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The possibility of rainfall estimation using $R(Z,Z_{DR},K_{DP},A_H)$: A case study of heavy rainfall on 25 August 2014 in Korea

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Abstract

To improve the accuracy of polarimetric rainfall relations for heavy rainfall, an extreme rainfall case was analysed and some methods were examined. The observed differential reflectivity (Z_{DR}) quality check was theoretically investigated using the relation between the standard deviation of differential reflectivity and cross correlation, and the light rain method for Z_{DR} bias was also applied to the rainfall estimation. The best performance for this heavy rainfall case was obtained when the moving average of Z_{DR} over a window size of 9 gates was applied to the rainfall estimation using horizontal reflectivity (Z_H) and Z_{DR} and to the calculation of Z_H bias. The differential reflectivity calculated by disdrometer data may be an alternative to the vertical pointing scan for calculating Z_{DR} bias. The accuracy of the combined rainfall relation, $R(Z,Z_{DR},K_{DP},A_H)$ was relatively insensitive to Z_{DR} and Z_H biases in both observations and simulations.

1 Introduction

Weather radar is a very useful remote sensing instrument for estimating rainfall amount due to its high spatial and temporal resolution compared with other instruments. Calculations of radar rainfall are based on the relationship between reflectivity (Z) and rain rate (R) known as the Z–R relation (hereafter $R(Z)$). Experimentally measured drop size distributions (DSDs) have been extensively used to obtain both radar reflectivity and rain rate (Compos and

Zawadzki, 2000). It can be shown that there is no unique global R(Z) relation because DSDs can vary from storm to storm and even within the storm itself (You et al., 2010). There have been a few studies on the calculation of the R(Z) relationship using disdrometer data with rainfall types and rain gage adjusted rainfall amount for operational Doppler weather radars in Korea (Jang et al., 2004; You et al., 2004; Suk et al., 2005).

Radar rainfall estimation may be contaminated by uncertainties such as hardware calibration, partial beam filling, rain attenuation, bright band, and non-weather echoes (Wilson and Brandes, 1979; Austin, 1989). To mitigate these problems, particle identification algorithms have been developed using polarimetric parameters for improving data quality control and rainfall estimates by discriminating non-meteorological artefacts such as anomalous propagation, birds, insects, second trip echo, and melting layer detection (Ryzhkov and Zrnic, 1998; Vivekanandan et al., 1999; Giangrande et al., 2008). The improvement of radar rainfall accuracy is a major reason for using polarimetric radar (Ryzhkov and Zrnic, 1996; May et al., 1999; Bringi and Chandrasekar, 2001). Ryzhkov et al. (2005a) developed a rainfall algorithm using polarimetric radar for the prototype WSR-88D (Weather Surveillance Radar-88 Doppler) system using different drop shape assumptions. Ciffelli et al. (2011) compared two rainfall algorithms, CSU-HIDRO (Colorado State University-Hydrometeor IDentification of Rainfall) and JPOLE (Joint Polarization Experiment)-like, in the high plains environment. Ryzhkov et al. (2014) recently investigated the potential use of specific attenuation (A_H) for rainfall estimation with X-band and S-band radar and found that the R(A_H) method yields robust estimates of rain rates even at S band where attenuation is very small.

As a result of these theoretical and other experimental studies, many countries are replacing or modifying their radars and using polarimetric radar operationally. There are three major agencies that operate radars to monitor and forecast severe weather and flash flooding operationally in Korea: the Ministry of National Defense (MND), the Ministry of Land, Infrastructure and Transportation (MoLIT), and the Korea Meteorological Administration (KMA), with the MoLIT the first to install polarimetric radars in Korea. The KMA installed an S-band polarimetric radar in the far northwest of Korea in 2014. For successful operational implementation of these radars, considerable research on rainfall estimation, hydrometeor classification, and DSD retrieval is required. However, there have been few studies on these polarimetric related issues other than the derivation of relationships using long period disdrometer data and the assessment of each relation after applying a very simple quality

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control for differential phase shift (You et al., 2014). You et al. (2014) found that the accuracy of rainfall estimation using horizontal reflectivity (Z_H) and differential reflectivity (Z_{DR}) obtained by DSDs in the Busan area in Korea was better than that obtained with relations calculated by DSDs measured in Oklahoma in the US. A quality control algorithm and unfolding of differential phase shift (Φ_{DP}) for calculating specific differential phase (K_{DP}) were applied to the rainfall estimation (You et al., 2014). Recently, You et al. (2015a) proposed a relation combining many polarimetric variables of the form $R(Z,Z_{DR},K_{DP},A_H)$ as a candidate for an optimum rainfall relation for S-band polarimetric data in Korea; this would allow a single relation to be used for different hydrometeor regimes in the absence of a stable hydrometeor classification algorithm. However, there are still issues to be resolved in improving Z_{DR} data quality and the robustness of $R(Z,Z_{DR},K_{DP},A_H)$ for the heavy rainfall case where error propagation from each polarimetric variable can occur.

This paper discusses how to improve the accuracy of rainfall estimation using moving averaged differential reflectivity and examines the robustness of the $R(Z,Z_{DR},K_{DP},A_H)$ relation for a heavy rainfall case in Korea. Sect. 2 describes the rain gage, DSD and radar dataset, together with the calculation of polarimetric variables from DSDs and the validation methods. Sect. 3 provides Z_H and Z_{DR} bias correction, an examination of Z_{DR} data quality, and the statistical results of rainfall estimation using observed and moving-average Z_{DR}. Sect. 4 contains a discussion of a possible method for improving $R(Z,Z_{DR})$ accuracy and the robustness of the $R(Z,Z_{DR},K_{DP},A_H)$ relation. Finally, we provide some conclusions in Sect. 5.

2 Data and methodology

2.1 Gage, disdrometer and radar dataset

The rainfall data from rain gages operated by the KMA were used to evaluate the accuracy of radar rainfall. Rain gages located within the radar coverage area at distances from 5 to 95 km of the radar are included in the analysis. Fig. 1 shows the location of all instruments used in this study. The circle is the radar coverage, the solid rectangle is the centre of the Bislsan radar, the plus signs show the rain gages within the radar coverage and the open rectangle is the location of a PARSIVEL (PARticle Size VELocity) and POSS (Precipitation Occurrence

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Sensor System; detailed specifications are provided by Sheppard, 1990) disdrometer installed ~82 km away from the radar.

Relations for converting radar variables into rain rate are required because the radar does not observe rainfall directly. To calculate these relations, disdrometer data that can measure the DSDs are needed. One-min DSDs obtained by the POSS from 2001 to 2004 were used. To improve the accuracy of Z_{DR}, DSDs observed by PARSIVEL on 25 August 2014 were used because POSS data were not available at that time. The PARSIVEL disdrometer is a laser-optic system that measures 32 channels from 0.062 to 24.5 mm (detailed specifications are given by Loffler-Mang and Joss, 2000).

Unreliable data, defined as belonging to the following categories, were removed: 1-min rain rate less than 0.1 mm h^{-1}; total number concentrations of all channels less than 10; drop numbers counted only in the lower 10 channels (0.84 mm for POSS and 1.187 mm for PARSIVEL); and drop numbers counted only in the lower 5 channels (0.54 mm for POSS and 0.562 mm for PARSIVEL) (You et al., 2015b).

Radar data were collected by the Bislsan polarimetric radar installed and operated by the MoLIT in Korea since 2009. The transmitted peak power is 750 kW, beam width is 0.95°, and frequency is 2.791 GHz. The polarimetric variables are estimated with a gate size of 0.125 km. The scan strategy is composed of 6 elevation angles with 2.5-min update interval. Polarimetric variables for 0.5° elevation angle were extracted from the volume data every 10 mins for this study.

2.2 Calculation of polarimetric variables from DSDs

Polarimetric variables were calculated using T-matrix scattering techniques derived by Waterman (1971) and later developed further by Mishchenko et al. (1996). The following raindrop shape assumptions are used for the calculation of variables from the DSDs:

$$\frac{b}{a} = 1.0048 + 0.500057\,D - 0.02628\,D^2 + 0.003682\,D^3 - 0.0001677\,D^4, \qquad (1)$$

$$\frac{b}{a} = 1.012 - 0.01445\,D - 0.01028\,D^2, \qquad (2)$$

where a, b and D are the major axis, minor axis, and equi-volume diameter of raindrop in millimetres, respectively.

Eq. (1) is for the equilibrium axis ratio derived from the numerical model of Beard and Chung (1987), which is in good agreement with the results from wind tunnel measurements. The actual shapes of raindrops in turbulent flow are expected to be different from the equilibrium shapes due to drop oscillations. Oscillating drops appear to be more spherical on average than drops with equilibrium shapes as shown by Andsager et al. (1999) in laboratory studies. They demonstrated that the shape of raindrops with diameter between 1.1 and 4.4 mm is better explained by Eq. (2). You et al. (2015a) found that combining Eq. (1) for drops less than 1.1 mm and larger than 4.4 mm with Eq. (2) for the drop diameter between 1.1 and 4.4 mm as proposed by Bringi et al. (2003) gave the best rainfall estimation compared with other drop axis ratio assumptions in Korea, and we use this combined formulation in this study. Other parameters in the T-matrix calculations include the temperature, which is assumed to be 20℃ in this study. The distribution of canting angles of raindrops is Gaussian with a mean of 0° and a standard deviation of 7°, as determined recently by Huang et al. (2008).

2.3 Validation

The localized rainfall on 25 August 2014 was caused by a low pressure system that passed through southern Korea. Fig. 2 shows the time series of hourly rainfall and accumulated rainfall from the three gages, ID 255 (North Changwon site), ID 926 (Jinbook site), and ID 939 (Geumjeong-gu site) that recorded the highest rainfall within the radar coverage area. The daily accumulated rainfall values were 243.5 mm, 269.0 mm, and 244.5 mm for these gages. The time period analysed was from 0900 LT to 1600 LT because the rainfall was concentrated in this period and radar data were available from 0900 LT.

The normalized error (NE), fractional root mean square error (RMSE), and correlation coefficients (CC) of the rainfall relations and 121 gages were used to investigate the performance of each rainfall relation:

$$NE = \frac{\frac{1}{N}\sum_{i=1}^{N}\left|R_{R,i} - R_{G,i}\right|}{\overline{R_G}}, \quad (3)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(R_{R,i} - R_{G,i})^2\right]^{1/2}, \quad (4)$$

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$$CC = \frac{\sum_{i=1}^{N}(R_{R,i}-\overline{R_R})(R_{G,i}-\overline{R_G})}{\left[\sum_{i=1}^{N}(R_{R,i}-\overline{R_R})^2\right]^{1/2}\left[\sum_{i=1}^{N}(R_{G,i}-\overline{R_G})^2\right]^{1/2}}, \quad (5)$$

where N is the number of radar rainfall (R_R) and gage rainfall (R_G) pairs, and $\overline{R_R}$ and $\overline{R_G}$ are the average hourly rain rates from the radar and gage, respectively. These statistical variables are calculated using hourly rainfall amounts derived from the radar and gage at the location of the gage. The radar rainfall at the rain gage was obtained by averaging rainfall over a small area (1 km × 1°) centered on each rain gage. The rainfall relations for calculating radar rainfall were obtained from the simulated polarimetric variables generated from DSDs and are summarized in Table 1.

3 Results

3.1 Improvement of Z_{DR} data quality

Z_{DR} is an important variable for hydrometeor classification and rainfall estimation. To check the quality of the Z_{DR} measurements, the radial profile of Z_{DR} was investigated as shown in Fig. 3. Fig. 3(a) shows the spatial distribution of Z_{DR} at 0.5° elevation at 1401 LT on 25 August 2014. Fig. 3(b) shows the radial profile of observed Z_{DR} (red line) and the standard deviation of Z_{DR} (black line) calculated using 9 gates along the line A–B shown in Fig. 3(a). The average standard deviation of Z_{DR} along the line was 0.615 dB. Fig. 3(c) shows the radial profile of the cross correlation; the average cross correlation was 0.982.

To find the accuracy of the observed Z_{DR} value, we use the theoretical relation between the standard deviation of Z_{DR} and the cross correlation following Bring and Chandrasekar (2003):

$$SD(Z_{DR}) = 10\log_{10}\left\{1+\left[\frac{2}{N}(1-|\rho_{co}|^2)\sum_{l=-(N-1)}^{N-1}(1-\frac{|l|}{N})|\rho_{co}(l)|^2\right]^{1/2}\right\}, \quad (6)$$

where SD(Z_{DR}) is standard deviation of Z_{DR}, N is the number of samples and ρ_{co} is the cross correlation, given by

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$$\rho[n] = \exp(-\frac{8\pi^2 {\sigma_v}^2 n^2 {T_s}^2}{\lambda^2}), \tag{7}$$

where ρ is the cross correlation, σ_v is Doppler width, n is sample number, and T_s is dwell time.

For a better comparison we display the correlations in *L* space, as proposed by Keat et al. (2015)

$$L = -10\log_{10}(1-\rho_{hv}), \tag{8}$$

where, ρ_{hv} is cross correlation. Fig. 4 shows the theoretical relation between the standard deviation of Z_{DR} and the cross correlation coefficient. Fig. 4(a) shows the results obtained using the scan configuration of the Bislsan radar. The dwell time is 56 ms, number of samples is 55, and the normalised Doppler width is 0.02. Fig. 4(a) suggests that for an accuracy of 0.1 dB in Z_{DR} with 1 ms^{-1} Doppler width, a value of L of over 3 (ρ_{hv} >0.999) is needed. Such values cannot be measured with the antenna. In Fig. 4(b) the number of samples is 495, which corresponds to 9 gates, 1.125 km in range; an accuracy of 0.2 dB in Z_{DR} (the moving-average Z_{DR}, hereafter mZ_{DR}) is achieved with 1 ms^{-1} Doppler width and a value of L of 1.7 (ρ_{hv} >0.980).

Fig. 5 shows the results for Z_{DR} measurements at 1401 LT on 25 August 2014. Fig. 5(a) shows the spatial distribution of a moving average Z_{DR} from 9 gates. Fig. 5(b) shows the radial profile of the Z_{DR} (red line) and its standard deviation (black line) calculated for 9 gates along the line A–B shown in Fig. 5(a). The average standard deviation of Z_{DR} along the ray was 0.169 dB. Fig. 5(c) shows the radial profile of the cross correlation; the average cross correlation was 0.985. Both the standard deviation of Z_{DR} and the averaged ρ_{hv} values are very close to the theoretical values (standard deviation of Z_{DR} is 0.160 and ρ_{hv} is 0.987) as shown in Fig. 4. Therefore, in the next Sect. a 9-gage moving average Z_{DR} was used for absolute Z_H bias correction and rainfall estimation, and its effect on the accuracy of radar rainfall estimation was examined.

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3.2 Absolute bias correction of Z_{DR} and Z_H

Before calculating radar rainfall, the Z_H and Z_{DR} must be corrected for system bias. Ryzhkov et al. (2005) calculated the required accuracy for classifying light rain and dry snow to be 1 dB and 0.2 dB for Z_H and Z_{DR}, respectively. The Z_{DR} bias correction is important for the absolute calibration of the radar using the self-consistency method. Gorgucci et al. (1999) proposed a vertical pointing scan of light rain to take advantage of the nearly spherical shape of the raindrops seen from below.

Ryzhkov et al. (2005b) used the elevation angle dependency of Z_{DR} as an alternative technique and concluded that the high variability of Z_{DR} in rainfall means it is not possible to achieve the required absolute calibration of 0.2 dB. They also proposed a method using the structural characteristics of the melting layer in stratiform clouds and measured the dry aggregated snow present above the melting layer, which gave a mean value of 0.2 dB at S band and an accuracy of 0.1 to 0.2 dB.

Trabal et al. (2009) evaluated two different methods using the intrinsic properties of dry aggregated snow present above the melting layer and measurements of light rain close to the ground and found that a Z_{DR} calibration accuracy of 0.2 dB or less was achieved for both events analysed when both methods are compared.

The vertical pointing data were not available for the case considered here and the scan strategy with six elevation angles does not detect the melting layer. Therefore, light rain measurements close to the ground were used to calibrate the Z_{DR} and Z_H biases using the self-consistency method in this study. Very light rain was defined by the thresholds 20 dBZ $\leq Z_H \leq$ 28 dBZ as proposed by Marks et al. (2011). The Z_H bias was determined following Ryzhkov et al. (2005b).

The Z_H biases calculated with the self-consistency method using observed Z_{DR} and mZ_{DR} are –1.95 dB and –1.48 dB, respectively. The Z_{DR} biases calculated by the very light rain method using observed Z_{DR} (0.26 dB) and mZ_{DR} (0.3 dB), respectively.

3.3 Validation

To investigate the performance of $R(Z,Z_{DR})$ and $R(Z,Z_{DR},K_{DP},A_H)$, which is related to the Z_H and Z_{DR} bias, NE, RMSE, and CC were calculated using hourly rainfall from each relation

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and from the gages. For the comparison of rainfall amount, two different Z_H and Z_{DR} biases were applied to observed variables as mentioned in Sect. 3.2. Each bias was calculated using observed Z_{DR} and mZ_{DR}.

Fig. 6 shows the scatter plot of 1 hour rainfall obtained using $R(Z,Z_{DR})$ and gage data. In Fig. 6 (a) the Z_H bias was obtained from the observed Z_{DR} bias and the Z_{DR} biases calculated from observed Z_{DR} (blue full circles) and mZ_{DR} (red full circles). The RMSE, NE, and CC of the relation using mZ_{DR} were as much as 8 mm h^{-1}, 0.1, and 0.18 better than those obtained using observed Z_{DR}, respectively. In Fig. 6(b) the Z_H bias is calculated from mZ_{DR}; the improved performance using mZ_{DR} is clear. The accuracy of the rainfall estimate using Z_H bias obtained by mZ_{DR} is statistically more robust than that for the estimate based on observed Z_{DR}. The RMSE, NE, and CC for the comparison of $R(Z,Z_{DR})$ rainfall obtained using different Z_H and Z_{DR} biases are summarized in Table 2.

Fig. 7 shows the scatter plots when $R(Z,Z_{DR},K_{DP},A_H)$ is used for rainfall estimation. Fig. 7(a) shows the radar rainfall calculated using the Z_H bias obtained from the observed Z_{DR} bias and the Z_{DR} biases obtained from observed Z_{DR} (blue full circles) and mZ_{DR} (red full circles). The RMSE, NE, and CC from each relation were not very different; differences of RMSE, NE, and CC in the two cases were 0.2 mm h^{-1}, 0.01, and 0, respectively. The statistics for the comparison of radar rainfall obtained using different Z_H and Z_{DR} biases are summarized in Table 3. These results show that $R(Z,Z_{DR},K_{DP},A_H)$ is less sensitive to Z_H and Z_{DR} error than $R(Z,Z_{DR})$. This will be discussed further in Sect. 4.2 using simulated data.

4 Discussion

4.1 Impact of disdrometer data on radar rainfall

In the cases described in Sect. 3.3, the accuracy of the $R(Z,Z_{DR})$ relation was improved when the moving-average Z_{DR} (i.e., mZ_{DR}) was used to estimate rainfall. To improve the accuracy of rainfall estimation using $R(Z,Z_{DR})$, we examined the impact of Z_{DR} bias (as obtained from disdrometer data) on the accuracy. The DSD data were quality controlled and polarimetric variables were calculated by T-matrix simulation with the same configuration as in Sect. 2. Before applying the DSDs to rainfall estimation, 10-min rainfall amounts obtained by DSDs and gages were compared.

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Fig. 8 shows the scatter plot of 10-min rainfall amount measured by PARSIVEL and the gage located less than 100 m away from PARSIVEL. The daily accumulated rainfall amounts were 116.0 mm for the gage and 129.4 mm for PARSIVEL. The RMSE, NE, and CC were 0.52 mm, 0.26, and 0.99, respectively. For the comparison the Z_{DR} of the radar was averaged over 3 km × 3° as shown in Fig. 9. The calculated Z_{DR} biases were 0.26 dB for observed Z_{DR} and 0.30 dB for mZ_{DR}. The Z_H biases described in Sect. 3.3 were used.

Fig. 10 shows the scatter plots of 1-hour rainfall obtained by $R(Z,Z_{DR})$ and gages. The radar rainfall was calculated after Z_{DR} bias correction using the bias result in the comparison between radar Z_{DR} and PARSIVEL Z_{DR}. The Z_{DR} biases were –0.05 dB for observed Z_{DR} and –0.07 dB for mZ_{DR}. In Fig. 10 (a) the Z_H bias was obtained from the observed Z_{DR} bias and Z_{DR} biases calculated from observed Z_{DR} (blue full circle) and mZ_{DR} (red full circle). The radar rainfall using mZ_{DR} was better than that using observed Z_{DR} by as much as 5.5 mm h^{-1} for RMSE and 0.36 for NE. In Fig. 10 (b) the Z_H bias was calculated from mZ_{DR}; the improved rainfall estimation using mZ_{DR} is clear. This result shows the better scores compared with the statistics shown in Fig. 6 that were obtained using Z_{DR} biases extracted from the radar Z_{DR} only. When the observed Z_{DR}, which fluctuates considerably along the ray, was applied to the rainfall estimation, the rainfall amount was much more variable with Z_H bias values (blue full circle) than that with mZ_{DR} (red circle) as shown in Fig. 10 (a) and (b). According to these results, when moving average Z_{DR} (i.e., mZ_{DR}) is used with the Z_{DR} bias measured by PARSIVEL, the accuracy of rainfall estimation was improved and was more stable than that of other configurations using $R(Z,Z_{DR})$.

Fig. 11 shows the scatter plots for $R(Z,Z_{DR},K_{DP},A_H)$ and gages. The statistical scores were not very different from Z_H and Z_{DR} biases. The differences of RMSE, NE, and CC between each relation were 0.4 mm h^{-1}, 0.01, and 0, respectively. These results were summarized in Table 3.

4.2 Simulation of $R(Z,Z_{DR},K_{DP},A_H)$ with error propagation from each variable

With the relation using combined polarimetric variables, $R(Z,Z_{DR},K_{DP},A_H)$, error propagation can affect the accuracy of radar rainfall estimation. To examine the contribution of errors from each variable, simulated polarimetric variables such as Z, Z_{DR}, K_{DP}, A_H, were generated with dimensions of 960 sizes of bins and 360 radials.

Fig. 12 shows the distribution function of the polarimetric variables generated assuming a Gaussian distribution in each case. Fig. 12(a) shows the occurrence frequency of Z_H generated

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with standard deviation of 7.0 dBZ and mean of 30.0 dBZ. Fig. 12(b) shows the corresponding occurrence frequency of Z_{DR} with 0.5 dB standard deviation and 1.0 dB mean. Fig. 12(c) shows the occurrence frequency of K_{DP} generated with 0.5° km^{-1} standard deviation and 1.0° km^{-1} mean. Fig. 12 (d) shows the occurrence frequency of A_H generated with 0.01° km^{-1} standard deviation and 0.0003° km^{-1} mean.

To investigate the extent of contamination of the rainfall amount by propagation of errors in each polarimetric variable for R(Z,Z_{DR},K_{DP},A_H), the errors of Z, Z_{DR}, and K_{DP} ingested to simulated data were 0 to 5 dBZ with interval 0.25 dBZ, 0 to 0.6 dB with interval 0.03 dB, and 0 to 0.2 degree km^{-1} with interval 0.01 degree km^{-1}, respectively. The rain rate was calculated by same R(Z,Z_{DR},K_{DP},A_H) as applied to real data in the previous Sect.. The RMSE and NE were calculated for rainfall amount with and without error-ingested polarimetric variables. The rainfall amount obtained using the raw simulated variables was used as a reference.

Fig. 13 shows the RMSE and NE distribution of different polarimetric rainfall relations with ingested error. The magenta, black, red, green, blue, and purple lines show RMSE and NE obtained by the rainfall relations R(Z), R(K_{DP}), R(Z,K_{DP},A_H), R(Z,Z_{DR}), R(K_{DP},Z_{DR}), and R(Z,Z_{DR},K_{DP},A_H), respectively. The threshold rainfall was from 0 to 300 mm h^{-1} for calculating statistical scores. Fig. 13(a) shows the RMSE distribution of each rainfall relation with different ingested error step. The RMSE of R(Z,K_{DP},A_H) is the largest of all the rainfall relations. The RMSE of R(Z,Z_{DR},K_{DP},A_H) is higher than that of R(Z), R(Z,Z_{DR}), and R(K_{DP},Z_{DR}) but less than that of R(K_{DP}). It means that not all errors from Z, Z_{DR}, and K_{DP} propagate into the R(Z,Z_{DR},K_{DP},A_H). Fig. 13(b) shows the corresponding distributions for NE. The value of NE increases in the order R(Z,Z_{DR},K_{DP},A_H), R(Z,K_{DP},A_H), R(K_{DP}), R(K_{DP},Z_{DR}), R(Z,Z_{DR}), and R(Z). In Sect. 3.3 and 4.1, the statistical scores of R(Z,Z_{DR},K_{DP},A_H) did not change significantly with respect to different Z_H and Z_{DR} biases. The results of the simulation and observations suggest that the accuracy of R(Z,Z_{DR},K_{DP},A_H) is relatively weakly affected by errors in each polarimetric variable.

5 Conclusions

To improve polarimetric rainfall estimation and examine the candidates for an optimum rainfall relation using polarimetric variables observed from the Bislsan radar, the first polarimetric radar in Korea, a heavy rainfall case of 7 hours duration caused by low-pressure conditions on 25 August 2014 was analysed.

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The theoretical approach to investigate the observed Z_{DR} quality used the relation between the standard deviation of Z_{DR} and ρ_{hv} using the scan strategy parameters of the Bislsan radar. The result showed that more samples were required to achieve the theoretical accuracy in Z_{DR}. The best performance was obtained when a moving average Z_{DR} with window size of 9 gates was applied to the rainfall estimation using $R(Z,Z_{DR})$ and to the calculation of Z_H bias. The Z_{DR} quality check should be performed before using Z_{DR} for quantitative applications like rainfall estimation and hydrometeor classification for the Bislsan radar. We also expect that the light rain method for obtaining the Z_{DR} bias may be used as an alternative to the vertical pointing scan method, because the rainfall estimation using this method performed well in our case. Using DSD data for the calculation of Z_{DR} bias might give more accurate rainfall estimation with $R(Z,Z_{DR})$.

Finally, the accuracy of $R(Z,Z_{DR},K_{DP},A_H)$ was not very sensitive to Z_{DR} and Z_H biases in both observations and simulations. Thus $R(Z,Z_{DR},K_{DP},A_H)$ is expected to be less sensitive to Z_{DR} and Z_H errors and could be used to estimate rainfall for heavy rainfall cases in Korea until an accurate hydrometeor classification algorithm is developed.

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Table 1. Polarimetric radar rainfall relations used in this study.

Relations		Relations	
$R(Z)$	$R=0.017Z^{0.714}$	$R(K_{DP})$	$R=61.5K_{DP}^{0.908}$
$R(A_H)$	$R=3409A_H^{1.02}$	$R(Z,Z_{DR})$	$R=0.0148Z^{0.818}Z_{DR}^{-3.72}$
$R(K_{DP},Z_{DR})$	$R=82.2K_{DP}^{0.855}Z_{DR}^{-1.977}$	$R(Z,K_{DP},A_H)$	$R=17211Z^{-0.027}K_{DP}^{0.62}A_H^{0.65}$
$R(Z,Z_{DR},K_{DP},A_H)$		$R=4502Z^{-0.014}Z_{DR}^{-0.389}K_{DP}^{0.486}A_H^{0.653}$	

Table 2. Statistics of the comparison of hourly rainfall amount between $R(Z,Z_{DR})$ and gages.

Relation	Z_H bias source	Z_{DR} bias source	RMSE	NE	CC
$R=0.0148Z^{0.818}Z_{DR}^{-3.72}$	Observed Z_{DR}	Observed Z_{DR}	17.2	0.66	0.77
		mZ_{DR}	9.2	0.56	0.95
	mZ_{DR}	Observed Z_{DR}	15.2	0.53	0.77
		mZ_{DR}	7.4	0.45	0.95

Table 3. Same as Table 2 but for $R(Z,Z_{DR},K_{DP},A_H)$.

Relation	Z_H bias source	Z_{DR} bias source	RMSE	NE	CC
$R=4502Z^{-0.014}Z_{DR}^{-0.389}K_{DP}^{0.486}A_H^{0.653}$	Observed Z_{DR}	Observed Z_{DR}	5.2	0.30	0.95
		mZ_{DR}	5.2	0.30	0.95
	mZ_{DR}	Observed Z_{DR}	5.3	0.30	0.95
		mZ_{DR}	5.4	0.31	0.95

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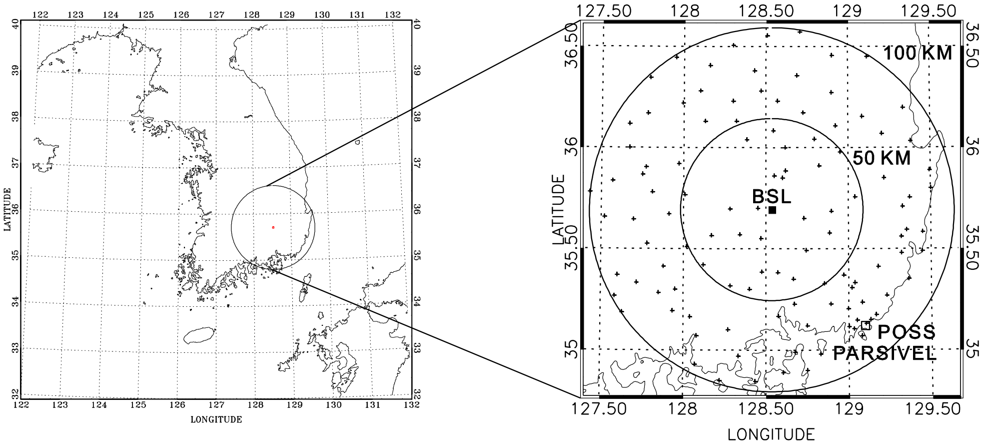
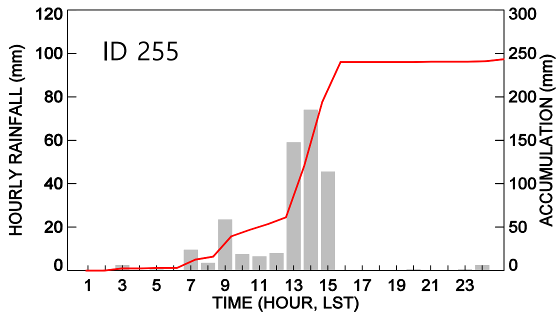
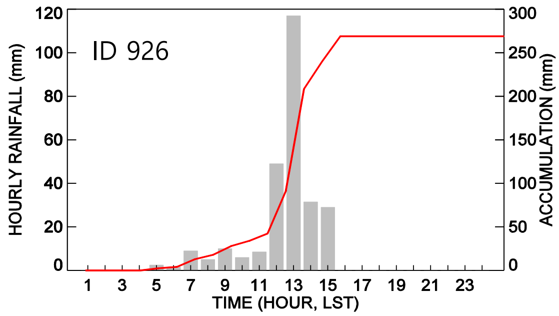


Figure 1. Location of Bislsan radar (solid rectangle), the POSS and PARSIVEL disdrometer (open rectangle), and rain gages (plus signs) distributed within 100 km of the radar. The circles are at 50 and 100 km from the radar.

(a)



(b)



(c)

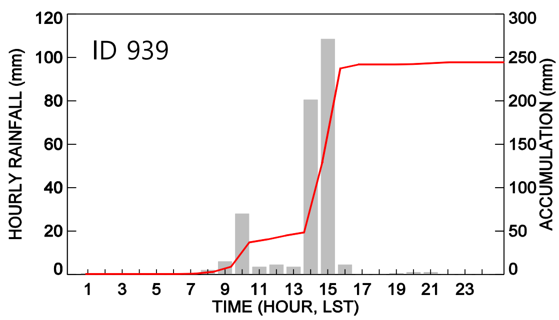


Figure 2. Time series of hourly rainfall (gray bars) and accumulation (red line) from the three gages that recorded the highest rainfall (a) ID 255, (b) ID 926, (c) ID 939.

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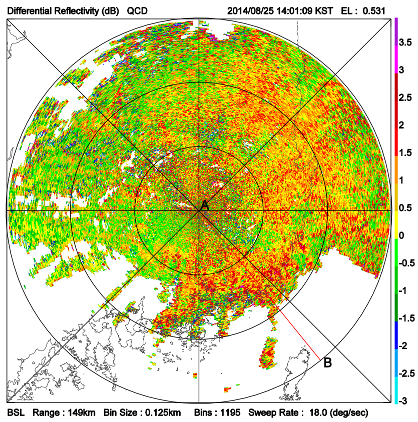
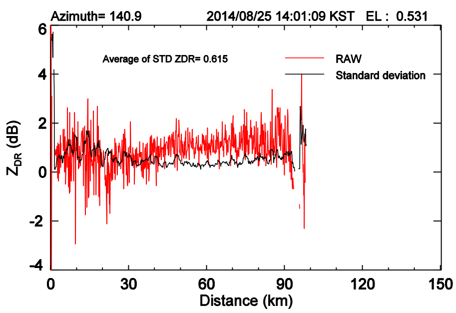
(a)



(b) (c)



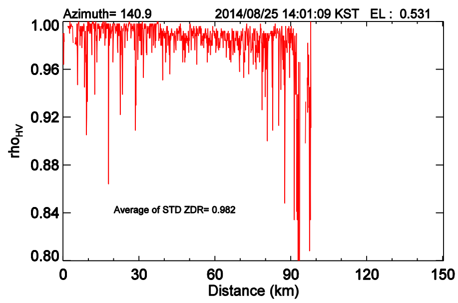


Figure 3. (a) Distribution of Z_{DR} within the radar coverage, (b) the radial profile of Z_{DR} and (c) cross correlation along the line A–B in (a) at 1401 LT 25 August 2014.

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(a) (b)

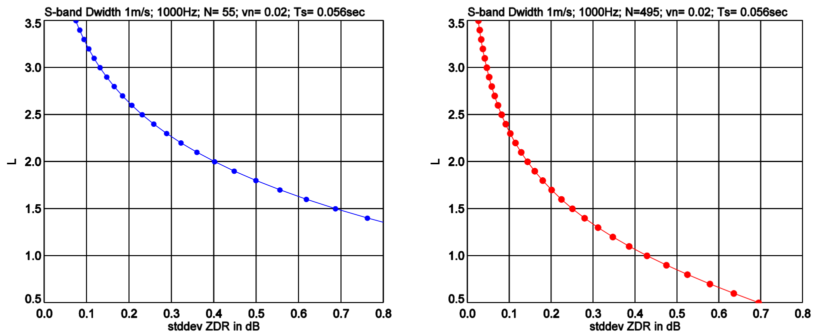

Figure 4. Theoretical relation between standard deviation of Z_{DR} and cross correlation using (a) the scan configuration of the Bislsan radar. Dwell time is 56 ms, number of samples is 55, normalized Doppler width is 0.02; (b) same as (a) but for 495 samples.

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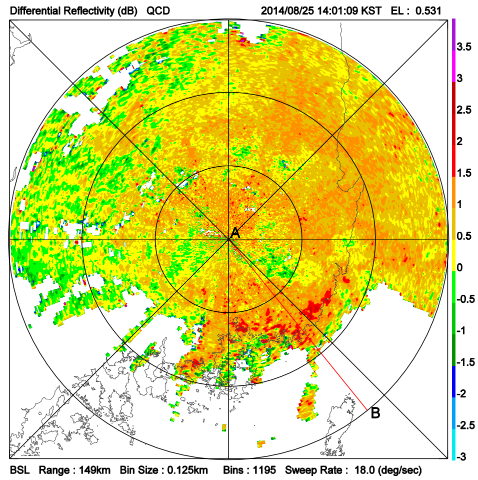
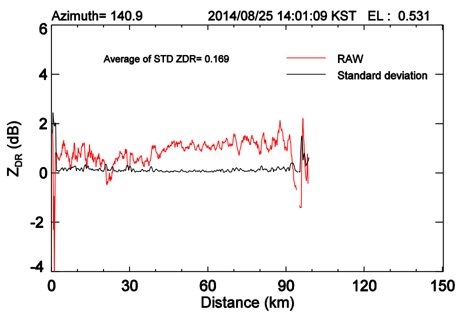
(a)



(b) (c)



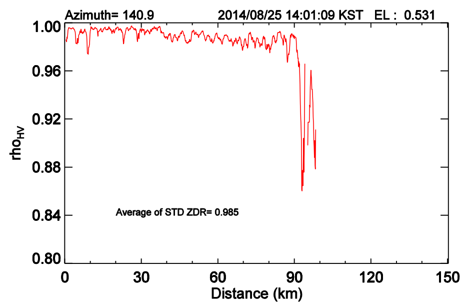


Figure 5. Same as Fig. 3 but for moving averages of Z_{DR}.

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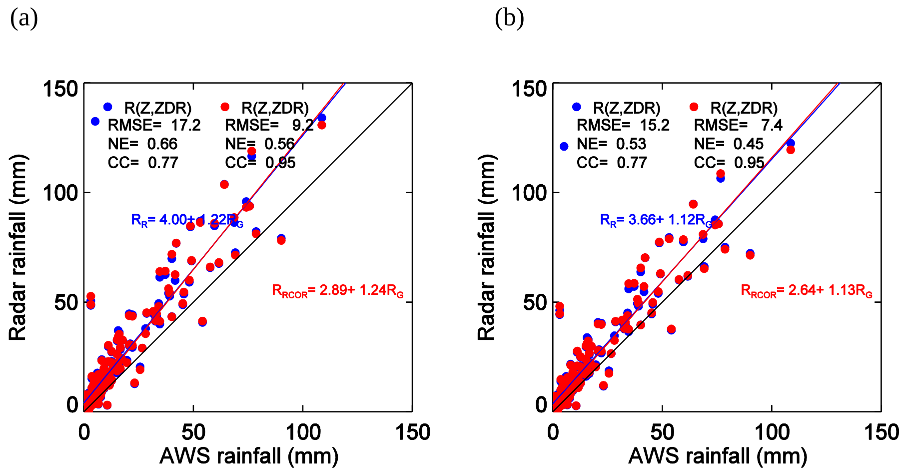

Figure 6. Scatter plot of 1 hour rainfall obtained by R(Z,Z_{DR}) against gage rainfall. (a) Radar rainfall was calculated using Z_H bias calculated from observed Z_{DR} bias and Z_{DR} biases calculated from observed Z_{DR} (blue full circles) and mZ_{DR} (red full circles), (b) same as (a) but for Z_H bias calculated from mZ_{DR}.

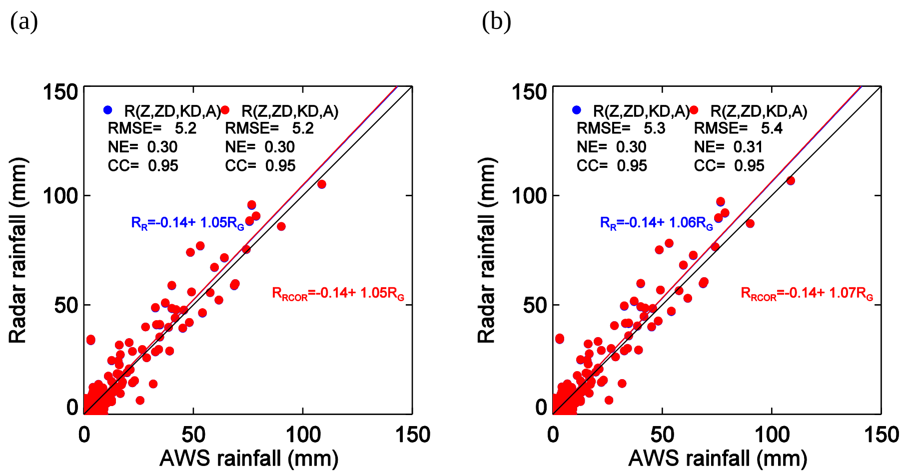

Figure 7. Same as Fig. 6 but for radar rainfall obtained by R(Z,Z_{DR},K_{DP},A_H).

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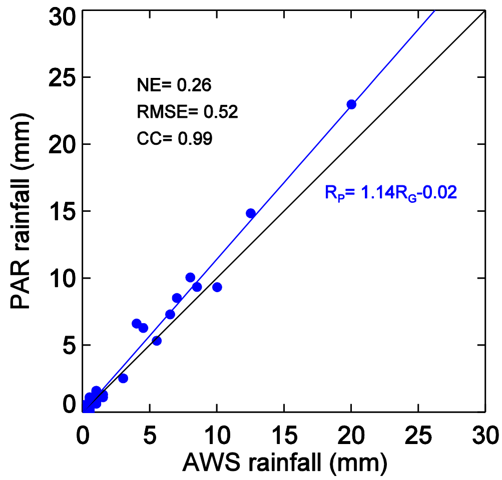

Figure 8. Scatter plot of 10 min rainfall amount measured by PARSIVEL and gage for 24 hours.

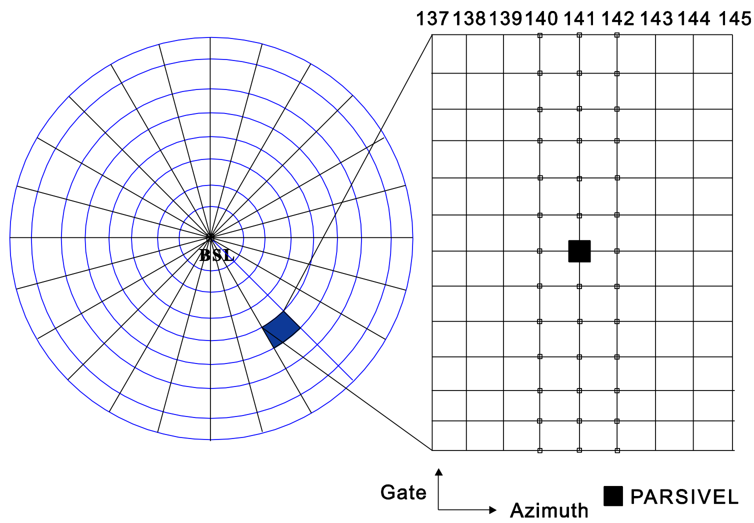

Figure 9. Schematic diagram for the comparison of radar and PARSIVEL Z_{DR}. The numbers refer to azimuth angle.

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(a) (b)

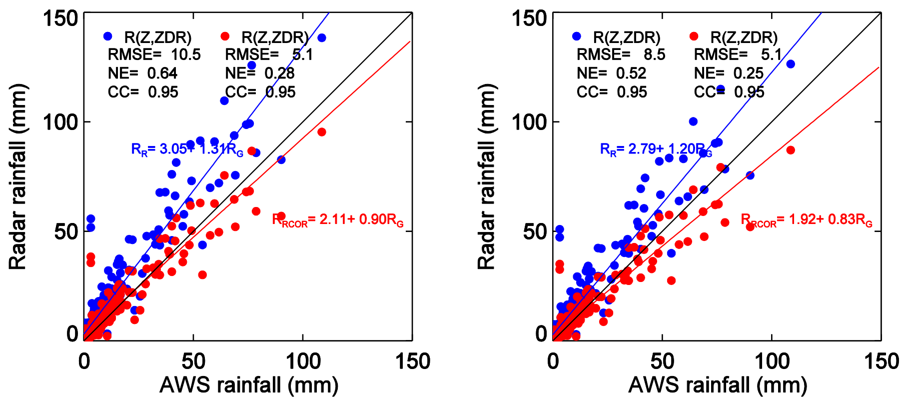

Figure 10. Same as Fig. 6 but for Z_{DR} biases determined by comparison between radar and PARSIVEL.

(a) (b)

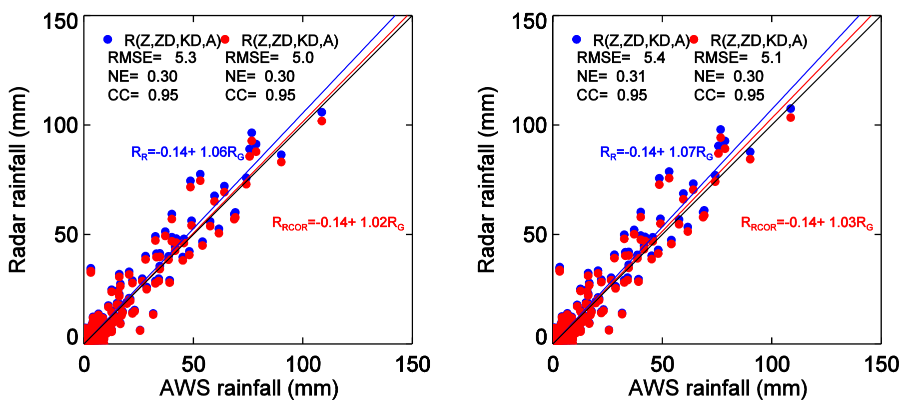

Figure 11. Same as Fig. 7 but for Z_{DR} biases determined by comparison between radar and PARSIVEL.

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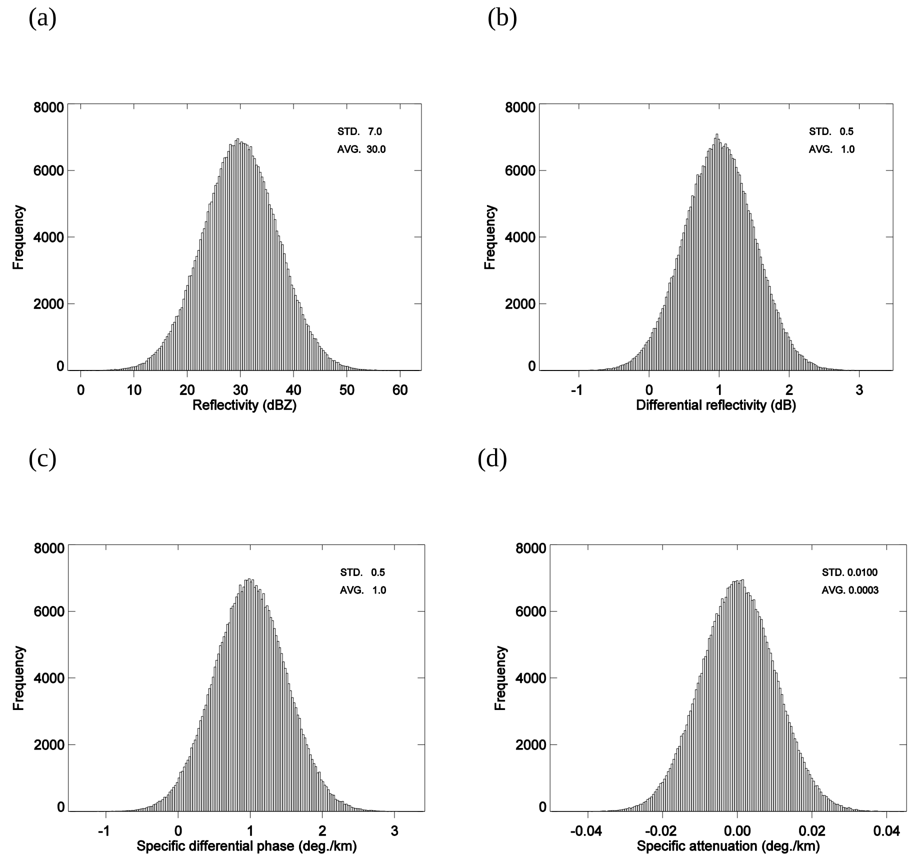

Figure 12. Distribution frequencies of the generated polarimetric variables. (a) Z_H, (b) Z_{DR}, (c) K_{DP}, and (d) A_H.

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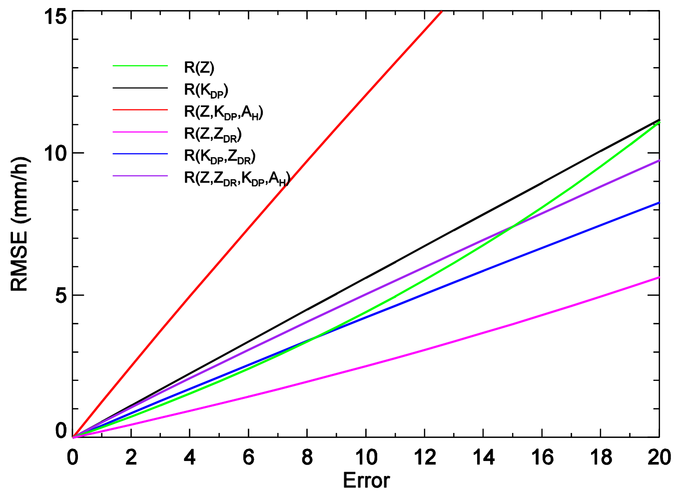
(a)



(b)

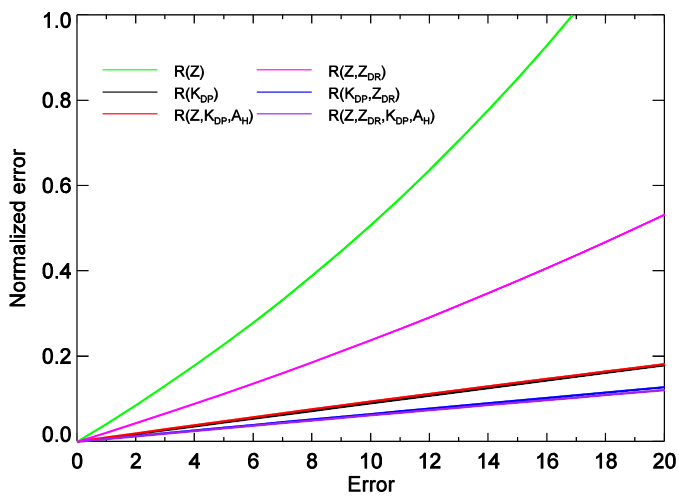


Figure 13. Distribution of (a) RMSE and (b) NE with generated errors for different rainfall relations. Magenta, black, red, green, blue, and purple lines show RMSE and NE obtained from the rainfall relations R(Z), R(K_{DP}), R(Z,K_{DP},A_H), R(Z,Z_{DR}), R(K_{DP},Z_{DR}), and R(Z,Z_{DR},K_{DP},A_H), respectively.