46 2.59 0.28 2.28 1.18 26.59 4.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BLG</td>
<td>665</td>
<td>4.04 0.51 1.04 0.31 10.33 7.31 2.72 0.33 2.19 1.13 25.66 4.44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DLD</td>
<td>503</td>
<td>3.95 0.46 1.10 0.30 8.69 6.16 2.67 0.31 2.35 1.17 26.60 4.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 9. Same as in Fig. 5 but for different rain types at six sites.

3.5 Implications for radar rainfall estimation with DSD

The sixth moment of raindrop diameter is proportional to the radar reflectivity factor and the 3.76th moment is approximately the rain rate (they can be calculated by Equations 4 and 5). Generally, the theoretical basis of the QPE for single polarization radar (ground-based or space-based) is the power relationship between the radar reflectivity and rainfall rate ($Z=AR^b$). This makes the coefficients $A$ and exponents $b$ of the power relationship heavily dependent on the variation of their DSD. Therefore, it is necessary to obtain the $A$ and $b$ of different sites according to different rainfall types.

Figure 10 shows the $Z$-$R$ scatter plots for different sites and the fitted power-law relationships for different rainfall types. The blue and red scatter points represent stratiform and convective rainfall, respectively. The purple, red and black solid lines indicate the $Z$-$R$ relationships for stratiform, convective and total rainfall, respectively. It shows that the $Z$-$R$ scatter points for HS and BLG were relatively scattered around the 5 mm h$^{-1}$ rain rate. Besides, the $Z$-$R$ relationship of total rainfall underestimated the stratiform rainfall at low R values and underestimated the convective rainfall at high R values. Based on the average of $Z$-$R$ relationship using a least-squares method, the dispersion degree of $A$ and $b$ in at different sites was 42.5% and 10.7%, respectively, which reveals there to be large differences in mountain areas.
Figure 10. Scatter plots of $Z$ (mm$^3$m$^{-3}$) versus $R$ (mm h$^{-1}$) for three rain types at (a) LB, (b) HS, (c) TL, (d) SD, (e)BLG, and (f) DLD. The blue, red and yellow scatter points circle data, respectively, representing stratiform, convective and transitional cases, respectively. The purple, red and black lines denote the $Z$-$R$ relations. The blue, red and black formula denote stratiform, convective and total $Z$-$R$ relationships.

In order to compare the six sites $Z$-$R$ relationships with some standard $Z$-$R$ relationships, the results for $Z = 300R^{1.4}$ for convective rainfall commonly used in mid-latitude areas, and $Z = 200R^{1.6}$ (i.e., M48) for stratiform rainfall commonly used in mid-latitude areas, are provided in Figure 11. Overall, convective rainfall has had smaller values of $A$ and larger values of $b$ than those of stratiform rainfall (excluding DLD). The $A$ values of convective rainfall are were smaller than the commonly used $Z$-$R$ relationship with large differences, but the $b$ values are were greater. The distribution of $A$ and $b$ for stratiform rainfall is was relatively concentrated, with $A$ and $b$ ranging from 186–238 and 1.3–1.35, respectively. The $A$ values of SR are were close to those of M48, and the $b$ values are were close to and smaller than the $Z$-$R$ of global SR.

Station: The DLD station had a similar $Z$-$R$ for stratiform rainfall with as M48, while its convective rainfall is was different from other sites, with a larger $A$ value (twice as large as other sites) and smaller $b$ value. In addition, it can make this clear that the $A$ value of stratiform rainfall increased from the southern slopes to northern slopes, while the opposite was the case for convective rainfall. And also, the $Z$-$R$ relationships of the same section side are more consistent, such as both of the interior side or the northern slopes, which have distinct geographic characteristics.
convective rainfall at six sites. The purple lines in Fig. 12(a) and cyan lines in Fig. 12(b) correspond to the global Z-R model \(Z = 295R^{1.49}\) for continental stratiform rainfall and \(Z = 278R^{1.54}\) for convective rainfall, respectively (Ghada et al., 2018). The cyan lines in Fig. 12(a) represent the midlatitude stratiform rainfall Z-R model \(Z = 200R^{1.60}\) (Marshall, 1948); and the cyan-purple lines in Fig. 12(b) represent the convective rainfall Z-R model \(Z = 500R^{1.49}\) applied to the operational weather radar (Fulton et al., 1998).

4 Discussion

The paper analyses the statistical characteristics of DSD at different sites in the Qilian Mountains during the rainy season, which not only contain rainfall classes and rainfall types but more importantly reflect the differences between different sites. The results from different aspects can be mutually confirmed and have a good representation of the spatial distribution, making serving as a strong factual basis for the discussion of the microphysical structure of precipitation. For example, with the rain rate class rising, the number concentration of all size bins is increased and the width of DSDs becomes wider, which as a feature are manifested in rain types that are of convective rainfall having a larger rain rate. In spatial terms of spatiotemporal characteristics of precipitation on in the interior of the mountains and on the southern slope are closer, whether considering the overall DSD distribution or the distributions of DSD parameters' distribution. However, there are some obvious variabilities in at the interior sites inside mountains for DSD parameters due to the influences of local dynamics and thermal effects. On the other hand, these characteristics also exhibit some differences between the interior middle and eastern sections of Qilian Mountains, especially in the discussion of DSD parameters for rainfall classes and rainfall types (shown as Figures 5 and 9). This spatial variation in DSD suggests that microphysical processes involved in the DSD are influenced by complex topography (altitude, mountain alignment) and potentially related to the source of water vapor, development of precipitation process and anthropogenic factors.

Compared to previous studies that are focused on eastern, southern and northern China as well as the Tibetan Plateau, the Qilian Mountains region has its own unique DSD characteristics and Z-R relationship during the rainy season, which include including the a smaller raindrop diameter with a higher number concentration. Moreover, the division of rainfall rate classes in the Qilian Mountains more adequately reflects the DSD characteristics at each class, unlike when using the classification.
method of other sites with larger rainfall rates. More importantly, the proposed classification of stratiform and convective rainfall can clearly distinguish between the distribution of log$_{10}N_0$ versus $D_m$ in different rainfall types, for which the dividing line (slope of $-1.6$ and intercept of $6.008$) between stratiform and convective rainfall has the same slope as the line (slope of $-1.6$ and intercept of $6.3$) given by Bringi et al. (2003). Furthermore, according to this method, it can be easily proven that convective events are more consistent with the continental-like cluster, conforming to the precipitation characteristics of the Qilian Mountains. Above all, it is Qilian Mountains that the proposed classification of stratiform and convective rainfall is applicable to, which is located on the arid and semi-arid regions.

As aforementioned above, the characteristics of DSD mainly describe on the diameters larger than 0.2 mm, which is limited by the observation instruments. Inability to detect the small drops on of diameter less than 0.2 mm. Therefore, it is not a complete DSD, and underestimates the number concentration of small drops on of diameter less than 0.5 mm is underestimated. Recent studies have been devoted to improving DSD observations in order to overcome the limitations of disdrometers. A study by Thurai et al. (2017) have obtained a more complete DSD by splicing the 2DVD and MPS (Meteorological Particle Spectrometer) measurements to observe DSDs and developed a technology to reconstruct the drizzle-mode DSD (Raupach et al., 2019), which has a good presentation of the DSD of small raindrops was provided, and more important applications were highlighted.

5 Summary and conclusion

Based on the six-months of DSD data observed in the southern slopes, northern slopes and interior of the inside of Qilian Mountains, the characteristics and their differences of DSD were studied, and the Z-R relationships of six districts were discussed. The main conclusions can be summarized as follows:

For small raindrops, the number concentrations on the inside and southern slopes of districts are greater than that on the northern slopes; for midsize raindrops, the number concentrations decrease sequentially on the northern slopes, southern slopes and inside districts; for large raindrops, the number concentrations on the inside districts are larger. In addition, the number concentrations of raindrops in the middle section of the mountainous area is slightly greater than that in the eastern section.

1. For all rainfall events, the number concentrations of small and large raindrops on the interior inside and on the southern slopes were greater than that on the northern slopes, while midsize raindrops were less. The DSD of the interior of the inside mountains showed a great variability, mainly in terms of the log$_{10}N_0$ and $D_m$ (DSD parameters), which was quite different to the case from the northern slopes.

2. The rainfall rates DSDs were divided into six categories based on rainfall rate and the DSD characteristics: C1, $R<0.5$; C2, $0.5 \leq R<2$; C3, $2 \leq R<4$; C4, $4 \leq R<6$; C5, $6 \leq R<10$; and C6, $>10$ mm h$^{-1}$. As the rainfall rate increased, the median of $D_m$ for each station is gradually larger and the median of $N_0$ rises on C1-C3 and then decreases on C4-C6, as well the differences of in number
concentration of each raindrop size increases, becoming significantly larger especially in the interior sites inside mountains. The most contribution to the total rainfall at different sites is C2 class and C3 class next, with the sum of contribution reaching 60%. Besides, classes the C5 and C6 class handled a relatively large contribution to the northern slope, with a greater probability of heavy precipitation events.

3. There is a rather clear boundary in the distribution of log₁₀Nₛ versus Dₛ between the rainfall types, which the split line between stratiform and convective rainfall has the same slope with the line given by Bringi et al. The dispersion degree of log₁₀Nₛ and Dₛ at the six sites was 8.3% and 10.0% for stratiform rainfall and 10.4% and 23.4% for convective rainfall, respectively. It is easier to increase the number concentration of large raindrops in the interior area of the mountains during convective rainfall. The standard deviations of DSD parameters on inside sites are larger, making it easier to increase the number concentration of large raindrops in convective rainfall. Meanwhile, there is a greater increase in the number concentration of raindrops over the northern slopes during convective rainfall.

4. The Z-R relationships of different sites in stratiform rainfall are similar and generally underestimated by the Z=200Rᵐ model used to the midlatitude stratiform rainfall; the Z-R relationships for convective precipitation vary greatly at different stations, which are overestimated by Z=200Rᵐ at lower rain rates values and underestimated at higher rain rates values. The dispersion degree of coefficient a and exponent b in the Z-R relationship for the six sites was 42.5% and 10.7%, respectively. Overall, the Z-R relationships of the ipsilateral sites were more consistent; and the a value of stratiform rainfall increases increased from the southern slopes to northern slopes, while the opposite was true for convective rainfall. The Z-R relationships of the ipsilateral sites are more consistent. The Z-R relationships of different sites in stratiform rainfall were similar and generally underestimated by the Z=200Rᵐ model used to the midlatitude stratiform rainfall; and the Z-R relationships for convective precipitation varied greatly at different stations, which were overestimated by Z=300Rᵐ at lower rain rates values and underestimated at higher rain rates values.

5. The analysis of DSD and DSD parameters can reflect the characteristics of the southern slope, northern slope and inside sites, as well as the differences between the eastern and middle sections of Qilian Mountains.

This study reveals the microphysical variability of precipitation over the complex topography of the arid and semi-arid regions of Northwest China, which can not only improve local numerical simulations, but also provides a basis for further understanding of the differences in DSD characteristics formed at the mesoscale due to topographic factors and the water vapor distribution, etc. This study holds importance as a basis to note that this should be one of the fundamental studies for the future implementation of weather modification techniques, which is of great
significance to solving the shortage of water resources in the arid and semi-arid regions.

Data availability. Disdrometer data used in this study are available by contacting the authors.

Author contributions. WM conducted the detailed analysis; WZ provided financial support and conceived the idea; MK collated the observation data; all the authors contributed to the writing and revisions.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgments

The work was supported by Weather modification ability construction project of Northwest China under grant No. ZQC-R18208 and The Second Tibetan Plateau Comprehensive Scientific Expedition Grant No. 2019QZKK0104. Thanks are given to Asi Zhang for her help in discussing some questions. The authors also thank reviewers and editors for their helpful suggestion for this study.
References


Li, Z., and Coauthors, 2019: Climate background, relative rate, and runoff effect of multiphase water transformation in Qilian Mountains, the third pole region. Science of The Total Environment, 663, 315-328.

Lim, Y. S., J. K. Kim, J. W. Kim, B. I. Park, and M. S. Kim, 2015: Analysis of the relationship between the kinetic energy and intensity of rainfall in Daejeon, Korea.

Quaternary International, 384, 107-117.


