Development of Dual-polarimetric QPE relations based on Disdrometer measurements in Metro Manila, Philippines

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Development of Quantitative Precipitation Estimation (QPE) relations for Dual-Polarization Radars based on Raindrop Size Distribution measurements in Metro Manila, Philippines

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ABSTRACT

Quantitative precipitation estimates (QPE) can be further improved using estimation algorithms derived from localized raindrop size distribution (DSD) observations. In this study, DSD measurements from two disdrometer stations within Metro Manila during the Southwest monsoon (SWM) period were used to investigate the microphysical properties of rainfall and develop localize dual-polarimetric relations for different radar bands and rainfall types. Observations show that the DSD in Metro Manila is more distributed to larger diameters compared to Southern Luzon and neighboring countries in the Western Pacific. This is reflected by the relatively higher mass-weighted mean diameter (D_m) and smaller shape (μ) and slope (Λ) parameters measured in the region. The average values of D_m and normalized intercept parameter (N_w) in convective rain samples also suggest that convective rains in Metro Manila are highly influenced by both continental and oceanic convective processes. Dual-polarimetric variables simulated using the T-matrix scattering method showed good agreement with disdrometer-derived reflectivity (Z_H) values. The 0.5 dB and 0.3° km^{-1} thresholds for the differential reflectivity (Z_{DR}) and specific differential phase (K_{DP}) based on the blended algorithm of Cifelli et al. (2011) and Thompson et al. (2017) are proven to be useful since the utility of the dual-polarimetric variables as rainfall estimators are shown to have dependencies on the radar band and rainfall type. Evaluation of the QPE products with respect to the C-band shows that R (K_{DP}, Z_{DR}) has the best performance among the dual-pol relations and statistically outperformed the conventional Marshall & Palmer relation [$R(Z_{MP})$]. The results show that dual-polarimetric variables such as Z_{DR} and K_{DP} can better represent the DSD properties compared to one-dimensional Z, hence providing more accurate QPE products than the conventional $R(Z)$ relations.

Keywords: Raindrop size distribution, Dual-polarization relations, Quantitative precipitation estimates, PARSIVEL^2 disdrometer

1. INTRODUCTION

The geographical location of the Philippines makes it susceptible to rainfall-inducing weather systems such as Tropical cyclones and Monsoons (Bagtasa, 2019; Cayanan et al., 2011). Heavy rainfall is frequently experienced in Metro Manila during the Southwest Monsoon (SWM) period (Cruz et al., 2013). The SWM, locally known as *Habagat*, brings significant amounts of rainfall during the months of June to September in the western regions of the Philippines (Matsumoto et al. 2020). Asuncion & Jose (1980) reported that 43% of the average annual rainfall in the Philippines is derived from the SWM period. While rainfall is a valuable water resource, it remains a disaster threat during extreme rainfall events (Jamandre and Narisma, 2013). It is essential, therefore, to have accurate rainfall estimates in the country, especially in the highly-urbanized area of Metro Manila. Measurements from rain gauges are usually considered to be the reference rainfall (Villarini et al., 2008). However, due to gaps in observation sites and time resolution of data, rain gauges are limited in providing accurate rainfall measurements for a wide range of areas. Satellite-derived rainfall measurements are also used to provide rain information at a global scale. However, satellite observations are not always available in real-time and are limited to lower spatial resolutions (Macuroy et al., 2021). High-quality rainfall measurements are important in numerical weather prediction models and hydrometeorological applications (Lee et al., 2019). Hence, it is necessary to have simultaneous rainfall observations with higher temporal and spatial resolution. Polarimetric weather radars are preferred over rain gauges and satellites in producing Quantitative Precipitation Estimates (QPE) because of their ability to cover a larger spatial range and provide real-time rainfall information (You et al., 2022). Weather radars estimate rainfall by measuring the resulting reflectivity (Z) scattered by raindrops within a scanning volume measured in decibels relative to Z (dBZ). One of the most common methods of retrieving rainfall from radar reflectivity is the use of Reflectivity-Rain rate ($R(Z)$) relations. The $R(Z)$ relation is often expressed as a power law ($Z = a*R^b$), wherein the values of a and b vary for different seasons, locations, and weather systems. Globally, the most used $R(Z)$ relations are the Marshall & Palmer relation ($Z=200*R^{1.6}$; Marshall & Palmer, 1948), Rosenfeld tropical relation ($Z=250*R^{1.2}$, Rosenfeld et al., 1993), and the United States WSR-88D radar network relation ($Z=300*R^{1.4}$, Ulbrich & Lee, 1999). However, using a single $R(Z)$ relation may result in inaccurate rainfall estimates since Z is highly variable for different rain types and locations (Seela et al., 2017). Hence, it is highly recommended to calibrate the $R(Z)$ relationship for a specific region in order to improve its performance in rainfall retrieval (Ji *et al.* 2019).

In addition to the conventional $R(Z)$ relations, rainfall can also be estimated from dual-polarimetric variables (will be referred to as dual-pol variables from hereon). Dual-pol relations are known to have advantages over the conventional $R(Z)$ relation (Zhang et al., 2019).

Dual-pol variables such as differential reflectivity (Z_{DR}) and specific differential phase (K_{DP}) can be used to estimate rain rate (R) with greater accuracy because they can constrain environmental factors such as signal attenuation and partial beam blocking as compared to the single-polarization Z (Thompson et al., 2018). The radar parameters being used for rainfall retrieval are related to the microphysical characteristics of rainfall thru the raindrop size distribution (DSD), which is a fundamental property of rainfall defined as the number concentration of raindrops as a function of diameter (Tapiador et al., 2010). DSD variability reflects the relative importance of governing microphysical processes such as collision-coalescence, drop break-up, evaporation, and cloud ice-water interactions (Houze, 2014). The DSD also varies with rainfall type (i.e., stratiform and convective), seasons, and topography (Thurai et al., 2016). Bringi et al. (2003) demonstrated that convective rainfall over tropical oceans is characterized by a higher number concentration of smaller raindrops ($D < 1$ mm) compared to continental locations. Moreover, Seela et al. (2018) and Zeng et al. (2019) reported relatively larger raindrops during the summer monsoon compared to the winter monsoon in Northern Taiwan and the South China Sea, respectively. Marzuki et al. (2013) and Seela et al. (2017) also reported terrain-induced convection resulting to drop size enhancements in Indonesia and Taiwan, respectively. More recently, Ibanez et al. (2023) reported larger raindrops in Clark, Pampanga compared to Metro Manila, which also demonstrates the effects of terrain-enhanced convections on the DSD.

In terms of radar applications, DSD measurements are of great importance in having accurate rainfall retrievals since Z is proportional to the sixth moment of the raindrop diameter (Hachani et al., 2017; Wu et al., 2018). Disdrometers are commonly paired with weather radars as they can explicitly measure the fall velocities and diameter of precipitation. (Tokay *et al.* 2013; Thompson *et al.* 2015). Integral rainfall parameters (IRPs) such as rain rate (R, mm hr^{-1}), total number concentration (N_t, m^{-3}), liquid water content (LWC, g m^{-3}), and reflectivity factor (Z, mm^{-6} m^{-3}) can also be derived from disdrometer measurements (Angulo-Martinez et al., 2018). You et al. (2018) derived dual-pol parameters and relations for different rainfall events in a coastal area in Korea using an optical disdrometer. It was found that using a linear ensemble method composed of $R(Z, Z_{DR})$ and $R(K_{DP})$ provided more accurate QPE than the conventional $R(Z)$ relation. The applicability of Z_{DR} and K_{DP} for tropical oceanic rain also was studied by Ciffeli et al. (2011) (hereinafter C11) by creating a blended QPE algorithm based on continental convection in Colorado. Thompson et al. (2015, 2018) (hereinafter TH15 and TH18, respectively) hypothesized that smaller raindrops observed in the Tropical oceans resulted in lower values of Z_{DR} and K_{DP} for a given LWC. Hence, TH18 lowered the threshold values of C11 for Z_{DR} in order to utilize it and explore precipitation in the Tropical Ocean. Previous radar QPE studies in the Philippines used pre-calculated values derived from other areas (Heistermann et al., 2013; Crisologo et al., 2014). The recent study of Macuroy et al. (2021) (will be referred to as MC21 from hereon) was the first study in the country to derive dual-pol parameters from DSD measurements using an optical disdrometer during the wet period in Southern Luzon. Results showed that although the $R(Z)$ relation performed well in terms of correlation and root mean square error, the $R(K_{DP})$ relation statistically outperformed other relations and exhibited the most accuracy in providing QPE. However, the results of the study are only limited to a single radar wavelength (i.e., C-band) and do not necessarily reflect the optimal QPE relations and DSD properties for other regions in the Philippines. Notably, the DSD properties and their application in calibrating dual-pol rainfall relations are rarely explored for Metro Manila.

In this study, the DSD characteristics in Metro Manila during the SWM period were investigated using measurements from two optical disdrometers installed in Science Garden and La Mesa watershed, Quezon City. The impacts of DSD variability on dual-pol parameters were also investigated in order to develop dual-pol rainfall estimators for S-, C-, and X-band radars using the T-matrix method (Waterman 1971; Mishchenko et al., 1996). In light of the modernization program of the country's weather bureau (i.e., Philippine Atmospheric, Geophysical, and Astronomical Services Administration or PAGASA), the DSD properties and rainfall estimators for different radar bands presented in this study can serve as a reference in optimizing the disdrometer and dual-pol radar network in different parts of the country. This study is organized as follows. Section 2 provides a brief discussion of the study site and data, which includes data cleaning and processing, and the calculation of IRPs and dual-pol radar parameters. The effects of DSD variability on the resulting radar parameters and rainfall estimators, as well as the utility of the dual-pol relations in different radar bands and rain types, are discussed in Section 3. Finally, Section 4 summarizes the results and provides the conclusion.

2. DATA AND METHODS

2.1. Instrumentation, Data set, and Study Site

The DSD measurements during the wet period in Metro Manila (i.e., June-September) from 2020 to 2022 are collected from the 2nd-generation Particle Size Velocity Disdrometer (hereafter referred to as PARSIVEL^2 disdrometer) installed in Science Garden, Quezon City (14.6° N, 121.04° E, 48 m.a.s.l.) and in La Mesa watershed, Quezon City (14.7° N, 121.07° E, 65 m.a.s.l.) (Figure 1).

The PARSIVEL^2 is an optical disdrometer that simultaneously measures the size and fall velocities of precipitation with a 1-minute sampling interval. However, due to limitations in data transmission, the disdrometers used in this study were programmed to average the 1-minute DSD measurements into 5-minute samples. The measured raindrop diameter and fall velocities are stored in 32 x 32 diameter-velocity (D-V) bins with uneven intervals ranging from 0.062 to 24.5 mm and 0.05 to 20.8 m s^{-1}, respectively. The first two bins that correspond to sizes less than 0.25 mm are left empty by the manufacturer because of the low signal-to-noise ratio (Loffler-Mang & Joss, 2000). The $PARSIVEL^2$ disdrometer is preferred over other disdrometer types and its first version model because of its better agreement with rain gauges and improved accuracy in measuring smaller raindrops (Tokay et al., 2014). To reduce sampling errors, the DSD measurements underwent data quality control (QC) procedures following the methods of previous studies (Seela et al., 2017; Angulo-Martinez et al., 2018). The QC procedure includes the removal of the following: (1) raindrops with diameters greater than 8 mm, (2) raindrops that have diameter and fall velocity values outside the 50% spread of the theoretical D-V curve of Beard (1976), and (3) DSD measurements corresponding to rain rates less than 0.1 mm hr^{-1} and number concentration less than 10 m^{-3}. 5-minute DSD samples within the 1000 km effective radius of tropical cyclones (TCs) were also not included in the analysis as TC-induced rainfall is known to have different microphysical properties (Janapati et al., 2021). It was also reported by Ibanez et al. (2023) that there are no pronounced differences in the DSD properties observed between Science garden and La Mesa watershed, hence the DSD measurements from the two disdrometer stations were combined. After the QC procedure, a total of 6,850 valid DSD samples were collected from the two stations.

2.2. DSD and Integral rainfall parameters (IRPs)

The raindrop concentration per unit volume $N(D_i)$ can be calculated from the $PARSIVEL^2$ disdrometer using the equation

$$N(D_i) = \sum_{i=1}^{32} \frac{n_i}{v(D_i)At\Delta D_i} \tag{1}$$

where $v(D_i)$ is the raindrop fall velocity in m s^{-1}, D_i is the raindrop diameter in mm, A is the sampling area (A = 0.0054 m^2), t is the sampling time (5 minutes = 600s), and ΔD_i is the width of the i^{th} diameter bin. The terminal velocity $v(D_i)$ is approximated using the theoretical D-V curve equation of Beard K.V. (1976) given by:

$$v(D_i) = 9.58\left[1 - exp\left(-\left(\frac{D_i}{0.171}\right)^{1.147}\right)\right] \tag{2}$$

The Integral rainfall parameters derived from the DSD, such as rain rate R (mm hr^{-1}), liquid water content LWC (g m^{-3}), total number concentration N_t (m^{-3}), and reflectivity factor Z (mm^6 mm^{-3}) are calculated from $N(D)$, D_i, and $v(D_i)$ using the following equations:

$$R = 6\pi \times 10^{-4} \sum_{i=1}^{32} v(D_i)N(D_i)D_i^3 \Delta D_i \tag{3}$$

$$LWC = \frac{\pi}{6000} \sum_{i=1}^{32} N(D_i)D_i^3 \Delta D_i \tag{4}$$

$$N_t = \sum_{i=1}^{32} N(D_i)\Delta D_i \tag{5}$$

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

The DSDs are parameterized using the widely used Gamma model (Ulbrich 1983) expressed as

$$N(D) = N_0 D^{\mu} exp(-\Lambda D) \tag{7}$$

Where N_0 is the number concentration parameter, μ is the shape parameter, and Λ (mm^{-1}) is the slope parameter. The gamma parameters were calculated using the method of moments expressed as

$$M_n = \int_{D_{min}}^{D_{max}} D^n N(D) dD \tag{8}$$

Where n stands for the nth moment of the DSD. A combination of 3.67th, 4^{th,} and 6th moments based on MC21 was used to calculate the gamma parameters using the following equations:

$$\mu = \frac{11G-8+\sqrt{G(G+8)}}{2(1-G)}, \tag{9}$$

$$\Lambda = \frac{(\mu+4)M_{3.67}}{M_4}, \tag{10}$$

$$N_0 = \frac{\Lambda^{\mu+4} M_{3.67}}{\Gamma(\mu+4)} \tag{11}$$

Where:

$$G = \frac{M_4^3}{M_{3.67}^2 M_6^1} \tag{12}$$

The mass-weighted mean diameter D_m (mm) is also computed using the 4th and 3rd DSD moments:

$$D_m = \frac{M_4}{M_3} \tag{13}$$

The normalized intercept parameter N_w (m^{-3} mm^{-1}), which represents the DSD when *N(D)* approaches the minimum value, is defined by Seela *et al.* (2017) as

$$N_w = \frac{4^4}{\pi\rho_w}\left(\frac{10^3 LWC}{D_m^4}\right) \tag{14}$$

Where ρ_w is the density of water (1×10^3 kg m^{-3}).

2.3. Derivation of dual-polarimetric variables

The dual-pol parameters were derived from the DSD using the openly available PyDSD python package (Hardin, 2014). The PyDSD makes use of disdrometer data to retrieve dual-pol parameters (i.e., Z_H, Z_{DR}, and K_{DP}) using the Mueller/T-matrix scattering method (Mishchenko et al., 1996). The process flow of implementing the T-matrix method using the PyDSD package is shown in Figure A1 in the Appendices. To estimate the dual-polarization parameters using the T-matrix method, conditions such as axis ratio, canting angle distribution, raindrop temperature, diameter range, and corresponding radar frequency and elevation angle must be given. Using the proposed values in MC21, the raindrop temperature was set to be 20°C, the raindrop's axis ratio was assumed to be oblate, the diameter range was from 0.1 mm to 8 mm, the average canting angle distribution was taken to be 0°, and the elevation angle was set to 0.5°. The dual-pol parameters were calculated for S, C, and X bands with frequencies 2.80Ghz, 5.61Ghz, and 9.67Ghz respectively.

The Z_h and Z_v, which correspond to the reflectivity factors in the horizontal and vertical polarization in dBZ, were calculated using the equation:

$$z_{H,V} = 10log \tag{15}$$

Where λ is the radar wavelength in mm, $\sigma_{H,V}(D)$ is the backscattering cross section for horizontal or vertical polarization and K_w is the dielectric constant of water at 20°C (80.4). The quantities Z_H and Z_V are dependent on the drop diameter D^6 and number concentration *N (D)* (see equation 6). The differential reflectivity (Z_{DR}), which is the logarithmic ratio of Z_H and Z_V expressed in dB (Seliga & Bringi, 1976), is expressed as

$$Z_{DR} = 10log\frac{Z_H}{Z_V} \tag{16}$$

The quantity Z_{DR} is zero for spherical drops and increases as the raindrop become more oblate, which usually happens as $D > 1$ mm. The specific differential phase (K_{DP}), expressed in ° km^{-1}, can be calculated using the equation:

$$K_{DP} = \frac{180}{\pi} \lambda \int_{Dmin}^{Dmax} \quad \Re \tag{17}$$

Where $f_{hh,vv}$ represents the real parts of the forward scattering amplitude for the horizontally and vertically polarized waves (Vivekanandan et al., 1991). K_{DP} is directly proportional to the LWC and oblateness of the raindrop, and inversely proportional to the radar wavelength; hence K_{DP} is higher at X-band than S-band.

The dual-pol relations, $R(Z_h)$, $R(K_{DP})$, $R(Z_H, Z_{DR})$, and $R(K_{DP,} Z_{DR})$ chosen for this study are expressed as

$$R(Z_H) = aZ_H^b \ , \tag{18}$$

$$R(K_{DP}) = aK_{DP}^b \ , \tag{19}$$

$$R(Z_H, Z_{DR}) = aZ_H^b Z_{DR}^C \ , \tag{20}$$

$$R(K_{DP}, Z_{DR}) = aK_{DP}^b Z_{DR}^C \ , \tag{21}$$

This study also uses the rain version of the blended optimization algorithm from TH18 and C11 which determines the rain estimators used according to the following data quality thresholds

$R(Z_H)$ if $Z_{DR} < 0.5$ dB and $K_{DP} < 0.3$°km^{-1}

$R(Z_H, Z_{DR})$ if $Z_{DR} > 0.5$ dB and $K_{DP} < 0.3$°km^{-1}

$R(K_{DP})$ if $Z_{DR} < 0.5$ dB and $K_{DP} > 0.3$°km^{-1} and $Z_H > 38$ dB

$R(K_{DP}, Z_{DR})$ if $Z_{DR} > 0.5$ dB and $K_{DP} > 0.3$°km^{-1}

Although these thresholds are optimized for S-band radars, they are designed to be wavelength independent (TH18). Hence, the algorithms can still be used for C- and X-band radars.

2.4. Statistical evaluation of the derived dual-pol relations

The rainfall values derived from the various relations (R_{est}) in equations (18) to (21) were compared to the rainfall rate retrieved from the DSD measurements (R_{DSD}) (i.e., considered as "ground truth"). In order to evaluate their QPE performance, four statistical validation variables were used in this study, namely: Pearson's correlation coefficient (r), percent bias (pBias), mean error (ME), and root-mean-square error (RMSE).

$$Pearson's(r) = \frac{\sum_{i=1}^{n} \left(R_{DSD} - \underline{R_{DSD}}\right) - \left(R_{est} - \underline{R_{est}}\right)}{\sqrt{\sum_{i=1}^{n} \left(R_{DSD} - \underline{R_{DSD}}\right)^2 \sum_{i=1}^{n} \left(R_{est} - \underline{R_{est}}\right)^2}}$$

(22)

$$Meanerror(ME) = \frac{\sum_{i=1}^{n} (R_{est} - R_{DSD})}{n} \quad (23)$$

$$Rootmeansquareerror(RMSE) = \sqrt{\frac{\sum_{i=1}^{n} (R_{est} - R_{DSD})^2}{n}} \quad (24)$$

$$Percentbias(pBIAS) = \frac{\sum_{i=1}^{n} (R_{est} - R_{DSD})}{\sum_{i=1}^{n} (R_{DSD})} * 100\%$$

(25)

r and *NSE* are dimensionless, *ME* and *RMSE* are in mm hr^{-1}, and *pBias* is expressed as a percentage.

3. RESULTS AND DISCUSSIONS

3.1. Average DSD characteristics

The average and gamma-fitted DSD during the SWM season in Metro Manila are shown in Figure 2. The number concentration (*N(D)*) in the y-axis is expressed in a logarithmic scale to account for large variations. The vertical dashed lines represent the raindrop size classification proposed by Krishna et al. (2016). Raindrops with diameters $D < 1$ mm are considered small, $1 \leq D < 3$ mm are midsize, and $D >$ 3 mm are large. There is a good agreement between the observed and gamma-fitted DSD. Similar to the values reported by Ibanez et al. (2023), the average mass-weighted mean diameter (D_m) of the total rainfall in Metro Manila during the SWM period (D_m = 1.53 mm) is slightly higher than the value reported in MC21 in Southern Luzon (D_m = 1.45 mm) and relatively larger than the values reported by Seela et al. (2017) in Taiwan (1.24 mm) and in Palau (1.11 mm). To further investigate the DSD variability in Metro Manila, the DSD dataset was categorized into stratiform and convective rainfall types using a rain intensity (*R*) threshold of 10 mm hr^{-1}. DSD measurements corresponding to $R \leq 10$ mm hr^{-1} were considered stratiform, while $R > 10$ mm hr^{-1} were considered convective (Banares et al. 2021). Stratiform and convective rainfall is different in terms of cloud vertical structure and particle growth processes. Hence, their DSD properties were also observed to be distinct (Tokay & Short, 1996; Tao et al., 2010). The mean values of the integral rainfall parameters (IRPs) and the shape (μ) and slope (Λ) parameters for stratiform and convective rainfall are shown in Table 1. Results show that stratiform rains generally have lower values of D_m and higher values of $\mathrm{Log}_{10}\, N_w$ than convective rains. The higher standard deviation (SD) of D_m during convective rains (SD = 0.57) compared to stratiform (SD = 0.28) is a clear function of R, while the higher SD of $\mathrm{Log}_{10}\, N_w$ in stratiform (SD = 0.53) compared to convective rains (SD = 0.38) is due to different microphysical processes (Bringi et al. 2003, Houze, 2014). Stratiform clouds with low concentrations of relatively large ice particles aloft result in DSD with relatively lower $\mathrm{Log}_{10}\, N_w$ and larger D_m. In radar observations, stratiform clouds exhibit a pronounced layer of high reflectivity called the bright band. The bright band is the layer where the downwards-settling ice particles start to melt (Yuter & Houze, 1997). On the other hand, stratiform clouds with smaller ice particles aloft undergo complete melting (i.e., the bright band is not pronounced) before reaching the surface, resulting in DSD with high $\mathrm{Log}_{10}\, N_w$ and smaller D_m. Both stratiform cloud conditions are present during the SWM period and can be seen in most stratiform rain samples with mid-sized drops (1 mm $< D_m \leq 3$ mm). Figure 3 also shows that the stratiform and convective rain samples during the SWM period in Metro Manila followed the c-s separation line proposed by Bringi et al. (2003). Moreover, convective samples that coincide with the maritime (MC) and continental (CC) clusters of Bringi et al. (2003, 2009) are both present during the SWM period. However, a higher percentage of convective samples, particularly those with larger D_m values, fall within the CC cluster more than the MC cluster.

3.2. Characteristics of DSD-derived dual-pol variables

The Z_H derived from the disdrometer and the Z_H simulated using the T-matrix method in different radar bands and rain types are compared in Figure 4. Results show that the disdrometer-derived Z_H shows good agreement with those derived by T-matrix in all radar bands, with r above 0.9. This shows that the T-matrix method is an effective tool for retrieving dual-pol radar parameters from DSD measurements. Figure 5 shows the frequency distribution of simulated Z_H, Z_{DR}, and K_{DP} for different radar bands. The frequency distribution of dual-pol parameters in Figure 5a shows that the simulated Z_H values did not exceed 60 dBZ in all radar bands. Although S-band has a slightly higher frequency at $Z_H \geq 25$ dBZ, all radar bands' mean values are notably close to ~29 dBZ. The Z_{DR} peaks at ~0.4 dB in all radar bands but is ~2-3% higher at Z_{DR} >1.4 dB for X-band (Figure 5b). The vertical broken lines in Figures 5b and 5c depict the threshold values for Z_{DR} and K_{DP} adopted from the study of C11. In the study of TH18, the Z_{DR} threshold was lowered from 0.5 dB to 0.25 dB as they observed that conditions needed to exceed the 0.5 dB threshold were rare for tropical oceanic rains. However, this is not the case in this study since ~55% of the simulated Z_{DR} values in all radar bands exceed 0.25 dB. Hence, this study retained the 0.50 dB thresholds for Z_H and 0.3° km^{-1} for K_{DP}. A lower Z_{DR} threshold of 0.5 dB would also increase the utility of Z_{DR} for rainfall estimation while remaining above the accepted noise level (Z_{DR} > 0.1 dB; Ryzhkov et al. 2005). ~67% of K_{DP} values are found at K_{DP} < 0.1° km^{-1} in all radar bands while higher frequencies are found for X-band at K_{DP} > 0.1° km^{-1}(Figure 5c). Although a 0.3° km^{-1} threshold for K_{DP} seems restrictive, lowering it is no longer practical for most radar QPE applications because of phase instability (TH18). The 2D histogram plots of simulated dual-pol parameters in Figure 6 also help visualize the difference between the dual-pol relations and the frequency of when they are utilized for different radar bands. In general, an increase in the use of dual-pol parameters (i.e., Z_{DR} and K_{DP}) can be observed with the increase in radar frequency. The bulk of the data points is found in the lower left quadrant of the 2D histogram for all radar bands. By following the blended algorithm of C11, this scenario suggests that $R(Z_H)$ is the most suitable QPE relation for S-band radars. Increased frequency of data points in the upper right quadrant is found for C- and X-band radars (Figure 6b & 6c), which suggests the option for $R(K_{DP})$ and $R(K_{DP}, Z_{DR})$ for QPE. To further elaborate on the effect of DSD variation on the utility of dual-pol relations, the average values of dual-pol variables in different radar bands and rainfall types are shown in Table 2. The average values of Z_H are similar for stratiform (26.4 dBZ) and convective rainfall (46.4 dBZ) in all radar bands except for the X-band which is found to be a little higher during convective rains (48 dBZ).

The average Z_{DR} values for convective rainfall are also higher than stratiform rainfall in all bands. Compared to stratiform rainfall, convective types have higher Z_H, Z_{DR}, and K_{DP}. This demonstrates that raindrops during convective rainfall are relatively larger in size than those of stratiform rainfall, hence the greater difference between Z_H and Z_V which results in larger diameter and more shape deformation. This is also consistent with the larger average D_m of convective rainfall in Table 1.Since K_{DP} is directly related to the liquid water content (*LWC*) and total number concentration (N_t) (Tang et al., 2004), the K_{DP} of convective rainfall is also higher compared to stratiform rainfall in all radar bands. This observation is also consistent with the higher *LWC* and N_t of convective rainfall in Table 1.

The sudden peak of Z_{DR} at Z_H > ~ 38 dBZ in stratiform rainfall (Figure 7a) could be a result of relatively larger raindrops and can also be a suggestive signal of the 38 dBz threshold for stratiform-convective separation regime (Gamache and Houze, 1981). For convective rainfall, C-band has the largest Z_{DR} values while a higher percentage of simulated Z_H exceeding 55 dBZ is found for X-band (Figure 5b). Unlike stratiform rainfall types, the DSD and dual-pol variables during convective rains exhibit more variation across different locations (Bringi et al. 2003). The values of simulated Z_{DR} and Z_H for convective rainfall are found to be more continental in nature, hence the higher magnitude compared to the dominantly oceanic DSD properties in TH18 (Figure 7b). The differences between maritime and continental DSDs in the tropics can be explained using the observed differences in the Z_{DR} vs. Z_H distributions. Compared to maritime convection, continental convection has stronger updrafts and more dominant ice microphysical processes, resulting in the formation of graupel and hail that can melt and reach the surface as larger raindrops (Marzuki et al., 2013). Large DSDs with lower N_w would lead to larger Z_H and Z_{DR} (TH18). Moreover, the continental convective cluster of DSDs in the tropics, as defined by Bringi et al. (2003), is more prone to evaporation below the cloud base which can reduce small raindrops and increase the Z_{DR}.

The distribution of Z_{DR} and K_{DP} in Figure 8 shows that a considerable percentage of both stratiform and convective samples met the 0.50 dB threshold for Z_{DR}. This motivates the option to use $R(Z_H, Z_{DR})$ for QPE. However, most stratiform DSD samples did not meet the 0.3° km^{-1} K_{DP} threshold, especially for the S-band (Figure 8a). Furthermore, Figure 8 also illustrates that DSD samples with $K_{DP} > 0.3°$ km^{-1} are always associated with $Z_{DR} > 0.5$ dB in all radar bands and rain types. Similar observations were reported in TH18, but for a lower threshold of $Z_{DR} > 0.25$ dB. Based on the distribution of simulated dual-pol variables, the Z_{DR} and K_{DP} thresholds adopted from the studies of C11 and TH18 suggest that $R(Z_H)$ and $R(Z_H, Z_{DR})$ relations are for stratiform rain types ($R <$ 10 mm hr^{-1}), while $R(K_{DP})$ or $R(K_{DP}, Z_{DR})$ can be utilized for convective rain types ($R \geq$ 10 mm hr^{-1}).

3.3. Evaluation of derived dual-polarimetric relations

Results discussed in Section 3.2 clearly demonstrated the applicability of dual-pol parameters on QPE differs for different DSD properties and radar bands. Table 3 presents the derived dual-pol relations for different radar bands and rain types during the SWM period in Metro Manila. It can be observed that coefficient a in $R(K_{DP})$ and $R(K_{DP}, Z_{DR})$ are larger compared to $R(Z_H)$ and $R(Z_H, Z_{DR})$ in all radar frequencies and rainfall types. The coefficient a in $R(K_{DP})$ and $R(K_{DP}, Z_{DR})$ derived from the total rainfall decreases as the radar frequency increases from S-band to X-band, while the coefficient c has a negative value for all rainfall types in order to constrain the positive correlation of Z_H and K_{DP} to R (TH18). It can also be noticed that there were no derived $R(Z_H)$ and $R(Z_H, Z_{DR})$ relations for convective rainfall in X-band. This is due to the implementation of K_{DP} and Z_{DR} thresholds of C11 and TH18 as discussed in section 3.2. In comparison with MC21, the $R(K_{DP})$ obtained in this study have similar values of a but slightly higher values of b

compared to MC21 (a = 21.18, b =0.71). In terms of $R(Z_H, Z_{DR})$, MC21 reported a relatively lower value of a, and higher values of b and c (a = 0.0025, b = 0.9340, c = -0.86). Finally, the $R(K_{DP}, Z_{DR})$ found in this study also has similar b but different a and c values compared to MC21 (a =31.27, b = 0.95, c = -0.70). The differences in the obtained dual-pol relations in Metro Manila and Southern Luzon show distinct DSD properties between the two regions despite being affected by a similar synoptic system during the SWM period. These observations also show the need to implement localized QPE relations for Metro Manila.

Rainfall data from the Science Gardena and La Mesa watershed disdrometer stations were used to evaluate the performance of the relationships. For this section and the succeeding discussions, the dual-pol relations will have the subscripts TOT, STR, and CNV which correspond to the derived relationships for the total, stratiform, and convective rainfall, respectively. The scatterplots of the observed rain rates with those derived from the dual-pol relationships for the C-band radar are shown in Figure 9. A significant improvement in the statistics was observed when the relationship is changed from the classic $R(Z_H)_T$ to $R(Z_{DR})_{\mathrm{T}}$ and $R(K_{DP})_{\mathrm{T}}$ or a combination of K_{DP} and Z_{DR}. The same improvements were observed for the S- and X-band but were not shown here. $R(K_{DP})_{\mathrm{T}}$ and $R(K_{DP}, Z_{DR})_{\mathrm{T}}$ significantly reduced the ME and RMSE when compared to $R(Z_H)_T$ which suggests that the relationship between R and K_{DP} is more linear in nature. Furthermore, $R(K_{DP}, Z_{DR})_{\mathrm{T}}$ statistically outperformed the other dual-pol relation and shows that a multiparameter relation can significantly lower the errors and biases in the rainfall estimates. To evaluate the performance of the derived dual-pol relations in generating QPEs, two continuous rain events in Metro Manila during the study period were chosen as test cases. For future operational purposes, only the dual-pol relations derived for the C-band Radar will be evaluated in the next sub-sections since the nearest dual-pol Radar in Metro Manila operates in C-band. The performance of each dual-pol relation is discussed in the succeeding sub-sections.

3.4.1. Event 1: *24 June 2021 heavy rainfall*

Event 1 was recorded by the Science Garden disdrometer station and lasted for ~2 hrs with an average R of 8.58 mm hr^{-1}. The highest R were recorded between 12:05 - 12:30 UTC and 13:20 - 13:45 UTC with maximum values of 33.6 mm hr^{-1} and 42 mm hr^{-1}, respectively. The average mass-weighted mean diameter (D_m) recorded during the entire event was 1.83 mm. Figure 10 shows the time series and scatter plots o R derived from the Science Garden disdrometer station and from the dual-pol relations. The standard Marshall & Palmer ($R(Z_{MP})$) relation (Z = 200$R^{1.6}$) was also used for comparison. The time series shows similar troughs and peaks throughout the rain event (Figure 10a). However, large discrepancies were observed during high rain rate periods between 12:00 - 12:30 UTC and 13:10 - 13:50 UTC. $R(Z_{MP})$ and $R(Z_H)_{\mathrm{Tot}}$ generally overestimate rainfall with a pBias of (+)29% and (+)39%, respectively. Meanwhile, $R(Z_H, Z_{DR})_{\mathrm{TOT}}$

is observed to underestimate rainfall by (-)27%. Among the relationships, $R(K_{DP})_{\mathrm{TOT}}$ and $R(K_{DP}, Z_{DR})_{\mathrm{TOT}}$ performed relatively better compared with other dual-pol relations, with r values of 0.96 and 0.99, respectively (Figure 10 b). $R(K_{DP})_{\mathrm{TOT}}$ and $R(K_{DP}, Z_{DR})_{\mathrm{TOT}}$ also statistically outperform all other Z_H-based QPEs in terms of RMSE [2.63 mm hr^{-1} and 1.48 mm hr^{-1}, respectively], ME [0.49 mm hr^{-1} and 0.58 mm hr^{-1}, respectively], and pBias [(+)5.43% and (+)6.32%, respectively]. Since Event 1 is a heavy rainfall event, the QPE products of dual-pol relations for convective rain are also evaluated in Figures 10c and 10d. Results show that both $R(Z_H)_{\mathrm{C}}$ and $R(Z_H, Z_{DR})_{\mathrm{C}}$ generally underestimated the rainfall, while $R(K_{DP})_{\mathrm{CNV}}$ and $R(K_{DP}, Z_{DR})_{\mathrm{CNV}}$ outperformed all dual-pol QPEs. In fact, $R(K_{DP})_{\mathrm{CNV}}$ and $R(K_{DP}, Z_{DR})_{\mathrm{CNV}}$ performed better than $R(K_{DP})_{\mathrm{TOT}}$ and $R(K_{DP}, Z_{DR})_{\mathrm{TOT}}$ in terms of all the statistical validation parameters. This can be easily observed by comparing the fitted lines of $R(K_{DP})_{\mathrm{T}}$ and $R(K_{DP}, Z_{DR})_{\mathrm{T}}$ in Figure 10b to the linear regression fit of $R(K_{DP})_{\mathrm{C}}$ and $R(K_{DP}, Z_{DR})_{\mathrm{C}}$ in Figure 11b. $R(K_{DP})_{\mathrm{CNV}}$ and $R(K_{DP}, Z_{DR})_{\mathrm{CNV}}$ also significantly reduced the RMSE [1.9 mm hr^{-1} and 1.05 mm hr^{-1}, respectively], ME [-0.097 mm hr^{-1} and 0.059 mm h^{-1}, respectively], and pBias [(-)1.14% and (+)0.68%, respectively] compared to $R(K_{DP})_{\mathrm{TOT}}$ and $R(K_{DP}, Z_{DR})_{\mathrm{TOT}}$.

3.4.2. Event 2: *19 July 2021 stratiform rain*

Event 2 was recorded by the La Mesa watershed disdrometer station. The rainfall event lasted for ~3 hrs and 30 mins. with an average R of 1.5 mm hr^{-1}. The maximum R = 7.97 mm hr^{-1} was observed at the beginning of the rain event around 17:15 UTC. The average mass-weighted mean diameter (D_m) recorded during the entire event was 1.23 mm. Compared to Figure 10a, $R(Z_H)_{\mathrm{TOT}}$ performed relatively better in stratiform than convective rainfall events. Although $R(Z_H)_{\mathrm{TOT}}$ has a slight overestimation, it still has lower pBias [(+)16%] and ME (0.29 mm hr^{-1}) compared to the $R(Z_{MP})$ [pBias = (+)21%, ME=0.4 mm hr^{-1})]. On the other hand, $R(Z_H, Z_{DR})_{\mathrm{TOT}}$ performed relatively better in Event 1 than here in Event 2 as it generally overestimated R having an RMSE = 1.62 mm hr^{-1} and pBias = (+)46.7%. $R(K_{DP})_{\mathrm{TOT}}$ also performed relatively poorer here in Event 2 and underestimated R (Figure 11b) having a pBias = (-)42% and ME = -0.44 mm hr^{-1}. $R(K_{DP}, Z_{DR})_{\mathrm{TOT}}$ statistically outperformed the other dual-pol relations having the lowest RMSE = 0.16 mm hr^{-1}, ME = -0.1 mm hr^{-1} and pBias = -7.4%. $R(K_{DP}, Z_{DR})_{\mathrm{TOT}}$ was able to capture the rainfall peaks better compared to the other dual-pol relations. $R(Z_H)_{\mathrm{STR}}$ provided the best statistics in Figures 11c and 11d in terms of the stratiform dual-pol relations. Similar to Figure 11a, $R(K_{DP})_{\mathrm{STR}}$, $R(Z_H, Z_{DR})_{\mathrm{STR}}$, and $R(K_{DP}, Z_{DR})_{\mathrm{STR}}$ failed to capture most of the rainfall peaks and overestimated R. $R(Z_H)_{\mathrm{STR}}$ also outperformed $R(Z_{MP})$ in terms of lower RMSE, ME, and pBias. The results presented in Events 1 and 2 show that K_{DP} and Z_{DR} can provide a more accurate QPE under heavy rain conditions compared to Z_H, while Z_H can still be considered a better estimator for light rains compared to $R(Z_{MP})$. All in all, $R(K_{DP}, Z_{DR})$ has the best performance in both convective and stratiform rain events. These findings agree with other dual-pol studies that $R(K_{DP})$ and $R(K_{DP}, Z_{DR})$ result in better rainfall estimates compared to conventional single-parameter relations (Chen et al., 2017; Voormansik et al., 2020) and further prove the effectivity of the threshold-based utilization of K_{DP} and Z_{DR} in C11 and TH18.

4. SUMMARY AND CONCLUSION

In this study, the three-year worth of DSD data collected from the Science Garden and La Mesa watershed disdrometer stations during the Southwest monsoon (SWM) period were used to investigate the microphysical characteristics of rainfall in Metro Manila and develop QPE relations for S-, C-, and X-band dual-polarimetric radars. The DSD characteristics during the SWM period are discussed and the performance of the QPE relations is also evaluated. The major conclusions are as follows.

1 The observed DSD characteristics in Metro Manila show higher variability in terms of raindrop sizes compared to neighboring countries such as Taiwan and Palau (Seela et al., 2017). The smaller values of μ and Λ parameters in Metro Manila during the SWM period also indicate that despite the similarities in D_m and N_w values in Southern Luzon (Macuroy et al., 2021), Metro Manila DSD is still more distributed to larger raindrops. A clear distinction between the DSD properties of stratiform and convective rainfall was also observed. The stratiform and convective DSD samples during the SWM period follow the convective-stratiform separation line of Bringi et al. (2003) and suggest that the microphysical processes of convective rainfall in Metro Manila during the SWM period are influenced by both continental and maritime convection.

2 The derived Z_H values using the T-matrix scattering method have good agreement with the DSD-derived Z_H values, thus showing that the T-matrix is an effective method in simulating dual-pol parameters using disdrometer measurements. In all radar bands, the simulated Z_H values for the total rainfall in Metro Manila during the SWM period did not exceed 60 dB. Moreover, 55% of simulated Z_{DR} were also found to be less than 0.25 dB, and 67% of K_{DP} values were less than 0.1° km^{-1}. Meanwhile, Z_{DR} > 1.4 dB and K_{DP} > 0.1° km^{-1} are found to have higher frequencies in X-band. In terms of rainfall type, the average value of Z_H of convective rains is found to be the same for S- and C-band (46.4 dBZ) but slightly higher for X-band (48 dBZ).

3 The distribution of the dual-pol parameters among different radar bands and rain types shows that there is a need to implement certain data quality thresholds to determine the usability of a certain dual-pol relation. The 0.5 dB and 0.3° km^{-1} thresholds for Z_{DR} and K_{DP} based on the blended

algorithm of C11 and TH18 show that dual-pol relations involving Z_{DR} and K_{DP} are recommended to be used especially for C- and X-band. Localized dual-pol estimators such as $R(Z_H)$, $R(K_{DP})$, $R(Z_H, Z_{DR})$, and $R(Z_{DR}, K_{DP})$ were also developed by applying the thresholds to the simulated dual-pol parameters. In general, the localized dual-pol relations can decrease the RMSE and ME by at least 7.43% and 30.25%, respectively relative to the conventional $R(Z_{MP})$. Evaluation of the QPEs from the dual-pol relations for the C-band radar shows that $R(Z_H)$ is most sensitive to DSD variations hence its poor performance, especially during convective rains. Moreover, according to MC21, $R(Z_H)$ and $R(Z_H, Z_{DR})$ relations are more sensitive to the number of small raindrops than the proportion of large raindrops. Hence, these two rainfall estimators are not recommended for convective rain types since they contain higher concentrations of large raindrops compared to stratiform rain types. On the other hand, the relatively good performance of $R(K_{DP})$ and $R(K_{DP}, Z_{DR})$ can be attributed to their lesser sensitivity to DSD variation compared to Z_H (Zhang et al., 2019) and to the immunity of K_{DP} to radar attenuation and calibration (MC21).

The comprehensive analysis of DSD properties is an important step in developing localized QPE relations since variation in the DSD is one of the major sources of error in radar QPE products. Hence, this study investigated the DSD characteristics of rainfall in Metro Manila during the SWM period using DSD measurements from two PARSIVEL^2 disdrometer stations. The study also introduced an effective method of developing dual-pol relations for S-, C-, and X-band radars using DSD measurements. Since this study is focused on the performance of the QPE products in C-band radar only, other dual-pol relations mentioned in this study can be further evaluated for S- and X-band. The DSD properties observed in this study, together with the derived localized QPE relations do not necessarily reflect the DSD characteristics and dual-pol relations of other monsoon seasons and locations in the Philippines. Nevertheless, the results presented in this study, especially the derived dual-pol relations, can provide possible improvements in the general rainfall retrieval operations of the country's dual-pol and single-pol radar networks.

AUTHOR CONTRIBUTIONS

Conceptualization, MP Ibanez.; Methodology, MP Ibanez and SC Martirez.; Formal analysis, MP Ibanez & SC Martirez.; Visualization; SC Martirez, MP Ibanez, and RA Sajulga.; Data acquisition, RA Sajulga and SC Martirez.; Data curation, SC Martirez, MP Ibanez, and RA Sajulga.; Funding acquisition, AG Pura and EO Cayanan.; Project Administration, EO Cayanan, AG Pura.; Supervision, W-Y Chang and BJ-D Jou.; Writing – original draft, MP Ibanez.; Review and editing, all authors.

DATA AVAILABILITY STATEMENT

Figure 1 was generated using available terrain shapefiles from ArcMap. The PyDSD processing codes are available through J. Hardin at https://github.com/josephhardinee/PyDSD and at Hardin (2014) under the doi: https://doi.org/10.5281/zenodo.9991

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COMPETING INTERESTS

The authors declare that they have no conflict of interest.

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APPENDICES

Table 1A. Drop size distribution class bins of the PARSIVEL^2 optical Disdrometer

Class Number	Classification of drops according to volume-equivalent diameter		Classification of drops according to fall velocity	
	Class average (mm)	Class spread (mm)	Class average (mm s^{-1})	Class spread (mm s^{-1})
1	0.062	0.125	0.050	0.1
2	0.187	0.125	0.150	0.1
3	0.312	0125	0.250	0.1
4	0.437	0.125	0.350	0.1
5	0.562	0.125	0.450	0.1
6	0.687	0.125	0.550	0.1
7	0.812	0.125	0.650	0.1
8	0.937	0.125	0.750	0.1
9	1.062	0.125	0.850	0.1
10	1.187	0.125	0.950	0.1
11	1.375	0.250	1.1	0.2
12	1.625	0.250	1.1	0.2
13	1.875	0.250	1.5	0.2
14	2.125	0.250	1.7	0.2
15	2.375	0.250	1.9	0.2
16	2.750	0.5	2.2	0.4
17	3.250	0.5	2.6	0.4
18	3.750	0.5	3	0.4
19	4.250	0.5	3.4	0.4
20	4.750	0.5	3.8	0.4
21	5.5	1	4.4	0.8
22	6.5	1	5.2	0.8
23	7.5	1	6	0.8
24	8.5	1	6.8	0.8
25	9.5	1	7.6	0.8
26	11	2	8.8	1.6
27	13	2	10.4	1.6
28	15	2	12	1.6
29	17	2	13.6	1.6
30	19	2	15.2	1.6
31	21.5	3	17.6	3.2
32	24.5	3	20.8	3.2

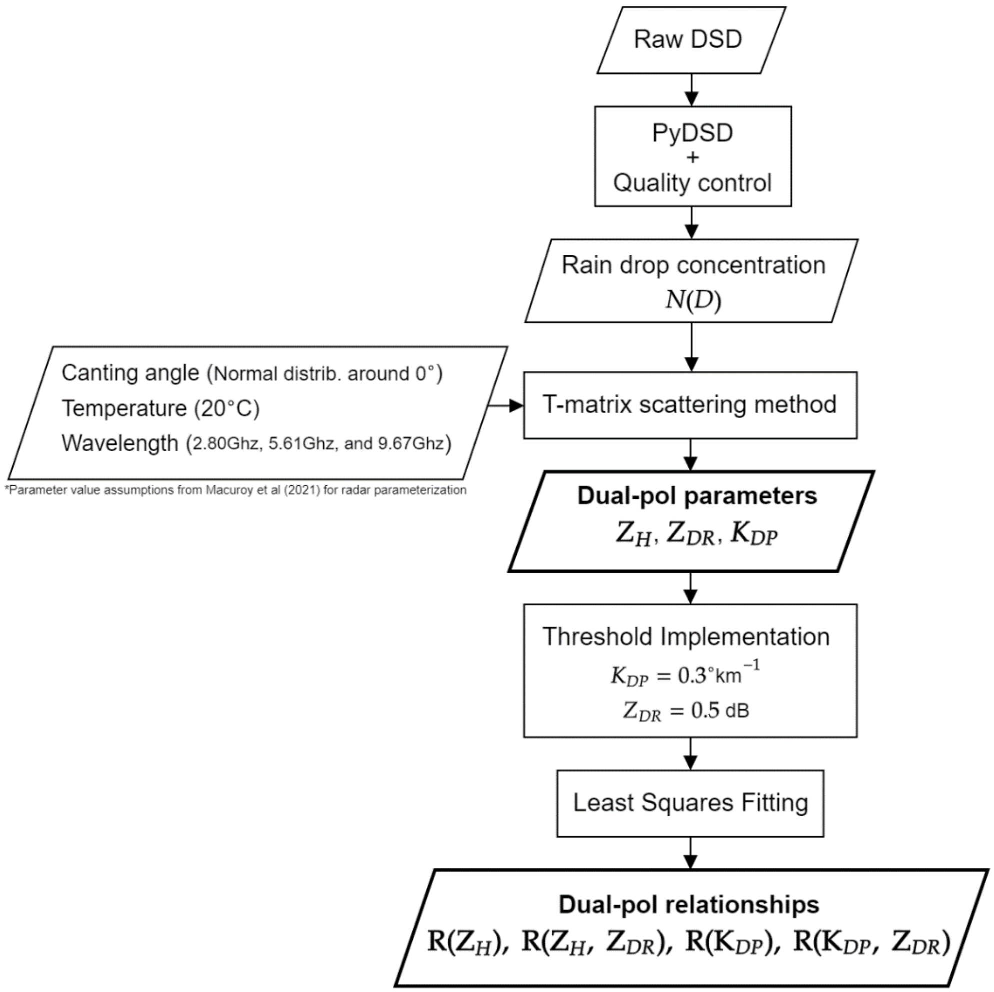

Fig. 1A Process flow of T-matrix from the PyDSD package for simulating the dual-pol parameters and relations from the DSD measurements

Figures

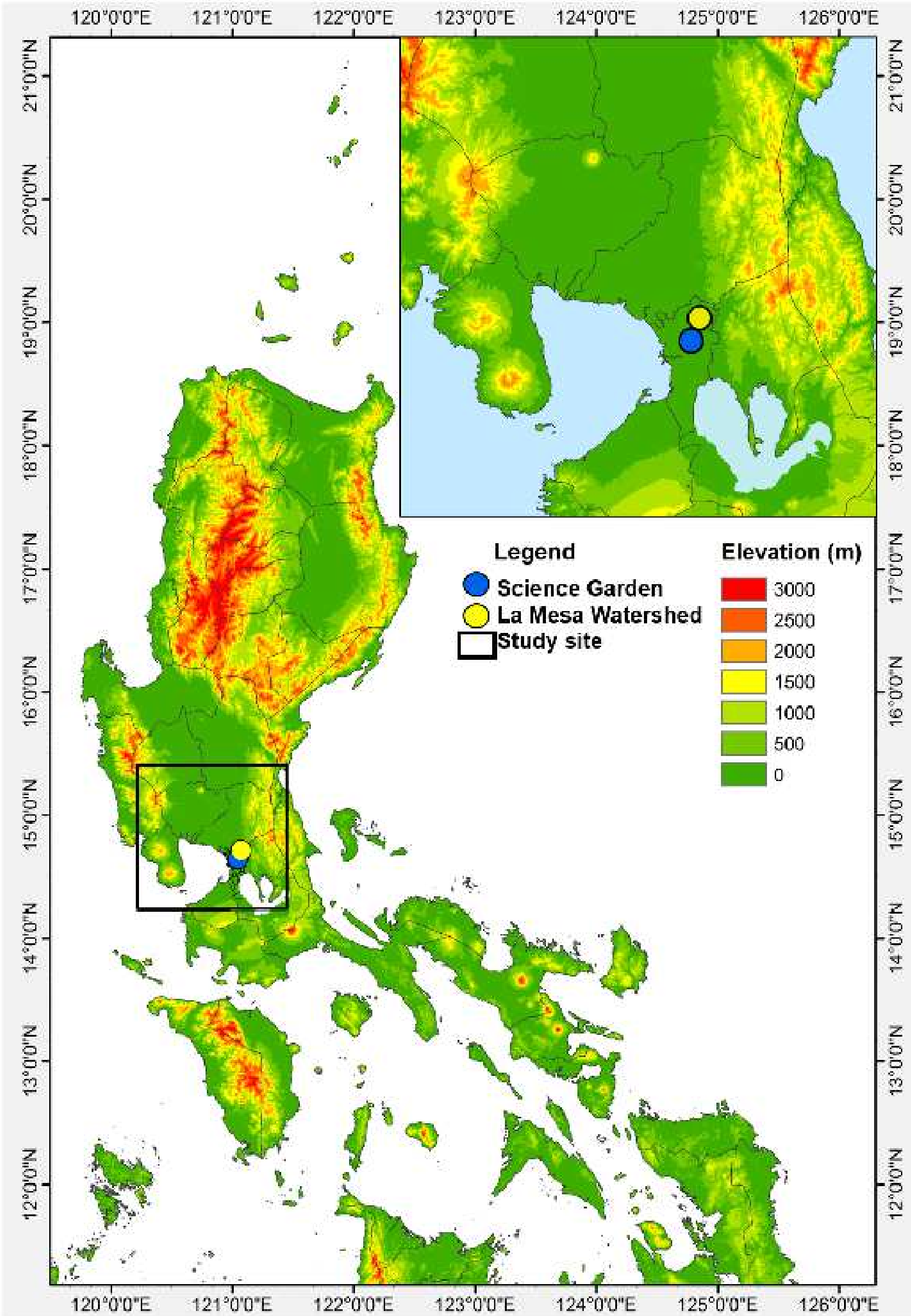

Figure 1

Digital elevation map showing the locations of the two disdrometer stations within the study site

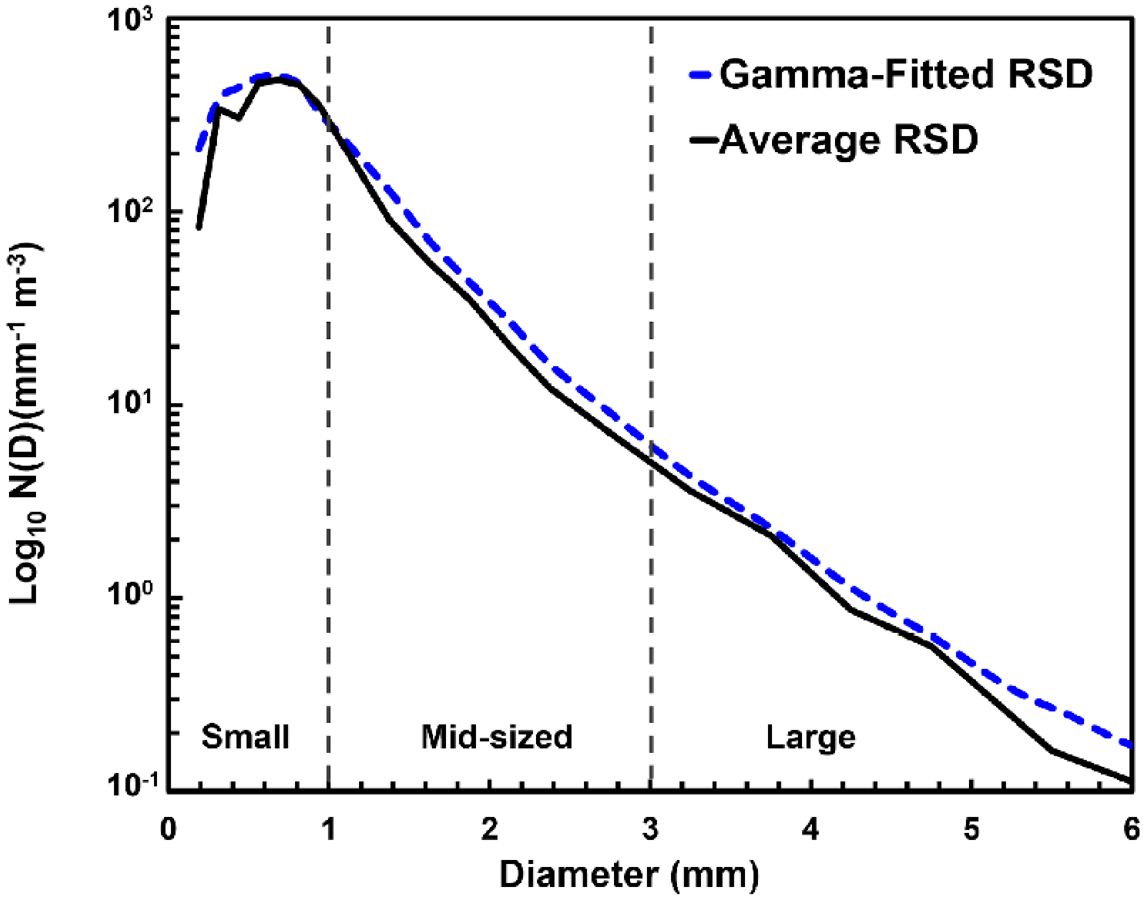

Figure 2

Average DSD (solid black line) and the fitted DSD using the gamma distribution (blue dashed line) for Metro Manila during the SWM period from 2020 to 2022. The vertical dashed lines represent the raindrop size classification

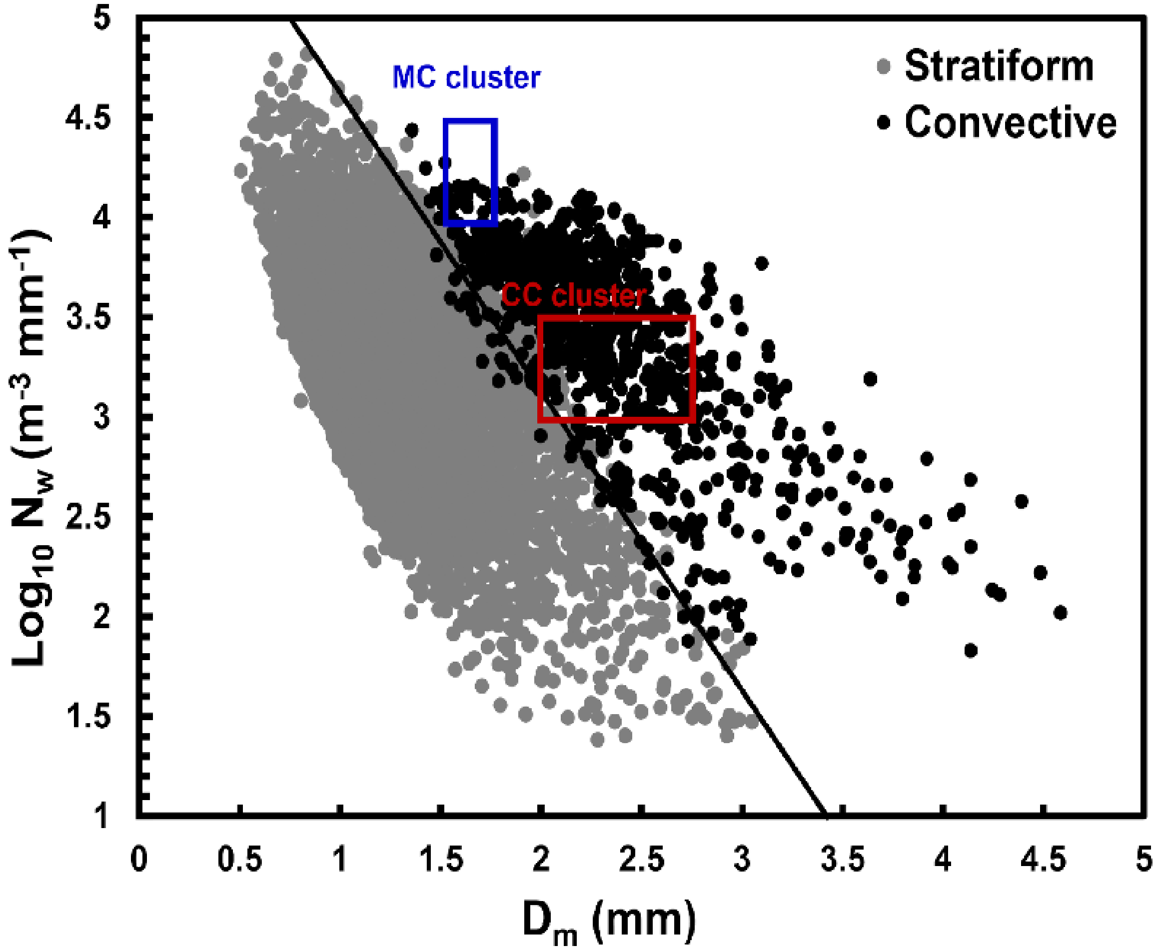

Figure 3

Scatterplot of the Dm vs. Log10 Nw values for stratiform (gray circles) and convective (black circles) rains in Metro Manila during the SWM periods of 2020 to 2022. The black solid line represents the convective-stratiform (c-s) separation line proposed by Bringi et al. (2003) while the blue and red boxes denote the maritime convective (MC) and continental convective (CC) clusters respectively

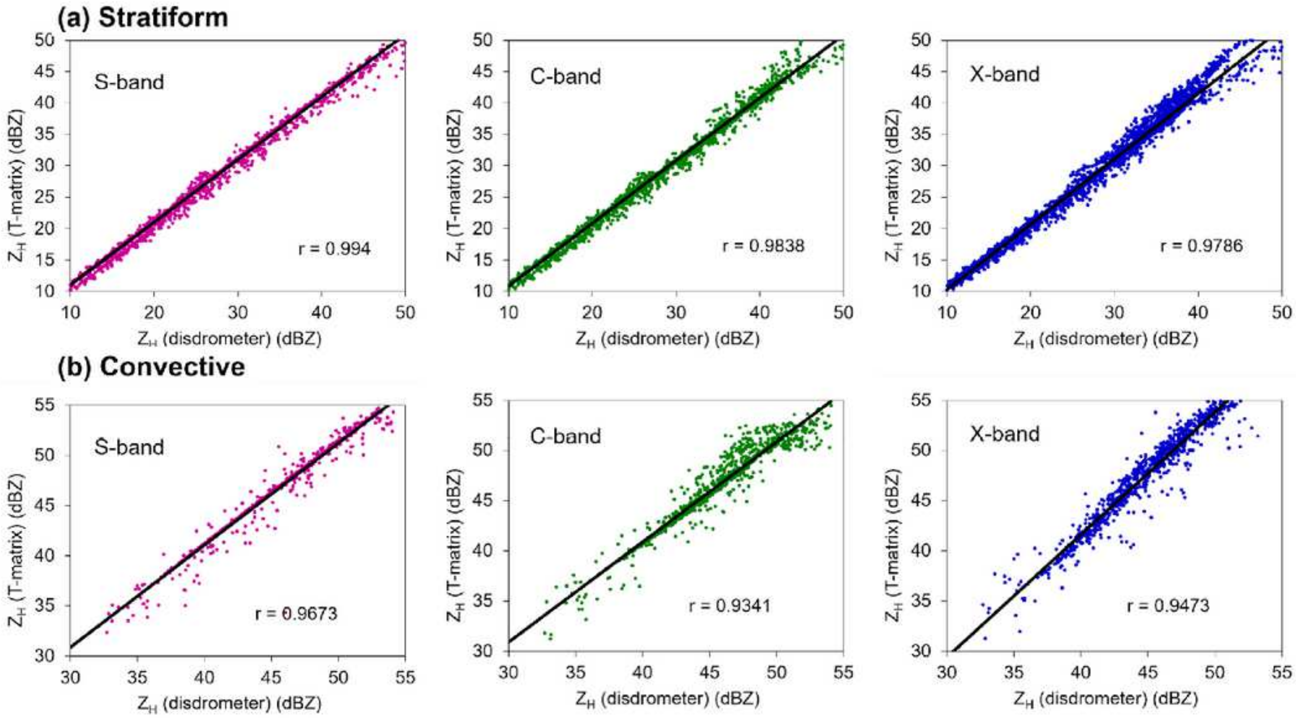

Figure 4

Comparison between ZH products of the disdrometer and T-matrix for stratiform and convective rainfall types in Metro Manila

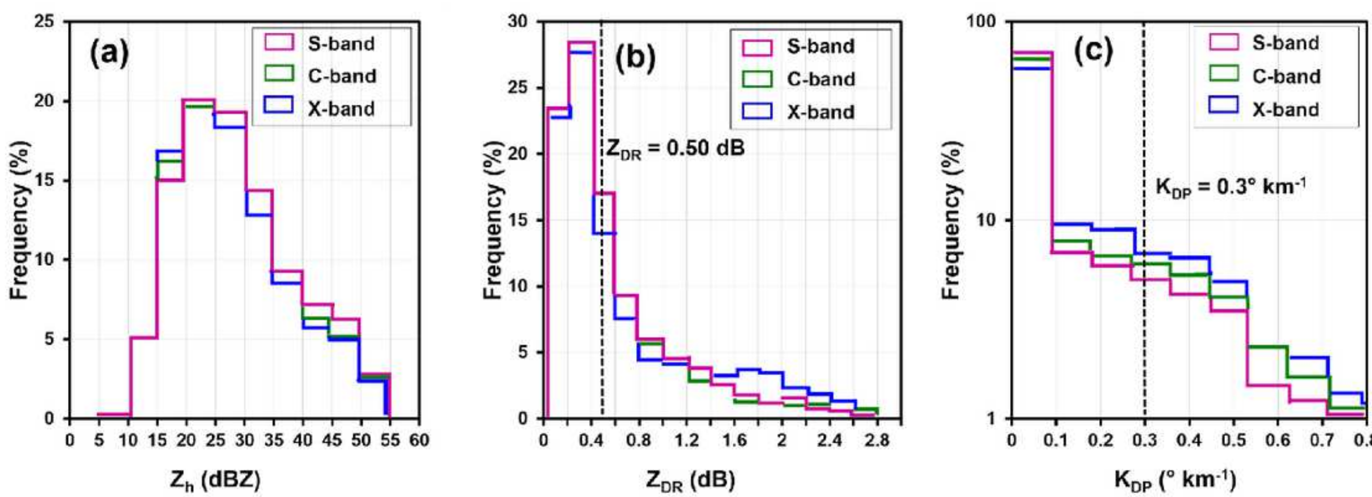

Figure 5

Frequency distribution of simulated Dual-pol variables using the T-matrix method: (a) Zh , (b) ZDR, and (c)KDP for Metro Manila during the SWM period. The broken lines in Figures 4b and 4c represent ZDR and KDP threshold values proposed by TH18 and C11

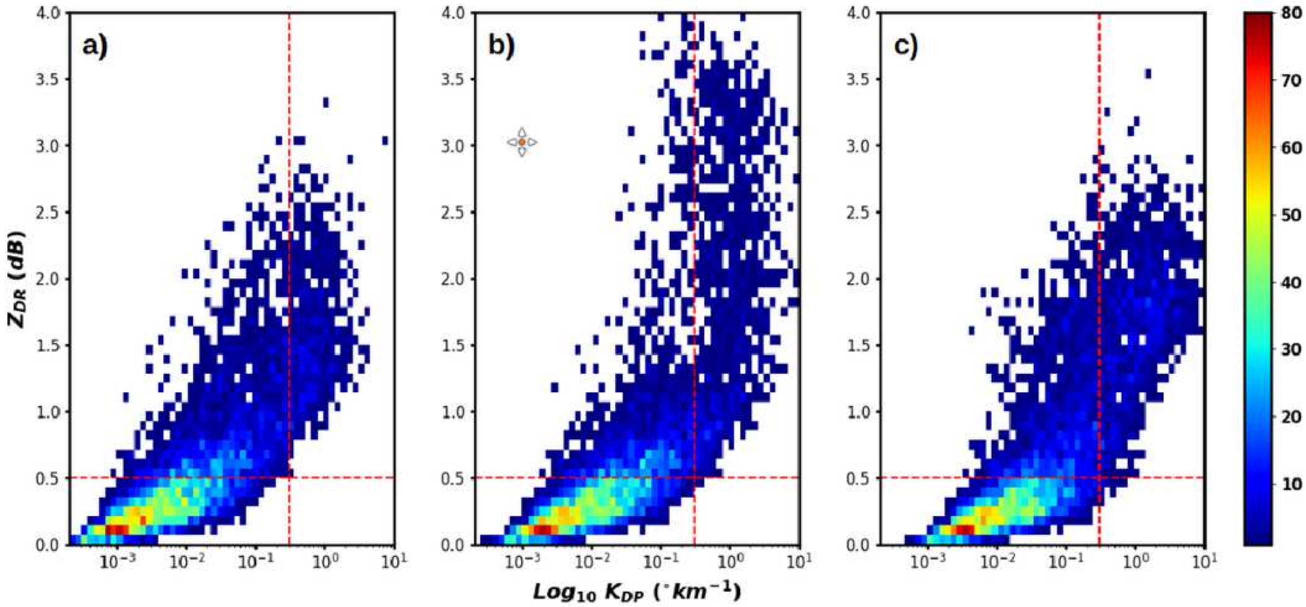

Figure 6

2D Histogram plot of simulated ZDR and KDP for (a) S-band, (b) C-band, and (c) X-band radar. The red horizontal and vertical broken lines represent the 0.5 dB and 0.3° km-1 thresholds for ZDR and KDP, respectively.

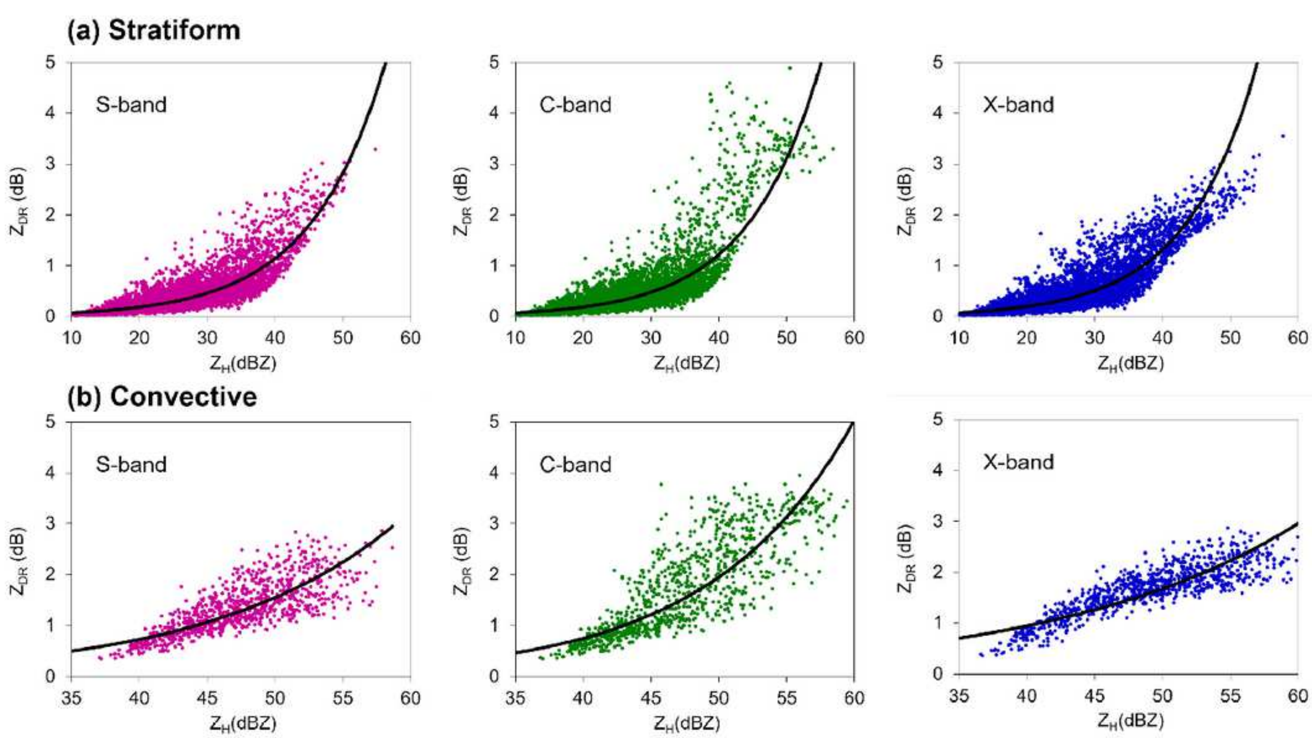

Figure 7

ZDR - ZH relations with fitted curves for (a) stratiform and (b) convective rainfall during the 2020-2022 SWM period in Metro Manila

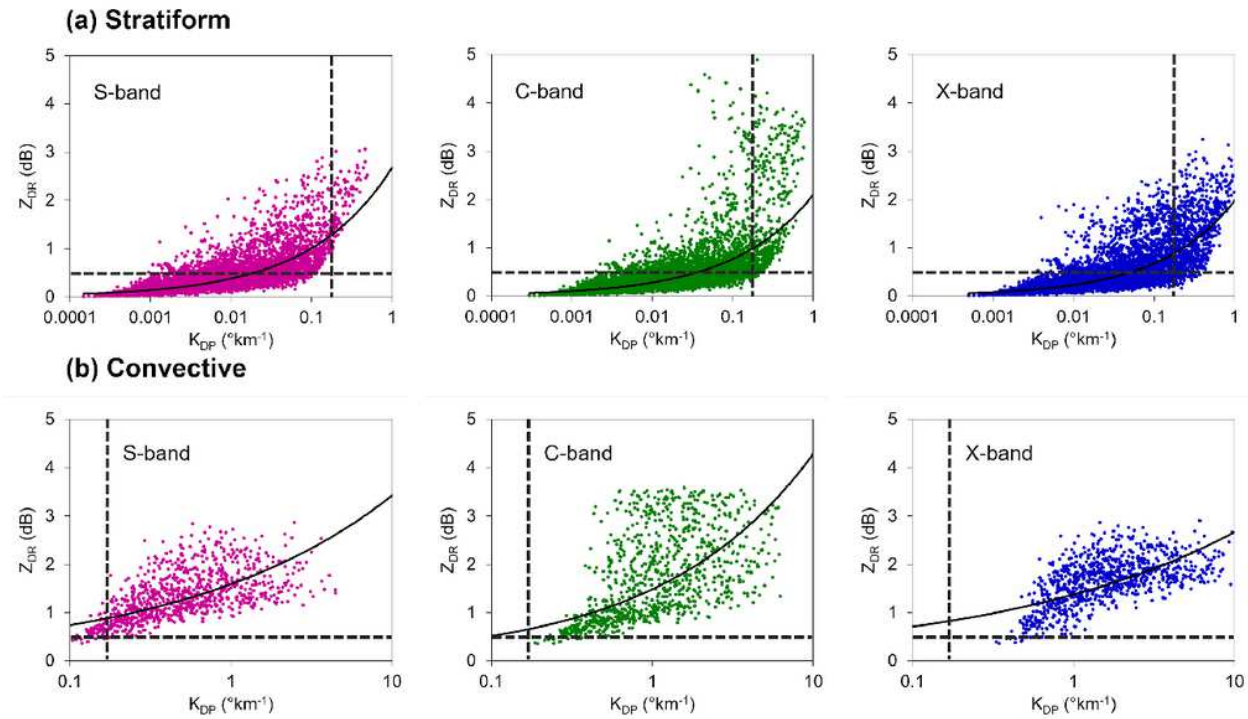

Figure 8

KDP - ZDR relations with fitted curves for (a) stratiform and (b) convective rainfall during the 2020-2022 SWM period in Metro Manila

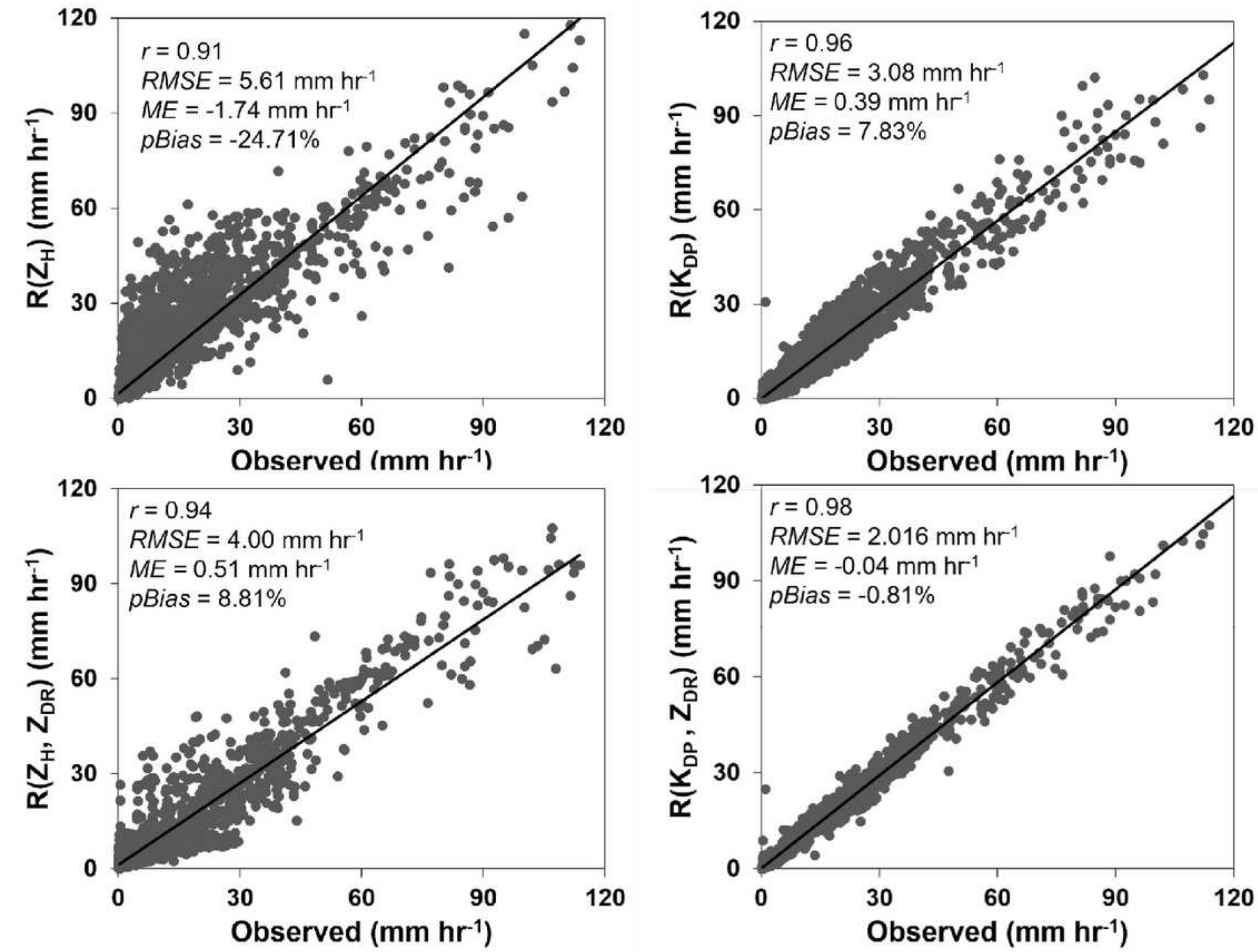

Figure 9

Scatterplots of rain rate estimates from the C-band relations for the total rainfall during the SWM period in Metro Manila. The correlation coefficient (r), root mean square error (RMSR), mean error (ME), and percent bias (pBias) are also included

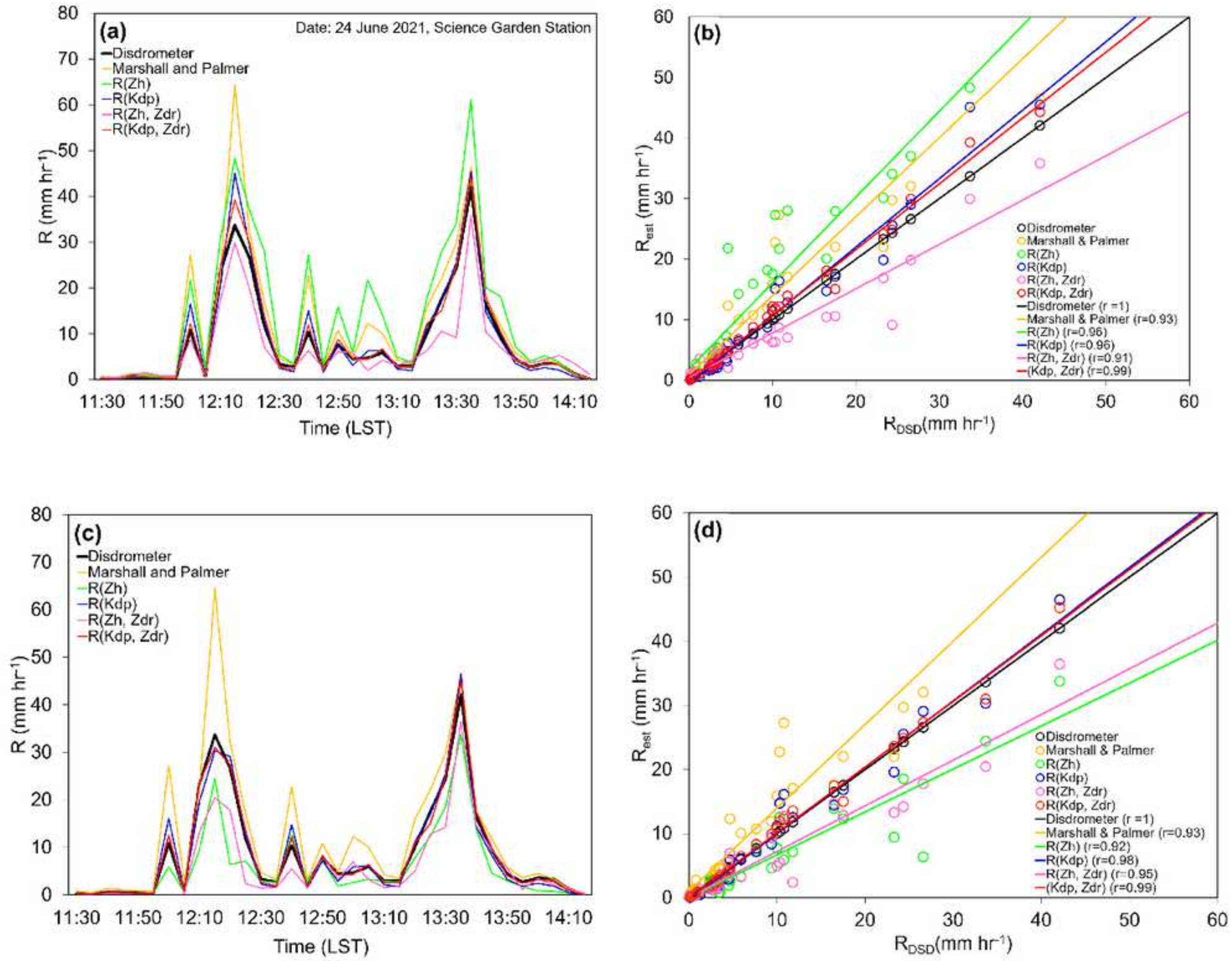

Figure 10

Comparison between the time series and scatter plots of R derived using the Marshall & Palmer relation (Z= 200R 1.6) and the C-band dual-pol relations. Figures (a) and (b) show the time series and scatterplot of derived R using the dual-pol relations for the total rainfall, while (c) and (d) show the derived R using the dual-pol relations for convective rainfall

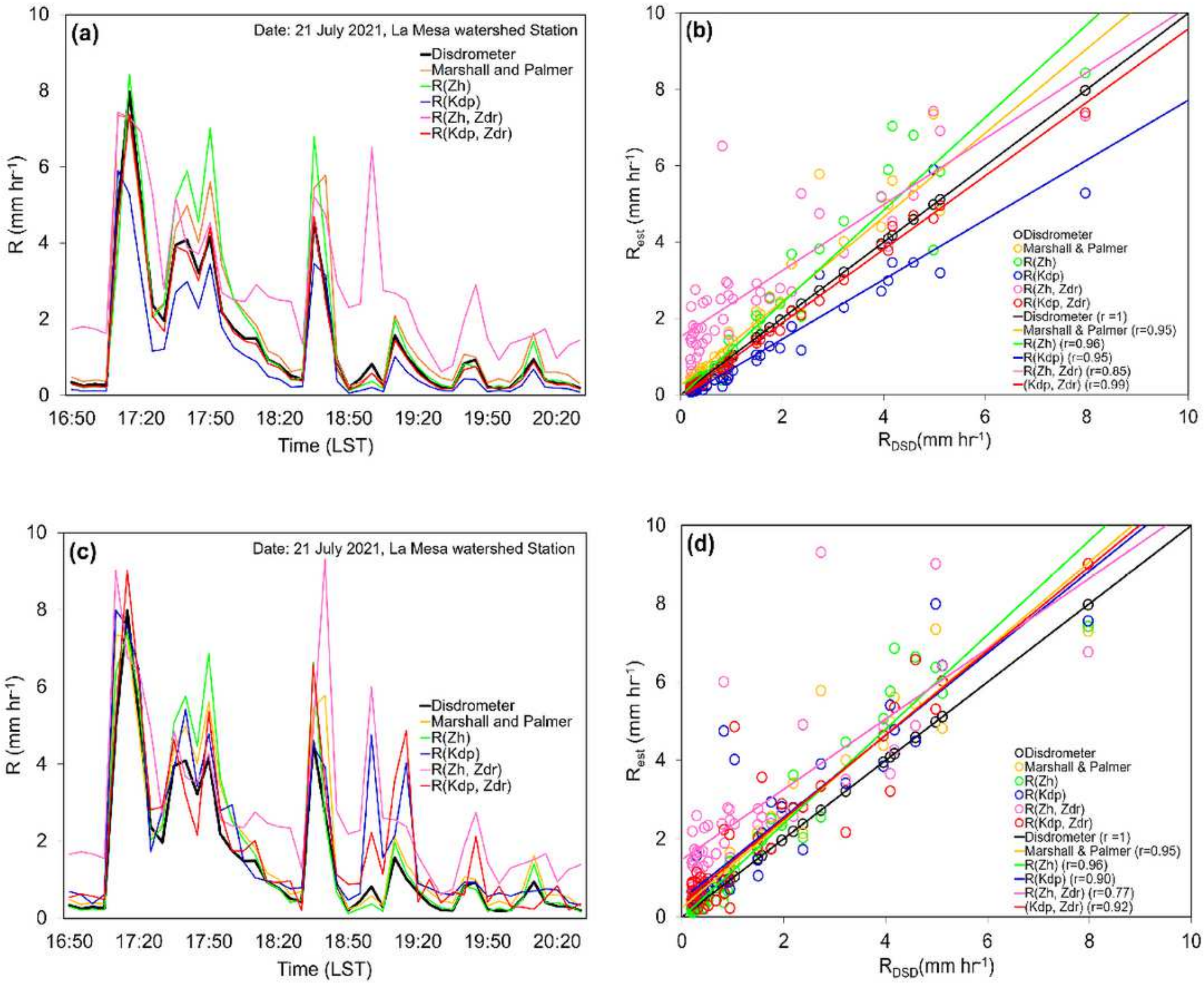

Figure 11

Comparison between the time series and scatter plots of R derived using the Marshall & Palmer relation (Z= 200R 1.6) and the C-band dual-pol relations. Figures (a) and (b) show the time series and scatterplot of derived R using the dual-pol relations for the total rainfall, while (c) and (d) show the derived R using the dual-pol relations for stratiform rainfall

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- TablesTAO.pdf