Can the GPM IMERG Hourly Products Replicate the Variation in Precipitation During the Wet Season Over the Sichuan Basin, China?

H. Wang¹, L. Wang², J. He³, F. Ge⁴, Q. Chen¹, S. Tang¹, and S. Yao¹

¹College of Atmospheric Sounding, Chengdu University of Information Technology, Chengdu, China, ²Chengdu Institute of Plateau Meteorology, CMA/Heavy Rain and Drought-Flood Disaster in Plateau and Basin Key Laboratory of Sichuan Province, Chengdu, China, ³Key Open Laboratory of Atmospheric Sounding, China Meteorological Administration, Chengdu, China, ⁴School of Atmospheric Sciences/Plateau Atmosphere and Environment Key Laboratory of Sichuan Province/Joint Laboratory of Climate and Environment Change, Chengdu University of Information Technology, Chengdu, China

Abstract Two near-real-time and one post-processing products from the Integrated Multi-satellite Retrievals for Global Precipitation Measurement Mission (GPM IMERG) were evaluated during the period from 2016 to 2018 in the wet seasons (June–November) over the Sichuan Basin, China. Results indicated the following: (1) The three products could generally replicate strong precipitation well; however, significantly large biases were observed when detecting weak precipitation. (2) All three products replicated summer precipitation more accurately than autumn precipitation. The IMERG “early run” product (IMERG-E) largely underestimated precipitation in the wet season, while the “latter run” (IMERG-L) and “final run” products (IMERG-F) could counteract this to a certain degree. (3) IMERG-F captured weak, moderate, and strong precipitation well during the wet season, and IMERG-E showed excellent potential in detecting different precipitation intensities. All the three products could replicate the diurnal cycle of the wet season precipitation. The findings of this study can facilitate the application of IMERG products in regions with complex topography and have also highlighted the potential of IMERG-E for rapid early warning and forecast systems.

1. Introduction

Precipitation is a critical factor affecting the global water cycle, atmospheric energy cycle, seawater salinity, and surface reflectance significantly and should be monitored with respect to climate change and global change (Kumar et al., 2017; Trenberth et al., 2007; H. Wang et al., 2015). It is characterized by spatiotemporal variations, making it difficult to estimate or measure accurately (H. Wang et al., 2013; H. Chen, Chandrasekar, et al., 2019). Ground rain gauge is a traditional precipitation observation instrument and can provide high precision at a specific station. However, they are distributed very unevenly, and considerable uncertainty is generated when regional precipitation characteristics are described through interpolation, particularly in complex terrain (Villarini & Krajewski, 2008; H. Wang et al., 2014). Ground-based weather radars, indirect precipitation detecting equipment, can indirectly acquire precipitation distribution based on certain hypotheses (Doviak et al., 1994). However, precipitation detected in this way is susceptible to diverse factors, including electromagnetic wavelengths, variation in raindrop spectrums, uncertainty in the reflectivity-rainfall (Z-R) relationship, ground clutters and obstacles, and errors associated with radar performance. This restricts accurate analysis of ground precipitation characteristics (Harrold et al., 1974; N. Li, Wang, et al., 2017; H. Wang et al., 2018; H. Chen, Cifelli, et al., 2019).

Satellite remote sensing technology has unique advantages (e.g., wide spatial coverage) and is extremely valuable in regions that lack measurement data (e.g., plateaus, mountains, oceans, deserts, and polar regions) (Huffman et al., 2007; Deo et al., 2017; Lu et al., 2018). Diverse satellite-based precipitation products are available to the public, including the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (Hsu et al., 1997; Sorooshian et al., 2000), Climate Prediction Center morphing technique (CMORPH) (Joyce et al., 2004), Global Satellite Mapping of Precipitation (Kubota et al., 2007), Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) (Huffman et al., 2007), and the Integrated Multi-satellite Retrievals for Global Precipitation Measurement Mission (GPM IMERG) (Huffman et al., 2014).
precipitation estimation) (N. Li, Wang, et al., 2017), these studies evaluate IMERG showed that TMPA was better than other comprehensive precipitation products at describing the area and intensity of precipitation (Z. Li et al., 2013; Luís et al., 2015; Tang et al., 2016). The GPM IMERG, a follow-up program of the TRMM, aims to provide higher performance than the TMPA series of products. Many studies have shown that the GPM products have improved in terms of detection rate and detection accuracy to a certain degree compared with TRMM in different geographic locations, such as the tropics (Tan & Duan, 2017; Tan & Santo, 2018), the subtropics (Z. Wang et al., 2017), and the midlatitude regions (Gebregiorgis et al., 2018; Tang et al., 2016) and with different underlying surface condition, such as in high mountain area (C. Zhang, Chen, et al., 2018), basin area (Jiang et al., 2018), plateau (S. Zhang, Wang, et al., 2018), and coastal area (Kim et al., 2017). In particular, the IMERG products are superior to TMPA in detecting precipitation of weak to moderate intensity (Muhammad et al., 2018; C. Zhang, Chen, et al., 2018). Compared to the TRMM, the GPM significantly widens the spatial coverage of the observations (from 35° to 65°), improves the detection accuracy of weak precipitation and snowfall processes (Ku band at 13.6 GHz and Ka band at 35.5 GHz), and boosts the ability to distinguish and identify liquid-state and solid-state precipitation (GPM Microwave Imager at 165.5 and 183.3 GHz) (Hou et al., 2014). The IMERG algorithm aims to perform mutual correction, integration, and interpolation among various precipitation estimates, including all GPM-associated results acquired through satellite microwave remote sensing, infrared satellite remote sensing, and ground rain gauges. The final goal is to generate a comprehensive precipitation product with high spatiotemporal resolution (half-hourly, 0.1° × 0.1°). Based on the time from receiving observation data and operating mode of the processing system, three types of precipitation products are available, which are two near-real-time products, namely, IMERG-E and IMERG-L, and one post-processing product IMERG-F (Huffman et al., 2013).

IMERG products have not been widely applied in meteorological or hydrological fields, and presently, several studies tend to concentrate on evaluating data reliability. Many studies have evaluated the application of IMERG-F at different spatiotemporal scales (Asong et al., 2017; H. Guo et al., 2016; Mahmoud et al., 2019; Reddy et al., 2019; Tang et al., 2016; Wei et al., 2018) under different topographic and climate characteristics (Kim et al., 2017; C. Zhang, Chen, et al., 2018; Lu et al., 2019, 2018; Anjum et al., 2019), and in the hydrological field (Jiang et al., 2018; Ma et al., 2019; N. Li, Tang, et al., 2017; Z. Wang et al., 2017). According to reference standards such as ground rain gauges or weather radar inversion products (e.g., quantitative precipitation estimation) (N. Li, Wang, et al., 2017), these studies evaluate IMERG-F solely or in conjunction with other satellite-based precipitation data analysis products (e.g., TMPA, CMORPH, and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks). IMERG-F can provide higher accuracy on multiple spatiotemporal scales than other satellite-based precipitation products and perform particularly well in terms of precipitation sensitivity, as observed in several studies. Some studies have also used related meteorological or topographic factors to correct the results of IMERG-F in specific fields, further improving its accuracy. For example, precipitation estimates acquired using ground rain gauges have been used to correct the results of IMERG-F (H. Guo et al., 2016). Under special topographic conditions, topographic factors are statistically selected to comprehensively correct the results of IMERG-F (Lu et al., 2018). In addition, some studies focus on near-real-time IMERG products because they play a very critical role in weather forecasting or hydrological models (Ma et al., 2019; Yuan et al., 2019) and can optimize the forecasting results. Z. Wang et al. (2017) provide diurnal comparisons among IMERG-E, IMERG-L, and IMERG-F, and results show that IMERG-E and IMERG-L are inferior to IMERG-F throughout the simulation but can satisfy the accuracy requirements for precipitation prediction during the study period. Tan and Santo (2018) demonstrate that IMERG-E and IMERG-L can be applied to extreme precipitation during the wet season in Malaysia on a daily basis.

The Sichuan Basin is located in the east of the Qinghai-Tibet Plateau and is dominated by a subtropical humid monsoon climate. Its peripheral region is characterized by complex landforms, ample moisture, and changeable weather. In particular, the precipitation process in the wet season has typical basin characteristics. The Sichuan Basin is a critical region for the eastward movement of the convection system of the Qinghai-Tibet Plateau. In the wet season, strong rainstorms occur frequently and trigger or intensify disastrous weather (e.g., rainstorms and floods) conditions in the middle and lower reaches of the Yangtze River (J. Chen & Li, 2013; Hao et al., 2016; H. Wang et al., 2013). The night rain phenomenon peculiar to the
Sichuan Basin is attracting attention in ongoing studies on disaster reduction and prevention and climate change. Therefore, the wide spatiotemporal coverage of IMERG data is of considerable theoretical and practical value to studies on variation in precipitation in the Sichuan Basin. However, studies focusing on this region have the following limitations: (1) Evaluation using IMERG does not effectively distinguish the basin from its external regions. (2) IMERG products are used in many studies spanning less than 1 year, thus making it difficult to prove their reliability; moreover, it is not clear whether the evaluation of different types of precipitation is objective. (3) The reliability of using IMERG-E and IMERG-L in the Sichuan Basin has not been studied on an hourly scale.

Based on the abovementioned limitations, this study comprehensively evaluated the three precipitation products (IMERG-E, IMERG-L, and IMERG-F) in the Sichuan Basin with special landforms on a longer temporal scale (wet season in three years from 2016 to 2018) and under a higher spatiotemporal resolution (0.1° × 0.1°, 1 hr) than previous studies. The evaluation covers the following aspects: (1) characteristics of the spatiotemporal distribution of statistical indices on a gridded scale and regional scale, (2) sensitivity in determining different precipitation intensities according to probability density function (PDF), (3) error produced by the three products in a diurnal cycle through composite analysis. The findings can be used as a reference for studies in regions with similar topographic structures and climatic characteristics and to improve GPM-related algorithms.

The rest of this paper is organized as follows. Section 2 describes the study area, precipitation data set, and evaluation methods. Section 3 evaluates the reliability of the three products on a gridded scale and regional scale as well as the sensitivity and accuracy of the three products. Section 4 gives conclusions and discussions.

2. Data and Methods
2.1. Study Area

The Sichuan Basin is one of China’s four major basins, covering an area of more than 260,000 km² located in the southern central part of the Asian continent (latitude 28°N to 32°N). The basin is in southwest China and harbors the upper reaches of the Yangtze River (Figure 1). It comprises the central and eastern parts of Sichuan and the vast majority of Chongqing and is encircled by the Qinghai-Tibet Plateau, Daba Mountain, Wushan Mountain, Daloushan Mountain, and Yunnan-Guizhou Plateau. Topographically, the Sichuan Basin mainly comprises mountains at its edge and a central basin bottom. The peripheral mountains mostly have elevation ranging from 1,000 to 3,000 m and cover an area of approximately 100,000 km². The basin bottom is low lying, with an elevation of 250 to 750 m, and covers approximately
160,000 km² (C. Chen et al., 2010). Areas with an elevation of less than 750 m were selected as the basin regions for this study.

The Sichuan Basin is dominated by a subtropical monsoon humid climate and has an annual precipitation of 1,000 to 1,300 mm that shows intra-annual variations characterized by dryness in winter, drought in spring, waterlogging in summer, and gentle rain in fall. Approximately 70% to 75% of the annual precipitation is concentrated in summer and fall. Precipitation occurs mainly at night; night precipitation accounts for 60% to 70% of the annual precipitation. The mountains on the edge of the basin experience high precipitation; for example, the mountainous area at the western edge, located between Leshan and Ya’an, has an annual precipitation of 1,500 to 1,800 mm, which is one of the highest in mainland China (H. Wang et al., 2013; Z. Wang et al., 2017). This is one of the reasons that the precipitation in the Sichuan Basin during the wet season was evaluated in this study.

2.2. Ground-Based Observations

Ground-based observations used as the reference for comparative analysis of IMERG products were obtained from the China Merge Precipitation Analysis (CMPA) (http://data.cma.cn/data/detail/dataCode/SEVP_CLI_CHN_MERGE_CMP_PRE_HOUR_GRID_0.10/keywords/cmorph.html), an hourly high-resolution gridded precipitation product released by the China Meteorological Administration. The CMPA integrates hourly precipitation observations acquired by at least 30,000 automatic weather stations (AWS) countrywide (including national weather stations (AWS-N) and regional weather stations (AWS-R)), as well as the CMORPH product (spatial resolution is 8 km and temporal resolution is 30 min) developed by the National Oceanic and Atmospheric Administration. To obtain a high-quality CMPA product, the PDF was used to correct errors contained in the CMORPH data against quality-controlled hourly precipitation observations acquired by AWS. Using optimal interpolation, a gridded precipitation product was then generated (spatial resolution is 0.1° × 0.1° and temporal resolution is 1 hr). Finally, the spatial distribution and error Characteristics were evaluated. The final accuracy of the integrated product is associated with the density of weather stations; the greater the number of weather stations, the better the integration effect (Tang et al., 2016). Although the density of the weather stations has a certain effect on the accuracy of the precipitation product (Prakash et al., 2019), Shen et al. (2013), after a comprehensive evaluation of CMPA data use in China, found that with only 700 basic/reference stations, the mean deviation is –0.132 mm/hr, the root-mean-square error (RMSE) is 2.046 mm/hr, and the correlation coefficient (CC) is relatively low at only 0.298; while with 30,000 basic/reference stations, the latter two numbers become 1.311 mm/hr and 0.792, respectively. At present, the density of the 30,000 automatic stations in China’s western and northeastern regions is roughly close to that of the 700 stations in the eastern region where stations are concentrated. A total of 4,107 precipitation stations across the Sichuan basin area was used in the integration of CMPA data (Figure 2). Therefore this density of stations can be considered as close to that with 30,000 stations, and the statistical results obtained are strongly rational and effective.
Table 1

| Evaluation Indices Applied to IMERG and CMPA |
|---------------------------------------------|
| Index                                       | Equation                                          | Optimal value |
| Pearson correlation coefficient (CC)         | \[ \frac{1}{N} \sum_{i=1}^{N} (S_i - \bar{S})(G_i - \bar{G})/\sigma_S \sigma_G \] | 1 |
| Root-mean-square error (RMSE)               | \[ \sqrt{\frac{1}{N} \sum_{i=1}^{N} (S_i - G_i)^2} \] | 0 |
| Relative bias (RB)                          | \[ \frac{\sum_{i=1}^{N} (S_i - G_i)}{\sum_{i=1}^{N} G_i} \] | 0 |
| Probability of detection (POD)              | \[ \frac{D}{D+M} \] | 1 |
| False alarm ratio (FAR)                     | \[ \frac{F}{F+D} \] | 0 |
| Critical success index (CSI)                | \[ \frac{D}{D+M+F} \] | 1 |

Note: \(i\) denotes one grid point; \(N\) denotes sample size; \(S_i\) denotes precipitation estimated by satellites; \(\bar{S}\) denotes the mean value of precipitation estimated by satellites; \(G_i\) denotes precipitation estimated by ground-based observations; \(\bar{G}\) denotes the mean value of precipitation estimated by ground-based observations; \(\sigma_S\) denotes the standard deviation of precipitation estimated by satellites; and \(\sigma_G\) denotes the standard deviation of precipitation estimated by ground-based observations. In addition, \(D\) denotes precipitation events detected by both satellites and ground-based observations; \(F\) denotes precipitation events detected by ground-based observations but not by satellites; and \(M\) denotes precipitation events detected by satellites but not by ground-based observations.

2.3. Satellite Observations

This study comprehensively evaluated three IMERG products (IMERG-E, IMERG-L, and IMERG-F) on an hourly scale. IMERG-E data were released first, approximately 4 hr after observation, primarily intended to give a rapid early warning regarding rainstorms or landslides. As more observations were received by the data processing center, IMERG-L data were released after 12 hr based on the IMERG-E output. IMERG-L is primarily used for weather forecasting and drought monitoring in agriculture. To satisfy the higher accuracy needs of scientific research, research-grade IMERG-F was released approximately 2 months after completion of the observations. This IMERG-F provides precipitation data corrected according to average monthly precipitation data acquired by the ground rain gauges in the Global Precipitation Climatology Center (GPCC). This improves the accuracy of precipitation observations (Huffman et al., 2015). The three precipitation products also differ in terms of their algorithms. For estimating transient passive microwaves, IMERG-E uses the morphing scheme to perform forward propagation, whereas IMERG-L and IMERG-F perform both forward and backward propagation. Theoretically, IMERG-L and IMERG-F can describe precipitation characteristics more accurately than IMERG-E (Sungmin et al., 2017). The GPM IMERG products can be downloaded from National Aeronautics and Space Administration’s website (https://pmm.nasa.gov/data-access/downloads/gpm). The three types of precipitation data have been available since 12 March 2014.

2.4. Methods

We selected three common statistical indices (Pearson CC, RMSE, and relative bias [RB]) to quantitatively evaluate the accuracy of three satellite-based precipitation products with CMPA (Table 1). CC indicates the degree of correlation between the three types of precipitation products, RMSE indicates the amplitude of variation in errors between them, and RB indicates the relative bias between them. We used three category scoring indices (probability of detection [POD], false alarm ratio [FAR], and critical success index [CSI]) to evaluate the ability of IMERG products to monitor precipitation events (Table 1). POD indicates the ratio of precipitation events correctly detected by IMERG products to precipitation events from CMPA. FAR indicates the ratio of precipitation events correctly detected by IMERG products to precipitation events not observed by CMPA. CSI was used to diagnose the ratio of precipitation events successfully detected by IMERG products, indicating whether there was any contingency when IMERG products were used for precipitation estimation.

During data processing, there was no intersection between IMERG-E and IMERG-L, and data sources of the CMPA. Hence, it was not necessary to separately analyze their independence. Monthly precipitation data from IMERG-F was corrected using data from four international exchange stations within the Sichuan Basin. The data collected by the four precipitation stations used in IMERG-F correction account for only
0.1% of total precipitation data collected by the 4,107 stations. Hence, we considered IMERG-F to also be independent from CMPA data. This study evaluated the three IMERG products with CMPA in the wet season of three years (2016 to 2018). To ensure spatiotemporal consistency between IMERG and CMPA, we accumulated the IMERG data with a temporal resolution of 30 min and extrapolated them a temporal resolution of 1 hr. For both these precipitation products, the spatial resolution is 0.1°. In this way, all the comparative analysis data are processed to have a temporal resolution of 1 hr and a spatial resolution of 0.1°, and both data are intensity with unit mm/hr. It needs to be further explained that (1) when evaluating the hourly precipitation, the intensity unit mm/hr is converted to the quantity unit mm. (2) When ground observation data are missing (less than 5% of the total data), any ground observation data is eliminated, together with the data at the same time and location from the IMERG hourly products, such that the final statistical result is obtained by calculating the remaining valid data. (3) The statistical indices have different meanings when analyzing different contents. For example, when using statistical indices for grid-scale research, the value refers to the average of the data at a single grid point on a 3-year time scale, while for regional scale, the value is the average of the data at all grid points at the same time in the region. (4) All statistics are for precipitation events, except that the precipitation probability was calculated when analyzing the sensitivity of precipitation.

3. Results and Discussions
3.1. Evaluation on a Gridded Scale
Kriging with a linear variogram model (Dingman et al., 1988) was used to interpolate the six evaluation indices on a gridded scale in the Sichuan Basin. In Figure 3, we can observe that the CC increases significantly from near-real-time products to the post-processing product, particularly on the eastern and western sides and in the central part of the Sichuan Basin. Specifically, the CC increased from 0.3–0.4 to 0.5–0.6. It was relatively low within a large area in the central and northwesterly parts of the Sichuan Basin where the RB value was high. There are several possible reasons for this, such as the following: (1) Ground rain gauges are much sparser in this area than in the peripheral areas of the Sichuan Basin (Figure 2a), and there is considerable uncertainty in the accuracy of gridded data. (2) It is an area of transition from plains to mountains, characterized by complex topographic and climatic variations and affected by subtropical high-pressure warm air and water vapor transfer from the Bay of Bengal. Under the combined action of orographic uplift and low pressure, it becomes a rainy area (Zhao, 2015), making satellite-based precipitation estimation difficult. As shown in Figure 2b, the precipitation intensity in this area is lower than in other areas of the Sichuan Basin. The low CC and high RB in this area show that there is considerable bias in the observation of weak precipitation among the three IMERG products; they fail to represent the subtle characteristics of weak precipitation, although IMERG-F makes a notable improvement compared to IMERG-E and IMERG-L. In addition, the mountainous area on the western edge of the Sichuan Basin is characterized by high precipitation frequency and intensity and is known as the “Rain screen of West China.” The CC and RB show that the three products can reveal the main trends in the precipitation variations in this area, but RB is underestimated by all three products. When evaluating the applicability of IMERG-F to Europe, Navarro et al. (2019) found that IMERG-F underestimated the RB of mountain precipitation. The high RMSE in this area is caused by strong precipitation intensity. IMERG-F provides higher POD of precipitation than IMERG-E and IMERG-L, particularly on the eastern and western sides of the Sichuan Basin (greater than 0.6). However, the distribution of high FAR across the three products proves that IMERG products have poor ability to detect weak precipitation; therefore, the zone of high CSI is mainly concentrated in the eastern and southern parts of the Sichuan Basin.

Using boxplots, we further investigated the distribution and variations in the statistical indices of the three precipitation products on a gridded point scale. IMERG-L and IMERG-F (particularly IMERG-F) are superior to IMERG-E in terms of CC, RMSE, POD, and CSI (Figure 4). This is primarily because IMERG-L and IMERG-F perform both forward and backward propagation through the morphing scheme, whereas IMERG-E performs forward propagation only. In addition, IMERG-F received more passive microwave-based information and corrected results of ground rain gauges on a monthly scale, so it performed better. However, in terms of RB and FAR, IMERG-L performs better. According to the spatial distribution of RB (Figure 3), IMERG-F corrects the underestimation of RB made by IMERG-E and IMERG-L in high precipitation areas at the edges of the Sichuan Basin; however, IMERG-F further exacerbates the RB in...
weak precipitation areas. Evidently, the observations subsequently added after IMERG-L stage or monthly precipitation data corrected by the GPCC contribute to overestimation of overall precipitation in the Sichuan Basin, particularly the overestimation of precipitation in weak precipitation areas.

3.2. Evaluation on a Regional Scale

To evaluate the three precipitation products on a regional scale, we analyzed the distribution and variation of hourly statistical characteristics of precipitation in the Sichuan Basin. The results revealed the overall ability of satellite-based precipitation products to detect precipitation in these topographic conditions, as well as the stability of these products in detecting different types of precipitation over different time periods during the wet season from 2016 to 2018.

**Figure 3.** Spatial distribution of six statistical indices of three precipitation products (IMERG-E, IMERG-L, and IMERG-F) on a gridded scale: (a–c) Pearson correlation coefficient (CC), (d–f) relative bias (RB; %), (g–i) root-mean-square error (RMSE; mm), (j–l) probability of detection (POD), (m–o) false alarm ratio (FAR), and (p–r) critical success index (CSI). The threshold of POD to precipitation intensity was set at 0.1 mm/hr.

The threshold of POD to precipitation intensity was set at 0.1 mm/hr.

**Figure 3.** Spatial distribution of six statistical indices of three precipitation products (IMERG-E, IMERG-L, and IMERG-F) on a gridded scale in the wet season from 2016 to 2018 (temporal resolution is 1 hr, and spatial resolution is 0.1° x 0.1°): (a–c) Pearson correlation coefficient (CC), (d–f) relative bias (RB; %), (g–i) root-mean-square error (RMSE; mm), (j–l) probability of detection (POD), (m–o) false alarm ratio (FAR), and (p–r) critical success index (CSI). The threshold of POD to precipitation intensity was set at 0.1 mm/hr.
the wet season. The three IMERG products are primarily characterized using six evaluation indices represented by long upper- or lower-end boxplot lines (Figure 5). In the Sichuan Basin, there are two principal types of precipitation in the wet season, including convective precipitation in summer and layered precipitation in fall (H. Wang et al., 2013), which have completely different characteristics. Convective precipitation is mainly characterized by high intensity and short durations, whereas layered precipitation shows the opposite characteristics. Long upper- or lower-end lines show that the three IMERG products differ significantly in terms of their ability to detect different types of precipitation in the Sichuan Basin. On a regional scale, IMERG-F counteracts the underestimation of wet season precipitation by IMERG-E and increases the overall POD of precipitation without increasing the FAR. IMERG-L does not differ significantly from IMERG-F. The RB of IMERG-F (20.8%) is considerably higher than those of IMERG-E (4.6%) and IMERG-L (4.5%; Figure 6b). Within the Sichuan Basin, there are several areas in which precipitation is overestimated and underestimated by IMERG-E and IMERG-L, respectively. These inaccurate estimations counteract each other, resulting in low RB values. In contrast, IMERG-F overestimates precipitation across almost the whole Sichuan Basin, so its RB values are relatively high.

According to the evaluation indices of the three precipitation products across different time periods (Table 2), IMERG-F is superior to IMERG-E and IMERG-L in terms of predicting summer precipitation, fall precipitation, and precipitation across the wet season. IMERG-F performs well in describing different types of precipitation. The performance of IMERG-L is more similar to that of IMERG-F than IMERG-E. Furthermore, the three products do not differ markedly in their depictions of the trends in the variation of convective precipitation in summer and layered precipitation in fall (the CC of the two types of precipitation are similar). In terms of POD and CSI, the products are better at detecting summer precipitation than fall precipitation. This implies that the IMERG products perform better when detecting strong precipitation than when predicting weak precipitation.
3.3. Evaluation of Precipitation Sensitivity

We compared the PDF by occurrence (PDFc) and PDF by rain volume (PDFv) detected by the three IMERG products with CMPA (Amitai et al., 2009; Kirstetter et al., 2013; S. Zhang, Wang, et al., 2018). The intent was to further compare performance of the products in terms of precipitation sensitivity. PDFc is equal to the ratio of the precipitation count under different intensities to the total precipitation count and indicates the probability of occurrence of precipitation intensity. PDFv is equal to the ratio of the volume contribution of each precipitation type under different intensities to the total precipitation volume and indicates the probability of occurrence of precipitation volume. Figure 7 shows the PDFc and PDFv of hourly precipitation at different stages during the wet season in the Sichuan Basin. In general, the higher the PDFc, the weaker the precipitation intensity, and the higher the PDFv, the stronger the precipitation intensity, which is consistent with the precipitation characteristics of the Sichuan Basin during the wet season, that is, weak precipitation occurs with a high frequency, while strong precipitation accounts for a large proportion of the volume (J. Guo & Li, 2009).

During precipitation in the wet season, most precipitation has an intensity of 0 to 0.1 mm/h, implying that no precipitation occurs most of the time (Figure 7a). IMERG-E and IMERG-L overestimated PDFc by 1.11% and 2.44%, respectively, whereas IMERG-F underestimated PDFc by 1.96%. All the three IMERG products overestimated PDFv by 1%. With increases in precipitation intensity, the three products performed differently. Overall, the results obtained using IMERG-E and IMERG-F are most similar to CMPA. When the precipitation intensity was lower than 1 mm/hr (weak precipitation), the PDFc of IMERG-F is 8.77% (the PDFc of CMPA is 8.00%), and the PDFv of IMERG-F is 17.28% (the PDFv of CMPA is 19.53%). H. Guo et al. (2016) argued that weak precipitation is prone to partial or total evaporation during the precipitation process and is
thus difficult to observe using ground rain gauges. This caused an overestimation of the PDFc by IMERG-F compared to CMPA. The results of IMERG-F were more similar to actual measurements than those of IMERG-E and IMERG-L; IMERG-F was better at detecting weak precipitation. When precipitation intensity increases to between 1 and 5 mm/hr (moderate precipitation), the PDFc errors of the three IMERG products are below 1%. However, IMERG-F overestimates the PDFv by 5.86%, whereas IMERG-E and IMERG-L overestimated the PDFv by 6.47% and 11.18%, respectively. Hence, IMERG-F performs best in detecting moderate precipitation. When the precipitation intensity became higher than 5 mm/hr (strong precipitation), IMERG-L performed poorly, whereas IMERG-E and IMERG-F resembled CMPA. Detection of strong precipitation in the Qinghai-Tibet Plateau by IMERG-F resulted in overestimation of the PDFv as the precipitation intensity increased owing to overestimation of the PDFc (S. Zhang, Wang et al., 2018). In southeastern Australia, moderate precipitation and strong precipitation may lead to underestimation of the PDFc, but the PDFc may also be overestimated significantly, particularly by near-real-time IMERG products (Sungmin et al., 2017). In this study, when detecting strong precipitation in the Sichuan Basin, increases in the PDFc led to underestimation of the PDFv. The ability of the GPM to detect precipitation varies with geographical characteristics and climate type (H. Guo et al., 2016; Tang et al., 2016). Overall, IMERG-F proved superior to IMERG-E and IMERG-L in terms of detecting weak, moderate, or strong precipitation in the wet season of the Sichuan Basin. However, IMERG-E presents considerable potential for monitoring precipitation of different intensities, making it possible to apply near-real-time IMERG products in the future evaluations of diurnal cycles.

We evaluated the three IMERG products using time series on an hourly scale through composite analysis of the diurnal cycle (G. Li et al., 2008). The analysis was intended to evaluate the ability of the products to reproduce diurnal variations in precipitation. The overall trend of variations in the diurnal cycle revealed by the three IMERG products was consistent with that recorded using CMPA (CC values are greater than 0.9;
Figure 8a). The IMERG products can reflect high and low value areas on an hourly scale and show the main characteristics of diurnal variation in precipitation. Precipitation in the wet season of the Sichuan Basin is dominated by nighttime precipitation, mainly occurring at night and in the early morning, this is consistent with other research findings (J. Chen & Li, 2013; J. Guo & Li, 2009; H. Wang et al., 2013). During the precipitation process throughout the wet season, the three IMERG products tended to overestimate precipitation compared to CMPA. Areas with peak precipitation intensity are consistent with observed areas, whereas areas of low precipitation intensity according to the IMERG products significantly differ from observed areas. This further demonstrates that the three IMERG products are to some extent deficient in detecting weak precipitation.

The precipitation process in the wet season is subdivided into summer and fall (Figures 8b and 8c). The times of minimum and maximum summer precipitation revealed by IMERG-F are consistent with observed values. However, the time of peak summer precipitation revealed by IMERG-E and IMERG-L is 2 hr behind the observed times, while the time of minimum summer precipitation is 6 hr ahead. Therefore, owing to the
introduction of more observations, IMERG-F can describe the trends in precipitation variation accurately, particularly summer precipitation dominated by convective precipitation. For fall precipitation dominated by layered precipitation, the three IMERG products differ marginally in terms of their absolute error but are similar in other aspects. Overall, the three IMERG products are still deficient in detecting weak precipitation. Therefore, with increases in subsequent observations compared to IMERG-L and cross validation with data from the ground rain gauges from GPCC, IMERG-F nevertheless fails to significantly improve the detection of weak precipitation in the Sichuan Basin. However, it can describe the variation in

Table 3
Statistics of Precipitation Frequency and Intensity in Different Time Periods Revealed by Three IMERG Products (IMERG-E, IMERG-L, and IMERG-F)

| Period | Time period (LST) | CMFA | IMERG-E | IMERG-L | IMERG-F |
|--------|------------------|------|---------|---------|---------|
| WS     | 01–07            | 0.32 | 0.25    | 0.30    | 0.24    | 0.33    | 0.25    | 0.32    | 0.31    |
|        | 07–13            | 0.29 | 0.19    | 0.28    | 0.22    | 0.26    | 0.21    | 0.27    | 0.22    |
|        | 13–19            | 0.20 | 0.12    | 0.22    | 0.12    | 0.22    | 0.11    | 0.21    | 0.14    |
|        | 19–01            | 0.20 | 0.13    | 0.20    | 0.14    | 0.20    | 0.13    | 0.21    | 0.15    |
| SUM    | 01–07            | 0.30 | 0.32    | 0.28    | 0.33    | 0.30    | 0.34    | 0.28    | 0.39    |
|        | 07–13            | 0.28 | 0.23    | 0.26    | 0.30    | 0.25    | 0.28    | 0.26    | 0.28    |
|        | 13–19            | 0.22 | 0.17    | 0.25    | 0.19    | 0.25    | 0.17    | 0.25    | 0.20    |
|        | 19–01            | 0.19 | 0.16    | 0.21    | 0.20    | 0.20    | 0.19    | 0.21    | 0.20    |
| FAL    | 01–07            | 0.32 | 0.18    | 0.35    | 0.15    | 0.37    | 0.17    | 0.36    | 0.22    |
|        | 07–13            | 0.29 | 0.14    | 0.30    | 0.14    | 0.28    | 0.14    | 0.29    | 0.17    |
|        | 13–19            | 0.18 | 0.07    | 0.16    | 0.05    | 0.16    | 0.06    | 0.16    | 0.08    |
|        | 19–01            | 0.20 | 0.09    | 0.19    | 0.07    | 0.19    | 0.08    | 0.20    | 0.10    |

Note. Shaded values are optimal (yellow denotes precipitation frequency, and light blue denotes precipitation intensity).
precipitation more accurately than IMERG-L and IMERG-E (CC values are 0.98, 0.99, and 0.97 in wet season, summer, and fall, respectively). To evaluate the ability of these precipitation products to reproduce diurnal variation in precipitation over different time ranges in the wet season, we used two characteristic variables (precipitation frequency and precipitation intensity) to analyze precipitation in four time periods, including 01:00 to 07:00 (second half of the night), 07:00 to 13:00 (first half of the day), 13:00 to 19:00 (second half of the day), and 19:00 to 01:00 (first half of the night). The precipitation frequency and intensity in different time periods according to the three IMERG products are consistent with CMPA. The products described the characteristics of the two types of precipitation well, including convective precipitation in summer (low frequency and high intensity) and layered precipitation in fall (high frequency and low intensity) (Figure 9). According to the distribution of optimal values in different time periods (Table 3), IMERG-F performs best in detecting precipitation frequency, and IMERG-L is best in detecting precipitation intensity.

4. Conclusions and Discussions

Because of its geographical location, the Sichuan Basin has a unique climatic environment, producing a complex and changeable precipitation system. It is extremely important both scientifically and practically to evaluate the accuracy of satellite-based precipitation products applied in this region. This study is the first to evaluate on an hourly scale the accuracy of near-real-time and post-processing IMERG products applied in the Sichuan Basin during the wet season across three years. Based on evaluations at gridded and regional scales, this study first examined the correlation and error range between the three products and ground observation data (CMPA). By calculating the variation in the PDFc and PDFv under different precipitation scales, this study assessed the ability of these products to reproduce diurnal variations in precipitation over different time ranges in the wet season, we used two characteristic variables (precipitation frequency and precipitation intensity) to analyze precipitation in four time periods, including 01:00 to 07:00 (second half of the night), 07:00 to 13:00 (first half of the day), 13:00 to 19:00 (second half of the day), and 19:00 to 01:00 (first half of the night). The precipitation frequency and intensity in different time periods according to the three IMERG products are consistent with CMPA. The products described the characteristics of the two types of precipitation well, including convective precipitation in summer (low frequency and high intensity) and layered precipitation in fall (high frequency and low intensity) (Figure 9). According to the distribution of optimal values in different time periods (Table 3), IMERG-F performs best in detecting precipitation frequency, and IMERG-L is best in detecting precipitation intensity.

Through composite analyses, the ability of these products to reproduce diurnal variations in precipitation was assessed. The following conclusions can be drawn from this study:

1. On a gridded scale, the three IMERG products all produce large errors when observing weak precipitation but perform satisfactorily when observing strong precipitation. In terms of spatial distribution, IMERG-F corrects the underestimation of strong precipitation at the edge areas of the Sichuan Basin made by IMERG-E and IMERG-L, but IMERG-F further exacerbates the RB in the weak precipitation areas of the Sichuan Basin. Evidently, the observational data added subsequently by IMERG-L or monthly precipitation data corrected by the GPCC exacerbate the overestimation of overall precipitation in the Sichuan Basin, particularly the overestimation of precipitation in weak precipitation areas.

2. On a regional scale, the ability of the IMERG products to detect summer precipitation significantly differs from that to detect fall precipitation. On a regional scale, IMERG-F corrects the underestimation of precipitation in the wet season by IMERG-E. In terms of specific values of the evaluation indices, IMERG-L does not significantly differ from IMERG-F. The IMERG products are much better at detecting summer precipitation than fall precipitation, implying that they perform better in detecting strong precipitation.

3. According to the evaluation of IMERG products at different precipitation intensities, IMERG-F is superior to both IMERG-E and IMERG-L in terms of detecting weak, moderate, or strong precipitation during the wet season in the Sichuan Basin. However, IMERG-E also presents considerable potential for monitoring precipitation with varying intensities, making it possible to apply near-real-time IMERG products in the future.

4. In the evaluation of the diurnal cycle, the overall trend in the variations of the diurnal cycle represented by the three IMERG products is consistent with CMPA. For precipitation across the wet season, the peak areas of precipitation intensity represented by the three IMERG products are highly consistent with the observed areas, but areas of low precipitation intensity represented by the three IMERG products significantly differ from the observed areas. This shows that the three IMERG products are somewhat deficient in detecting weak precipitation. The piecewise analysis of diurnal precipitation shows that IMERG-F performs best in detecting precipitation frequency, whereas IMERG-L performs best in detecting precipitation intensity.

In summary, our results show that GPM IMERG hourly products can replicate the variation precipitation during the wet season over the Sichuan Basin with complex topography. But the IMERG products need to be further improved in terms of detecting weak precipitation in the region, and (particularly for IMERG-F) errors need to be further reduced. However, we noted the application potential of near-real-time products, and subsequent studies will concentrate on the evaluation and application of
Acknowledgments
This work was supported by the National Key R&D Program of China (2018YFC1506104), National Natural Science Foundation (41805056), Application Basic Research of Sichuan Department of Science and Technology (2019YJ03016), and the Natural Science General Project of Sichuan Education Department (2018Z098). The authors would like to express their sincere thanks to the National meteorological Department (2018Z098). The authors also thank the reviewers for their constructive comments and editorial suggestions that significantly improved the quality of this paper.

Author Contributions
Hao Wang and Lei Wang conceived this research and designed the study. The paper was written by Hao Wang. Qingqing Chen, Shuxian Tang, and Shuangyu Yao wrote the code and processed the data. Jianxin He and Fei Ge derived the conclusions.

References
Amiet, E., Llort, X., & Sempere-Torres, D. (2009). Comparison of TRMM radar rainfall estimates with NOAA next-generation QPE. Journal of the Meteorological Society of Japan. Ser. II, 87, 109–118. https://doi.org/10.2151/jmsj.87a.109
Anjum, M. N., Ahmad, I., Ding, Y., Shangguan, D., Zaman, M., Ijaz, M. W., et al. (2019). Assessment of IMERG-V06 precipitation product over different hydro-climatic regimes in the Tian Shan mountains, North-Western China. Remote Sensing, 11(19), 2314. https://doi.org/10.3390/rs11192314
Asong, Z. E., Razavi, S., Wheater, H. S., & Wong, J. S. (2017). Evaluation of integrated multisatellite retrievals for GPM (IMERG) over southern Canada against ground precipitation observations: A preliminary assessment. Journal of Hydrometeorology, 18(4), 1033–1050. https://doi.org/10.1175/JHM-D-16-0187.1
Chen, C., Pang, Y. M., & Zhang, Y. F. (2010). On the characteristics of climate change in Sichuan basin in the recent 50 years. Journal of Southwest University (Natural Science Edition), 32(9), 115–120.
Chen, H., Chandrasekar, V., Tan, H., & Cifelli, R. (2019). Rainfall estimation from ground radar and TRMM precipitation radar using hybrid deep neural networks. Geophysical Research Letters, 46(17–18), 10669–10678. https://doi.org/10.1029/2019GL084771
Chen, H., Cifelli, R., & White, A. (2019). Improving operational radar rainfall estimates using profiler observations over complex terrain in Northern California. IEEE Transactions on Geoscience and Remote Sensing, 58(3), 1821–1832. https://doi.org/10.1109/TGRS.2019.2949224
Chen, J., & Li, G. (2013). Diurnal variations of ground-based GPS-PWV under different solar radiation intensity in the Chengdu Plain. Journal of Geodynamics, 72, 81–85. https://doi.org/10.1016/j.jog.2013.08.002
Deo, A., Walsh, J. K., & Peltier, A. (2017). Evaluation of TMPA 3B42 precipitation estimates during the passage of tropical cyclones over New Caledonia. Theoretical and Applied Climatology, 128(3–4), 711–727. https://doi.org/10.1007/s00704-016-1803-0
Dingman, S. L., Seely, R. M., & Reynolds, D. R. III (1988). Application of kriging to estimating mean annual precipitation in a region of orographic influence I. JAWRA Journal of the American Water Resources Association, 24(2), 329–339. https://doi.org/10.1111/j.1752-1688.1988.tb02991.x
Doviak, R., Zrnic, D., & Schotl览. (1994). Doppler radar and weather observations. Applied Optics, 33(21), 4531.
Gebregiorgis, A. S., Kirstetter, P. E., Hong, Y. E., Gourley, J. J., Huffman, G. J., Petersen, W. A., et al. (2018). To what extent is the day 1 GPM IMERG satellite precipitation estimate improved as compared to TRMM TMPA-R7T? Journal of Geophysical Research: Atmospheres, 123(3), 1694–1707. https://doi.org/10.1002/2017JD027606.
Guo, H., Chen, S., Bao, A., Behrangi, A., Hong, Y., Ndayisaba, F., et al. (2016). Early assessment of integrated multi-satellite retrievals for global precipitation measurement over China. Atmospheric Research, 176, 121–133.
Guo, J., & Li, G. (2009). Climatic characteristics of precipitable water vapor and relations to surface water vapor column in Sichuan and Chongqing region. Journal of Natural Resources, 24(2), 343–350. (in Chinese)
Hao, W., Yue, W., & Yongqian, W. (2016). A comprehensive analysis of a heavy precipitation event in Chengdu Plain (China) based on ground-based GPS. Earth, 5(4), 48–55. https://doi.org/10.11614/j.earth.20160504.11
Harrollo, T. W., English, E. J., & Nicollas, C. A. (1974). The accuracy of radar-derived rainfall measurements in hilly terrain. Quarterly Journal of the Royal Meteorological Society, 100(425), 331–350. https://doi.org/10.4018/jqi.2017040256.
Hou, A. Y., Kakar, R. K., Neek, S., Asrarzian, A. A., Kummerow, C. D., Kojima, M., et al. (2014). The Global Precipitation Measurement Mission. Bulletin of the American Meteorological Society, 95(5), 701–722. https://doi.org/10.1175/BAMS-D-13-00164.1
Hsu, K. L., Gao, X., Somosniah, S., & Gupta, H. V. (1997). Precipitation estimation from remotely sensed information using artificial neural networks. Journal of Applied Meteorology, 36(9), 1176–1190. https://doi.org/10.1175/1520-0450(1997)036<1176:PEFRSI>2.0.CO;2
Huffman, G. J., Bolvin, D., Braithwaite, D., Hsu, K., Joyce, R., & Xie, P. (2013). NASA Global Precipitation Measurement (GPM) Integrated MultisatellitE Retrievals for GPM (IMERG). Algorithm theoretical basis doc, version 4.1, NASA, 29 pp.
Huffman, G. J., & Bolvin, D. T. (2011). TRMM and other data precipitation data set documentation, Laboratory for Atmospheres, NASA Goddard Space Flight Center and Science Systems and Applications, Inc. Maryland, United States: Inc, Goddard.
Huffman, G. J., Bolvin, D. T., & Nelkin, E. J. (2015). Integrated Multi-satellite Retrievals for GPM (IMERG) technical documentation. NASA/GSFC Code, 412(47), 2019.
Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., et al. (2007). The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. Journal of Hydrometeorology, 8(1), 38–55. https://doi.org/10.1175/JHM560I
Jiang, S., Ren, L., Xu, C. Y., Yong, B., Yuan, F., Liu, Y., et al. (2018). Statistical and hydrological evaluation of the latest Integrated Multi-satellite Retrievals for GPM (IMERG) over a midlatitude humid basin in South China. Atmospheric Research, 214, 418–429. https://doi.org/10.1016/j.atmosres.2018.08.021
Joyce, R. J., Janowiak, J. E., Arkin, P. A., & Xie, P. (2004). CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. Journal of Hydrometeorology, 5(3), 487–503. https://doi.org/10.1175/1525-7541(2004)005<0487:CMORPH>2.0.CO;2
Kim, K., Park, J., Baik, J., & Choi, M. (2017). Evaluation of topographical and seasonal feature using GPM IMERG and TRMM 3B42 over East Asia. *Atmospheric Research, 187*, 95–105. https://doi.org/10.1016/j.atmosres.2016.12.007

Kirstetter, P. E., Hong, Y., Gourley, J. J., Schwaller, M., Petersen, W., & Zhang, J. (2013). Comparison of TRMM 2A25 products, version 6 with 7, and NOAA/NSSL ground radar–based National Mosaic QPE. *Journal of Hydrometeorology, 14*(2), 661-669. https://doi.org/10.1175/JHM-D-13-030.1

Kubota, T., Shige, S., Hashizume, H., Aonashi, K., Takahashi, N., Seto, S., et al. (2007). Global precipitation map using satellite-borne microwave radiometers by the GSMap project: Production and validation. *IEEE Transactions on Geoscience and Remote Sensing, 45*(7), 2259–2275. https://doi.org/10.1109/TGRS.2007.895337

Kumar, D., Gautam, A. K., Palmate, S. S., Pandey, A., Suryavanshi, S., Rathore, N., & Sharma, N. (2017). Evaluation of TRMM Multi-satellite Precipitation Analysis (TMPA) against terrestrial measurement over a hum sub-tropical basin, India. *Theoretical and Applied Climatology, 129*(3–4), 783–799. https://doi.org/10.1007/s00704-016-1807-9

Li, G., Kimura, F., Sato, T., & Huang, D. (2008). A composite analysis of diurnal cycle of GPS precipitable water vapor in central Japan during calm summer days. *Theoretical and Applied Climatology, 92*(1–2), 15–29. https://doi.org/10.1007/s00704-006-0293-x

Li, N., Tang, G., Zhao, P., Hong, Y., Gou, Y., & Yang, K. (2017). Statistical assessment and hydrological utility of the latest multi-satellite precipitation analysis IMERG in Ganjiang River basin. *Atmospheric Research, 183*, 212–223. https://doi.org/10.1016/j.atmosres.2016.07.020

Li, N., Wang, Z., Sun, K., Chu, Z., Leng, L., & Lv, X. (2017). A quality control method of ground-based weather radar data based on statistics. *IEEE Transactions on Geoscience and Remote Sensing, 56*(4), 2211–2219.

Li, Z., Yang, D., & Hong, Y. (2013). Multi-scale evaluation of high-resolution multi-sensor blended global precipitation products over the Yangtze River. *Journal of Hydrology, 500*, 157–169. https://doi.org/10.1016/j.jhydrol.2013.07.023

Lu, X., Tang, G., Wang, X., Liu, Y., Jia, L., Xie, G., et al. (2019). Correcting GPM IMERG precipitation data over the Tianshan Mountains in China. *Journal of Hydrology, 575*, 1239–1252. https://doi.org/10.1016/j.jhydrol.2019.06.019

Lu, X., Wei, M., Tang, G., & Zhang, Y. (2018). Evaluation and correction of the TRMM 3B43V7 and GPM IMERGM satellite precipitation products by use of ground-based data over Xinjiang, China. *Environmental Earth Sciences, 77*(5), 209. https://doi.org/10.1007/s12665-018-7378-6

Luis, A., Diez, L., Luis, G., Daniel, A., & Marcos, A. (2015). Precipitation comparison for the CFSR, MERRA, TRMM3B42 and combined scheme datasets in Bolivia. *Atmospheric Research, 163*, 117–131.

Ma, Q., Xiong, L., Xia, J., Xiong, B., Yang, H., & Xu, C. Y. (2019). A censored shifted mixture distribution mapping method to correct the bias of daily IMERG satellite precipitation estimates. *Remote Sensing, 11*(11), 1345.

Mahmoud, M. T., Hamouda, M. A., & Mohamed, M. M. (2019). Spatiotemporal evaluation of the GPM satellite precipitation products over the United Arab Emirates. *Atmospheric Research, 219*, 200–212. https://doi.org/10.1016/j.atmosres.2018.12.029

Muhammad, N. A., Yongjian, D., Donghui, S., Ijaz, A., Muhammad, W., Hafiz, U. F., et al. (2018). Performance evaluation of latest integrated multi-satellite retrievals for Global Precipitation Measurement (IMERG) over the northern highlands of Pakistan. *Atmospheric Research, 205*, 134–146.

Navarro, A., García-Ortega, E., Merino, A., Sánchez, J. L., Kummerow, C., & Tapiador, F. J. (2019). Assessment of IMERG precipitation estimates over Europe. *Remote Sensing, 11*(21), 2470. https://doi.org/10.3390/rs11212470

Prakash, S., Seshadri, A., Srinivasan, J., & Pai, D. S. (2019). A new parameter to assess impact of rain gauge density on uncertainty in the estimate of monthly rainfall over India. *Journal of Hydrology, 20*, 821–832.

Reddy, M. V., Mitra, A. K., Momin, I. M., Mitra, A. K., & Pai, D. S. (2019). Evaluation and inter-comparison of high-resolution multi-satellite rainfall products over India for the southwest monsoon period. *International Journal of Remote Sensing, 40*(12), 4577–4603. https://doi.org/10.1080/01431161.2019.1569786

Shen, Y., Pan, Y., Yu, J. J., Zhao, P., & Zhou, Z. J. (2013). Quality assessment of hourly merged precipitation product over China. *Transactions of Atmospheric Sciences, 36*(1), 37–46. (in Chinese)

Shoroshchan, S., Hsu, K. L., Gan, X., Gupta, H. V., Imam, B., & Brabham, D. (2000). Evaluation of PERSIANN system satellite-based estimates of tropical rainfall. *Bulletin of the American Meteorological Society, 81*(9), 2035–2046. https://doi.org/10.1175/1520-0477(2000)081<2035:EOAPST>2.0.CO;2

Sungmin, O., Ulrich, F., Gottfried, K., Juergen, F., Jackson, T., & Walter, A. (2017). Evaluation of GPM IMERG early, late, and final rainfall estimates using WegenerNet gauge data in southeastern Austria. *Hydrology and Earth System Sciences, 21*(12), 6559–6572.

Tan, M. L., & Duan, Z. (2017). Assessment of GPM and TRMM precipitation products over Singapore. *Remote Sensing, 9*(7), 720. https://doi.org/10.3390/rs9070720

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. https://doi.org/10.1016/j.atmosres.2017.11.006

Tang, G., Ma, Y., Long, D., Zhong, L., & Hong, Y. (2016). Evaluation of GPM Day-1 IMERG and TMPA Version 7 legacy products over Mainland China at multiple spatiotemporal scales. *Journal of Hydrology, 533*, 152–167. https://doi.org/10.1016/j.jhydrol.2015.12.008

Trenberth, K. E., Smith, L., Qian, T., Dai, A., & Fasullo, J. (2007). Estimates of the global water budget and its annual cycle using observational and model data. *Journal of Hydrometeorology, 8*(4), 758–769. https://doi.org/10.1175/JHM600.1

Villarini, G., & Krajewski, W. F. (2008). Empirically-based modeling of spatial sampling uncertainties associated with rainfall measurements by rain gauges. *Advances in Water Resources, 31*(7), 1015–1023. https://doi.org/10.1016/j.advwatres.2008.04.007

Wang, H., Chandrasekar, V., He, J., Shi, Z., & Wang, L. (2018). Characteristic analysis of the downburst in Greeley, Colorado on 30 July 2017 using WPEA method and X-band radar observations. *Atmosphere, 9*(9), 348. https://doi.org/10.3390/atmos9090348

Wang, H., He, J., Wei, M., & Zhang, Z. (2015). Synthesis analysis of one severe convection precipitation event in Jiangsu using ground-based GPS technology. *Atmosphere, 6*(7), 908–927. https://doi.org/10.3390/atmos6070908

Wang, H., Wei, F., Li, G., Zhou, S., & Zeng, Q. (2013). Analysis of precipitable water vapor from GPS measurements in Chengdu region: Distribution and evolution characteristics in autumn. *Advances in Space Research, 52*(4), 656–667. https://doi.org/10.1016/j.asr.2013.04.005

Wang, H., Wei, M., & Zhou, S. H. (2014). A feasibility study for the construction of an atmospheric precipitable water vapor model based on the neural network technology. *Desalination and Water Treatment, 52*(37–39), 7412–7421. https://doi.org/10.1080/19434944.2014.933041

Wang, Z., Zhong, R., Lai, C., & Chen, J. (2017). Evaluation of the GPM IMERG satellite-based precipitation products and the hydrological utility. *Atmospheric Research, 196*, 151–163. https://doi.org/10.1016/j.atmosres.2017.06.020
Wei, G., Lü, H., Crow, W. T., Zhu, Y., Wang, J., & Su, J. (2018). Comprehensive evaluation of GPM-IMERG, CMORPH, and TMPA precipitation products with gauged rainfall over Mainland China. Advances in Meteorology, 2018, 1–18. https://doi.org/10.1155/2018/3024190

Yuan, F., Zhang, L., Soe, K. M. W., Ren, L., Zhao, C., Zhu, Y., et al. (2019). Applications of TRMM-and GPM-era multiple-satellite precipitation products for flood simulations at sub-daily scales in a sparsely gauged watershed in Myanmar. Remote Sensing, 11(2), 140. https://doi.org/10.3390/rs11020140

Zhang, C., Chen, X., Shao, H., Chen, S., Liu, T., Chen, C., et al. (2018). Evaluation and inter-comparison of high-resolution satellite precipitation estimates—GPM, TRMM, and CMORPH in the Tianshan Mountain area. Remote Sensing, 10(10), 1543. https://doi.org/10.3390/rs10101543

Zhao, Y. (2015). A study on the heavy-rain-producing mesoscale convective system associated with diurnal variation of radiation and topography in the eastern slope of the western Sichuan plateau. Meteorology and Atmospheric Physics, 127(2), 123–146. https://doi.org/10.1007/s00703-014-0356-y

Zhu, X., Fraedrich, K., Liu, Z., & Blender, R. (2010). A demonstration of long-term memory and climate predictability. Journal of Climate, 23(18), 5021–5029. https://doi.org/10.1175/2010JCLI3370.1