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Comparison of Raindrop Size Distributions in a Midlatitude Continental Squall Line during Different Stages as Measured by PARSIVEL over East China

Hongsheng Zhang, Yun Zhang*, Hongrang He, Yanqiong Xie, Qingwei Zeng

Institute of Meteorology and Oceanography, PLA University of Science and Technology, Nanjing, China

*Corresponding author address: Yun Zhang, Department of Atmosphere Science, Institute of Meteorology and Oceanography, PLA University of Science and Technology, Shuanglong Street 60, Nanjing 211101, China.

E-mail: zhangyun.1207@yahoo.com
The characteristics of raindrop size distributions (DSDs) during a midlatitude continental squall line on 30 July 2014 in East China are studied, and the different life stages are observed by OTT Parsivel\textsuperscript{2} disdrometers at Chuzhou during the mature stage and Nanjing during the declining stage. The observed rainfall is classified into convective line, transition, and stratiform regions based on the structure of the radar reflectivity and rainfall intensity. The results show that the DSD characteristics of the different precipitation types and different squall line stages are very different. The convective center has the largest number concentration and quantity of large drops corresponding to the highest rain rate; the rain rates in the trailing edge and stratiform regions are similar, although a lower concentration of small drops is present in the latter. Between the two stages, the drop size and number concentration for the convective center decrease, although the leading edge during the declining stage has more numerous larger drops; the number concentration is similar in the stratiform rainfall, but the drops become much smaller. For the normalized distribution, the scaled spectra for the convective center are closer to an exponential distribution, and the $\mu$ value during the declining stage is larger than that during the mature stage for the stratiform region and similar during both stages for the convective center. The declining stage has a larger exponent b and smaller coefficient A in the $Z$-$R$ relationship based on fits for the entire dataset. Moreover, the $R(Z_H, Z_{DR})$ estimator is more accurate than that when using the $Z$-$R$ relation algorithm.
1. Introduction

The raindrop size distribution (DSD) is a significant aspect of precipitation observations and can be used to indicate different microphysical properties during different rain events. The variability of the DSD is very important for estimating precipitation using weather radar or satellite observations and the parameterization of microphysical processes in numerical models (Thompson et al. 2004; Milbrandt and Yau 2005). In numerical models, different precipitation hydrometeor classes are generally represented by a gamma distribution with one or two prognostic parameters (called single-moment or double-moment bulk schemes, respectively). The power-law relationship $Z=AR^b$ of the radar reflectivity factor $Z$ and rainfall rate $R$ or polarimetric radar algorithms based on the reflectivity ($Z_{hh}$), differential reflectivity ($Z_{DR}$), and specific differential phase ($K_{dp}$) are generally employed for radar quantitative rainfall estimation (Rosenfeld et al. 1993; You et al. 2014). Polarimetric radar in China is still in the research stage; therefore, the $Z$-$R$ relationship is mainly applied to precipitation estimation for Chinese meteorological stations. However, it has been found that the DSDs vary with precipitation type, topographical location, climatic region, choice of disdrometer, etc. (Testud et al. 2001; Bringi et al. 2003; Rosenfeld and Ulbrich, 2003; Ulbrich and Atlas 2007).

The different properties of convective and stratiform rainfall have long been an area of focus, and several classification approaches for different rain types have been proposed and discussed. Tokay and Short (1996) used a relationship between $N_0$ and $R$ ($N_0=4\times10^9R^{-4.3}$) as a reference to classify convective and stratiform rainfall; rainfall
that has $R > 5$ (0.5) mm h$^{-1}$ and the standard deviation of $R > (\cdot) 1.5$ mm h$^{-1}$ over five consecutive 2-min samples is classified as convective (stratiform) precipitation (Bringi et al. 2003). Ulbrich and Atlas (2007) emphasized the importance of dividing each rainfall event into different $Z-R$ relations according to convective, transition, and stratiform rain. Wen et al. (2016) identified shallow rain by combining a 2-DVD disdrometer and micro-rain radar (MRR) observations, which have received little attention in the literature. Squall lines are significant mesoscale systems and provide a useful framework for studying the characteristics of different rain types and the variability of the raindrop size distribution because the two typical rain types are contained in their three different regions, which are usually called the convective line, transition, and trailing stratiform regions (Braun and Houze 1994; Bringi et al. 2002). Maki et al. (2001) selected fifteen tropical continental squall lines that occurred in Darwin, Australia, for a DSD analysis, and the convective line was further divided into three components (leading edge, convective center, and trailing edge) using a 20 mm h$^{-1}$ rain rate threshold. A typical case study of a squall line event that occurred in northern Mississippi was presented by Uijlenhoet et al. (2003), and the scaling-law method was applied in the rainfall estimation. Jung et al. (2012) studied maritime squall line DSD characteristics in Taiwan. Chen et al. (2016) presented the DSD properties of a midlatitude squall line (parallel stratiform type) in Shandong Province, eastern China, as observed by four Thies disdrometers, and discussed the spatial variability of the DSDs in the squall line.

However, research on the DSD properties of a squall line during different life
stages and the temporal variability of the DSD of convective and stratiform rainfall (Montopoli et al. 2008) is relatively rare. In this paper, a structurally typical midlatitude continental squall line that occurred in the Yangtze River and Huaihe River basins is selected for DSD analysis. On 30 July 2014, the squall line hit the eastern part of China, bringing heavy rainfall and thunderstorms and causing casualties and economic losses. The raindrop size distributions during the different life stages were observed using two OTT Parsivel\textsuperscript{2} devices (second-generation Parsivel disdrometers) at Chuzhou (hereafter CZ), China, for the mature stage and Nanjing (NJ), China, for the declining stage. Thus, the temporal variability of the DSD in the squall line could be analyzed. The instrumentation, methodology and identification method of the convective line, transition, and stratiform regions are given in section 2, which is followed by the DSD analysis results and discussion in Section 3. Section 4 provides a summary and conclusions.

2. Data and methods

a. PARSIVEL disdrometer and dataset

The data selected for the analysis consisted of two time series of 1-min DSD data that were measured by Parsivel disdrometers at CZ (in Anhui Province) and NJ (in Jiangsu Province) in China. CZ is 65 km northwest of NJ (white points in Figure 1). The two disdrometers were mounted on the roofs of buildings, approximately 18 m high in CZ and 15 m high in NJ. The squall line passed over the two cities from west to east on 30 July 2014, and the maximum wind speed at the disdrometer sites was
5-8 m s$^{-1}$. The two disdrometers observed different life stages of the squall line; CZ observed the mature stage, while NJ measured the declining stage, providing microphysical characteristics during the different stages of the squall line. Figure 1 shows radar images of the movement of the squall line based on data collected by the CINRADA/SA Doppler Weather Radar (2.85 GHz) in Hefei (in Anhui Province). Figures 1a-d show the Plan Position Indicators (PPIs) of the storm at a 0.57° elevation angle, which correspond to 15:59, 16:51, 17:17 and 19:14 UTC, respectively, when the squall line was approaching CZ and NJ (white points in Figs. 1a-d). Figures 1e and 1f show vertical cross-sections along the white solid lines in Figs. 1a and 1c, which transect the squall line through the two cities. The horizontal width of the squall line is approximately 140 km in Figure 1e and only 80 km in Figure 1f. We observe a representative structure with three distinct parts: a convective line (high reflectivity of approximately 50 dBZ), a transition region (low reflectivity of less than 30 dBZ), and a stratiform region (intermediate reflectivity of approximately 35-40 dBZ) in these images. Obvious differences existed in the horizontal and vertical structures between the two phases of the squall line, with a bow-shaped convection region with high reflectivity that reached 8 km in the convective line for CZ contrasted with scattered convective clouds, low high-reflectivity heights (only 5 km) and smaller scale for NJ.

The OTT Parsivel$^2$ disdrometer that was used here is a second-generation optical disdrometer that was designed to measure the falling speeds and concentrations of different precipitation particle sizes (Loeffler-Mang and Joss, 2000; Tokay et al.,
The laser diode in Parsivel can produce a horizontal sheet of light that is 30 mm wide and 180 mm long. The maximum attenuation of the signal is used to estimate the size of particles that fall into the laser beam. The duration of the attenuation provides the fall speed. Its one-sample output is a two-dimensional matrix with 32 classes of particle diameters that range from 0.062 to 24.5 mm and 32 classes of falling speeds that range from 0.05 to 20.8 m s\(^{-1}\) (Table A1.2 in Yuter et al. 2006). The first two size classes are set to zero because of the low signal-to-noise ratio, so the minimum particle size that can be measured by the disdrometer is 0.312 mm. The shape of a small falling raindrop is spherical, while the shape of a large drop tends to be an oblate spheroid because of the effects of surface tension and aerodynamic pressure. For nonspherical particles, the polarization effect has been taken into account in the polarimetric radar data. A series of polarimetric variables could be measured by including radar reflectivity factors at horizontal and vertical polarization \(Z_{H,V}\), differential reflectivity \(Z_{DR}\), etc. The shape and the drop axis ratio \(r=b/a\) (vertical axis \(b\) divided by the horizontal axis \(a\)) has a significant impact on the retrieval of the DSD parameters and quantitative radar precipitation estimation. The axis ratio for drop sizes between 1 and 5 mm is assumed to vary linearly from 1 to 0.7; for drops larger than 5 mm, this ratio is assumed to be 0.7 in the Parsivel models (Tokay et al., 2014).

Some measurement error sources, such as strong winds, margin fallers, splashing effects, etc., can induce the misclassification of raindrops (Yuter et al. 2006; Friedrich et al. 2013a,b). Thus, the data quality control procedure in Friedrich was implemented.
Fallers with diameters above 8 mm or falling speeds 60% larger or slower than the empirical speed–diameter relationship for rain (Gunn and Kinzer 1949; Atlas et al. 1973) were eliminated. In addition, samples with one-minute raindrop numbers less than 10 or $R$ less than 0.5 mm h$^{-1}$ were excluded in each of the analyses except the time-series analyses. Finally, the squall line event consisted of 164 1-min effective DSD samples: 119 samples for CZ and 45 for NJ.

**b. Raindrop size distribution**

The raindrop size distribution is calculated from the Parsivel disdrometer counts as follows:

$$N(D_i) = \frac{1}{S_{\text{eff}}(D_i) \cdot T \cdot \Delta D_i} \sum_{j=1}^{32} n_{ij} V_j,$$

(1)

where $N(D_i)$ (mm$^{-1}$m$^{-3}$) is the number concentration of raindrops per unit volume per unit size interval for raindrop diameter $D_i$ (mm); $n_{ij}$ is the number of raindrops within size bin i and velocity bin j; $S_{\text{eff}}(D)$ (m$^2$) and $T$ (s) are the effective sampling area (Tokay et al. 2013) and sampling time, respectively; and $V_j$ (m s$^{-1}$) is the falling speed for velocity bin j. $S_{\text{eff}}(D)$ is calculated as follows:

$$S_{\text{eff}}(D_i) = 180 \times (30 - \frac{D_i}{2}).$$

(2)

The integral rainfall parameters, including the radar reflectivity factor $Z$ (mm$^6$ m$^{-3}$), rain rate $R$ (mm h$^{-1}$), rain water content $W$ (g m$^{-3}$) and total concentration of raindrops $N_t$(mm$^{-3}$), are derived from $N(D_i)$ as follows:

$$Z = \sum_{i=1}^{32} N(D_i) D_i^6 \Delta D_i,$$

(3)
The mass-weighted mean diameter $D_m$ (mm) is a widely used characteristic raindrop diameter. $D_m$ is computed as the ratio of the 4th to the 3rd moment of the DSD, where the nth-order moment is defined in Eq. (8):

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

The three-parameter gamma function model is widely used to represent the measured raindrop spectra (Ulbrich 1983) and is expressed as

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

where $D$ (mm) is the raindrop diameter and $N(D)$ (mm$^{-1}$m$^{-3}$) is the number concentration of raindrops in a unit volume and a unit size interval, and $N_0$ (mm$^{-1}$µm$^{-3}$), $\mu$ and $\lambda$ (mm$^{-1}$) are the intercept parameter, the shape parameter, and the slope parameter, respectively. The truncated moment method (Ulbrich and Atlas 1998; Zhang et al. 2003) is chosen to calculate the three parameters ($N_0$, $\mu$ and $\lambda$), and the second, fourth and sixth moments are used.

To solve the non-independence problem of the parameters of the gamma DSD model, a normalization method has been proposed (Willis 1984; Sempere Torres et al.)
The normalized DSD model makes it possible to compare DSDs regardless of the timescale and rain rate and accurately examine the substantial variations related to the physical rainfall regimes. The normalized gamma DSD model is defined as

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

(10)

where

\[ f(\mu) = \frac{6}{4^4} (4 + \mu)^{4+\mu} \frac{(4 + \mu)^4}{\Gamma(4 + \mu)}, \]  

(11)

and the normalized intercept parameter \( N_w \) (mm\(^{-1}\)m\(^{-3}\)) is related to the rain water content \( W \) and \( D_m \) as follows:

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

(12)

where \( \rho_w \) is the water density.

c. Calculated polarimetric radar variables

Polarimetric radars have been practically applied to retrieve rainfall rates. The combination of the radar reflectivity in the horizontal or vertical polarization \( Z_{H,V} \) (10\( ^{\ast} \)log10 \( Z_{h,v} \)), the differential reflectivity \( Z_{DR} \), the specific differential phase \( K_{dp} \), etc. provide detailed information on the precipitation particles and helps produce more accurate precipitation estimations. These variables are computed as follows:

\[ Z_{h,v} = \frac{4A^4}{\pi^4 |K_w|^2} \int_{D_{max}}^{D_{min}} \left| f_{br,vv}(D) \right|^2 N(D)dD, \]  

(13)

\[ Z_{DR} = 10 \log_{10} \left( \frac{Z_h}{Z_v} \right), \]  

(14)
$$K_{dp} = 10^{-3} \frac{180}{\pi} \lambda \Re \left\{ \int_{D_{min}}^{D_{max}} \left[ f_{h}(D) - f_{v}(D) \right] N(D) dD \right\},$$  

(15)

where $\lambda$ is the radar wavelength; $K_w$ is the water dielectric factor; and $f_{hh,vv}(D)$ and $(f_{h,v}(D))$ are the backscattering (forward-scattering) amplitudes of a raindrop for the horizontally and vertically polarized waves, respectively. In this paper, these dual-polarization radar variables are calculated from the disdrometer data by using the T-matrix (Mishchenko, 2001; Kalogiros et al. 2013) scattering method. The frequency of the radar’s electromagnetic wave is assumed to be 2.85 GHz (S-band), and the drop temperature is assumed to be 10°C. The mean and standard deviation of the canting angle is assumed to be 0 and 7° with a Gaussian model, respectively. The axis ratio model reported by Beard and Chuang (1987) is used as follows:

$$r = 1.0048 + 5.7 \times 10^{-4} D - 2.628 \times 10^{-2} D^2 + 3.682 \times 10^{-3} D^3 - 1.677 \times 10^{-4} D^4.$$  

(16)

d. Classification of rain types

The conceptual model and segmentation of squall lines has been reported and discussed based on radar data analysis and numerical simulations (Braun and Houze 1994; Parker and Johnson, 2000), showing the different precipitation properties induced by the spatial structures of different squall line regions. The convective line (C) usually consists of organized deep convection and exhibits a linear region of high radar reflectivities. The stratiform region (S) is characterized by a weak updraft and bright band in vertical cross-section radar images. The transition region (T) is the zone between the convective line and stratiform region with low rainfall intensity and radar reflectivity. A rainfall classification approach similar to that used in Maki et al.
(2001) was adopted in this study. First, radar data were used for rough classification. The 88d2arps module in the ARPS (Advanced Regional Prediction System) model (Xue et al. 2000) was used to interpolate the radar data that were measured by the CINRADA/SA radar (2.85 GHz) in NJ to obtain grid data with a horizontal and vertical resolution of 2 km and 0.5 km, respectively. Then, the data at the nearest grid point of the disdrometers were extracted and plotted in time series as the evolution of the radar reflectivity factor over the DSD observation sites. Three significantly different areas are depicted in Fig. 2a: a high-reflectivity area between 16:00 and 16:40 UTC, a moderate-reflectivity area between 17:30 and 17:50 UTC, and a weak-reflectivity area between 17:00 and 17:25 UTC. The squall line is generally in its mature stage when passing CZ, and three different precipitation types can be identified: the convective-line, transition, and stratiform regions. In Fig. 2b, the mean reflectivity factor at NJ is lower than that at CZ, and the maximum reflectivity factor is approximately only 45 dBZ. The height of the high reflectivity zone (>40 dBZ) is below 4 km; thus, the squall line is in the declining stage when passing NJ. A rain-free period occurred between 18:10 and 19:20 UTC. A weak reflectivity factor area (20-30 dBZ) appeared at 19:20 to 19:40 UTC with 20 min of weak rainfall. This should be classified as trailing stratiform rainfall during the declining stage. The update time of the NJ radar was 6 min, which was longer than that of the Parsivel disdrometer (1 min). Second, the rainfall rate time series was used for the final classification. For the raindrop dataset, the sections with \( R < 1 \) mm were classified as transition regions, and a rainfall rate of 20 mm h\(^{-1}\) was used to partition the convective line to the convective
center (CC), leading edge (LE), and trailing edge (TE) regions. The classification results are shown in Figure 3 and Figure 4.

3. Results and discussion

a. Time series analyses

Figures 3 and 4 show the time series of the raindrop concentration \( N(D) \), rainfall rate \( R \) and three DSD parameters, i.e., \( \log_{10} N_w \), \( \log_{10} N_0 \) and \( \mu \), during the event for CZ and NJ, respectively. For the mature stage, the rainfall rate of the CC was very high (approximately 80 mm h\(^{-1}\)); in the stratiform region, the rate had a secondary peak and was relatively steady (less than 10 mm h\(^{-1}\)). Moreover, the rainfall rate is smallest in the transition region (less than 1 mm h\(^{-1}\)). Figure 3a shows that the maximum diameter is approximately 5 mm or larger for the CC region, below 2 mm for the transition, and approximately 3 mm for the stratiform region. The concentration of small drops (diameter less than 1 mm) in the CC was greater than 1000 m\(^3\)mm\(^{-1}\) but only 100-500 m\(^3\)mm\(^{-1}\) in the stratiform region. Hence, the CC region had more large drops (diameters greater than 3 mm) and abundant small drops (diameters smaller than 1 mm). The DSD characteristics in the LE are very different from those in the CC. The number concentration is smaller in the LE, especially for small drops. The parameter \( N_w \) is the normalized intercept parameter and is related to the number concentration of raindrops. In Figs. 3b and 3c, \( \log_{10} N_w \) and \( \log_{10} N_0 \) sharply increased in the LE region and then remained nearly constant in the CC region. The maximum mean \( \log_{10} N_w \) occurs in the convective line region, with the minimum
in the stratiform region and the transition between them. In the CC phase, log10 $N_0$ and $\mu$ were almost constant, and the DSDs sometimes reached an ‘equilibrium’ state (List et al. 1987).

For the NJ dataset (Figure 4), the rain rate in the CC was weaker than that in CZ and exhibited moderate rainfall rates (20-50 mm h$^{-1}$), and the stratiform region had very weak precipitation of approximately 1 mm h$^{-1}$; a 70-min rain-free period occurred between the convective and stratiform regions. The rain rates in the LE and CC regions were comparable, while log10 $N_w$ in the leading edge was much smaller, and the number concentration in the leading edge was much lower than that in the convective center. The largest raindrops appeared in the LE region, and more large drops and fewer small drops were present in LE than in CC. Thus, large drops substantially contributed to the rain rate in the LE. The LE was probably in the vertical updraft airflow region. The flow prevented all but the largest drops from reaching the surface. Additionally, small drops may have been left suspended in the cloud and/or carried elsewhere by horizontal air currents before they reached the ground.

Waldvogel (1974) noted that there are sudden increases in $N_0$ from uniform rain to convective rain while the rainfall rate remains approximately constant, which is commonly called the “$N_0$ jump”. Maki et al. (2001) and Uijlenhoet et al. (2003) also discussed the phenomenon and found an abrupt decrease in $N_0$ when the rainfall changed from the transition to stratiform region. Fig. 5 provides scatter plots of $N_0$ versus $R$ for the rainfall types. The rain rate in the TE was comparable to that in the
stratiform region; therefore, the “$N_0$ jump” was evident in both stages. The relationship $N_0 = 4 \times 10^9 R^{4.3}$ was established by Maki et al. (2001) because these authors noted that $N_0$ without the truncation effect was estimated to be 10 times larger than that from the truncated moments method (Ulbrich and Atlas 1998). This method successfully distinguished the rainfall in the CC and stratiform regions; however, points for the LE and TE regions were distributed below the $N_0$-$R$ line. Hence, the $N_0$-$R$ relation derived from tropical oceanic rainfall is effective to some degree but is not completely suitable for midlatitude continental precipitation.

b. Distribution of $D_m$ and $N_w$

Figure 6 shows scatter plots of $D_m$ and log10 $N_w$ for the squall line DSD data. The LE rainfall is characterized by small values for log10 $N_w$ and the largest value for $D_m$, which may be related to the size-sorting effect, i.e., only drops that were large enough could fall through the strong vertical updrafts, as mentioned in the previous section. The phenomenon is more obvious for the declining stage in the NJ dataset than for the mature stage, and this may be indirect evidence for the size sorting effect by the updraft aloft (Ulbrich and Atlas 2007). Because the updraft decreases in strength during the declining phase and it cannot support large drops, there are more numerous large drops in the LE for NJ than CZ. The log10 $N_w$ and $D_m$ values for the CC were both large where the precipitation was greatest. Additionally, the average values of log10 $N_w$ and $D_m$ both decreased from the mature stage to the declining stage. The value of $N_w$ for the TE was similar to that for the CC, but $D_m$ was much smaller and
closer to the stratiform reference line. Hence, the decreased rain rate in the TE is mainly due to the decrease in drop size. The mean log10 $N_w$ for the transition region was greater than that for the stratiform region (for both CZ and NJ), and the $D_m$ value for the transition region was the smallest. Thus, the rainfall in the transition region consisted of many small drops, possibly due to mesoscale subsidence, in which the riming and collision–coalescence processes were restricted (Biggerstaff and Houze 1993). For the stratiform rainfall, most of the CZ points were above the reference line, while the NJ points were below this line; from the mature to declining stage, the average value of $D_m$ decreased from 2.0 mm to 1.3 mm while log10 $N_w$ increased from 2.7 to 3.2, which is different from the change in the convective center. Comparing the scatters for the trailing edge and stratiform where the rain rate was comparable indicated that the stratiform rainfall was characterized by small log10 $N_w$ and large $D_m$ while the TE exhibited the opposite, which originated from the different microphysical mechanisms of the convention and stratiform rainfall. The distribution of log10 $N_w$ and $D_m$ was distinctly different for the continental and marine precipitation. The two rectangles corresponded to the average maritime and continental convective clusters, as reported by Bringi et al. (2003). The classification of convective rain in Bringi et al. (2003) included samples with $R>$5 mm h$^{-1}$ and the standard deviation of $R>$1.5 mm h$^{-1}$ over five consecutive 2-min samples. Therefore, the convective edge precipitation could be filtered out by this method. We focused on precipitation at the CC. The average $D_m$ values for this region were 2.2 mm and 2.4 mm, within the range of continental convective storms, while log10 $N_w$ was slightly
larger than this range. This observation was likely associated with the local climate background at that time. This event occurred in late July during the post-Meiyu (called Baiu in Japan) period, when the supply of moisture was adequate during theAsian summer monsoon season. In addition, aerosol concentrations were relatively high in eastern China (Streets et al. 2008). These factors may be related to the high raindrop concentration in the CC and additional research is required.

c. Drop size spectra

Figure 7 shows the composite drop size spectra for the three rain types after averaging all the instantaneous size spectra from each subset. The convective distribution has the highest concentration in all diameter bins compared to the stratiform and transition rainfall categories, resulting in a high rainfall intensity and rain water content (showed in Table 1). The location of the peak concentration for the CC is similar for both CZ and NJ (i.e., 0.5 mm). In other size ranges, the concentration in the CC for NJ is smaller than that for CZ. The concentration in the stratiform region for NJ is higher than that for CZ when the sizes are less than 1 mm, whereas the situation is the opposite when the diameters are greater than 1 mm. The concentration for the transition region is comparable to that of the stratiform region at small size ranges, although it decreases sharply with increasing diameter, and drops with a diameter exceeding 2.5 mm are few in the transition region.

Table 1 shows the integral parameters and characteristic diameters for the convective center and stratiform regions. The average rain rate in the CC for CZ was
82.93 mm h^{-1}, much higher than that for NJ, and the rain water content was two times higher than that for NJ, which mainly resulted from the significant decrease in the number concentration \( N_t \) (2514.5 m\(^{-3}\) in CZ and 1526.8 m\(^{-3}\) in NJ). In addition, the mean values of \( D_m, D_0, \) and \( D_{\text{max}} \) for the stratiform region are smaller than that for the convective center, although the mean diameter \( D_a \) for the stratiform region (CZ) is larger, which is mainly due to the large difference in the number concentration between the two rainfall types. These results also indicate that large drops play a more significant role in stratiform rainfall, and small drops are relatively deficient.

Apart from the moment method for estimation, the shape parameter \( \mu \) can also be estimated via the \( \mu \) search method (Testud et al. 2001; Bring et al. 2003), which searches for \( \mu \) by minimizing the absolute deviation between the measured normalized DSD data and the normalized gamma distribution using the following expression:

\[
\mu_i = \min_{\mu} \sum_{i=1}^{\text{obs}} \left| \frac{\log_{10} N_{\text{obs}}(D_i) - \log_{10} N_{\text{model}}(D_i)}{N_w} \right| \quad (17)
\]

Scatterplots of the normalized concentration \( N(D)/N_w \) versus the normalized drop diameter \( D/D_m \) for different phases are presented in Figure 8. The heavy solid lines indicate the normalized gamma function. To better understand how the DSDs fit with the normalized gamma model, the superimposition of the \( \mu \) values is also shown. The results clearly indicate that the measured DSDs are well bounded by the scaled gamma functions with a superimposed \( \mu \) varying from −3 to 20, especially for convective rainfall, which is consistent with the findings reported by Bringi et al. (2003). Moreover, in the CC, the shape of the normalized distributions for CZ is bent slightly downward in the small raindrop bins, while parts of the normalized spectra
for NJ are bent slightly upward. In the stratiform region, the shape of the normalized distributions is bent strongly downward. In addition, the normalized diameters $D/D_m$ are almost all less than 2 for stratiform rain, while the maximum $D/D_m$ is greater than 2.5 for CZ convection and less than 2.5 for NJ convection. $N_w$ is equal to $N_0$ under the circumstance $\mu = 0$, and the gamma distribution is simplified as an exponential distribution. In general, convective rainfall is more exponential than that in the stratiform region due to its smaller $\mu$ values. This result is different from Maki et al. (2001), which may be due to 1) the difference between midlatitude and tropical squall lines and 2) the observation instrumentation; the RD-69 disdrometer used by Maki et al. (2001) struggles to capture small drops after observing large drops. The number of small drops was thus probably underestimated during this time. In the meantime, the inability of the Parsivel device to measure the smallest diameter bins significantly influenced the shape of the gamma distribution, and a more accurate measurement of small raindrops could result in more DSDs with negative shape parameters.

**d. Rainfall estimation relationship**

Precipitation estimation based on radar data is one of the applications of DSDs. The power-law relationship $Z=AR^b$ has been widely used for precipitation estimation by using both ground-based and space-borne radar, such as the Precipitation Radar (PR) in the Tropical Rainfall Measuring Mission (TRMM) and the Dual-frequency Precipitation Radar (DPR) in the Global Precipitation Measurement (GPM) mission. However, the DSDs were found to vary with precipitation type, topographical location,
climatic regime, choice of disdrometer, etc. Hence, the parameters in the $Z-R$ relation are also changeable due to the correlation with the DSD variability (Chandrasekar et al. 2003; Rosenfeld and Ulbrich 2003). Figure 9 shows scatterplots of $Z$ versus $R$ for the observed squall line. The power-law equations are obtained using the least-squares method and are shown with different color lines. Table 2 gives the power-law $Z-R$ relationships for each rainfall phase and for three combinations. For the same rain rate, the radar reflectivity for the stratiform region was greater than that for the convective region, which created larger coefficient and exponent values. This is mainly due to the fact that the large drops in the stratiform region constitute a larger proportion of the rainfall than in the convective region, as mentioned before. For the combined situation (stratiform plus transition), a smaller coefficient and larger exponent are obtained. Thus, the classification of a transition region has a large effect on the $Z-R$ relationship, as noted by Uijlenhoet et al. (2003) and Ubrich and Atlas (2007).

Nearly all the stratiform data points were distributed to the left of the black dashed line, which stands for the $Z = 300R^{1.4}$ relationship that was previously used by the US National Weather Service, i.e., exhibiting a smaller rain rate for a given reflectivity, which implies that the radar would overestimate stratiform rainfall when using this reference $Z-R$ relationship. The cyan line was much closer to the reference $Z-R$ relationship; thus, $Z = 300R^{1.4}$ was relatively suitable for estimating rainfall from the CC, where the rainfall rate was greater than 20 mm h$^{-1}$. Moreover, the fitted line for the LE is much higher than the average line and the reference line, which is related to the larger values of $D_m$ for the LE. Therefore, the estimation bias is comparatively
larger for the LE. Contrasting the two stages, the exponent $b$ for the mature stage fitted using all data is smaller, and the coefficient $A$ is larger than those for the declining stage.

Recent studies have indicated that polarimetric radar has advantages in rainfall estimation because of its comprehensive detection abilities, and many empirical relationships that are used for rainfall estimation, such as $R(Z_H, Z_{DR})$, $R(K_{dp})$, and $R(Z_{DR}, K_{dp})$, have previously been reported (e.g., Zhang et al. 2001; Cao et al. 2008, 2010; You et al. 2014). Figure 10 shows scatterplots of $Z_{DR}$ versus $Z_H$ and $K_{dp}$ versus $Z_H$ for the observed squall line, and the exponential relationship between them for the convective and stratiform regions was fitted by using the least-squares method. In Figs. 10a and 10b, the distribution of $Z_{DR}$ for stratiform rainfall was concentrated on the upper-left side of the convection rainfall during both the mature and declining stages. Thus, for the same $Z_H$ value, the $Z_{DR}$ stratiform rainfall was larger than the convection rainfall. This feature may be used as a criterion for rainfall classification but requires more observation data to support. In Figs. 10c and 10d, the values of $K_{dp}$ were very small (below 0.5 deg km$^{-1}$) when the reflectivity factor was less than 45 dBZ. Additionally, when the reflectivity factor was greater than 45 dBZ, $K_{dp}$ quickly increased with increasing reflectivity. The reflectivity factor for weak and moderate precipitation and even for some heavy rainfall was generally below 45 dBZ. Additionally, unavoidable instrument noise was present in the actual radar observations. Thus, estimation error using $K_{dp}$ in the S-band may be relatively large.

The $R(Z_H, Z_{DR})$ relationships for the convective line and stratiform rainfall during
the two stages of development are given in Table 3 in the form of \( R = c \times 10^{-3}Z_H^2Z_{DR}^e \)

using the least-squares method. To compare the different rainfall estimation methods, the \( Z-R \) relationship determined using DSD data in both stages is \( Z=472R^{1.21} \) and \( R(Z_H, Z_{DR}) \) relationship is \( R=3.66 \times 10^{-3}Z_H^{0.91}Z_{DR}^{-0.98} \). For comparison, the normalized mean bias (NB) and the normalized standard error (NSE) were defined as

\[
NB = \frac{\sum (R_{\text{matrix}} - R_{\text{DSD}})}{\sum R_{\text{DSD}}} \tag{18}
\]

\[
NSE = \frac{\sum |R_{\text{matrix}} - R_{\text{DSD}}|}{\sum R_{\text{DSD}}} \tag{19}
\]

where \( R_{\text{DSD}} \) and \( R_{\text{matrix}} \) are the one-minute precipitation values from the raindrop spectrum data and the radar parameters based on the T-matrix simulation, respectively. The results showed that the NB errors were 27\%, -13\%, and 11\% for the NEXRAD \( Z-R \) relationship, \( Z = 472R^{1.21} \) and \( R(Z_H, Z_{DR}) \), respectively, and the NSE errors were 45\%, 34\%, and 24\%, respectively. The results indicate that the polarimetric estimation is more accurate than \( Z-R \) relationship. The \( R(Z_H, Z_{DR}) \) estimator has an advantage over the \( Z-R \) relation because the \( Z_{DR} \) parameter is closely related to the number concentration of medium and large raindrops and reflects the information of the precipitation type to some degree (Fig. 11). Hence, the polarimetric observations help improve the accuracy of the precipitation estimation when lacking a classification of rain types.

4. Summary and conclusions

In this paper, the variability of DSDs in a typical midlatitude squall line during
different life stages was studied using data collected by Parsivel\textsuperscript{2} disdrometers in CZ and NJ in China. Due to the simple structure of a typical squall line, the convective line, stratiform, and transition zone regions are identified by combining the structure of the radar reflectivity and rain intensity. The following conclusions are obtained:

1. The number concentration and drop size in the convective region, especially the number concentration of small drops, was larger than that in the stratiform region; the size for transition zone was smallest, and number concentration was comparable with that in stratiform. Moreover, the stratiform region exhibited a secondary rain rate peak, and large drops play a more significant role in the region. The intercept parameter $N_0$ and the normalized intercept parameter $N_w$ decreased when the rainfall transitioned from convective to stratiform precipitation.

2. From the mature stage to the declining stage, the drop size and number concentration at the CC both decreased; for stratiform rainfall, the number concentration was similar, although the drop size became much smaller. The LE had more large drops, which may have been related to updrafts in this region.

3. The rain rates in the convective trailing edge and stratiform regions are comparable, although, for stratiform rainfall, the mean $D_m$ is approximately 2 mm, which is much larger than that for the trailing edge, while $N_w$ is much smaller than that for the trailing edge, which indicates that the microphysical mechanism is different for different rainfall types. This is probably because the aggregation of ice crystals and the melting of dry snow in the weak mesoscale updraft are important microphysical processes in the stratiform region, while collision, coalescence, and
break-up processes play significant roles in convective rainfall.

4. The form of the normalized gamma DSD was bent downward in the stratiform region and was more exponential in the convective center. When contrasting the two stages, portions of the scaled spectra for NJ were bent slightly upward, and the $\mu$ value was similar for the convective center and larger for the stratiform region during the declining stage.

5. The radar reflectivity for the stratiform region is larger than that for convective region for the same rain rate, which leads to larger coefficient and exponent values for stratiform precipitation. The exponent $b$ for the mature stage fitted using all collected data is smaller, and the coefficient $A$ is larger than that for the declining stage when comparing the $Z-R$ relationship in the two stages. Rainfall estimation using the $R(Z_H, Z_{DR})$ estimator is more accurate than that using a single-parameter estimator ($Z-R$ relation) algorithm without classification of rain types because the additional $Z_{DR}$ parameter reflects the DSD differences between rainfall types to some degree.

This paper analyzed the characteristics of the DSDs in a squall line that occurred in eastern China, and some findings regarding different precipitation types in a summer squall line were obtained. However, the results are not necessarily conclusive because it is only a typical case study, and more data should be collected via long-term observations. Additionally, because the dynamical and microphysical processes are highly coupled via the feedback of latent heat release and/or cooling (Miltenberger et al. 2015), more observations and effective numerical simulations might assist with reproducing and understanding the kinematic field and microphysical processes.
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Wen, L., K. Zhao, G. Zhang, M. Xue, B. Zhou, S. Liu, and X. Chen, 2016: Statistical characteristics of raindrop size distributions observed in east China during the Asian summer monsoon season using 2-D video disdrometer and Micro Rain


Table 1 Mean values of integral parameters for the CC and S regions of the squall line. The terms $R$, $Z$, $W$, $N_t$, and $N_w$ represent the rain rate (mm h$^{-1}$), radar reflectivity (dBZ), rainwater content (g m$^{-3}$), total drop concentration (m$^{-3}$), and normalized intercept parameter (m$^{-3}$ mm$^{-1}$), respectively. The mean values of the mean diameter $D_o$ (mm), mass-weighted diameter $D_m$ (mm), and maximum diameter $D_{ma}$ (mm) are also provided.

Table 2 Coefficient $A$ and exponent $b$ values of the fitted $Z$–$R$ relationship for the convective line (C), transition region (T), and stratiform region (S) (and combinations thereof).

Table 3 Parameter values of the fitted $R(Z_H,Z_{DR})$ relationship in the form of $R = c \times 10^{-3}Z_H^aZ_{DR}^b$ for the convective line and stratiform regions during the two development stages (the units of $Z_H$ and $Z_{DR}$ are mm$^6$ m$^{-3}$ and dB, respectively).
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<table>
<thead>
<tr>
<th>Site</th>
<th>$R$</th>
<th>$Z$</th>
<th>$W$</th>
<th>$D_a$</th>
<th>$D_m$</th>
<th>$D_{max}$</th>
<th>$N_t$</th>
<th>$\log_{10}(N_w)$</th>
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<td>0.07</td>
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<td>1.30</td>
<td>1.97</td>
<td>92.6</td>
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Table 2 Coefficient $A$ and exponent $b$ values of the fitted $Z$–$R$ relationship for the convective line (C), transition region (T), and stratiform region (S) (and combinations thereof).

<table>
<thead>
<tr>
<th>Site</th>
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<th>Stratiform</th>
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<th>T+S</th>
<th>C+T+S</th>
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<td>232</td>
<td>341</td>
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<tr>
<td></td>
<td>b</td>
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<td>1.67</td>
<td>1.46</td>
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<tr>
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<td>A</td>
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<td>-</td>
<td>371</td>
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<tr>
<td></td>
<td>b</td>
<td>1.56</td>
<td>-</td>
<td>1.66</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 3 Parameter values of the fitted $R(Z_H, Z_{DR})$ relationship in the form of $R = c \times 10^{3Z_H}Z_{DR}^{d}$ for the convective line and stratiform regions during the two development stages (the units of $Z_H$ and $Z_{DR}$ are mm$^3$m$^{-3}$ and dB, respectively).

<table>
<thead>
<tr>
<th>Site</th>
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<th>$d$</th>
<th>$e$</th>
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</tr>
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<tr>
<td>total</td>
<td>3.66</td>
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<td>0.98</td>
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Figure 1 Plan Position Indicators (PPIs) at a 0.57° elevation angle for the 30 July 2014 squall line based on reflectivity data from the CINRADA/SA Doppler Weather Radar at Hefei (Anhui Province) as the squall line moved through CZ and NJ at (a) 15:59, (b) 16:51, (c) 17:17 and (d) 19:14 UTC. (e, f) Vertical-cross sections (RHI) that correspond to the white solid lines in (a) and (c), which show typical vertical structures of squall lines. The distance between two adjacent circles in (a)–(d) is 50 km. The intervals of the X axis and Y axis are 4 km and 20.4 km, respectively. The white curve in the figure is the provincial boundary of Jiangsu Province and Anhui Province.

Figure 2 Time series of the vertically pointed radar reflectivity factor for (a) CZ and (b) NJ when using the CINRADA/SA radar data in NJ. The color shading represents the reflectivity factor (unit: dBZ), and the Y axis represents the altitude (unit: km).

Figure 3 Temporal evolution of the (a) rain rate $R$ (solid line), and raindrop size distribution $N(D)$ (color shading) and the (b) $\log_{10} N_w$, (c) $\log_{10} N_0$, and (d) $\mu$ parameters of the gamma distribution fit to the raindrop size distributions in the three regions of the squall line based on the CZ dataset.

Figure 4 Same as Fig. 3 except for the NJ dataset. A 70-min rain-free period occurred between 18:10 and 19:25 (dashed line).

Figure 5 Empirical relationship between the intercept parameter $N_0$ of the gamma fit and the rain rate $R$ for the observed squall line. The squares, dots, circles, small dots, and pluses indicate the raindrop size distributions in the LE, CC, TE, T, and S regions, respectively. The blue symbols are for the CZ dataset, and the red symbols are for the NJ dataset. The dashed line indicates the separator between tropical convective (above) and tropical stratiform (below) rain according to Tokay and Short (1996).

Figure 6 Scatterplot of $\log_{10} N_w$ versus $D_m$ for the observed squall line. The squares, dots, diamonds, small dots, and pluses indicate the raindrop size distributions in the LE, CC, TE, T, and S regions, respectively. The triangles indicate the average value of each region, with blue (cyan) symbols for the CZ dataset and red (magenta) symbols for the NJ dataset. The two gray rectangles correspond to the maritime and continental convective clusters reported by Bringi et al. (2003), and the black dashed line is that of Bringi et al. (2003) for stratiform rain.

Figure 7 Composite raindrop spectra (fitted to the observations) for the convective center, stratiform, and transition regions of the squall line. The circles, crosses and pluses represent data from the concentration center, stratiform and transition regions for CZ, respectively; the triangles and squares are data for the convective center and stratiform regions in NJ, respectively.

Figure 8 Scaled DSD $N(D)/N_w$ versus the normalized diameter parameter $D/D_m$ for the measured samples (gray pluses). The gray solid lines indicate the normalized gamma distribution for values of $\mu$ between $-3$ and 20, and the black solid lines indicate the normalized gamma distribution from the $\mu$ search method. (a) and (b) show the CC region for CZ and NJ, and (c) and (d) indicate the S region of CZ and NJ, respectively.

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Figure 10 Scatterplots of $Z_H-Z_{DR}$ & $Z_H-K_{dp}$ for the observed squall line (a, c) for the CZ dataset and (b, d) for the NJ dataset. The squares, dots, circles, asterisks, and pluses indicate the data from the LE, CC, TE, T, and S regions, respectively. The fitted power-law relationships of the convective and stratiform regions are shown using solid and dashed lines, respectively. The coefficient and exponent values of the fitted power-law equations are also provided.