Characteristics of the raindrop size distributions and their retrieved polarimetric radar parameters in northern and southern China

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\begin{abstract}

The characteristics of raindrop size distributions (RSDs) and polarimetric radar parameters retrieved by T-matrix for stratiform and convective precipitation in Beijing and Zhangbei (northern China), and Yangjiang (southern China) are studied and compared based on RSD data observed with PARSIVEL disdrometers in these three different climatic regions. The effects of observed and fitted RSD on scattering simulation are also discussed. The conclusions further confirm the obvious variation of RSDs in different climatic regions and rain types. There is significant regional difference in rainfall microphysical parameters for convective precipitation, and small regional difference for stratiform precipitation, instead. Convective precipitations from Beijing and Yangjiang both have higher mass-weighted mean diameter $D_m$ and log$_{10}$N$_w$ ($N_w$, normalized intercept parameter) values than stratiform precipitations. The averaged RSDs from both rain types in Beijing and Yangjiang are in good agreement with gamma distribution while those in Zhangbei cannot be well fitted either by gamma or M–P (Marshall–Palmer) distribution. It is essential to take into account the effect of air density on raindrop fall velocity in highlands far away from sea level, such as Zhangbei. The $\mu$–$\Lambda$ relation varies with location. For a given $\Lambda$ value, the fits to the data in the three regions have higher $\mu$ values than Florida relation (Zhang et al., 2003). It is robust to retrieve polarimetric radar parameters by T-matrix. There is an exponential relationship between differential reflectivity $Z_{DR}$ and radar reflectivity factor $Z_{HH}$, as well as the relation between specific differential phase $K_{DP}$ and $Z_{HH}$. The variation of the relations in different climate regions and rain types results from RSD’s sensitivity to climatic regions and rain types. Observed RSD is superior to the fitted one in retrieving polarimetric radar parameters.

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\end{abstract}

\section{Introduction}

Raindrops are created by the interaction of dynamical and microphysical processes. Information about raindrop size distribution (RSD) is the fundamental microphysical property of precipitation. Therefore, observation of RSD is essential for the understanding of formation and microphysical structure of precipitation, radar estimation of precipitation, improvement of microphysics parameterization in numerical weather prediction models, and effect evaluation of artificial precipitation.

Raindrop size distribution is affected by many physical factors, including collision-coalescence, breakup, condensation, evaporation, updraft, downdraft, and horizontal wind shear and so on, which contribute to RSD variation both spatially and temporally (Bringi et al., 2003; Tokay and Short, 1996; Ulbrich, 1983). The effect of these factors on RSD is
complex, and RSDs vary not only within a climatic regime but also within a specific rain type (Nzeukou et al., 2004). The microphysical characteristics of the drop size distributions from various climatic regimes and rain types have been demonstrated by numerous studies using the observed disdrometer data (Atlas and Ulbrich, 2006; Bringi et al., 2003; Chang et al., 2009; Chapon et al., 2008; Chen et al., 2013; Lee et al., 2009; Martner et al., 2008; Marzano et al., 2010; Moumouni et al., 2008; Niu et al., 2010; Tapiador et al., 2010; Tokay et al., 2008). Chen et al. (2013) showed that characteristics of DSDs observed in Nanjing (a big city in eastern China) during the Meiyu season are different from those observed in some other tropical or subtropical locations even though eastern China is situated in a similar latitudinal belt, which is likely due to local atmospheric tropical locations even though eastern China is situated in a different from those observed in some other tropical or sub-

Section 3. Section 4 examines polarimetric radar parameters retrieved by T-matrix in different climatic regions and rain types, and the effect of observed and fitted RSD on retrieved polarimetric radar parameters. The major findings are summarized in Section 5.

2. Data and analysis methods

2.1. PARSIVEL disdrometer

RSDs analyzed in this study were collected with a PARSIVEL precipitation particle disdrometer manufactured by OTT Messtechnik, Germany. Löffler-Mang and Joss (2000) provided a detailed description of this instrument. Briefly, the instrument is a laser-based optical disdrometer for simultaneous measurement of particle size and velocity of all liquid and solid precipitation. The core element of the instrument is an optical sensor that produces a shallow and broad horizontal radiation band. Hydrometeors falling through the measurement area cause variations in the radiation intensities. The amplitude of the signal deviation is a measure of particle size, and the duration of the signal allows an estimate of particle fall velocity. The instrument can measure the amount (rate) of precipitation and the size distribution and velocity of particles, and also indentify the type of precipitation and provide precipitation code. Additionally, radar reflectivity and visibility are derived. All results can be transferred to the personal computer and data storage in real time, and then analyzed with radar data, which can improve quantitative precipitation estimation. It can operate in any climate weather regime and the incorporated heating device minimizes the negative effect of freezing and frozen precipitation accreting critical surfaces on the instrument. Like other measurement of a physical process, disdrometer measurements are affected by noise and sampling effects (Jaffrain and Berne, 2011).

Particles with diameters between 0.125 mm and 24.5 mm and fall velocities between 0.05 m s\(^{-1}\) and 20.8 m s\(^{-1}\) can be detected by PARSIVEL. The particle size and velocity are each subdivided into 32 size and velocity bins, respectively, with different bin widths.

The shape of a falling raindrop in still air is determined by a balance of three types of forces, hydrostatic pressure, surface tension and aerodynamic pressure. A small drop has a spherical shape, whereas a larger drop tends to have an oblate spheroid shape with a flatter base. This means that the particle sizes directly derived by the instrument (i.e. \(2a\)) frequently underestimate the large raindrop diameter. To minimize the potential instrument error, the observed raindrop diameter should be corrected (Yang et al., 2012). The drop axis ratio \(r = b/a\) (here vertical axis \(b\) divided by the horizontal axis \(a\)) is well approximated with

\[
\begin{align*}
 r &= 0.9971 + 0.2193D_{eq} - 3.5105D_{eq}^2 + 5.0746D_{eq}^3 - 2.3559D_{eq}^4 \\
 &= 0.9971 + 0.2193D_{eq} - 3.5105D_{eq}^2 + 5.0746D_{eq}^3 - 2.3559D_{eq}^4
\end{align*}
\]

where \(D_{eq}\) is the equivalent-volume drop diameter in cm. Eq. (1) is fitted based on the data of the experimental fit line shown in Fig. 2 of Brandes et al. (2004) due to obvious difference between their fitted relation and experimental data. Equivalent-volume drop diameter \(D_{eq}\) can be calculated by a combination of Eq. (1) and \(D_{eq} = 2a^{3/2}b^{1/2}\). After shape correction, raindrop diameter is
smaller than that directly derived by the instrument. The drop axis ratio decreases with the increase of \(D_\text{eq}\), which means that the bigger the diameter, the flatter the shape, and the greater the difference between \(D_\text{eq}\) and drop size directly derived by the instrument. The difference is up to about 1 mm at a raindrop diameter of 6.5 mm. It demonstrates the necessity of shape correction before analysis of the observed data.

2.2. Raindrop size distribution

Two of the widely used raindrop size distribution functions are M–P function (Marshall and Palmer, 1948) and gamma function (Ulbrich, 1983).

Marshall and Palmer (1948) proposed a well-known raindrop size exponential distribution, known as M–P function given by

\[
N(D) = N_0 \exp(-\Lambda D) \tag{2}
\]

where \(D\) (mm) is the drop diameter, \(N(D)\) (mm\(^{-1}\) m\(^{-3}\)) is the number of drops per unit volume per unit size interval, \(N_0\) is the number concentration parameter in a unit of mm\(^{-1}\) m\(^{-3}\), \(\Lambda\) is the slope parameter, and \(N_0 = 8000 \text{ mm}^{-1} \text{ m}^{-3}\). \(\Lambda = 4.11^{-0.21} \text{ mm}^{-1}\), here I is the rainfall rate in mm h\(^{-1}\).

The gamma drop size distribution was derived by Ulbrich (1983) by introducing a shape parameter \(\mu\) into the M–P function:

\[
N(D) = N_o D^\mu \exp(-\Lambda D) \tag{3}
\]

where \(N_0\) is the number concentration parameter in a unit of mm\(^{-1}\) m\(^{-3}\). Eq. (3) degenerates into M–P function (Eq. (2)) when the shape parameter \(\mu\) is zero.

Research demonstrates that M–P distribution function is a good approximation for steady stratiform precipitation, while for precipitation with great variation, like convective precipitation, it can produce big fitting errors at small and large drop sizes. But, it has been widely used for its simple form and representative of common characteristics of drop size distributions. Compared to M–P function, gamma distribution function has much more applicability, which is a good approximation for any precipitation types, especially at small drop size (Chen et al., 1998; Zheng and Chen, 2007). The present paper uses the gamma distribution function.

2.3. Characteristic parameters of RSD

When the drop size distribution is given, the rain rate \(R\) (mm h\(^{-1}\)) and rain water content \(M\) (mg m\(^{-3}\)) can be calculated by

\[
R = \frac{\pi}{6} \sum N(D_i) \cdot D_i^3 \cdot V(D_i) \tag{4}
\]

\[
M = \frac{\pi \rho}{6} \sum N(D_i) \cdot D_i^3 \tag{5}
\]

where \(D_i\) is the drop diameter for the size bin \(i\), \(N(D_i)\) is the number concentration at the diameter \(D_i\), \(V(D_i)\) is the fall velocity at the diameter \(D_i\), and \(\rho\) is the water density \((=10^3 \text{ kg m}^{-3})\). The rain water content \(M\) is one of the important parameters in meteorology, the vertical distribution of which is useful for understanding the evolution of precipitation processes in clouds.

The mass-weighted mean diameter \(D_m\) (mm) equals the ratio of the 4th to the 3rd moment of the size distribution,

\[
D_m = \frac{\langle D^4 \rangle}{\langle D^3 \rangle} \tag{6}
\]

where \(D^n\) stands for the \(n\)-th order moment of the DSD, which is expressed as

\[
\langle D^n \rangle = \int_{0}^{\infty} D^n N(D) dD. \tag{7}
\]

The normalized intercept parameter \(N_w\) (mm\(^{-1}\) m\(^{-3}\)) is computed from \(M\) and \(D_m\):

\[
N_w = \frac{4^3 \langle M \rangle}{\pi D_m^3}. \tag{8}
\]

The median volume diameter \(D_0\) is given by

\[
2 \int_{D_{\text{min}}}^{D_0} D^3 N(D) dD = \int_{D_{\text{min}}}^{D_{\text{max}}} D^3 N(D) dD. \tag{9}
\]

2.4. Polarimetric radar parameters

The latest advancement in weather radar is dual polarization, which has promoted the development of radar meteorology as well as physics of cloud and precipitation. For dual-polarimetric radar, a set of polarimetric variables are available, including radar reflectivity factor \(Z_{H,V}\) at horizontal or vertical polarization, differential reflectivity \(Z_{DR}\), differential phase \(\Phi_{DP}\), and specific differential phase \(K_{DP}\) and so on.

Radar reflectivity factor \(Z_{H,V}\) (mm\(^6\) m\(^{-3}\)) is defined by

\[
Z_{H,V} = \frac{\lambda^4}{4\pi} \frac{m^2 + 2}{m^2 - 1} \int_{D_{\text{min}}}^{D_{\text{max}}} \sigma_{H,V} N(D) dD \tag{10}
\]

where \(\lambda\) is the radar wavelength, \(m\) is the complex refractive index of water, and \(\sigma_{H,V}\) is the backscatter cross section at the horizontal or vertical polarization.

The radar reflectivity factor \(Z_{H,V}\) can be defined in terms of the elements of Mueller matrix as

\[
Z_H = C_n (\sigma_H) = 2\pi C_n (\langle M_{11} - M_{12} - M_{21} + M_{22} \rangle) \tag{11a}
\]

\[
Z_V = C_n (\sigma_V) = 2\pi C_n (\langle M_{11} + M_{12} + M_{21} + M_{22} \rangle) \tag{11b}
\]

where brackets mean volume average of the elements of Mueller matrix, \(n_0\) is the number concentration, \(C = 10^{18} \lambda^4 / \pi^3 |K|^2\), \(K = (m^2 - 1)/(m^2 + 2)\). \(\langle M_{ij} \rangle\) means the element of Mueller matrix in back scatter alignment (BSA).
The differential reflectivity 

\[ Z_{DR} = 10 \log_{10} \left( \frac{Z_H}{Z_V} \right) = 10 \log_{10} \left( \frac{(M_1 + M_2 + M_3)}{(M_1 - M_2 - M_3)} \right) \]  

(12)

The differential reflectivity \( Z_{DR} \) is a measure of the reflectivity-weighted mean axis ratio of the hydrometeors in a radar sampling volume, and the difference of hydrometeors at horizontal and vertical axis. For a spherical particle, \( Z_{DR} \) is zero.

The specific differential phase \( K_{DP} (\text{° km}^{-1}) \) is given by

\[ K_{DP} = 10^{-3} \frac{180}{\pi} \operatorname{Re} \int f_{\text{in}}(D) \, f_{\text{out}}(D) \, N(D) \, dD \]  

(13)

where \( \operatorname{Re} \) refers to the real part of the integral, \( f_{\text{in}} \) and \( f_{\text{out}} \) are the forward-scattering amplitudes at horizontal and vertical polarizations, respectively.

The specific differential phase \( K_{DP} \) is a difference between the phases of the radar signals at orthogonal polarizations. Compared to radar reflectivity factor, \( K_{DP} \) is less sensitive to the variability of drop size distribution and immune to rain attenuation and partial blockage of the radar beam. And, \( K_{DP} \) is related to the number concentration of the particles in a radar sampling volume.

2.5. Data

Beijing is located in the northwestern of the North China Plain, surrounded by mountains to the east, the west and the north to form a gulf-like landform enclosing a little flat. It is a warm temperate semi-humid continental monsoon climate. Zhangbei County is situated in the northeast of Hebei Province, and belongs to the Bashang region in the southern edge of Inner Mongolia Plateau, which has difficult terrain and unique climate. The county is located in an alpine zone, with a semi-arid, windy and temperate continental monsoon climate. Yangjiang City is located on the southwest coast of Guangdong Province, nesting under the mountain and beside the sea with the terrain tilting from north to south. The city has a subtropical climate, ample rain and mild climate. Fig. 1 shows the location of these three observational sites — Beijing, Zhangbei and Yangjiang.

The RSD data were collected continuously from July to October 2008 in Beijing, from April to August 2009 and from April to June 2010 in Zhangbei, and from July to August 2010 in Yangjiang, respectively, with PARSIVEL disdrometer. The time interval of each RSD sampling was 60 s.

To minimize the potential instrumental artifacts and qualify the data, the following criteria are used in choosing data for analysis: 1) the total drop number of an RSD is over 50 (counts of each 60-s sample); 2) raindrops in the two smallest-sized bins (\(<0.25 \text{ mm}\) ) and at the diameter of more than 8 mm are discarded; 3) the raindrops whose difference between the observed velocity and Atlas speed (Atlas et al., 1973) is more than 5 m s\(^{-1}\) are discarded.

Many studies have demonstrated that parameters of drop size distribution are related to rain types (Testud et al., 2001; Tokay and Short, 1996). It is important and necessary to classify rain types before data analysis. Precipitation is generally considered to be divided into two types: stratiform and convective. Numerous methods and models have been proposed to distinguish between the two precipitation types (Bringi et al., 2003; Chen et al., 2013; Gosset et al., 2010; Johnson and Hamilton, 1988; Maki et al., 2001; Marzano et al., 2010; Moumouni et al., 2008; Testud et al., 2001; Tokay and Short, 1996). In this paper, a classification method, similar to that of Bringi et al. (2003) and Marzano et al. (2010), is adopted. It classifies a sample of the rain rate \( R \) at the instant \( t_i \), \( R(t_i) \), as stratiform if the \( R \) values from \( t_i - N_s \) to \( t_i + N_s \) lie in the range of 0.1–5 mm h\(^{-1}\) and their standard deviation is less than 1.5 mm h\(^{-1}\): otherwise the sample is classified as convective. Herein \( N_s \) has been set to 5. The number of RSDs after rain type classification was shown in Table 1. For Beijing and Zhangbei, there are more stratiform precipitation samples in the number of RSDs, and the percentages of RSDs from stratiform precipitation are close to each other, being around 75%, while RSDs from convective precipitation account for only 23%–26%, which show that stratiform precipitation has a higher occurring probability during the observing period. However, for Yangjiang, there are more convective precipitation samples, and the percentage of RSDs from stratiform precipitation drops to 36%, while that from convective precipitation rises to 64%. The increase of percentage of RSDs from stratiform precipitation and

<table>
<thead>
<tr>
<th>Location</th>
<th>Rain type</th>
<th>Number of samples</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>Stratiform</td>
<td>3656</td>
<td>77.33</td>
</tr>
<tr>
<td></td>
<td>Convective</td>
<td>1072</td>
<td>22.67</td>
</tr>
<tr>
<td>Zhangbei</td>
<td>Stratiform</td>
<td>1577</td>
<td>74.04</td>
</tr>
<tr>
<td></td>
<td>Convective</td>
<td>553</td>
<td>25.96</td>
</tr>
<tr>
<td>Yangjiang</td>
<td>Stratiform</td>
<td>541</td>
<td>36.24</td>
</tr>
<tr>
<td></td>
<td>Convective</td>
<td>952</td>
<td>63.76</td>
</tr>
</tbody>
</table>

Fig. 1. The geographical locations of Beijing (BJ), Zhangbei (ZB), and Yangjiang (YJ) in China.
decrease of percentage of RSDs from convective precipitation in Yangjiang result from the frequent convective activities in summer in south China, where Yangjiang is located.

3. Characteristics of RSDs

3.1. Average characteristics of rainfall microphysical parameters

Several averaged rainfall microphysical parameters from the three different climate regions and the two different rain types were calculated, including the total number concentration of raindrop \( N_t \), medium volume diameter \( D_m \), maximum diameter \( D_{\text{max}} \), rain water content \( M \), rain rate \( R \), mass-weighted mean diameter \( D_m \), \( \log_{10}N_w \left( N_w: \text{normalized intercept parameter in mm}^{-1}\text{m}^{-3} \right) \) and the contribution of raindrops at the diameter of less than 1 mm to \( N_t \) (\( N_t/N_i \)), to \( R \) (\( R/R_t \)) and to \( M \) (\( M/M_t \)), which were shown in Table 2. According to Table 2, the total number concentration \( N_t \) and rain water content \( M \) of convective precipitation are much larger than those of stratiform precipitation. For example, in Yangjiang, \( N_t \) of convective precipitation is up to 674.5 mm\(^{-3}\) while that of stratiform precipitation is only 154.8 mm\(^{-3}\); \( M \) of convective precipitation reaches 0.676 g m\(^{-3}\) while that of stratiform precipitation is 0.068 g m\(^{-3}\), only a tenth of \( M \) in convective precipitation. The contribution of raindrops at the diameter of less than 1 mm to \( N_t \) (\( N_t/N_i \)), is 60%–65% for convective precipitation and 72%–85% for stratiform precipitation, respectively, which demonstrates that there are more raindrops less than 1 mm in stratiform precipitation in all three different climatic regions. Zhangbei has the largest \( N_t/N_i \) in both stratiform and convective precipitation, which may be accounted for Zhangbei’s higher altitude and higher evaporation than Beijing and Yangjiang, resulting in a large number of small raindrops (Niu et al., 2010; Rosenfeld and Ulbrich, 2003). Taking Zhangbei as an example, the percentage of raindrops at the diameter of less than 1 mm in stratiform precipitation is 84.6%, and their contribution to \( R \) and \( M \) is up to 51.9% and 57.0%, respectively; whereas in convective precipitation the percentage is up to 64.6%, and their contribution to \( R \) and \( M \) is only 16.6% and 21.5%, respectively. It demonstrates that the contribution of small drops to \( R \) and \( M \) in stratiform precipitation is great while the contribution to large \( R \) and \( M \) in convective precipitation is mainly made by large drops, which can also be derived from \( D_{\text{max}} \) and \( D_{\text{max}} \) as shown in Table 2. Small \( R \) and \( M \) in stratiform precipitation are due to small \( D_{\text{max}} \) and \( N_t \). Although there exists big difference in the locations of these three regions, \( N_t \), \( R \) and \( M \) in convective precipitation in Yangjiang are much larger than those parameters even in stratiform precipitation in Beijing and Zhangbei, while these three parameters differ little in stratiform precipitation in three different places, which is due to the small difference of \( D_0 \) and \( D_{\text{max}} \). As shown in Table 2, convective precipitations from Beijing and Yangjiang both have higher \( D_m \) and \( \log_{10}N_w \) values than stratiform precipitations, while \( \log_{10}N_w \) value for convective precipitation in Zhangbei, 3.64, is lower than for stratiform precipitation, 3.75. For stratiform precipitation, \( D_m \) values in Beijing, Zhangbei and Yangjiang are all lower than that obtained during Meiyu season in Nanjing (Chen et al., 2013; 1.30 mm for \( D_m \)), while \( \log_{10}N_w \) values in these three locations are all higher than that obtained by Chen et al. (2013), 3.45. It suggests that RSDs for stratiform precipitation in Beijing, Zhangbei and Yangjiang have a higher concentration of smaller-sized drops than those in Nanjing. For convective precipitation, Bringi et al. (2003) identified a maritime-like cluster around \( D_m = 1.50–1.75 \text{ mm} \) and \( \log_{10}(N_w) = 4.0–4.5 \) and a continental-like cluster around \( D_m = 2.00–2.75 \text{ mm} \) and \( \log_{10}(N_w) = 3.0–3.5 \). It can be seen that \( D_m \) values for convective precipitation in Beijing, Zhangbei and Yangjiang vary from 1.50 to 1.70 mm, which match the maritime-like convective cluster. But \( \log_{10}N_w \) values, in the range of 3.6 to 3.9, are lower than that for maritime-like convective cluster. It indicates that RSDs in Beijing, Zhangbei and Yangjiang have lower concentration of raindrops, and this conclusion was also supported by Chen et al. (2013) for Nanjing.

The results above show that there is significant regional difference in rainfall microphysical parameters for convective precipitation, and small regional difference for stratiform precipitation, instead.

3.2. Characteristics of averaged RSD

Fig. 2 presents the averaged RSDs from convective and stratiform precipitation observed in Beijing, Zhangbei and Yangjiang, which are also fitted in gamma form by truncated-moment method using second, fourth, and sixth moments. Through the comparison between Fig. 2a and b, we find that the maximum \( N(D) \) of RSD of convective precipitation, being \( 4 \times 10^4–10^5 \text{ mm}^{-3} \text{ mm}^{-1} \), is larger than that of stratiform precipitation; so is the spectrum width of RSD of convective precipitation. For stratiform precipitation (Fig. 2b), the maximum \( N(D) \) of RSD in Zhangbei is a little larger than that in Beijing and Yangjiang. However, in general, the spectrums of RSD in three different climate regions differ little for stratiform precipitation. For convective precipitation (Fig. 2b), the maximum \( N(D) \) of RSD in Yangjiang is the largest, followed by Beijing and then Zhangbei, but the spectrum width of RSD in Zhangbei is the widest, followed by Beijing and then Yangjiang.

<table>
<thead>
<tr>
<th>Location</th>
<th>Rain type</th>
<th>( N_t ) (m(^{-3}))</th>
<th>( D_0 ) (mm)</th>
<th>( D_{\text{max}} ) (mm)</th>
<th>( M ) (g m(^{-3}))</th>
<th>( R ) (mm h(^{-1}))</th>
<th>( D_m ) (mm)</th>
<th>( \log_{10}N_w )</th>
<th>( N_t/N_i ) (%)</th>
<th>( R/R_t ) (%)</th>
<th>( M/M_t ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>Stratiform</td>
<td>174.7</td>
<td>1.04</td>
<td>1.85</td>
<td>0.068</td>
<td>1.2</td>
<td>1.14</td>
<td>3.60</td>
<td>77.3</td>
<td>41.1</td>
<td>46.2</td>
</tr>
<tr>
<td></td>
<td>Convective</td>
<td>429.1</td>
<td>1.50</td>
<td>2.94</td>
<td>0.449</td>
<td>10.9</td>
<td>1.64</td>
<td>3.67</td>
<td>59.6</td>
<td>14.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Zhangbei</td>
<td>Stratiform</td>
<td>230.0</td>
<td>0.95</td>
<td>1.76</td>
<td>0.059</td>
<td>1.0</td>
<td>1.04</td>
<td>3.75</td>
<td>84.6</td>
<td>51.9</td>
<td>57.0</td>
</tr>
<tr>
<td></td>
<td>Convective</td>
<td>377.7</td>
<td>1.52</td>
<td>3.16</td>
<td>0.307</td>
<td>7.0</td>
<td>1.69</td>
<td>3.64</td>
<td>64.6</td>
<td>16.6</td>
<td>21.5</td>
</tr>
<tr>
<td>Yangjiang</td>
<td>Stratiform</td>
<td>154.8</td>
<td>1.06</td>
<td>1.79</td>
<td>0.086</td>
<td>1.2</td>
<td>1.16</td>
<td>3.59</td>
<td>71.6</td>
<td>39.1</td>
<td>42.4</td>
</tr>
<tr>
<td></td>
<td>Convective</td>
<td>674.5</td>
<td>1.40</td>
<td>2.74</td>
<td>0.876</td>
<td>15.8</td>
<td>1.52</td>
<td>3.88</td>
<td>61.2</td>
<td>16.9</td>
<td>22.1</td>
</tr>
</tbody>
</table>

Table 2

Averaged microphysical parameters of RSDs from convective and stratiform precipitation in Beijing, Zhangbei and Yangjiang, including the total number concentration of raindrop \( N_t \), medium volume diameter \( D_m \), maximum diameter \( D_{\text{max}} \), rain water content \( M \), rain rate \( R \), mass-weighted mean diameter \( D_m \), \( \log_{10}N_w \left( N_w: \text{normalized intercept parameter in mm}^{-1}\text{m}^{-3} \right) \) and the contribution of raindrops at the diameter of less than 1 mm to \( N_t \) (\( N_t/N_i \)), to \( R \) (\( R/R_t \)) and to \( M \) (\( M/M_t \)).
By comparison between averaged and fitted RSDs shown in Fig. 2, the averaged RSDs from both rain types in Beijing and Yangjiang are in good agreement with gamma distribution while in Zhangbei tend to be in M–P distribution.

3.3. Raindrop fall velocity

Raindrop fall velocity is also an important parameter in precipitation, and closely related to remote measurements of RSDs and various integral quantities such as rain rate. There are many studies which exhibit a one-to-one relationship between raindrop fall velocity and drop sizes based on the fall speed data of Gunn and Kinzer (1949) for raindrops at standard pressure and temperature (Atlas et al., 1973; Brandes et al., 2002). However, besides drop sizes, raindrop fall velocity is affected by many other factors, such as air density (Foote and Toit, 1969), updrafts and downdrafts (Battan, 1964), turbulence (Pinsky and Khain, 1996), and raindrop breakup/coalescence (Montero-Martínez et al., 2009).

Fig. 3 shows the observed mean number concentration as a function of the drop diameter and raindrop fall velocity for stratiform and convective precipitation in Beijing, Zhangbei and Yangjiang. For reference, the relations of Atlas et al. (1973) and Brandes et al. (2002) are presented in black and red line, respectively. There are large spreads in the drop velocities at all the drop diameters. The convective precipitation has an even larger spread than stratiform precipitation, with a velocity range of 1–10 m s$^{-1}$ and 1–7 m s$^{-1}$ for the convective and stratiform precipitation, respectively. The spreads in all three climatic regions are larger than that in
Guyuan reported by Niu et al. (2010). The speed line of Atlas et al. (1973) is close to that of Brandes et al. (2002), because they were all based on the laboratory measurements of terminal velocities by Gunn and Kinzer (1949). These two speed lines for convective and stratiform precipitation in Beijing (Fig. 3) and Yangjiang (Fig. 3c) all pass through the contour center, while in Zhangbei (Fig. 3b) these two speed lines are below the contour center, especially for stratiform
precipitation, which may be due to not taking into account the effect of air density on fall velocity in the speed lines of Atlas et al. (1973) and Brandes et al. (2002). The actual Gunn and Kinzer data were obtained under the standard atmospheric conditions at sea level, with an air density of 1.23 kg m\(^{-3}\). However, the air properties in Zhangbei are dramatically different, with an altitude of 1410 m, which will result in a larger fall velocity than the corresponding fall velocity from Atlas et al. (1973) and Brandes et al. (2002). To quantify the effect of air density on raindrop fall velocity, a correction factor \((\rho_0/\rho)^{0.5}\) is multiplied in the right-hand side of the fall velocity equation of Atlas et al. (1973).

\[
V = \left(9.65 - 10.3e^{-0.6D}\right) (\rho_0/\rho)^{0.5}
\]

where \(V\) (m s\(^{-1}\)) is the fall velocity of a raindrop at diameter \(D\) in mm, \(\rho_0\) is the air density at the sea level, and \(\rho\) is the air density at the Zhangbei site.

The blue speed line in Fig. 3b is corrected for the effect of lower air density at the Zhangbei site. It is obvious that compared to the fall velocities of Atlas et al. (1973) and Brandes et al. (2002), the corrected fall velocities are much closer to the experimental fall velocities. This improved agreement indicates that it is essential to take into account the effect of air density on raindrop fall velocity in highlands far away from sea level.

### 3.4. \(\mu\)--\(\Lambda\) relation

A three-parameter gamma distribution (Eq. (3)) is often used to characterize a raindrop size distribution (RSD) in cloud and precipitation numerical simulations, with an assumption of a constant shape parameter \(\mu\). However, the intercept parameter \(N_0\), the shape parameter \(\mu\) and slope parameter \(\Lambda\) in gamma distribution are not mutually independent, with an \(N_0\)--\(\mu\) relation (Ulbrich, 1983) and a \(\mu\)--\(\Lambda\) relation (Brandes et al., 2003; Cao et al., 2008; Zhang et al., 2001, 2003). Fig. 4 shows scatter plots between \(\mu\) and \(\Lambda\) in Beijing, Zhangbei and Yangjiang. The \(\mu\) and \(\Lambda\) values are obtained using truncated-moment method. Retrievals of \(\mu\) and \(\Lambda\) using truncated-moment method show better correlation than the corresponding set retrieved using the untruncated-moment method (Vivekanandan et al., 2004). To minimize the error due to sampling effects, a data-filtering method was adopted, which is similar to Zhang et al. (2003). Only RSDs with rain rate \(R > 5\) mm h\(^{-1}\) and the number of raindrops \(N_t > 500\) m\(^{-3}\) were selected. Dashed lines show the Florida relation (Zhang et al., 2003), and dash-dotted lines correspond to the Nanjing relation (Chen et al., 2013). The coefficients of the fitted \(\mu\)--\(\Lambda\) relations are presented in Table 3. Zhang et al. (2003) fit the \(\mu\)--\(\Lambda\) relation with RSDs only for \(R > 5\) mm h\(^{-1}\) and \(N_t > 1000\) m\(^{-3}\). Cao et al. (2008) demonstrates that the \(\mu\)--\(\Lambda\) relation is applicable for a \(\Lambda\) ranging from 0 to 20 mm\(^{-1}\), and larger \(\Lambda\) values are associated with the RSDs with very small drops and thought to be the result from measurement errors rather than storm physics (Zhang et al., 2003). As shown...
Table 3  
Coefficients of the fitted \( \mu - \Lambda \) relations.

<table>
<thead>
<tr>
<th>Location</th>
<th>( \Lambda = a \mu^2 + b \mu + c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>0.0075 0.7230 1.1721</td>
</tr>
<tr>
<td>Zhangbei</td>
<td>0.0097 0.7226 1.7415</td>
</tr>
<tr>
<td>Yangjiang</td>
<td>0.0240 0.4596 1.9920</td>
</tr>
</tbody>
</table>

in Fig. 4, the range of \( \Lambda \) varies between 0 and 20 mm\(^{-1}\), which is similar to Zhang et al. (2003) and Chen et al. (2013). The relations in Beijing, Zhangbei, and Yangjiang are more close to the Nanjing relation (Chen et al., 2013), compared to the Florida relation (Zhang et al., 2003). For a given \( \Lambda \) value, our fits have higher \( \mu \) values than Florida relation. The difference between the Beijing relation and the Nanjing relation is the smallest, followed by the difference between the Yangjiang relation and the Nanjing relation. The smallest difference of the relations in Beijing and Nanjing may be accounted for the fact that these two cities both have bad air pollution and high aerosol concentration. The above conclusions suggest that the \( \mu - \Lambda \) relation varies with location.

4. Characteristics of polarimetric radar parameters

According to the RSDs of two different rain types observed in Beijing, Zhangbei, and Yangjiang, the present paper makes a comparison between \( Z_H \) derived by T-matrix and by PARSIVEL for stratiform and convective precipitation in these three different regions, which is shown in Fig. 5. The values of \( Z_H \) derived by T-matrix are in good agreement with those derived by PARSIVEL for all rain types in all three different locations, with correlation coefficients all above 0.99. From rain types, the stratiform precipitation has a better agreement than convective precipitation, for which \( Z_H \) derived by T-matrix above 40 dBZ is a little larger than that derived by PARSIVEL. Compared to Beijing and Zhangbei, Yangjiang has a better retrieval of \( Z_H \) by T-matrix. In general, it is robust to retrieve polarimetric radar parameters by T-matrix.

In T-matrix computation, one of the necessary information is drop size distribution. The present paper uses the averaged RSDs and fitted RSDs in gamma function to retrieve polarimetric radar parameters at X-band (wavelength of 3.2 cm), which are shown in Table 4. \( Z_H - c \) is the average of \( Z_H \) directly calculated from the observed RSDs. \( Z_H \) for two rain types in Beijing, Zhangbei, and Yangjiang is more than 35 dBZ for stratiform precipitation, which may result from larger drops in stratiform precipitation, while \( Z_H \) for convective precipitation is more rapidly increased when \( Z_H \) is larger than 45 dBZ, whereas the stratiform precipitation has a much smaller \( Z_H \) than convective precipitation.

demonstrates that the stratiform precipitation has a much smaller \( Z_H \) than convective precipitation.

The differential reflectivity \( Z_{DR} \) is a measure of the difference of hydrometeors between horizontal and vertical axes. From Table 4, the values of \( Z_{DR} \) for convective precipitation vary between 1.7 and 2.9 dB, while for stratiform precipitation between 0.6 and 0.9 dB. It demonstrates that hydrometeors of convective precipitation have greater difference between horizontal and vertical axes and those of stratiform precipitation have smaller difference, which may be due to bigger size of hydrometeors of convective precipitation and hence greater shape deformation. According to Table 2, \( D_0 \) of convective precipitation are all larger than those of stratiform precipitation, which may account for larger \( Z_{DR} \) for convective precipitation. Many studies (Bringi et al., 1998; Seliga and Bringi, 1976) have also demonstrated that \( Z_{DR} \) is highly relevant to medium volume diameter \( D_0 \).

Because the specific differential phase \( K_{DP} \) is related to the number concentration of the particles and \( N_t \) of convective precipitation is larger than that of stratiform precipitation, the \( K_{DP} \) values of convective precipitation are all significantly larger compared to those of stratiform precipitation. Taking Beijing as an example, for convective precipitation \( K_{DP} \) is 3.89° km\(^{-1}\), while for stratiform precipitation only 0.21° km\(^{-1}\).

There are certain relationships between \( Z_{DR} \), \( K_{DP} \), and \( Z_H \) — a linear relationship between \( Z_{DR} \) and \( Z_H \) and an exponential relationship between \( K_{DP} \) and \( Z_H \) (Park et al., 2005), which are of great help to attenuation correction for \( Z_H \) and \( Z_{DR} \). Figs. 6 and 7 show the relationships between \( Z_{DR} \), \( K_{DP} \), and \( Z_H \) for two rain types in Beijing, Zhangbei, and Yangjiang. As shown in Fig. 6, for a given \( Z_{DR} \), \( Z_H \) values vary in some range. Other than the linear relationship between \( Z_{DR} \) and \( Z_H \) given by Park et al. (2005), the relationship between \( Z_{DR} \) and \( Z_H \) is more exponential presented in Fig. 6. There is a sudden increase of \( Z_{DR} \) when \( Z_H \) is more than 35 dBZ for stratiform precipitation, which may result from larger drops in stratiform precipitation of \( Z_H \) more than 35 dBZ. A similar exponential relationship of \( Z_{DR} - Z_H \) was derived by Li et al. (2011). According to Fig. 7, there is an exponential relationship between \( K_{DP} \) and \( Z_H \), \( K_{DP} \) increases with the increase of \( Z_H \). For convective precipitation, \( K_{DP} \) increases more rapidly when \( Z_H \) is larger than 45 dBZ, whereas the stratiform precipitation has a more rapid \( K_{DP} \) increase when \( Z_H \) is above 30 dBZ.

The fitted curves of the relations between \( Z_{DR} \), \( K_{DP} \), and \( Z_H \) for stratiform and convective precipitation in Beijing, Zhangbei, and Yangjiang are presented in Figs. 8 and 9. Table 5 shows the coefficients of these fitted relations. According to Fig. 8, for convective precipitation, Zhangbei has the largest \( Z_{DR} \) for a given \( Z_H \) followed by Beijing and Yangjiang. As presented in Table 2, Zhangbei has the largest \( D_0 \) of 1.52 mm, followed by Beijing and then Yangjiang with \( D_0 \) of 1.50 mm and 1.40 mm, respectively, for convective precipitation. This suggests a close relation between \( Z_{DR} \) and \( D_0 \). For stratiform precipitation, the fitted curves of the relation between \( Z_{DR} \) and \( Z_H \) in Beijing, Zhangbei, and Yangjiang are close to each other, especially the fitted curves in Beijing and Yangjiang. This result can be explained by a small difference of \( D_0 \) between Beijing and Yangjiang, only 0.02 mm. According to Fig. 9, for convective precipitation, Yangjiang has the largest \( K_{DP} \) for a given \( Z_H \), followed by Beijing and Zhangbei. It suggests that \( K_{DP} \) is related
Fig. 5. a. Comparison between $Z_H$ derived by T-matrix and by PARSIVEL for stratiform and convective precipitation in Beijing. b. Comparison between $Z_H$ derived by T-matrix and by PARSIVEL for stratiform and convective precipitation in Zhangbei. c. Comparison between $Z_H$ derived by T-matrix and by PARSIVEL for stratiform and convective precipitation in Yangjiang.
Table 4
Polarimetric radar parameters retrieved by averaged and gamma fitted RSDs. \( Z_{H-c} \) is the average of \( Z_H \) directly calculated from the observed RSDs. \( Z_{H-m}, Z_{V-m} \) and \( K_{DP-m} \) refer to the parameters retrieved from the average of measured RSDs. \( Z_{H-f}, Z_{V-f}, Z_{DR-f} \) and \( K_{DP-f} \) denote the parameters retrieved from the fitted RSDs in gamma function.

<table>
<thead>
<tr>
<th>RAIN type</th>
<th>Location</th>
<th>( Z_{H} ) (dBZ)</th>
<th>( Z_{V} ) (dBZ)</th>
<th>( Z_{DR} ) (dB)</th>
<th>( K_{DP} ) (° km(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( Z_{H-c} )</td>
<td>( Z_{H-m} )</td>
<td>( Z_{H-f} )</td>
<td>( Z_{V-m} )</td>
</tr>
<tr>
<td>Stratiform</td>
<td>Beijing</td>
<td>26.2</td>
<td>26.0</td>
<td>25.7</td>
<td>25.3</td>
</tr>
<tr>
<td></td>
<td>Zhangbei</td>
<td>24.7</td>
<td>24.7</td>
<td>24.3</td>
<td>23.8</td>
</tr>
<tr>
<td></td>
<td>Yangjiang</td>
<td>25.8</td>
<td>25.6</td>
<td>25.3</td>
<td>25.0</td>
</tr>
<tr>
<td>Convective</td>
<td>Beijing</td>
<td>40.4</td>
<td>42.2</td>
<td>41.9</td>
<td>39.9</td>
</tr>
<tr>
<td></td>
<td>Zhangbei</td>
<td>39.5</td>
<td>42.1</td>
<td>41.8</td>
<td>39.3</td>
</tr>
<tr>
<td></td>
<td>Yangjiang</td>
<td>41.0</td>
<td>41.8</td>
<td>41.6</td>
<td>40.1</td>
</tr>
</tbody>
</table>

Fig. 6. a. \( Z_{DR}-Z_{H} \) relation for stratiform and convective precipitation in Beijing. The black lines are the curves fitted to the dots. b. \( Z_{DR}-Z_{H} \) relation for stratiform and convective precipitation in Zhangbei. The black lines are the curves fitted to the dots. c. \( Z_{DR}-Z_{H} \) relation for stratiform and convective precipitation in Yangjiang. The black lines are the curves fitted to the dots.
to number concentration of raindrops \(N_t\), and Yangjiang has the largest \(N_t\) for convective precipitation, up to \(674.5 \text{ m}^{-3}\), followed by Beijing and Zhangbei with \(N_t\) of \(429.1 \text{ m}^{-3}\) and \(377.7 \text{ m}^{-3}\), respectively. Compared to convective precipitation, the stratiform precipitation has a smaller difference of \(N_t\) among three different places. This smaller difference contributes to the closer fitted curves of the relation between \(KDP\) and \(ZH\) for stratiform precipitation in Beijing, Zhangbei and Yangjiang.

Based on the above analysis, the relations between \(ZDR\), \(KDP\) and \(ZH\) vary in different climate regions and different rain types, which may be due to the variation of \(D_0\) and \(N_t\). After all, the relations’ variation results from RSD’s sensitivity to climate regions and rain types.

The simulated results presented in Table 4 show that, compared to \(ZH_f\), \(ZH_m\) is much closer to \(ZH_c\), which demonstrates that the observed RSD is superior to the fitted one in retrieving polarimetric radar parameters, because the fitted RSD could produce a more unrealistic drop size distribution. Compared to convective precipitation, stratiform precipitation has a better retrieval, which may be due to its more uniform precipitation and smaller RSD variation as well as more RSD samples. Take Zhangbei as an example, for convective precipitation, the difference of \(ZH_c\) and \(ZH_m\) is 2.6 dBZ, while their values are equal for stratiform precipitation. Because of dielectric constant’s variation with temperature, the observed \(ZH\) is affected by temperature. This paper makes a comparison between \(ZH\) derived by PARSIVEL and retrieved by T-matrix in Zhangbei at the temperature of 10 °C and 20 °C, respectively. Three quantitative parameters presented in Table 6 are calculated:

\[
\epsilon_1 = \left[ \frac{1}{k} \sum_i \left( \frac{Z_H^T - Z_H^P}{Z_H^T} \right)^2 \right]^{1/2}
\]

(15)

\[
\epsilon_2 = \frac{1}{k} \sum_i \left( \frac{Z_H^T - Z_H^P}{Z_H^T} \right)
\]

(16)

\[
\epsilon_3 = \left[ \frac{1}{k} \sum_i \left( \frac{Z_H^T - Z_H^P}{Z_H^T} \right)^2 \right]^{1/2}
\]

(17)

where \(\epsilon_1\) is standard deviation, \(\epsilon_2\) is mean relative bias, \(\epsilon_3\) is rms percentage difference, \(Z_H^T\) (dBZ) is \(ZH\) retrieved by T-matrix, \(Z_H^P\) (dBZ) is \(ZH\) derived by PARSIVEL, and \(k\) is a total number of samples.

According to the quantitative parameters shown in Table 6, for both two rainfall types, \(ZH\) at the two different temperatures differs little and are all very close to \(Z_H^f\), which suggest that \(ZH\) is not obviously affected by temperature.

5. Summary and discussion

Based on RSD data observed with PARSIVEL disdrometer in Beijing and Zhangbei (north), and Yangjiang (south), China, the present paper aims to study the characteristics of RSDs and polarimetric radar parameters retrieved by T-matrix for stratiform and convective precipitation in these three different climatic regions, and discuss the effect of observed and fitted RSD on scattering simulation. The main conclusions are reached as follows:

1. There is significant regional difference in rainfall microphysical parameters for convective precipitation, and small regional difference for stratiform precipitation, instead. The total number concentration of raindrops \(N_t\) and rain water content \(M\) of convective precipitation are much larger than those of stratiform precipitation. The contribution of small drops to rain rate \(R\) and rain water content \(M\) in stratiform precipitation is great while the
contribution to large $R$ and $M$ in convective precipitation is mainly made by large drops. Convective precipitations from Beijing and Yangjiang both have higher $D_m$ and $\log_{10}N_w$ values than stratiform precipitations, while $\log_{10}N_w$ value for convective precipitation in Zhangbei is lower than for stratiform precipitation.

(2) The averaged RSDs from both rain types in Beijing and Yangjiang are in good agreement with gamma distribution while those in Zhangbei cannot be well fitted either by gamma or M–P distribution. The maximum $N(D)$ and spectrum width of convective precipitation are larger than those of stratiform precipitation.

(3) There are large spreads in the drop velocities at all the drop diameters. The convective precipitation has an even larger spread than stratiform precipitation, with a velocity range of 1–10 m s$^{-1}$ and 1–7 m s$^{-1}$ for the convective and stratiform precipitation, respectively. It is essential to take into account the effect of air density on raindrop fall velocity in highlands far away from sea level, such as Zhangbei.

(4) The $\mu$–$\Lambda$ relation varies with location. For a given $\Lambda$ value, our fits have higher $\mu$ values than Florida relation (Zhang et al., 2003). The difference between the Beijing relation and the Nanjing relation (Chen et al., 2013) is the smallest.

(5) It is robust to retrieve polarimetric radar parameters by T-matrix. There is an exponential relationship between $Z_{DR}$ and $Z_{HH}$ as well as the relation between $K_{DP}$ and $Z_{HH}$.

Fig. 7. a. $K_{DP}$–$Z_H$ relation for stratiform and convective precipitation in Beijing. The black lines are the curves fitted to the dots. b. $K_{DP}$–$Z_H$ relation for stratiform and convective precipitation in Zhangbei. The black lines are the curves fitted to the dots. c. $K_{DP}$–$Z_H$ relation for stratiform and convective precipitation in Yangjiang. The black lines are the curves fitted to the dots.
The variation of the relations in different climate regions and different rain types results from RSD's sensitivity to climatic regions and rain types.

(6) In retrieving polarimetric radar parameters, observed RSD is superior to the fitted one, for fitted RSD may produce unrealistic drop size distribution. Compared to convective precipitation, stratiform precipitation has a better retrieval of polarimetric radar parameters.

The analyses above further confirm the obvious variation of RSD in different climatic regions and rain types. The geographical locations (orographic effect), climatic regimes, local atmospheric aerosols and rain types may be responsible for the differences in RSD characteristics. For example, compared to Beijing and Yangjiang, Zhangbei has the largest number of raindrops less than 1 mm, which may be accounted for its higher altitude and evaporation. Beijing's smallest difference of the $\mu-A$ relations with Nanjing, compared to Zhangbei and Yangjiang, is likely associated with similar bad air pollution and high aerosol concentration both in Beijing and Nanjing.

The variation in RSD will be one major source of error in quantitative precipitation estimation (QPE) with polarimetric radar. In the future study, we will propose to further study the sensitivity of QPE to the variability of RSDs in different

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**Fig. 7 (continued).**

**Fig. 8.** The fitted curves of $K_{DP}$-$Z_H$ relation for stratiform and convective precipitation in Beijing, Zhangbei and Yangjiang.
climatic regions and different precipitation types, and try to develop an optimization algorithm to minimize the error due to variation in RSD and improve QPE.

Acknowledgment

This work was partially supported by the National Grand Fundamental Research 973 Programs of China (Grant Nos. 2013CB430105, 2014CB441403), the National Natural Science Foundation of China (Grant No. 41205099), and the Special Scientific Research Project of Meteorological Public Welfare Profession of China (Grant No. GYHY201006031).

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