

Submitted on 05 Nov 2015

# Anonymous Referee #1

Suggestions for revision or reasons for rejection (will be published if the paper is accepted for final publication)

The authors have generally addressed my comments in an acceptable manner. I have a few suggestions for further corrections with regard to my earlier comments. Once those and the other reviewers' comments have been addressed, the manuscript can be published, but should be thoroughly proofread by a native/fluent English speaker.

**Answer:** Thank you for your comment. Originally, this manuscript was proofread by professional English edit company. However, we read and modified the manuscript very carefully according to Referee's suggestion..

1) The comments about snow detection and  $R > 200$  mm/h cases would be good to mention in appropriate places in the manuscript text in addition to your reply to reviewers.

**Answer:** Thank you for your comment. According to Referee's suggestion, we added the sentences as follows;

[Line 187-189]

'i) Non-liquid type data (e.g., snow, hail etc.) were excluded by routine observation and surface weather chart provided by Korea Meteorological Administration (KMA).'

[Line 192-194]

'data for  $R > 200$  mm  $h^{-1}$  were not included in the analyses, even though the number of samples was only 64 for the entire period.'

2) The tendency of the Gamma DSD to overestimate at  $D_0 < 0.5$  mm is not an intrinsic property of the Gamma DSD. I'm afraid that the authors have misunderstood the statements in the studies they have cited. This statement should be removed from the text in order to avoid misrepresenting the cited studies.

**Answer:** Thank you for your comment and we understood Referee's meaning. Therefore we removed this sentence to avoid misunderstanding.

3) Regarding the T-Matrix, allow me to rephrase my original question because the authors still have not answered it after two revisions. What I tried to ask was: did you write your T-Matrix program yourself, or did you use somebody else's code? If you used code from somebody else, which code was it?

**Answer:** Thank you for your comment and we apologize for misunderstand Referee's comment exactly. This T-matrix program code was given by Prof. Bringi at Colorado State University.

We added sentence about this in the Acknowledgments as follows;

[Line 565-567]

The authors acknowledge providing, weather chart, and AWS data for this work from the Korea Meteorological Administration. The authors also acknowledge providing codes for scattering simulation from Professor V. N. Bringi at Colorado State University.

Submitted on 29 Nov 2015

## Anonymous Referee #4

Suggestions for revision or reasons for rejection (will be published if the paper is accepted for final publication)

The paper has been improved and corrected with the proposed comments and suggestions.

There's just a new error that must be corrected at line 239: the exponent must be preceded by a minus sign.

**Answer:** Thank you for your comment. I corrected the equation as follows

[Line 244]

$$N_0 > 4 \times 10^9 R^{-4.3} \text{ in } \text{m}^{-3} \text{mm}^{-1}$$

# **Climatological Characteristics of Raindrop Size Distributions in Busan, Korea**

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## Abstract

Raindrop size distribution (DSD) characteristics within the complex area of Busan, Korea (35.12°N, 129.10°E) were studied using a Precipitation Occurrence Sensor System (POSS) disdrometer over a four-year period from February 24th 2001 to December 24th 2004. Also, to find the dominant characteristics of polarized radar parameters which is differential radar reflectivity ( $Z_{dr}$ ), specific differential phase ( $K_{dp}$ ) and specific attenuation ( $A_h$ ), T-matrix scattering simulation was applied in present study. To analyze the climatological DSD characteristics in more detail, the entire period of recorded rainfall was divided into 10 categories not only covering different temporal and spatial scales, but also different rainfall types. When only convective rainfall was considered, mean values of mass weighted mean diameter ( $D_m$ ) and normalized number concentration ( $N_w$ ) values for all these categories converged around a maritime cluster, except for rainfall associated with Typhoons. The convective rainfall of a Typhoon showed much smaller  $D_m$  and larger  $N_w$  compared with the other rainfall categories.

In terms of diurnal DSD variability, we ~~observe~~analyzed maritime (continental) precipitation during the daytime (DT) (nighttime, NT), which likely results from sea (land) wind identified through wind direction analysis. These features also appeared in the seasonal diurnal distribution. The DT and NT Probability Density Function (PDF) during the Summer was similar to the PDF of the entire study period. However, the DT and NT PDF during the Winter season displayed an inverse distribution due to seasonal differences in wind direction.

**Keyword:** DSD, POSS disdrometer, Climatological characteristics, Land and sea wind.

## 1. Introduction

~~Drop-Raindrop~~ Size Distribution (DSD) is controlled by the microphysical processes of rainfall and therefore it plays an important role in ~~the~~ development of ~~the quantitative-Quantitative rainfall-Precipitation estimation-Estimation (QPE)~~ algorithms based on forward scattering simulations of radar measurements (Seliga and Bringi, 1976). DSD data accurately reflects local rainfall characteristics within an observation area (You et al., 2014). Many DSD models have been developed to characterize spatial-temporal differences in DSDs under various atmospheric conditions (Ulbrich, 1983). Marshall and Palmer (1948) developed an exponential DSD model using DSD data collected by a filter paper technique ( $N(D) = 8 \times 10^3 \exp(-410R^{-0.21}D)$  in  $m^{-3}mm^{-1}$ ,  $D$  in mm and  $R$  in  $mm\ h^{-1}$ ). In subsequent studies, a lognormal distribution was assumed to overcome the problem of exponential DSD mismatching with real data (Mueller, 1966; Levin, 1971; Markowitz, 1976; Feingold and Levin, 1986).

To further investigate natural DSD variations, Ulbrich (1983) developed a gamma DSD that permitted changing the dimension of the intercept parameter ( $N_0$  in  $m^{-3}mm^{-1-\mu}$ ) with ~~( $N(D) = N_0 D^\mu \exp(-\Lambda D)$ )~~. In addition, to enable the quantitative analysis of different rainfall events, the development of a normalized gamma DSD model that accounted for the independent distribution of DSD from the disdrometer channel interval enabled a better representation of the actual DSD (Willis, 1984; Dou et al., 1999; Testud et al., 2001).

DSDs depend on the rainfall type, geographical and atmospheric conditions and, ~~and~~ observation time, ~~and~~ Also these are closely linked to microphysical characteristics that control rainfall development mechanisms. In the case of stratiform rainfall, raindrops grow by the accretion mechanism because of the relatively long residence time in weak updraft

~~conditions~~, in which almost all water droplets are changed to ice particles. With time, the ice particles grow sufficiently and fall to the ground. The raindrop size of stratiform rainfall observed at the ground level is larger than that of convective rainfall for a same rainfall ~~intensity~~~~rate~~ due to the resistance of the ice particles to break-up mechanisms. In contrast to stratiform rainfall, ~~in~~-convective rainfall raindrops grow by the collision-coalescence mechanism associated with relatively strong vertical wind speeds and short residence time in the cloud. Fully-grown raindrops of maritime precipitation are smaller in diameter than those in stratiform rainfall due to the break-up mechanism in case of same rainfall rate (Mapes and Houze Jr, 1993; Tokay and Short, 1996). Convective rainfall can be classified into two types based on the origin and direction of movement. Rainfall systems occurring over ocean and land are referred to as maritime and continental rainfall, respectively (Göke et al., 2007). Continental rainfall is related to a cold-rain mechanism whereby raindrops grow in the form of ice particles. In contrast, maritime rainfall is related to a warm-rain mechanism whereby raindrops grow by the collision-coalescence mechanism. Therefore, the mass-weighted drop diameter ( $D_m$ ) of continental rainfall observed on the ground is larger than that of maritime rainfall, and a smaller normalized intercept parameter ( $N_w$ ) is observed in continental rainfall (Bringi et al., 2003). Specific heat is a major climatological feature that creates differences between DSDs in maritime and continental regions. These two regions have different thermal capacities and thus ~~display~~-different temperature variations are occurred with time. The surface temperature of the ocean changes slowly because of the ~~water's~~-higher thermal capacity compared with land, w. While the continental regions, which have comparatively lower thermal capacity, ~~display~~-show greater diurnal temperature variability. Sea winds generally ~~is~~-are occurred in from afternoon to early evening when the temperature gradient between the sea and land becomes negative, which is ~~the~~-opposite ~~of the~~-gradient in the daytime (DT). In coastal regions, the land and sea

wind effect causes a pronounced difference between the DT and nighttime (NT) DSD characteristics. Also, when mountains are located near the coast, the difference is intensified by the effect of mountain and valley winds (Qian, 2008).

In the present study, we analyzed a four-year dataset spanning from 2001 to 2004, collected from Busan, Korea (35.12°N, 129.10°E) using a Precipitation Occurrence Sensor System (POSS) disdrometer, to investigate the characteristics of DSDs in Busan, Korea which consist complex mid-latitude region comprising both land and ocean. To quantify the effect of land and sea wind on these characteristics, we also analyzed diurnal variations in DSDs. The remainder of the manuscript is organized as follows. In Section 2 we review the normalized gamma model and explain the DSD quality control method and the classification of rainfall. In Section 3 we report the results of DSD analysis with respect to stratiform/convective and continental/maritime rainfall, and discuss diurnal variations. Finally, a summary of the results and the main conclusions are presented in Section 4.

## 2. Data and Methods

### 2.1. Normalized Gamma DSD

~~The DSDs~~ is-are defined by  $N(D) = N_0 \exp(-\Lambda D)$  ( $\text{m}^{-3}\text{mm}^{-1}$ ) and ~~the one of the methods to~~ are reflect the microphysical characteristics of rainfall using the number concentration of rain~~fall~~-drops ( $N(D)$ ). Also, DSDs ~~is-are~~ able to calculate the many kind of parameters which show the dominant feature of raindrops. Normalization is used to define the DSD and to solve the non-independence of each DSD parameter (Willis, 1984; Dou et al., 1999; Testud et al., 2001). Furthermore, a normalized gamma DSD enables the quantitative



comparison for rainfall cases regardless of time scale and rain rate. Here, we use the DSD model designed by Testud et al. (2001):

$$N(D) = N_w f(\mu) \left(\frac{D}{D_m}\right)^\mu \exp \left[ -\left(4 + \mu\right) \frac{D}{D_m} \right]. \quad (1)$$

where  $D$  is the volume equivalent spherical raindrop ~~size-diameter~~ (mm), and  $f(\mu)$  is defined using the DSD model shape parameter ( $\mu$ ) and gamma function ( $\Gamma$ ) as follows:

$$f(\mu) = \frac{6}{4^4} \frac{(\mu+4)^{4+\mu}}{\Gamma(4+\mu)}. \quad (2)$$

From the value of  $N(D)$ , the median volume diameter ( $D_0$  in mm) can be obtained as follows:

$$\int_0^{D_0} D^3 N(D) dD = \frac{1}{2} \int_0^{D_{\max}} D^3 N(D) dD. \quad (3)$$

Mass-weighted mean diameter ( $D_m$  in mm) is calculated as the ratio of the fourth to the third moment of the DSD:

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

129

130 The normalized intercept parameter ( $N_w$  in  $m^{-3}mm^{-1}$ ) is calculated as follows:

131

$$N_w = \frac{4^4}{\pi \rho_w} \left( \frac{LWC}{D_m^4} \right). \quad (5)$$

133

134 The shape of the DSD is calculated as the ratio of  $D_m$  to the standard deviation (SD) of  $D_m$   
 135 ( $\sigma_m$  in mm) (Ulbrich and Atlas, 1998; Bringi et al., 2003; Leinonen et al., 2012):

136

$$\sigma_m = \left[ \frac{\int_0^{D_{\max}} D^3 (D - D_m)^2 N(D) dD}{\int_0^{D_{\max}} D^3 N(D) dD} \right]^{\frac{1}{2}}. \quad (6)$$

138

139 In addition,  $\sigma_m/D_m$  is related to  $\mu$  as follows:

140

$$\frac{\sigma_m}{D_m} = \frac{1}{(4+\mu)^{1/2}}. \quad (7)$$

142

143 Liquid water content (LWC in  $g m^{-3}$ ) can be defined from the estimated DSD:

144

$$LWC = \frac{\pi}{6} \rho_w \int_0^{D_{\max}} D^3 N(D) dD. \quad (8)$$

146

147 where  $\rho_w$  is the water density ( $\text{g m}^{-3}$ ) and it assumed as  $1 \times 10^6 \text{ g m}^{-3}$  for a liquid ~~water~~.  
 148 Similarly, the rainfall rate ( $R$  in  $\text{mm h}^{-1}$ ) can be defined as follows:

149

$$R = \frac{3.6}{10^3} \frac{\pi}{6} \int_0^{D_{\max}} v(D) D^3 N(D) dD. \quad (9)$$

151

152 where the value of factor  $3.6 \times 10^3$  is the unit conversion which converts the mass flux unit  
 153 ( $\text{mg m}^{-2} \text{ s}^{-1}$ ) to the common unit ( $\text{mm h}^{-1}$ ) for the convenience.  $v(D)$  ( $\text{m s}^{-1}$ ) is the ~~fall~~  
 154 terminal velocity for each raindrop size. The relationship between  $v(D)$  ~~and~~ equivalent  
 155 spherical raindrop size ( $D$  in  $\text{mm}$ ) is given by Atlas et al. (1973) who developed an empirical  
 156 formula based on the data reported by Gunn and Kinzer (1949):

157

$$v(D) = 9.65 - 10.3 \exp[-0.6D]. \quad (10)$$

159

## 160 2.2 Quality Control of POSS Data

161 POSS ~~was~~is used to measure the number of raindrops within the diameter range of 0.34-  
 162 5.34 mm, using bistatic, continuous wave X-band Doppler radar (10.525 GHz) across 34  
 163 channels (Fig. 1; Sheppard and Joe, 2008). To estimate DSDs, Doppler power density spectrum

is ~~generated~~calculated as follows;

$$S(f) = \int_{D_{\min}}^{D_{\max}} N(D_m) V(D_m, \rho, h, w) \bar{S}(f, D_m, \rho, h, w) dD_m. \quad (11)$$

Where  $S(f)$  means Doppler spectrum power density,  $V(D_m, \rho, h, w) \bar{S}(f, D_m, \rho, h, w)$  means weighting function of  $S(f)$ ,  $\bar{S}$  is the mean of  $S(f)$ ,  $\rho$  is density of precipitation distribution,  $h$  is the shape of precipitation distribution,  $w$  ( $\text{m s}^{-1}$ ) is wind speed and  $V(x)$  is sample volume and the symbol 'x' means arbitrary parameters which affect the sampling volume. The Doppler power density spectrum has a resolution of 16Hz and terminal velocity ( $v_t$ ) has a resolution of  $0.24 \text{ m s}^{-1}$ . Transmitter and receiver skewed about  $20^\circ$  toward each other, and cross point of signal is located over 34 cm from transmitter-receiver. Transmitter-receiver toward upper side detects  $N(D)$ -~~of raindrops~~ in ~~observation volume~~ ( $V(Dx)$ ) (Sheppard, 1990). Also, Sheppard (1990) and Sheppard and Joe (1994) noted some shortcomings as the overestimation of small drops at horizontal wind larger than  $6 \text{ m s}^{-1}$ . However, in present study, the quality control of POSS for wind effect was not considered because it lies beyond this work. Detailed specifications and measurement ranges and raindrop sizes for each observation channel of the POSS disdrometer are summarized in Table 1.

A POSS disdrometer ~~was installed~~have been operating in Busan, Korea ( $35.12^\circ\text{N}$ ,  $129.10^\circ\text{E}$ ), along with other atmospheric instruments, the locations of which are shown in Fig. 2. Estimating raindrop ~~size~~diameter correctly is challenging and care should be taken to ensure

reliable data are collected. We performed the following quality controls to optimize the accuracy of the disdrometer estimates. i) Non-liquid type event data (e.g., snow, hail etc.) detected by POSS were excluded by routine observation and surface weather chart provided by Korea Meteorological Administration (KMA). ~~to focus only on liquid state rainfall.~~ ii) DSD spectra in which drops were not found in at least five consecutive channels were removed as non-atmospheric. iii) Only data recorded in more than 10 complete channels were considered. iv) To compensate for the reduced capability to detect raindrops smaller than 1 mm when  $R > 200 \text{ mm h}^{-1}$  (as recorded by the disdrometer), data for  $R > 200 \text{ mm h}^{-1}$  were not included in the analyses, even though the number of samples was only 64 for the entire period. ~~data collected when  $R > 200 \text{ mm h}^{-1}$  were not included in the analyses.~~ v) To eliminate wind and acoustic noise, data collected when  $R < 0.1 \text{ mm h}^{-1}$  ~~are~~were removed (Tokay and Short, 1996). ~~vi) The value of  $D_g$  which is calculated by Eq. (3) tends to be overestimated when  $D_g < 0.5 \text{ mm}$  (Leinonen et al., 2012). Because the correlation coefficient between  $D_g$  and  $D_m$  was 0.985 for the whole study period, we considered that  $D_m$  could be used for the analysis instead of  $D_g$ .~~

After performing all quality control procedures, 99,388 spectra were left from ~~an~~ original ~~total~~ data (of 166,682) for 1-min temporal resolution. Accumulated rainfall amount from POSS during the entire period was 4261.49 mm. To verify the reliability of the POSS data, they were compared with data collected by a 0.5 mm tipping bucket rain gauge at an automatic weather system (AWS) located ~368 m from the POSS (Fig. 3).

## 2.3 Radar Parameters

First, the radar reflectivity factor ( $z_{in}$ , mm<sup>6</sup>m<sup>-3</sup>) and non-polarized radar reflectivity ( $Z_{in}$ , dBZ) were computed using the DSD data collected by POSS, as follows:

$$z = \int_0^{D_{max}} D^6 N(D) dD. \quad (12)$$

$$Z = 10 \log_{10}(z). \quad (13)$$

The T-matrix method used in this study is initially proposed by Waterman (1965, 1971) to calculate electromagnetic scattering by single non-spherical raindrops. The adaptable parameters for this calculation are frequency, temperature, hydrometeor types, raindrop's canting angle and ~~drop~~-axis ratio ( $\gamma$ ) and explained the following sentences. Axis ratios of raindrops differ with atmospheric conditions and rainfall type. To derive the drop shape relation from the drop diameter, we applied the results of numerical simulations and wind tunnel tests employing a forth-polynomial equation, as in many previous studies (Beard and Chuang, 1987; Pruppacher and Beard, 1970; Andsager et al., 1999; Brandes et al., 2002). The ~~drop shape axis~~ ratio relation used in the present study is a combination of those from Andsager et al. (1999) and Beard and Chuang (1987) for three raindrop size ranges (Bringi et al., 2003).

The raindrop axis ratio relation of Andsager et al. (1999) is applied in the range of  $1 < D \text{ (mm)} < 4$ , as follows:

$$r = 1.0048 + 0.0057D - 2.628D^2 + 3.682D^3 - 1.677D^4. \quad (14)$$

229

230 The drop-shape relation of Beard and Chuang (1987) is applied in the range of  $D < 1$  mm  
231 and  $D > 4$  mm, as follows:

232

233 
$$r = 1.012 + 0.01445D - 0.01028D^2. \quad \text{_____}(15)$$

234

235 We assumed SD and the mean canting angle of raindrops as  $7^\circ$  and  $0^\circ$ , respectively. The  
236 refractive indices of liquid water at  $20^\circ\text{C}$  were used (Ray, 1972). Also, the condition of  
237 frequency for electromagnetic wave of radar is 2.85 GHz (S-band). We calculated dual  
238 polarized radar parameters based on these conditions. The parameters of differential reflectivity;  
239  $(Z_{dr}$  in  $Z_{dr}$  (dB), specific differential phase  $(K_{dp})$  (K<sub>dp</sub> in  $\text{deg km}^{-1}$ ), and attenuation;  
240  $(A_h)$  in  $(\text{dB km}^{-1})$ , using DSD data were calculated and analyzed.

241

#### 242 **2.4. Classification of Rainfall Types and Rainfall Events**

243 Rainfall systems can be classified as stratiform or convective in nature, via analysis of the  
244 following microphysical characteristics: i) DSD, using relationships between  $N_0$  and  $R$  ( $N_0 >$   
245  $4 \times 10^9 R^{-4.3}$  in  $\text{m}^{-3}\text{mm}^{-1}$  is considered as convective rainfall, Tokay and Short, 1996;  
246 Testud et al., 2001); ii) ~~radar reflectivity~~ $Z$ , where, according to Gamache and Houze (1982), a  
247 rainfall system that displays radar reflectivity larger than 38 dBZ is considered to be  
248 convective; and iii) ~~rainfall rate~~ $R$ , where average value larger than 0.5 mm per 5 min is  
249 considered as convective rainfall (Johnson and Hamilton, 1988). Alternatively, rainfall that has

1-min  $R > 5$  ( $0.5$ )  $\text{mm h}^{-1}$  and a SD of  $R > (<) 1.5 \text{ mm h}^{-1}$  is considered as convective (stratiform) type (Bringi et al., 2003). The rainfall classification method proposed by Bringi et al. (2003) is applied in the present study.

It is necessary to categorize different rainfall systems because their microphysical characteristics show great variation depending on the type of rainfall, as well as the type of rainfall event; e.g., Typhoon, Changma, heavy rainfall and seasonally discrete rainfall. To investigate the temporal variation in DSDs, we analyzed daily and seasonal DSDs. Likewise, to investigate diurnal variability in DSD, DT and NT data were considered by using the sunrise and sunset time in Busan (provided by the Korea Astronomy and Space Science Institute [KASI]). In the middle latitudes, and including Busan, the timings of sunrise and sunset vary due to solar culminating height. The earliest and latest sunrise (sunset) time of the entire period is 0509 KST (1712 KST) and 0733 KST (1942 KST), respectively. DT (NT) is defined as the period from the latest sunrise (sunset) time to the earliest sunset (sunrise) time for the unity of classification of each time group (Table 2).

To analyze the predominant characteristics of DSDs for Typhoon rainfall, nine Typhoon events were selected from throughout the entire study period which is summarized in Table 2.

—

This study utilizes ~~the Korea Meteorological Administration (KMA)~~ rainfall warning regulations to identify heavy rainfall events. The KMA issues a warning if the accumulated rain amount is expected to be  $>70 \text{ mm}$  within a 6-hour period, or  $>110 \text{ mm}$  within a 12-hour period. Rainfall events classified as Changma and Typhoon were not included in the classification ‘heavy rainfall’.

Changma is the localized rainfall system or rainy season that is usually present over the Korean Peninsula between mid-June and mid-July which is similar to the Meiyu (China) or Baiu



(Japan). The selected dates and periods of each rainfall category are summarized in Table 2.

### 3. Results

#### 3.1. DSD and Radar Parameters

Figure 4 shows the Probability Density Function (PDF) and Cumulative Distribution Function (CDF) of DSDs and radar parameters with respect to the entire, stratiform and convective rainfall. The PDFs of DSD and radar parameters were calculated using the non-parameterization kernel estimation to identify the dominant distribution of each parameter recorded in Busan. Non-parameterization kernel estimation was also used to identify continuous distributions of DSDs. The PDF of stratiform rainfall is more similar to that of the dataset for the entire analysis period due to the dominant contribution of stratiform rainfall (about 62.93%) to the overall rainfall than that of convective rainfall. However, the PDF for convective rainfall is significantly different from that of the entire analysis period, and as the convective rainfall contributes only 6.11% of the overall rainfall (Table 3). When  $\mu < 0$  the distribution of  $\mu$  for convective rain has more value of PDF than that for stratiform rain (Fig. 4a). Alternatively, the frequency of  $\mu$  for stratiform rainfall is higher than that of convective rainfall when  $0 < \mu < 5$ . The value of  $\mu$  for convective rainfall is higher than that for stratiform rainfall because the break-up mechanism would be increase the number concentration of small raindrops. The number concentrations of mid-size raindrops increased due to the decrease in the number concentration of relatively large raindrops (Hu and Srivastava, 1995; Sauvageot and Lacaux, 1995). However, we observed a higher frequency of convective

rainfall than stratiform rainfall in the negative  $\mu$  range.

The PDF of  $D_m$  displays peak around 1.2 and 1.4 mm for stratiform rainfall and the entire rainfall dataset, respectively. We note that a gentle peak exists around 0.7 mm for both stratiform and convective rainfall datasets (Fig. 4b). These features are similar to the distribution of  $D_m$  observed in a high-latitude region at Järvenpää, Finland (Fig. 4 of Leinonen et al., 2012). For  $D_m$  values  $> 1.7$  mm, the PDF for convective rainfall is higher than stratiform rainfall. Accordingly, the value of DSD for stratiform rainfall is higher than that of convective rainfall when  $D_m < 1.7$  mm. Generally, stratiform rainfall that develops by the cold rain process displays weaker upward winds and less efficient break-up of raindrops. Therefore, in the same rainfall rate, stratiform rainfall tends to produce larger raindrops than convective rainfall that develops by the warm rain process. However, the average  $D_m$  values for convective and stratiform rain for the entire period are approximately 1.45 and 1.7 mm, respectively. In short,  $D_m$  is proportional to  $R$  regardless of rainfall type. This finding is consistent with the results of Atlas et al. (1999) who found that the  $D_m$  of convective rainfall is larger than that of stratiform rainfall on Kapingamarangi Island, Micronesia.

The PDF of  $\log_{10}(N_w)$  for the entire rainfall dataset was evenly distributed between 1.5 and 5.5, with a peak at  $N_w = 3.3$  (Fig. 4c). The PDF of  $\log_{10}(N_w)$  for stratiform rainfall is rarely  $> 5.5$ , while for convective rainfall it is higher at  $> 5.5$  than that of stratiform. There is a similar frequency in the stratiform and convective rainfall at 4.4.

The PDF distributions for  $\log_{10}(R)$  and  $\log_{10}(LWC)$  are similar each other (Fig. 4d and e). It is inferred that the similar results come from the using of alike moment of DSD as 3.67 and 3 for  $R$  and  $LWC$ , respectively. The PDF of  $\log_{10}(R)$  for the entire rainfall dataset ranged between -0.5 and 2. A peak exists at 0.3 and the PDF rapidly decreases from the peak value as

R increases. The PDF for stratiform rainfall has a higher frequency than that of the entire rainfall when  $-0.3 < \log_{10}(R) < 0.7$ , while the PDF for convective rainfall is denser between 0.4 and 2. Furthermore, the frequency of the PDF for convective rainfall was higher than that of stratiform rainfall in case of  $\log_{10}(R) > 0.65$  and the peak value shown ~~was as~~ 0.9.

The PDF and CDF for ~~non-polarized reflectivity ( $Z$ ), differential reflectivity ( $Z_{dr}$ ), specific differential phase ( $K_{dp}$ ), and specific attenuation of horizontal reflectivity ( $A_h$ )~~ are shown in Fig. 4f-i. The PDF of  ~~$Z_{H}Z$~~  for stratiform rainfall (Fig. 4f) is widely distributed between 10 and 50 dBZ with the peak at approximately 27 dBZ. Conversely, for convective rainfall, the value of PDF lie between 27 and 55 dBZ and the peak frequency value at approximately 41 dBZ. The frequency value of reflectivity is higher for convective rainfall than for stratiform rainfall in the range of  $\sim >35$  dBZ. Furthermore, the shape of the PDF for convective rainfall is similar to that reported for Darwin, Australia (Steiner et al., 1995); however, for stratiform rainfall there are significant differences between Busan and Darwin in terms of the shape of the frequency distribution. The PDF of  $Z_{dr}$  for the entire rainfall primarily exists between 0 and 2.5 dB, and the peaks are at 0.3 and 1.8 dB (Fig. 4g). The distribution of  $Z_{dr}$  for convective and stratiform rainfall is concentrated between 0.6 and 1.6 dB, and between 0.3 and 2 dB, respectively. The frequency of  $Z_{dr}$  for convective (stratiform) rainfall exists in ranges higher (lower) than stratiform (convective) at 0.9 dB.

The dominant distribution of  $K_{dp}$  for the entire dataset and for stratiform rainfall lies between 0 and  $0.14 \text{ deg km}^{-1}$ , with a peak value of  $0.03 \text{ deg km}^{-1}$  and  $0.08 \text{ deg km}^{-1}$ . However, for convective rainfall the PDF of  $K_{dp}$  is evenly exist between 0.01 and  $0.15 \text{ deg km}^{-1}$ . Furthermore, when  $K_{dp} > 0.056 \text{ deg km}^{-1}$ , the frequency of the PDF for convective rainfall is higher than that of stratiform rainfall (Fig. 4h).

The PDF of  $A_h$  is similar to that of  $K_{dp}$  and is exist between 0 and  $0.01 \text{ dB km}^{-1}$ . For the case of the entire rainfall dataset and for stratiform rainfall, the PDF of  $A_h$  is concentrated between 0 and  $2.0 \times 10^{-3} \text{ dB km}^{-1}$  and that of convective rainfall is strongly concentrated between  $1.0 \times 10^{-3}$  and  $8.0 \times 10^{-3} \text{ dB km}^{-1}$  (Fig. 4i). Unlike the PDF of  $A_h$  for convective rainfall, the PDF for stratiform rainfall shows a strong peak at about  $7.0 \times 10^{-4} \text{ dB km}^{-1}$ .

### 3.2. Climatological Characteristics of DSD in Busan

The climatological characteristics of DSDs for 10 rainfall categories are analyzed in this study. Sample size and ratio rainfall for each category are summarized in Table 3. Figure 5a illustrates the distribution of all 1-min stratiform rainfall data, and Fig. 5b shows scatter plots of averaged  $D_m$  and  $\log_{10}(N_w)$  for all 10 rainfall categories for stratiform rainfall data. Figure 5a displays a remarkable clear boundary in the bottom sector and shows that most of the data lie below the reference line used by Bringi et al. (2003) to classify convective and stratiform rainfall. The average value of  $D_m$  and  $\log_{10}(N_w)$  for all rainfall categories, except for heavy rainfall, exist between 1.4 mm and 1.6 mm and between 3.15 and 3.5, respectively (Fig. 5b). These values are relatively small compared with the reference line presented by Bringi et al. (2003). The distribution of 1-min convective rainfall data is displayed in Fig. 6a and the distribution of average values of  $D_m$  and  $N_w$  for the 10 rainfall categories in the case of convective rainfall in Fig. 6b. The blue and red plus symbols represent maritime and continental rainfall, respectively, as defined by Bringi et al. (2003). The scatter plot of 1-min convective rainfall data shows more in the continental cluster than the maritime cluster; however, the average values for the 10 rainfall categories are all located around the maritime cluster, except for the

Typhoon category. By considering the entire average values including Typhoon event (Fig. 6b), we can induce the simple linear equation using  $D_m$  and  $\log_{10}(N_w)$  as follows:

$$\log_{10}(N_w) = -1.8D_m + 6.9. \quad (16)$$

Even the coefficients in ~~Equation-Eq.~~ 16 might be changed slightly with the Typhoon values, this result does not represent in  $D_m < 1.2$  mm and  $D_m > 1.9$  mm. The  $D_m$  ( $N_w$ ) value for the Typhoon category was considerably smaller (larger) than that of the other categories as well as that of stratiform type of Typhoon. This result does not agree with that reported by Chang et al. (2009), who noted that the  $D_m$  of convective rainfall Typhoon showed a large value compared with that associated with stratiform rainfall.

### 3.3 Diurnal Variation in Raindrop Size Distributions

#### 3.3.1. Diurnal Variations in DSDs

Figure 7a shows a histogram of normalized frequency of 16 wind directions recorded by the AWS, which is the same instrument as that used to collect the data shown in Fig. 3. To establish the existence of a land and sea wind, the difference in wind direction frequencies between DT and NT were analyzed. Figure 7b shows the difference between DT and NT, difference frequency means normalized frequency of wind direction for DT subtract to that of NT for each direction, in terms of the normalized frequency of 16 wind directions. In other word, positive (negative) values indicate that the frequency of wind is more often observed during DT (NT). Also, land (sea) wind defined in present study from  $225^\circ$  ( $45^\circ$ ) to  $45^\circ$  ( $225^\circ$ ) according to the

geographical condition in Busan. The predominant frequency of wind direction in the DT (NT), between  $205^{\circ}$  ( $22.5^{\circ}$ ) and  $22.5^{\circ}$  ( $205.5^{\circ}$ ), is higher than that in the NT (DT) (Fig. 7b). The observation site where the POSS was installed at western side from the closest coast line, distance is about 611 m, suggesting that the effect of the land and sea wind would have been recorded.—

To understand the effects of the land and sea wind on DSD characteristics, we analyzed the PDF and 2-hour averaged DSD parameters for DT and NT. Figure 8 illustrates the distributions of  $\mu$ ,  $D_m$ ,  $\log_{10}(N_w)$ ,  $\log_{10}(LWC)$ ,  $\log_{10}(R)$ , and  $Z$ . There were large variations of  $\mu$  with time. The  $\mu$  values varied from 2.41 to 3.17 and the minimum and maximum  $\mu$  values occurred at 0800 KST and 1200 KST, respectively (Fig. 8a). A  $D_m$  larger than 1.3 mm dominated from 0000 KST to 1200 KST, before decreasing remarkably between 1200 and 1400 KST. The minimum and maximum  $D_m$  appeared at 1400 KST and 0800 KST, respectively (Fig. 8b).

$N_w$  ~~distribution showed generally varies~~ inversely to  $D_m$ ; however, no inverse relationship was identified between  $D_m$  and  $N_w$  in case of the time series (Fig. 8c). The maximum and minimum values of  $N_w$  were found at 0600 KST and 2200 KST.

Variability through time was similar for  $R$ ,  $LWC$ , and  $Z_h$  as  $D_m$ . There was an increasing trend from 0000 KST to 0800 KST followed by a remarkably decreasing trend from 0800 KST to 1400 KST (Figs 8d, 11e and 11f). Note that the time of the sharp decline for  $R$  between 1200 KST and 1400 KST is simultaneous with a  $D_m$  decrease. Larger (smaller) drops would contribute to higher  $R$  in the morning (afternoon). These variations considerably matched with the diurnal sea wind time series (Fig. 8g). Sea wind is the sum value of normalized wind frequency between  $45^{\circ}$  and  $225^{\circ}$ . From 0200 (1400) KST to 1200 (2000) KST shows smaller

(larger) value of sea wind frequency which is opposite to the relatively larger (smaller) parts of each parameter ( $D_m$ ,  $R$ ,  $LWC$  and  $Z_h$ ).

The PDF distribution of  $\mu$  between -2 and 0 is more concentrated for NT than for DT. Furthermore, when  $\mu > 0$ , DT and NT frequency distributions are similar (Fig. 9a). A larger  $N(D)$  of small or large raindrops would be expected in NT than in DT.

The distribution of DT  $D_m < 0.7 \text{ mm}$  is wider than that of the NT. However, between 0.7 and 1.5 mm the frequency for NT is higher than that for DT, whereas the distribution in the range  $D_m \rightarrow 1.5 \text{ mm}$  is similar for both DT and NT (Fig. 9b). We note that the smaller peak of  $D_m$  around 0.6 mm for the entire rainfall dataset (Fig. 4b) was observed only in DT.

The distribution of  $\log_{10}(N_w)$  for DT has higher value of PDF at larger  $\log_{10}(N_w)$  than that of NT at  $\log_{10}(N_w) > 4$  (Fig. 9c).

Bringi et al. (2003) noted that the maritime climatology displayed larger  $N_w$  and smaller  $D_m$  values than the continental climatology, based on observed DSDs in the low and middle latitude. Also, Göke et al. (2007) emphasized that rainfall type can be defined by the origin location and movement direction. In accordance with these previous results, we consider NT rainfall in the Busan region to be more likely caused by a continental convective system.

In the present study, the shape of the PDF of  $LWC$  and  $R$  for DT and NT are similar which is the same reason with the results of Fig. 4e-f.  $LWC$  and  $R$  distributions during the DT (NT) are higher (lower) than in the NT (DT) when  $\log_{10}(LWC)$  and  $\log_{10}(R)$  are larger (smaller) than -1.2 and 0, respectively (Fig. 9d and e). ~~The~~  $Z$  has similar pattern with  $LWC$  and  $R$  during the DT (NT) was higher (lower) than in the NT (DT) in the range below (above) about 27 dBZ (Fig. 9f).

### 3.3.2. Diurnal Variations of DSDs with respect to Season

Busan experiences distinct atmospheric conditions that are caused by the different frequencies and magnitudes of land and sea winds in response to variable sunrise and sunset times. To identify seasonal variations of DSDs with respect to the effect of the land and sea wind, we analyzed the DT and NT PDF of  $D_m$  and  $N_w$  in the Summer and Winter. The start and end times of DT (NT) were sorted using the latest sunrise (sunset) and the earliest sunset (sunrise) time for each season (Table 4) which is same method that of entire period classification.

Figure 10a shows a histogram of wind directions in Summer (light grey) and Winter (dark grey). The frequencies of Summer and Winter wind directions are similar to each other. However, in Fig. 10b, the DT and NT distributions of Winter wind direction display opposing frequencies. Note that Winter season shows remarkable frequency of land (sea) wind between  $0^\circ$  ( $157.5^\circ$ ) and  $45^\circ$  ( $202.5^\circ$ ) at DT (NT) compared with results of those for Summer season. The accumulated value of normalized wind frequencies at the sea and land wind show different feature between Summer and Winter season (Table 5).

To identify the variability of DSDs caused by the land and sea wind in Summer and Winter, a 2-hour interval time series of  $D_m$ ,  $N_w$  and  $R$  was analyzed. In the Summer, the time series of  $D_m$  displays considerably large values between 0000 KST and 1200 KST, compared with the period between 1400 KST and 2200 KST (Fig. 11a). The mean value of  $D_m$  decreases dramatically between 1200 KST and 1400 KST.  $\log_{10}(N_w)$  generally has a negative relationship with  $D_m$  (Fig. 11b). However, the inverse relation between  $\log_{10}(N_w)$  and  $D_m$  is not remarkable. ~~The~~  $\log_{10}(R)$  tends to increase gradually from 0000 KST to 0800 KST and decrease from 0800 KST to 1400 KST, which is similar to the pattern that of entire period (Fig. 11c). Kozu et al. (2006) analyzed the diurnal variation in  $R$  at Gadanki (South India),



455 Singapore, and Kototabang (West Sumatra) during the Summer monsoon season. All regions  
 456 displayed maximum  $R$  at approximately 1600 LST, except for Gadanki. Also, Qian (2008),  
 457 who analyzed the diurnal variability of wind direction and  $R$  on Java Island during the  
 458 Summer season using 30 years (from 1971 to 2000) of NCEP/NCAR reanalyzed data. They  
 459 found that a land wind occurred from 0100 LST to 1000 LST and a sea wind from 1300 LST  
 460 to 2200 LST (Fig. 7 of Qian (2008)). Normalized wind frequency for each direction is similar  
 461 pattern to the results of Qian (2008) but pattern of  $R$  is different with that of Kozu et al. (2006).  
 462 The diurnal variation of rain rate in the present study from 0200 (1200) KST to 1000 (2000)  
 463 KST shows relatively smaller (larger) frequencies of sea wind. It is different pattern with the  
 464 result of Kozu et al. (2006). However, these patterns matched with the time series of  $D_m$  and  
 465  $\log_{10}(N_w)$ . Larger frequency of sea wind direction shows counter-proportional (proportional)  
 466 relationship to the smaller (larger) frequency of  $D_m$  ( $\log_{10}(N_w)$ ).  
 467 Variability of ~~the~~  $D_m$  time series for Winter is the inverse of the Summer time series (Fig. 11a).  
 468 The mean value of  $D_m$  steadily increases from 0000 KST to 1600 KST and then decreases  
 469 from 1600 KST to 2200 KST. The Winter  $\log_{10}(N_w)$  time series displays a clear inverse  
 470 pattern compared with the  $D_m$  variation with time and increases from 1600 KST to 0400 KST  
 471 and then steadily decreases from 0400 KST to 1600 KST (Fig. 11b). The peak of  $\log_{10}(N_w)$   
 472 occurs at 0400 KST. However, the time series of  $\log_{10}(R)$  for Winter season shows similar  
 473 pattern with that of Summer unlike to another parameters (Fig. 11c). Based on the diurnal  
 474 variation of  $R$ , the variations of  $D_m$  and  $N_w$  would be independent to  $R$ .  
 475 Alike to the  $D_m$  and  $\log_{10}(N_w)$ , normalized wind frequency of wind direction for Winter  
 476 season shows inverse relationship to that of Summer season (Fig. 11d). The value of frequency  
 477 generally decreases (increases) from 0400 (1400) KST to 1400 (0400) KST. Also, it shows

478 symmetry pattern with that of Summer season.

479 The PDF distribution of Summer  $D_m$  displays a relatively large DT frequency compared with  
 480 NT when  $D_m < 1.65 \text{ mm}$ , except for the range between 0.6 and 0.9 mm. However, in the  
 481 range of  $D_m > 1.65 \text{ mm}$ , the NT PDF displays a larger frequency (Fig. 12a). The PDF of  
 482  $\log_{10}(N_w)$  for DT (NT) has a larger frequency than the NT (DT) when  $\log_{10}(N_w) > (<) 3.3$   
 483 but smaller frequency when  $\log_{10}(N_w) < (>) 3.3$  (Fig. 12c).

484 The DT and NT PDFs of  $D_m$  and  $\log_{10}(N_w)$  during Winter display an inverse distribution  
 485 to that of Summer. For the PDF of  $D_m$ , there is a considerable frequency for NT (DT) when  
 486  $D_m < (>) 1.6 \text{ mm}$  (Fig. 12b). The PDF of  $\log_{10}(N_w)$  of Summer season for NT (DT) is  
 487 larger than that of the DT when  $\log_{10}(N_w) < (>) 3.5$  (Fig. 12d). In the PDF analysis, relatively  
 488 large (small)  $D_m$  and small (large)  $\log_{10}(N_w)$  are displayed during the NT (DT) when a land  
 489 wind (sea wind) occurs.

490 Bringi et al. (2003) referred that the convective rainfall type is able to be classified as the  
 491 continental and maritime-like precipitation using  $D_m$  and  $N_w$ . As the previous study result, we  
 492 analyzed the PDF of DSDs for Summer and Winter with respect to convective rainfall type.  
 493 These feature would be shown more clearly in convective type. The convective rainfall type of  
 494 PDFs of DT and NT for Summer show similar shape of distribution to that of all rainfall type  
 495 (Fig. 3a). For the PDF of  $D_m$ , there is a more frequency for DT (NT) than NT (DT) when  $D_m$   
 496  $< (>) 2.0 \text{ mm}$  except for between 0.7 mm and 1.2 mm (Fig. 13a). The PDF of convective  
 497 rainfall type's  $\log_{10}(N_w)$  for DT (NT) has a larger frequency than the NT (DT) when  
 498  $\log_{10}(N_w) > (<) 3.4$  except for between 4.3 and 5.5 (Fig. 12c). PDF distributions for Winter  
 499 season show more clear pattern compared with those of the entire rainfall type. The value of  
 500 PDF for  $D_m$  in DT (NT) have considerably larger than NT (DT) when  $D_m > (<) 1.9 \text{ mm}$ ,

especially between 2.15 mm and 2.3 mm (Fig. 13b). Also, those for  $\log_{10}(N_w)$  in DT (NT) show dramatic values when  $\log_{10}(N_w) < (>) 3.6$ . Furthermore, PDF values significantly concentrated on between  $3 < \log_{10}(N_w) < 3.2$  (Fig. 13d). In short, considering the DSD parameters with wind directions, the maritime (continental)-like precipitation would depend on the sea (land) wind.

#### 4. Summary and Conclusion

Climatological characteristics of DSDs in Busan were analyzed using the DSD data observed by POSS over a four-year period from February 24<sup>th</sup> 2001 to December 24<sup>th</sup> 2004. Observed DSDs were filtered to remove errors by performing several quality control measures, and an AWS rain gauge installed nearby was used to verify the rainfall amount recorded by the POSS. We analyzed DSD characteristics of convective and stratiform rainfall types, as defined by Bringi et al. (2003). The rainfall dataset was thus divided into stratiform and convective rainfall and their contributions to the total rainfall were 62.93% and 6.11%, respectively. Also, to find the climatological characteristics of DSD for rainfall case, the entire rainfall data was classified as 10 rainfall categories including the entire period case.

According to the study by Bringi et al. (2003), the rainfall in Busan shows maritime climatological DSD characteristics. The mean values of  $D_m$  and  $N_w$  for stratiform rainfall are relatively small compared with the average line of stratiform rainfall produced by Bringi et al. (2003), except for heavy rainfall events. In case of convective type, mean values of  $D_m$  and  $N_w$  are converged around the maritime cluster, except for the Typhoon category. The convective rainfall associated with a Typhoon has considerably smaller  $D_m$  and larger  $N_w$  values compared with the other rainfall categories. This is likely caused by increased raindrop break-

up mechanism as a result of strong wind effects. Furthermore, the distributions of mean  $D_m$  and  $N_w$  values for all rainfall categories associated with convective rainfall displays a linear relationship including the Typhoon category.

The analysis of diurnal variation in DSD yielded the following results: first, the frequency of  $\mu$  is higher at NT than during the DT in the negative value. The PDF of  $R$  is higher at NT than during the DT when  $\log_{10}(R) > 0.6$ . The value of PDF for  $D_m$  during DT is larger than NT smaller than 0.65 mm. For  $N_w$ , which tends to be inversely related to  $D_m$ , its frequency is higher at NT than DT when  $\log_{10}(N_w) > 3.8$ . This feature is matched with the time series of normalized frequency of sea wind which shows inverse relationship to  $D_m$ . Smaller  $D_m$  corresponds to the larger sea wind frequency. In short, maritime (continental) –like precipitation are observed in the DT (NT) more often than in the NT (DT) according to the features of wind. The above-mentioned DSD characteristics are likely due to the land and sea wind caused by differences in specific heat between the land and ocean. These features are also apparent in the seasonal diurnal distribution. The PDF of DT and NT for convective rainfall type during the Summer is similar to the PDF of the entire period; however, those of the Winter displays the significant inverse distribution compared to the Summer because of obvious seasonal differences in wind direction.

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557 **Author contributions**

558 Cheol-Hwan You designed the study. Sung-Ho Suh modified the original study theme and  
559 performed the study. Cheol-Hwan You and Sung-Ho Suh performed research, obtained the  
560 results and prepared the manuscript along with contributions from all of the co-authors. Dong-  
561 In Lee examined the results and checked the manuscript.

562

563 **Acknowledgement**

564 This work was funded by the Korea Meteorological Industry Promotion Agency under Grant  
565 KMIPA 2015-1050. The authors acknowledge providing, weather chart, and AWS data for this

work from the Korea Meteorological Administration. The authors also acknowledge providing  
codes for scattering simulation from Professor V. N. Bringi at Colorado State University.

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## Tables

**Tables 1.** Specification of POSS disdrometer.

Specifications	Detail
Manufacturer	ANDREW CANADA INC
Module	PROCESSOR
Model number	POSS-F01
Nominal power	100 mW
Bandwidth	Single frequency

<b>Emission</b>	43 mW
<b>Pointing direction</b>	20 ° (to the vertical side)
<b>Antenna</b>	Rectangular pyramidal horns
<b>Range of sample area</b>	< 2 m
<b>Wavelength</b>	10.525 GHz $\pm$ 15 GHz
<b>Physical dimension</b>	277×200×200 cm <sup>3</sup>
<b>Net weights</b>	Approximately 110 kg

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685 **Table 2.** Designated date with respect to the source of rainfall.

<b>Rainfall Category</b>	<b>Period</b>			
	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>
<b>Typhoon</b>	-	7.5-7.6, 8.31	5.29, 6.19, 8.7, 9.11-12	6.20, 8.19, 9.6
<b>Changma</b>	6.18-6.19, 6.23-6.26, 6.29-6.30, 7.1, 7.5-7.6 7.11-7.14	6.23-6.25, 6.30, 7.1-7.2	6.12-6.14, 6.23, 6.27 6.30, 7.1, 7.3- 7.15	7.11-7.13, 7.14

<b>Heavy rainfall</b>	02.04.15. 20:13 to 02.04.16 06:29			
<b>Seasonal</b>	<b>Spring</b>	<b>Summer</b>	<b>Autumn</b>	<b>Winter</b>
	Mar. to May	Jun. to Aug.	Sep. to Nov.	Dec. to Feb.
<b>Diurnal</b>	<b>DT (KST)</b>		<b>NT (KST)</b>	
	0733 - 1712		1942 - 0509	

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696 **Table 3.** Rainfall rate for each rainfall category and the number of sample size for 1-min data.

<b>Rainfall Category</b>	<b>Total precipitation</b>	<b>Stratiform precipitation (%)</b>	<b>Convective precipitation (%)</b>
<b>Typhoon</b>	5095	3118 (61.19)	652 (12.79)
<b>Changma</b>	18526	11099 (59.91)	1611 (8.69)
<b>Heavy rainfall</b>	359	153 (42.61)	150 (41.78)
<b>Spring</b>	30703	20370 (66.34)	1478 (4.81)
<b>Summer</b>	37187	22566 (60.68)	3409 (9.16)
<b>Autumn</b>	19809	12033 (60.74)	850 (4.29)
<b>Winter</b>	11689	7582 (64.86)	339 (2.90)
<b>Daytime</b>	41328	26373 (63.81)	2539 (6.14)
<b>Nighttime</b>	37455	23063 (84.00)	2242 (5.89)
<b>Entire</b>	99388	62551 (62.93)	6076 (6.11)

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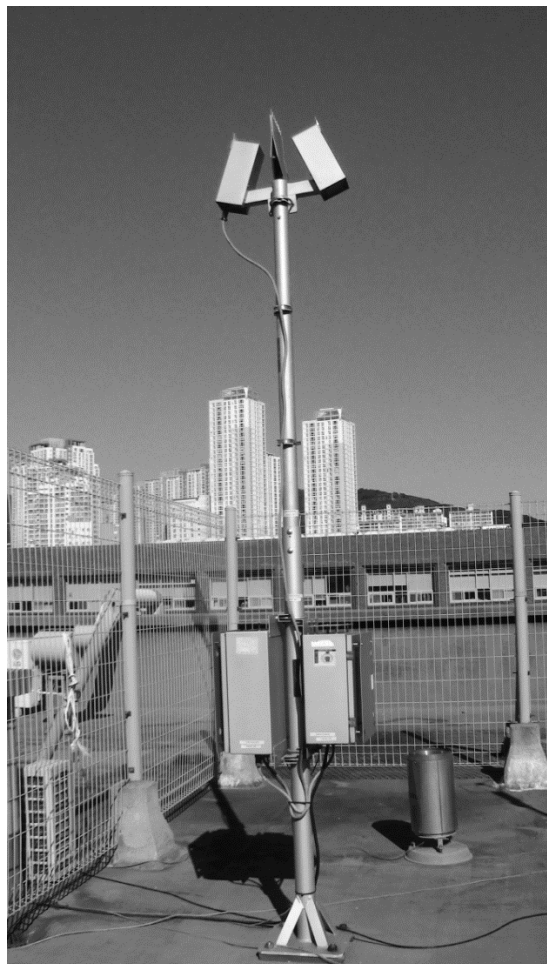
**Table 4.** DT and NT (KST) in Summer and Winter season.

<b>Rainfall Category</b>	<b>Period</b>	<b>Beginning time (KST)</b>	<b>Finishing time (KST)</b>
<b>Summer</b>	<b>DT</b>	0533	1927
	<b>NT</b>	1942	0509
<b>Winter</b>	<b>DT</b>	0733	1712
	<b>NT</b>	1819	0654

**Table 5.** Sum of the normalized wind direction frequencies between Summer and Winter.

Sum of the normalized wind direction frequencies				
Season	Summer		Winter	
Type	Sea wind	Land wind	Sea wind	Land wind
Frequency	0.4139	0.5861	0.3137	0.6863
Difference of the normalized wind direction frequency between DT and NT (DT-NT)				
Season	Summer		Winter	
Type	Sea wind	Land wind	Sea wind	Land wind
Frequency	0.0731	-0.0731	-0.0697	0.0697

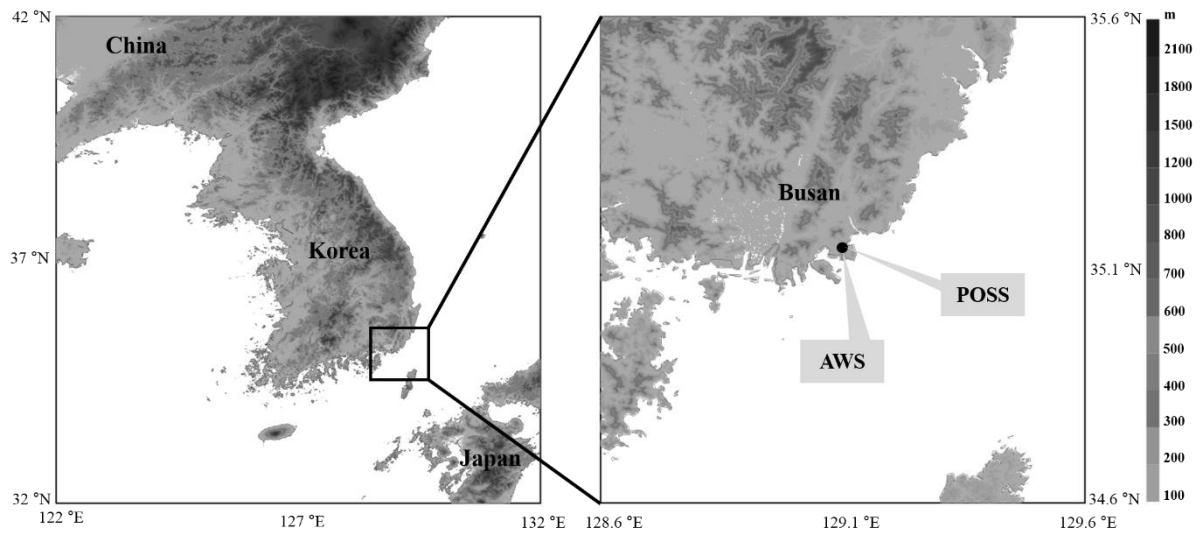
## Figures



**Figure 1.**

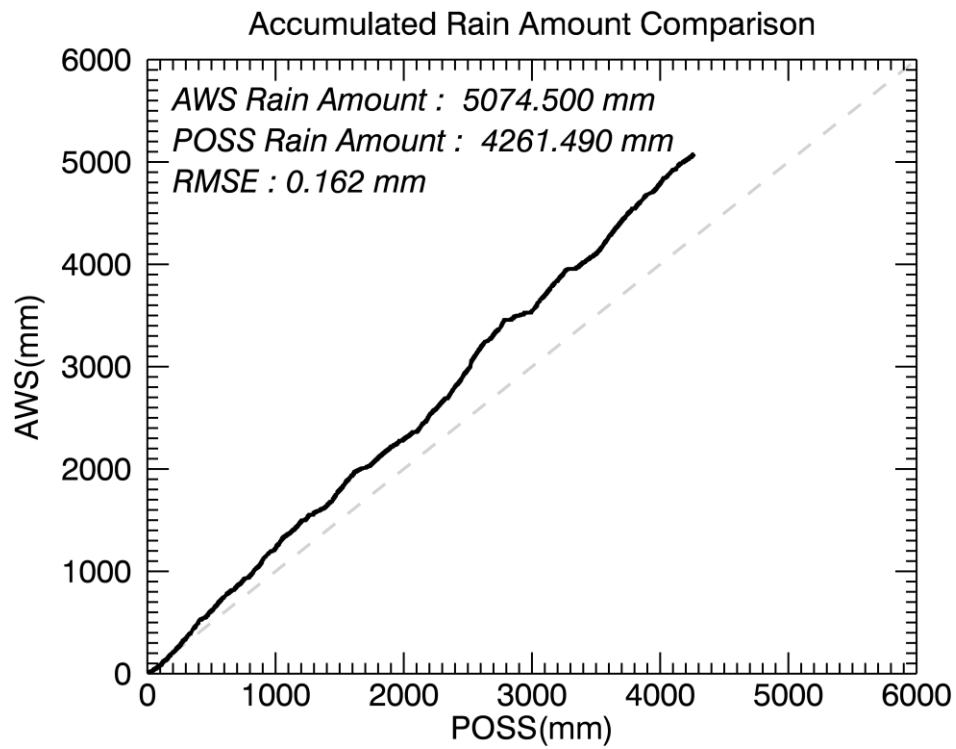
Photograph of the POSS instrument used in this research.





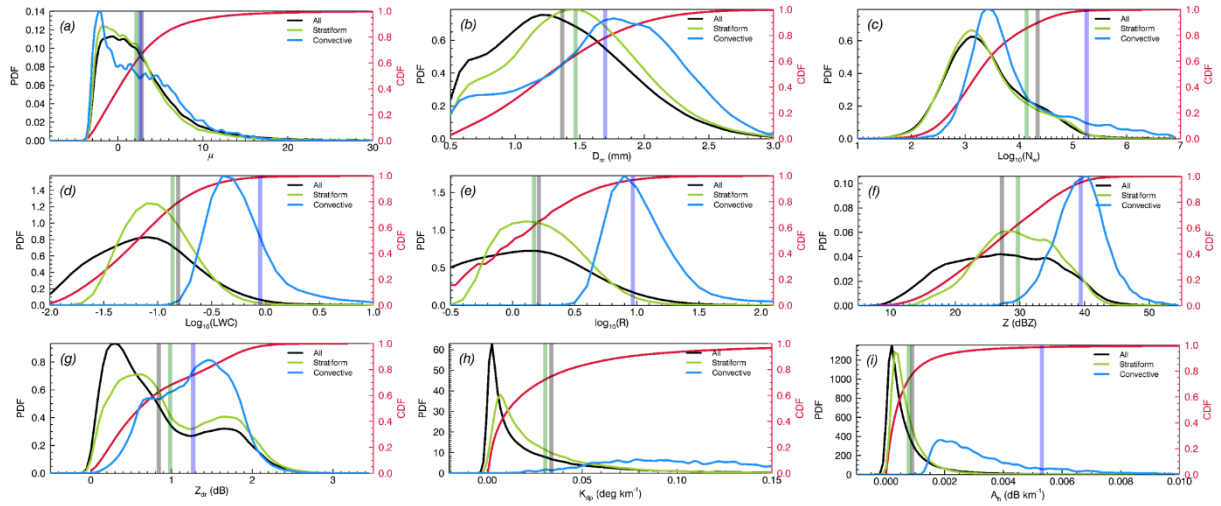
**Figure 2.**

Locations of the POSS and the AWS rain gauge installed in Busan, Korea.



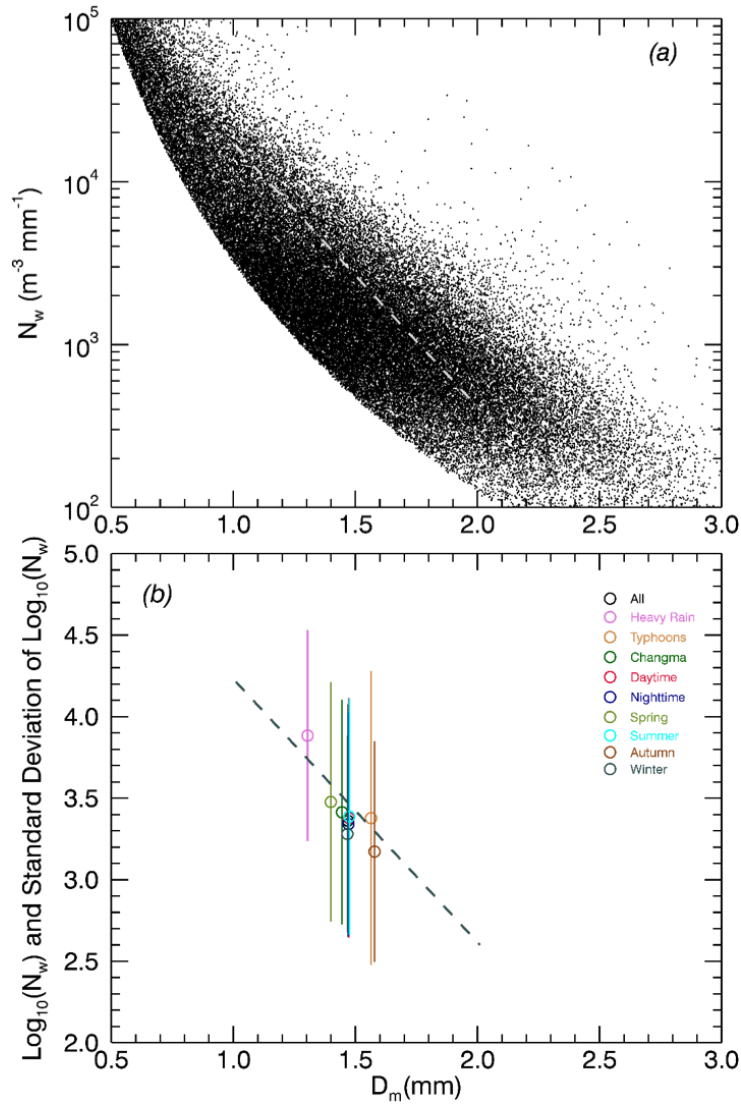
**Figure 3.**

Comparison of the recorded rainfall amounts between the POSS and AWS instrument.



**Figure 4.**

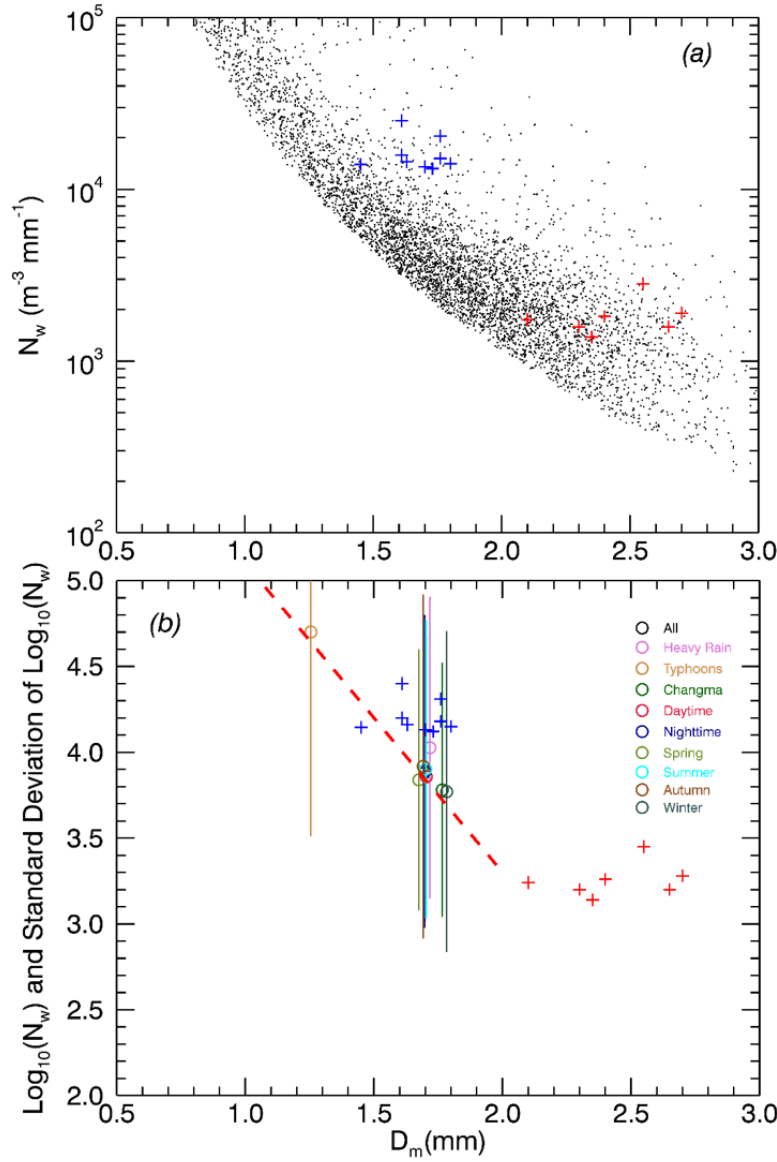
PDF and CDF curves for (a)  $\mu$ , (b)  $D_m$ , (c)  $\log_{10}(N_w)$ , (d)  $\log_{10}(R)$ , (e)  $\log_{10}(LWC)$ , (f)  $Z$ , (g)  $Z_{dr}$ , (h)  $K_{dp}$ , and (i)  $A_h$  for the entire rainfall dataset (solid black line), stratiform rainfall (solid green line), and convective rainfall (solid blue line). The solid red line represents the CDF for entire rainfall dataset. The solid vertical line represents the mean value of each type.



**Figure 5.**

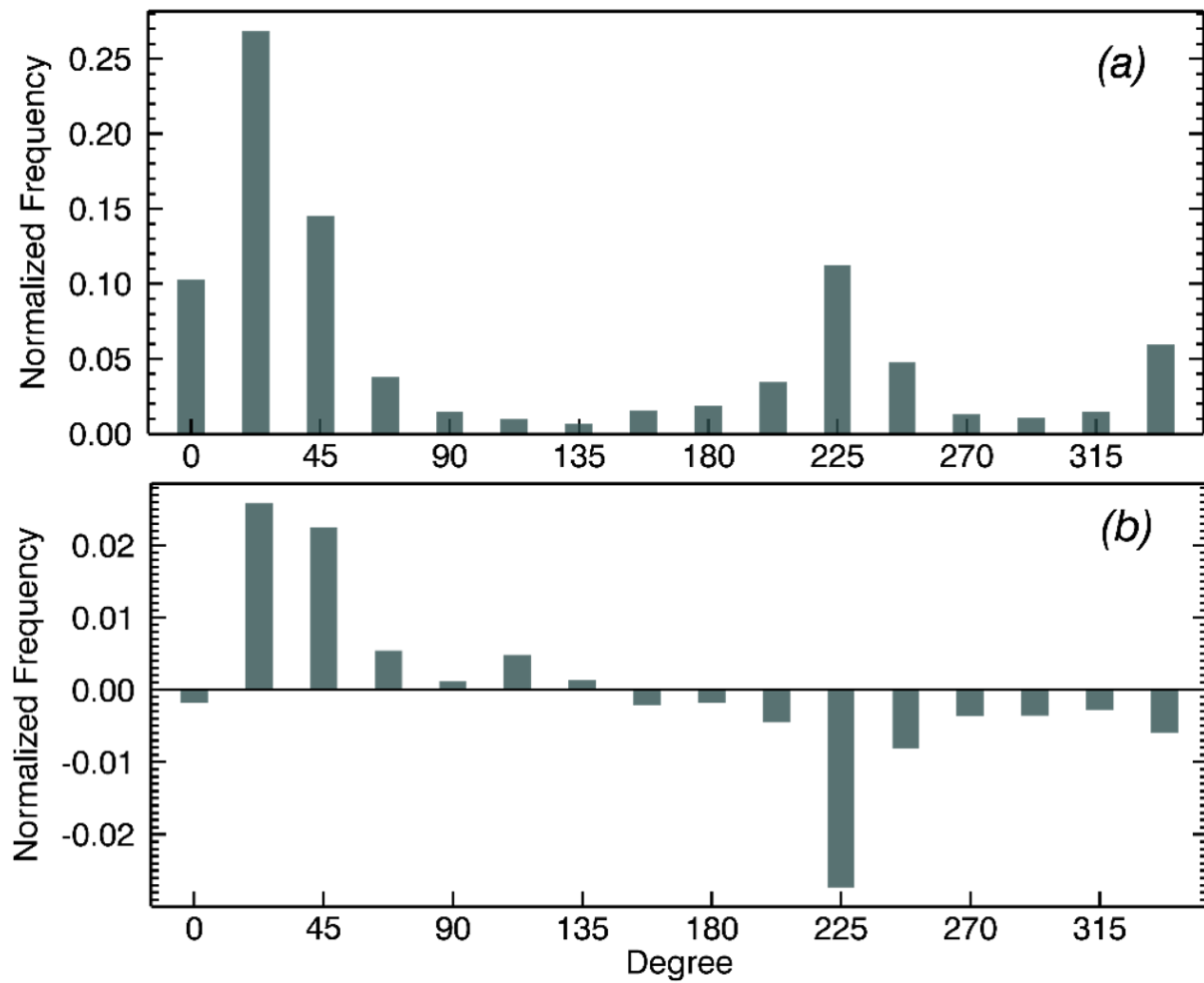
(a) Scatter plot of 1-min  $D_m$  and  $N_w$  for the 10 rainfall categories with respect to stratiform rainfall data. The broken grey line represents the average line as defined by Bringi et al. (2003).

(b) Scatter plot of mean  $D_m$  and  $\log_{10}(N_w)$  values of the 10 rainfall categories with respect to stratiform rainfall and these mean values for each rainfall type are shown as circle symbols. The vertical line represents  $\pm 1\sigma$  of  $\log_{10}(N_w)$  for each category.



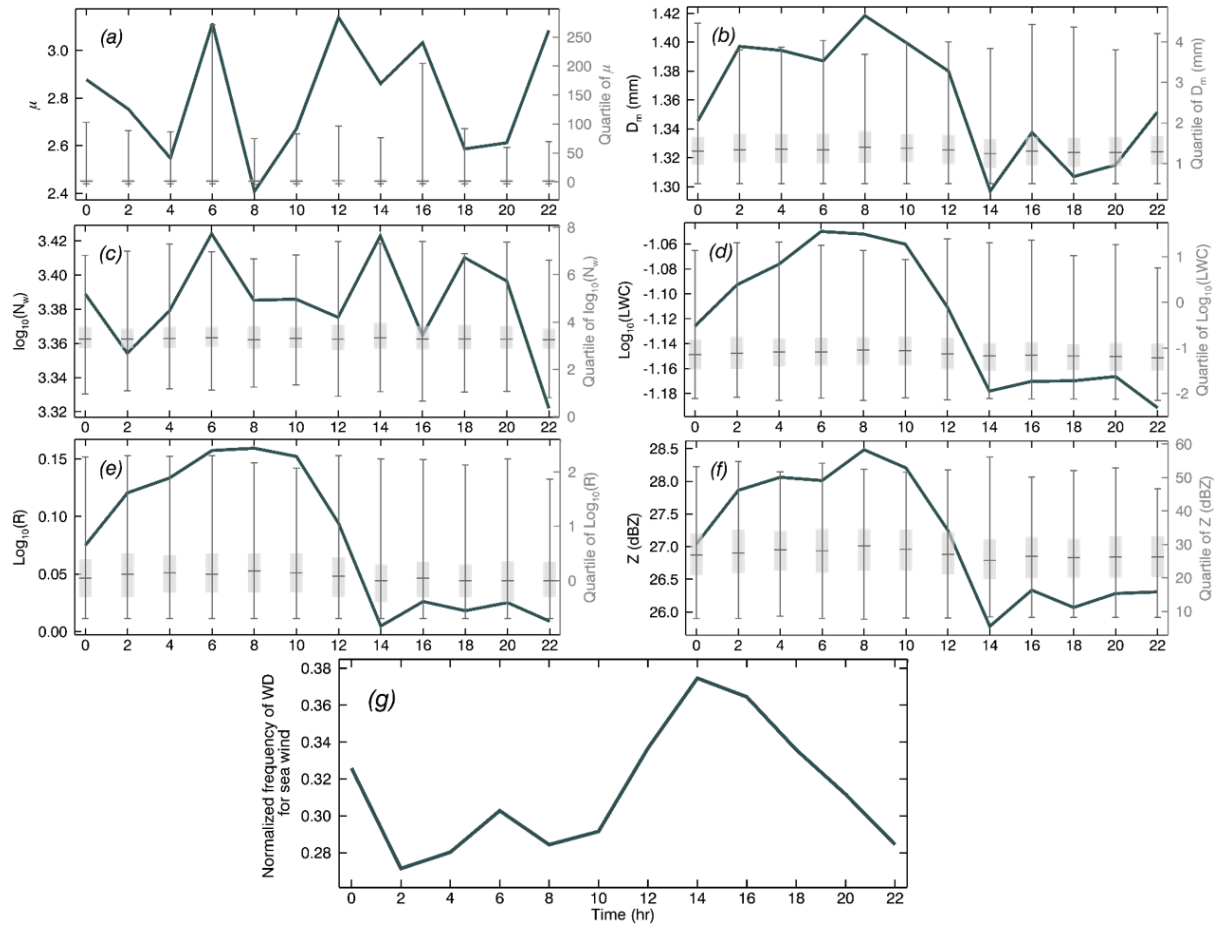
**Figure 6.**

(a) As in Figure 5(a), but for convective rainfall. The blue and red plus symbols represent maritime and continental rainfall, respectively, as defined by Bringi et al. (2003). (b) As in Figure 5(b), but for convective rainfall. The broken red line represents the mathematical expression described in Eq. (16).



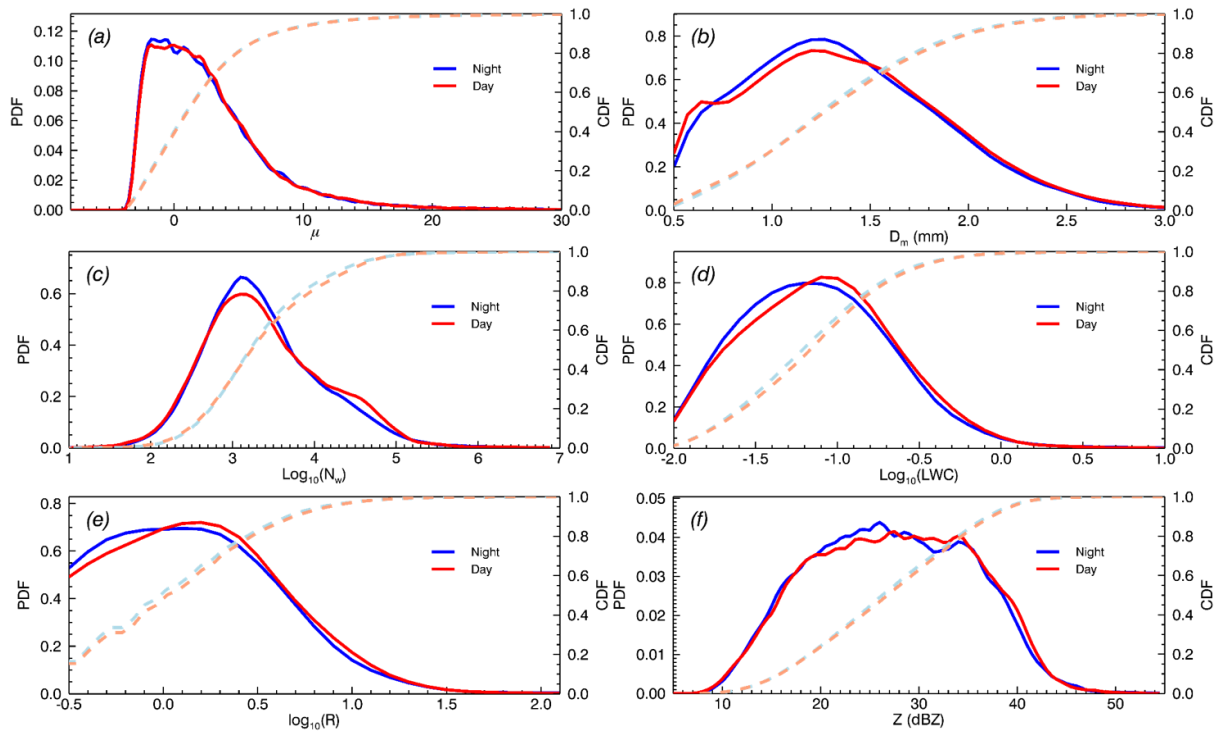
**Figure 7.**

(a) Histogram of normalized frequency of 16 wind directions for the entire study period. (b) Difference values of wind direction frequencies between DT and NT (DT - NT).



**Figure 8.**

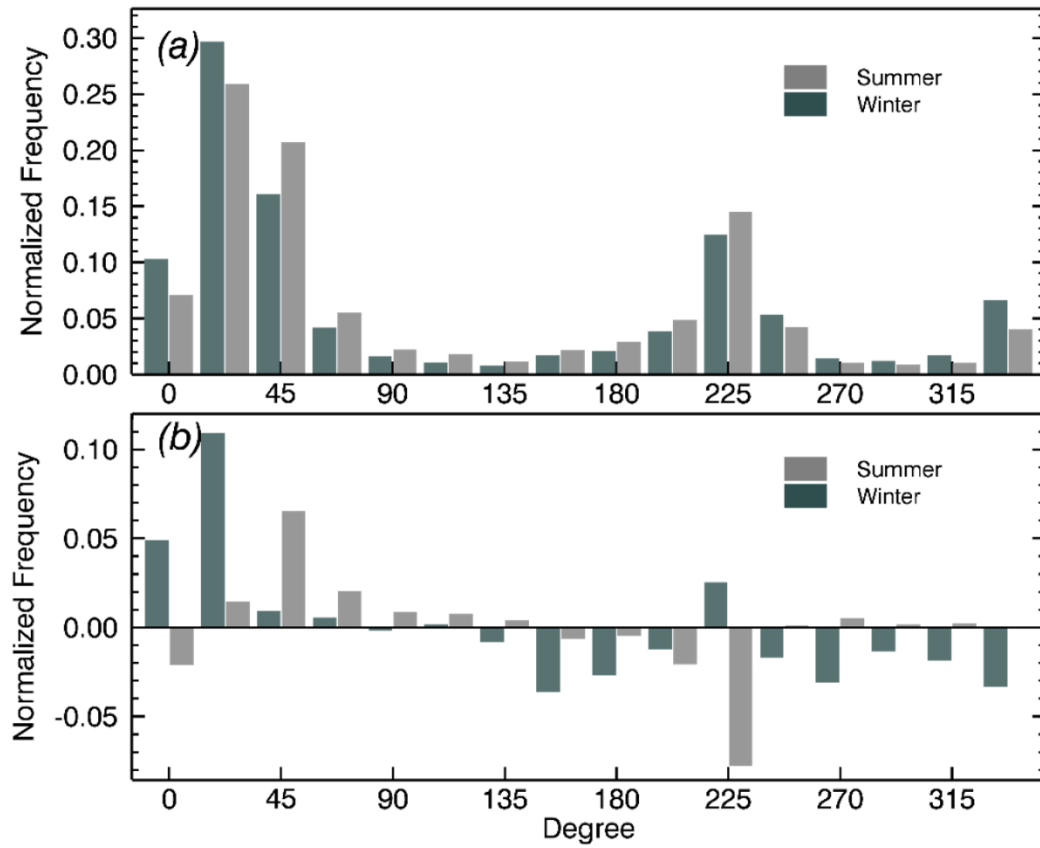
Two hour interval time series of (a)  $\mu$ , (b)  $D_m$ , (c)  $\log_{10}(N_w)$ , (d)  $\log_{10}(R)$ , (e)  $\log_{10}(LWC)$ , (f)  $Z_h$  and (g) normalized frequency of wind direction for sea wind ( $45^\circ$  to  $225^\circ$ ) with quantiles for the total period. Solid lines are quantiles for each time.



**Figure 9.**

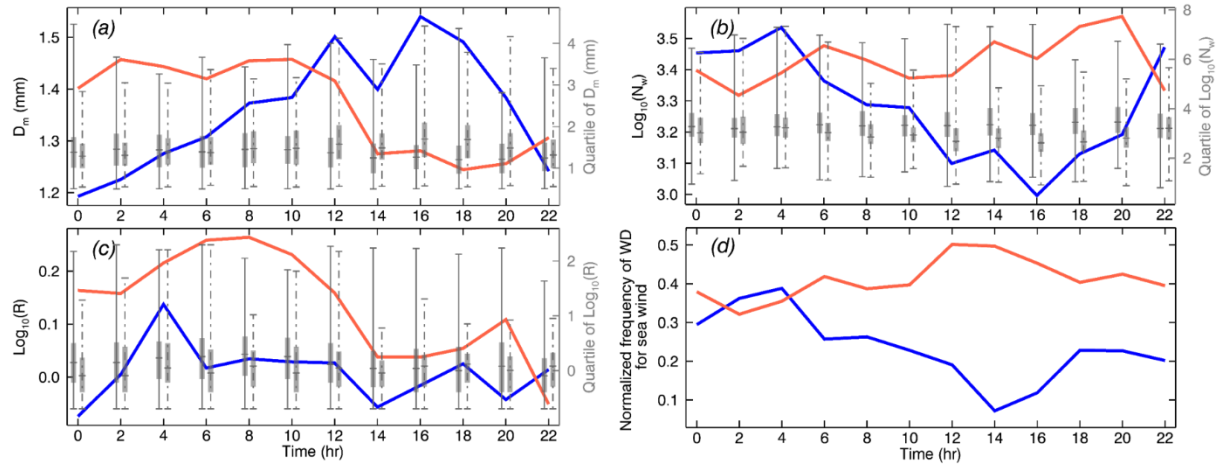
PDF and CDF curves for (a)  $\mu$ , (b)  $D_m$ , (c)  $\log_{10}(N_w)$ , (d)  $\log_{10}(R)$ , (e)  $\log_{10}(LWC)$ , and (f)  $Z$  for DT and NT according to the entire period. The solid red and blue lines represent the PDF for DT and NT, respectively. The broken light red and blue lines represent the CDF for DT and NT, respectively.





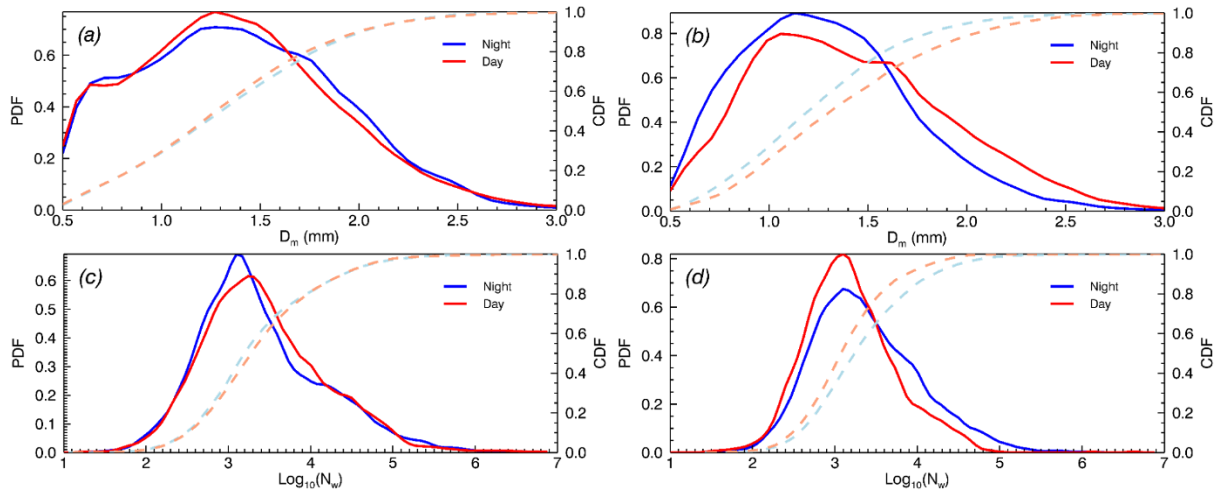
**Figure 10.**

Histogram of normalized frequency for 16 wind directions in (a) the entire period and (b) differences of normalized frequency with respect to wind directions between DT and NT (DT - NT) for Summer (light grey) and Winter (dark grey) season.



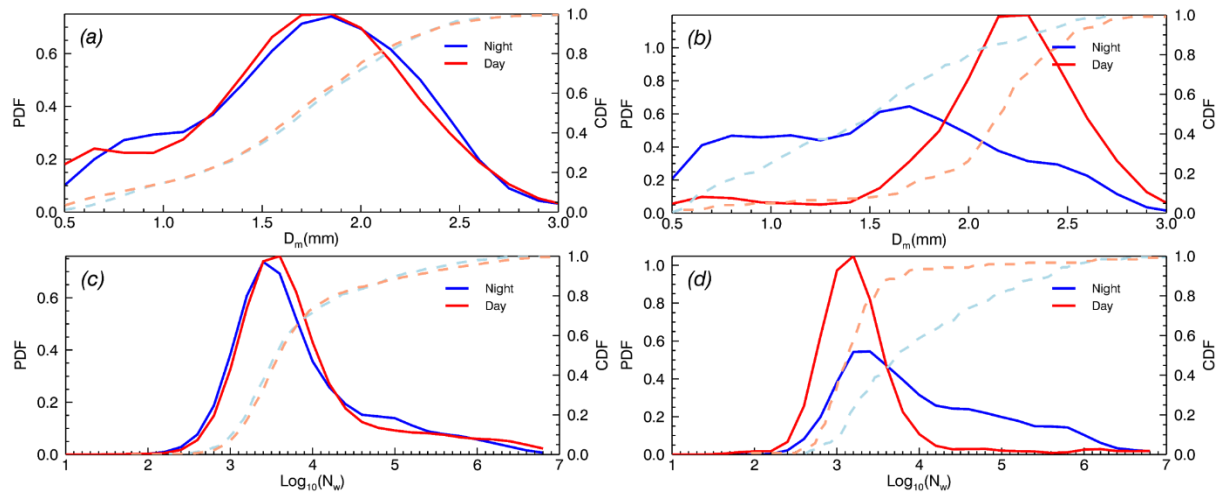
**Figure 11.**

Two hour interval time series and quartiles of (a)  $D_m$ , (b)  $\log_{10}(N_w)$  (c)  $\log_{10}(R)$  and (d) normalized frequency of wind direction for sea wind (45° to 225°) for the Summer (red) and Winter (blue) season. Solid (broken) lines are quartiles of Summer (Winter) for each time, respectively.



**Figure 12.**

PDF and CDF of (a)  $D_m$  ((b)  $D_m$ ) and (c)  $N_w$  ((d)  $N_w$ ) for the entire rainfall type in the Summer (Winter) season. Red and blue solid lines represent the PDF of DT and NT, respectively. The light red and blue broken lines represent the CDF for each season



**Figure 13.**

As in Figure 12, but for convective rainfall type.