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Quantitative Precipitation Estimation Using X-band Phased Array Weather Radar

Shaoyu HOU[1,2], Xuejiao CHEN[2,3], Chunnan SUO[2,4], Xiangfeng HU[1,5]*

1. Hebei Provincial Weather Modification Center, Shijiazhuang 051432, China; 2. China Meteorological Administration Xiong'an Atmospheric Boundary Layer Key Laboratory, Xiong'an New Area 071000, China; 3. Hebei Xiong'an New Area Meteorological Service, Xiong'an New Area 070001, China; 4. Hebei Cangzhou Meteorological Observatory, Cangzhou 061000, China; 5. Hebei Key Laboratory of Meteorology and Ecological Environment, Shijiazhuang 050021, China

Abstract This study utilized data from an X-band phased array weather radar and ground-based rain gauge observations to conduct a quantitative precipitation estimation (QPE) analysis of a heavy rainfall event in Xiong'an New Area from 20:00 on August 21 to 07:00 on August 22, 2022. The analysis applied the Z – R relationship method for radar-based precipitation estimation and evaluated the QPE algorithm's performance using scatter density plots and binary classification scores. The results indicated that the QPE algorithm accurately estimates light to moderate rainfall but significantly underestimates heavy rainfall. The study identified disparities in the predictive accuracy of the QPE algorithm across various precipitation intensity ranges, offering essential insights for the further refinement of QPE techniques.

Key words X-band phased array radar; Quantitative precipitation estimation

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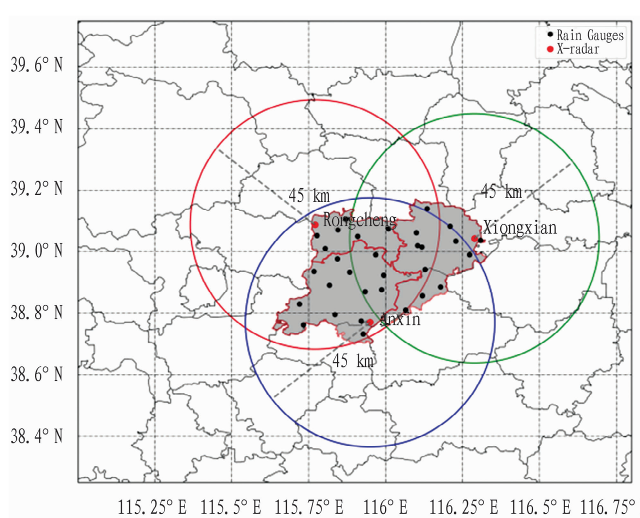
In the 1940s, Marshall and Palmer established an exponential relationship between radar reflectivity and precipitation, expressed as $Z = 200 \times R^{1.6}$ [1]. Subsequent studies have generally fallen into two categories[2]: physically-based methods and statistically-based methods. The latter, from a climatological perspective, develop stable precipitation estimation models using large samples of historical radar and rain gauge data, including optimal processing methods, A-value averaging, probability matching[3–4], and neural networks.

Physically-based methods focus on modeling the relationship between radar observations and raindrop size distribution, often used in radar precipitation estimation. Since the introduction of the Z – R relationship, numerous algorithms have been developed, often using dual-polarization radar observations, either singly or in combination. For instance, Gou *et al.*[5] proposed a Z – R relationship based on cloud type classification; Wu *et al.*[6] developed a Z – R relationship based on echo top height classification; Vivekanandan *et al.*[7] studied estimation algorithms based on hydrometeor phase classification. Additionally, some researchers have classified radar echo intensity by distance from the radar, applying different Z – R relationships for various ranges[8].

As observational methods continue to improve, using X-band phased array weather radar for precipitation estimation is also a crucial approach for enhancing accuracy. This study employed X-band phased array weather radar deployed in Xiong'an New Area to estimate precipitation during a heavy rainfall event on August 21 – 22, 2022, and compared the results with ground-based rain gauge observations.

1 Data and methods

1.1 Data The radar data used in this study were from the X-band phased array weather radar, with a temporal resolution of 1 min, spatial resolution of 30 m, and vertical resolution of 100 m. Ground-based rain gauge data were collected from 31 stations within Xiong'an New Area, with hourly precipitation records. The overall distribution was shown in Fig. 1.



Note: Red dots represent the location of X-radar, and black dots represent the locations of ground-based rain gauges.

Fig. 1 Schematic distribution of the X-band phased array weather radar and ground-based rain gauges in Xiong'an New Area

1.2 Methods Following the Z – R relationship proposed by Marshall and Palmer[1], the 1-min radar echo intensity was used

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* Corresponding author.

to calculate the 1-min radar precipitation estimates, which were then aggregated to obtain hourly radar estimated precipitation. The specific process was shown in Fig. 2.

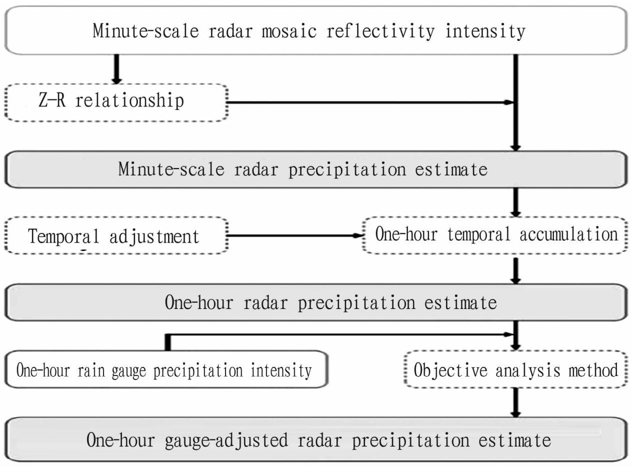

Fig. 2 Flowchart of the quantitative precipitation estimation (QPE) process

2 Evolution of radar echoes

From 20:00 on August 21 to 07:00 on August 22, 2022, heavy rainfall occurred in Xiong'an New Area, with localized torrential rain. The average rainfall over the area was 36.8 mm, with the maximum rainfall and highest hourly intensity both recorded in Laohutou Town, Anxin County, at 72.0 mm and 39.8 mm/h, respectively.

Radar echo imagery revealed the precipitation system underwent a complete life cycle, including rapid development, intensity enhancement, system maturity, and gradual dissipation. During the development stage (Fig. 3a), multiple discrete strong echo cores appeared in Xiong'an New Area, indicating intense convective activity and deep convective cloud development. In the enhancement stage (Fig. 3b), the strong echo region expanded significantly, exhibiting the characteristics of a Linear Convective System (LCS) with a width exceeding 60 km and a length of approximately 20 – 30 km, suggesting a potential cold pool-driven mechanism. As the system matured (Fig. 3c), high reflectivity areas persisted along its leading edge, indicating intense downdrafts and potentially destructive straight-line winds. In the dissipation stage (Fig. 3d), the strong echo area diminished significantly, indicating weakening convective activity. These changes highlighted the typical evolution of mesoscale convective systems, reflecting complex atmospheric dynamics and thermodynamics.

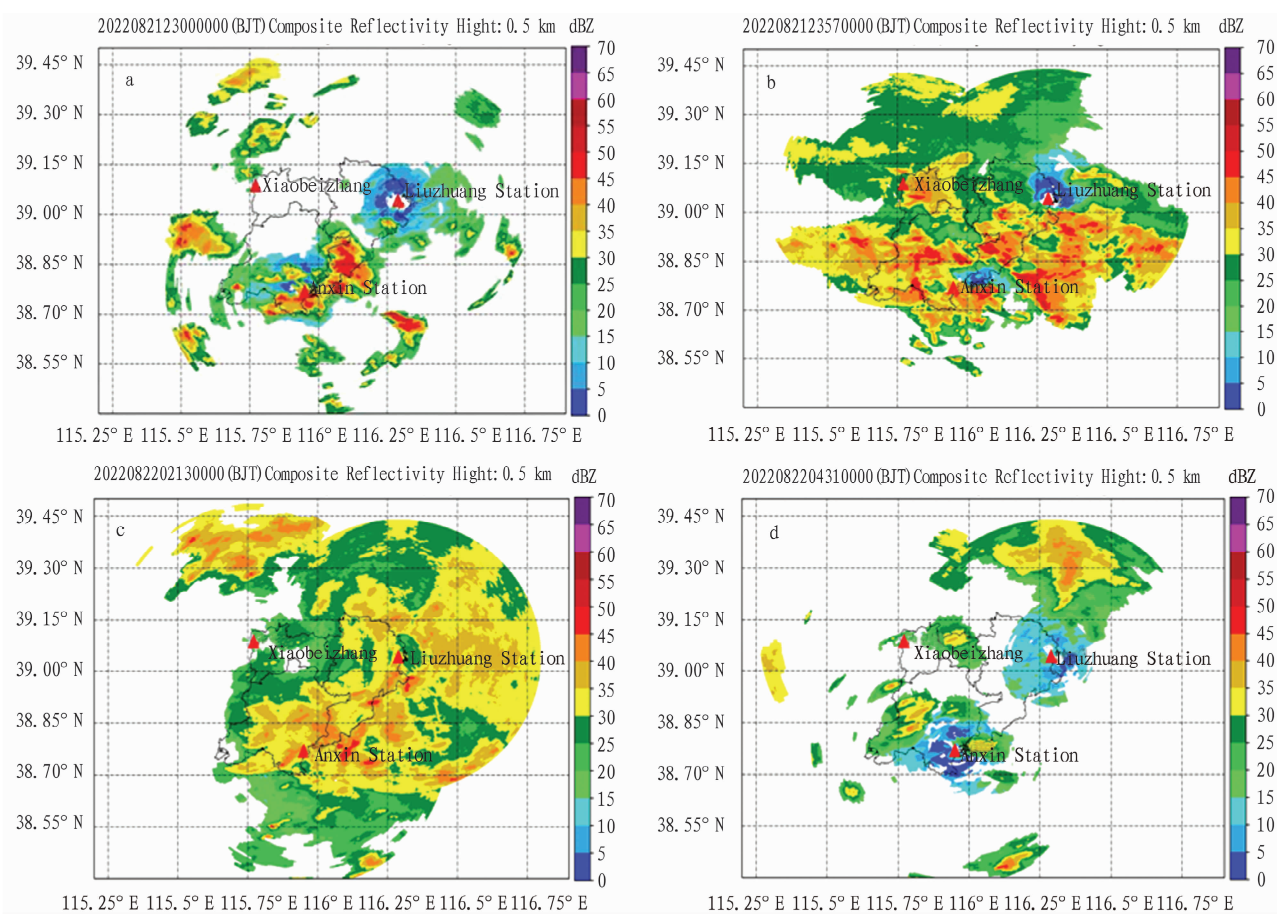

Fig. 3 Composite radar reflectivity at 23:00 on August 21, 2022 (a), 23:57 on August 21, 2022 (b), 02:13 on August 22, 2022 (c), and 04:31 on August 22, 2022 (d)

3 Error analysis of quantitative precipitation estimation

The results (Fig. 4) indicated that the QPE performed with higher accuracy in the low precipitation range (0 – 10 mm), where data points were dense and close to the 1 : 1 line. However, as precipitation intensity increased, the QPE showed a systematic underestimation trend, with the bias widening as precipitation amounts increase. In the moderate precipitation range (10 – 30 mm), underestimation became more pronounced, with most estimates falling below the 1 : 1 line. For heavy precipitation events (> 30 mm), sample size decreased but the underestimation became most severe, reaching up to 50%. Correlation coefficient (0.809), mean bias (– 1.277), relative error (0.558), and root mean square error (4.439) results indicated that scatter plot dispersion increased with precipitation amount, showing QPE is more reliable for small to moderate precipitation estimates.

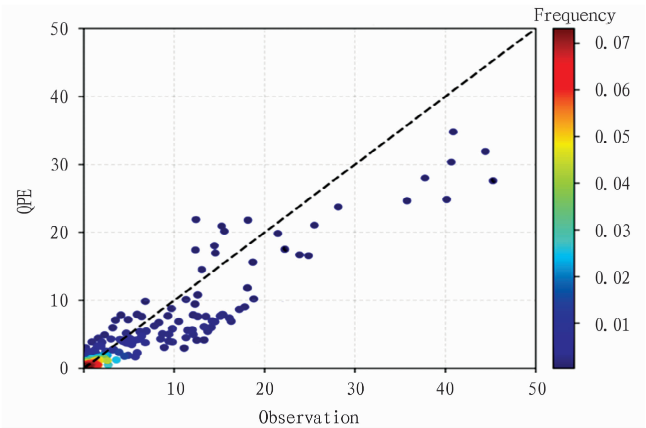

Fig. 4 Probability density plot of ground-based rain gauge observations versus radar quantitative precipitation estimates

A binary classification scoring method was also used to evaluate the performance of the radar QPE systematically. The trends of various scores with precipitation thresholds were shown in Fig. 5, including Probability of Detection (POD), Threat Score (TS), Equitable Threat Score (ETS), and Miss Rate (MAR). Results revealed that QPE skill decreased significantly with increasing precipitation intensity. Specifically, POD, TS, and ETS decreased sharply when the threshold reached approximately 10 – 12 mm, indicating a marked reduction in QPE's predictive ability under heavy precipitation conditions. Conversely, MAR increased significantly with higher thresholds, further confirming QPE's limitations in estimating heavy precipitation. Notably, within the lower precipitation threshold range (0 – 5 mm), POD, TS, and ETS remained high, while MAR stayed low, indicating high reliability in estimating light to moderate precipitation. All metrics performed best near the 0 mm threshold, reflecting QPE's excellent ability to discern whether precipitation occurs.

4 Conclusion

This study demonstrated that the X-band phased array radar-based QPE algorithm was generally effective for precipitation estimation (correlation coefficient of 0.809), but exhibited a systematic underestimation trend. The algorithm performed well in estimating light to moderate precipitation (0 – 10 mm), but its capability diminished significantly for heavy precipitation (> 30 mm), with maximum underestimation reaching 50%.

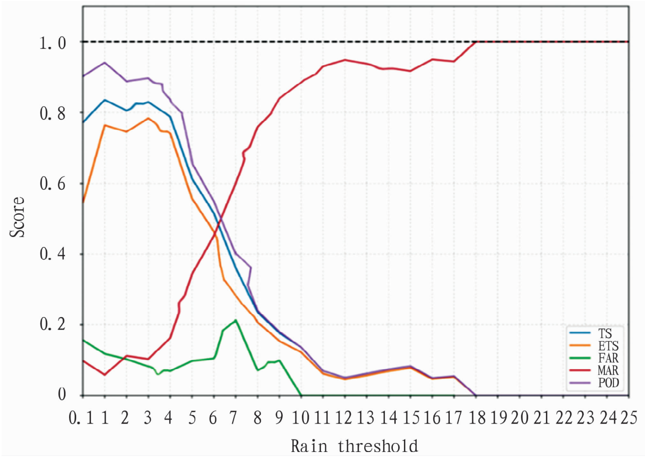

Fig. 5 Variation characteristics of different scoring functions (TS, ETS, FAR, MAR, POD) with precipitation thresholds

Binary classification scoring analysis revealed a significantly negative correlation between QPE skill and precipitation intensity. With increasing thresholds, POD, TS, and ETS declined overall, with a sharp drop at the 10 – 12 mm threshold, while MAR increased markedly. These results further confirmed the QPE algorithm's limitations in estimating heavy precipitation.

The findings provide clear directions for improving the QPE algorithm, particularly for applications in heavy precipitation scenarios. Future work should focus on optimizing the dynamic adjustment mechanism of the Z – R relationship and consider incorporating dual-polarization parameters to enhance QPE accuracy across varying precipitation intensities.

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