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Research Article

Decadal Variation in Raindrop Size Distributions in Busan, Korea

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This paper investigated the variability of raindrop size distributions (DSDs) in Busan, Korea, using data from two different disdrometers: a precipitation occurrence sensor system (POSS) and a particle size velocity (Parsivel) optical disdrometer. DSDs were simulated using a gamma model to assess the intercomparability of these two techniques. Annual rainfall amount was higher in 2012 than in 2002, as were the annually averaged D_m (which was 0.1 mm greater in 2012) and the frequency of convective rain. Severe rainfall (greater than 20 mm h^{-1}) occurred more frequently and with a larger D_m in 2012. The values of D_m from July, August, and December, 2012, were much greater than from other months when compared with 2002. Larger raindrops contributed to the higher rain rates that were observed in the morning during 2012, whereas relatively smaller raindrops dominated in the afternoon. These results suggest that the increase in raindrop size that has been observed in Busan may continue in the future; however, more research will be required if we are to fully understand this phenomenon. Rainfall variables are highly dependent on drop size and so should be recalculated using the newest DSDs to allow more accurate polarimetric radar rainfall estimation.

1. Introduction

Drop size distributions (DSDs) provide important information for the microphysical structure of precipitation and describe the statistical distribution of falling raindrops' size and number concentration. Also DSDs play an important role in the remote sensing of rainfall and the behavior of electromagnetic waves in the atmosphere [1, 2]. Measurements of DSDs have been used extensively to calculate both radar reflectivity and the rate of rainfall from conventional radar data, but no single reflectivity-rainfall (Z-R) relationship can be used across the world because DSDs can vary both between storms and within an individual storm [3, 4].

The earliest disdrometers that were developed to measure DSDs used ground-based measurements that relied on the flour method [5] and the filter paper method [6]. Subsequently, other techniques were developed, including the impact-type disdrometer [7], the radar-type disdrometer [8], the laser-optical-type disdrometer [9], and the advanced 2D video disdrometer (2DVD) [10]. The particle size velocity (Parsivel) optical disdrometer is a low cost, durable, and reliable instrument, making it well suited to deployment into networks for the study of small-scale variability in DSDs [11]. The POSS (precipitation occurrence sensor system) is a small Doppler radar and is more sensitive to wind effects than other disdrometers [12, 13]. Several studies have compared the various disdrometers; for example, in experimental research, the 2DVD produced better matches gages than the Joss-Waldvogel [14] and the Parsivel disdrometers [15, 16]. Krajewski et al. [17] showed that the Parsivel measures greater numbers of small drops (0.2 to 0.4 mm) than the 2DVD and generally reports higher rainfall rates. Thurai et al. [15] found that the Parsivel records higher mass-weighted mean diameters and rainfall rates than the 2DVD, and this was most prominent when the rain rate was greater than 30 mm h^{-1}. However, they also noted that this is dependent on climatology. There have been several studies in Korea focusing on the characteristics of DSDs [18], Z-R relationship calculations [19], and polarimetric applications [20, 21] using the POSS.

Much effort has been directed towards the modeling of DSDs based on observations of real DSDs. Initially, Laws and Parsons [5] proposed that DSDs were best described by an exponential distribution and then Marshall and Palmer [6] suggested fixed values for the intercept of 8000 $mm^{-1}\,m^{-3}$ and the slope-rainfall rate relationship. Subsequently, the gamma model was introduced to better depict natural DSDs [22] using three parameters: the intercept, shape, and slope. Normalization was introduced into the model by Willis [23] and adapted by Testud et al. [24] and Illingworth and Blackman [25, 26] to explain the physical description of DSD parameters with respect to the gamma model.

As variability in DSDs is dependent on climatological conditions and geographical location [27], many observational studies have taken place in a variety of climatic locations such as in midlatitude [28, 29], maritime [30], continental [31], tropical [32–34], and equatorial environments [35]. However, there have been few studies of the climatological variation of DSDs at one location using observed disdrometer data.

This paper uses POSS and Parsivel data to quantify the changes in DSDs that occurred between 2002 and 2012 in Busan, Korea. In Section 2, POSS and Parsivel datasets, quality control, and gamma model simulations using different drop-size channels are described. Section 3 discussed the yearly and monthly variation in DSDs followed by a discussion of diurnal variations. Finally, we provide concluding remarks and a summary of our results in Section 4.

2. Data and Methodology

2.1. Disdrometers and Data Processing. The POSS is a low-power X-band bistatic system radar capable of measuring 34 channels from 0.34 to 5.34 mm (a more detailed description is provided by Sheppard and Joe [12]). The Parsivel disdrometer is a laser-optic system that measures 32 channels from 0.062 to 24.5 mm (detailed specifications are described by Löffler-Mang and Joss [9]). One-minute DSDs were obtained from POSS for 2002 and from Parsivel for 2012, excluding wintertime and rainfall events caused by typhoons. Unreliable data, defined as belonging to the following categories, were removed: 1-min rain rate less than 0.1 $mm\,h^{-1}$; total number concentrations of all channels less than 10; drop numbers counted only in the lower 10 channels (0.84 mm for POSS and 1.187 mm for Parsivel); and drop numbers counted only in lower 5 channels (0.54 mm for POSS and 0.562 mm for Parsivel). The data were also removed if the difference in the amount of rainfall measured between disdrometers and gage was greater than 50%. The DSD data analyzed in this study comprised 26,427 and 16,591 samples in 2002 and 2012, respectively.

2.2. Normalized Gamma Distribution. The normalized gamma distribution was used in this study because its parameters provide the physical meaning for DSDs [24, 26, 29]. The

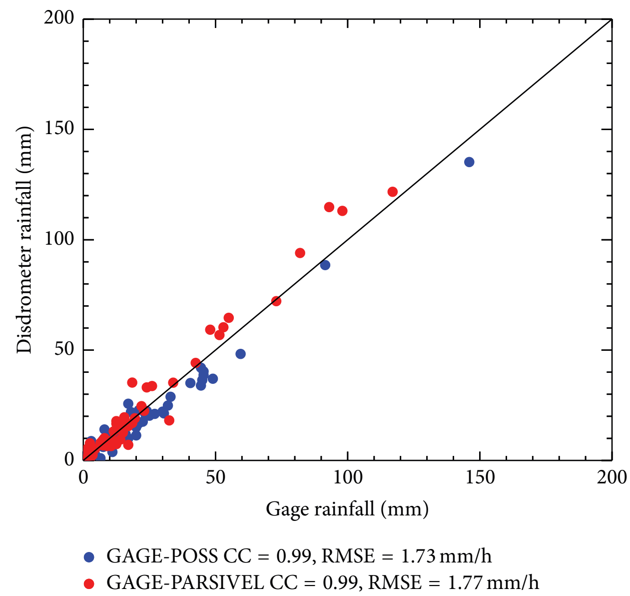

FIGURE 1: Scatter plots of daily rainfall from disdrometers and gages in 2002 and 2012. Blue circles indicate the gage-POSS relationship and red circles the gage-Parsivel relationship.

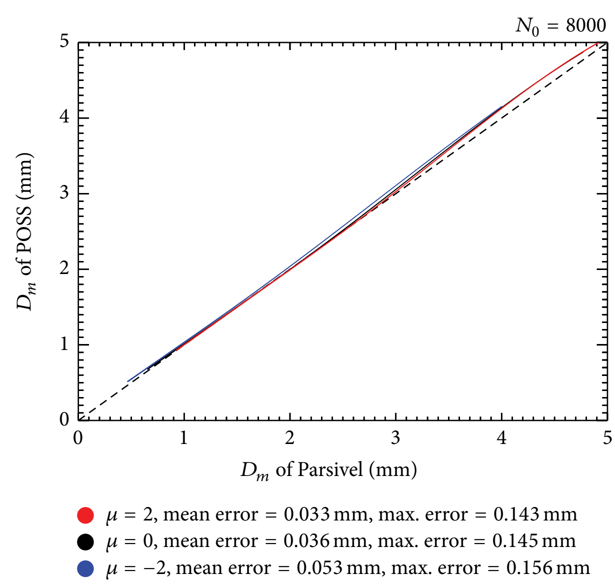

FIGURE 2: Comparisons between the D_m calculated from DSDs simulated by the gamma model using the same channels as the Parsivel and the POSS system. The red, black, and blue solid line shows the difference between Parsivel and POSS with different shapes, 2, 0, and −2, respectively.

mass-weighted mean diameter (D_m) can be calculated as the ratio between the fourth and third moments of the DSD:

$$D_m = \frac{\int_0^{D_{\max}} D^4 N(D)\,dD}{\int_0^{D_{\max}} D^3 N(D)\,dD}. \quad (1)$$

The rainwater content (W) is calculated as

$$W = \frac{\pi}{6}\rho_w \int_0^{D_{\max}} D^3 N(D)\,dD, \quad (2)$$

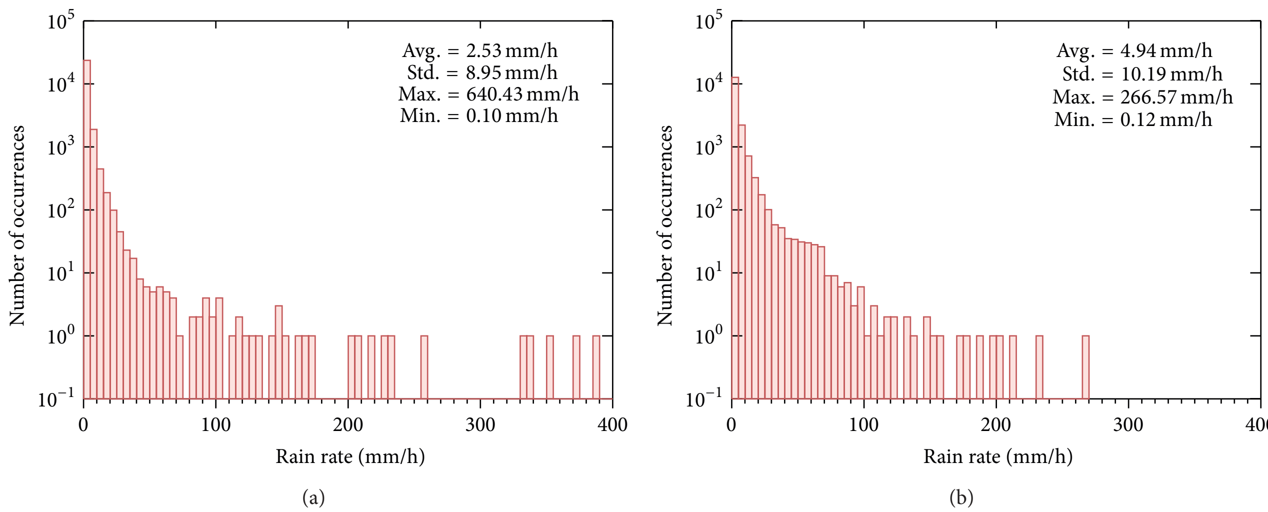

Figure 3: Comparison of rainfall-rate frequency obtained from the DSDs in (a) 2002 and (b) 2012.

where ρ_w is the water density. The normalized intercept parameter (N_w) of the gamma distribution is computed from W and D_m:

$$N_w = \frac{4^4}{\pi\rho_w}\left(\frac{W}{D_m^4}\right), \quad (3)$$

where N_w is the same as the parameter N_0 of an equivalent exponential DSD. The standard deviation of D_m is given as

$$\sigma_m = \left[\frac{\int_0^{D_{\max}} (D - D_m)^2 D^3 N(D)\, dD}{\int_0^{D_{\max}} D^3 N(D)\, dD}\right]^{1/2}. \quad (4)$$

In the case of gamma the shape parameter μ can be derived as

$$\frac{\sigma_m}{D_m} = \frac{1}{(4+\mu)^{1/2}}. \quad (5)$$

Other ways to calculate μ exist, but the above form has been found to be the most stable [29].

The slope parameter Λ can be calculated by shape and second, fourth, and sixth moments [36]:

$$\Lambda = \left[\frac{\int_0^{D_{\max}} D^2 N(D)\, dD\,\Gamma(\mu+5)}{\int_0^{D_{\max}} D^4 N(D)\, dD\,\Gamma(\mu+3)}\right]^{1/2}. \quad (6)$$

To discriminate between convective and stratiform rain, convective rain was defined as $R > 5\,\mathrm{mm\,h^{-1}}$ and the standard deviation of rainfall rate over five consecutive samples (σ_R) > $1.5\,\mathrm{mm\,h^{-1}}$ [26]. To analyze the characteristics of DSDs with rainfall rate, the data were categorized into four groups; $0 < R \le 5\,\mathrm{mm\,h^{-1}}$ (Category I), $5 < R \le 10\,\mathrm{mm\,h^{-1}}$ (Category II), $10 < R \le 20\,\mathrm{mm\,h^{-1}}$ (Category III), and $R > 20\,\mathrm{mm\,h^{-1}}$ (Category IV).

2.3. Rainfall Cases. Rainfall caused by typhoons was removed from the dataset for both years. The data used for the analysis amounted to 77 days in 2002 and 65 days in 2012. Figure 1 shows the comparison between daily rainfall measured by the disdrometer and gage for 2002 and 2012. The total rainfall measured by POSS and gage in 2002 was 1,113.5 and 1,247.0 mm, respectively; the rainfall measured by Parsivel and gage in 2012 was 1,365 mm and 1290.5 mm, respectively. The cross correlation coefficient between disdrometer and gage was 0.99 for both years, and the root mean square error was 1.73 and 1.77 $\mathrm{mm\,h^{-1}}$ for 2002 and 2012, respectively.

3. Results

3.1. Comparison of D_m. The gamma model [22] was used to determine the extent to which using disdrometers with different drop size channels affects the calculation of DSDs. The DSDs were simulated using an intercept and shapes of $8{,}000\,\mathrm{mm^{-1}\,m^{-3}}$ and −2, 0, and 2, respectively, while the slope was incrementally increased from 0 to 6.5 in steps of 0.001. The DSDs were generated at the same channels measured by the POSS and the Parsivel. D_m was calculated as shown in (1) using the simulated DSDs. To match the minimum and maximum diameters of the POSS channels, drops less than 0.3 mm (≤0.35 mm) and larger than 5.5 mm (≥5.35 mm) were set to 0 in the Parsivel (2DVD) dataset. The average rainfall rates calculated from the simulated DSDs based on the POSS and Parsivel channel sizes were 20.3 and 20.1 $\mathrm{mm\,h^{-1}}$, respectively (after removing samples with a rainfall rate greater than 300 $\mathrm{mm\,h^{-1}}$). Figure 2 shows the intercomparison of D_m using DSDs obtained from the simulation with same channels as the Parsivel and the POSS. The mean error and maximum error of D_m between Parsivel and POSS were 0.033~0.053 and 0.143~0.156 mm, respectively. As this difference was so small, we were able to compare DSDs from POSS and Parsivel directly and without interpolation.

3.2. Annual Variation in DSDs. The average rainfall rate observed by POSS in 2002 and Parsivel in 2012 was 2.53 and 4.94 $\mathrm{mm\,h^{-1}}$, respectively (Figure 3). The percentage

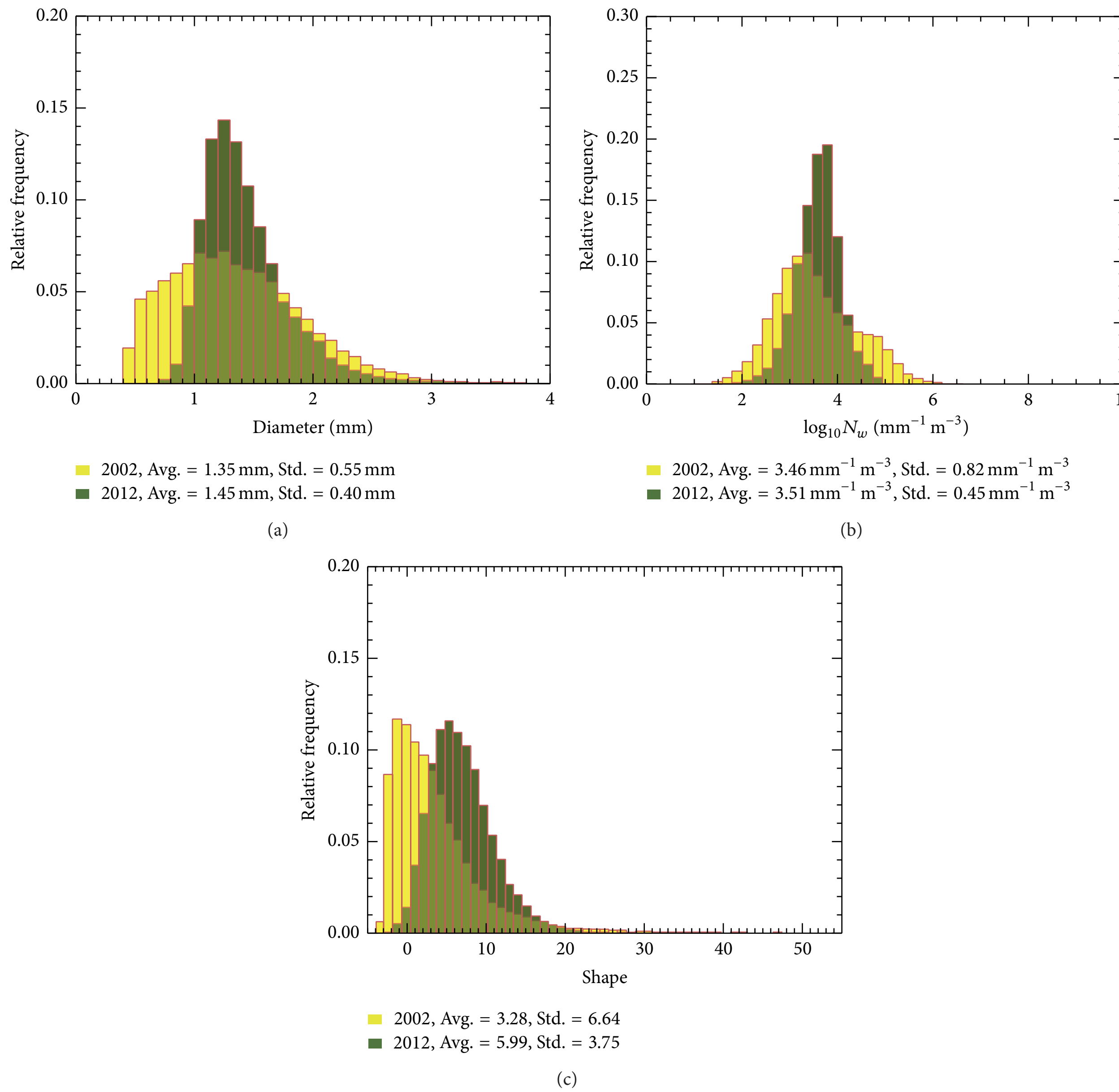

FIGURE 4: Comparison of (a) D_m, (b) $\log_{10}N_w$, and (c) shape parameter for 2002 and 2012.

occurrences of rainfall rates greater than 5 mm h^{-1} were 24.1% in 2012 and 10.8% in 2002. The percentage occurrences of rainfall rates less than 5 mm h^{-1} in 2002 and 2012 were 89.2% and 75.9%, respectively. It appears that changes in the frequency of more intense rainfall events may have contributed most to changes in the precipitation system in Busan over the 10-year period studied here.

To examine annual variations in DSDs, three parameters, D_m, $\log_{10}N_w$, and the slope, were compared for both 2002 and 2012 (Figure 4). The average D_m and its standard deviation were 1.35 and 0.55 mm, respectively, for 2002, and 1.45 and 0.4 mm, respectively, for 2012. This result is slightly larger than the statistical analysis by Leinonen et al. [29] in high latitudes. From the $\log_{10}N_w$ histogram (Figure 4(b)), the average $\log_{10}N_w$ for both years appears to be similar; however, the dispersion of $\log_{10}N_w$ in 2002 was greater than in 2012. Figure 4(c) shows that lower shape values dominated in 2002. This suggests that larger raindrops were the main cause of the higher rainfall rate in 2012.

Episodes of convective and stratiform rain were classified based on the definition outlined by Bringi et al. [26]. Figure 5 shows the histogram of D_m and $\log_{10}N_w$ for convective and stratiform rain in 2002 and 2012, and the proportion of convective rain in each year was 10.9% and 19.5%, respectively, with concomitant occurrences of greater rates in rainfall during both years. The average D_m and standard deviation in 2002 were slightly larger than in 2012 for both convective and stratiform rain, in contrast to N_w. The average D_m and $\log_{10}N_w$ value of stratiform rain was 1.47 and 1.38 mm, respectively, in 2002, and 3.44 and 3.48 mm^{-1} m^{-3},

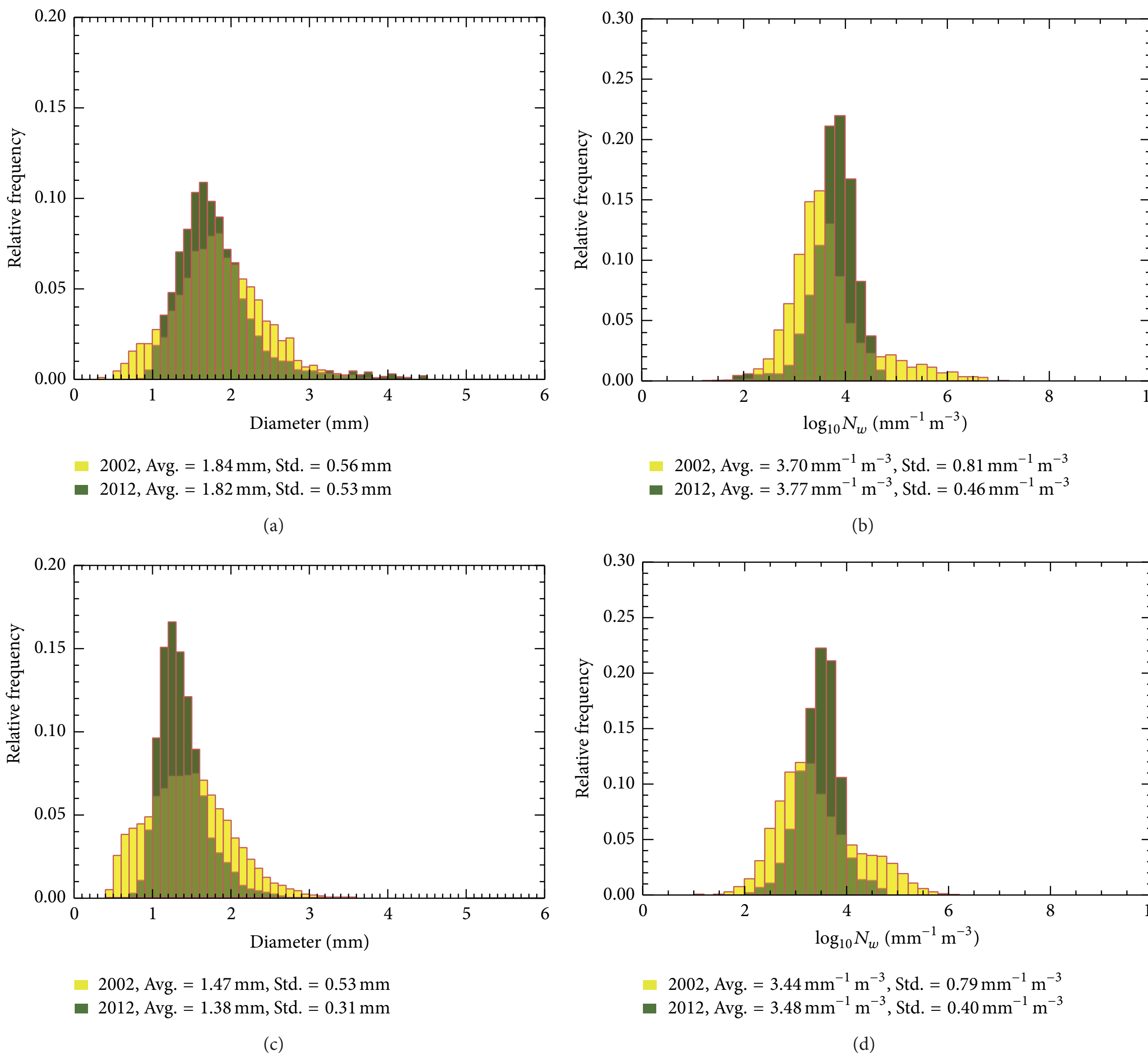

FIGURE 5: Histogram of D_m and $\log_{10}N_w$ for convective (a and b) and stratiform rain (c and d) in 2002 and 2012.

respectively, in 2012. In comparison with the results observed by Bringi et al. [26], the averaged D_m and $\log_{10}N_w$ in 2002 and 2012 were distributed in the maritime rain regime.

Whilst D_m for all samples in 2012 was higher than for 2002, the opposite was observed for both stratiform and convective rain. This may be related to exclusion of samples during the classification of convective and stratiform rain. To examine variation in DSDs, the three parameters (D_m, N_w, and slope) were compared in the rainfall rate categories I to IV. For categories I to IV, the sample numbers were 23574, 1946, 646, and 261, respectively, in 2002, and 12600, 2299, 1055, and 637, respectively, in 2012. Higher intensity rainfall events became more frequent during the 10-year period under study. Values of D_m for categories I and IV were larger in 2012 than in 2002; however, D_m for categories II and III was larger in 2002. The average D_m values for categories I to IV were 1.29, 1.78, 1.96, and 1.92 mm, respectively, in 2002, and 1.36, 1.63, 1.79, and 2.18 mm, respectively, in 2012. The average values of $\log_{10}N_w$ and slope are shown in Table 1.

3.3. Monthly and Hourly Variation in DSDs. To understand monthly variation in DSDs during 2002 and 2012, DSDs were recalculated by month. The data for July 2012 were not available for this study. Figure 6 shows a scatter plot of averaged D_m and $\log_{10}N_w$ for each month in 2002 and 2012. During the spring and autumn seasons, there were no major differences in D_m and $\log_{10}N_w$ between 2002 and 2012. The largest difference in D_m and $\log_{10}N_w$ between the two years occurred in June, August, and December. During the summer season, average D_m increased in 2012, but $\log_{10}N_w$ decreased in 2012. In December, $\log_{10}N_w$ showed very little change,

Table 1: Comparison between D_m, N_w, μ, and sample number for each rainfall rate category during 2002 and 2012.

Category	2002				2012			
	D_m (mm)	$\log_{10}N_w$ (mm^{-1}m^{-3})	μ	Num.	D_m (mm)	$\log_{10}N_w$ (mm^{-1}m^{-3})	μ	Num.
0–5 mm h^{-1}	1.29	3.44	3.36	23,574	1.36	3.43	6.13	12,600
5–10 mm h^{-1}	1.78	3.58	2.50	1,946	1.63	3.72	5.87	2,299
10–20 mm h^{-1}	1.96	3.61	4.18	646	1.79	3.79	5.89	1,055
>20 mm h^{-1}	1.92	4.19	3.37	261	2.18	3.84	5.02	637

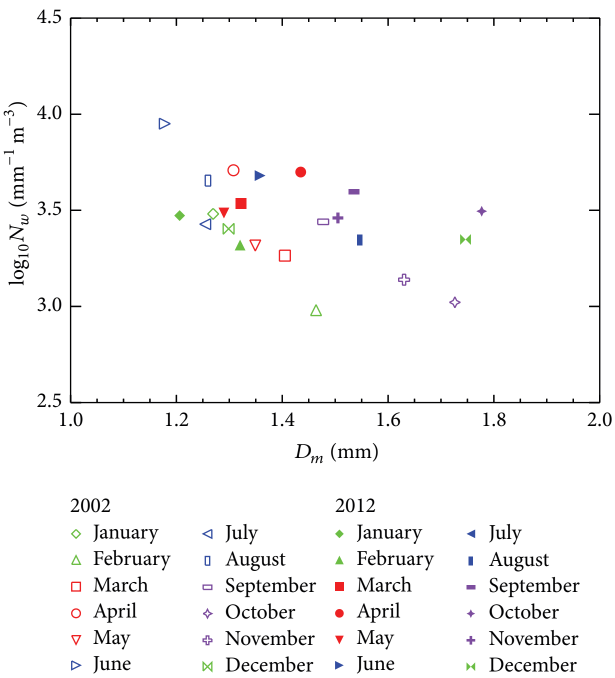

Figure 6: Scatter plots for monthly D_m and $\log_{10}N_w$ in 2002 and 2012. The green symbols represent data from December, January, and February; red represents March, April, and May; blue represents June, July, and August; and purple represents September, October, and November. Open symbols indicate 2002 and solid symbols 2012.

but D_m was much larger in 2012, suggesting that these three months contributed most to the larger D_m observed for 2012.

Figure 7 shows the time series of average rainfall rate, D_m, and normalized number concentration for 2002 and 2012. The peak rainfall rate in 2002 occurred in the morning, and the highest rainfall rate of 4.2 mm h^{-1} in 2002 appeared between 0200 and 0300 local time (LT). Peak rainfall rates in 2012 occurred in the morning and midafternoon. The average rainfall rate for 2012 was much higher than that for 2002, and D_m in 2012 was much higher than in 2002 for almost every time period. The largest D_m was 1.48 mm, which occurred between 6 and 7 AM in 2002. In 2012, the peak of D_m was 1.69 mm, which occurred between 6 and 7 AM. Frequent episodes of heavy rainfall occurred in the morning during 2012 and were associated with larger raindrops; however, relatively smaller raindrops dominated during the afternoons. Values of $\log_{10}N_w$ were comparable in 2002 and 2012.

4. Summary and Concluding Remarks

To investigate the variation in DSDs obtained by POSS and Parsivel disdrometers during the years 2002 and 2012 in Busan, Korea, annual, monthly, and hourly distributions of three parameters (D_m, N_w, and shape) were calculated using a normalized gamma model.

To determine whether substantial differences exist between D_m calculated using POSS and Parsivel, which have different bin sizes, DSDs were simulated using the gamma model and compared. The maximum difference of D_m between both disdrometers was 0.143~0.156 mm, and the average difference was 0.033~0.053 mm; as this difference was so small, we were able to compare DSDs from POSS and Parsivel directly and without interpolation.

The annually averaged rainfall rate increased during the course of this study in Busan. Classification of convective and stratiform rain was performed using the method proposed by Bringi et al. [26]. Convective rain occurred more frequently in 2012 compared with 2002. The D_m of convective and stratiform rain was higher in 2002 than in 2012. Concordantly, the distribution of N_w exhibited an inverse trend. The frequency of rainfall rates greater than 20 mm h^{-1} also increased and were associated with larger D_m in 2012. The D_m associated with medium ($5 < R < 10$ mm h^{-1}) and strong ($10 < R < 20$ mm h^{-1}) rainfall rate categories were greater in 2002 than in 2012.

Monthly variation in DSDs was also investigated during this study. The increase in D_m over other months for July, August, and December was more marked in 2012 than in 2002. In spring and autumn, there were no substantial changes in D_m and N_w between 2002 and 2012. Peak rates of rainfall in 2002 occurred in the morning, and the highest observed rainfall rate (4.2 mm h^{-1}) occurred between 0200 and 0300 LT. In contrast, peak rates of rainfall occurred in both the morning and the afternoon in 2012. D_m was much higher than that in 2002 in almost every time period. Larger raindrops contributed to the high rate of rainfall that occurred in the mornings, but relatively smaller raindrops dominated in the afternoon during 2012.

These results suggest that the increase in raindrop size that has been observed in Busan may continue in the future; however, more research will be required if we are to fully understand this phenomenon. Rainfall variables are highly dependent on drop size and so should be recalculated using the newest DSDs to allow more accurate polarimetric radar rainfall estimation.

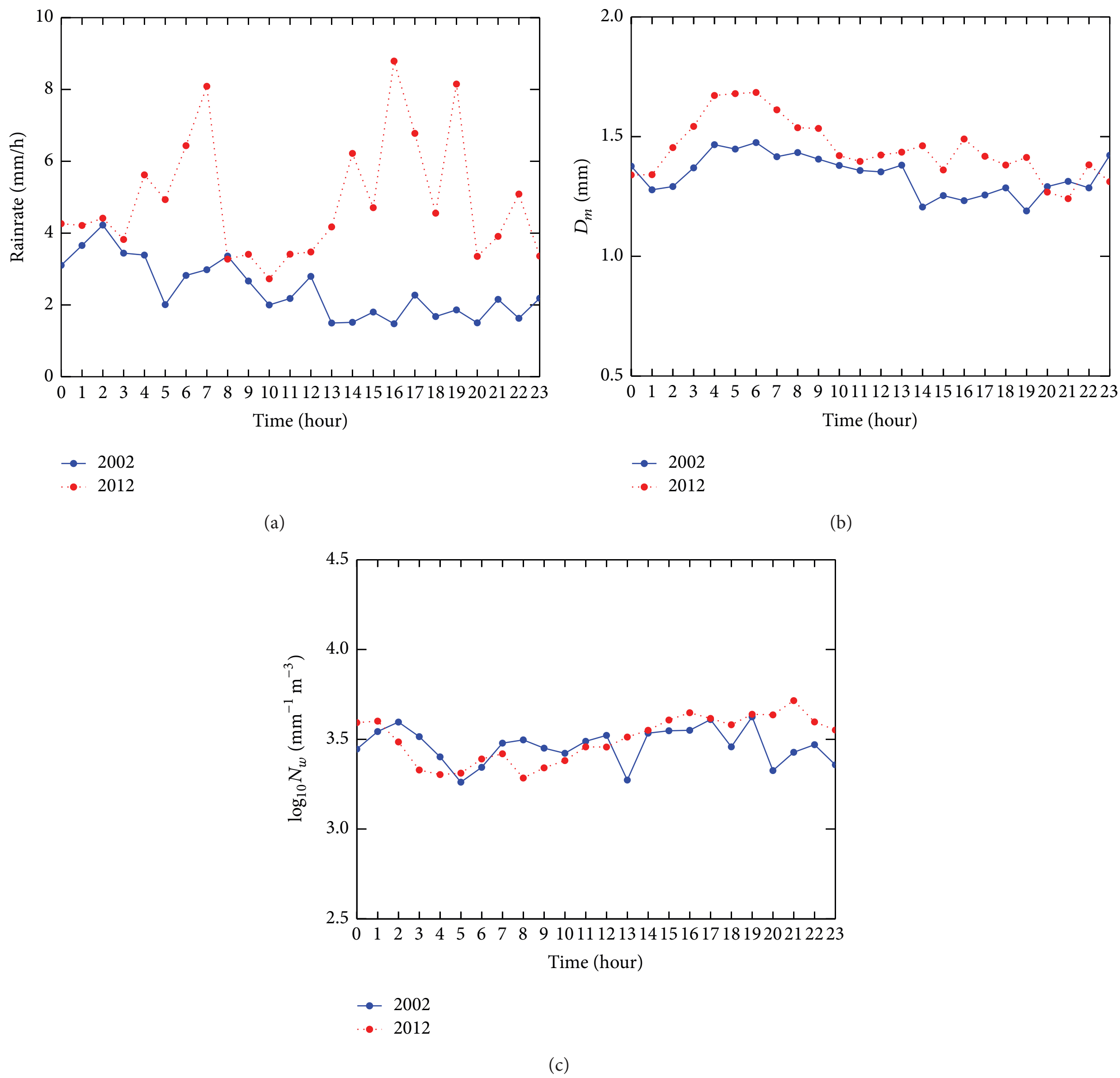

Figure 7: Time series of averaged (a) rainfall rate, (b) D_m, and (c) $\log_{10}N_w$ in 2002 and 2012.

Conflict of Interests

The authors declare that they have no conflict of interests regarding the publication of this paper.

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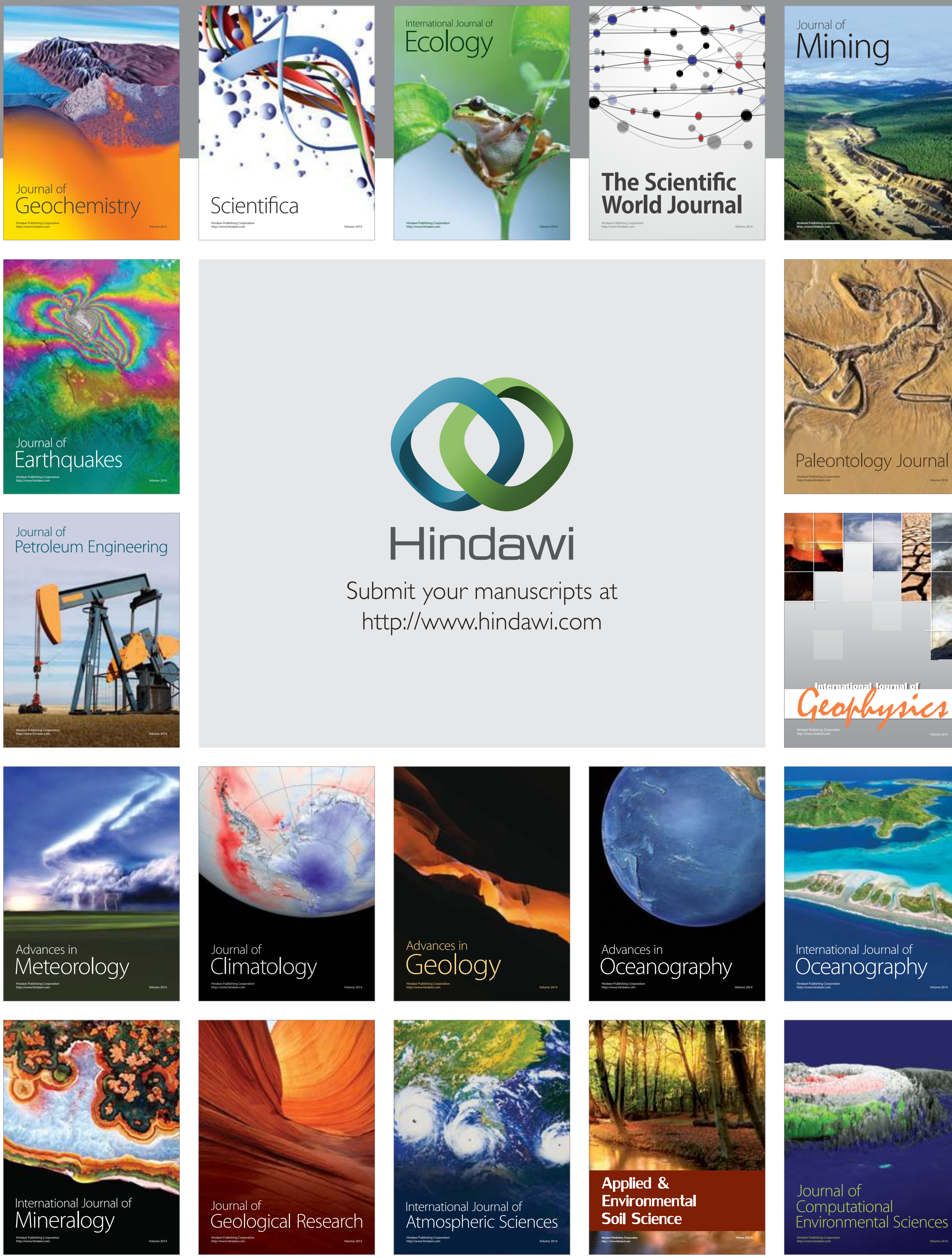
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