Raindrop Size Distribution in a Midlatitude Continental Squall Line Measured by Thies Optical Disdrometers over East China

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ABSTRACT

Disdrometer data measured by ground-based optical disdrometers during a midlatitude continental squall line event on 18 August 2012 in Shandong Province, eastern China, are analyzed to study characteristics of raindrop size distribution (DSD). Four disdrometers simultaneously performed continuous measurements during the passage of the convective line. The convective line was partitioned into three regions: the convective center, leading edge, and trailing edge. Results show distinct differences in DSDs and integral rainfall parameters between the convective-center and the edge regions. The convective center has higher drop concentrations, larger mean diameters, and wider size distributions when compared with the edge regions. The leading and trailing edges have similar drop concentrations, but the latter has larger mean diameters and wider size distributions. The shape of DSD for the convective center is convex downward, whereas it is convex upward in tropical continental squall lines, as reported in the literature. There is also spatial variability of the DSD and its integral rainfall parameters in the along-convective-line direction.

1. Introduction

Squall lines are linear or quasi-linear mesoscale convective systems that can produce heavy rains, hail, strong winds, and possibly tornadoes. According to the Glossary of Meteorology of the American Meteorological Society (Glickman 2000), the squall line is defined as “a line of active thunderstorms, either continuous or with breaks, including contiguous precipitation areas resulting from the existence of the thunderstorms.” Squall lines have been frequently observed in both the tropics and mid-latitudes. There exist three distinct modes of squall lines (Parker and Johnson 2000): trailing stratiform (TS), leading stratiform (LS), and parallel stratiform (PS). Observations indicate that about 60% of midlatitude squall lines are of the TS type, while the remaining 40% are of the LS and PS types (Parker and Johnson 2000; Meng et al. 2013).

The squall line is an ideal precipitation system for studying microphysical properties of different precipitation types, since it combines two distinctly different precipitation types (convective and stratiform) in one single event. As the most fundamental aspect of precipitation microphysics, knowledge of the raindrop size distribution (DSD) is essential for understanding precipitation processes, estimating rainfall, and improving microphysics parameterizations in numerical cloud models. There have been several studies of DSD measurements in squall lines. Maki et al. (2001) analyzed the characteristics of the DSD in 15 tropical continental squall lines observed in Darwin, Australia, with the Joss–Walldvogel (JW) impact disdrometer. They showed distinct differences in DSD patterns between the convective-center and stratiform regions of the squall line. Nzeukou et al. (2004) and Moumouni et al. (2008) also studied the DSD characteristics of tropical squall lines using disdrometer data collected at Dakar (Senegal) and Benin in West Africa with the JW and
optical disdrometers, respectively. Jung et al. (2012) reported microphysical properties of DSD in a subtropical maritime squall line in Taiwan, using Palomar Observatory Sky Survey (POSS) observation data. Relatively few published studies have focused on the DSD of midlatitude continental squall lines (Uijlenhoet et al. 2003). Although squall lines have been frequently observed in midlatitude eastern China, and their general features have also been investigated (Meng et al. 2013), not much is known about the DSD characteristics in squall lines occurring in this region because of the lack of disdrometer measurements.

Although studies mentioned above have addressed the DSD of squall lines, they mainly focused on the difference in two rain types (convective and stratiform) or three precipitation regions (convective line, stratiform, and transition). Many recent studies have shown the small-scale spatial variability of DSDs and their integral rainfall parameters, especially for convective rainfall (e.g., Tokay and Bashor 2010; Jaffrain and Berne 2012; Jameson et al. 2015a). Since a squall line is an organized line of convective storms, is there any spatial difference in DSD along the convective line direction?

In this paper, we report the characteristics of the DSD in a midlatitude continental PS squall line observed in eastern China. The data observed during the passage of convective lines with four Thies optical disdrometers are analyzed to study the characteristics of the DSD and its spatial variability.

2. Data and methods
a. Thies disdrometer

The DSD data used in this study were collected with the Thies disdrometer during a squall line that passed eastward over the central part of Shandong Province, eastern China, on 18 August 2012. During the overpass of the squall line, four Thies disdrometers simultaneously performed continuous measurements at a time resolution of 60 s. Figure 1 shows a horizontal radar image of the squall line at 1.5° elevation angle observed by the China New Generation Weather Radar (CINRAD)-SA Doppler weather radar located at Jinan (36.80°N, 116.78°E). The disdrometer observation sites are indicated in the figure: Zhangqiu (ZHQ), Baquan (BQ), Duozhuang (DZH), and Sanchacun (SCC). The radar image corresponds to a time around 1842 LST, when the storm had developed into the mature stage, showing a typical PS squall line structure as defined in Parker and Johnson (2000). Since all of four disdrometers were located in the convective precipitation region of the squall line system, we have not studied the characteristics of the DSD from the stratiform precipitation region because of the lack of disdrometer data.

Thies is a laser-optical disdrometer, which can simultaneously count and measure the size and fall velocity of hydrometeors (Bloemink and Lanzinger 2005). Thies instruments were assessed in detail by Frasson et al. (2011) and Sarkar et al. (2015) and have been used in many other studies (e.g., Brawn and Upton 2008; Fernández-Raga et al. 2010; Jameson et al. 2015a,b). The core element of the instrument is an optical sensor that generates a parallel horizontal light beam of 0.75-mm thickness with a measuring area of 45.6 cm² (228 mm long, 20 mm wide). When the precipitation particles fall through this beam, the receiving signal is reduced. The amplitude of the reduction is related to the size of the particles, and the duration of the reduction is related to the fall speed. Particle sizes are subdivided into 22 classes, and the measurement range is 0.2–8 mm in diameter. The size class width is varied from 0.125 to 0.5 mm. Fall speeds are subdivided into 20 classes, and the measurement range is 0.2–10 m s⁻¹. The velocity class width is also varied from 0.2 to 1.0 ms⁻¹. For a detailed description of the instrument, please refer to the instrument’s manual (Thies Clima 2007).
The measurement accuracy of optical-like disdrometers might be affected by strong winds and heavy rainfall, resulting in spurious particles with unrealistic fall speeds and diameters to be observed in the data (Friedrich et al. 2013). In addition, if particles are not totally within the light beam, they may be registered as small particles that fall faster than other particles observed at that size. These particles are called as "margin fallers" (Yuter et al. 2006). To minimize the measurement errors caused by strong winds, splashing, or margin fallers, particles outside the \(60\%\) of the fall speed–diameter relationship for rain (Atlas et al. 1973) are removed from the observed data following Friedrich et al. (2013). The data containing fewer than 10 drops or with a rain rate less than \(0.1\) mm h\(^{-1}\) have been also disregarded as noise (Tokay and Bashor 2010). Comparing the disdrometer-derived rain rate (Figs. 2, 3), one can see that the quality-controlled data gave a closer agreement with rain gauge measurements, especially during heavy rainfall. Non-quality-controlled data tended to overestimate significantly the rain rate; the same as reported by Lanzinger et al. (2006). The quality control substantially decreased bias between the disdrometer and rain gauge, indicating that the quality control scheme is reliable. While the bias after quality control is likely caused by miscalculation of the disdrometer’s sensing area as pointed out by Frasson et al. (2011).

### b. Raindrop size distribution and rainfall integral parameters

The number concentration of raindrops per unit volume per unit size interval at the discrete time interval has been calculated from the Thies disdrometer counts using the following equation:

\[
N(D_i) = \sum_{j=1}^{20} \frac{n_{ij}}{A \Delta V_j \Delta D_i},
\]

where \(N(D_i)\) is the drop size distribution in size class \(i\) (m\(^{-3}\) mm\(^{-1}\)), \(D_i\) is the mean diameter of class \(i\) (mm), \(\Delta D_i\) is the width of size class \(i\) (mm), \(n_{ij}\) is the number of drops within the size class \(i\) and velocity class \(j\), \(A\) is the measuring area (m\(^2\)), \(\Delta t\) is the time interval in seconds, and \(V_j\) is the fall speed of velocity class \(j\) (m s\(^{-1}\)).

Measured DSDs can be used to calculate rainfall microphysical parameters. Here we selected four integral parameters to characterize the observed DSD, including the total number concentration \(N_T\) (m\(^{-3}\)), rainwater content \(W\) (g m\(^{-3}\)), rain rate \(R\) (mm h\(^{-1}\)), and radar reflectivity factor \(Z\) (mm\(^6\) m\(^{-3}\)), which were computed as follows:

\[
N_T = \sum_{i=1}^{22} \sum_{j=1}^{20} \frac{n_{ij}}{A \Delta V_j},
\]

\[
W = \frac{\pi}{6} \times 10^{-3} \rho_w \sum_{i=1}^{22} \sum_{j=1}^{20} D_i^3 \frac{n_{ij}}{A \Delta V_j},
\]
The gamma size distribution proposed by Ulbrich (1983) is used to parameterize the observed DSD:

\[ N(D) = N_0 D^\mu \exp(-\Lambda D), \]  

where \( D \) is the raindrop diameter (mm), \( N_0 \) is the intercept parameter (mm\(^{-1}\) \( \cdot \) m\(^{-3}\)), \( \mu \) is the shape parameter, and \( \Lambda \) is the slope parameter (mm\(^{-1}\)). The three parameters were estimated from the truncated-moment method using the second, fourth, and sixth moments of the observed spectra, respectively. Detailed descriptions on the truncated-moment method have been addressed by Ulbrich and Atlas (1998) and Vivekanandan et al. (2004) and are not presented herein.

In addition, the mass-weighted mean diameter \( D_m \) (mm) and the generalized intercept parameter \( N_W \) (mm\(^{-2}\) \( \cdot \) m\(^{-3}\)) were used to illustrate the observed DSDs. The \( N_W \) can be derived as follows (Bringi et al. 2003):

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

c. Partitioning of convective lines

According to Maki et al. (2001), DSDs in tropical continental squall lines show distinct differences between the convective-center and the edge regions of convective lines. The convective center was defined by Maki et al. (2001) as the strongest part of the convective line, which had a rain rate larger than 20 mm h\(^{-1}\). The leading and the trailing edges were defined as the front and rear sides of the convective center, respectively. As a primary purpose of this study is to characterize the DSDs of different regions for the convective line in the observed continental squall line and to further compare

<table>
<thead>
<tr>
<th>Site</th>
<th>No. of 1-min spectra</th>
<th>Convective center</th>
<th>Leading edge</th>
<th>Trailing edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZHQ</td>
<td>77</td>
<td>1837–1854 (70.4, 191.4)</td>
<td>1823–1836 (2.5, 7.4)</td>
<td>1855–1940 (3.6, 14.7)</td>
</tr>
<tr>
<td>BQ</td>
<td>77</td>
<td>1835–1853 (68.2, 154.5)</td>
<td>1822–1834 (1.8, 9.1)</td>
<td>1854–1938 (4.7, 18.0)</td>
</tr>
<tr>
<td>DZH</td>
<td>72</td>
<td>1829–1909 (47.4, 95.1)</td>
<td>1813–1828 (5.6, 12.6)</td>
<td>1910–1925 (5.1, 17.8)</td>
</tr>
<tr>
<td>SCC</td>
<td>66</td>
<td>1833–1853 (61.8, 95.1)</td>
<td>1812–1832 (1.7, 6.7)</td>
<td>1854–1917 (1.3, 9.7)</td>
</tr>
</tbody>
</table>

the DSDs with those of tropical continental squall lines reported in Maki et al. (2001), the method for partitioning convective lines proposed by Maki et al. (2001) is adopted in this work. It can be seen from Table 1 that the three regions and the four observation locations were diverse in terms of duration and intensity of rainfall. Convective centers have higher rain rates than the edge regions. Precipitation originating in the convective center was observed 21%–58% of the time (34% for four-site averaging), but 84%–95% of the total rainfall (90% for four-site averaging) was provided by convective centers. One should keep in mind that the current study used 20 mm h\(^{-1}\) as the threshold for separating convective centers. Sensitivity tests showed that the changing threshold [e.g., 10 mm h\(^{-1}\) as in Testud et al. (2001)] had an impact on the DSD and integral rainfall parameters. However, there are insignificant differences between the two results because of a few samples observed in the range of 10–20 mm h\(^{-1}\) (three for ZHQ, six for BQ, two for DZH, and zero for SCC).

3. Results and discussion

a. Time series of raindrop size distribution

Figure 4 shows the time evolution of the drop size distribution \( N(D) \) during the passage of the squall line, as derived from the 1-min disdrometer observations at the four sites, respectively. Rain rate during the convective center phase was also plotted to separate the three phases of the convective line. All four DSDs exhibit a similar behavior, namely, low number concentrations and narrow size spectra during the leading and trailing edges where the maximum drop diameter was less than 4.75 mm, and high concentrations and wide size spectra during the convective center phase in which the maximum drop diameter was more than 6.25 mm. This figure clearly demonstrates that the convective center tends to produce wide spectra, whereas the leading and trailing edges exhibit narrow spectra.

We note from Fig. 4 that nearly all of the raindrops with concentration exceeding 1000 m\(^{-3}\) mm\(^{-1}\) were concentrated entirely in the size range of \( D < 1 \) mm, and they contributed to about 90% of the total number concentration. Further, it is found that the raindrops
with concentration larger than 10,000 m⁻³ mm⁻¹ were below 0.6 mm in diameter, occurring in the convective center phase and contributing to more than 95% of the total concentration in this period. It is also noted that the highest concentration of drops measured by disdrometers at all four sites was in the first two size classes, which correspond to an average diameter of 0.188 and 0.312 mm. Such a large number of small drops, however, contributed to over 50% of the total concentration, though they contributed only 0.7% of the rain rate.

Comparing Figs. 4a and 4b, there were similar structure in the time series of DSD between ZHQ and BQ, where their separation distance was about 4 km. The maximum raindrop diameter in the spectra at the two sites was 8 mm. The overall coefficient of drop variation (CV_D) for the entire time period, here defined as the standard deviation of the maximum diameter divided by the mean value of the maximum diameter to measure the fluctuating magnitude of DSD’s width, was 0.40 and 0.42 for ZHQ and BQ, respectively. When considering the convective center phase, the derived value of CV_D from this period was 0.23 at both sites. The differences between the two time series were found in the number concentration. The highest total number concentration was 30,978 m⁻³ in ZHQ, occurring at 1846 LST, and 26,690 m⁻³ in BQ at 1844 LST. The time series of DSD during the convective line’s passage in DZH showed a substantial difference from the previous two sites (Fig. 4c). The event’s highest total number concentration, 21,615 m⁻³, was observed at 1831 LST. The largest drop at DZH was 6.25 mm in diameter, and CV_D was 0.25 for the entire period and 0.11 for the convective center phase, both smaller than those in the previous two sites. During the convective line’s passage in SCC (Fig. 4d), the highest total number concentration was 21,795 m⁻³ occurring at 1849 LST, and the maximum drop diameter was 8 mm. The values of CV_D were 0.47 and 0.12, respectively, for the entire period and the convective center phase. The results showed temporal and spatial variability of the DSD in convective lines.

It can be seen from Fig. 4 that there is an abrupt change in DSDs during the transition period from the leading edge to the convective center, and then to the trailing edge. To illustrate this variation, we plotted the size distributions for the last minute of the leading edge (LE_E), the first and last minutes of the convective center (CC_S and CC_E, respectively), and the first minute of the trailing edge (TE_E) at each observation site (Fig. 5). The standard deviation of the mass spectrum \( \sigma_M = D_m/(4 + \mu)^{1/2} \), as defined by Ulbrich and Atlas (1998), was also presented to quantify the spectrum width. The CC_S had a wider spectrum breadth than LE_E, but there was no significant difference between CC_E and TE_E. The drop concentration in the CC_S (CC_E) was higher than in LE_E (TE_E) at all size ranges. This shows that there is a sudden increase of the drop size and concentration from the leading edge to convective center and a decrease of the drop size and concentration from the convective center to the trailing edge, thereby resulting in a dramatic increase or decrease in rain rates. Furthermore, the difference in DSDs between LE_E and CC_S was noticeably larger than that between CC_E and TE_E.

### b. Averaged raindrop spectra

The averaged raindrop spectra and their integral rainfall parameters for the leading edge (LE), convective center (CC), and trailing edge (TE) of the convective line at each observation site are shown in Fig. 6 and Table 2, respectively. Here we used the empirical fall speed–diameter relationship of Atlas et al. (1973) to compute rain rate from the average spectra. In addition, the gamma distribution fits on average spectra is also
plotted in the figure, and the corresponding parameter values are listed in Table 3.

As shown in Fig. 6 and Table 3, the DSDs in the convective center at all four sites are convex down, with the shape parameter \( \mu \) in the range from \(-1.631\) to \(-1.272\), whereas the DSDs in the leading edge and trailing edge have convex shapes downward or upward, with the parameter \( \mu \) in the ranges from \(-0.319\) to \(-1.229\) and from \(-1.705\) to \(-0.170\) for the leading edge and trailing edge, respectively. The maximum raindrop diameters exhibit a similar tendency at four sites, all in the order of CC > TE > LE. The slope parameter \( \Lambda \) for the convective center is in the range of \(0.689\)–\(1.001\), while for the leading edge and trailing edge they are in the \(2.148\)–\(3.462\) and \(1.018\)–\(2.195\) ranges, respectively. The slope parameters at all sites are in the order of CC > TE > LE. Overall, Table 3 shows that among the three precipitation regions the convective center had the highest \( N_0 \), the lowest \( \mu \), and the smallest \( \Lambda \), while all these three parameters had higher values for the leading edge than for the trailing edge.

Compared to the leading edge or trailing edge for each observation site, the convective center had higher drop concentrations at all size regimes. This is the reason why the convective center has the highest total number concentration. Meanwhile, it is also one of the reasons why the convective center has the highest rain rate and rainfall content and the highest reflectivity. It is found from Table 2 that the trailing edge at ZHQ and BQ had larger values for all integral rainfall parameters than the leading edge, since the DSD of the trailing edge had higher concentration at all size ranges (Figs. 6a,b). However, the distribution patterns of the DSD for the two edge regions differed in some size intervals at
the other two sites. Comparing the trailing edge with the leading edge for DZH (Fig. 6c), we found a decrease in the number of small and intermediate drops ($D < 3\text{ mm}$) and an increase in the number of large drops ($D > 3\text{ mm}$). This characteristic DSD is the reason why the trailing edge has a lower concentration, less rainwater content and rainfall rate, and a higher reflectivity than the leading edge. For SCC (Fig. 6d), we noted from comparing the trailing edge with the leading edge 1) an increase in the number of small drops ($D < 1\text{ mm}$), 2) a decrease in the number of midsize drops ($1 < D < 3\text{ mm}$), and 3) an increase in the number of large drops ($D > 3\text{ mm}$). Such DSD behavior may explain why there are no significant differences in the integral rainfall parameters at this site between the leading edge and the trailing edge.

The small drops dominated the number concentration. However, they contributed less than 10% of the rain rate on average. The rainfall intensity is mainly contributed by the midsize and large drops, accounting for 55%–70% and 20%–35% of the total rainfall over the four sites, respectively. The contributions to the rain rate from small, midsize, and large drops are different in three precipitation regions. For the leading edge the small and midsize drops contributed 11%–28% and 70%–85% of the rain rate, respectively, while the contribution of the large drops was very insignificant. For the trailing edge the contributions from the small, midsize, and large drops was 8%–13%, 47%–74%, and 18%–44%, respectively. Very large drops ($D > 5\text{ mm}$) contributed negligibly to the rain rate since they were occasionally observed during the trailing
edge. For the convective center the contributions of the small, midsize, and large drops to the rain rate were 4%–6%, 35%–49%, and 45%–59%, respectively, while the contribution from very large drops achieved 3%–12%.

It is noted from Table 2 that there are differences in the integral rainfall parameters derived from average size spectra between the four different sites. For example, the site-to-site relative difference of the total drop concentration varies from 4.2% to 175.5% and from 1.4% to 61% for the leading and trailing edges, respectively, while it varies from 1.1% to 18.8% for the convective center. Larger variability is found in the rain rate, ranging from 0.272 to 1.519, respectively. Tokay et al. (2001) found a larger variation as compared to the other parameters exhibited an intraphase variation during the passage of the convective center over the four observation sites. All three parameters exhibited an intraphase variation during the passage of the convective center over the four observation sites, with the coefficient of variation from 0.47 to 0.55 for \( N_W \), from 0.13 to 0.37 for \( \mu \), and from 0.31 to 0.41 for \( \Lambda \). The \( N_W \) had a larger variation as compared to the other two gamma parameters. For the whole convective-center dataset the \( N_W \) was in the 900–14 700 mm\(^2\) m\(^{-3}\) range, while the \( \mu \) and \( \Lambda \) ranges were from −2.379 to −0.322 and from 0.272 to 1.519, respectively.

Note that all \( \mu \) of convective centers in this study are negative, while they are mostly positive in tropical continental squall lines observed in Darwin (Maki et al. 2001). The disdrometer data used in Maki et al. (2001) were collected with the JW disdrometer, which allowed the measurement of drops ranging from 0.3 to 5.5 mm in diameter (Joss and Waldvogel 1967). Tokay et al.

**Table 2.** Rainfall integral parameters derived from the averaged drop size spectra for the LE, CC, and TE. Terms \( N_T \), \( W \), \( R \), and dBZ represent total drop concentration (m\(^{-3}\)), rain rate (mm h\(^{-1}\)), and radar reflectivity, respectively. Mean mass diameter \( D_m \) (mm) and maximum diameter \( D_{\text{max}} \) (mm) are also given for each case.

<table>
<thead>
<tr>
<th>Site</th>
<th>( N_T )</th>
<th>( W ) (mm h(^{-1}))</th>
<th>( R ) (m)</th>
<th>dBZ</th>
<th>( D_m ) (mm)</th>
<th>( D_{\text{max}} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZHQ</td>
<td>387.4</td>
<td>0.146</td>
<td>2.69</td>
<td>31.4</td>
<td>1.47</td>
<td>3.25</td>
</tr>
<tr>
<td>CC</td>
<td>13489.5</td>
<td>3.705</td>
<td>90.7</td>
<td>55.1</td>
<td>2.76</td>
<td>8.00</td>
</tr>
<tr>
<td>TE</td>
<td>546.8</td>
<td>0.193</td>
<td>4.12</td>
<td>36.2</td>
<td>1.90</td>
<td>4.70</td>
</tr>
<tr>
<td>BQ</td>
<td>329.9</td>
<td>0.097</td>
<td>1.90</td>
<td>31.1</td>
<td>1.62</td>
<td>3.75</td>
</tr>
<tr>
<td>CC</td>
<td>11309.0</td>
<td>3.619</td>
<td>95.2</td>
<td>56.6</td>
<td>3.23</td>
<td>8.00</td>
</tr>
<tr>
<td>TE</td>
<td>812.2</td>
<td>0.309</td>
<td>7.20</td>
<td>40.3</td>
<td>2.23</td>
<td>4.75</td>
</tr>
<tr>
<td>DZH</td>
<td>1245.7</td>
<td>0.347</td>
<td>7.32</td>
<td>38.0</td>
<td>1.84</td>
<td>4.75</td>
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<tr>
<td>CC</td>
<td>12751.2</td>
<td>2.555</td>
<td>60.7</td>
<td>51.5</td>
<td>2.50</td>
<td>6.25</td>
</tr>
<tr>
<td>TE</td>
<td>823.9</td>
<td>0.253</td>
<td>6.09</td>
<td>40.8</td>
<td>2.44</td>
<td>5.25</td>
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<tr>
<td>SCC</td>
<td>344.1</td>
<td>0.098</td>
<td>1.91</td>
<td>31.7</td>
<td>1.64</td>
<td>4.25</td>
</tr>
<tr>
<td>CC</td>
<td>11187.8</td>
<td>3.407</td>
<td>86.8</td>
<td>55.0</td>
<td>2.95</td>
<td>8.00</td>
</tr>
<tr>
<td>TE</td>
<td>462.5</td>
<td>0.087</td>
<td>1.82</td>
<td>35.0</td>
<td>2.03</td>
<td>4.75</td>
</tr>
<tr>
<td>All</td>
<td>576.1</td>
<td>0.171</td>
<td>3.42</td>
<td>34.2</td>
<td>1.70</td>
<td>4.75</td>
</tr>
<tr>
<td>CC</td>
<td>12264.6</td>
<td>3.143</td>
<td>78.2</td>
<td>54.3</td>
<td>2.82</td>
<td>8.00</td>
</tr>
<tr>
<td>TE</td>
<td>659.6</td>
<td>0.224</td>
<td>5.07</td>
<td>38.6</td>
<td>2.14</td>
<td>5.25</td>
</tr>
</tbody>
</table>

**Table 3.** Gamma distribution parameters derived from the average spectra using the truncated-moment method.

<table>
<thead>
<tr>
<th>Site</th>
<th>( N_0 ) (mm(^{-2}) m(^{-3}))</th>
<th>( \mu )</th>
<th>( \Lambda ) (mm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZHQ</td>
<td>5505.9</td>
<td>1.229</td>
<td>3.462</td>
</tr>
<tr>
<td>CC</td>
<td>3996.0</td>
<td>−1.616</td>
<td>0.845</td>
</tr>
<tr>
<td>TE</td>
<td>1349.0</td>
<td>0.170</td>
<td>2.195</td>
</tr>
<tr>
<td>BQ</td>
<td>1273.5</td>
<td>0.285</td>
<td>2.579</td>
</tr>
<tr>
<td>CC</td>
<td>2520.2</td>
<td>−1.631</td>
<td>0.689</td>
</tr>
<tr>
<td>TE</td>
<td>727.6</td>
<td>−0.548</td>
<td>1.451</td>
</tr>
<tr>
<td>DZH</td>
<td>2256.6</td>
<td>−0.319</td>
<td>2.148</td>
</tr>
<tr>
<td>CC</td>
<td>3836.9</td>
<td>−1.455</td>
<td>1.001</td>
</tr>
<tr>
<td>TE</td>
<td>379.2</td>
<td>−1.099</td>
<td>1.095</td>
</tr>
<tr>
<td>SCC</td>
<td>950.9</td>
<td>−0.112</td>
<td>2.317</td>
</tr>
<tr>
<td>CC</td>
<td>3689.6</td>
<td>−1.272</td>
<td>0.939</td>
</tr>
<tr>
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<td>1.018</td>
</tr>
<tr>
<td>All</td>
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<td>2.795</td>
</tr>
<tr>
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</tr>
<tr>
<td>TE</td>
<td>734.6</td>
<td>−0.432</td>
<td>1.647</td>
</tr>
</tbody>
</table>

further illustrates the difference (similarity) in the distribution shapes in the edge (convective center) regions between different observation sites.

c. Gamma distribution parameters for the convective center regions

Here only the convective center regions have been studied since the convective center dominated the precipitation of the convective line. Since the units of the intercept parameter \( N_0 \) depend on the value of the shape parameter \( \mu \), this makes it very inconvenient to discuss the variability of \( N_0 \). The generalized intercept parameter \( N_W \) is independent of the shape of the DSD, which means that whatever the shape of an observed DSD is, the corresponding \( N_W \) is the intercept parameter of the equivalent exponential DSD [i.e., Eq. (6) with \( \mu = 0 \)] with the same \( W \) and \( D_m \). Hence, we used \( N_W \) instead of \( N_0 \). The temporal evolution of the parameters \( N_W, \mu, \) and \( \Lambda \) during the convective center phases is shown in Fig. 8. All three parameters exhibited an intraphase variation during the passage of the convective center over the four observation sites, with the coefficient of variation from 0.47 to 0.55 for \( N_W \), from 0.13 to 0.37 for \( \mu \), and from 0.31 to 0.41 for \( \Lambda \). The \( N_W \) had a larger variation as compared to the other two gamma parameters. For the whole convective-center dataset the \( N_W \) was in the 900–14 700 mm\(^{-1}\) m\(^{-3}\) range, while the \( \mu \) and \( \Lambda \) ranges were from −2.379 to −0.322 and from 0.272 to 1.519, respectively.
(2001) found that the JW disdrometer severely underestimated the number of small drops ($D < 1.5 \text{ mm}$), thus producing a pronounced effect on the shape parameter of gamma-fitted DSDs. The size ranges of the Thies disdrometer are 0.2–8.0 mm in diameter. Large concentrations of small drops that were measured by Thies are likely the main reason why the DSD in the convective center tends to be convex down and to have negative values of $m$. To illustrate this, the concentration of small drops for diameters less than 1.5 mm in the average size spectra for the convective center region at ZHQ was decreased by 50% and 90%, respectively. The resulting value of $m$ was $2.0.937$ and $0.861$, respectively, indicating that the shape parameter increases with decreasing small-drop concentrations.

Since the Thies measured very large drops that were beyond the JW disdrometer maximum size limit, the effect of very large drops on the shape parameter for the convective center was also examined by removing raindrops with diameters larger than 5.5 mm. The corresponding value of $m$ was $2.1.893$, which was very close to the value of $2.1.616$ calculated from the untruncated spectra. Therefore, the differences in the DSD patterns for the convective center between this study and Maki et al. (2001) are mainly due to the concentration of small drops measured by the Thies and JW disdrometers.

**Fig. 7.** Average raindrop size spectra for (a) LE, (b) CC, and (c) TE regions of convective lines. The standard deviation of the mass spectrum is shown in parentheses.

**Fig. 8.** Temporal evolution of the generalized intercept parameter $N_0$ (mm$^{-1}$ m$^{-3}$), slope parameter $\Lambda$ (mm$^{-1}$), and shape parameter $\mu$ during the convective center phases.
For each observation site, the time series of $\mu$ and $\Lambda$ showed a rather similar behavior and a very strong correlation. Brandes et al. (2003) and Zhang et al. (2003) proposed an empirical polynomial $\mu-\Lambda$ relation for convective precipitation with rain rates greater than 5 mm h$^{-1}$ as follows:

$$\Lambda = 0.0365\mu^2 + 0.735\mu + 1.935. \quad (8)$$

This $\mu-\Lambda$ relation was obtained from disdrometer observations in Florida during the summer of 1998, and it should be tuned using local disdrometer data collected at various geographical locations or climatological regimes and in various seasons (Zhang et al. 2003; Vivekanandan et al. 2004). Recent studies have demonstrated the variability in the $\mu-\Lambda$ relation at different locations (e.g., Brawn and Upton 2008; Chu and Su 2008; Chang et al. 2009; Kumar et al. 2011; Chen et al. 2013). The characteristics of $\mu$ and $\Lambda$ in squall lines have been studied as well (e.g., Maki et al. 2001; Uijlenhoet et al. 2003); nevertheless, not much is known about the $\mu-\Lambda$ relation of squall lines.

The scatterplots of $\mu-\Lambda$ values for convective-center regions at the four sites are shown in Fig. 9. The corresponding $\mu-\Lambda$ relations derived here using a polynomial least squares fit are shown as solid lines. The specific equations are given as follows:

$$\Lambda(ZHQ) = 0.0860\mu^2 + 0.845\mu + 1.959, \quad (9)$$

$$\Lambda(BQ) = 0.0460\mu^2 + 0.704\mu + 1.697, \quad (10)$$

$$\Lambda(DZH) = 0.0209\mu^2 + 0.838\mu + 2.169, \quad \text{and} \quad (11)$$

$$\Lambda(SCC) = 0.1462\mu^2 + 1.333\mu + 2.524, \quad (12)$$

where acronyms in parentheses indicate the observation sites. All four fitted curves in Fig. 9 show a similar behavior, namely, the smaller the value of $\Lambda$ (higher rain rates), the smaller the negative value of $\mu$. This suggests that the DSD tends to be more convex down with increasing rainfall intensity and to have a lower fraction of midsize drops and a higher fraction of small and large drops, reflecting less evaporation of small drops or more active drop breakup and coalescence mechanisms at higher rain rates. The fitted $\mu-\Lambda$ relations exhibited a rather large difference among the four different sites and therefore have different $\mu$ values given the same $\Lambda$ value. This suggests that the $\mu-\Lambda$ relation obtained from single-point observations cannot reliably represent the convective line.

The $\mu-\Lambda$ relations obtained in this work differ from that in Florida given in Eq. (8). The differences are likely attributed in part to the natural variability of rainfall and in part to dataset processing, because the threshold values of rain rate to determine convective spectra are different. To eliminate the errors from different criteria, the thresholds for drop counts $>$1000 and rain rate $>$5 mm h$^{-1}$ used in Brandes et al. (2003) and Zhang et al. (2003) were adopted to separate convective spectra. The revised plot is shown in Fig. 10 and the corresponding $\mu-\Lambda$ relation is given in Eq. (13). Here the disdrometer data with the above-mentioned threshold collected at all four sites were put together to obtain an overall reliable formula. The figure contains 108 data points and their $\mu$ values are still negative:

$$\Lambda = 0.0585\mu^2 + 0.812\mu + 1.934. \quad (13)$$

The revised $\mu-\Lambda$ relation agrees well with Florida’s, and the difference is found in the squared term and linear term. Comparing Eqs. (8) and (13), we see that the coefficients of the squared term and linear term in Eq. (8) are smaller than those in Eq. (13); hence, for a given $\mu$ value Eq. (8) gives a higher $\Lambda$ value than Eq. (13), as shown in Fig. 10.

d. Distribution of $D_m$ and $N_W$

The mass-weighted mean diameter $D_m$ and the generalized intercept parameter $N_W$ can be used to characterize an overall feature of the DSD. Observation studies have shown that both the $N_W$ and $D_m$ vary with climatic regimes, rain types, and rainfall intensity (e.g., Bringi et al. 2003; Ulbrich and Atlas 2007; Sharma et al. 2009; Marzano et al. 2010; Thurai et al. 2010; Chen et al. 2013). To examine the dependence of these two
parameters on rainfall intensity, Fig. 11 shows $\log_{10} N_W$ and $D_m$ versus rain rate $R$ for the four observation sites. In addition, the fitted power-law relationships using a least squares method are also provided in the figure to obtain a quantitative description of the two parameters with respect to rain rate. Both the $N_W$ and $D_m$ values tend to increase with increasing rain rates, and the exponents in the $N_W$–$R$ and $D_m$–$R$ relations are positive. Note that both the $N_W$–$R$ and $D_m$–$R$ relations exhibit slight differences between different sites. This indicates that $N_W$ and $D_m$ are likely different at various locations even though they are measured within the same one precipitation system and at the same rain rate.

Previous studies (e.g., Bringi et al. 2003; Ulbrich and Atlas 2007) showed that the behavior of the DSD parameters $N_W$ and $D_m$ was distinctly different for the maritime and continental convective storms. For maritime-like spectra, $\log_{10}(\langle N_W \rangle) \approx 4.45$ with $\langle D_m \rangle \approx 1.5$–1.75 mm (angle brackets denote averages), that is, a higher concentration of smaller-sized drops. For continental-like spectra, $\log_{10}(\langle N_W \rangle) \approx 3$–3.5 with $\langle D_m \rangle \approx 2$–2.75 mm, that is, a higher concentration of larger-sized drops. Figure 12 shows the average $D_m$ and $\log_{10}N_W$ for convective spectra in the squall line. It should be noted that the separation of convective spectra in this section is different from the above-mentioned method. Herein we adopted the classification scheme of Bringi et al. (2003) to compare our data with those of their study. The scheme is based on the standard deviation of rain rate over five consecutive 2-min samples. If the standard deviation is $>1.5$ mm h$^{-1}$ and rain rate is $\approx 5.0$ mm h$^{-1}$, then it is classified as convective. The classification procedure used here is similar to Bringi et al. (2003), except for the standard deviation over 11 consecutive 1-min samples. It can be seen from Fig. 12 that all of the data points are centered near the continental convective clusters reported by Bringi et al. (2003). The $\log_{10}N_W$ ranges from 3.43 to 3.68.
and $D_m$ ranges from 2.25 to 2.9 mm. The four-site average is 3.55 for $\log_{10} N_W$ and 2.53 mm for $D_m$. The $N_W$–$D_m$ pair matches the continental-like cluster well, which further demonstrates the continental characteristics of the squall line in the present study.

The $N_W$–$D_m$ pair for convective rain in Darwin matches the maritime-like cluster, as reported by Bringi et al. (2003) and implied in Thurai et al. (2010), which is distinctly different from ours. This is likely associated with local atmospheric aerosols and/or moisture. The observation study by May et al. (2011) showed that tropical thunderstorms in Darwin have a lower $N_W$ and larger median volume diameter $D_0$ (which is closely related to $D_m$ for gamma DSD) under the high-aerosol conditions when compared with low-aerosol conditions. The sounding in Zhangqiu at 0000 UTC on 18 August 2012 shows that the squall line forms in a warm, moist atmospheric conditions with a warm layer of ~5 km MSL and a water vapor mixing ratio of ~19 g kg$^{-1}$. The thermodynamical conditions are similar to that in Darwin. However, in eastern China, aerosol concentrations are markedly high (Streets et al. 2008). With increased aerosol loading, the warm-rain processes in deep convective clouds can be suppressed, resulting in lower raindrop concentrations; meanwhile, the ice-phase processes can be enhanced, thus producing more graupel/hail and resulting in larger raindrops via the melting. Further research is needed to validate that hypothesis.

4. Summary and conclusions

Raindrop size distributions representative of a parallel stratiform squall line that occurred on 18 August 2012 in Shandong Province in eastern China were analyzed. Four Thies disdrometers with different separation distances simultaneously performed continuous measurements during the passage of the convective line. The convective line was further partitioned into the convective center, leading edge, and trailing edge using a threshold rain rate of 20 mm h$^{-1}$ following Maki et al. (2001). The continental characteristic of the squall line was identified well in the $N_W$–$D_m$ space following Bringi et al. (2003).

There are distinct differences in DSDs between the convective-center and edge regions of the convective line. The convective center has higher drop concentrations, larger mean diameters, and wider size distributions as compared to the leading and trailing edges. The leading and trailing edges have similar drop concentrations, but the latter has larger mean diameters and wider size distributions. The shape of DSD for the convective center is convex down, but it is not monodisperse for the leading and trailing edges. The DSD shape of the convective center distinctly differs for this study and Maki et al. (2001) in which it is convex upward. There are also differences in DSDs and the integral rainfall parameters in the convective line direction. The leading and trailing edges show substantial differences in their distribution shapes and spectrum widths of the average DSDs between different observation sites, for the convective center the spectrum widths are distinctly different and the distribution shapes are similar. The $\mu$–$\Lambda$ relations are varied in different observation sites.

The results reveal distinct characteristics of the DSD in continental squall lines between midlatitude eastern China and tropical regions, particularly the DSD shape for the convective center. The convective-center DSD observed in this study is characterized by a downward convex shape with an extremely high concentration of small drops in the presence of very large drops (>6 mm in diameter), likely reflecting the microphysical mechanisms of rain formation in the squall line through the melting of graupel and hailstones followed by drop coalescence and breakup. In future work we plan to use cloud-resolving models with two-moment bulk microphysics scheme to investigate the impact of gamma shape parameters on the structure and precipitation of the squall line to improve model representative. Cloud modeling with spectral bin microphysics would be valuable for understanding aerosol effects on DSDs in this region. The findings of this
paper were limited to a case study of PS squall lines in eastern China. Different types of squall lines (i.e., TS and LS types) should be also considered in future work.

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