# Postprint of Multi-Source Precipitation Fusion Experiment in Xinjiang Region

**Authors:** Lu Xinyu, Liu Yan, Wang Xiuqin, Liu Jing, Wei Ming, Song Zhiguo, Zhang Yingxin, Liu Yan

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## Abstract

Using hourly precipitation data from nearly 2000 regional automatic weather stations in Xinjiang during the summer of 2016 (June–August), with the latest-generation GPM (Global Precipitation Measurement Mission) IMERG (Integrated Multi-satellite Retrievals for GPM) satellite precipitation product as the initial field, a multi-source precipitation fusion experiment was conducted in an arid region employing a two-step fusion correction method based on probability density function matching and optimal interpolation (probability density function-optimal interpolation, PDFOI). First, bias correction of IMERG precipitation was achieved by performing probability density function (PDF) matching between observed data and satellite-retrieved precipitation; then, using the bias-corrected IMERG precipitation as the background field and observed precipitation as the observation field, the bias-corrected IMERG precipitation estimates were combined with rain gauge observations through optimal interpolation (OI), ultimately obtaining hourly precipitation data for Xinjiang after two-step correction. Cross-validation results indicate that, compared with rain gauge observations and original satellite precipitation data, the fused precipitation constructed by the PDF-OI two-step correction method not only substantially eliminates systematic errors but also significantly improves data accuracy.

## Full Text

## Multisource Precipitation Data Merging Experiment in Xinjiang

**LU Xin-yu[1], LIU Yan[1], WANG Xiu-qin[1], LIU Jing[1], WEI Ming[2], SONG Zhi-guo[3], ZHANG Ying-xin[1]**

[1] Institute of Desert Meteorology, China Meteorological Administration, Urumqi 830002, Xinjiang, China

[2] Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science and Technology, Nanjing 210044, Jiangsu, China
[3] Yishui Meteorological Bureau of Shandong, Linyi 276400, Shandong, China

## Abstract

Precipitation is a fundamental atmospheric process associated with latent heat release, which redistributes solar radiation received at the Earth’ s surface to the interior of the atmosphere, thereby driving large-scale circulation. Understanding the spatiotemporal distribution of precipitation in a specific region is essential for comprehending ecological and environmental changes in that area, with the most critical requirement being accurate acquisition of precipitation data across the entire region. Due to significant spatial and temporal variability, obtaining precise regional and global precipitation information remains a formidable challenge.

Current methods for acquiring precipitation information 主要包括 three approaches: station observations, radar estimates, and satellite remote sensing retrievals. Station observations offer high accuracy but are mostly located in low-altitude areas with uneven distribution, limiting their ability to effectively reflect spatial precipitation variations. Radar-based precipitation data provide certain regional estimation advantages, yet the Z-R relationship varies substantially across different precipitation systems, seasons, and regions, affecting accuracy. Moreover, radar detection suffers from ground clutter blockage, beam effects, and velocity ambiguity, restricting its practical application. The rapid development of remote sensing and geographic information science has provided new methods for large-scale precipitation synchronous observation, with satellite-retrieved precipitation products offering unique advantages of all-weather capability, global coverage, and accurate representation of precipitation spatial distribution, making them crucial tools for systematically understanding regional and global precipitation patterns and their variations.

However, since satellite observations are indirect, the physical principles and algorithms for satellite precipitation retrieval have limitations, resulting in considerable uncertainty and relatively low accuracy. Therefore, correction of satellite precipitation products is necessary before application. Numerous studies have focused on developing fusion methods combining satellite precipitation with ground observations, including objective statistical analysis, interpolation techniques, neural networks, dual-kernel smoothing, and geographical difference analysis. The National Meteorological Information Center has conducted extensive research on multisource precipitation fusion, with its developed precipitation fusion products distributed through the national comprehensive meteorological information sharing platform and widely applied in operations and research. However, these fusion precipitation products primarily use CMORPH satellite precipitation as the initial field. Comparative assessments of various satellite precipitation products in Xinjiang show that the latest-generation GPM IMERG product demonstrates higher accuracy in arid Xinjiang, particularly at hourly scales. Consequently, this study conducts multisource precipitation fusion experiments in Xinjiang using IMERG as the initial field to obtain higher-quality hourly precipitation fusion products.

This study employs hourly precipitation data from approximately 2000 regional automatic weather stations in Xinjiang, using the latest-generation IMERG (Integrated Multi-satellite Retrievals for GPM) satellite precipitation product from the Global Precipitation Measurement Mission as the initial field. A two-step fusion correction method based on probability density function (PDF) matching and optimal interpolation (OI) is implemented for arid region multisource precipitation fusion experiments. First, bias correction of satellite-retrieved precipitation is achieved through PDF matching with observed precipitation. Then, using bias-corrected IMERG precipitation as the first-guess field and observed precipitation as the observation field, the two correction steps are combined through OI to obtain final hourly precipitation data for Xinjiang.

Cross-validation results demonstrate that compared with gauge observations and original satellite precipitation data, the fusion precipitation constructed through this two-step correction method not only substantially eliminates systematic errors but also significantly improves data accuracy. This research represents valuable exploration in developing a gridded precipitation dataset for mid-to-high latitude arid regions like Xinjiang. The resulting high spatiotemporal resolution gridded precipitation dataset will enhance understanding of hourly heavy precipitation characteristics and evolution patterns in Xinjiang, provide data support for improving forecast accuracy and preventing meteorological secondary disasters, and establish a technical foundation for developing high-resolution precipitation products across Central Asia.

**Keywords:** satellite-gauge merging; hourly precipitation; fusion; Xinjiang

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### 1.1 GPM IMERG Satellite Precipitation

The Global Precipitation Measurement Mission (GPM) is a global precipitation measurement system developed by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), representing the successor to the Tropical Rainfall Measuring Mission (TRMM) satellite precipitation program. The GPM constellation consists of one core satellite and multiple satellite groups, providing global precipitation distribution data every 3 hours. The core satellite carries a dual-frequency radar and microwave radiometer. The dual-frequency radar includes an additional high-frequency band compared to TRMM, enabling more sensitive detection of light rain and snowfall. Unlike satellites that primarily observe moderate to heavy precipitation, GPM improves observation capabilities for light rain and solid precipitation. Since these precipitation types constitute the majority of precipitation in Xinjiang, GPM’ s observations hold significant research importance for this study area.

This study selects the IMERG product as the precipitation initial field, with spatiotemporal resolution of 0.1°$×$0.1° and 0.5 hours. The study period covers June–August 2016, with 0.5-hour IMERG precipitation accumulated to hourly intervals to match hourly observed precipitation.

### 1.2 Observed Precipitation

The study utilizes hourly precipitation data from nearly 2000 regional automatic weather stations across Xinjiang. The observed precipitation (designated as OBS) covers the same time period as the IMERG data. The data were compiled by the Xinjiang Meteorological Information Center and underwent quality control including climate extreme value checks, single-station extreme value checks, and data consistency verification. To ensure independent validity for modeling and validation, 20 international exchange stations in Xinjiang were excluded. Since most Xinjiang regional automatic stations use tipping-bucket rain gauges that only measure rainfall and cease observations during the cold season, the study focuses on the warm season (June–August) of 2016.

Figure 1 shows the distribution of station counts within 0.1°$×$0.1° grids across Xinjiang. There are 658 valid grids (those containing at least one rain gauge), with a total of 2000 rain gauge stations. Further subdivision reveals that 158 grids contain 1 rain gauge, 183 grids contain 2 rain gauges, and the remaining grids contain 3 or more rain gauges, with the vast majority of valid grids having 1–3 stations. A 10-fold cross-validation approach is applied: valid grids are randomly divided into 10 groups, with 9 groups used for constructing the PDF matching table and the remaining group serving as an independent dataset for bias correction and final fusion product validation. This process repeats 10 times, ensuring each station is independently corrected and validated, thereby guaranteeing representativeness and objectivity of training and validation samples.

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### 2.1 Establishing Valid Grid Data Pairs

For the 658 valid grids in Xinjiang, satellite data are spatially and temporally matched with ground observations. All observed precipitation values falling within the same grid are averaged to form a grid-scale observed precipitation value, which is then paired with the corresponding grid satellite precipitation value. Temporally, matching occurs at the same time steps, noting that satellite precipitation uses Universal Time Coordinated (UTC) while observed precipitation uses Beijing Time (UTC+8). The paired data samples serve as the foundation for subsequent PDF correction and fusion.

### 2.2 PDF Matching Method for Error Correction

The PDF matching correction method "calibrates" the probability density of satellite precipitation estimates using the probability density of gauge observations, thereby matching their probability density values to remove systematic errors in satellite precipitation. The specific procedure is as follows:

1) Given the high probability of zero-precipitation events and characteristics at finer spatiotemporal scales, a spatial window of 4°$×$4° is selected centered on the IMERG grid point to be corrected (hereafter "current grid") to obtain valid grid data pairs. Considering the diurnal variation of hourly precipitation, a temporal window of $±$15 days from the current date and $±1*hourfromthecurrenttimeisapplied,yielding*3*timestepspercorrectionperiod.Thiscollects*45*timestep*
spatial range as correction samples.
2) Based on these valid grid data pairs, samples with non-missing values for both observed and satellite precipitation are selected as effective data samples. For each sample, the most effective samples are screened using spatiotemporal distance to the current grid point and time as weights.
3) For each current grid point, cumulative probability densities of observed and satellite precipitation are calculated separately for each precipitation density class. This yields a matching table between observed and satellite precipitation cumulative probability densities. The satellite precipitation value at the current grid point is located within the satellite precipitation cumulative probability density table to obtain its probability density value, which is then matched to the corresponding observed precipitation cumulative probability density value. The corrected satellite precipitation value is designated as $R_{pdf\_CRT}$. Detailed procedures can be found in reference [**?**].

### 2.3 Optimal Interpolation (OI)

The optimal interpolation analysis uses bias-corrected IMERG precipitation as the first-guess field and station observed precipitation as truth values. The final precipitation analysis value $A_k$ at each grid point consists of two components: the first-guess value $F_k$ (satellite-retrieved precipitation) and the deviation between satellite precipitation and observed precipitation at that grid point. Since most grids lack observation stations, this deviation is estimated through weighted deviations from $n$ valid grid data pairs within a certain radius, as follows:

$$A_k = F_k + \sum_{i=1}^{n} W_i \times (O_i - F_i)$$

where $k$ and $i$ represent the current analysis grid point and surrounding valid grid points, respectively; $W_i$ is the weight function for valid grid data pairs, representing the weight assigned to the deviation between observed and first-guess values at point $i$ during correction. Notably, due to sparse station networks in Xinjiang, the analysis radius is set to 200 km to ensure sufficient valid grid points can be found within the region. Valid grid points are sorted by distance from nearest to farthest, and the $n$ nearest points participate in optimal interpolation, with $n$ set to 8.

The weight coefficient $W_i$ is determined by minimizing the error variance of the analysis point precipitation value $A_k$. Assuming both the observation field and first-guess field are unbiased and their errors are uncorrelated [**?**], the weight coefficient $W_i$ in the equation can be obtained by solving the following linear system:

$$\sum_{j=1}^{n}(\mu_f^{ij} + \lambda_i\lambda_j\mu_o^{ij})W_j = \mu_f^{ik} \quad (i = 1, 2, \dots, n)$$

where $\mu_f^{ij}$ and $\mu_o^{ij}$ represent the first-guess field error covariance and observation error covariance, respectively; $\lambda_i = \sigma_o/\sigma_f$ is the ratio of observation error standard deviation $\sigma_o$ to first-guess field error standard deviation $\sigma_f$ at point $i$. The key to OI lies in quantifying the error structures of the first-guess and observation fields, which requires determining the parameters $\mu_f^{ij}$, $\mu_o^{ij}$, and $\lambda_i$ in the equation.

In this study, these parameter values are obtained through statistical analysis of sample data from June–August 2016. Figure 2 shows the scatter distribution of mean square error versus rain rate for satellite-retrieved precipitation (IMERG), with the fitted function used to determine $\sigma_f^i$. Similarly, $\sigma_o^i$ can be calculated from the scatter distribution of observed precipitation mean square error versus rain rate. Figure 3 presents the error correlation between any two grid points for bias-corrected IMERG as a function of separation distance, with the fitted function used to determine $\mu_f^{ij}$ for given distances between grid points $i$ and $j$. In these parameters, $\mu_o^{ij}$ represents observation error covariance, based on the premise that each station' s observation error is only related to its own measurements, yielding $\mu_o^{ij} = 1$ when $i = j$ and $\mu_o^{ij} = 0$ when $i \neq j$.

After determining the weight coefficient $W_i$ by solving the linear system, the final precipitation analysis value $A_k$ is obtained through the OI equation.

### 2.4 Validation and Evaluation

Station observations represent the most accurate precipitation measurements. This study employs 10-fold cross-validation using independent stations to evaluate the fusion precipitation product, with results compared against original IMERG hourly precipitation. Four statistical metrics are selected for assessment, divided into two categories: (1) Correlation Coefficient (CC), reflecting consistency between fusion precipitation and observed precipitation; and (2)

Mean Error (ME), Relative Bias (RB), and Root Mean Squared Error (RMSE), describing error magnitude relative to observations:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)$$

$$RB = \frac{\sum_{i=1}^{n}(y_i - x_i)}{\sum_{i=1}^{n} x_i} \times 100\%$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2}$$

$$CC = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where $x_i$ and $y_i$ represent observed and estimated precipitation values, respectively; $\bar{x}$ and $\bar{y}$ are their means; and $n$ is sample size.

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### 3.1 Bias Correction Effects

Through PDF matching with observed precipitation probability density, systematic errors in original IMERG satellite precipitation are corrected. Figure 4 compares the probability density distributions of observed precipitation (OBS), original satellite precipitation (IMERG), and bias-corrected precipitation (pdf_{CRT}) for summer 2016. Given that zero-precipitation events dominate hourly precipitation, the figure begins statistics from 0.1 mm $\cdot$ h$^{-1}$. The results show that original IMERG precipitation probability distribution substantially exceeds observations in most cases, only falling below observed precipitation at higher rates (>2 mm$\cdot$h$^{-1}$). After PDF matching correction, pdf_{CRT} precipitation probability density values align much more closely with observations, specifically reducing probability density when original IMERG is too high and increasing it when too low, demonstrating the regulating effect of observed precipitation probability distribution on satellite precipitation.

Quantitative assessment in Table 1 reveals that after PDF correction, relative bias decreases from 23.77% to -27.14% (absolute value reduced by 48.41%), though correlation coefficient decreases slightly (by 0.03). Figure 5 shows temporal variation of independent verification statistics, indicating pdf_{CRT} precipitation bias is significantly reduced compared to original IMERG across all time periods, with correlation coefficient showing slight improvement.

### 3.2 OI Improvement Effects

Cross-validation results demonstrate that precipitation after two-step correction (designated pdf-oi_{CRT}) performs optimally across all metrics compared to original IMERG and pdf_{CRT}. Correlation coefficient increases by 53.3%, absolute mean error decreases by 31.6%, and relative bias decreases by 55.7%, reflecting substantial improvement. Figure 5 shows that pdf-oi_{CRT} precipitation quality is greatly enhanced over original IMERG at most time points.

Analysis based on single statistical indicators is limited. Figure 6 presents Taylor diagrams for the three precipitation products, which graphically quantify similarity among models through correlation coefficient, RMSE, and standard deviation relative to observations [?]. Points closer to the reference observation (labeled "OBS" ) indicate better consistency. Taylor diagrams are particularly useful for evaluating overall performance across multiple models. Figure 6 shows that throughout the study period, the standard deviation of observed precipitation (black dashed line) is 1.16 $\mathrm{mm} \cdot \mathrm{h}^{-1}$, while pdf-oi_{CRT} precipitation standard deviation (green dashed line) is closest to observations. The results consistently show pdf-oi_{CRT} nearest to observations, indicating best performance. Monthly Taylor diagrams (Figure 6b–d) reflect the same pattern.

### 3.3 Precipitation Case Analysis

On August 1, 2016, a large-scale precipitation event occurred across Xinjiang from west to east, with the most significant heavy rainfall in the Ili region. The process peaked between 17:00–20:00 UTC+8, ending around 23:00. Figure 7 shows precipitation intensity distributions at 03:00 UTC+8 from: (a) surface automatic weather station observations, (b) IMERG satellite precipitation, (c) pdf_{CRT} corrected precipitation, and (d) final pdf-oi_{CRT} fused precipitation.

Observations show precipitation concentrated in Ili, Bortala, and Tacheng regions, with the maximum center in Ili. IMERG satellite retrieval indicates a precipitation area far exceeding observed distribution, with the maximum center displaced northward to Toli County in Tacheng region where observations show only sparse stations reporting precipitation. This reflects the common satellite retrieval phenomenon of underestimating high values and overestimating low values. After PDF matching correction (Figure 7c), original satellite precipitation false alarms and overestimation are significantly improved, with precipitation maxima shifting downward to align with observations in the Ili region. However, pdf_{CRT} filters out many areas where observations recorded precipitation, particularly in western Ili and Bortala.

The final pdf-oi_{CRT} fused precipitation (Figure 7d) shows that on the basis of bias correction, subsequent fusion with observed precipitation not only restores precipitation areas incorrectly filtered by pdf_{CRT} but also ensures consistency with observations in gauge-containing grids while preserving satellite-retrieved distribution in observation-sparse areas, effectively combining advantages of both observation methods.

### 3.4 Comparison with Similar Fusion Products

This study builds upon the methodology in reference [**?**] but differs by selecting the more accurate GPM IMERG satellite precipitation product as the initial field for Xinjiang and implementing localized algorithm adjustments based on regional precipitation characteristics. Therefore, it is necessary to compare the resulting pdf-oi_{CRT} fused precipitation with the national-scale precipitation fusion product developed by the National Meteorological Information Center (CMORPH-based). Due to lack of independent validation data, comprehensive comparative evaluation is not possible; instead, spatial distribution differences are analyzed.

Using the same August 1, 2016 case, Figure 8 compares precipitation distributions at 03:00 UTC+8 from: (a) CMORPH satellite data, (b) CMORPH-gauge merged product, (c) IMERG satellite data, and (d) this study' s pdf-oi_{CRT} product. Compared with observations, CMORPH shows significant overestimation of precipitation extent, particularly over northern Xinjiang (Altay, Tacheng) and southern Xinjiang (Kashgar, Hotan). The CMORPH-gauge merged product improves this but still shows substantial overestimation in southern Xinjiang. In contrast, pdf-oi_{CRT} demonstrates better consistency with observations, particularly showing more accurate regional precipitation amounts.

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## 4 Conclusions

This study conducts a multisource precipitation fusion experiment in Xinjiang using the latest-generation GPM IMERG satellite precipitation product as the initial field and a two-step correction method combining PDF matching and OI. The main conclusions are:

1) The PDF matching method effectively corrects systematic errors in IMERG satellite precipitation, significantly reducing absolute mean error and relative bias. After correction, relative bias decreases from 23.77% to -27.14% (48.41% reduction in absolute value).

2) Cross-validation results show that based on significant reduction of systematic bias in IMERG precipitation products, further fusion with observed precipitation through OI substantially improves the quality of the final gridded precipitation dataset pdf-oi_{CRT}. All metrics show optimal performance, with correlation coefficient increasing by 53.3%, absolute mean error decreasing by 31.6%, and relative bias decreasing by 55.7% compared to original IMERG.

3) Case analysis demonstrates that the two-step correction method properly handles both overestimation and underestimation issues. After PDF cor-

rection, original satellite precipitation false alarms and overestimation are significantly improved. Subsequent OI fusion not only restores incorrectly filtered precipitation areas but also ensures consistency with observations in gauge-containing grids while preserving satellite-retrieved distribution in observation-sparse areas, effectively combining advantages of both observation methods.

4) Comparison with similar fusion products shows that selecting IMERG satellite precipitation as the initial field and implementing localized algorithm adjustments based on Xinjiang' s precipitation characteristics yields a fusion product more consistent with observations than CMORPH-based products, particularly in southern Xinjiang where CMORPH shows substantial overestimation.

This study demonstrates the effectiveness of applying the PDF-OI method to IMERG satellite precipitation products in Xinjiang' s arid region. The resulting fusion precipitation shows better consistency with observations and provides higher-quality precipitation data for the region. The developed high spatiotemporal resolution gridded precipitation dataset will support improved understanding of hourly heavy precipitation characteristics, enhance forecast accuracy, and provide technical foundation for developing high-resolution precipitation products across Central Asia.

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*Note: Figure translations are in progress. See original paper for figures.*