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Evaluation of GPM IMERG V05B and TRMM 3B42V7 Precipitation Products over High Mountainous Tributaries in Lhasa with Dense Rain Gauges

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Received: 6 August 2019; Accepted: 3 September 2019; Published: 5 September 2019



Abstract: In most Asian high mountain areas, ground-based observations of precipitation are sparse. It is urgent to assess and apply satellite precipitation products (SPPs). In recent years, relatively dense rain gauges have been established in five tributaries in Lhasa. Therefore, based on high-density rain gauges, two SPPs (GPM IMERG V05B, TRMM 3B42V7) were evaluated at the grid, region, and time scales with different statistical indices in the five tributaries. Besides, the dependence of SPPs performances on the precipitation intensities, elevation, and slope was investigated. The results indicate that: (1) both 3B42V7 and IMERG showed similarly low correlation with rain gauges at daily scale and high correlation at monthly scale, but 3B42V7 tended to suffer from systematic overestimation of monthly precipitation; (2) IMERG product outperformed 3B42V7 except for obvious overestimation of trace precipitation (0.1~1 mm day⁻¹) and underestimation of torrential precipitation (>50 mm day⁻¹); (3) the precipitation over the five tributaries showed significant spatial variability with difference of characteristic values (e.g., average daily precipitation) more than 20% in some IMERG grids and most 3B42V7 grids; (4) elevation had an obvious effect on the accuracy of 3B42V7 and IMERG, and the accuracy of the two SPPs decreased significantly with the increase of elevation.

Keywords: evaluation; compare; precipitation; rain gauge; 3B42V7; IMERG

1. Introduction

Precipitation plays an important role in hydrological and meteorological applications [1]. The change of precipitation in mountainous areas directly affects the development of local agriculture and ecological environment [2,3]. Moreover, the heavy precipitation events in mountainous areas often form flash floods [4]. Therefore, high-precision precipitation information in mountainous areas is of great significance to the sustainable development of local agriculture, the protection of the ecological environment, and the scientific decision of water affairs [5]. Rain gauge observation could provide a relatively accurate method for point-based precipitation measurement. However, gauges in mountainous regions are often sparse, uneven, and sometimes not available [2,6,7]. Thus, in the applications that need high spatiotemporal resolution precipitation data, such as flood disaster forecasts, gauge data are often not sufficient [8,9].

In recent decades, satellite precipitation products (SPPs) provide an alternative to gauge-based precipitation estimates [10–13]. A series of relatively high spatiotemporal resolutions SPPs, such as Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) [14], National Oceanic and Atmospheric Administration/Climate Prediction Center (NOAA/CPC) morphing technique (CMORPH) [15,16], Tropical Rainfall Measuring Mission (TRMM)



Multi-satellite Precipitation Analysis (TMPA) [17] and so on, are widely used in previous studies. Among them, TMPA 3B42V7 precipitation product is superior to other products, especially in estimating extreme precipitation events in several areas around the world [18–20]. The TMPA Version-7 offers quasi-global coverage ($50^{\circ}N-50^{\circ}S$) precipitation estimates at a high spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ and temporal resolution of 3 hours [21]. Global Precipitation Measurement (GPM) mission, as the successor of TRMM, was launched in February 2014. Compared with TRMM, the abilities of GPM to detect trace precipitation and solid precipitation are improved by carrying spaceborne dual-frequency precipitation radar [22]. Furthermore, the GPM Core Observatory carrying a conical scanning multichannel microwave imager offers a wider measurement range [23]. The newly released IMERG further expands quasi-global coverage from $50^{\circ}N-50^{\circ}S$ to $60^{\circ}N-60^{\circ}S$ and provides precipitation estimates with a finer spatial resolution of $0.1^{\circ} \times 0.1^{\circ}$ and temporal resolution of 30 minutes [24].

The performance of these SPPs in hydrological applications varies from region to region because errors of different products depend significantly on the retrieval algorithms, instrument characteristics, orbit geometry, atmospheric conditions, and topography conditions (plain or mountainous) [3,25–27]. To date, several studies have been evaluated comparing IMERG and TMPA precipitation products with reference to the gauge observations in different topographic or climatic regions. Most of the studies showed that the performances of IMERG products are generally better than TMPA in several regions, such as in Iran [28], Mainland China [29], Far-East Asia [30], the upper Mekong River basin [31], Titicaca, Poopó, Desaguadero, and Salar system (TDPS) watershed of Bolivian [32], and India [33]. Beria et al. [33] discovered that IMERG outperforms 3B42V7, and the accuracy of 3B42V7 declines obviously with the elevation increasing compared to IMERG in India. However, in some mountainous areas with varied topography, no obvious advantages have been discovered in IMERG, or the 3B42V7 even outperforms IMERG, such as in Hexi region located in the northeastern Tibetan Plateau [34], the Chindwin River basin in Myanmar [1], the wet Amazon region, and the La Plata watersheds of Bolivian [32]. Frédéric et al. [32] revealed that over the La Plata river watershed, 3B42V7 highly outperforms IMERG during the wet season, and precipitation estimates from IMERG are more influenced by local relief than 3B42V7. The topography is a well-known factor influencing SPPs, and usually, SPPs are more biased in mountainous regions than in relatively flat regions [35–37].

Over the Tibetan Plateau, errors of SPPs in precipitation estimation are unavoidable due to the indirect measurement, lack of high-quality microwave data, and accurate algorithms in areas distinguished by unique height, complex topography, cold land temperatures, covered in snow and ice [2,38]. Over the Tibetan Plateau, Tang et al. [39] showed that GPM dual-frequency precipitation radar data solve the problem of precipitation overestimates in some grids with high elevation compared with the TRMM precipitation radar data; Zhang et al. [40] concluded that IMERG is superior to 3B42V7 on multiple timescales; Ma et al. [41] found that IMERG displays appreciably lower errors and better correlations than 3B42V7, but the probability of detection (POD) of IMERG is lower than 3B42V7 in region of elevation above 4200m; Xu et al. [42] revealed that assessment indices, such as relative bias (BIAS) and root mean square error (RMSE), from 3B42V7, are obviously related to the variation of topography but similar correlations are not found in IMERG, and 3B42V7 performs better than IMERG in low-elevation regions.

However, SPPs evaluations are limited due to sparse rain gauges on the whole Tibetan Plateau [40–42]. Few studies have concentrated on the evaluation of 3B42V7 and IMERG products in a mountain valley or inside a pixel to show whether a pixel value represents the overall situation of the domain. In this study, we focused on five tributaries in Lhasa, which are typical plateau mountain regions [43]. High-density rain gauges in the five tributaries can provide special resources for ground validation and evaluation of SPPs. The purpose of this study was to cross-evaluate the performance of precipitation estimates from TMPA 3B42V7 and IMERG Final run V05B precipitation products, against gauge observations, over high mountainous tributaries in Lhasa. First, IMERG and 3B42V7 were evaluated and compared at the grid, region, and time scales. Second, the effects of precipitation intensity, elevation, and slope on the accuracy of 3B42V7 and IMERG were compared and analyzed.

Our results would help algorithm developers further improve the precipitation retrieval algorithms of IMERG and 3B42V7.

2. Materials and Methods

2.1. Study Area

This study was conducted in five tributaries (respectively, named as R1, R2, R3, R4, and R5) located in the south of the Tibetan Plateau (Figure 1). R1, R2, R3, R4 are tributaries of the Lhasa River and R5 named Nimumaqu River is a tributary of the Yarlung Zangbo River. The study area is of high elevation, and the topography varies greatly.



Figure 1. Location of the five tributaries in Lhasa and the distribution of rain gauges.

The Lhasa River is a major branch of the Yarlung Zangbo River, originates from the southern foot of the Nyaiqentanglha Mountain [44]. The river is about 568 km long, and its drainage area is 32,588 km² [44]. The topography is characterized by the transition from riverbeds to valley slopes. The basin has a typical continental plateau semi-arid frigid climate regime with a mean annual temperature of about 5.3 °C and the mean annual precipitation of about 500 mm [45]. The intra-annual distribution of precipitation is extremely uneven, with more than 85% of the annual precipitation distributed between June and September [43,46,47].

The Nimumaqu River originating from the Qiongmugangfeng in the Nimu county, Lhasa city, is an important tributary of the Yarlung Zangbo River. The river is about 83 km long with an area of 2378 km² and flows into the Yarlung Zangbo River in the south Luomai village.

2.2. Data

2.2.1. Ground Data

Six-hourly precipitation data of 67 rain gauges were obtained from the Bureau of Hydrological and Water Resources of Tibet Autonomous Region (Figure 1). Among these rain gauges, 11 rain gauges are distributed in R1, 13 rain gauges in R2, 15 rain gauges in R3, 9 rain gauges in R4, and 10 rain gauges in R5. It is significant to emphasize that the rain gauge network used in this paper is not included in the Global Precipitation Climatology Center (GPCC) network [40]. To ensure the high-quality of the rain gauge data, we applied a strict data quality control procedure that includes an internal consistency check and an extreme value check, developed by Shen and Xiong [48]. Considering that

IMERG Final Run V05B precipitation product has been released since March 12th, 2014, and snowfall causes erroneous records in rain gauges, especially when snowfall accounts for a large proportion of precipitation [49], the evaluation period was determined to be warm seasons (from April 1st to September 30th) from 2014 to 2017.

2.2.2. Satellite Precipitation Products

In this study, two types of satellite precipitation products, namely, the post-real-time version 7 TMPA 3B42 three-hourly precipitation product (hereafter 3B42V7) and Final Run V05B IMERG 30-minutes precipitation product, named as "3IMERGHH" (hereafter IMERG), during the period of April 1st to September 30th, 2014–2017 were acquired from the National Aeronautics and Space Administration (NASA) website (http://pmm.nasa.gov). More detail information of 3B42V7 and IMERG is obtainable in [21,24]. Before accumulating the dataset to daily and monthly precipitation, both 3B42V7 and IMERG were converted from UTC 0 to UTC 8 to unify the time with the study area [34]. Besides, we only accumulated 30-minutes IMERG data set to six-hourly precipitation to evaluate IMERG at six-hourly scale. For 3B42V7, we could not accumulate three-hourly 3B42V7 data set to six-hourly precipitation without interpolation because the local time is ahead of world coordinated time by 8 hours, i.e., not an integral multiple of 3 hours, and interpolation will inevitably introduce errors. Thus, the same thing was not done for 3B42V7.

2.3. Method

2.3.1. Scale Handling of Rain Gauges and Pixels and Classification of Precipitation Events

In this study, the different spatial resolutions of the 3B42V7 and IMERG products (0.25° and 0.1°) was ignored, and a method of point-to-pixel evaluation between the rain gauge and gridded satellite data were adopted. The precipitation data from each satellite precipitation product (SPP) were extracted according to the locations of gauges to generate pairings of satellite-gauge data for cross-evaluation.

Five 3B42V7 grids (namely A1, A2, A3, A4, and A5) and five IMERG grids (namely B1, B2, B3, B4, and B5) were chosen from five tributaries to analyze whether the pixel values of 3B42V7 and IMERG could represent the overall situation of their corresponding grid boxes. Each chosen 3B42V7 grid should contain at least three rain gauges, and each chosen IMERG grid should contain at least two rain gauges. Besides, rain gauges distributed in each chosen IMERG grid were also distributed respectively in the same 3B42V7 grid. Based on the above conditions, we tried to choose the grid that contains the most gauges. We used rain gauges in the grid of B1, B2, B3, B4, and B5 to evaluate and compare the accuracy of IMERG and 3B42V7 at the grid-scale. Characteristic values during the period of April 1st to September 30th, 2014–2017, such as the number of precipitation days, average precipitation in precipitation days, and average daily precipitation, were analyzed. The chosen grids are shown in Figure 1.

We divided daily precipitations into four categories (with five ranks). Light precipitation, defined as $0.1 \sim 10 \text{ mm day}^{-1}$; moderate precipitation, defined as $10 \sim 25 \text{ mm day}^{-1}$; heavy precipitation, defined as $25 \sim 50 \text{ mm day}^{-1}$; torrential precipitation, defined as daily precipitation greater than 50 mm. Besides, the trace precipitation of $0.1 \sim 1 \text{ mm day}^{-1}$ was separated from light precipitation. Wang et al. [50] also used a similar classification of daily precipitations.

Then, the study adopted the method of linear regression to analyze the influence of topographic features on the accuracy of SPPs, and set significance level at 0.05. The equation and regression coefficient were tested, and the value of $p \le 0.05$ was considered statistically significant [51,52].

2.3.2. Statistical Metrics for Evaluating Satellite Precipitation Products

Four continuous statistical indices were used as follows to cross-evaluate 3B42V7 and IMERG precipitation estimates. The Pearson correlation coefficient (CC) reflects the consistency between SPP and gauge observations. The RMSE measures the deviation between the SPP and gauge observations.

The mean absolute error (MBE) simply describes the average difference between the SPP and gauge observations. The BIAS indicates the systematic bias of SPP.

Besides, four categorical statistical indices were adopted as follows to assess the ability of SPP in describing precipitation/no precipitation events. The POD is the ratio of precipitation occurrences correctly detected to the total number of observed precipitation events. The false alarm ratio (FAR) is the ratio of precipitation occurrences falsely alarmed to the total number of detected precipitation events. The frequency bias index (FBI) indicates whether the dataset tends to overestimate (FBI>1) or underestimate (FBI<1) precipitation events. Equitable threat score (ETS) shows comprehensive prediction capability of SPP. Table 1 presents the formulas and perfect values of these metrics, and there are more details obtainable in [35,53]. Besides, precipitation of 0.1 mm day⁻¹ was selected as the threshold of the precipitation event.

Table 1. List of the statistical indices to quantify the performance of the SPPs (satellite precipitation products).

Statistical Index	Unit	Formula	Perfect Value
Correlation coefficient (CC)	NA	$CC = \frac{\left[\sum_{i=1}^{n} (S_i - \overline{S})(G_i - \overline{G})\right]^2}{\sum_{i=1}^{n} (S - G)^2 \sum_{i=1}^{n} (G - G)^2}$	1
Root mean square error (RMSE)	mm	$\frac{RMSE =}{\sqrt{\frac{1}{n}\sum_{i=1}^{n} (S_i - G_i)^2}}$	0
Mean absolute error (MBE)	mm	$ABE = \frac{1}{n} \sum_{i=1}^{n} S_i - G_i $	0
Relative bias (BIAS)	NA	$Bias = \frac{\sum_{i=1}^{n} (S_i - G_i)}{\sum_{i=1}^{n} G_i}$	0
Probability of detection (POD)	NA	$POD = \frac{a}{a+c}$	1
False alarm ratio (FAR)	NA	$FAR = \frac{b}{a+b}$	0
Frequency bias index (FBI)	NA	$FBI = \frac{a+b}{a+c}$	1
Equitable threat score (ETS)	NA	$ETS = \frac{\ddot{a} + \ddot{H}_{e}}{a+b+c-H_{e}}$ $H_{e} = \frac{(a+b)(a+c)}{(a+b+c+d)}$	1

Notation: n, the number of satellite/gauge data; i, the ith of satellite-gauge data; Gi, gauge observed precipitation; Si, satellite precipitation estimates; $\overline{G_i}$ and $\overline{S_i}$, the average precipitation of gauge observed and satellite estimates, respectively. Each pairing of satellite-gauge data can be classified as a hit represented by a (observed precipitation detected correctly), a false alarm represented by b (detected precipitation not observed), a miss represented by c (observed precipitation not detected), or a correct negative represented by d (precipitation not observed and not detected) event.

The probability distribution functions in both precipitation occurrence (PDFc) and precipitation volume (PDFv) under different precipitation-rate ranks were used to provide details about the frequency of precipitation events [54]. PDFc is the percentage of the number of detected events under a specific precipitation-rate rank, while PDFv is the percentage of accumulative precipitation accordingly. These metrics were widely used in previous studies to evaluate SPPs [40,42,54–56].

3. Results

3.1. Evaluation of IMERG and 3B42V7 at Grid Scale

Tables 2 and 3 were calculated to separately analyze whether the pixel values of 3B42V7 and IMERG could represent the overall situation of their corresponding grid boxes. Table 3 was also used to evaluate and compare the accuracy of 3B42V7 and IMERG at grid scale. Compared with the average of the characteristic values of gauges in these grids, the numbers of precipitation days detected by 3B42V7 were closer to the gauge measured values. However, the average precipitations in precipitation days

from 3B42V7 data were larger than those from rain gauge data in every grid, and the similar situation was observed further in comparison of average daily precipitation. However, IMERG overestimated precipitation days. For average precipitations in precipitation days and average daily precipitation, estimates from IMERG were closer to the gauge values. On the whole, the detection accuracy of 3B42V7 for precipitation days was higher than that of IMERG, while the IMERG was more accurate in detecting average daily precipitation.

In Tables 2 and 3, we could see that the characteristic values of gauges were quite different in both IMERG and 3B42V7 grids. As for average precipitation in precipitation days, the differences were more than 20% in the grids A1, A3, and B1. Meanwhile, the differences in average daily precipitation were up to 20% in the grids of A1, A2, A3, A5, B1, B3, and B5. Moreover, in the grids of A1 and B1, the differences in average daily precipitation were even more than 30%. The characteristic values were different greatly in most 3B42V7 grids and some IMERG grids.

3.2. Evaluation of IMERG and 3B42V7 at Region Scale

Spatial distribution of average daily precipitation from rain gauges, 3B42V7, and IMERG, respectively, during warm seasons from 2014 to 2017 (Figure 2), was used to analyze spatial performances of 3B42V7 and IMERG over the five tributaries. The spatial distribution of rain gauge data was interpolated by Inverse Distance Weighting (IDW) technique, and its power was two. It could be seen from the distribution of gauge precipitation that the spatial difference of precipitation in different areas was large. Region of R4 received the most precipitation, while the region of R2 and R5 received the least precipitation. The median precipitation (about 2.40~3.60 mm day⁻¹) was observed in R1 and R3. Overall, good agreement existed between the SPPs and rain gauge estimates in terms of average daily precipitation. Both 3B42V7 and IMERG showed higher precipitation rates in R4 and lower precipitation rates in R5 and west of R2, but the high precipitation rates from 3B42V7 covered a larger area than that of the gauge observation and IMERG. At the region scale, 3B42V7 overestimated precipitation, and IMERG was closer to the gauge observation value. Besides, it was noteworthy that spatial distribution of average daily precipitation derived from IMERG showed more subtle spatial variations than 3B42V7.



Figure 2. Spatial distribution of average daily precipitation derived from rain gauges, 3B42V7, and IMERG over five tributaries and its peripheral regions, from April 1st to September 30th, 2014–2017.

Grid	Name of Gauges	Number of Precipitation Days ^a			Average Preci	pitation (mm/day) i Days	n Precipitation	Average Precipitation (mm/day)		
	-	Gauge	Average ^b	3B42V7	Gauge	Average ^c	3B42V7	Gauge	Average ^d	3B42V7
	Bolaqie	219		206	7.6		9.1	3.0		
	Wumatang	237			6.9			3.0	3.0	3.4
	Dangquka	232			6.6			2.8		
	Guoqing	231	222		6.6	7.2		2.8		
AI	Dishugang	244	255		8.7			3.9	5.0	
	Baqiongduo	239			6.9			3.0		
	Gesangka	225			7.0			2.9		
	Longreng	234			7.1			3.0		
A2	Zhalangduo	218		208	6.2	6.2	9.4	2.5	2.4	3.6
	Mengga	205	200		6.1			2.3		
	Maxiang	216	209		6.7			2.6		
	Ema	196			5.9			2.1		
	Chundui	222	216	220	7.7	7.7		3.1		4.0
	Kadong	213			8.4			3.3	3.0	
	Kazi	206			6.9			2.6		
A3	Palangdui	219			7.7		10.1	3.1		
	Nianbo	224			8.0			3.3		
	Baya	216			7.8			3.1		
	Baiding	212			7.4			2.9		
A4	Emuduo	264		247	7.1		9.8	3.4		4.4
	Niaoduogang	243	255		8.1	7.9		3.6	3.7	
	Demoxiong	257			8.5			4.0		
A5	Puba	173		177	6.8		9.7	2.1		3.1
	Laduo	190	101		6.8	7.0		2.4	2.2	
	Pusong	188	101		7.7	7.0		2.6	2.3	
	Xuela	171			6.8			2.1		

^a Days with precipitation ≥ 1 mm; ^b Average of the precipitation day measured by gauges in a grid; ^c Average precipitation in precipitation days measured by gauges in a grid; ^d Average precipitation measured by gauges in a grid.

Grids	Name of Gauges —	Number of Precipitation Days ^a			Average Precipitation (mm/day) in Precipitation Days				Average Precipitation (mm/day)				
		Gauge	Average ^b	3B42V7	IMERG	Gauge	Average ^c	3B42V7	IMERG	Gauge	Average ^d	3B42V7	IMERG
B1	Guoqing Dishugang Baqiongduo	231 244 239	238	206	261	6.6 8.7 6.9	7.4	9.1	7.4	2.8 3.9 3.0	3.2	3.4	3.5
B2	Zhalangduo Mengga Maxiang	218 205 216	213	208	242	6.2 6.1 6.7	6.3	9.4	6.3	2.5 2.3 2.6	2.5	3.6	2.8
B3	Kazi Nianbo	206 224	215	220	260	6.9 8.0	7.5	10.1	7.0	2.6 3.3	2.9	4.0	3.3
B4	Emuduo Niaoduoganą	264 g 243	254	247	267	7.1 8.1	7.6	9.8	7.1	3.4 3.6	3.5	4.4	3.5
В5	Puba Laduo Pusong Xuela	173 190 188 171	181	177	214	6.8 6.8 7.7 6.8	7.0	9.7	6.4	2.1 2.4 2.6 2.1	2.3	3.1	2.5

Table 3. Comparison of characteristic values between 3B42V7, IMERG, and rain gauge precipitation in the chosen IMERG grids during warm seasons from 2014 to 2017.

Subsequently, CC, RMSE, MBE, and BIAS between satellite-based and rain gauge data were also examined and compared, which was calculated for every rain gauge and their nearest satellite pixel at daily scale during the study period. The results are shown in Figure 3. IMERG performed significantly better than 3B42V7 with higher CC values and lower RMSE, MBE, and Bias values. Figure 4 shows the spatial distribution of these continuous statistical indices. Both 3B42V7 and IMERG in R2, R3, R4, and R5 correlated with the rain gauge observations better than those in R1 with higher CC values, except that the values at very few gauges were abnormal. The RMSE values of both 3B42V7 and IMERG generally performed better in R2 and R5 than those in other regions. In terms of the MBE, both 3B42V7 and IMERG had smaller MBE values in R2 and R5, besides 3B42V7 also had smaller MBE values in R1. As for Bias, the positive and negative deviations of IMERG precipitation estimates were relatively balanced, while 3B42V7 showed positive deviation at most gauges. 3B42V7 showed minor bias in R1 and at some gauges in R5, while IMERG showed minor deviation in R2, R3, R4, and R5 except that the values at very few gauges were abnormal. In general, except Bias, other continuous statistical indices from 3B42V7 and IMERG had similar spatial trend variations. Also, once again, it was not hard to see that these indices of IMERG were better than 3B42V7.



Figure 3. Boxplot of correlation coefficient (CC), root mean square error (RMSE), mean absolute error (MBE), and relative bias (BIAS) between satellite-based and rain gauge daily precipitation at 67 gauges, during the period of April 1st to September 30th, 2014–2017. Five lines from bottom to top for one box represent minimum value, 25th percentile, 50th percentile, 75th percentile, and maximum value, respectively.

Furthermore, a set of categorical statistical metrics at gauge locations in the five tributaries were used to evaluate the ability of IMERG and 3B42V7 in detecting the occurrence of precipitation at a daily scale (Figure 5). It showed that IMERG performed better than 3B42V7 with higher values of POD, lower values of FAR, and higher values of ETS except for slightly higher values of FBI. Thus, for the detection of precipitation frequency, IMERG was superior to 3B42V7 with smaller omission and false alarm of precipitation events except for overestimation of precipitation occurrences.





Figure 4. Spatial distribution of CC, RMSE, MBE, and BIAS between satellite-based and rain gauge daily precipitation over five tributaries during the period of April 1st to September 30th, 2014–2017.



Figure 5. Boxplot of the detecting ability of precipitation occurrences of 3B42V7 and IMERG at 67 gauges. Five lines from bottom to top for one box represent minimum value, 25th percentile, 50th percentile, 75th percentile, and maximum value, respectively.

3.3. Evaluation of IMERG and 3B42V7 at Different Time Scale

At first, the variation of the accuracy of IMERG with time scale was compared and analyzed. Figure 6a,b,d are scatterplots of precipitation from IMERG and rain gauges at six-hourly, daily, and monthly scale. The correlation coefficient (CC) increased from 0.37 at six-hourly scale to 0.50 at daily scale and 0.92 at monthly scale. It was not difficult to find that the error of IMERG decreased with the increase of time scale. Categorical statistical metrics of IMERG at six-hourly and daily scales are shown in Figure 7. IMERG performed significantly better at daily scale than at six-hourly scale, with higher values of POD and ETC, lower values of FAR, lower values of FBI. Besides, the fluctuation range of statistical metrics value of IMERG at the daily scale was narrower than at six-hourly scale, which further indicated that the detection accuracy of IMERG at the daily scale changed little with the location of the gauges, and its regional changes were relatively stable. In a word, IMERG showed good accuracy at the monthly scale, followed by the daily scale and poor accuracy at six-hourly scale.

Then, the precision of 3B42V7 and IMERG at daily and monthly scales were compared and analyzed. Figure 6b–e show the inter-comparison of daily and monthly precipitation from all 67 rain gauges and the two SPPs at the corresponding grids collocated with rain gauges. At daily scale, compared with gauge data, 3B42V7 had a larger error with high relative biases (BIAS) and of 29% than IMERG with BIAS of 10%. Additionally, the consistency (CC) between two SPPs and rain gauges was comparable, with slight favor for IMERG (Figure 6b,c). On the monthly scale, IMERG showed good performance with higher CC value of 0.92, 3B42V7 also showed a relatively good correlation, with a CC value of 0.85 (Figure 6d,e). The accuracy of 3B42V7 and IMERG products at monthly scale was superior to that at daily scale. Meanwhile, IMERG performed better than 3B42V7 at daily and monthly scales.

The distribution of monthly precipitation, from gauges, 3B42V7, and IMERG, was summarized, as shown in Figure 8, to further elucidate the accuracy of 3B42V7 and IMERG. From the rain gauge data, we could see that April–September mean monthly precipitation of 2014–2017 in the five tributaries was concentrated in June, July, and August, and there was less precipitation in April and May. Both 3B42V7 and IMERG data described this distribution characteristic correctly, but the 3B42V7 tended to suffer from a systematic overestimation of monthly precipitation.

3.4. Evaluation of 3B42V7 and IMERG under Different Precipitation Intensity

Figure 9 inter-compares the PDFc and PDFv of the daily precipitation from the gauge measurements and the SPPs. In terms of PDFc and PDFv, IMERG was superior to 3B42V7 except for detection of extreme precipitation events (0~1 mm day⁻¹ and >50 mm day⁻¹). Both 3B42V7 and IMERG tended to overestimate the trace precipitation events, but the error of IMERG was greater than 3B42V7 in detecting trace precipitation and torrential precipitation. However, there was a bigger error of 3B42V7 in detecting heavy precipitation (25~50 mm day⁻¹), and IMERG demonstrated better ability in capturing light precipitation events (1~10 mm day⁻¹). When the precipitation rate was moderate (10~25 mm day⁻¹), 3B42V7 performed slightly better than IMERG.



Figure 6. Scatterplots of precipitation between IMERG, 3B42V7 products, and rain-gauge data at six-hourly (**a**, only scatterplots of IMERG and rain-gauge data), daily (**b**,**c**), and monthly (**d**,**e**) timescales during the whole study period. The diagonal reference line is indicated by a dashed line, and the fitting line (determined via the least-squares method) is indicated by a red solid line.





Figure 7. Boxplot of the detecting ability of precipitation occurrences of daily and six-hourly IMERG products at 67 gauges. Five lines from bottom to top for one box represent minimum value, 25th percentile, 50th percentile, 75th percentile, and maximum value, respectively.



Figure 8. Mean monthly precipitation in the five tributaries from rain gauges, 3B42V7, and IMERG, from April to September 2014–2017.



Figure 9. PDFc (probability distribution function in precipitation occurrence) and PDFv (probability distribution function in precipitation volume) of daily precipitation with different precipitation rates, as derived from rain gauges, IMERG, and 3B42V7.

4. Discussion

The aforementioned analysis provided a quantitative comparison between 3B42V7 and IMERG with corresponding gauge data at different scales. The deficiencies and possible sources of errors may be related to the influence of different sensors, topography, precipitation patterns, and retrieval algorithms adopted in the precipitation estimates [57].

3B42V7 and IMERG had similarly high correlation with the gauge precipitation (mean CC values of 0.85 and 0.92 for 3B42V7 and IMERG, respectively) at monthly scale, but both SPPs showed low correlation with the gauge precipitation (mean CC values of 0.41 and 0.50 for 3B42V7 and IMERG, respectively) at daily scale (Figure 3). The main reason is that both 3B42V7 and IMERG provide precipitation estimates from multiple satellites via monthly gauge analyses [21,24]. The error might also be from the historical records from rain gauges. Besides, the five tributaries are typical plateau mountain area characterized by complex topography and strong convectional weather, which would still be challenging for 3B42V7 and IMERG to have relatively accurate precipitation estimates under current observation skills. On the one hand, it was found in this study that the characteristic values in a 3B42V7 or IMERG grid were different greatly (Tables 2 and 3). Several studies have shown that the complex topography affects the circulation system of precipitation, resulting in a significant spatial difference of precipitation [58–61]. On the other hand, the passive microwave algorithms of SPPs rely mainly on scattering by ice, but the orographic precipitation might not produce enough ice aloft [62]. Therefore, complex topography and related warm rain process are a possible explanation for the underperformances of both SPPs over the five tributaries [36,41].

To further verify that the accuracy of IMERG and 3B42V7 is affected by terrain features, the variations of correlation coefficient (CC), relative bias (BIAS), probability of detection (POD), and equitable threat score (ETS) with increasing elevation and slope were investigated, as shown in Figures 10 and 11. From Figure 10, we could see that the CC value of 3B42V7, BIAS value, POD value, and ETS value of both 3B42V7 and IMERG tended to decrease significantly as the elevation increased with a *p*-value less than 0.05 and relatively high correlation coefficient. It was clear that the accuracy of the two SPPs was significantly correlated with elevation. As a whole, the accuracy of 3B42V7 and IMERG decreased with the increase of elevation over the five tributaries, although the variation of BIAS value indicated that 3B42V7 and IMERG had gradually changed from overestimation

to underestimation of precipitation as altitude increased. Figure 11 shows that there was no obvious correlation between these evaluation indices and slope. The possible reason for this is that most gauges located on slopes between 3 and 7 degrees made it hard to see how these evaluation indices varied with slope.



Figure 10. Relations between evaluation metrics from 3B42V7, IMERG, and elevation in the five tributaries. Each dot represents a rain gauge. Solid lines represent the linear trends estimated by the least-squares error method.

IMERG generally outperformed 3B42V7 in detecting precipitation in terms of CC, RMSE, MBE, BIAS, POD, FAR, and ETS, which is consistent with the findings of most previous studies over the Tibetan Plateau [40–42,62]. Figures 10 and 11 again indicate the superiority of IMERG in detecting precipitation amount and comprehensive prediction capability of capturing daily precipitation events with higher CC, POD, and ETS and lower BIAS.

IMERG underestimated torrential precipitation (greater than 50 mm day⁻¹). The result of this study is similar to some previous reports, such as the study in Malaysia [63], in a mountainous watershed in Myanmar [1], over high-elevation (>4500 m) regions of the Tibetan Plateau [42]. However, it was reported that IMERG has a relatively good detection accuracy for heavy precipitation events (>50 mm day⁻¹) in lower elevation (<3500 m) regions of the Tibetan Plateau [42]. Besides, over the upper Mekong River Basin, He et al. [31] showed that IMERG overestimates the amounts of torrential precipitation (greater than 50 mm day⁻¹). Measuring surface precipitation is of cardinal significance, especially for the heavy precipitation events occurring in mountainous areas that are prone to causing floods.



Figure 11. Relations between evaluation metrics from 3B42V7, IMERG, and slope in the five tributaries. Each dot represents a rain gauge. Solid lines represent the linear trends estimated by the least-squares error method.

Besides, both 3B42V7 and IMERG overestimated the occurrences and amounts of trace precipitation (0.1~1.0 mm day⁻¹). It might be due to evaporation and the small and tiny raindrops that could not fall in the atmosphere profiles during the warm seasons. However, the error of IMERG in detecting trace precipitation was greater than 3B42V7 (Figure 8), which is different from the conclusion that IMERG has an advantage in capturing light precipitation events (less than 1.0 mm day⁻¹) compared with 3B42V7 on the Tibetan Plateau [40]. The dual-frequency precipitation radar, carried by the GPM Core Observatory, has a higher sensitivity for capturing light precipitation rates than the precipitation radar onboard the TRMM satellite, providing a better ability of IMERG in detecting no-precipitation and light-precipitation. Thus, the IMERG significantly overestimated the trace precipitation and underestimated torrential precipitation over the five tributaries, which requires exceptional attention from algorithm developers.

In this study, we only described that elevation and slope might affect the accuracy of 3B42V7 and IMERG, but the effect of topographic features are quite complex [64]. Therefore, further exploration of the errors in SPPs needs to continue.

5. Conclusions

This paper cross-evaluated 3B42V7 and IMERG over high mountainous tributaries in Lhasa. Based on a high-density network of rain gauges, our evaluation focused on examining the performance of 3B42V7 and IMERG products at the grid, region, and time scales. Furthermore, we have investigated the effect of precipitation intensity and topographical features on performances of both SPPs. The major conclusions are summarized as follows.

(1) Compared with the ground precipitation, both 3B42V7 and IMERG showed a similarly low level of correlation (mean CC values of 0.41 and 0.50 for 3B42V7 and IMERG, respectively) at daily

scale. Elevation had a significant influence on the accuracy of 3B42V7 and IMERG in the five tributaries. The accuracy of 3B42V7 and IMERG decreased with the increase of elevation.

(2) IMERG performed better than 3B42V7 at daily and monthly scales. Both 3B42V7 and IMERG showed high correlation (mean CC values of 0.85 and 0.92 for 3B42V7 and IMERG, respectively) at monthly scale, but 3B42V7 tended to suffer from a systematic overestimation of monthly precipitation. Besides, IMERG performed better at a monthly scale, followed by daily scale and poor accuracy at six-hourly scale.

(3) At the grid cell, the 3B42V7 could better reflect the precipitation occurrences than IMERG, while the IMERG could better represent the average daily precipitation and the average daily precipitation in precipitation days. Besides, the precipitation in the five tributaries showed obvious spatial variability with a difference of characteristic values (average precipitation in precipitation days, and average daily precipitation) of rain gauges more than 20% in some IMERG grids and most 3B42V7 grids.

(4) IMERG overestimated trace precipitation and underestimated torrential precipitation. For light and heavy precipitation, the detection accuracy of IMERG was higher than 3B42V7, while for moderate precipitation, IMERG detection accuracy was slightly lower than 3B42V7.

Author Contributions: Conceptualization, S.W. and J.L.; methodology, S.W.; software, S.W. and X.Q.; data curation, S.W. and J.W.; writing—original draft preparation, S.W.; writing—review and editing, S.W. and J.Z.; visualization, X.Q. and J.W.; supervision, J.W. and J.L.; project administration, J.Z.; funding acquisition, J.L.

Funding: This research was funded by the National Natural Science Foundation of China (NSFC) (grants 91647108 and 91747203), and the Special Fund of the State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering (no 20185044312).

Acknowledgments: The authors would like to acknowledge Bureau of Hydrological and Water Resources of Tibet Autonomous Region for their support for this research and the TRMM and GPM research communities for making the data available to international users.

Conflicts of Interest: The authors declare no conflict of interest.

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