Hydrology Research

© 2021 The Authors

Hydrology Research Vol 00 No 0, 1 doi: 10.2166/nh.2021.029

British

Hydrological Society Check for updates

Evaluation of satellite-based precipitation products from GPM IMERG and GSMaP over the three-river headwaters region, China

Hua Wang^a, Yixian Yuan^{a,*}, Suikang Zeng^b, Wuyan Li^c and Xiaobo Tang^a

^a Zhejiang University of Finance and Economics Dongfang College, Haining 314408, China

^b POWERCHINA Sichuan Electric Power Engineering Co., Ltd., Chengdu 610041, China

^c Zhejiang University of Finance & Economics, Hangzhou 310018, China

*Corresponding author. E-mail: smarcle@zufe.edu.cn

ABSTRACT

The three-river headwaters region (TRHR) is the birthplace of the Yangtze River, the Yellow River and the Lantsang River in China. Based on the grid surface precipitation data released by China Meteorological Administration (CMA), this paper evaluated the accuracy and error components of four near-real-time satellite precipitation products (GSMaP-NRT, GSMaP-MVK, IMERG-Early and IMERG-Late) in the era of a GPM (Global Precipitation Measurement) in TRHR. The conclusions are as follows: (1) The precipitation in TRHR is concentrated in the east and south, and the precipitation in the west is very low. IMERG (Early and Late) has a good spatial distribution of precipitation, while GSMaP has an obvious spatial smoothing of precipitation distribution, and does not better highlight the local precipitation characteristics. (2) The inversion accuracy of the satellite products is the best in the source region of the Lantsang River, followed by the source region of the Yellow River. The satellite products all show the lower correlation coefficient and serious underestimation of precipitation in the west of the TRHR. In addition, the closer to the west of the TRHR, the lower hit rate and the higher false alarm rate of the satellite products, especially the NRT and MVK products. In the eastern margin of the Yellow River headwater region and the Lantsang River headwater Region, RMSE and overestimated precipitation were higher in NRT and MVK, and FAR was higher in spite of higher POD and CSI. (3) The errors of GSMaP in the source region of the Yellow River and the Lantsang River are mainly caused by misreporting precipitation and overestimating the precipitation level, while the errors of GSMaP in the west of the TRHR are mainly caused by missing measurements of precipitation events. The underestimated precipitation of IMERG mainly comes from the missed measurement of precipitation and the underestimate of precipitation level, and there is no large false precipitation. (4) In addition, we found that the satellite products in the lake distribution area of the TRHR have serious missed precipitation errors, indicating that the GPM satellite products have the poor detection ability of precipitation near plateau lakes. On the whole, the precipitation inversion accuracy of IMERG (Early and Late) products is higher, which can better detect the occurrence of precipitation events, but the estimation of precipitation level is still not accurate. The precision of precipitation of satellite products near inland lakes on the plateau is poor, so the algorithm improvement of new products needs to be further solved in the future.

Key words: accuracy evaluation, error decomposition, GSMaP, IMERG, the three-river headwaters region

HIGHLIGHTS

- The error performance of IMERG and GSMaP products over the three-river headwaters Region in China.
- IMERG has a good spatial distribution of precipitation.
- The satellite products all show the lower correlation coefficient in the west of the study area.
- The estimation of precipitation level of IMERG is still not accurate.
- GPM satellite products have the poor detection ability of precipitation near plateau lakes.

1. INTRODUCTION

Precipitation is the key to the simulation of hydrometeorological processes, and precipitation has strong spatial and temporal variability. Although ground-based radar and traditional rain gauge observations are accurate, they cannot obtain continuous precipitation in large-scale regions (Liu *et al.* 2011). Satellite remote sensing sensor has the characteristics of real-time all-weather earth observation, which just makes up for the deficiency of conventional rainfall measurement technology. In recent years, using satellite remote sensing technology to retrieve ground precipitation has become a hot spot in precipitation monitoring research.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (http://creativecommons.org/licenses/by/4.0/).

Since the 21st century, many countries have been vigorously developing meteorological satellites to observe precipitation, including Fengyun meteorological satellite of China, NOAA meteorological satellite of the United States, Sunflower satellite of Japan, etc. In 2014, NASA proposed GPM (Global Precipitation Measurement; Hou *et al.* 2013). GPM program is a new generation of global precipitation observation mission jointly developed by NASA and JAXA (Japan Aerospace Exploration Agency) after the Tropical Rainfall Measuring Mission (TRMM). GPM platform is equipped with the most advanced dual-band rain-measuring radar and microwave sensor, and the inversion algorithm of the product is continuously improved, and the spatial and temporal resolution is further enhanced. IMERG (Integrated Multi-satellite Retrievals for GPM; Huffman *et al.* 2015) is a 3-level product released by NASA in The GPM program, with the highest spatial and temporal resolution platform, with the highest resolution (GSMaP) dataset using satellite sensor data from the GPM observation platform, with the highest resolution up to 1 h/0.1° (Ushio *et al.* 2005). Both GSMaP and IMERG are a new generation of global precipitation datasets with high spatial and temporal resolution derived from the GPM program, which have great application and research prospects.

Up to now, the accuracy verification work of satellite precipitation products in the GPM era in the regional or global scale has accumulated a lot. Sahlu et al. (2016), Mayor et al. (2017) and Tan & Santo (2018), respectively, compared the precipitation accuracy of IMERG with the previous generation of CMORPH and TMPA satellites in the Nile Basin of Ethiopia, Mexico, Singapore and Malaysia. The results show that IMERG has a good correlation and a low deviation with the real precipitation on the ground. IMERG performs well on both daily and seasonal scales, but the accuracy decreases with the increase of rainfall intensity. Therefore, it is necessary to further improve the observation ability of IMERG under heavy rainfall conditions. Ayoub et al. (2020) and Prakash et al. (2016), respectively, analyzed the precipitation accuracy of GSMaP satellite products and TMPA products in Malaysia and India, and the results showed that GSMaP could better detect the spatial distribution pattern of precipitation than TMPA, and the accuracy was the highest in summer. In addition, Aslami et al. (2019), Zhou et al. (2020) and Lu & Yong (2018) also compared the difference in precipitation accuracy between GSMaP and IMERG in Iran, mainland China and the Qinghai-Tibet Plateau, and found that the precipitation value estimated by IMERG was relatively close to the meteorological station record, and could replace the observation station in the study area where there was a lack of meteorological stations, thus having high hydrological simulation effect. Therefore, regional geographical and climatic differences will affect the accuracy of satellite products, and the accuracy of satellite products of the new generation of GPM program has significantly improved the accuracy of satellite precipitation inversion (Wang & Hong 2018). GPM satellite products have been used in many areas of accuracy analysis and application. As an important water source area in China and even East Asia, precipitation research in the three-river headwaters region (TRHR) still remains at the stage of precipitation observation by meteorological stations, and satellite precipitation products are not well promoted and applied. Therefore, it is necessary to carry out accuracy verification and error analysis of satellite products in the GPM era in the TRHR.

In order to verify the applicability and error characteristics of near-real-time satellite products of GPM in the TRHR of China, this paper compares the accuracy and error characteristics of four precipitation products of GSMaP and IMERG series in the Qinghai-Tibet Plateau based on the automatic weather station fusion precipitation dataset provided by the Meteorological Bureau. The results can provide information reference for the hydrometeorological research and application of GPM precipitation products in the TRHR.

2. STUDY AREA, DATA AND METHODS

2.1. Study area

The TRHR is located in the Tibetan Plateau of China, between 31°39′–36°16′N and 89°24′–102°23′E (as shown in Figure 1). It is the birthplace of the Yangtze River, the Yellow River and the Lantsang River in China. It is known as the 'water tower of China' and is regarded as an important barrier for ecological security in China. The total area of the region is 363,000 km², with an average altitude of about 4,500 m. The climate of the region is a typical plateau continental climate, with an average annual precipitation of 262.2–772.8 mm, which generally presents a decreasing trend from southeast to northwest (Xi *et al.* 2018). The ecosystem in the TRHR is mainly composed of alpine grassland, wetland, glacier and alpine permanent snow cover. It is an important ecological barrier and an ecological regulation area with the largest influences range in the middle and lower reaches of rivers and their surrounding areas, and the variation of precipitation has a bearing on the water ecological security of China and even Asia (Li *et al.* 2020).



Figure 1 | Geographic map showing the topography over the TRHR.

2.2. Data

2.2.1. Satellite precipitation products

The satellite precipitation products evaluated and analyzed in this paper include GSMaP and IMERG satellite precipitation data in the GPM program. GSMaP was developed with JAXA's Precipitation Measuring Mission (PMM). The PMM team developed three precipitation datasets in the GSMaP project. These products include Global Rainfall Map in Near Real Time (GSMaP-NRT), Global Satellite Mapping of Precipitation Microwave-IR Combined Product (GSMaP-MVK) and Gauge-calibrated Rainfall Product (GSMaP-Gauge) (Kubota *et al.* 2020). GSMaP-MVK and GSMaP-NRT are generated by a fusion of passive microwave radiometer data and infrared data based on the Kalman filter model. The main difference lies in that the NRT algorithm is based on the MVK algorithm, but some simplifications are made in the process to improve the timeliness of the data. The NRT algorithm only uses the forward cloud movement vector algorithm in the microwave infrared merging module, while the MVK algorithm uses the forward and backward cloud movement vector algorithm and fills in the missing moments of microwave data. In addition, on the basis of GSMaP-MVK, the PMM team adjusted GSMaP-MVK precipitation estimation by using the Unified Gauge-Based Analysis of Global Daily Precipitation (CPC) provided by the NOAA Climate Center, and obtained the GSMaP-Gauge with relatively high accuracy (Mega *et al.* 2014).

IMERG is the latest generation of multi-satellite fusion inversion precipitation data developed by NASA in the GPM program and is a Level 3 product of GPM. According to different data processing levels and application requirements, IMERG provides three series of precipitation data, namely Early Run, Late Run and Final Run (Tapiador *et al.* 2012). The data generation system runs once in the near-real-time phase to get the Early product and runs again to get the Late Run. The Early Run only adopts the forward propagation of the cloud moving vector propagation algorithm, whereas the Late Run adopts the forward and backward propagation algorithm. They are pure satellite sensor fusion precipitation products, maintaining nearreal-time data. On the basis of the Late product, the Final product adopts the monthly scale ground station data of GPCC for deviation correction (Tan *et al.* 2019).

In this paper, pure satellite products of GSMaP and IMERG (GSMaP-NRT, GSMaP-MVK, IMERG-Early and IMERG-Late) were used for evaluation and error analysis. None of the four products introduced ground observation precipitation data for deviation correction, which maintained good timeliness, and the time span was from January 2015 to December 2017.

2.2.2. CMA data

In this paper, the hourly precipitation grid dataset (CPA) fusion of China Automatic Station and CMORPH is used as the ground reference precipitation data. The ground data consists of about 30,000 automatic weather stations nationwide observation data and the U.S. climate prediction center (CPC) published by the world 30 min, 8 km resolution CMORPH real-time rainfall data, the precipitation probability density matching, and OI a mix model of optimal interpolation algorithm, data resolution of 1 h/0.1°, effective coverage in mainland China (15°–59°N, 70°–140°E) (Shen *et al.* 2014). Previous studies have shown that CMPA data is the most reasonable in terms of precipitation value and spatial distribution in China, and the overall error of the data is less than 10%, and the error is controlled within 20% in western China where automatic stations are sparse (Yu *et al.* 2015). CMA data can accurately capture the heavy precipitation process in typical regions, which is the most

accurate high-resolution surface precipitation observation data within the scope of mainland China. The precipitation products used in this paper are shown in Table 1.

2.3. Methods

2.3.1. Precipitation precision evaluation method

In this study, Correlation Coefficient (CORR), Relative Bias (RB), Root Mean Squared Error (RMSE) and other statistical indexes were used to analyze the accuracy and error characteristics of remote sensing precipitation data (Wang et al. 2019; Zeng & Yong 2019). The CORR coefficient can measure the degree of linear correlation between the evaluated product and the measured data, and the optimal value is 1. Bias can reflect the degree of systematic deviation of satellite data, and the optimal value is 0. RMSE can show the degree of discretization between the evaluated product and the measured site data, reflecting the average error size of the product, and the optimal value is 0.

In particular, the refined Index of Agreement (DI) and Performance Index (PI) are selected to evaluate the accuracy of satellite precipitation relative to ground precipitation (Alvares et al. 2013). The index DI (-1 to 1) quantifies the prediction error of the model relative to the observed mean. DI = 1 means that the consistency between the datasets is perfect. A value of DI of 0.5 indicates that the model errors are half of the errors resulting from use of the observed mean. A DI value of 0 indicates that the predictive ability of the model is similar to that of the observed mean (Melo et al. 2015). Negative DI values indicate that model errors exceed those from using the observed mean. The performance index, Pi (0-1), is the product of the coefficient of correlation 'Corr' and refined agreement index 'DI', combining accuracy and precision. The criteria for interpreting the performance index, Pi, is: Pi > 0.75, optimum performance; 0.6 < Pi < 0.75, very good performance; 0.45 < Pi < 0.6, good performance; $0.3 \le Pi < 0.45$, tolerable performance; $0.15 \le Pi < 0.3$, poor performance; $0 \le Pi < 0.15$, very bad performance. Each statistical index is calculated as follows:

$$\operatorname{Corr} = \frac{\sum_{i=1}^{n} (G_i - \overline{G})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n} (G_i - \overline{G})^2 \times \sqrt{\sum_{i=1}^{n} (S_i - \overline{S})^2}}}$$
(1)

$$BIAS = \frac{\sum_{i=1}^{n} (S_i - G_i)}{\sum_{i=1}^{n} G_i} \times 100\%$$
(2)

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (S_i - G_i)^2}$$
(3)

$$DI = \begin{cases} 1 - \frac{\sum\limits_{i=1}^{n} |S_i - G_i|}{2\sum\limits_{i=1}^{n} |G_i - \overline{G}|}, & \text{if } \sum\limits_{i=1}^{n} |S_i - G_i| \le 2\sum\limits_{i=1}^{n} |G_i - \overline{G}| \\ \frac{\sum\limits_{i=1}^{n} |S_i - G_i|}{2\sum\limits_{i=1}^{n} |G_i - \overline{G}|} - 1, & \text{if } \sum\limits_{i=1}^{n} |S_i - G_i| > 2\sum\limits_{i=1}^{n} |G_i - \overline{G}| \\ PI = \text{Corr} \times DI \end{cases}$$
(4)

 $PI = Corr \times DI$

 $\sum_{i=1}$

Table 1 | Main characteristics of four satellite precipitation products

Product		Organization	Resolution	Coverage	Real time
GSMaP	NRT	JAXA	0.1°, daily	Global (60°N–60°S)	Delay 4 h
	MVK	JAXA	0.1°, daily	Global (60°N–60°S)	Delay 3 days
IMERG	Early	NASA	0.1°, daily	Global (90°S–90°N)	Delay 4 h
	Late	NASA	0.1°, daily	Global (90°S–90°N)	Delay 12 h
СМА		China Meteorological Administration	0.1°, hourly	15°–59°N, 70°–140°E	-

Hydrology Research Vol 00 No 0, 5

where *n* represents the number of samples; S_i to stay assessment data, \overline{S} mean to stay assessment data; G_i on behalf of the measured data, \overline{G} is the mean value of measured data.

According to different precipitation thresholds, remote sensing precipitation can be divided into Hit, False and Miss precipitation events (as shown in Table 2), and then the classified statistical index can be used to evaluate the detection ability of remote sensing precipitation data to real precipitation events on the ground (Zhang *et al.* 2018). Classified statistical indexes include the Probability of Detection (POD), the False Alarm Ratio (FAR) and the Critical Success Index (CSI). The higher POD Index, the lower FAR indicates the better monitoring ability of remote sensing precipitation data to real precipitation events, while CSI comprehensively reflects the ability of remote sensing data to detect actual precipitation events. In this paper, 1.0 mm was taken as the threshold value of whether precipitation events occurred on the daily scale, and the three rainfall classification statistical indexes in Formulae (6)–(8) were calculated, respectively.

$$POD = \frac{H}{H + M}$$
(6)
$$FAB = \frac{F}{M}$$
(7)

$$H + F$$

$$CSI = \frac{H}{H + M + F}$$
(8)

2.3.2. Precipitation error decomposition method

Since the Hit, False and Miss precipitation events on satellite remote sensing data are independent of each other, an effective error decomposition method can be used to divide the total error of satellite data into three independent error components, and then analyze the main manifestation of the overall observation error (Xu *et al.* 2016). According to Table 2 for the dividing method of precipitation events, the satellite remote sensing data of total error (T_E) is divided into Hit ME (H_E), Miss ME (M_E), False ME (F_E), and $T_E = H_E - M_E + F_E + R$, where *R* represents a random error, which can be generally ignored. According to the set threshold value, the calculation formula of each error component is shown in Equations (9)–(12) (Yong *et al.* 2016):

$$T_E = \sum_{i=1}^{N} (S_i - G_i) / N, \quad (S_i \ge 0 \text{ mm}, \ G_i \ge 0 \text{ mm})$$
(9)

$$H_E = \sum (S_H - G_H)/N, \quad (S_H \ge 1 \text{ mm/day}, \ G_H \ge 1 \text{ mm/day})$$
(10)

$$M_E = \sum (S_M - G_M)/N, \quad (S_M \ge 1 \text{ mm/day}, \ G_M \ge 1 \text{ mm/day})$$

$$\tag{11}$$

$$F_E = \sum (S_F - G_F)/N, \quad (S_F \ge 1 \text{ mm/day}, \ G_F \ge 1 \text{ mm/day})$$
(12)

In the above formula, *N* represents the total number of samples involved in calculations, *S* represents satellite remote sensing precipitation data and *G* represents measured data.

3. RESULTS

n

3.1. Spatial distribution characteristics of precipitation

Figure 2 shows the spatial distribution of average daily precipitation in the TRHR by CMA and four satellite precipitation data. It can be seen from the figure that the precipitation in the TRHR tends to be more in the southeast and less in the

Table 2 | Contingency table for evaluating the occurrence of precipitation events

		Satellite Product		
		Estimate \geq Threshold	$\textbf{Estimate} \leq \textbf{Threshold}$	
СМА	Observation \geq Threshold	Н	М	
	$Observation \leq Threshold$	F	_	

Note: ① H (Hit): the number of times that real precipitation events are correctly observed by satellite products; ② M (Miss): the number of precipitations actually produced on the ground when the satellite did not observe precipitation; ③ F (False): The number of times that the satellite observed precipitation while there was no precipitation on the ground.



Figure 2 | Spatial distributions of mean daily precipitation over the TRHR, China from (a) GSMaP-NRT, (b) GSMaP-MVK, (c) IMERG-Early, (d) IMERG-Late and (e) CMA for the period 2015–2017.

northwest, and the precipitation is mainly concentrated in the Yellow River headwater region (YERHR) and the Lantsang River headwater region (LARHR) (Figure 2(e)). The reason is closely related to the geographical location and topographic distribution characteristics of the study area. On the whole, the four satellite products all show the spatial distribution of precipitation in the TRHR, and the spatial distribution of precipitation in the Late product is the best. Early and Late products are significantly lower than CMA in terms of spatial precipitation level, on the contrary, NRT and MVK products are significantly higher than CMA in terms of precipitation level, and the two products of GSMaP have an obvious smoothing phenomenon in terms of spatial distribution, which may lead to the failure of GSMaP products to better detect extreme precipitation in local typical regions. In addition, compared with NRT and Early, the optimization of spatial distribution of precipitation of MVK and Late products is not obvious. Therefore, the spatial distribution accuracy of precipitation products based on GPM satellite inversion in the near-real-time stage is not significantly improved, while the spatial distribution of precipitation precipitation products is better than that of GSMaP products with the same processing level.

3.2. Accuracy analysis of satellite precipitation

Figure 3 shows the spatial distribution of correlation coefficients of four satellite products relative to CMA products. The correlation coefficient showed that the two products of IMERG were significantly higher than GSMaP. The correlation coefficients of GSMaP-NRT and GSMaP-MVK were significantly different in the whole study area. The correlation coefficient is the best in the LARHR, followed by the YERHR, and the worst in the Yangtze River headwater region (YARHR). In particular, the correlation coefficient of NRT and MVK products in the central and western regions of the YARHR is generally below 0.3. By comparing Figure 3(a) and 3(b), it can be found that the spatial distribution of the correlation coefficient of MVK is improved compared with that of NRT in the LARHR and the YARHR. In contrast, the correlation coefficient of IMERG products is lower in the western edge of the YARHR. The correlation coefficient of IMERG products in the YARHR can reach above 0.8. In contrast, the correlation coefficient of IMERG products in most of the three source regions is generally above 0.5, and the three source regions is generally above 0.5, and the three source regions is generally above 0.5, and the correlation coefficient of IMERG products in the YARHR can reach above 0.8. In contrast, the correlation coefficient of IMERG products in most of the three source regions is generally above 0.5, and the three source regions is generally above 0.5, and the correlation coefficient of IMERG products in the YARHR. The correlation coefficient of IMERG products in the YARHR can reach above 0.8. As can be seen from Figure 3(c) and 3(d), there is little difference in the correlation coefficient between Early and Late products. On the whole, the four products showed the best correlation coefficient in the downstream region.



Figure 3 | Spatial distributions of the Correlation Coefficient (Corr) index computed from GSMaP and IMERG precipitation products at $0.1^{\circ} \times 0.1^{\circ}$ resolution over the TRHR, China ((a)–(d) for NRT, MVK, Early and Late products, respectively).

The RMSE can well represent the dispersion degree and the whole error level between the satellite data and the reference data. Figure 4 shows the spatial distribution of RMSE. The RMSE value of IMERG (Early and Late) products were significantly lower than that of GSMaP (NRT and MVK), and the RMSE value of IMERG products in the three source regions were all below 4.0 mm. The RMSE of Late products compared with Early products did not significantly decrease. In contrast, the RMSE of NRT and MVK products is larger, especially in the east of the YERHR, the RMSE is more than 6.0 mm, followed by the LARHR, the RMSE is the smallest in the YARHR. The RMSE of MVK is lower than that of NRT, which indicates that the inversion of MVK and the improved algorithm can improve the accuracy of GSMaP and reduce the root mean square error. It is obvious that the root mean square error of the eastern and southern regions is significantly larger than that of the western and northern regions in the TRHR. The root mean square error of the YERHR is the largest, the main reason is that the precipitation in this region is relatively large, which improves the RMSE level on the whole. Compared with the satellite products of the same level, the root mean square error of IMERG is obviously smaller.



Figure 4 | Spatial distributions of the Root Mean Squared Error (RMSE) index computed from GSMaP and IMERG precipitation products at $0.1^{\circ} \times 0.1^{\circ}$ resolution over the TRHR, China ((a)–(d) for NRT, MVK, Early and Late products, respectively).

Relative deviation can significantly reflect the precipitation deviation degree of satellite products relative to ground products. Figure 5 shows the relative deviation (RB) distribution of satellite products. The relative deviation of satellite products has obvious regional distribution difference. Figure 5(a) and 5(b) shows that GSMaP has an obvious positive relative deviation in the YERHR and the YARHR, and the RB value in some areas is more than 80%. Obviously, NRT and MVK products greatly overestimate the precipitation in these areas. GSMaP products in the west of the YARHR and the northwest of the YERHR show a negative relative deviation, and the RB index in some regions is less than -40%, indicating that GSMaP underestimates the precipitation in this region. The relative deviation is small only in the area where the three source regions converge. It can be seen that GSMaP underestimates precipitation for the relatively low altitude in the YERHR and the LARHR, and underestimates precipitation in the high altitude areas such as the western of the YARHR. As shown in Figure 5(c) and 5(d), IMERG products generally underestimate precipitation in the TRHR, with the RB index less than 0 in most regions. Only at the intersection of the three source regions and the boundary of the YARHR, there are partial overestimated precipitation zones. IMERG products underestimated precipitation less than GSMaP, and on the whole, underestimated precipitation by 10-40%. The reasons for the above situation are closely related to the unique topography and climate of the region. First of all, the TRHR is located in the southeast edge of the Tibetan Plateau, with complex terrain, continental climate and mountain vertical climate, part of the surface is perennial glaciers and permafrost, and the precipitation is less. Especially in the boundary and the intersection area of the basin, where the altitude is higher, both GSMaP and IMERG show a larger overestimation of precipitation.

We calculated the spatial distribution of DI and PI of four kinds of satellite products in the TRHR (Figure 6). We find that the accuracy of IMERG algorithm is obviously better than GSMaP algorithm in precipitation inversion. The DI index of Early and Late products is above 0.65 in most regions, and there is no obvious difference between the two, both of them perform well. While the DI index of NRT and MVK products is mainly below 0.6, and the DI index of some regions, such as the central of LARHR, is above 0.65. In addition, the distribution of PI index also shows that the accuracy of IMERG is better than that of GSMaP. Especially in the YARHR, the PI index distribution of NRT and MVK products of GSMaP is generally low, and the algorithm performance is poor. From the analysis of regional distribution, the accuracy of satellite products in the YERHR and the southern part of the LARHR is higher, while the accuracy in the western Yangtze River basin is the lowest, and the PI index is the worst. It can be found that there is a certain relationship between the accuracy of precipitation of satellite products and the complexity of terrain and climate. The DI and PI indexes show a downward trend in the region closer to the west, and the decrease of GSMaP products is obvious.

Furthermore, we calculated the accuracy evaluation indexes of satellite products in the three source regions and plotted the color scatter plots (Figure 7). Based on the analysis of the spatial distribution characteristics of the error index above, it can be



Figure 5 | Spatial distributions of the Relative Bias (RB) index computed from GSMaP and IMERG precipitation products at $0.1^{\circ} \times 0.1^{\circ}$ resolution over the TRHR, China ((a)–(d) for NRT, MVK, Early and Late products, respectively).



Figure 6 | Spatial distributions of refined index of agreement (DI) and Performance index (PI) computed from GSMaP and IMERG precipitation products at $0.1^{\circ} \times 0.1^{\circ}$ grid resolution.

concluded that the precipitation accuracy of IMERG in the three source regions is higher than that of GSMaP. The correlation coefficient of Early and Late products in the three source regions is above 0.6, and the correlation coefficient of Late products is the highest, which reaches 0.63 in the LARHR and the YARHR. In addition, the RMSE of IMERG is significantly lower than that of GSMaP. The RMSE of NRT and MVK products in the source region of the Yellow River is the largest, reaching 4.85 and 5.56 mm, respectively. It can be seen that MVK algorithm does not improve the accuracy of NRT, but increases the RMSE. From the perspective of relative deviation, IMERG products underestimated precipitation by about 30% in the three regions, and the underestimation was relatively serious in the source region of the Yellow River. The RB index of Early and Late products was -35.1 and -36.0%, respectively. GSMaP has the best relative deviation in the source region of the Yangtze River, but according to the spatial distribution above, there are regional differences of overestimation and underestimation of NRT and MVK products in the east and west of the YARHR, resulting in a low overall RB index. GSMaP has the most severe overestimation of precipitation in the source region of the Yellow River, among which MVK products overestimated by 45.5%. It can be seen that the accuracy of satellite products in estimating precipitation level



Figure 7 | Scatterplots of grid-based daily precipitation between GPM-based satellite products and CMA observation over different basin regions. 1st, 2nd, and 3rd rows for Yangtze basin, Yellow basin, and Lantsang basin, respectively.

is the highest in the LARHR, the second in the Yangtze River source region, and the largest in the YERHR. In the Yellow River source region, GSMaP and IMERG products have the phenomenon of overestimating and underestimating precipitation to a large extent, respectively.

According to the analysis of Figures 3–7, the accuracy of IMERG and GSMaP algorithms in precipitation inversion has great regional differences, and the accuracy of IMERG algorithm is the best overall. In particular, the four kinds of satellite products, especially GSMaP (NRT, MVK) products, show large errors on the watershed boundary or around the watershed. As we know, the watershed is located near the ridge line, with high terrain and elevation, and the most complex terrain, which is the easiest to form topographic rain. Meanwhile, the ups and downs of the terrain are also easy to interfere with the satellite detection, increasing the difficulty of precipitation inversion. The inversion accuracy of GSMaP algorithm is obviously lower than that of IMERG algorithm in terrain complex areas. Although the accuracy of IMERG is also affected by terrain interference to some extent, the overall accuracy and stability of IMERG algorithm are better than GSMaP algorithm.

In order to analyze the ability of different satellite products to detect precipitation events from the scale of precipitation events, we calculated the distribution of classified statistical indices (POD, FAR and CSI) for four satellite products. The spatial distribution is shown in Figure 8, and the classified statistical index of each source area is shown in Table 3. According to the chart and analysis, the satellite products in the eastern and southern parts of the TRHR (most areas of the YERHR and the LARHR) have higher precipitation detection accuracy, because the results show a higher POD, a lower FAR and a higher



Figure 8 | Spatial distributions of classified statistical indices computed from GSMaP and IMERG daily precipitation products at $0.1^{\circ} \times 0.1^{\circ}$ resolution over the TRHR.

Table 3 S	ummary of	classified statistical	indices for satellit	e precipitation	products in different	t elevation areas (The shadow is the	e best)
-------------	-----------	------------------------	----------------------	-----------------	-----------------------	---------------------	-------------------	---------

Product	Region	POD	FAR	CSI
NRT	Yangtze	0.48	0.39	0.38
	Yellow	0.61	0.40	0.43
	Lantsang	0.66	0.31	0.51
MVK	Yangtze	0.53	0.33	0.41
	Yellow	0.67	0.44	0.43
	Lantsang	0.74	0.32	0.54
Early	Yangtze	0.58	0.26	0.48
	Yellow	0.51	0.26	0.43
	Lantsang	0.64	0.24	0.53
Late	Yangtze	0.56	0.24	0.47
	Yellow	0.51	0.24	0.44
	Lantsang	0.64	0.24	0.52

CSI (CSI > 0.4). The detection accuracy of precipitation in the north of the YERHR and the west of the YARHR is poor, especially the detection accuracy of GSMaP (NRT, MVK) products is the worst. It can be seen from Figure 8(a1)-8(a4) that the hit ratio index of GSMaP has obvious regional differences. Although the hit ratio of NRT and MVK is high in the eastern part of the LARHR and the YERHR, it is extremely poor in the western part of the YARHR and the northern part of the YERHR. The hit ratio of Early and Late products in the three source areas was better as a whole, and there was no significant difference in the spatial distribution of the hit ratio between them. The hit ratio index of Late products was

better (as can be seen in Table 2). Figure 8(b1)-8(b4) shows that NRT and MVK have large false alarm precipitation error (FAR = 0.39 and 0.33, respectively) in the west of the YARHR, followed by the YERHR and the LARHR with the lowest false alarm rate. Similarly, the CSI index of satellite products in the LARHR is the best, followed by the YERHR, and the CSI index of GSMaP products in the western of the YARHR is the worst (CSI is 0.38 and 0.41, respectively). Therefore, on the whole, the precipitation detection accuracy of IMERG series products is better than that of GSMaP products, and the IMERG-late products are the best. GSMaP has a great difference in precipitation event detection between the east and the west, and the precipitation detection accuracy of the western part of the YARHR is extremely poor.

The precipitation detection accuracy of satellite products in the LARHR is the best, followed by the YERHR and the YARHR. The main reasons are the topography and the frequency of precipitation events. The LARHR is located on the wind-ward side of India's warm and wet airflow, with a large topographic drop, more precipitation and more satellite detection frequency. The YERHR is located in the north of the Qinling Mountains in China. Although the topography is not very undulating, the complex topography and climate type of the Loess Plateau make the precipitation in this region less. The most complex terrain is the western region of the YARHR, which is located in the Tanggula Mountains in the northern part of the Tibetan Plateau. The terrain is extremely complex, with surface water mostly coming from the fusion of glaciers and snow, and very little precipitation.

3.3. Analysis of satellite precipitation error components

In order to analyze the characteristics of Total ME and error components of different satellite precipitation products, the Total errors of GSMaP and IMERG were decomposed into hit error, miss error and false error, and the spatial distribution of each error component was given (as shown in Figure 9). According to the analysis, NRT and MVK present a larger total mean error than Early and Late, especially in the YERHR and the LARHR. The spatial distribution shows that GSMaP has a large positive deviation in the YERHR and the LARHR, and the overestimation deviation of precipitation in this region is mainly caused by the misreporting of precipitation (Figure 9(d) and 9(h)). Secondly, the performance of hit precipitation deviation is good (Figure 9(b) and 9(f)). According to the previous analysis results, GSMaP has a high hit rate of precipitation in this region, but it also leads to excessive estimated precipitation events, resulting in large false precipitation reports. GSMaP products in the western region of the YARHR mainly show negative deviation, and this deviation mainly comes from missed precipitation events. This phenomenon indicates that GSMaP precipitation has a poor ability to capture precipitation events in the western region of the YARHR and cannot accurately capture the occurrence of precipitation events. In contrast, the



Figure 9 | Spatial distribution of Total ME and sub error components computed from GSMaP and IMERG daily precipitation products at $0.1^{\circ} \times 0.1^{\circ}$ resolution over the TRHR.

overall error of Early and Late products is small, and the total error of IMERG in the YERHR is less than 0. This underestimate error mainly comes from the missed precipitation events and the underestimate of precipitation level, and there is no large false alarm of precipitation. In the LARHR and the YARHR, the miss error and hit error of IMERG products are relatively flat, and they all concentrate within -1 to 1 mm. The source of the total error is mainly the hit precipitation error. It can be seen that the error of IMERG in the TRHR is mainly the detection error of precipitation level, which can better detect the precipitation events, but there is still a large room for improvement in the estimation of precipitation level. It is worth noting that the four satellite products all have large local error areas of missed precipitation in the northwest of the YERHR, the surrounding area of Qinghai Lake and the west of the YARHR. The analysis shows that there are lakes in all of these areas, indicating that the GPM satellite has a poor ability to detect precipitation near plateau lakes, which is consistent with the research results of Ren *et al.* (2019) in mainland China. The reason for this phenomenon may be that the underlying surface in the region with lake distribution is complex, and the large local evapotranspiration is easy to interfere with the signal reception of the satellite sensor.

Furthermore, Figure 10 shows the histogram of different error components of the four satellite products in three source regions. As can be seen from Figure 10(a), the miss error of satellite products at the YARHR is the largest, especially when the NRT and MVK reach about 0.4 mm. In addition, the NRT and MVK also have large false error and the hit error is the least. The total error of Early and Late precipitation in the YARHR mainly comes from Miss ME, followed by Hit ME. Figure 10(b) shows that GSMaP and IMERG have overestimate and underestimate precipitation errors in the YARHR. The overestimate error of GSMaP mainly comes from the false report of precipitation, while the underestimate of IMERG mainly comes from the miss error of precipitation, followed by the hit error, and the false error is very small. Figure 10(c) shows that there are large miss error, hit error and false error of IMERG mainly comes from the underestimate of precipitation levels and the omission of precipitation events, which results in the severe underestimate of IMERG precipitation over the LARHR.

4. DISCUSSION AND CONCLUSION

In this paper, the characteristics of precision and error components of GPM satellite precipitation inversion products (GSMaP, IMERG) in the TRHR of China are analyzed comprehensively by using various statistical indexes, and the following conclusions are drawn.



Figure 10 | Histogram of Total and sub error components computed from GSMaP and IMERG products over different basin regions ((a)–(c) for the Yangtze, Yellow and Lantsang basin, respectively).

- 1. The spatial distribution of precipitation in China is more in the southeast and less in the northwest. The satellite products can represent the spatial distribution of precipitation, among which the Early and Late products have better spatial distribution performance. The NRT and MVK products overestimate the regional precipitation levels in the YERHR and the YARHR, and the smoothing phenomenon of precipitation spatial distribution cannot highlight the local precipitation characteristics.
- 2. On the whole, the inversion accuracy of satellite products in the LARHR is the best, followed by the YERHR and the western part of the YARHR. The satellite products in the western part of the TRHR all show low correlation coefficient and low precipitation. In the YERHR and the eastern margin of the LARHR, NRT and MVK have large RMSE and overestimate precipitation, on the contrary, Early and Late in this region show the phenomenon of underestimation of precipitation.
- 3. Satellite products in the eastern the YERHR and the LARHR have the best ability to detect precipitation events, showing a higher hit rate and a CSI. GSMaP has the highest hit rate in this region, but the false alarm rate is higher than IMERG. Satellite products, especially NRT and MVK products, are less capable of detecting precipitation events in the areas closer to the west of the TRHR.
- 4. The overestimation error of GSMaP in the YERHR and the LARHR mainly comes from the missed measurement of rainfall, followed by the overestimation of precipitation level. The underestimation error of GSMaP in the west of the TRHR mainly comes from the missing measurement of precipitation events. The underestimated precipitation of IMERG mainly comes from the missed precipitation events and the underestimated precipitation levels, and there is no large false precipitation phenomenon. In addition, the satellite products have serious missed measurement errors in the areas where lakes are distributed, indicating that the GPM satellite has a poor ability to detect precipitation near plateau lakes.

On the whole, IMERG shows better accuracy of precipitation inversion in the TRHR. GSMaP has many false and missed precipitation events, and IMERG can better detect the precipitation events, but the estimation of precipitation level is still not accurate. The closer the satellite is to the west of the TRHR, the worse the precipitation accuracy and data reliability of satellite products are. The inversion accuracy in the western part of the TRHR and the northern part of the YERHR as well as near plateau lakes is poor, which should be considered in the future product inversion algorithm upgrading work.

AUTHOR CONTRIBUTIONS

H.W. and Y.Y. designed the experiments; H.W. and W.L. wrote the method part; H.W., S.Z. and T.X. processed the data; S.Z. and T.X. analyzed the data and wrote the original paper, and all authors contributed to the revising of the manuscript. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. IMERG and GSMaP were downloaded through FTP. The FTP download address of IMERG is: ftp://jsimpson.pps.eosdis.nasa.gov/data/imerg/. The FTP download address of GSMaP is: ftp://rainmap:Niskur+1404@hokusai.eorc.jaxa.jp/. The download address for CMA is http://www.cma.gov.cn/.

FUNDING

This study was supported by the Zhejiang Philosophy and Social Science Planning Project (Grant No. 21NDJC097YB), the Zhejiang University of Finance and Economics Dongfang College (No. 2020dfy005) and the Department of Education Foundation of Zhejiang (No. Y202147968).

INSTITUTIONAL REVIEW BOARD STATEMENT

Not applicable.

INFORMED CONSENT STATEMENT

Not applicable.

ACKNOWLEDGEMENTS

Thanks to data producers for providing available satellite precipitation data, such as the GPM science team at NASA and JAXA, and the Earth Observation Research Center, Japan Aerospace Exploration Agency (EORC/JAXA). Thanks to the China Meteorological Administration for providing the station data.

REFERENCES

- Alvares, C. A., Stape, J. L., Sentelhas, P. C. & Moraes Gonçalves, J. L. 2013 Modeling monthly mean air temperature for Brazil. *Theoretical and Applied Climatology* 113 (3–4), 407–427.
- Aslami, F., Ghorbani, A., Sobhani, B. & Esmali, A. 2019 Comprehensive comparison of daily IMERG and GSMaP satellite precipitation products in Ardabil Province, Iran. *International Journal of Remote Sensing* **40** (8), 3139–3153.
- Ayoub, A. B., Tangang, F., Juneng, L., Tan, M. L. & Chung, J. X. 2020 Evaluation of gridded precipitation datasets in Malaysia. Remote Sensing (Basel) 12 (4), 613.
- Hou, A. Y., Kakar, R. K., Neeck, S., Azarbarzin, A. A., Kummerow, C. D., Kojima, M., Oki, R., Nakamura, K. & Iguchi, T. 2013 The global precipitation measurement mission. Bulletin of the American Meteorological Society 95 (5), 701–722.
- Huffman, G., Bolvin, D., Braithwaite, D., Hsu, K., Joyce, R., Kidd, C., Nelkin, E., Sorooshian, S., Wang, J. & Xie, P. 2015 First results from the Integrated Multi-Satellite Retrievals for GPM (IMERG). In: *EGU General Assembly Conference*, 2015.
- Kubota, T., Aonashi, K., Ushio, T., Shige, S. & Oki, R. 2020 The Global Satellite Mapping of Precipitation (GSMaP) Project Part II Algorithm and Precipitation Model Development.
- Li, S., Yao, Z., Wang, R. & Liu, Z. 2020 Dryness/wetness pattern over the Three-River Headwater Region: variation characteristic, causes, and drought risks. *International Journal of Climatology* **40** (7), 3550–3566.
- Liu, Y. B., Fu, Q. N., Song, P., Zhao, X. S. & Cuicui, Dou. 2011 Review of satellite remote sensing retrieval of precipitation. Progress in Earth Science 26 (11), 1162–1172.
- Lu, D. & Yong, B. 2018 Evaluation and hydrological utility of the latest GPM IMERG V5 and GSMaP V7 precipitation products over the Tibetan plateau. *Remote Sens-Basel* 10 (12), 2022.
- Mayor, Y. G., Tereshchenko, I., Fonseca-Hernández, M., Pantoja, D. A. & Montes, J. M. 2017 Evaluation of error in IMERG precipitation estimates under different topographic conditions and temporal scales over Mexico. *Remote Sensing (Basel)* **9** (5), 503.
- Mega, T., Ushio, T., Kubota, T., Kachi, M., Aonashi, K. & Shige, S. 2014 Gauge Adjusted Global Satellite Mapping of Precipitation (GSMaP_Gauge). General Assembly & Scientific Symposium.
- Melo, D. D. C. D., Xavier, A. C., Bianchi, T., Oliveira, P. T. S., Scanlon, B. R., Lucas, M. C. & Wendland, E. 2015 Performance evaluation of rainfall estimates by TRMM multi-satellite precipitation analysis 3b42v6 and V7 over Brazil. *Journal of Geophysical Research: Atmospheres* 120 (18), 9426–9436.
- Prakash, S., Mitra, A. K., Aghakouchak, A., Liu, Z., Norouzi, H. & Pai, D. S. 2016 A preliminary assessment of GPM-based multi-satellite precipitation estimates over a monsoon dominated region. *Journal of Hydrology* 556, 865–876.
- Ren, Y. J., Yong, B., Lu, D. K. & Chen, H. Y. 2019 Multi scale accuracy evaluation of global precipitation program and multi satellite precipitation combined retrieval of IMERG satellite precipitation products in Chinese mainland. *Lake Science* **31** (02), 560–572.
- Sahlu, D., Nikolopoulos, E. I., Moges, S. A., Anagnostou, E. N. & Hailu, D. 2016 First evaluation of the Integrated Multi-satellitE Retrieval for GPM Day-1 IMERG over the upper Blue Nile Basin. *Journal of Hydrometeorology* **17** (11), 2875–2882.
- Shen, Y., Zhao, P., Pan, Y. & Yu, J. 2014 A high spatiotemporal gauge-satellite merged precipitation analysis over China. *Journal of Geophysical Research: Atmospheres* **119** (6), 3063–3075.
- Tan, M. L. & Santo, H. 2018 Comparison of GPM IMERG, TMPA 3b42 and PERSIANN-CDR satellite precipitation products over Malaysia. Atmospheric Research 202, 63–76.
- Tan, J., Huffman, G. J., Bolvin, D. T. & Nelkin, E. J. 2019 IMERG v06: changes to the morphing algorithm. Journal of Atmospheric & Oceanic Technology 36 (12), 2471–2482.
- Tapiador, F. J., Turk, F. J., Petersen, W., Hou, A. Y., Garcia-Ortega, E., Machado, L. A. T., Angelis, C. F., Salio, P., Kidd, C. & Huffman, G. J. 2012 Global precipitation measurement: methods, datasets and applications. *Atmospheric Research* 104–105, 70–97.
- Ushio, T., Okamoto, K., Iguchi, T., Takahashi, N., Iwanami, K., Kazumasa, Aonashi, Shige, S., Hashizume, H. & Kubota, T. 2005 The global satellite mapping of precipitation (GSMaP) project. *IGARSS Proceedings* **5**, 3414–3416.
- Wang, C. & Hong, Y. 2018 Review on inversion, verification and application of satellite remote sensing of precipitation. *Water Resources & Hydropower Engineering* **49** (8), 1–9.
- Wang, X., Ding, Y., Zhao, C. & Wang, J. 2019 Similarities and improvements of GPM IMERG upon TRMM 3b42 precipitation product under complex topographic and climatic conditions over Hexi region, Northeastern Tibetan Plateau. Atmospheric Research 218, 347–363.
- Xi, Y., Miao, C., Wu, J., Duan, Q., Lei, X. & Li, H. 2018 Spatiotemporal changes in extreme temperature and precipitation events in the Three-Rivers Headwater Region, China. *Journal of Geophysical Research: Atmospheres* **123** (11), 5827–5844.
- Xu, S., Shen, Y. & Du, Z. 2016 Tracing the source of the errors in hourly IMERG using a decomposition evaluation scheme. *Atmosphere* (*Basel*) 7 (12), 161.

- Yong, B., Chen, B., Tian, Y., Yu, Z. & Hong, Y. 2016 Error-component analysis of TRMM-based multi-satellite precipitation estimates over Mainland China. Remote Sensing (Basel) 8 (5), 440.
- Yu, J. J., Shen, Y., Pan, C. & Xiong, A. Y. 2015 Comparative evaluation of daily integrated precipitation data set in China and international precipitation products. *Acta Meteorologica Sinica* 73 (02), 394–410.
- Zeng, S. K. & Yong, B. 2019 Evaluation of the GPM-based IMERG and GSMaP precipitation estimates over the Sichuan region. *Acta Geographica Sinica* 74 (7), 1305–1318.
- Zhang, S., Wang, D., Qin, Z., Zheng, Y. & Guo, J. 2018 Assessment of the GPM and TRMM precipitation products using the rain gauge network over the Tibetan Plateau. *Journal of Meteorological Research* **32** (2), 324–336.
- Zhou, Z., Guo, B., Xing, W., Zhou, J., Xu, F. & Xu, Y. 2020 Comprehensive evaluation of latest GPM era IMERG and GSMaP precipitation products over mainland China. *Atmospheric Research* **246**, 105132.

First received 31 March 2021; accepted in revised form 18 September 2021. Available online 6 October 2021