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Rainwater content estimated using polarimetric radar parameters in the Heihe River Basin

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The rainwater content of cold and arid regions has strong spatial and temporal heterogeneity. Representing rainwater content at high resolution can help us understand the characteristics of inland river basin water cycles and improve the prediction accuracy of hydrological models. Data were used from the Watershed Allied Telemetry Experimental Research (WATER) project of the Heihe River Basin, which is the second largest inland river basin in the arid regions of northwest China. We used raindrop size distributions to improve the rain water content estimation of meteorological radar and to obtain accurate rain water content data in this area. Subsequently, four estimation methods applied in the polarimetric radar were tested. The results of a non-linear regression method show that $M(K_{DP}, Z_H, Z_{DR})$ has the highest accuracy for measuring rain water content. Finally, the formula for measuring the spatial rain water content was applied to a polarimetric radar with an X-band (714XDP). The influence of raindrop size distribution (DSD) on the formula $M(K_{DP}, Z_H, Z_{DR})$ is lowest sensitivity, and it can be explained as follows. On the one hand, the horizontal and vertical front reflection cross sections of the radar are different, so K_{DP} is proportional to the 3rd power of the raindrop diameter. On the other hand, the rear cross section of the radar is proportional to the sixth power of the raindrop diameter. The rainfall's spatial water content M is proportional to the 3rd power of the raindrop diameter, so the influence of the drop size distribution (DSD) on K_{DP} is much smaller than that of Z_H.

1. Introduction

Our state of knowledge of the physical properties of clouds is far from complete, and as a result, ideas about cloud formation and growth can only be tentative at best. Clouds strongly influence the Earth's energy budget. Clouds partially control the amount of solar radiative energy absorbed by the climate system, partitioning the energy between the atmosphere and the Earth's surface. They also control the loss of energy to space by their effect on thermal emission. The cloud rainwater content is an important physical parameter in cloud precipitation physics, it is an important component of the atmospheric moisture balance, and it plays an important role in the Earth's radiation energy balance. Because radiation and the liquid water of clouds have intense interaction, this feedback can exert a great impact on global climate change (Paltridge, 1980; Somerville and Remer, 1984; Stephens and Greenwald, 1991). Radiometric data can be retrieved for cloud liquid water (Warner et al., 1985). Techniques for cloud liquid water retrieval over land have been developed using data from the Special Sensor Microwave/Imager 85.5 GHz (3.5 mm) channels (Jones and Vonder, 1990; Greenwald et al., 1997). A technique was presented for deriving tropospheric water vapor and cloud liquid water from a suite of ground-based sensors (Han and Westwater, 1995). Solheim et al. (1998) developed a similar radiometer to obtain the vertical distribution of water vapor by

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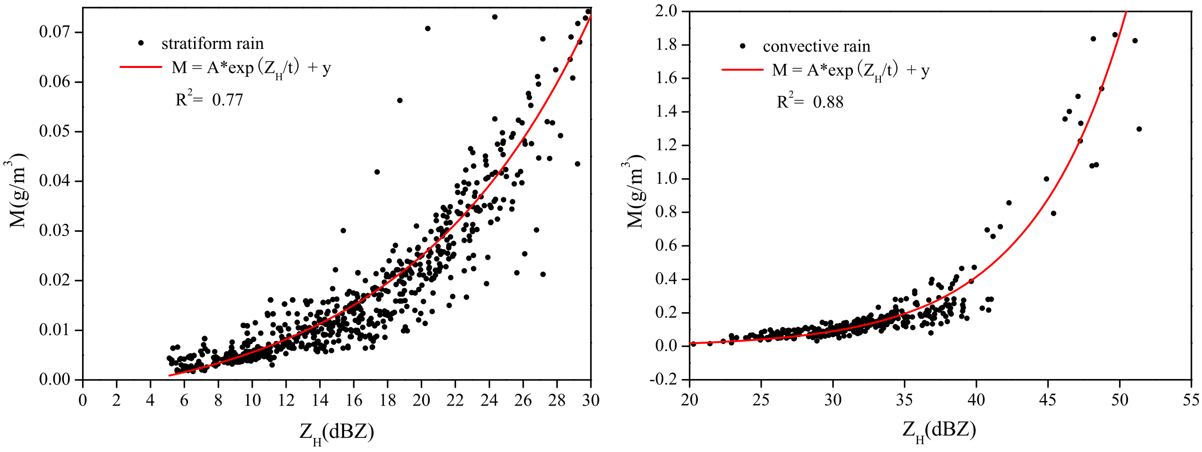

Fig. 1. Scatter plots of the radar reflectivity (Z) and rain water content (M).

making observations on the pressure-broadened water vapor line from 22 to 29 GHz; these wavebands also contain information on cloud liquid water profiles. Although space-based and ground-based microwave radiometer data can retrieve cloud liquid water, their faults cannot be ignored. With the advent of dual-polarized radar techniques, it is possible to achieve significantly higher accuracies in the estimation of cloud liquid water, and in some cases, of hydrometeor amounts. Hong et al. (2008) investigated the relationship between ice water content (IWC) and equivalent radar reflectivity (Z_H) at 94 GHz for clouds consisting of nonspherical ice particles with geometrical shapes of hexagonal solid and hollow columns, plates, 6-branch bullet rosettes, aggregates, and droxtals. Radar signals attenuation is already an important problem at C and X band frequencies. Research studies for attenuation on the C band wavelength were done by May et al. (1999), Carey et al. (2000), Keenan et al. (2001), and Bringi and Chandrasekar (2001). The formula can be applied directly into correction for attenuation to radar echoes during data processing for quantitative measurement of precipitation. Many researches and operational meteorological radars employ shorter wavelengths, such as those at X band. The attenuation effects at X band are more serious when compared with C band, and account for these effects has been a significant problem for quantitative estimates of rainfall rate based on reflectivity measurements at these wavelengths. An error structure was been analyzed at the X band (Chandrasekar et al., 2002). A unique dataset consisting of high-resolution polarimetric radar measurements and dense rain gauge and disdrometer observations collected in east-central Florida during the summer of 1998 was examined by Brandes et al. (2002). The most significant improvement was reported in the latest study in Oklahoma (Ryzhkov et al. 2002) using the $R(K_{DP}, Z_{DR})$ relation. Relatively modest improvement was observed in Florida (Brandes et al., 2002, 2003, 2004) with the best results obtained from the $R(Z_H, Z_{DR})$ relation.

In this work, we use raindrop size distribution data to quantitatively study the statistical errors of polarimetric rain water content estimators due to DSD variations. We use polarization radar parameters, including differential reflectivity (Z_{DR}) and the specific differential propagation phase (K_{DP}), to improve the quantitative estimation of rain water content.

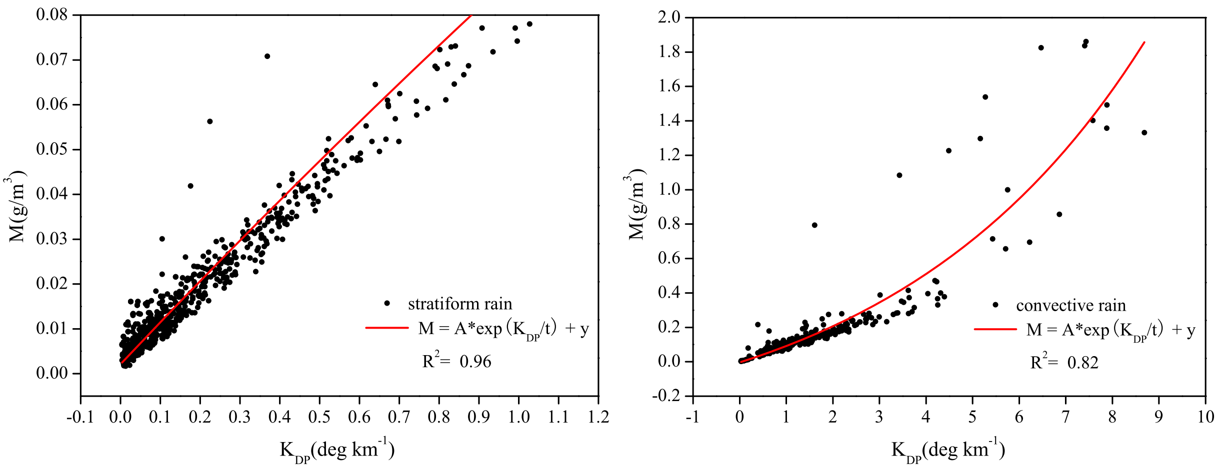

Fig. 2. Scatter plots of the specific differential phase (K_{DP}) and rain water content (M).

Table 1a
Coefficients of the $M(Z_H, Z_{DR})$.

Rain type	a	b	c
Stratiform	0.0014	0.1682	−0.7379
Convective	0.0006	0.1883	−0.3396

2. Experiment

The Watershed Airborne Telemetry Experimental Research (WATER) project is a large-scale experiment integrated with aviation, satellite and ground-based remote sensing. The experiment was conducted at Heihe River Basin, which is the second largest inland river at the northeast of China's Qinghai–Tibet Plateau. The experimental site is located at the east longitude of 100.41° and the north latitude of 38.85°, with an altitude of 1515 m. The Heihe River Basin is of great significance to northwest China's economic and social development. The Heihe River Basin is the foundation of agriculture, and it makes an enormous contribution to the restoration of ecosystems and the environment. The Heihe River Basin is an arid, semi-arid and mountainous area, and the glacier–river–oasis–desert landscape is closely related to water. The DSD data were collected between May and July in 2008 during the second phase of the test period of the Watershed Allied Telemetry Experimental Research (WATER) project (Li et al., 2009).

The disdrometer used in the experiment was a Parsivel produced by OTT, which is a new type of laser raindrop spectrometer using a new type of laser technology. The disdrometer can divide the raindrop diameter and the terminal velocities into 32 classes. 714XDP polarimetric radar was used in the experiment. This radar uses a Vaisala Sigmet Digital IF Receiver and an RVP8 Signal Processor, and its mode is simultaneous transmission and receiving (STSR). The Parsivel was 30 km from the radar. The stratiform clouds usually have a large range and most of them have a bright band, and the convective clouds usually have a convection bubble in Heihe river basin. The DSD data were divided into stratiform and convective rainfall. The echo images of the X-band polarimetric radar were used to distinguish between convective and stratiform rainfall.

3. Rain water content

Equations for the shape of a falling raindrop and polarimetric parameters are listed in the article by Zhao et al. (2011). The rain water content M (gm^{-3}) is given by

$$M = \frac{\rho_w \pi}{6} \int_{D_{min}}^{D_{max}} D^3 N(D) dD \quad (1)$$

where ρ_w is the water density (10^3 kgm^{-3}), D is the diameter (mm) of a raindrop, D_{max} is the maximum drop diameter, D_{min} is the minimum drop diameter, and $N(D)d(D)$ is the number of drops (m^{-3}) in the diameter interval D to $D+dD$. The raindrop diameters and distributions were directly obtained from PASIVEL. The rainwater content M is one of the most important parameters in meteorology. The vertical distribution information of M is useful for understanding the evolution of precipitation processes in clouds and also is a useful parameter for the very short-range forecasting of rainfall. On larger scales, the change in M with height over a long period is related to the latent heat release in the surrounding atmosphere, which is an important heat source in global-scale circulation.

Table 1b
Coefficients of the $M(K_{DP}, Z_H, Z_{DR})$.

Rain type	a	b	c	d
Stratiform	0.0017	0.1474	0.5761	−0.7234
Convective	0.0008	0.1703	0.1104	−0.3219

4. Estimation methods of rain water content by polarimetric radar parameters

The traditional method of estimating the liquid water content of the air is subject to error from the DSD changes, mainly because a one-to-one relationship does not exist between M and Z_H. Because Z_H and M are impacted by various DSD moments, the same Z_H may not always correspond to the same M, and the same M may not always correspond to the same Z_H. In the case of Rayleigh scattering, Z_H is proportional to D^6, while M is proportional to D^3. In this case, the natural raindrop size distribution will impose great uncertainty on the M–Z_H relationship. To improve the estimation accuracy of the air moisture content, it is highly effective to divide rainfall types into stratiform and convective clouds. Fig. 1 shows the scatterplot of the M–Z_H relationship of the stratiform and convective clouds. The vertical axis M includes the direct calculations of DSD data within 30 s. From Fig. 1, it can be found that there is a relationship between M and Z_H as follows: $M = Ae^{ZH/t} + y$. Each coefficient value of the M–Z_H relationship of stratiform and convective clouds is obtained by fitting as follows: $M = 0.005e^{ZH/10.96} - 0.007$, $M = 0.001e^{ZH/6.68} - 0.003$, where R^2 is 0.77 and 0.88, respectively. Fig. 1 shows some dispersed points, which may be caused by non-meteorological data.

The unique advantages of polarimetric radar can be applied to the estimation of the rain water content. We constructed a model with a combination of polarimetric radar parameters to estimate the rain water content. A simple approach is to use only K_{DP}. Fig. 2 shows a scatter plot of K_{DP} and M for stratiform and convective clouds. K_{DP} and M were directly calculated from the DSD data. It can be found that M–K_{DP} meets the following relationship: $M = Ae^{KDP/t} + y$. Each coefficient value of the M–K_{DP} relationship of stratiform and convective clouds obtained by fitting is as follows: $M = 0.005e^{KDP/10.96} - 0.007$, $M = 0.001e^{KDP/6.68} - 0.003$, where R^2 is 0.96 and 0.82, respectively.

Due to the attenuation of electromagnetic waves in the rainfall zone, it was long believed that X-band radar was not suitable for estimation of the ground rainfall rate and liquid water content of the air, but this situation fundamentally changed with the introduction of polarimetric radar. Polarimetric radar can obtain the polarimetric information of precipitation clouds, the differential reflectivity Z_{DR}, and the specific differential phase K_{DP} so that the use of X-band radar to estimate the liquid water content of the air becomes feasible. There is a very small impact from DSD changes and radar hardware calibration on K_{DP}, so the attenuation in the rain area is also very small. Due to the presence of hail in the rain area, the estimated value of rain water content may be large, and this effect will be reduced when K_{DP} is introduced. The differential phase can be used to revise electromagnetic wave attenuation in the propagation process (Ryzhkov and Zrnic, 1996; Ryzhkov et al., 2000). Due to these advantages, it is of great importance to establish the model with a combination of polarimetric parameters, such as $M(Z_H, Z_{DR})$ and $M(K_{DP}, Z_H, Z_{DR})$, to measure rain water content. The polarimetric parameters were used to establish the following relationship: $M = a \times e^{b \times Z_H + c \times Z}{}_{DR}$ and $M = a \times e^{b \times Z_H \times K}{}_{DP}{}^{+d \times X}{}_{DR}$. The nonlinear regression analysis method was adopted to obtain the values of various parameters. The concrete results are shown in Tables 1a and 1b.

In Figs. 3 and 4, the rain water content M calculated from the various formulas $M(Z_H)$, $M(K_{DP})$, $M(Z_H, Z_{DR})$, and $M(Z, Z_{DR}, K_{DP})$, and the rain water content M_{dis} directly calculated from DSD data were compared. From the scatter plot, it can be concluded that in the four methods, the impact of the DSD on $M(Z, Z_{DR}, K_{DP})$ is the minimum, and it is closest to the calculated value of the DSD. $M(Z_H)$ has the maximum deviation, and it is greatly impacted by the DSD. For the quantitative test of the accuracy of these four methods, the mean relative error (*MRE*) was calculated. This error is defined as

$$MRE = \sum_n |M_{cal} - M_{dis}| / M_{dis} / n \tag{2}$$

where R_{cal} is the rain water content calculated by the estimators and R_{dis} is the rain water content calculated from DSD data through actual observation. In the four methods, the *MRE* values corresponding to stratiform clouds were 32.0%, 29.6%, 23.7.0%, and 22.1%. The *MRE* values corresponding to convective clouds were 26.9%, 20.2%, 22.1% and 17.6%, respectively. Through the above comparison, it can be concluded that the impact of DSD changes on $M(Z, Z_{DR}, K_{DP})$ is the minimum.

5. Cloud water content retrieved by polarimetric radar

A convective rain process occurred on 13 June 2008, for which we used the X-band polarimetric radar test rain water content estimators. Some sources of error in radar remote sensing for quantitative precipitation estimation were existed. The sensitivity of Z_H–R relations to variations in raindrop size distributions (DSD) is the major source of error (Joss and Waldvogel, 1990; Collier, 1996). The use of different artificial intelligence (AI) techniques for clutter signals identification in the context of radar based precipitation estimation was presented (Isiam et al., 2012). The radar data quality was been corrected before used. The shape of raindrops can be approximated by oblate spheroids for light rain. Radar and in situ aircraft-based observations show that on average the raindrops are oriented with the symmetry axis in the vertical direction. This implies that the shape of raindrops seen at an elevation angle of 90 is nearly circular. Therefore, Z_{DR} measure-

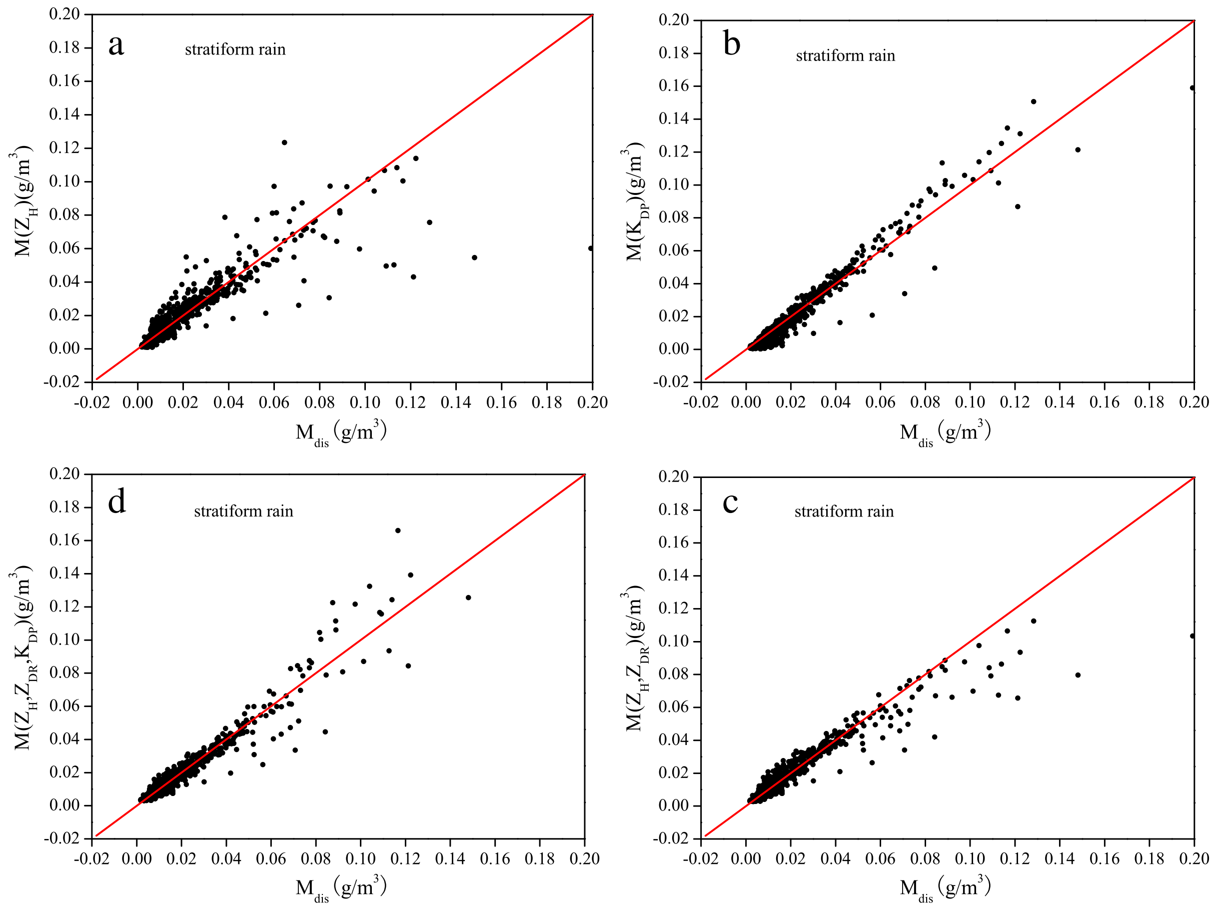

Fig. 3. Scatter plots of M_{dis} calculated from measured drop size distribution and M estimated by four types (a) $M(Z)$, (b) $M(K_{DP})$, (c) $M(Z, Z_{DR})$ (d) $M(Z, Z_{DR}, K_{DP})$ for stratiform rain.

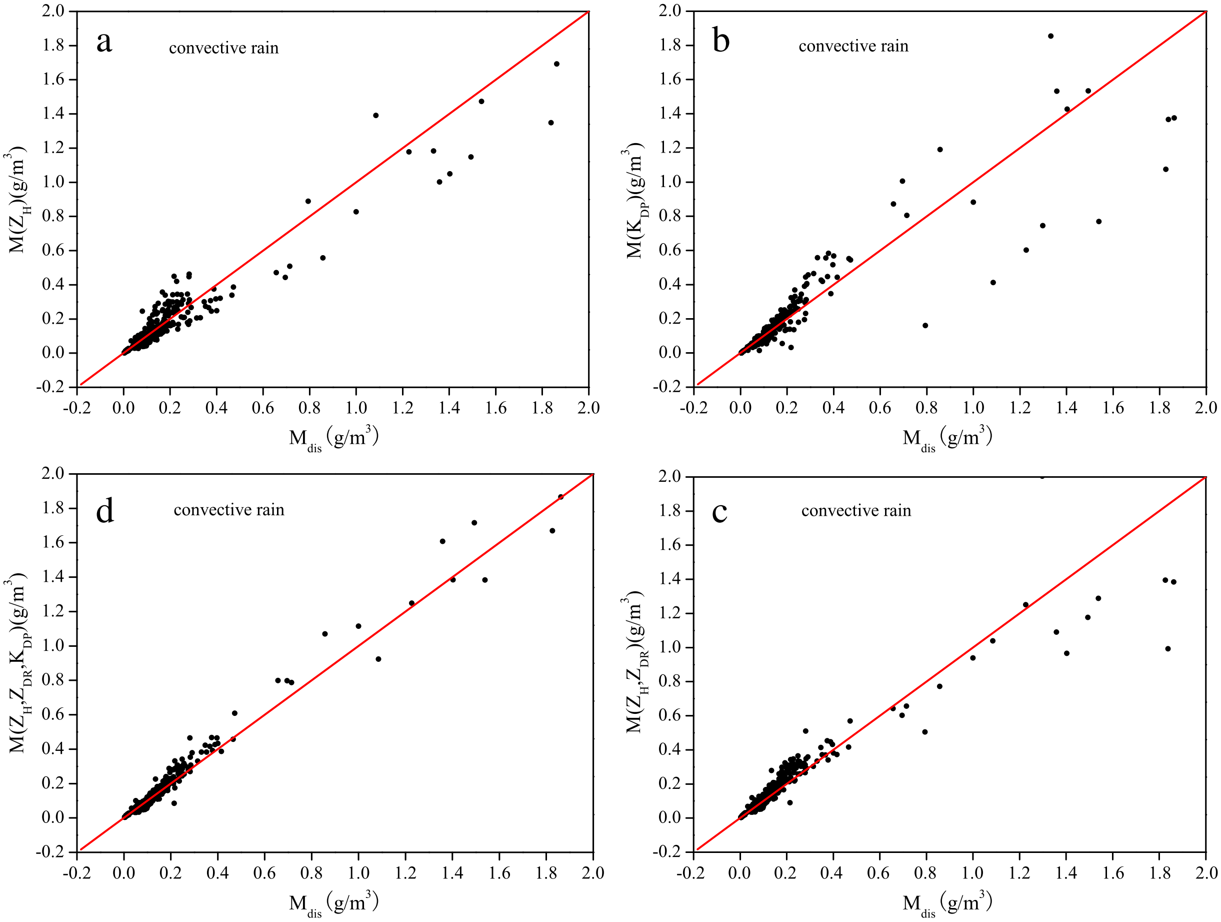

Fig. 4. Scatter plots of M_{dis} calculated from measured drop size distribution and M estimated by four types (a) $M(Z)$, (b) $M(K_{DP})$, (c) $M(Z, Z_{DR})$ (d) $M(Z, Z_{DR}, K_{DP})$ for convective rain.

ments performed with the antenna pointing at an elevation of 90 should be 0 dB. However if there is nonzero Z_{DR} due to the system bias, it does not change with the different H and V orientations looking vertical. In many of radars, the different H and V orientations can be achieved by changing the azimuth positioning over zero to 360, keeping the elevation angle at 90.

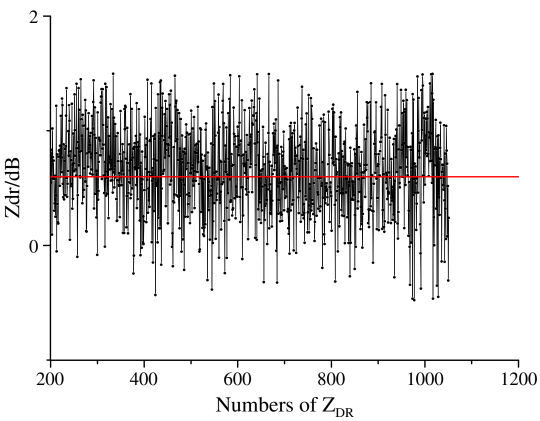

Fig. 5. Mean value of the Z_{DR} for 88°elevation.

However, the exact procedure depends on the set up of the scanning servo system of the radar. In summary, the average Z_{DR} computed with all possible orientations of the polarization states of the radar antenna pointing in the vertical direction should be zero. Fig. 5 shows the mean value of the Z_{DR} is 0.6 for 88°elevation. This is the system deviation. It is well known that convective storms cause significant attenuation and differential attenuation at X-band. As a consequence, radar measurements of reflectivity and differential reflectivity must be corrected for rain attenuation before they can be used quantitatively. in addition, polarimetric radars at X band have, one important advantage, the specific differential phase K_{DP} is much larger than that at longer wavelengths From scattering simulations, compared to C and S bands, respectively, K_{DP} at X band is larger by about 1.5 and 3 times for the same rain rate. We used the K_{DP} to correct the attenuated Z_H and Z_{DR} (Bringi et al., 2001). The specific attenuation (A_H) and the specific differential attenuation (A_{DP}) can be gat as follows:

$$A_H = \alpha \cdot Z_h{}^{\beta} \quad (Z_H < 25\,\text{dBz}) \tag{3}$$

$$A_H = a_1 \cdot K_{DP} \quad (Z_H \geq 25\,\text{dBz}) \tag{4}$$

$$A_{DP} = \gamma \cdot A_H{}^{d} \quad (Z_H < 25\,\text{dBz}) \tag{5}$$

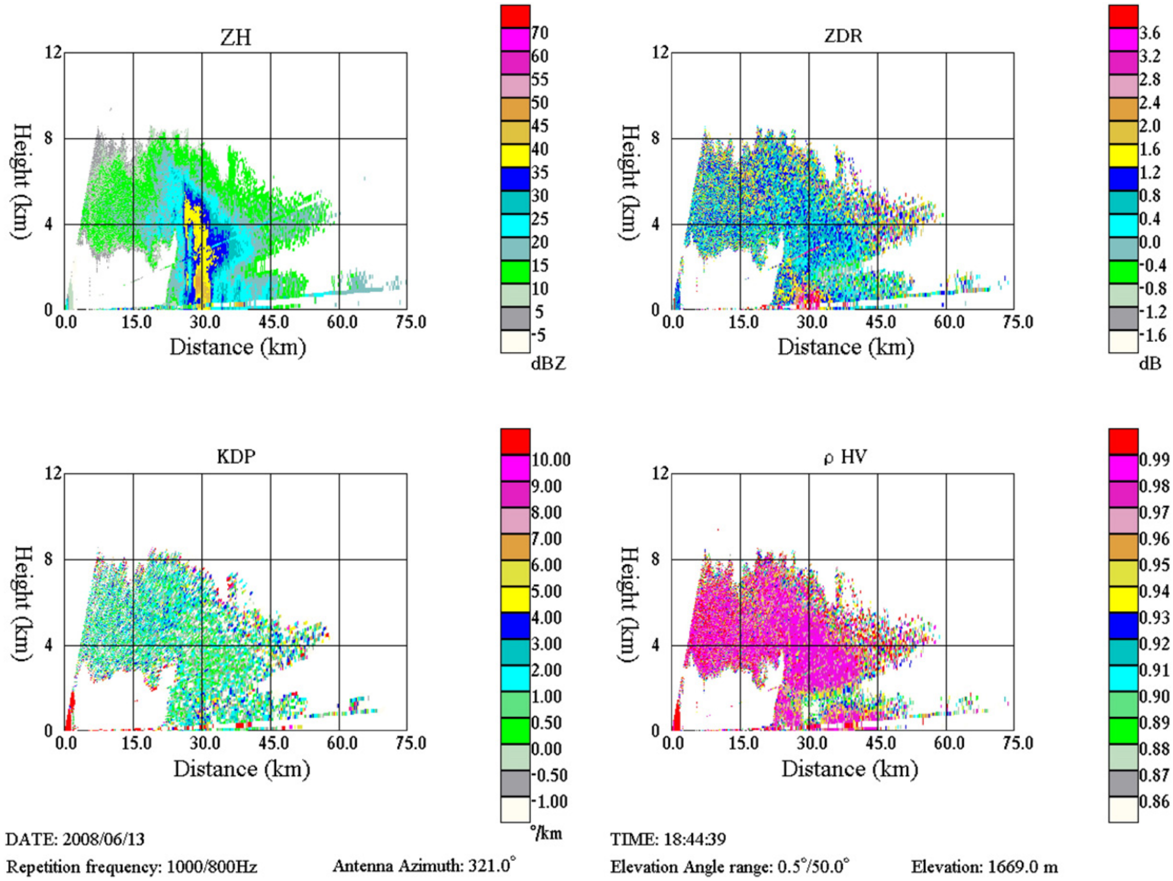

Fig. 6. The image of the RHI.

$$A_{DP} = a_2 \cdot K_{DP} \quad (Z_H \geq 25\,\text{dBz}). \tag{6}$$

Then, Z_H and Z_{DR} can be corrected as follows:

$$Z_H(r) = Z_{Ha}(r) + 2\int_0^r A_H(s)ds \tag{7}$$

$$Z_{DR}(r) = Z_{DRa}(r) + 2\int_0^r A_{DP}(s)ds. \tag{8}$$

Fig. 6 presents an image of the RHI, which was obtained from the X-band polarimetric radar on 13 June 2008. The Z_H, Z_{DR}, and K_{DP} were also obtained by the X-band polarimetric radar, and the quality of these radar data was also corrected. We used the rain water content estimator $M(Z_H, Z_{DR}, K_{DP})$ to obtain the rain water content, and the result is shown in Fig. 7. Because of a lack of rainfall in the northeastern areas of the Qinghai–Tibet Plateau, rocket rain enhancement and artificial suppression of hail have become important for agriculture in these areas. This result can guide weather modification, in the Qinghai–Tibet Plateau.

6. Summary

In this article, 1040 units of DSD data measured by a Parsivel disdrometer were used to calculate the radar reflectivity factor, Z_H, the specific differential phase, K_{DP}, and the differential reflectivity, Z_{DR}. Subsequently, the four methods for measuring the spatial liquid water content are as follows: $M(Z_H)$, $M(K_{DP})$, $M(Z_H, Z_{DR})$ and $M(K_{DP}, Z_H, Z_{DR})$. The coefficient value of each relationship was obtained through nonlinear fitting. A quantitative analysis was made of the impact of the DSD on the four methods. The simulation results show that the impact of DSD on the estimator $M(K_{DP}, Z_H, Z_{DR})$ is the minimum. The mean relative errors (*MREs*) of $M(Z_H)$ and $M(K_{DP}, Z_H, Z_{DR})$ corresponding to stratiform and convective clouds were 32.0%, 22.1% and 26.9%, 17.6%, respectively. In the definition of K_{DP}, the forward-scattering amplitudes of radar are proportional to the 3rd power of the raindrop diameter, while the radar reflectivity Z_H is proportional to the 6th power of the raindrop diameter. X-band polarization radar parameters were used to retrieve the rainwater content was given for the Qinghai–Tibet Plateau.

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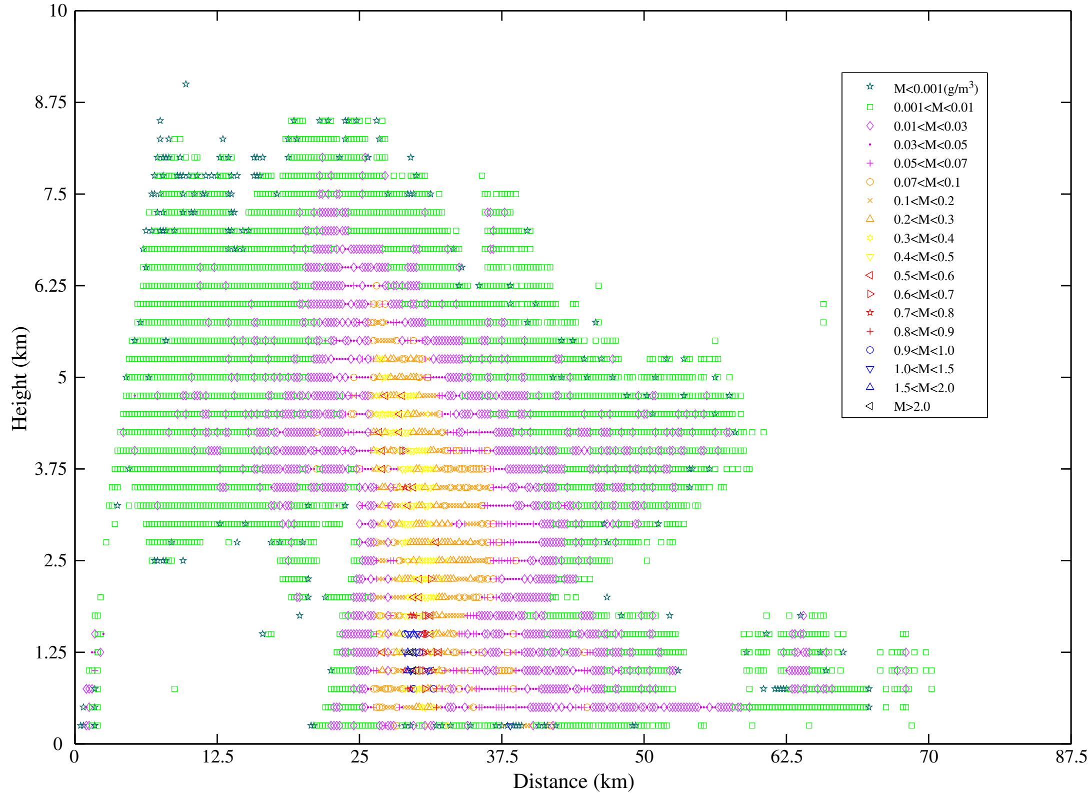

Fig. 7. The cloud water content of convective rain.

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