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Assessing the Applicability of Multi-Source Precipitation Merged Products on the Northeast Side of Tibetan Plateau

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Abstract

Based on the automatic station observations in central Gansu, the applicability of multi-source precipitation merged products in Lanzhou and Wuwei cities, which are located on the northeast side of the Tibetan Plateau, is assessed using usual station verification and near gridding verification methods. Data are provided by the National Meteorological Information Center. The results are as follows. 1) The assimilation abilities of the two sources merged precipitation data and the three sources merged precipitation data to actual precipitation are great. The precipitation product merged from three sources is better than that from two sources, which is due to the smaller error and higher accuracy of three source merging precipitation data. However, the two types of precipitation-merged products underestimated the observational ones to certain extend. 2) Altitude has little effect on precipitation error, and the error in the transition zone from mountain to plain is relatively large. 3) The hourly merged precipitation analysis product has stronger reproducibility for weak precipitation and is closer to the observed precipitation. 4) The frequency of precipitation reflected by the merged product is larger than the observational field, while the precipitation intensity is reverse.

Keywords

Multi-Source Precipitation Merged Products, Near Gridding Verification, Northeast Side of Tibetan Plateau

1. Introduction

High-quality and high-resolution actual precipitation products are crucial for improving numerical weather forecast models and improving the level of detailed weather forecasting. Gansu, located in the northwest of China, features complex and varied terrain. Compared to eastern coastal regions of China, Gansu has fewer meteorological observation stations, a limited observation scope, and the spatial continuity and representativeness of the observation data are insufficient, making it difficult to comprehensively and accurately reflect the spatio-temporal characteristics of precipitation. In recent years, with the rapid development of the meteorological observation system, the use of multi-source data-merged technology, combined with satellite inversion, radar estimation, and ground observation precipitation data, has led to the development of multi-source precipitation-merged products that achieve continuous coverage of precipitation grid data in complex terrain. Among these, the China Regional Merged Precipitation Analysis System (CMPAS) of the National Meteorological Information Center (NMIC), which provides multi-source precipitation merged products, officially entered national operational service in 2018. The product has a temporal resolution of 1 hour and a spatial resolution of 5 km × 5 km. The two-source merged precipitation (CMPAS_FAST) data sources of this product include nearly 40,000 Chinese automatic weather stations' hourly precipitation data that have undergone real-time quality control [1] and the American CMORPH satellite inversion precipitation product [2]. The three-source merged precipitation (CMPAS_FRT) data source adds the Chinese regional radar quantitative precipitation estimation product to the basis of the two-source merged precipitation data. Studies have shown that the accuracy of the merged product from three-source is superior to any single source precipitation product, especially in areas with sparse stations, where the accuracy of precipitation improves after merged, achieving good results [3].

As a representative of actual observation data, the multisource merged gridded actual analysis product still requires further testing and analysis to evaluate its simulation effect on actual conditions. Therefore, in recent years, the applicability analysis of the multi-source precipitation merged actual analysis product developed by the National Meteorological Information Center in different provinces and cities has become a focus of attention for meteorological workers. Yu *et al.* [4], through comparison with surface station observation data in Jiangsu, found that the spatial pattern of gridded precipitation actual fields is very close to station observations, and the precipitation at levels below moderate rain is similar to measured precipitation, but it somewhat weakens the intensity of heavy rain and above. Sun Jing *et al.* [5] further demonstrated in their verification of the 2018 5 km resolution 24 h cumulative precipitation gridded merged product that the magnitude of gridded merged precipitation products is smaller than the actual, and the degree of underestimation increases with the increase in precipitation levels. Additionally, Li Xianfeng *et al.* [6] assessed the application quality of precipitation products merged form multiplr sources in Jiangxi. Yu *et al.* [7] and Long *et al.* [8] analyzed the applicability of multi-source merged precipitation products in heavy precipitation processes in the southwest region, showing that the product can well reflect the spatiotemporal trend of heavy precipitation areas, but somewhat underestimates the maximum precipitation. Wu Wei *et al.* [9] found that multisource precipitation merged products can effectively reflect the spatio-temporal characteristics of precipitation in Sichuan, especially within the basin. Xu Guanying *et al.* [10] showed that the precipitation merged product has relatively small estimation errors for the Jialing River, Min Tuo River and the middle reaches of the Yangtze River, and compared to two-source merged precipitation products, the multi-source precipitation merged product significantly improves the accuracy of estimating precipitation below 5 mm.

Overall, the effectiveness evaluation work of the multisource precipitation merged product in different regions is steadily progressing, and most studies indicate that its accuracy in complex terrain still needs further testing and assessment. In addition, most verification work was based on non-independent sites, and there was relatively little verification and evaluation work based on independent sites. Some research has shown that under the same testing conditions, the accuracy displayed by independent site testing is reduced to varying degrees compared to non-independent site testing. That is, independent site-based verification tests the accuracy of the multisource merged product and better reflects the deviation between grid fused products and observations [5]. Gansu, with an average elevation of about 1500 m, is a transition region between the Tibetan plateau and the plains [11], where the terrain is complex. In 2021, portable meteorological observation stations for flash flood sources were built in Lanzhou and Wuwei, which started operation in March of the same year, providing more possibilities for the applicability assessment of multisource merged precipitation actual analysis products in Gansu. This paper uses surface observed precipitation data from central Gansu, and through usual site verification and near gridding verification methods, evaluates the applicability of the multi-source precipitation merged product developed by the National Meteorological Information Center in central Gansu, with the aim of providing a scientific basis for the application of this product in the Gansu region.

2. Data and Methods

2.1. Data Selection

The hourly surface precipitation data for station verification are collected from 282 national automatic weather stations (NAWS) and regional automatic weather stations (RAWS) in Lanzhou and Wuwei. Among them, 33 RAWS (15 RAWS in Lanzhou and 18 RAWS in Wuwei) were newly built in 2021. These 33 RAWS are independent stations. **Figure 1** shows the distributio of the stations. The period in this part is from March 2021 to April 2022.

Surface precipitation data for near-gridding verification are collected from the newly built RAWS and the original RAWS in the Lanzhou area. RAWS with a distance of 1.5 km or less from the CMPAS grids were selected for verification (resulting in 47 RAWS in the Lanzhou area, as shown in **Figure 2**). The period from June to August 2021 was chosen for near-grid verification. The 1.5 km matching radius was selected to balance spatial accuracy and adequate sample size in near-grid analysis, while the period from June to August 2021 in Lanzhou was chosen to capture typical summer meteorological and environmental conditions with consistent data quality.

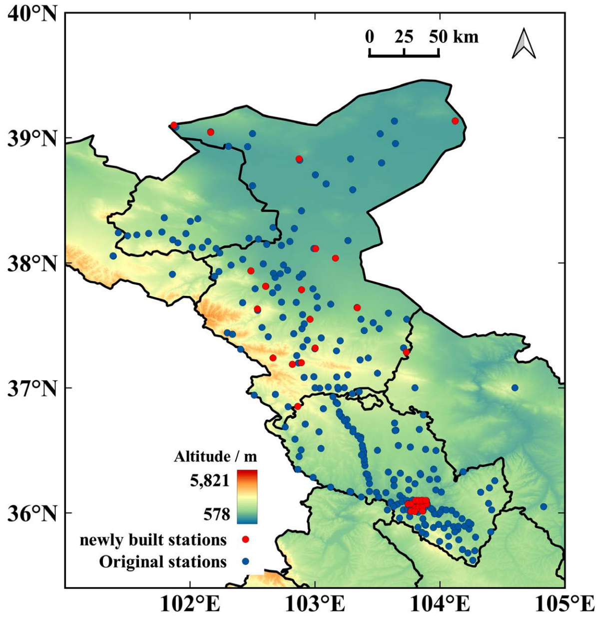

Figure 1. Spatial distributions of stations for station verification.

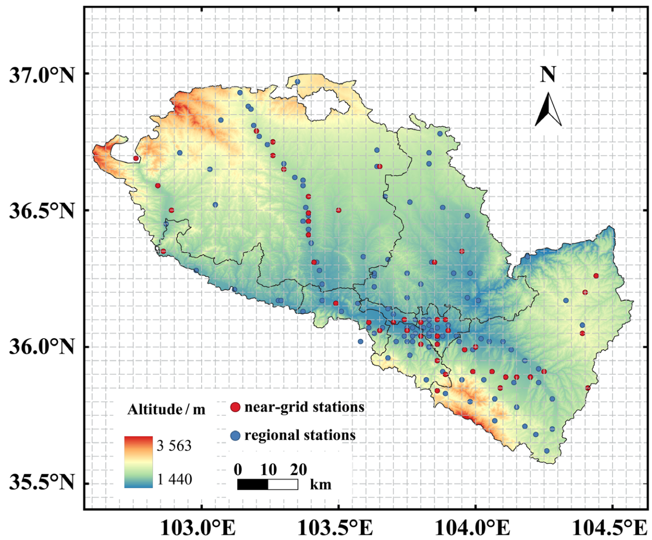

Figure 2. Distribution of all the regional weather station. (The red dots represent the sites used for near grid verification. The dotted line represents 0.05˚ × 0.05˚ grid.)

The CMPAS datasets are provided by the NMIC, CMA. In this study, two CMAPS precipitation products are evaluated: CMPAS_FAST and CMPAS_FRT. The temporal resolution of these two products is hourly and the horizontal resolution is 0.05˚ × 0.05˚ (native resolution: 5 km).

All observational data has been quality controlled. The maps involved in the figures in this study are based on standard maps downloaded from the National Mapping and Geographic Information Bureau standard map service website, with the audit number GS (2019) 1824. No modifications were made to the base maps and the time used is Beijing time.

2.2. Evaluation Method

Considering the discontinuity of precipitation, the intelligent grid business standard inspection method released by the China Meteorological Bureau is adopted, with station observations as true values. The "neighboring point substitution" scheme is used [12], which selects the actual value of the fusion of the nearest point of the grid to the observation station as the corresponding actual value of the fusion (if there are multiple points on the grid with equal distances, the grid point in the northeast direction is preferred). In this study, meteorological stations and CMPAS grids were spatially matched through nearest-interpolation to evaluate the applicability of multisource precipitation fusion products in the central region of Gansu from two aspects: conventional station verification and near-gridding verification. In station verification, the evaluation is mainly based on statistical indicators such as Mean Error (ME), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), as well as meteorological indicators such as Threat Score (TS), Miss Alarm Rate (MR), and False Alarm Rate (FAR), as shown in formulas (1) to (6). Near-gridding verification mainly involves a comparative analysis of the amount, frequency, and intensity of the precipitation. The definition of hourly precipitation frequency (Freq) is the number of times with precipitation in the statistical period divided by the number of non-missing times, and the hourly intensity (Inten) is defined as the amount of precipitation divided by the number of times with precipitation [13], as shown in formulas (7) and (8).

$$\text{ME} = \frac{1}{N}\sum_{i=1}^{N}\left(G_i - O_i\right) \tag{1}$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(G_i - O_i\right)^2} \tag{2}$$

$$\text{MAE} = \frac{1}{N}\sum_{i=1}^{N}\left|G_i - O_i\right| \tag{3}$$

Here, O_i is the station observation value, G_i is the value obtained by interpolating the CMPAS products to stations, and N is the total number of samples (number of stations) used for verification.

$$\text{TS} = \frac{NA}{NA + NB + NC} \tag{4}$$

$$\text{MR} = \frac{NC}{NA + NC} \tag{5}$$

$$\text{FAR} = \frac{NB}{NA + NB} \tag{6}$$

Here, NA is the number of station times with correct forecasts, NB is the number of false alarm station times, NC is the number of missed station times, and ND is the number of station times with correct forecasts where no heavy precipitation is predicted.

$$Freq(h) = \frac{N_{rain}}{N_{sample}} \tag{7}$$

$$Inten(h) = \frac{A_{rain}}{N_{rain}} \tag{8}$$

Here, h represents the forecast time, N_{rain} is the number of effective precipitation hours (precipitation ≥ 0.1 mm/h) at the time of h during the statistical period, N_{sample} is the total number of non-missing samples at the time of h during the statistical period, and A_{rain} is the cumulative precipitation amount at the time of h during the statistical period.

3. Station Verification

3.1. Precipitation Error Analysis

Since meteorological observation data come from spatially discrete weather stations, reflecting changing climate conditions over time at specific locations, spatiotemporal characteristic analysis is important to fully utilize meteorological data [14].

First, the temporal variation characteristics of the precipitation merged product are analyzed to assess its performance in representing precipitation trends. The daily error variation of the two products (**Figure 3**) shows that the ME before

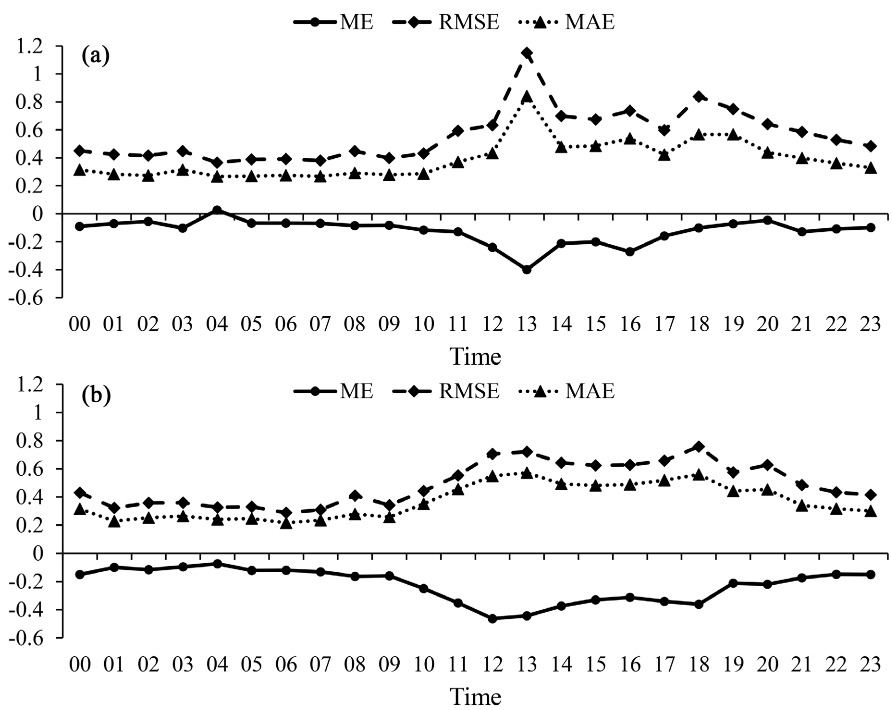

Figure 3. Daily variation of errors of hourly precipitation products from March 2021 to April 2022 ((a) CMPAS_FAST, (b) CMPAS_FRT).

08:00 (Beijing time, the same as after) is relatively small, but after 08:00, the ME gradually increases and reaches its maximum at 13:00 (CMPAS_FAST has a maximum ME of −0.40 mm; CMPAS_FRT has a maximum ME of −0.46 mm). After that, the error gradually decreases. Two peaks of RMSE and MAE occur at 18:00 and 13:00. Li Rong *et al.* [15] analyzed the fine-scale characteristics of precipitation in Lanzhou, and the results showed that the peak values of daily precipitation occur mainly at 18:00 and 13:00. This shows that the maximum error value between the CMPAS product and the observations corresponds to the time when the peak precipitation occurs. Additionally, the ME is generally negative, with values less than 0.5 mm, indicating that the two products of CMPAS underestimate precipitation to some extent.

The monthly variation of the CMPAS precipitation product errors (as shown in **Figure 4**) indicates that the overall trend of errors for both CMPAS_FAST and CMPAS_FRT is essentially consistent. Both RMSE and MAE are significantly higher in the summer half year compared to the winter half year. This is mainly due to excessive precipitation in the summer half year, especially from June to September, which is prone to a large amount of level precipitation, resulting in relatively large errors. However, all errors are within 1.1 mm. The ME is generally negative, suggesting that the CMPAS precipitation product underestimates the observations.

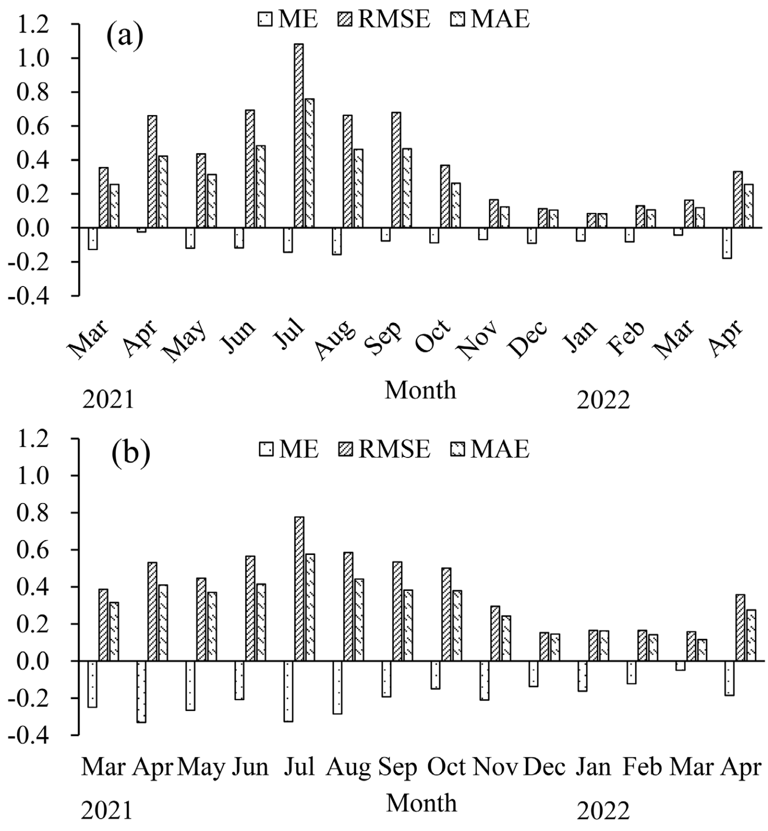

Figure 4. Monthly variation of errors of hourly precipitation products from March 2021 to April 2022 ((a) CMPAS_FAST, (b) CMPAS_FRT).

Further analysis of the spatial differences in the errors of the CMPAS precipitation product quantitatively evaluates the accuracy of the CMPAS. The spatial distribution of the errors (**Figure 5**) shows that the distribution of the two products of CMPAS is basically consistent, but the error of CMPAS_FRT is relatively smaller. The RMSE is generally less than 2 mm and the MAE is less than 1 mm. The larger error values of these two products are mainly concentrated in the transition zone from mountains to plains. The ME is predominantly negative, ranging between −0.4 mm and 0.2 mm, with no obvious spatial variation. Overall, both CMPAS_FAST (figure omitted) and CMPAS_FRT have a good assimilation ability for the hourly precipitation of observations, with tCMPAS_FRT having smaller errors, higher accuracy, and stronger capability to describe actual weather conditions.

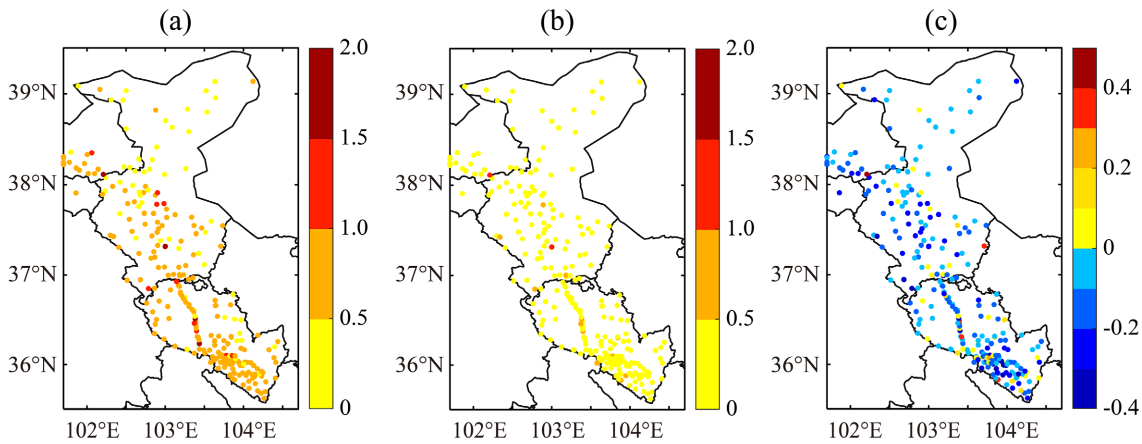

Figure 5. Spatial distributions of RMSE (a), MAE (b) and ME (c) of hourly precipitation product.

3.2. Verification of Different Precipitation Level

To further determine the error source of the CMPAS precipitation product, a verification is conducted for different precipitation levels and performance. Based on the intensity of the rainfall, hourly precipitation is classified into four levels: light rain (0.1 - 1.5 mm), moderate rain (1.6 - 6.9 mm), heavy rain (7.0 - 14.9 mm), and torrential rain (15.0 - 29.9 mm) [4]. The TS score, Miss Alarm Rate (MR) and False Alarm Rate (FAR) are tested for each precipitation level. **Figure 6** shows that the FAR for light rain is higher than the MR, while the MR for moderate rain and above is higher than the FAR. The TS for moderate rain is the highest 0.6, and that of torrential rain is the lowest 0.1. This indicates that the CMPAS precipitation product has insufficient capability in reflecting short-duration heavy precipitation and struggles to capture localized heavy rainfall.

The amounts of hourly precipitation are accumulated to obtain daily precipitation, and the verification is carried out for four levels: light rain (0.1 - 9.9 mm), moderate rain (10 - 24.5 mm), heavy rain (25 - 49.9 mm), and torrential rain (50 - 100 mm) (**Figure 7**). The TS for daily precipitation is generally better than that for hourly precipitation. The TS for light rain is the highest 0.58, followed by moderate rain at 0.56.

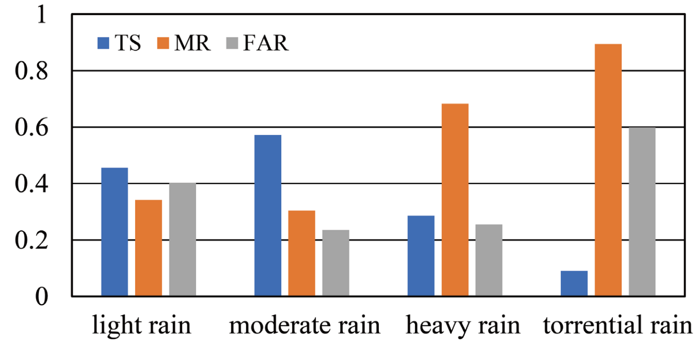

Figure 6. Verification of hourly precipitation product under different precipitation intensities.

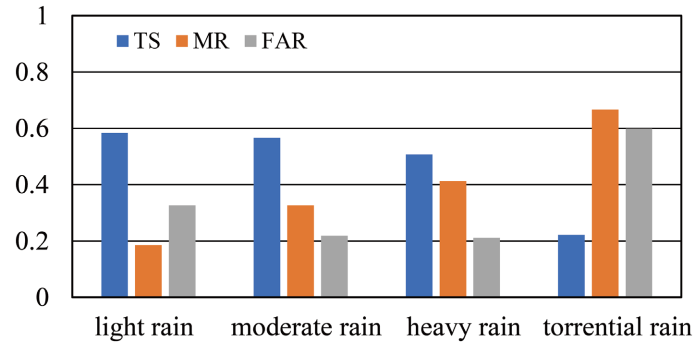

Figure 7. Verification of daily precipitation product under different precipitation intensities.

4. Near-Gridding Verification

Compared to the traditional method of interpolating grid data to stations for verification, near-gridding verification involves direct point-to-point error analysis between station and grid data. This approach is beneficial for a deeper understanding of the differences and representativeness between grid merged data and station observation data, enabling more detailed verification and evaluation. Therefore, this section conducts a more in-depth verification and evaluation of the multisource precipitation merged product using points within a 1.5 km distance from the station as the objects of verification.

4.1. Precipitation Amount Analysis

First, the frequency distribution of different levels of precipitation intensity is analyzed. The results show that the CMPAS has a higher frequency of light rain in average daily precipitation compared to actual conditions, while the frequency of moderate rain is roughly the same as the observations of the stations (**Figure 8(a)**). Correspondingly, the frequency distribution of the hourly precipitation amounts also shows that the frequency of CMPAS between 2 - 5 mm/h is higher than the station observations, but the frequency of CMPAS above 5 mm/h is lower than that of the station observations (**Figure 8(b)**).

Further analysis of the spatial distribution of the ME of the average daily precipitation amounts (**Figure 9**) reveals that the ME in the Lanzhou urban area is both positive and negative, with Yongdeng showing a predominantly positive ME, while Yuzhong has a majority of negative ME. To further compare the characteristics of precipitation errors in different areas, the sites are categorized according to the underlying surface conditions into Yongdeng mountains, the urban basin, and the Yuzhong mountains. The results show: in Yongdeng, CMPAS_FRT is generally more than observations, indicating an overestimation; in Yuzhong, it is less than observations, indicating a certain degree of underestimation; while in the Lanzhou urban area, the two are roughly similar (**Figure 10(a)**). This is mainly because

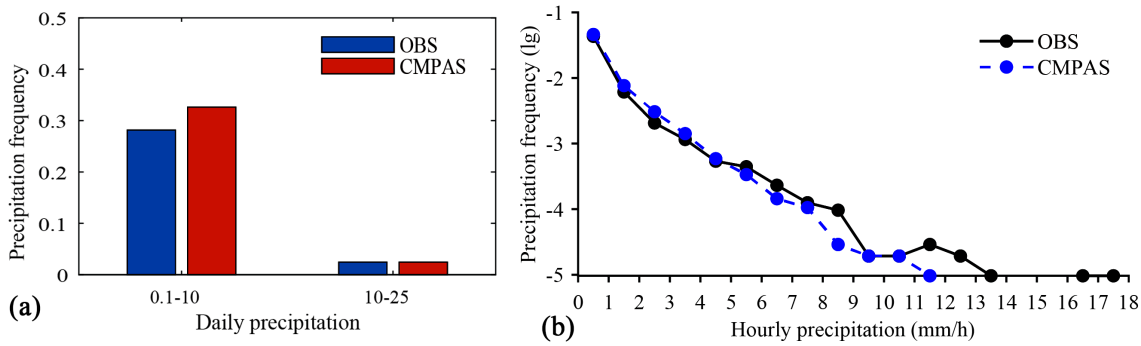

Figure 8. Frequency distribution of daily precipitation (a) and hourly precipitation (b).

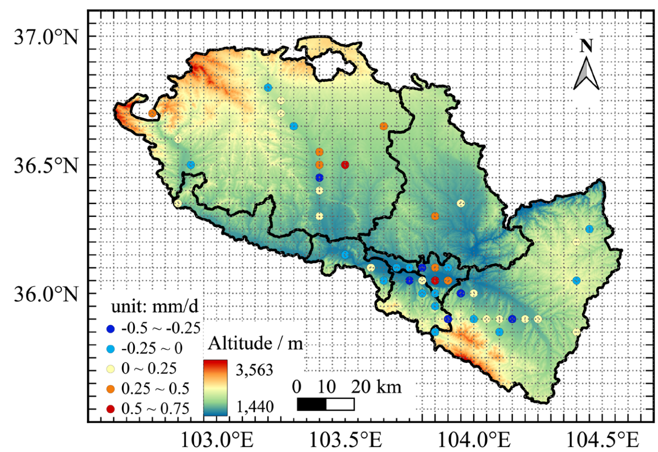

Figure 9. Spatial distribution of ME of average daily precipitation.

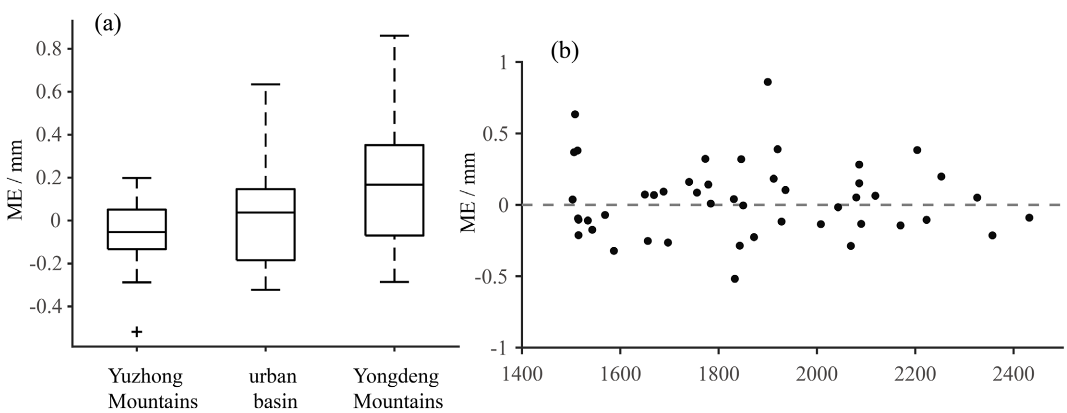

Figure 10. Comparison chart of average daily precipitation's ME in different regions (a) and variation chart of average daily precipitation's ME with altitude (b).

the Lanzhou urban area has a dense network of RAWS, resulting in better multi-source precipitation merged effects; whereas the Yongdeng area has relatively sparse RAWS, leading to less effective merged; in the Yuzhong area, where heavy precipitation is frequent, the merged precipitation data has less capability in capturing heavy rainfall, thus resulting in lower merged precipitation compared to actual precipitation. Additionally, there is no clear relationship between ME and altitude (**Figure 10(b)**).

The spatial distribution of the ME in hourly precipitation amounts is basically consistent with that of daily precipitation—CMPAS_FRT is generally more than observations in Yongdeng, indicating an overestimation; it is less than observations in Yuzhong, indicating a certain degree of underestimation; while in the Lanzhou urban area, the two are roughly similar. Similarly, there is no apparent trend in error with increasing altitude (figure omitted).

4.2. Precipitation Frequency and Intensity Analysis

From the spatial distribution of the daily precipitation frequency and intensity presented in **Figure 11**, the daily precipitation frequency of CMPAS_FRT is 35.08%, while the observed daily precipitation frequency is 30.69%. CMPAS_FRT shows a higher frequency compared to the observed precipitation. This is particularly evident in the urban and Yuzhong areas, where more RAWS are used for CMPAS merged, resulting in a less noticeable overestimation of frequency. In contrast, the Yongdeng area has relatively fewer RAWS, leading to a larger discrepancy in frequency (**Figure 12**). The precipitation intensity characteristics of both are the opposite of their precipitation frequency. The observed precipitation intensity is 3.41 mm/d, while the CMPAS_FRT intensity is 3.09 mm/d, indicating that the intensity of CMPAS_FRT is weaker than that of the observed precipitation (figure omitted).

Further analysis of the diurnal variation characteristics of precipitation frequency and intensity shows that CMPAS_FRT and observed precipitation exhibit highly consistent daily variation trends, effectively reflecting the local precipitation

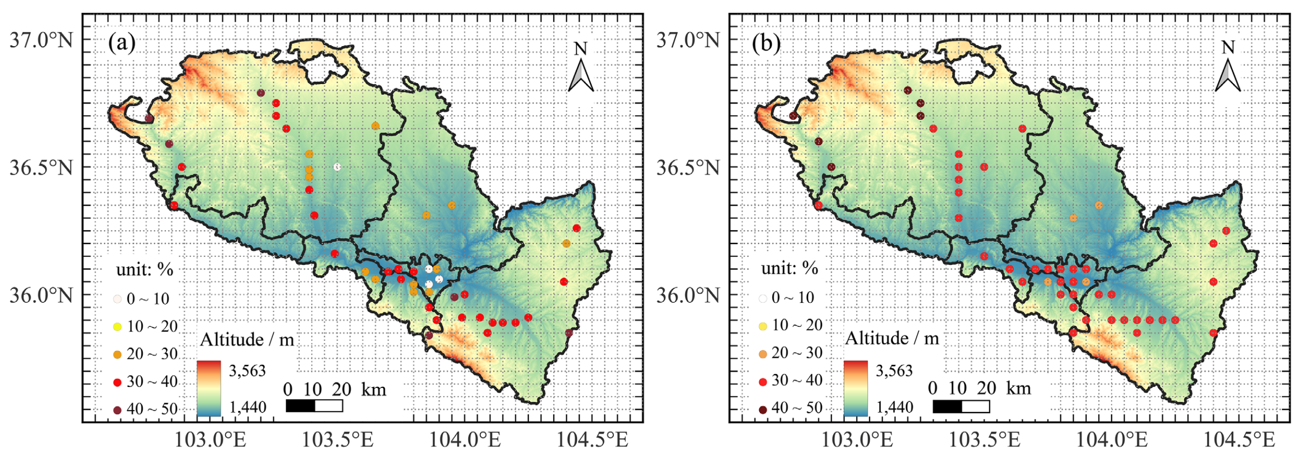

Figure 11. Comparison of spatial distribution of daily precipitation frequency ((a) Observation; (b) CMPAS).

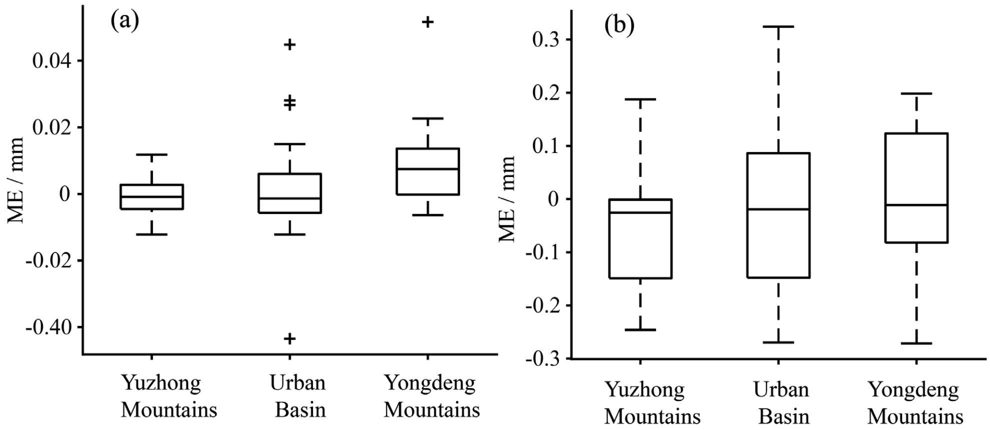

Figure 12. Comparison chart of ME with hourly precipitation frequency (a) and intensity (b) in different regions.

characteristics. However, the quantitative analysis reveals that between 12:00 and 02:00, the frequency of CMPAS_FRT is higher than actual conditions, but its intensity is lower than actual conditions. Between 02:00 and 12:00, the frequency of the precipitation merged product is lower than that of the observed precipitation, but its intensity is higher than that of the observations (**Figure 13**).

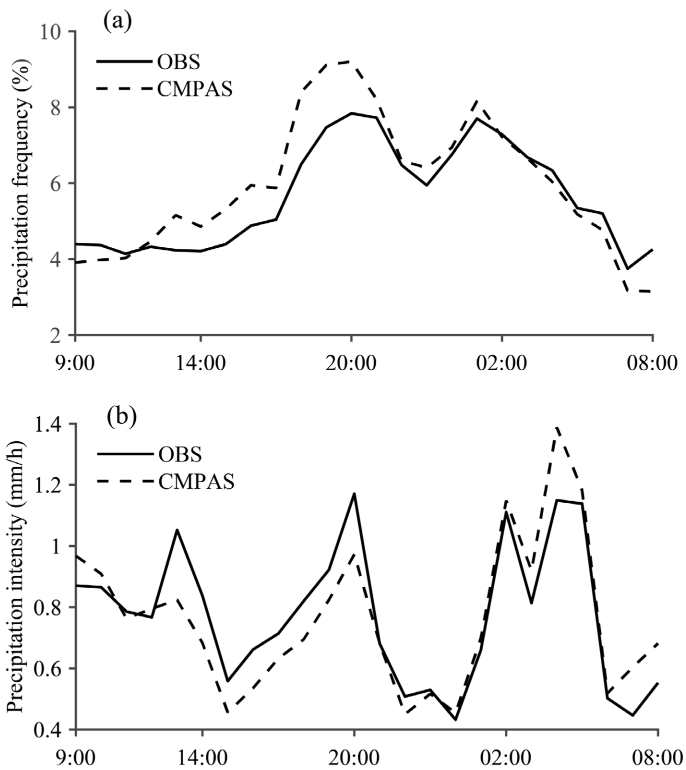

Figure 13. The temporal change of frequency (a) and intensity (b) of hourly precipitation.

In addition, the diurnal variation of rainfall is obvious in Lanzhou, the precipitation is less in morning and more at night, and the precipitation in urban areas is generally less than that in mountain areas under the influence of altitude. This result is consistent with that of Li *et al.* [15].

The characteristic of the "higher frequency but lower intensity" pattern. can be partly attributed to spatial smoothing effects and multi-source merging schemes applied in the precipitation product, which tend to fill in weak or scattered precipitation signals while reducing peak values. As a result, the product captures more light-precipitation events but underestimates strong rainfall intensities.

5. Conclusions and Discussion

This paper conducts a detailed evaluation and analysis of the application effects of CMPAS precipitation products in the cities of Lanzhou and Wuwei, which located on the northeast side of the Tibetan Plateau through the usual site verification of conventional error elements and analysis of precipitation amounts, frequency, and intensity at near-grid sites. The following conclusions were obtained:

1) Station verification results show that the ME of the merged product of hourly precipitation is generally negative, indicating that the CMPAS products tend to underestimate observed precipitation levels. The RMSE and MAE of the CMPAS product are higher in the summer half year, due to more frequent precipitation, but the RMSE is always less than 1 mm, and the MAE is less than 0.7 mm. Overall, both products of CMPAS (CMAPS_FAST and CMPAS_FRT) demonstrate good assimilation ability for surface observed hourly precipitation, with the CMPAS_FRT having smaller errors and higher accuracy. Altitude has a minor impact on precipitation error, although errors are relatively larger in the transition zones from mountains to plains.

2) Precipitation intensity level verification indicates that the CMPAS product has better reproducibility for moderate and light rain. The product performs better in capturing moderate rain than light rain for hourly precipitation but shows a noticeable underestimation for heavy rain and above, reflecting an insufficient ability to capture short-duration heavy precipitation and difficulty in grasping local heavy rain.

3) Near-gridding verification further confirms the precipitation intensity level verification results, showing that the light rain of average daily precipitation in the CMPAS product is more than actual observations, while moderate rain is roughly the same as actual observations. Additionally, the spatial distribution of ME indicates that the CMPAS precipitation product in Yongdeng is more than actual observations, which is overestimated. The CMPAS in Yuzhong is less than the actual observations, underestimating to some extent, and in the Lanzhou urban area, the two are roughly similar. The relationship between precipitation amount error and the altitude is not clear.

4) The CMPAS product has a significantly higher frequency than the actual precipitation but a weaker intensity. The characteristics of the diurnal variation show that between 12:00 and 02:00, the frequency of the CMPAS is higher than the actual observations, but the intensity is lower. Between 02:00 and 12:00, the frequency of the CMPAS is lower than the actual one, but the intensity is higher.

Based on conventional station verification, this study conducts a near-gridding verification, which can more intuitively compare and analyze the precipitation data of grid merged product and station observation, and understand the differences and representativeness between grid merged data and station observation data. This study shows that multi-source precipitation merged products can effectively reflect the spatio-temporal characteristics of actual precipitation in central Gansu, and the CMPAS_FRT product that includes radar quantitative precipitation estimation data has higher accuracy. However, there are some issues: 1) The CMPAS products tend to underestimate actual observations, and this underestimation increases with increasing precipitation levels. 2) From the perspective of various evaluation indicators, larger errors occur mainly in the transition zones between mountains and plains, where the geographical environment is complex, and the representativeness of the stations and the spatial matching methods require further research. 3) In near-gridding verification, the 1.5 km matching radius was selected to balance spatial accuracy and adequate sample size in near-grid analysis, while the period from June to August 2021 in Lanzhou was chosen to capture typical summer meteorological and environmental conditions with consistent data quality. These settings ensure the near-grid results reliably represent local characteristics in Lanzhou during summer but limit their generalizability to other seasons or larger regions. We further clarify that the "higher frequency but lower intensity" pattern is partially induced by spatial smoothing and multi-source merging in the precipitation product. These processes dilute localized peak intensities while expanding the coverage of weak precipitation, leading to more frequent detections of light rain but underestimation of intense convection. This finding has significant implications for short-duration heavy-rain monitoring, as smoothing-induced attenuation may bias the detection threshold and degrade the reliability of convective storm nowcasting. Finally, this paper mainly evaluates and assesses central Gansu (Wuwei, Lanzhou), but Gansu which located on the northeast side of the Tibetan Plateau has a large east-west span with significant climate differences, so the application effects of multisource precipitation merged products in other areas still need further verification and evaluation.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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