



Applicability analysis of multiple precipitation products in the Qaidam Basin, Northwestern China

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Abstract

In the Qaidam Basin, meteorological stations are sparsely distributed, and the observational precipitation data are therefore not comprehensive, which significantly hampers the accurate assessment and optimal allocation of regional water resources. This study aims to evaluate the accuracy of three precipitation products (MSWEP V2, GPM IMERG V6, and TRMM 3B43) against gauged-based precipitation data from nine meteorological stations and 12 hydrologic stations in the Qaidam Basin from 2001 to 2016. The results reveal the following: (1) At the annual and monthly scales, the MSWEP product has the highest accuracy, followed by the GPM product. However, the TRMM product only reveals a correlation at the monthly scale; (2) the MSWEP product performs better in the wet season than the dry season, and the TRMM product has an abnormally high value of precipitation in the wet season. Moreover, it was shown that the accuracy of the GPM product is superior to that of the TRMM product; however, it has a low detection capability in some mountainous areas; and (3) the average error of each precipitation product at the meteorological stations is smaller than that at the hydrological stations.

Keywords Qaidam Basin · MSWEP · GPM · TRMM · Accuracy evaluation

Introduction

Precipitation is a major component of the hydrological cycle. Accurate precipitation information plays a critical role in regional water resources assessment (WRA), water resources management, and flood forecasting (Ebert et al. 2007). The distribution of precipitation, which can vary with elevation, geographic location, etc., has spatial variability and temporal discontinuity (Liu 2017), and accurate precipitation data is the prerequisite for research associated with precipitation. Traditional precipitation monitoring methods primarily include station observation, weather radar, and satellite inversion (Ren 2018). Among them, station observation is the most accurate and direct way to obtain precipitation information.

However, due to accessibility issues, maintenance costs, and other reasons, precipitation stations are scarce and poorly representative in many regions, which hinders the acquisition of spatiotemporal information about regional precipitation and thus impedes the accurate simulation of hydrological processes (Henn et al. 2015). The Qaidam Basin, a typical semi-arid alpine inland basin in Qinghai Province, Northwestern China, is an industrial base with advantages for the large-scale development of Western China and is additionally the largest circular-economy experimental area in China. The basin is the most dynamic region in Qinghai Province in terms of economic and social development and thus bears the heavy responsibility of supporting the economic and social development of the province and the construction of border areas and is furthermore an effective component for maintaining the ecological barrier of the Qinghai-Tibet Plateau. Moreover, the Qaidam Basin is an important node of the “Belt and Road” initiative. The scarcity of meteorological stations and incomplete observational precipitation data in the basin hamper the accurate assessment and optimal allocation of water resources. Remote sensing precipitation products, the reanalysis of precipitation data, and the assimilation of precipitation data are of great significance to watershed water resource management and planning (Liu et al. 2017). The evaluation

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of the applicability of remote sensing precipitation products and the assimilation of precipitation data in the Qaidam Basin is conducive to comprehensively revealing the spatiotemporal pattern of precipitation in typical alpine inland basins in China and is of considerable significance for improving the input of hydrological models and hydrological simulation capabilities in the future.

Multiple studies have been performed in China and abroad to evaluate the applicability of precipitation products in alpine regions. For example, Raziqi et al. (2010) showed that Global Precipitation Climatology Center (GPCC) data were reliable for monitoring drought conditions in the Iranian Plateau. Additionally, Cai et al. (2013) analyzed the applicability of Tropical Rainfall Measuring Mission (TRMM) 3B43 precipitation data in an inland river basin in Northwestern China using precipitation data from meteorological stations, and the results suggested that TRMM could better reflect the temporal and spatial variation characteristics of precipitation in the research area. The aforementioned research is targeted at a single precipitation product. However, other studies have performed comparative evaluations of the applicability of multiple precipitation products in regions where measurement stations are scarce. For instance, Wang et al. (2017a) took Daba Mountain in the Qinling Mountains as the research area and investigated the applicability of five precipitation products (CMORPH, GPCP-2, TRMM 3B43, GPCC, and ITPCAS) at different timescales using precipitation data from surface rainfall stations from 2000 to 2014. Furthermore, Gao et al. (2017) explored the applicability of two sets of reanalysis precipitation data (CFSR and ERA-Interim) in the Kashi River Basin in the western Tianshan Mountains based on observational hydrological data and meteorological station data from 1990 to 2000. The TRMM (Huffman et al. 2007) is an international program jointly sponsored by NASA and the Japan Aerospace Exploration Agency (JAXA) intended to quantitatively measure tropical and subtropical rainfall. A large number of studies have suggested that TRMM precipitation data have certain applicability in the Qinghai-Tibet Plateau region of China (Hao et al. 2011; Zeng and Li 2011; Qi et al. 2013; Li et al. 2017; Yu et al. 2018). Global Precipitation Measurement (GPM) data (Hou et al. 2014) are precipitation data that have a higher accuracy and spatial resolution than TRMM data, providing higher precision in mountainous areas, especially in locations with snow and ice cover and a rain accumulation layer (Ren et al. 2019). The Integrated Multi-satellite Retrievals for GPM (IMERG) data, GPM's three-level product, were updated to the sixth version in April 2019, when the time range was extended from June 2000 to the present for the first time (Tan et al. 2019); therefore, the precision of the precipitation data in this new version should be evaluated. The time series of the Multi-Source Weighted-Ensemble Precipitation (MSWEP) precipitation product generated by Beck et al. (2017, 2019) has been extended to 1979–2017,

and the new grid precipitation product has been widely applied in China (Deng et al. 2018; Xu et al. 2019) and has a substantial potential for the estimation of precipitation in mountainous areas which lack observational data (Liu et al. 2016; Huang et al. 2020). However, the applicability of the MSWEP product in mountainous alpine areas has not been fully explored. Due to the difference between basic data and calculation methods, there are differences in the precipitation estimates of different precipitation products in the same area. The accuracy of the same precipitation product, which is greatly affected by product version, topography, climate, etc., should be analyzed in specific areas (Huang and Cao 2019).

Mountain basins (e.g., the Qaidam Basin) have great spatial and temporal variability of orographic precipitation. In areas with complex terrain, meteorological stations are often located in valleys and populated regions, while hydrological stations are clustered at higher elevations and the outlets of rivers. Several researchers have evaluated satellite-based precipitation products using gauge data from meteorological stations (Cai et al. 2013; Wang et al. 2017a). However, few studies have used gauge data from hydrological stations or compared satellite precipitation products with observational data from meteorological and hydrological stations.

In this study, in order to evaluate the accuracy of MSWEP in mountainous areas in Northwestern China and compare long time series of GPM and TRMM remote sensing precipitation products, the applicability of three precipitation products (MSWEP, GPM IMERG, and TRMM 3B43) in the Qaidam Basin from 2001 to 2016 is analyzed based on 21 ground observation stations in the basin. This work involved an analytical comparison of the differences in the spatial and temporal distributions of precipitation products, an evaluation of the precision at annual, monthly, and seasonal timescales, and an investigation of the factors which influence the precision (meteorological and hydrological stations, and the elevation). It should be highlighted that this study was the first to estimate the performance of the latest released GPM IMERG V6 product for a relatively long period compared to previous versions of GPM IMERG over the semi-arid climate area with a great spatiotemporal variability of orographic precipitation in the Qaidam Basin, northwest China. Besides satellite precipitation products GPM IMERG V6 and TRMM 3B43, the performance of the new multi-sensor blended product MSWEP V2 in the Qaidam Basin was also estimated. The results of this research can provide a basis for obtaining accurate precipitation data for the Qaidam Basin and promote the regional climate and hydrological research. Additionally, it can provide important reference for the evaluation of satellite-based precipitation products in semi-arid area and the improvement of passive microwave algorithms in mountainous areas.

Study area and data

Study area

The Qaidam Basin (35° 00′–39° 20′ N, 90° 16′–99° 16′ E) is located in the northeast Qinghai-Tibet Plateau and is one of the three major inland basins in China (Fig. 1). The basin covers an area of 257,700 km². The Qaidam Basin and the Tarim Basin, in the Xinjiang Uyghur Autonomous Region, are the central inland basins in Asia. The elevation of the basin floor is between 2675 and 3200 m a.s.l., and the elevation of the mountains enclosing the basin is between 3500 and 6860 m a.s.l., rising gradually from the southeast to the northwest. The Qaidam Basin features a typical plateau continental climate with a mean annual precipitation of 100.76 mm, a mean annual potential evapotranspiration of 1528.1 mm, an annual mean temperature of −5.6 to 5.2 °C, and notable regional differences in temperature. In the southeast of the basin, the precipitation in the southeast of the basin is over 200 mm, the annual evaporation is 1000 mm, and the relative humidity is 40% (Han et al. 2015; Han et al. 2019). Meanwhile, in the northwest of the basin, precipitation is less than 50 mm and the annual evaporation is 2000 mm, while in the middle of the basin, the precipitation is 20 mm. Moreover, precipitation in the basin is unevenly distributed throughout the year; the flood season is from May to September, and the precipitation can occupy 87.4% totally throughout the year.

Precipitation data

Gauge-based precipitation data

In this study, the measured precipitation data were obtained from the monthly precipitation dataset of 21 ground observation stations in the Qaidam Basin collected by various meteorological and hydrological departments in Qinghai province from 2001 to 2016. The 21 ground observation stations include nine meteorological stations and 12 hydrological stations. Among these 21 ground observation stations, nine meteorological stations are included in the Global Precipitation Climatology Centre (GPCC) gridded gauge-analysis precipitation dataset, while 12 hydrological stations are not included in this dataset. These data have undergone strict quality control. The data accuracy of gauges from meteorological stations and hydrological stations is 0.1 mm, recorded by weighing rain gauges, which can measure other forms of precipitation including rain, hail, and snow. The spatial distribution of the ground observation stations is shown in Fig. 1. The meteorological stations are evenly distributed in the Qaidam Basin, while hydrological stations are mainly distributed in the east of the basin. The basic information of the ground observation stations is shown in Table 1. The elevation range of the ground observation stations is 2765–3559 m a.s.l. For research purposes, the elevations of the 21 ground observation stations were divided into five grades using the natural discontinuous point classification method (Yang et al. 2017), namely, 2765–

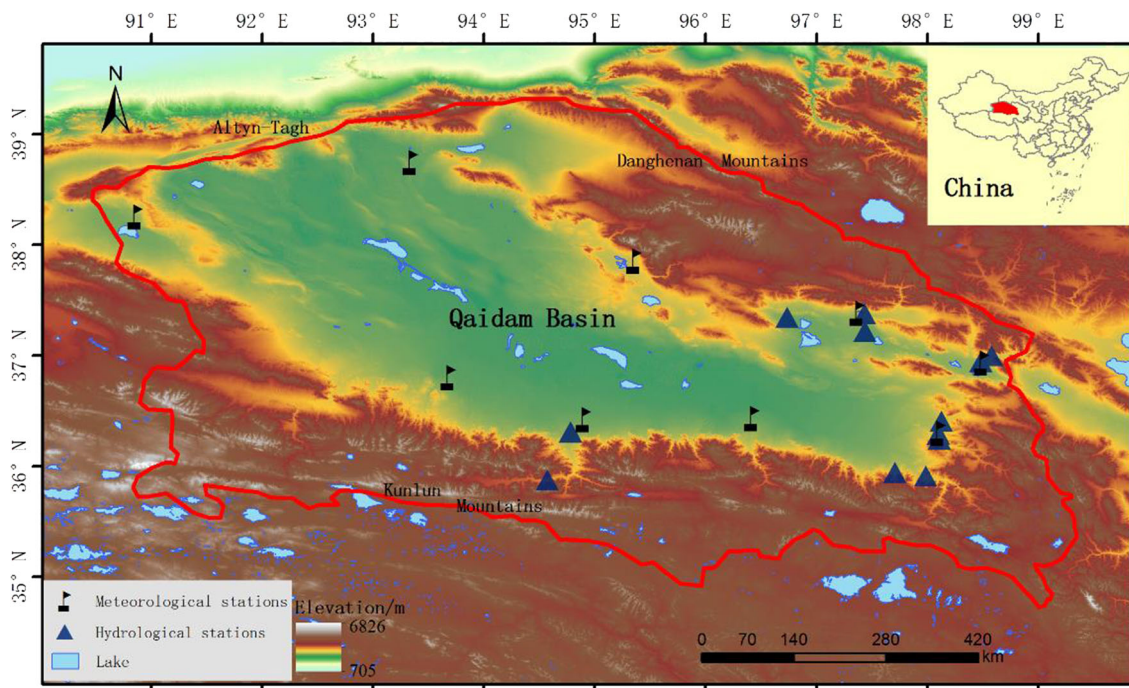


Fig. 1 Locations of the Qaidam Basin, lakes, meteorological and hydrological stations

Table 1 Basic information of the 21 ground observation stations used in this study

Category	Station name	Latitude (°N)	Longitude (°E)	Elevation (m)	Elevation grade
Meteorological station	Dachaidan	37.85	95.35	3179	4
	Delingha	37.38	97.36	3001	3
	Dulan	36.29	98.09	3185	4
	Golmud	36.42	94.90	2809	1
	Lenghu	38.74	93.33	2765	1
	Mangya	38.25	90.85	2938	3
	Nomuhong	36.43	96.42	2767	1
	Wulan	36.93	98.48	2980	3
	Xiaoduhuo	36.80	93.68	2779	1
	Hydrological station	Chahanhe	36.94	98.48	2957
Chahanwusu		36.24	98.11	3240	4
Delingha (3)		37.38	97.43	3025	3
Dulan rainfall station		36.29	98.09	3194	4
Gahai		37.22	97.44	2860	2
Huaitoutala		37.34	96.73	2848	2
Shanggaba		36.99	98.57	3135	4
Xiaraha		36.40	98.12	3104	4
Xiangride		35.91	97.98	3199	4
Nachitai		35.87	94.57	3559	5
Ke'er		35.94	97.70	3249	4
Golmud (4)	36.31	94.78	2919	2	

2809 m (grade 1, four stations), 2809–2919 m (grade 2, three stations), 2919–3025 m (grade 3, five stations), 3025–3249 m (grade 4, eight stations), and 3249–3559 m (grade 5, one station). The four stations in elevation grade 1 are all meteorological stations, and the station in elevation grade 5 is a hydrological station. The mean elevation of the hydrological stations is greater than that of the meteorological stations.

Precipitation products

In this study, we used three precipitation products which were Multi-Source Weighted-Ensemble Precipitation (MSWEP) V2 (Beck et al. 2019), Global Precipitation Measurement (GPM) IMERG V6 (Tan et al. 2019), and Tropical Rainfall Measuring Mission (TRMM) 3B43 (Duan and Bastiaanssen 2013) (Table 2).

The MSWEP dataset is a new multi-element precipitation data product that integrates station data (CPC Unified and

GPCC), satellite observation data (CMORPH, GSMap MVK, and TRMM 3B42RT), and atmospheric reanalysis data (ERA-Interim and JRA 55) (Xu and Wang 2018). The latest version (version 02) of MSWEP products was released in 2019 (Beck et al. 2019); it has 3-hourly and 0.1° global-gridded precipitation dataset covering 1979–2017. In this study, monthly precipitation data of version 2 from January 2001 to December 2016 were used. The data is simply referred to MSWEP for conciseness hereafter.

The GPM dataset is the successor of the TRMM (Hou et al. 2014). IMERG is the third-level product of GPM, and multiple versions have been released since 2014; the most recent is version 6, which was released in April 2019 and provides precipitation data from June 2000 to the present (Tan et al. 2019). In this study, the Final-Run product of GPM IMERG V6 at the monthly timescale was used (hereafter referred to as GPM); it is calibrated by the gauge-interpolated monthly precipitation data GPCC and has the best accuracy and quality (Tang et al. 2020).

Table 2 Basic information of the three precipitation products used in this study

Product	Spatial resolution	Time series length	Data source
MSWEP	0.1°	1979–2017	http://www.gloh2o.org/
GPM	0.1°	June 2000–present	http://pmm.nasa.gov/GPM
TRMM	0.25°	1998–present	https://pmm.nasa.gov/TRMM

The TRMM 3B43 dataset is one of the TMPA (TRMM Multi-satellite Precipitation Analysis) products, providing monthly precipitation at spatial resolution of 0.25° for the quasi-global region of 50° N to 50° S from 1998 to present (Huffman et al. 2007). The latest Version 7 TRMM 3B43 monthly precipitation data (hereafter referred to as TRMM) was released in May 2012 and used in this study. It estimates precipitation using TMPA algorithm that combines microwave with infrared satellites as well as the Global Precipitation Climatology Centre (GPCC) monthly precipitation data (Duan and Bastiaanssen 2013).

Methods

Based on the grid precipitation data of the MSWEP, GPM, and TRMM precipitation products for the Qaidam Basin from 2001 to 2016, the cell statistics tool in the ArcGIS software (Esri, Redlands, CA, USA) was used to calculate a precipitation grid; the spatial distributions of multi-year mean precipitation and seasonal precipitation in the Qaidam Basin were obtained, and the spatial and temporal distribution characteristics and variation trends of the different precipitation products in the basin were evaluated.

The 21 ground observation stations used in this study are unevenly distributed in the research area. In order to investigate the accuracy of the grid precipitation data by comparison with the station precipitation data, a pixel-point comparison method that was employed in many previous studies (Li et al. 2013; Wang et al. 2017b; Xu et al. 2019) was used to avoid additional error brought by interpolation. For the location of each ground observation station, the corresponding pixel was identified in the different precipitation products, and then precipitation values were extracted from the pixel to evaluate precipitation products by pixel-point data pairs. The evaluation was conducted at the annual, monthly, and seasonally scale; annual precipitation estimates were generated by analyzing a 12-month dataset, while seasonal analyses were performed on three-month datasets (February to April (spring), May to July (summer), August to October (autumn), and November to January (winter)).

Several quantitative indexes, namely, the correlation coefficient (R), relative deviation (BIAS), mean absolute error (MAE), and root-mean-square error (RMSE), were employed to evaluate the accuracy of the precipitation products (Chen et al. 2015; Moazami et al. 2016; Liu et al. 2018, 2019b; Wang et al. 2019). The specific formulas and optimal values of the four quantitative indexes are shown in Table 3. The correlation coefficient represents the degree of linear correlation between the precipitation products and the measured precipitation values at the measuring stations; the BIAS represents the degree of systematic deviation of the precipitation product data, with positive and negative values indicating the overestimation

or underestimation with respect to the measured data, respectively, while the mean absolute error and root-mean-square error are used to reflect the mean errors between the precipitation products and the observed precipitation values.

Additionally, the spatial distributions of the errors of the three monthly precipitation products were obtained based on the four quantitative indexes. The meteorological stations and hydrological stations in the Qaidam Basin vary greatly in terms of their spatial distribution and elevation distribution; the hydrological stations are primarily concentrated in the east of Qaidam Basin at relatively high elevations, whereas the meteorological stations have a relatively uniform distribution; therefore, the errors in the precipitation products in meteorological and hydrological stations and the errors due to elevation changes were analyzed.

Results and discussion

Spatial distribution of precipitation

The multi-year mean precipitation distribution maps and seasonal precipitation distribution maps for the Qaidam Basin for 2001 to 2016 are shown in Figs. 2 and 3, respectively.

Figure 2 shows that the estimated spatial distribution of precipitation in the Qaidam Basin is consistent between the three precipitation products: In the map for each product, the precipitation increases from the northwest to the southeast, and the precipitation amount is greater in mountainous areas than in basin areas. The annual precipitation values of the MSWEP and GPM products range from 20 to 560 mm. However, there are large differences in the precipitation values between the three products. For example, in the middle of the basin, the precipitation of GPM is greater than that of MSWEP, while in the southern and northeastern mountainous areas, the precipitation of GPM is lower than that of MSWEP. Overall, the precipitation values of TRMM are larger than those of the other two products, with abnormally high values in the central area of the basin, near the Huaitoutala hydrological station, where the precipitation value is twice the maximum value of the MSWEP and GPM precipitation values. The TRMM product also has abnormally high precipitation in the western basin, near the Mangya meteorological station. The precipitation of the MSWEP product is approximately 200 mm in the southeast of the basin, 20 mm in the middle of the basin, and 350–560 mm in the mountainous area, which is closer to the measured values of precipitation than the values of the other two products.

Additionally, as shown in Fig. 3, the performances of the precipitation products vary greatly in different seasons. For example, in the MSWEP product, the precipitation distribution in winter is markedly different from that in other seasons; in winter, precipitation is low in the southwest mountainous area and

Table 3 Calculation formulae and optimal values of the quantitative indexes used in this study

Quantitative index	Formula	Optimal value
Correlation coefficient (R)	$R = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}}$	1
Relative deviation (BIAS)	$BIAS = \frac{\sum_{i=1}^n (Y_i - X_i)}{\sum_{i=1}^n X_i} \times 100\%$	0
Mean absolute error (MAE)	$MAE = \frac{1}{n} \sum_{i=1}^n Y_i - X_i $	0
Root-mean-square error (RMSE)	$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (X_i - Y_i)^2}$	0

Notation: X_i and Y_i respectively represent the precipitation (mm) at the measuring station and the grid point where the precipitation products are located; i represents the number of precipitation sequences evaluated; \bar{X} and \bar{Y} respectively represent the mean precipitation value (mm) at the measuring stations and the grid points where the precipitation products are located; and n is the estimated precipitation sequence length

highest in the northern mountainous area. Meanwhile, in the GPM product, the lowest precipitation value occurs in the north-west of the basin in all four seasons, while in winter, there are high precipitation values in the mountainous areas in the central and northeast of the basin, which is different from the three other seasons. In the TRMM product, abnormally high precipitation values in the central Qaidam Basin only occur in summer and autumn, and there is little difference in the spatial distribution of precipitation in winter. The precipitation values of the MSWEP and GPM products are very similar in each season, and the smallest differences among the three precipitation products are observed in spring. The three precipitation products perform similarly in summer and autumn. The precipitation value of MSWEP is generally lower than those of GPM and TRMM, especially in the central and southern basin. In the southern mountainous area, the precipitation values of the GPM product are lower than those of the MSWEP and TRMM products. The precipitation values of TRMM are greater overall. The abnormally high precipitation values in the central basin observed in the TRMM product are around twice the highest values observed in the GPM and MSWEP products in summer and autumn. The differences in the spatial distribution of precipitation for the three precipitation products are largest in winter.

The Qaidam Basin has a typical arid and semi-arid climate and experiences a great spatiotemporal variability of orographic precipitation. The average annual precipitation decreases from the surrounding mountain area (approximately 300 mm) to the interior of the basin (less than 50 mm) (Jia et al. 2011). The seasonal variability of precipitation is significant due to the effect of the monsoon, with most the rain falling between May and September. The results show that among the three precipitation products, MSWEP is the closest to the actual distribution of precipitation in the Qaidam Basin, followed by GPM. Previous studies have found that the TRMM 3B42 (Qin et al. 2014) and TRMM 3B43 (Chen and Li, 2016) contain many isolated grid boxes of anomalous overestimation in North China, which is consistent with the abnormally high precipitation value we found in the central Qaidam Basin. These areas with abnormally high value of precipitation are near the inland water bodies such as the Qarhan Salt Lake (Fig. 1), since the poor identification of differences in emissivity and temperature between water bodies and land surface in the passive microwave (Tang et al. 2016) and mountain area might have a high cloud temperature threshold resulting in regarding the no rainy clouds near the inland water bodies as rainy ones (Hussain et al. 2017).

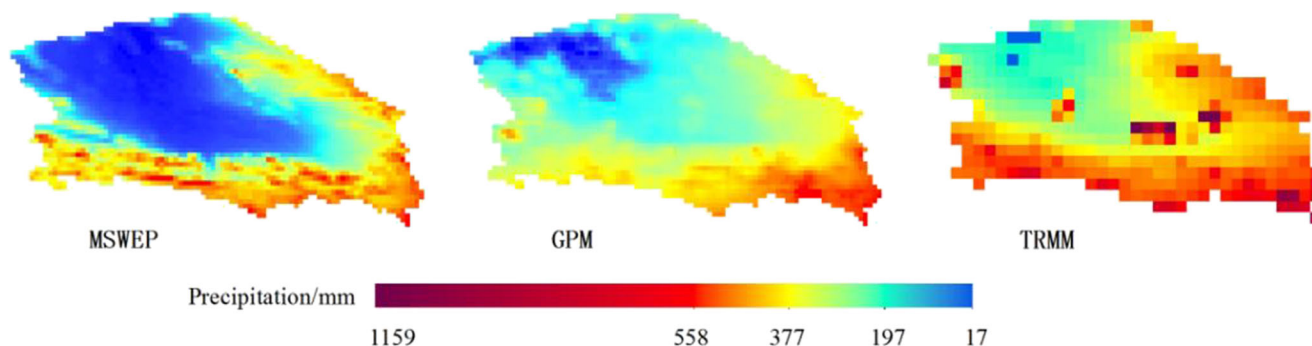


Fig. 2 Maps showing the mean precipitation in the Qaidam Basin between 2001 and 2016 for different precipitation products. MSWEP, Multi-Source Weighted-Ensemble Precipitation. GPM, Global Precipitation Measurement. TRMM, Tropical Rainfall Measuring Mission

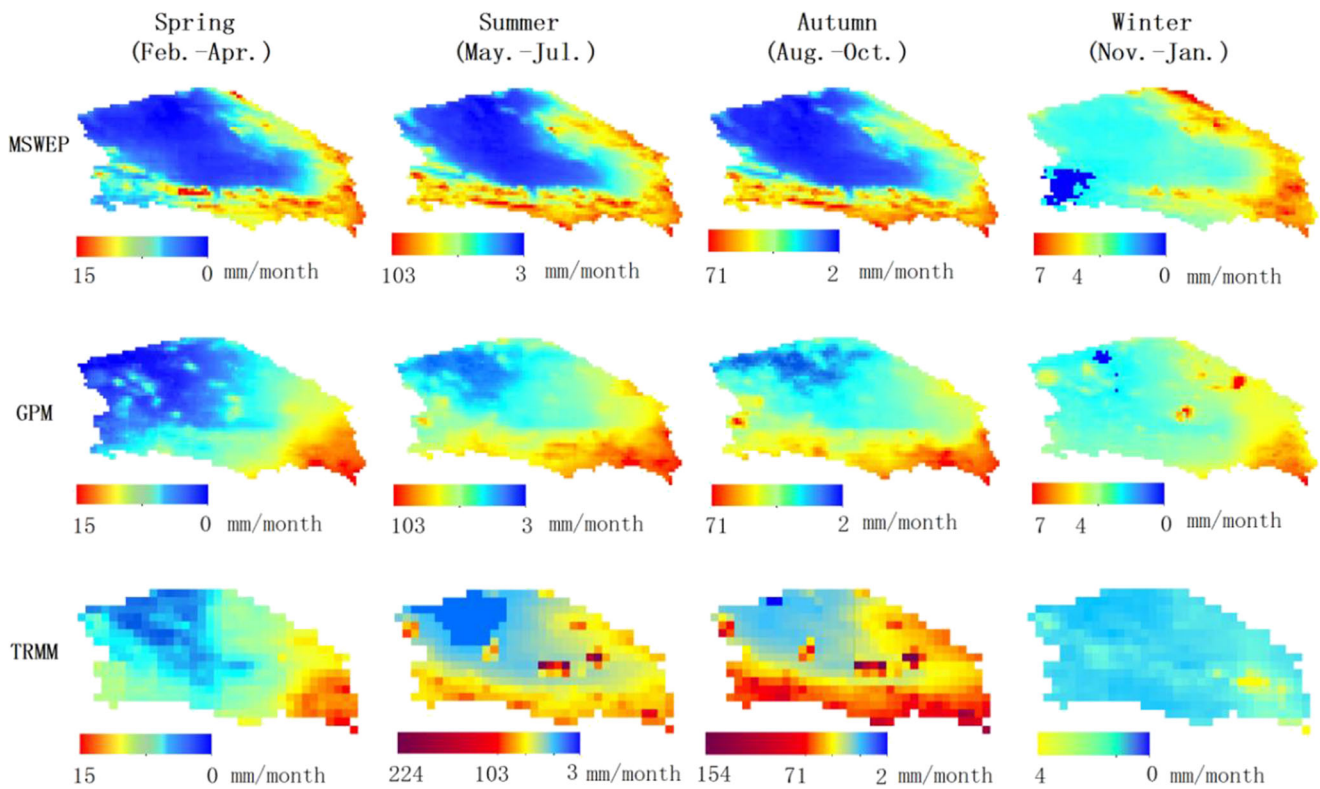


Fig. 3 Maps showing the seasonal mean precipitation distribution in the Qaidam Basin between 2001 and 2016 for different precipitation products

Therefore, the mixed pixels with lake and land perform anomalous overestimation. These salt lakes generally have no ice period due to the high salinity; we speculate that in summer and autumn with heavier precipitation, the temperature differences between water bodies and land surface are higher, causing the precipitation anomalies to be more significant in the wet seasons. The reason of GPM which does not have this case is mainly ascribed to the updated passive microwave algorithm and higher spatial resolution (Satgé et al. 2018).

Cross comparison of precipitation products

Annual precipitation

In order to quantitatively express the accuracy of the three precipitation products at the annual timescale, the BIAS, MAE, and RMSE between the grid values of the three precipitation products and the 21 ground observation stations in the Qaidam Basin are calculated (Fig. 4), and the precipitation data of the three precipitation products and the measured data at the annual timescale are analyzed, as shown in Fig. 4. As shown in the figure, the correlations were significant at $p < 0.01$ for all three precipitation products. The strongest correlation was obtained for MSWEP (0.87), followed by GPM (0.77), while the weakest correlation (0.15) was obtained for TRMM.

Figure 4 showed that the GPM product obtained the lowest absolute value of BIAS. Additionally, the fact that GPM had a

positive BIAS value indicates that the estimation of annual precipitation obtained using this product was slightly greater (2.56%) than the measured value. Meanwhile, the MSWEP product underestimated the annual precipitation by 11.58%, and the TRMM product overestimated the annual precipitation by 17.40%. As also shown in Fig. 4, the lowest MAE and RMSE values were obtained for the MSWEP product, followed by GPM, while the largest values were obtained for TRMM, showing that the mean error at the annual scale increases in the order MSWEP < GPM < TRMM.

A comparison of the annual distribution of the three precipitation products and the measured precipitation at the ground observation stations is shown in Fig. 5. In all of the precipitation products, the precipitation is primarily concentrated in May–August, with the highest monthly precipitation occurring in July and the lowest seasonal precipitation occurring in winter (November–January). The GPM product is closest to the measured precipitation. The MSWEP product underestimates the precipitation in summer (May–July), while the TRMM product overestimates the precipitation in summer and autumn.

Monthly precipitation

The BIAS, MAE, and RMSE (Fig. 6) between the precipitation values of the three precipitation products of the ground observation stations and the grids were calculated to

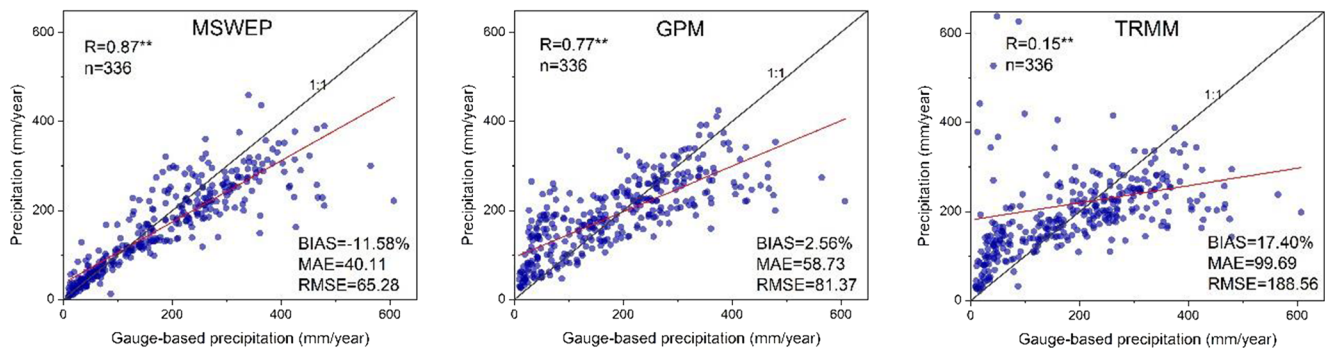


Fig. 4 Scatterplots showing yearly precipitation from gauges against the MSWEP, GPM, and TRMM precipitation products at the grid-scale. ** represents significance at $p < 0.01$

quantitatively express the monthly precipitation accuracy of the three precipitation products. Additionally, Fig. 6 also shows the correlations between the extracted monthly precipitation values and the measured values. As shown in the figure, the correlations are significant at $p < 0.01$ for all three precipitation products. The strongest correlation coefficient (0.9) was observed for MSWEP, followed closely by GPM (0.86), while the weakest correlation (0.53) was observed for TRMM.

As shown in Fig. 6, the BIAS values demonstrate that the MSWEP product underestimates the monthly precipitation by 11.58%, while the GPM and TRMM products overestimate the monthly precipitation by 2.56 and 17.40%, respectively. Regarding MAE and RMSE, MSWEP has the lowest values, followed by GPM, while TRMM has the largest values, exhibiting that the mean error between MSWEP and measured monthly precipitation is the smallest. Generally, MSWEP and GPM have higher accuracy, with MSWEP tending to underestimate the precipitation but having the highest correlation with the measured precipitation and the smallest mean error. Meanwhile, TRMM has the worst performance of the three products.

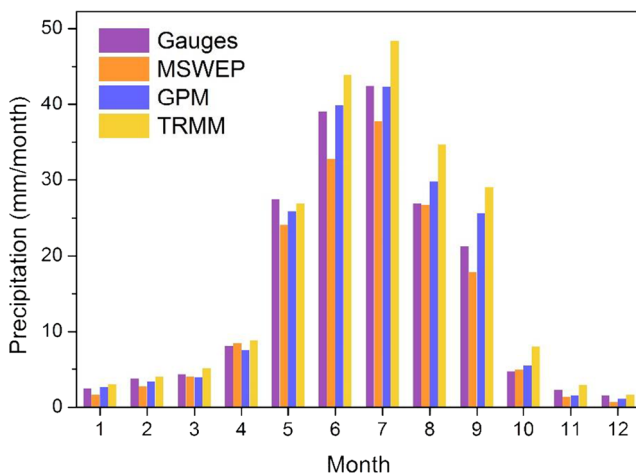


Fig. 5 A comparison between the monthly average precipitation for different precipitation products during 2001–2016 and gauge-based monthly average precipitation for the same period

Seasonal precipitation

Figure 7 shows the accuracy of the three precipitation products as quantitatively expressed by the four quantitative indexes at the seasonal scale and scatterplots for the three precipitation products at the seasonal scale produced according to the measured precipitation values at the ground observation stations.

As can be seen from Fig. 7, the performances of the three precipitation products vary greatly in different seasons. As shown in the figure, in terms of the correlation coefficient, MSWEP performs best in summer (0.89) and autumn (0.81) and moderately well in spring (0.78) and winter, with the lowest value being obtained in winter (0.56). The correlation coefficients of GPM are high (above 0.8) in spring and summer and moderate in autumn (0.76) and winter (0.63). In spring and winter, TRMM is moderately correlated with the measured monthly precipitation, while the correlation coefficients are relatively low (less than 0.5) in summer and autumn. With respect to the BIAS, MSWEP has negative values in all seasons, indicating an underestimation of the precipitation, with the greatest degree of underestimation (41.6%) being observed in winter. Meanwhile, GPM overestimates precipitation in autumn and underestimates in all other seasons, whereas TRMM overestimates precipitation in all four seasons, with the greatest overestimation (35.7%) occurring in autumn. Furthermore, the MAE and RMSE of the three precipitation products are all lowest in winter and highest in summer, which indicates that the mean error between the precipitation products and the measured precipitation is smallest in winter and highest in summer.

Compared to ground observation stations, MSWEP performed highest accuracy among three precipitation products at annual and monthly scales, followed by GPM. MSWEP is a multi-element precipitation product, merging and making full use of the complementary strengths of gauge, satellite, and reanalysis data (Bai et al. 2020). Therefore, MSWEP generally outperforms satellite-based precipitation products. A previous study indicated that MSWEP generally overestimated precipitation over the whole Qinghai-Tibet Plateau (Liu et al.

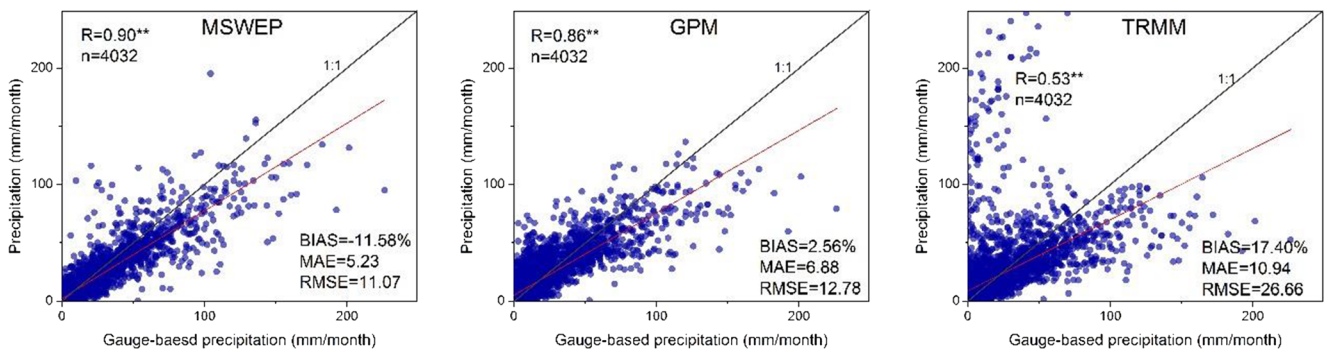


Fig. 6 Scatterplots showing monthly precipitation from gauges against the MSWEP, GPM, and TRMM precipitation products at the grid-scale. ** represents significance at $p < 0.01$

2019a). Our study shows that MSWEP underestimates the precipitation in the Qaidam Basin at annual, monthly, and seasonal scales. In the large area of the Qinghai-Tibet Plateau, the Qaidam Basin is a typical arid region with strong evaporation, which can explain the aforementioned underestimation. Additionally, the sparse coverage of gauge in the Qaidam Basin is partially responsible for this underestimation. In the Qilian Mountains, Huang and Cao (2019) reported a similar underestimation of MSWEP in an arid area.

GPM and TRMM overestimate precipitation at annual and monthly scales, which mainly because the satellite-based precipitation products misidentify the zero rainfall showed at gauge as greater than zero (Chen et al. 2018). However, GPM has obviously smaller BIAS than TRMM, due to the improvement of measurement algorithm and higher spatial resolution in GPM. In addition, our results corroborate a previous study which found that GPM performs significantly better in the Qinghai-Tibet Plateau compared with TRMM (Chen and Li 2016).

One limitation of our work is that the gauge data we collected are sparse. However, this is an unavoidable limitation in such complex terrain. However, we believe that our results obtained using gauge-based data from meteorological stations and hydrological stations to evaluate satellite-based precipitation products using a point-pixel comparison method are reliable. Additionally, the TRMM 3B43, GPM IMERG, and MSWEP products come from multiple data sources with different spatial resolutions, which introduces uncertainties to the final estimation. However, to identify these error sources, a dense network of ground observation stations is essential, such as that used by Xu et al. (2017) in the southern Tibetan Plateau.

Factors influencing precipitation accuracy

Spatial distribution of quantitative indexes

The spatial distributions of the four quantitative indexes of the measured monthly precipitation values at the 21 stations and

grid values corresponding to the three precipitation products in the Qaidam Basin are shown in Fig. 8.

As can be seen from Fig. 8, the MAE and RMSE values of the three precipitation products generally increase from west to east, and the mean error is greater at the ground observation stations near the mountainous area in the east. Additionally, compared to the other two precipitation products, TRMM has higher MAE and RMSE values at the Mangya meteorological station in the west of the basin and the Huaitoutala hydrological station in the northeast of the basin. Regarding the BIAS, the spatial pattern of the GPM and TRMM products are relatively similar: These products overestimate the precipitation values in the western and central basin and underestimate the values in the eastern basin. For GPM, the maximum absolute value of the BIAS occurs at the meteorological stations in the southern basin near the mountainous areas, where there is a mean overestimation of 200% in the measured precipitation values. Meanwhile, TRMM has the highest degree of overestimation at the Mangya meteorological station and the Huaitoutala hydrological station in the south of the basin, with overestimations of 400% and 600%, respectively. A possible reason for this is that these stations are near the lakes, which leads to some abnormally high precipitation value compared with gauges (Guo et al. 2015). In addition, there is a relatively low spatial resolution of TRMM, which makes it difficult to detect the precipitation in a mountain grid with sink. Furthermore, MSWEP underestimates the measured precipitation at most stations in the basin. However, the correlation coefficient has no notable spatial distribution pattern. The correlation coefficients of the three precipitation products are all less than 0.5 at the Lenghu meteorological station, while the correlation coefficient of the TRMM product is also low (less than 0.5) at the Mangya meteorological station. The correlation coefficients of the three precipitation products are mostly above 0.8 in the eastern stations.

The GPM and TRMM products tend to overestimate the precipitation at stations located at relatively low elevations in the mountainous parts of the study area. The measurement algorithm of the remote sensing precipitation products tends to have higher accuracy in areas with relatively large

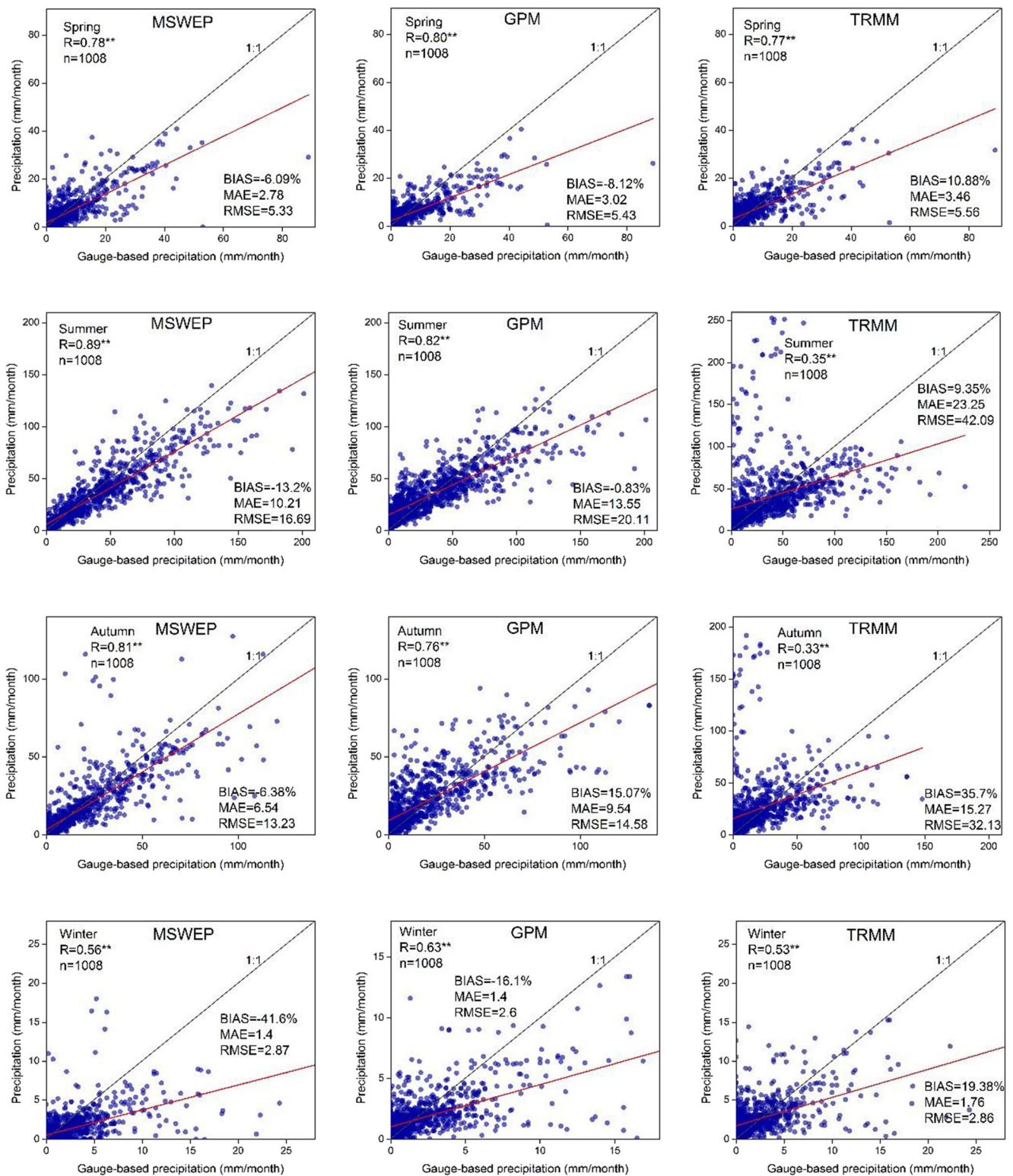


Fig. 7 Scatterplots showing seasonal precipitation from gauges against the MSWEP, GPM, and TRMM precipitation products at the grid-scale. ** represents significance at $p < 0.01$

precipitation; however, the accuracy in areas with low precipitation is not satisfactory (Chen et al. 2015). The stations in the southern Qaidam Basin (the Xiaozahuo, Golmud, and

Nuomuhong meteorological stations) are located at relatively low elevations and experience little precipitation, resulting in the poor accuracy of the remote sensing precipitation

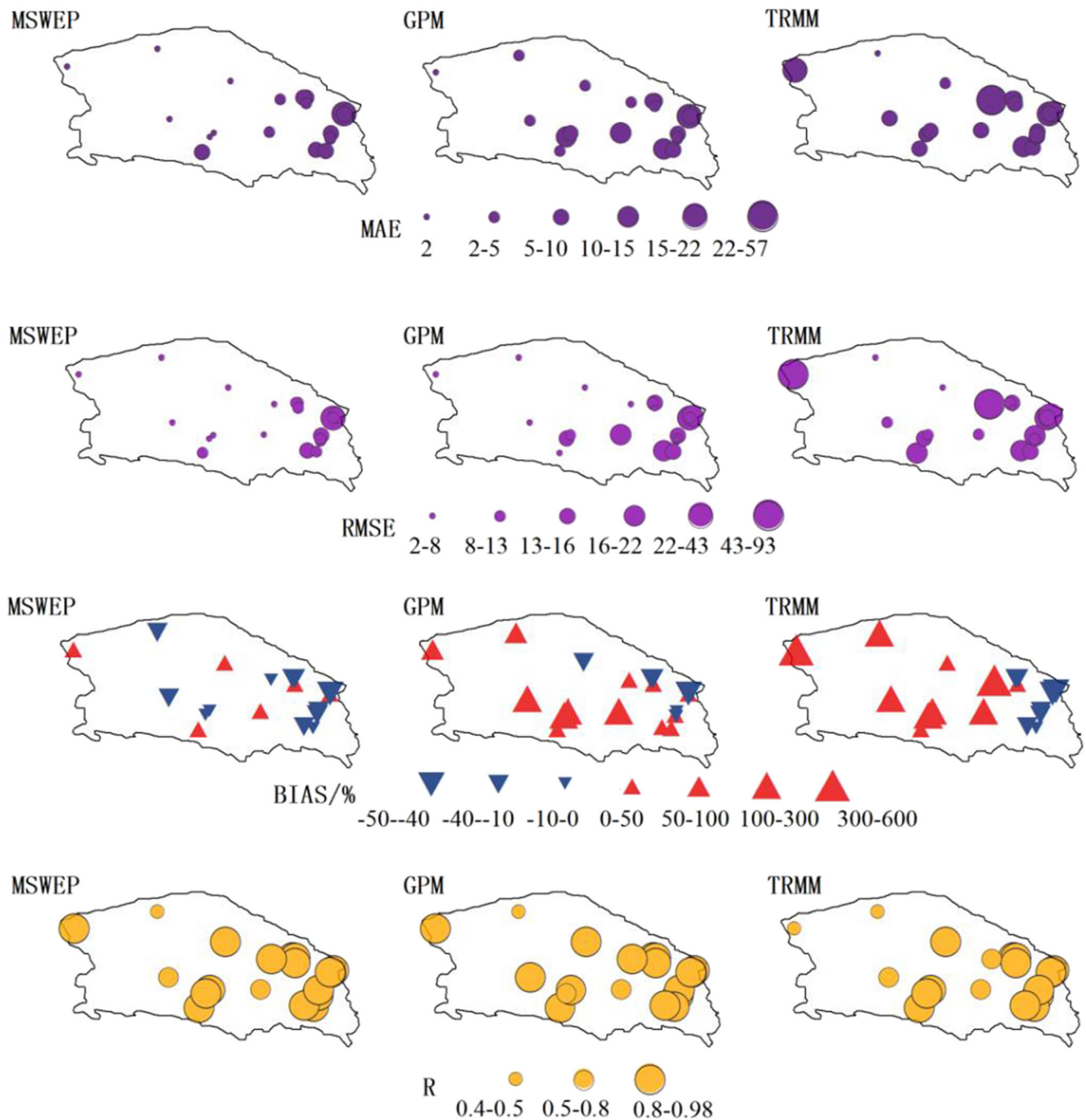


Fig. 8 The spatial distributions of the MAE, RMSE, BIAS, and R of the three monthly precipitation products

products. Moreover, the GPM and TRMM satellites correct ground data through GPCC, and therefore, since GPCC stations are sparsely distributed in Western China, the quality of precipitation products in the Qaidam Basin is not optimal (Ren et al. 2019).

Relationship between precipitation accuracy and elevation

In alpine mountainous areas, as elevation rises, there is a critical elevation for the level of precipitation; that is, below this

elevation, precipitation increases with increasing elevation, while above this elevation, precipitation decreases with increasing elevation (Liu et al. 2017). The elevations of the 21 ground observation stations used in this study are between 2765 and 3559 m, and these stations were divided into five elevation zones from low to high (Table 1). Then, the relationship between the monthly precipitation accuracy of the three studied precipitation products and elevation was analyzed. The results are shown in Fig. 9. As shown in the figure, the accuracy of the different precipitation products varied with

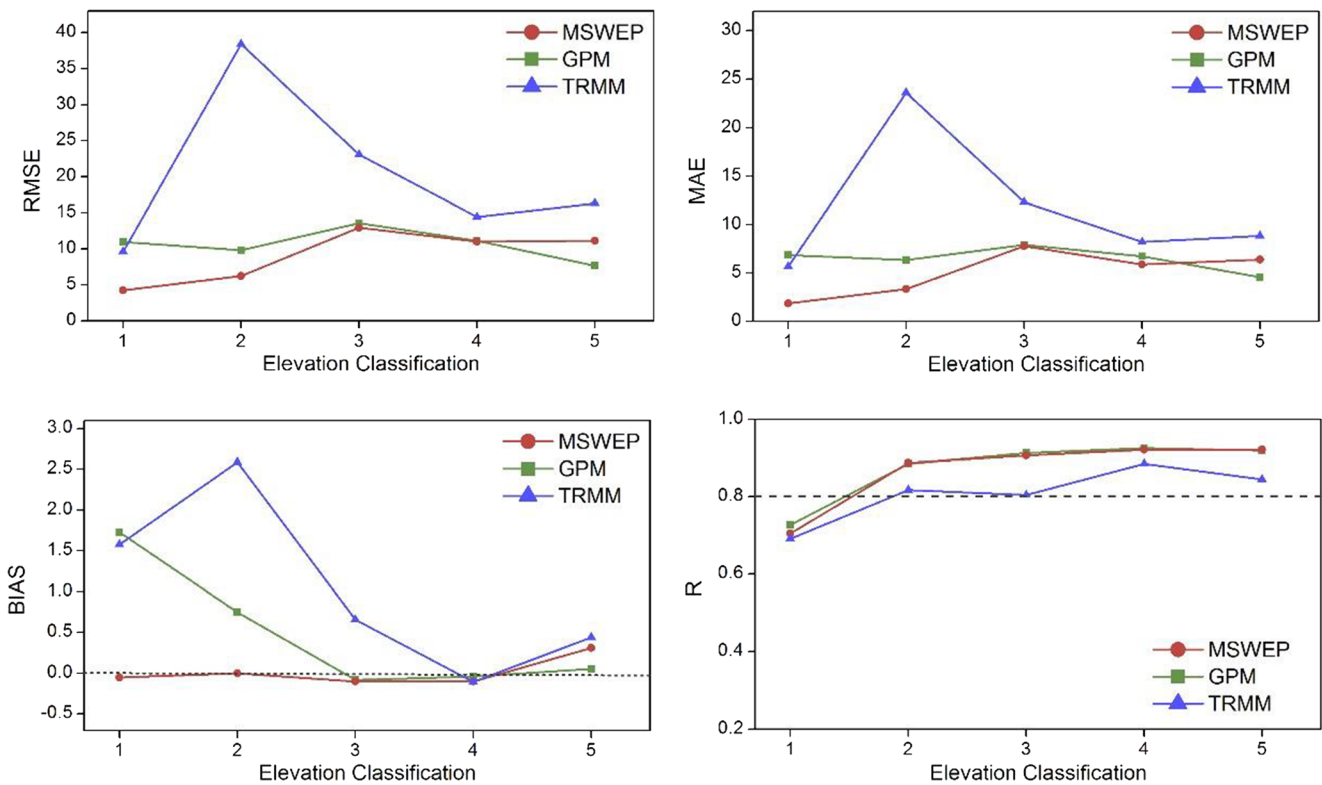


Fig. 9 Variation of the four quantitative indexes with elevation grade for each of the three monthly precipitation products; 2765–2809 m (grade 1, four stations), 2809–2919 m (grade 2, three stations), 2919–3025 m

(grade 3, five stations), 3025–3249 m (grade 4, eight stations), and 3249–3559 m (grade 5, one station)

elevation to varying degrees. For example, for MAE and RMSE, the largest variation occurred for the TRMM product, whose mean error was largest in the elevation zones of grades 2 and 3 (2809–3025 m). The mean error of the GPM and MSWEP products was relatively less affected by elevation, and for these products, the maximum mean error occurs in the elevation band of grade 3. Meanwhile, the GPM and TRMM products have a higher BIAS and a lower correlation coefficient at lower elevations; however, the accuracy improves (i.e., the BIAS and R decrease and increase, respectively) with increasing elevation. Our results indicate that the topographic gradient affects the quality of satellite-based precipitation products. Insufficient spatial resolution and quality of precipitation products impedes the capturing of the variability of precipitation caused by the topographic gradient (Immerzeel et al. 2015). Our results show that GPM and MSWEP perform significantly better than TRMM for estimating the precipitation variability of mountain basins, which might explain by the greatest influence of topographic transition on TRMM (Chen et al. 2018). However, since the ground observation stations used in this study are small in number and unevenly distributed, there are certain limitations to the interpretation of precipitation variability followed by the topographic gradient and the observed variation trend; that is, the precipitation accuracy improves with increasing elevation.

Comparison of precipitation accuracy between meteorological stations and hydrological stations

Figure 10 shows box plots comparing the precipitation values of the three precipitation products with the values measured at meteorological and hydrological stations at the annual, seasonal, and monthly scales. As shown in the figure, there is a consistent variation trend at all three timescales, namely, the mean values of the precipitation products and measured precipitation at hydrological stations are greater than those at meteorological stations: The mean and median values of the precipitation products at meteorological stations are generally larger than the measured precipitation values; conversely, the mean and median values of the precipitation products at hydrological stations are generally lower than the measured precipitation values. The precipitation products and measured precipitation values at the annual and monthly scales have similar data distribution types, and there are outliers of TRMM at hydrological stations.

Table 4 shows the four quantitative indexes of the three precipitation products for meteorological stations and hydrological stations at the annual, seasonal, and monthly timescales. As shown in the table, for MAE and RMSE, the values of the three precipitation products are all lower at meteorological stations than at hydrological stations at all three timescales. However, there was no consistent variation trend for

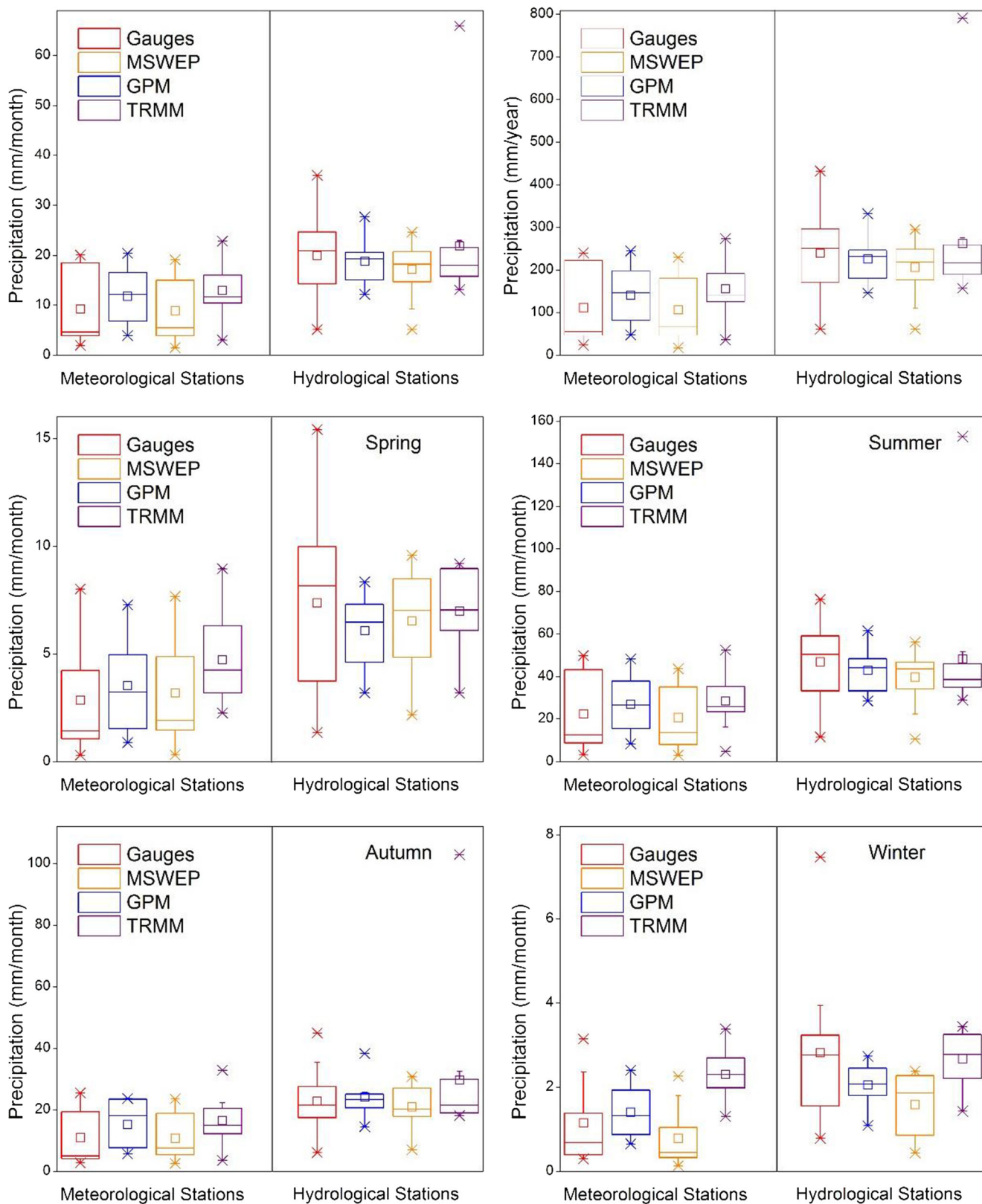


Fig. 10 Box plots comparing the precipitation values of the three precipitation products with the values measured at meteorological and hydrological stations at the annual, seasonal, and monthly scales

BIAS. At the annual and monthly scales, the MSWEP product underestimates the measured precipitation values at

meteorological stations and hydrological stations and has a higher degree of underestimation for hydrological stations

Table 4 Values of the four quantitative indexes for meteorological stations and hydrological stations at the annual, seasonal, and monthly timescales for the three precipitation products used in this study

		MAE			RMSE			BIAS (%)			R		
		MSWEP	GPM	TRMM	MSWEP	GPM	TRMM	MSWEP	GPM	TRMM	MSWEP	GPM	TRMM
Year	Meteorological station	22.52	52.07	69.53	29.41	56.16	82.39	-4.6	26.93	40.03	0.94	0.76	0.41
	Hydrological station	57.7	65.39	129.86	65.98	72.64	140.83	-14.01	-5.91	9.53	0.77	0.65	-0.17
Month	Meteorological station	3.06	5.42	7.32	6.13	9.03	13.75	-5.3	25.89	38.6	0.93	0.84	0.6
	Hydrological station	6.86	7.97	13.65	12.07	13.08	23.09	-13.81	-5.72	9.87	0.89	0.86	0.49
Spring	Meteorological station	1.61	1.95	2.70	3.21	3.40	4.01	12.17	24.34	67.10	0.76	0.76	0.75
	Hydrological station	3.66	3.82	4.03	5.32	5.51	5.54	-11.36	-17.47	-5.31	0.77	0.80	0.77
Summer	Meteorological station	5.96	11.09	15.20	8.40	13.83	22.02	-7.23	20.89	27.85	0.94	0.83	0.49
	Hydrological station	13.38	15.39	29.29	18.05	20.57	37.68	-15.33	-8.56	2.77	0.86	0.79	0.22
Autumn	Meteorological station	3.88	7.79	9.86	7.53	10.51	14.92	-0.67	40.63	51.66	0.88	0.75	0.46
	Hydrological station	8.54	10.86	19.32	14.48	14.73	25.39	-8.42	5.97	30.08	0.77	0.75	0.24
Winter	Meteorological station	0.78	0.87	1.52	1.49	1.36	2.15	-31.93	21.41	99.54	0.59	0.73	0.57
	Hydrological station	1.87	1.80	1.95	2.94	2.62	2.77	-44.00	-27.56	-5.20	0.52	0.59	0.53

than meteorological stations. Meanwhile, at the seasonal scale, the MSWEP product underestimates the measured precipitation values at hydrological stations and meteorological stations in summer, autumn, and winter and overestimates the measured precipitation values at meteorological stations by 12% in spring, and the deviation at hydrological stations is greater than that at meteorological stations. Meanwhile, at the annual and monthly scales, the GPM product overestimates the precipitation values at meteorological stations and underestimates the precipitation values at hydrological stations. Since the same type of rain gauges (which is weighing rain gauge) used by meteorological stations and hydrological stations, the differences of accuracy might contribute to the different elevation of them. Additionally, for the GMP product, the absolute values of BIAS at meteorological stations are greater than those at hydrological stations, and in winter the underestimation for hydrological stations is slightly greater than that for meteorological stations. Furthermore, for the GPM product, in spring, summer, and autumn, the absolute values of BIAS at meteorological stations are greater than those at hydrological stations. Meanwhile, at the annual and monthly timescales, the TRMM product overestimates the precipitation at meteorological and hydrological stations, with the degree of overestimation being greater for meteorological stations than for hydrological stations. Moreover, for the TRMM product, the absolute value of BIAS at meteorological stations is greater than that at hydrological stations in all seasons. For the GPM precipitation product, at the annual and monthly timescales, there is little difference between the correlation coefficients between the predicted values and the measured precipitation at meteorological stations and the correlation coefficients between the predicted values and the measured precipitation at hydrological stations. The

correlation between the precipitation values of the MSWEP and TRMM products and the measured precipitation at meteorological stations is higher than the correlation between the precipitation values of MSWEP and TRMM and the measured precipitation at hydrological stations. The difference in the correlation between the precipitation products and the precipitation measured at meteorological and hydrological stations is generally small in all seasons. Additionally, the correlation between the TRMM product in summer and autumn and at meteorological stations is higher than that between the TRMM product in summer and autumn and at hydrological stations.

Conclusion

In semi-arid climate area with complex terrain and sparse rain gauge networks, such as the Qaidam Basin, satellite-based precipitation products are an important alternative to observed data. They can provide higher-resolution precipitation data, which is not only a major driving force of hydrological process (Tuo et al. 2016) but also a key element of precipitation-related research. Since the differences in sources, passive microwave algorithm, and resolution of precipitation products, the accuracy of different products in specific zone should be evaluated before use. In this study, the applicability of the GPM IMERG, MSWEP, and TRMM 3B43 precipitation products in the Qaidam Basin was investigated, and the factors influencing the precipitation accuracy were analyzed. The primary conclusions are as follows:

- (1) At the annual scale, the MSWEP product has the highest correlation with the observed precipitation, with the

smallest mean error and relative deviation, followed by the GPM product, while the TRMM product has the lowest correlation with the observed precipitation, with the greatest mean error and relative deviation. At the monthly scale, MSWEP has the highest accuracy, followed by GPM, while the TRMM product has the lowest accuracy, although it can still represent the measured precipitation to an acceptable degree. At the seasonal scale, the MSWEP has the highest accuracy in summer and autumn, while the accuracy of the three precipitation products is approximately equivalent in spring and winter, being moderately correlated with the measured precipitation value.

- (2) Based on an analysis of the spatial and temporal accuracies of the three precipitation products, it was found that the MSWEP product generally underestimates the precipitation in the Qaidam Basin and has a poor estimation ability in winter. Meanwhile, in summer and autumn, the TRMM product has areas of abnormally high precipitation, resulting in a poor evaluation capability for annual precipitation. Lastly, the GPM product has improved the precipitation accuracy of TRMM to a certain extent; however, it tends to overestimate the precipitation at stations that are located at relatively low elevations in mountainous areas.
- (3) Precipitation in the Qaidam Basin varies with elevation. The correlation between the TRMM product in different elevation segments and measured precipitation is the lowest, and the accuracy of all three precipitation products varies greatly with elevation.
- (4) Hydrological stations are primarily distributed in the eastern Qaidam Basin, meteorological stations are relatively evenly distributed throughout the basin, and the mean precipitation at hydrological stations is greater than that at meteorological stations. At the annual, seasonal, and monthly timescales, the mean error of the three precipitation products at meteorological stations is smaller than that at hydrological stations. The MSWEP product has a higher degree of underestimation for hydrological stations compared with meteorological stations, while the TRMM product has a higher degree of overestimation for meteorological stations compared with hydrological stations.

These results suggest that three products have its own pros and cons of accuracy performance in the Qaidam Basin. MSWEP V2 shows the most reliable performance among three products. GPM IMERG V6 has significant improvement compared to TRMM 3B43. The Qaidam Basin is a crucial part of the ecological barrier of Qinghai-Tibet Plateau, providing abundant precipitation for Sanjiangyuan region through atmospheric circulation as a result of strong evaporation. Thereby, hydrological simulation, water balance, and water resources

conservation studies using satellite-based precipitation products are of significant importance in the Qaidam Basin. Future research should focus on the evaluation of accuracy at daily or diurnal scales and the applications of precipitation products in hydrological modeling and the role of hydrological drought events over this alpine area (Satgé et al. 2019).

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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