Response to Review Comments

Re: Manuscript essd-2020-16

Earth System Science Data

2020-06-24

Dear Editor,

We would like to thank you and two reviewers for your valuable time and efforts in reviewing our manuscript and providing encouraging and constructive comments. We have revised the manuscript very carefully following all the comments. Below are our responses to each of the comments. The comments are in *italic* and each comment is followed by a response and a tracked change in the revised manuscript.

Please contact us if further information is requested. Thank you in advance.

Yours Sincerely,

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Reviewer #1:

General comment:

Comment 1: *Overall, I believe this is an excellent work, and will be a highly cited paper. The Upper Brahmaputra River Basin is a very important region to both China and South Asia, and is also an important region for studying the Tibetan Plateau, which is considered as 'The Water Tower of Asia'. The sparse gauge observation data in this region have caused troubles to many scientific studies. The academic community has been expecting a study to integrate various sources of data to develop a better datasets with high spatial and temporal resolutions. This paper fulfils this expectation. The authors used in situ gauge data and hydrological model simulation to evaluate the developed data. The approaches used are rigorous, and the results show the dataset is promising in water related studies. The presentation and literature review are also very good. This paper should be accepted.*

Response: Many thanks for your valuable time and efforts in reviewing our manuscript. We do appreciate your positive and encouraging comments.

Review #2:

General comment:

Comment 1: *In the paper, the authors integrated five satellite/reanalysis data to generate a new precipitation dataset set in the Yarlung Tsangpo basin in South Tibetan Plateau (TP). Actually, the issue is important for the hydrological studies in TP including this study area, but it is also a difficult issue, as there lacks enough observed data. The authors did a good try to generate this precipitation dataset, and it would be useful for the relevant studies in the basin. Overall, I suggest the authors consider more the following issues before its acceptance.*

Response: Many thanks for your constructive comments. We have revised the manuscript accordingly following your kind suggestions.

Detailed Comments:

Comment 1: *The authors assumed that daily precipitation conforms to a normal distribution. However, precipitation data generally follow skew distribution. The reasonability of this assumption should be discussed more.*

Response: Of course, the assumption of a normal distribution may lead to uncertainty when analyzing extremely high daily precipitation. Generally, the non-normal (skewed) distribution of precipitation is caused by the zero rainfall events at single observational site (Kumar et al., 2009; Semenov, 2008; Sloughter et al., 2007). We calculated the average values of the observed precipitation from 166 rain gauges to reduce the zero rainfall values. Another associated problem is the quantity and reliability of the data that are used to fit the distribution. If we use different probability distributions to describe the observed time series of daily precipitation, different extreme values may be obtained (Angelidis et al., 2012). This study provides a foundation from which further studies can be carried out to explore these aspects in more detail.

Change: We have added discussions and references in the revised manuscript (L360-L366).

Angelidis, P., Maris, F., Kotsovinos, N., and Hrissanthou, V.: Computation of Drought Index SPI *with Alternative Distribution Functions. Water Resour. Manage., 26(9), 2453-2473, 2012.*

Kumar, M.N., Murthy, C.S., Sai, M.V., and Roy, P.S.: On the use of Standardized Precipitation Index (SPI) for drought intensity assessment. Meteorol. Appl., 16(3), 381-389, 2009.

Semenov, M.A.: Simulation of extreme weather events by a stochastic weather generator. Clim. Res., 35(3), 203-212, 2008.

Sloughter, J.M., Raftery, A.E., Gneiting, T., and Fraley, C.: Probabilistic Quantitative Precipitation Forecasting Using Bayesian Model Averaging. Mon. Weather Rev., 135(9), 3209-3220, 2007.

Comment 2: *Some contents can be added to discuss more about the altitude effects on the quality of the new precipitation data, especially on the IDW practices, although some discussions have been given in Conclusions.*

Response: Thank you for the comments. Generally, these rain gauges were installed at relatively plain area, which may lead to large uncertainty in estimating precipitation (rain or snow) at high mountains, especially in the daily or finer time scales (Ahrens, 2006; Haiden and Pistotnik, 2009). This limitation can be even more severe, due to the orographic effect on precipitation rates, in mountainous regions and transition zones between the low and high altitudes, which will results in the underestimates of the actual basin-wide precipitation (Anders et al., 2006; Hashemi et al., 2020).

Regarding the IDW practices, on the one hand, most of the studied operational precipitation products have already dealt with the altitude effects during data production, and thereby we didn't repeatedly consider the altitude effects when interpolating and integrating these products into 5 km grids with the IDW method. On the other hand, the available gauges (number and distribution) are still far from enough to derive a reasonable spatial distribution of basin-wide altitude gradient for precipitation, due to the complex topography in the study area.

Change: We have added discussions and references in the revised manuscript (L347-L356).

Ahrens, B.: Distance in spatial interpolation of daily rain gauge data. Hydrol. Earth Syst. Sci., 10, 197-208, 2006.

Anders, A.M., Roe, G.H., Hallet, B., Montgomery, D.R., and Putkonen, J.: Spatial patterns of precipitation and topography in the himalaya. Geol. Soc. Am. Spec. Pap., 398, 39-53, 2006.

Haiden, T., and Pistotnik, G.: Intensity-dependent parameterization of elevation effects in precipitation analysis. Adv. Geosci., 33-38, 2009.

Hashemi, H., Fayne, J.V., Lakshmi, V., and Huffman, G.J.: Very high resolution, altitude-corrected, TMPA-based monthly satellite precipitation product over the CONUS. Sci. Data, 7(1), 2020.

Comment 3: *In lines 252-253, it is interesting to find that the weights become smaller with time periods, why? Is it due more reliable quality of the five datasets in recently years? or due to more observed data used? Some contents can be added to simply explain this.*

Response: We finally adopted the same weight of each product through the trial-and-error method. Table 1 lists the time ranges of different precipitation products, which are very different and lead to different weights during different periods. As a result, during 1981-1997 (only GLDAS, ITP-Forcing, MERRA2 are available), the weight of each product is 1/3. Similarly, during 1998-2007 and 2008-2016, the weights of each product are 1/4 and 1/5 respectively.

Table 1. The precipitation products used in this study.

Precipitation products	Time range	Temporal resolution	Spatial resolution
CMA gridded data	2008-2016	hourly	0.1°×0.1°
GLDAS	1981-2016	3-hour	0.25°×0.25°
ITP-Forcing	1981-2016	3-hour	0.1°×0.1°
MERRA2	1981-2016	hourly	0.5°×0.625°
TRMM	1998-2016	3-hour	0.25°×0.25°

Change: We add some description to explain the weight (L252-L257) in the revised manuscript.

Comment 4: *In Figure 6, does the P_int have similar PDF as the CMA? Why?*

Response: Yes, the PDF of the *P_int* is the closest to that of CMA. Parameters of the normal distribution for the *P_int* and the CMA data are also very similar, with a mean value of 77.0 and 75.3 mm, a standard deviation of 62.3 and 62.6 mm, respectively.

The advantage of the CMA product is that it has incorporated more gauge observations (including many unpublished ones of CMA). The short time duration may be the demerit of this product, since it is only available from 2008.

For our newly integrated data, we have incorporated valuable observational gauge data from Ministry of Water Resources (MWR), China. This greatly helps us to calibrate and validate the *P_int.*

Therefore, both of two data products have utilized lots of observational information (that provides the ground truth), which leads to the similar PDF.

Change: There is no change about this in the manuscript.

Comment 5: *This study area should be called "Yarlung Tsangpo" or "Yarlung Zangbo"? please check it.*

Response: This area can be called as "Yarlung Zangbo" or "Yarlung Tsangpo", both of which are acceptable since they are transliterated from Tibetan language (also mentioned in Abstract).

Changes: There is no change about this in the manuscript.

An integration of gauge, satellite and reanalysis precipitation datasets for the largest river basin of the Tibetan Plateau

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Abstract: As the largest river basin of the Tibetan Plateau, the Upper Brahmaputra River Basin (also called "Yarlung Zangbo" in Chinese) has profound impacts on the water security of local and downstream inhabitants. Precipitation in the basin is mainly controlled by the Indian Summer Monsoon and Westerly, and is the key to understand the water resources available in the basin; however, due to sparse observational data constrained by a harsh environment and complex topography, there remains a lack of reliable information on basin-wide precipitation (there are only nine national meteorological stations with continuous observations). To improve the accuracy of basin-wide precipitation data, we integrate various gauge, satellite and reanalysis precipitation datasets, including GLDAS, ITP-Forcing, MERRA2, TRMM and CMA datasets, to develop a new precipitation product for the 1981-2016 period over the Upper Brahmaputra River Basin, at 3-hour and 5-km resolution. The new product has been rigorously validated at different temporal scales (e.g. extreme events, daily to monthly variability, and long-term trends) and spatial scales (point- and basin-scale) with gauge precipitation observations, showing much improved accuracies compared to previous products. An improved hydrological simulation has been achieved (low relative bias: -5.94%; highest NSE: 0.643) with the new precipitation inputs, showing reliability and potential for multi-disciplinary studies. This new precipitation product is openly accessible at https://doi.org/10.5281/zenodo.3711155 (Wang et al., 2020) and, additionally at the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn, login required).

1. Introduction

Precipitation plays a very important role in the research of hydrology, meteorology, ecology, and even social economics, as it is a critical input factor for various models (e.g. hydrological and land surface models) (Qi et al., 2016; Wang et al., 2017a; Fang et al., 2019; Miri et al., 2019; Wang et al., 2019a). Specifically, precipitation is a key part of the water balance and energy cycle and will directly impact runoff generation and soil moisture movement (Su et al., 2008). As a result, water resource management tasks such as flood forecasting and drought monitoring, ecological environment restoration (e.g. vegetation growth and protection), and many other scientific and social applications are closely linked with precipitation patterns (Funk et al., 2015).

The Tibetan Plateau (TP), known as the highest plateau in the world, is covered by massive glaciers, snow and permafrost, which significantly affect the hydrological processes of all the large rivers that are fed by it; the Brahmaputra, the Salween, and the Mekong, among others. Therefore, it is necessary to explore the hydrological variations over the TP to achieve efficient utilization and protection of its water resources and a better understanding of the effects of climate change on the surrounding region. However, due to the irregular and sparse distribution of national meteorological stations, particularly in the Upper Brahmaputra (precipitation data from only nine stations are available, and are sparsely distributed; see Sang et al., 2016; Cuo et al., 2019), there are large data constraints on research on these hydrological processes and their responses to climate change. Although there are many more rain gauges managed by the Ministry of Water Resources (MWR), most of them are located in middle-stream regions and rainfall datasets are only recorded over short time periods. Simply using the linear mean of these station observations to calculate variations in precipitation for the entire basin is impractical and prone to problems (Lu et al., 2015). Accurate spatial distributions of precipitation are unavailable. This influences the generation of historical runoff data (Mazzoleni et al., 2019), meaning that the specific contributions of glaciers, snow cover, permafrost and vegetation to hydrological processes in this area cannot be analyzed and quantified, posing a threat to regional sustainable development and living conditions (Shen et al., 2010; Guo et al., 2016; Kidd et al., 2017; Shi et al., 2017; Ruhi et al., 2018; Sun et al., 2018).

A longer time series of spatially consistent and temporally continuous precipitation products could be used to improve our understanding of feedback mechanisms between different meteorological and hydrological components, especially under the background signal of climate change. Various satellite rainfall products have been widely used in previous studies, such as the National Oceanic and Atmospheric Administration/Climate Prediction Centre (NOAA/CPC) morphing technique (CMORPH) (Ferraro et al., 2000; Joyce et al., 2004), and the Tropical Rainfall Measuring Mission (TRMM) (Huffman et al., 2007). However, there are still problems in estimating daily (Meng et al., 2014; Bai and Liu, 2018) and extreme precipitation (Funk et al., 2015; Zhou et al., 2015b; Fang et al., 2019), especially in mountainous regions with high elevations and fewer ground measurements, such as the Upper Brahmaputra (Xia et al., 2015; Xu et al., 2017; Qi et al., 2018). Additionally, there are several reanalysis datasets that have been widely used by researchers, such as the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004; Zaitchik et al., 2010; Wang et al., 2011) and the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA2) dataset (Gelaro et al., 2017; Reichle et al., 2017a, 2017b). Evaluation of GLDAS data has generally been limited to the United States and other regions with adequate ground observations (Kato et al., 2007; Qi et al., 2016). Most studies have focused on evapotranspiration, soil moisture and groundwater products derived from GLDAS or MERRA2 (Bibi et al., 2019; Deng et al., 2019; Li et al., 2019a); meanwhile, to the best of our knowledge, there has been less focus on the evaluation of methods of precipitation estimation and little work on the corresponding river discharge simulations within the Upper Brahmaputra River Basin. These precipitation products generally have the advantage of wide and consistent coverage and have shown great potential in many applications (Li et al., 2015; Zhang et al., 2017; Fang et al., 2019), but also suffer from large uncertainties over the Upper Brahmaputra River Basin due to indirect observations, insufficient gauge calibration, and complex topography (Tong et al., 2014; Yong et al., 2015; Xu et al., 2017).

In this study, we focus on integrating gauge, satellite and reanalysis precipitation datasets to generate a new dataset over the Upper Brahmaputra, suitable for use in hydrological simulations and other scientific researches related to climate change. The remainder of this study is structured as follows. Section 2 briefly describes the study area, datasets, and methodology used. Section 3 presents and discusses the evaluation results of different products and validates the accuracy and reliability of our integrated dataset. Then Section 4 is the data availability. Finally, conclusions are given in Section 5.

2. Materials and Methods

2.1. Study Area

This study is conducted in Upper Brahmaputra River Basin (27°-32°N, 81°-98°E) located in the south of the Tibetan Plateau (Figure 1). The Brahmaputra River is an important part of the whole GBM basin (Ganges, Brahmaputra, Meghna) which significant influences the natural resources and social development of the Tibetan Plateau and South Asia. The river is approximately 2,057 km long with a drainage area of 240,000 km^2. The climatic conditions are complicated by the extremely high altitude and highly varying topography (Wang et al., 2018; Wang et al., 2019b); elevation varies by up to 6,500 m throughout the study region. Generally, the intra-annual distribution of precipitation is extremely uneven, with more precipitation distributed in the warm seasons (Wang et al., 2019a). Since the Indian and East Asian monsoons bring more water vapor in summer and the westerlies dominate in winter (Yi et al., 2013; Wang et al., 2018; Li et al., 2019a, 2019b), there is a declining trend of precipitation from the humid southeast to the arid northwest, on average. In recent decades, the TP has been experiencing a significant warming trend exceeding that in the Northern Hemisphere (Liu and Chen, 2000; Yang et al., 2014), which will affect the generation and distribution of precipitation and influence hydrological processes throughout the Upper Brahmaputra.

2.2. Datasets

Monthly precipitation data (1981-2016) from nine meteorological stations were obtained from the China Meteorological Administration (CMA), and daily precipitation data (May to October in 2014 and 2016) from166 rain gauges were accessed through the Ministry of Water Resources (MWR), China (Figure 1). Both of these are regarded as observed precipitation data. Daily river discharge data at Nuxia station (Figure 1) are used to assess the simulation performance when forced by different precipitation products.

In this study, we chose five types of satellite and reanalysis precipitation products (Table 1). We, first, evaluated their performance at detecting precipitation, and second, integrated them to generate a better product, designed to enhance the strengths of each product.

The three satellite and reanalysis data products, GLDAS, MERRA2 and TRMM, were acquired from the National Aeronautics and Space Administration (NASA) website (https://disc.gsfc.nasa.gov/). GLDAS ingests satellite- and ground-based observational data products and applies advanced land surface modeling and data assimilation techniques (Rodell et al., 2004; Zaitchik et al., 2010; Xia et al., 2019); it has been widely used for river discharge simulations, groundwater monitoring and many other fields (Wang et al., 2011; Chen et al., 2013; Qi et al., 2018; Verma and Katpatal, 2019). MERRA2 is the first long-term global reanalysis dataset to assimilate space-based observations of aerosols and represent their interactions alongside other physical processes in the climate system (Marquardt Collow et al., 2016; Reichle et al., 2017a, 2017b), and TRMM is a joint mission between the NASA and the Japan Aerospace Exploration Agency (JAXA) to study rainfall for weather and climate research (Xu et al., 2017; Ali et al., 2019; Wang et al., 2019a). The ITP-Forcing dataset has been developed by the hydrometeorological research group at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (He, 2010), and has been shown to perform well on the TP (Yang et al., 2010; Chen et al., 2011). These data were downloaded from the Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn/).

2.3. Methods

In this study, because of the different spatial resolutions of different products, we extracted the precipitation values from each product according to the locations of the gauges to generate product-gauge data pairings for evaluation. Where there are at least two gauges in the pixel of one product, we used the average value of the gauges to evaluate the performance of the corresponding precipitation product data.

To ensure the consistency of different products, we interpolated all the products into the same 5 km spatial resolution grid using the inverse distance weighted (IDW) method (Ma et al., 2019; Qiao et al., 2019; Sangani et al., 2019) and calculated them at 3-hourly resolution. Due to its good performance on the TP, we then used the ITP-Forcing data (1981-2016) to derive the multi-year mean 3-hour data as background climatological precipitation. Then, the precipitation anomalies between CMA, GLDAS, ITP-Forcing, MERRA2, TRMM and the background were calculated 3-hourly, using:

$$
\begin{aligned}
\varepsilon_c &= P_C - P_B \\
\varepsilon_g &= P_G - P_B \\
\varepsilon_i &= P_I - P_B \\
\varepsilon_m &= P_M - P_B \\
\varepsilon_t &= P_T - P_B
\end{aligned} \tag{1}
$$

where P_B, P_C, P_G, P_I, P_M, P_T represent the background precipitation and different products, respectively, and ε denotes the corresponding precipitation anomalies. Considering different weights for these anomalies, we combined the background precipitation with these anomalies,

$$P\_int = P_B + w_1\varepsilon_c + w_2\varepsilon_g + w_3\varepsilon_i + w_4\varepsilon_m + w_5\varepsilon_t \tag{2}$$

where w represents the weight for each anomaly and *P_int* refers to the new integrated precipitation at 5 km and 3-hourly resolution.

After *P_int* was acquired, we corrected its probability distribution function (PDF) based on the rain gauges, and undertook several validation steps for spatial distribution and at different time scales (e.g. extreme events, seasonal to inter-annual variability, and long-term trends). At the same time, we also analyzed the changing trend over the 36 years, and the extremely high precipitation events during the warm months in 2014 and 2016. In order to identify the extreme events, we first assumed that daily precipitation conforms to a normal distribution. From this we calculated a threshold, above which the probability of precipitation values occurring is less than 0.05 (e.g. Fang et al., 2019 use 0.1). We considered events with precipitation values above this threshold as extreme events.

$$P\left(precipitation \geq threshold\right) \leq 0.05 \tag{3}$$

where P denotes the probability. Finally, based on the observed discharge data at

Nuxia Station, we compared the simulated daily discharges (normalized) from 2008 to 2016 using a water and energy budget-based distributed hydrological model (WEB-DHM) to check the accuracy and reliability of our integrated precipitation. Evaluation criteria used in the discharge error assessment include relative bias (RB) and the Nash-Sutcliffe coefficient of efficiency (NSE).

$$Q_{normalized} = \frac{Q - \min Q_{obs}}{\max Q_{obs} - \min Q_{obs}} \tag{4}$$

$$RB = \frac{\sum_{i=1}^{n} Q_{sim} - \sum_{i=1}^{n} Q_{obs}}{\sum_{i=1}^{n} Q_{obs}} \times 100\% \tag{5}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(Q_{obs} - Q_{sim}\right)^2}{\sum_{i=1}^{n} \left(Q_{obs} - \overline{Q_{obs}}\right)^2} \tag{6}$$

Where $Q_{normalized}$, Q_{obs}, Q_{sim} represent the normalized discharge, observed discharge, and simulated discharge, respectively. The perfect value of *RB* is 0 and that of *NSE* is 1. More information about this model can be found in many studies (Wang et al., 2009; Wang and Koike, 2009; Xue et al., 2013; Zhou et al., 2015a; Wang et al., 2016; Wang et al., 2017a). Figure 2 shows the flowchart of this study and Figure 3 presents the final spatial distribution of our integrated product.

3. Results and Discussion

3.1. Evaluation of precipitation products at the basin and grid scale

Figures 4 and 5 analyze the overall regime of different precipitation products at the basin scale. Figure 4 is the spatial distribution in warm (May to Oct.) and cold

(Nov. to Apr.) months, and Figure 5 presents the time series of basin-averaged annual and monthly precipitation values. The spatial pattern indicates that more precipitation occurs in warm seasons and less in cold seasons. During the warm months, GLDAS and TRMM present obvious regional differences between upstream and downstream, while CMA gridded data show the lesser values in the upstream source region. In the cold seasons, all products present almost the same pattern, among which MERRA2 gives the lowest precipitation values.

For annual precipitation, CMA, ITP-Forcing and MERRA2 show similar characteristics (annual mean value: 615 mm, 550 mm and 506 mm, respectively), while GLDAS and TRMM are 789 mm and 757 mm, respectively. There are also significant (p < 0.01) increasing trends in annual precipitation of GLDAS, ITP-Forcing, and MERRA2 (6.42, 3.28, 4.68 mm/year, respectively) over the 36 years of the data. For monthly precipitation, GLDAS and TRMM greatly overestimate summer precipitation compared to the others, which explains why these two products give anomalously high annual values (nearly 200 mm greater than the other three data products). On the other hand, the monthly variations indicate that the intra-annual distribution of precipitation is extremely uneven.

Figures 6 and 7 compare the accuracy of monthly rainfall from different products at the grid scale. Due to the coarse spatial resolution of MERRA2 (0.5°×0.625°), there are fewer product-gauge data pairings available for evaluation. All the products show similar correlation relationships with the observations, with most rain gauges overestimating monthly precipitation (Figure 7). The highest correlation coefficient is

0.63 (MERRA2) and the lowest is 0.51 (GLDAS). The PDFs, however, show different characteristics (Figure 6). The CMA data are more consistent with the gauge data, while GLDAS and TRMM exhibit clear overestimations. As for ITP-Forcing, its precipitation is more concentrated on the average value, as indicated by the narrow curve.

3.2. Integration of precipitation products and validation of *P_int*

3.2.1. Integration of precipitation products and validation against different time series

Figure 3 presents the spatial distribution of annual and seasonal precipitation estimated by our integrated dataset, which shows a declining trend from the southeast to northwest. Figure 5 then compares the monthly and annual precipitation calculated from our integrated dataset with the satellite and reanalysis products. As discussed in Section 2.3, we interpolated all the products into a spatial resolution of 5 km using the IDW method, and calculated them at a temporal resolution of 3 hours. Comparing different weights for the anomalies mentioned in Equation 2, we finally adopted the same weight for each product and the sum of the weights is 1 (w = 1/3 from 1981 to 1997; w = 0.25 from 1998 to 2007; w = 0.2 from 2008 to 2016) to develop the new product. We made the integrated precipitation data using equal weights essentially according to the number of available precipitation products at different time periods (Table 1). Then we corrected the PDF of the newly integrated data based on the rain gauge observations (Figure 6).

After *P_int* was derived, we first validated its performance against short time series (Figure 8). *P_int* shows optimal performance at detecting daily precipitation with the correlation coefficients of 0.43 in 2014 and 0.55 in 2016. In 2014, the average bias is 0.20 mm and the root mean square error (RMSE) is 4.18 mm. *P_int* successfully captures the daily variation of precipitation except for late September and early October. For 2016, the average bias and RMSE are -0.006 mm and 2.62 mm, respectively, much better than those for 2014.

We then check the spatial distribution of *P_int* from May to October in 2014 and 2016 (Figure 9). Every rain gauge is compared with its corresponding grid in *P_int* to explore the spatial heterogeneity. *P_int* well reproduces the precipitation pattern described by less rain in the upstream (western) regions and more rain in the downstream (eastern) regions. Meanwhile, abundant rainfall occurs in summer, particularly for July.

Building on this, further validation was undertaken against a long time series. We chose the average monthly precipitation from the nine meteorological stations as the evaluation standard against which to assess *P_int* (Figure 10). The PDF of *P_int* is consistent with that of the station data, which indicates that the mean value and standard deviation of *P_int* are much closer to the observed value (Figure 10a). Similar to the short time series, the average bias (-4.50 mm) and the RMSE (13.6 mm), especially with respect to the correlation coefficient (0.96), prove that the *P_int* is applicable and reliable.

3.2.2. Trend and extreme events analysis compared across different precipitation products

The trend analysis (Figure 11) over 36 years indicates that there are different patterns of precipitation in different seasons and different regions. In summer, there are more complicated trends, as the variations between up and down stream differ greatly. On the contrary, trends of winter precipitation values over most of the study region vary by merely ±2 mm/year, illustrating that precipitation in winter generally remains unchanged or experiences minimal change. To find if *P_int* is able to reflect the true varying trend, we added a comparison between meteorological stations (triangles in Figure 11 and their direction represent the true trend) and precipitation products. For observed annual precipitation, all the stations give an insignificant increasing trend, except for Bomi station, which is located in the easternmost part of the study region. For seasonal precipitation, different stations present different patterns. As a result, *P_int* appears to reflect the changing pattern of more stations than any other product, with the exception of the ITP-Forcing dataset on an annual timescale or over autumn (Figure 12).

We notice that there is increasing trend in annual precipitation almost in the whole basin for *P_int*; only precipitation in the midstream area near the Himalaya mountains and small part of the upstream region are decreasing. Moreover, the majority of the increased precipitation in the downstream regions occurs over spring and summer, with only slight changes found in autumn and winter.

After the volume, the spatial distribution, and the trend of *P_int* at different time scales were completely verified, we continued to inspect if *P_int* could capture the extreme events from May to October in 2014 and 2016 according to the rain gauge data (Figure 13). There are 27 days in total (19 days in 2014 and 8 days in 2016) when extremely high daily precipitation occurred. All the products are comparable with each other in underestimating the frequency of extreme events. Nine days are identified out of the *P_int* data, lesser only to the number of days detected by ITP-Forcing (11 days).

3.2.3. Evaluation of daily discharges simulated by different precipitation products

All the comparison and validation steps undertaken above support the accuracy and reliability of our integrated dataset. Furthermore, Figure 14 indicates the superior suitability and application of *P_int* in hydrological simulation and investigation, with an RB of -5.94% and an NSE of 0.643 (the highest). We simulate the daily discharge of Nuxia station using the various precipitation datasets as the input with the same initial conditions and physical parameters. All products overestimate the daily discharge, except for *P_int* (-5.94%) and MERRA2 (-2.24%). In terms of NSE, *P_int* (0.643), ITP-Forcing (0.543) and MERRA2 (0.544) are higher than others, explaining their better simulation performance. GLDAS and TRMM offer the worst performance in discharge simulation, which is consistent with their overestimation of precipitation in summer (Figure 5). This indicates that these datasets should be corrected when undertaking hydrological research over the Upper Brahmaputra.

4. Data availability

This high spatiotemporal resolution (5km, 3h) precipitation dataset over the Upper Brahmaputra River Basin from 1981 to 2016 is freely available at https://doi.org/10.5281/zenodo.3711155 (Wang et al., 2020), which can be downloaded in TXT format.

5. Conclusion

In order to acquire suitable and accurate precipitation datasets which are helpful in hydrology, meteorology and other scientific research over the Upper Brahmaputra, we produced a new precipitation product by integrating gauge, satellite and reanalysis precipitation datasets to reduce the uncertainties associated with a single product and limitation of few observation stations. Our integrated dataset performs better than the input datasets in estimating daily and monthly precipitation, describing the spatial heterogeneity, capturing variation trends and extreme events and simulating river discharges. Furthermore, it is successful in reproducing daily precipitation variation, with smaller average biases (0.2 mm in 2014 and -0.006 mm in 2016) and RMSE values (4.18 mm in 2014 and 2.62 mm in 2016). Monthly precipitation shows higher correlation coefficients with the in-situ data for various time series (0.69 for all the rain gauges in the warm months of 2014 and 2016; 0.86 for the nine meteorological stations over 1981-2016). This high spatio-temporal resolution assures us that we can use this new dataset to explore more detailed physical processes and further understand the impacts of climate change on the water resources of the Upper Brahmaputra River Basin, and we are confident that our precipitation dataset will greatly assist future research in this basin.

With this in mind, we note some aspects of this study that deserve further consideration. The effect of altitude on precipitation has not been taken into account in the development of this dataset. The 166 rain gauges used in this paper, are all located at the elevations above 3500 m, except for several eastern gauges. Generally, these gauges were installed at relatively plain area, which may lead to large uncertainty in estimating precipitation (rain or snow) at high mountains, especially in the daily or finer time scales (Ahrens, 2006; Haiden and Pistotnik, 2009). This limitation can be even more severe, due to the orographic effect on precipitation rates, in mountainous regions and transition zones between the low and high altitudes, which will result in the underestimates of the actual basin-wide precipitation (Anders et al., 2006; Hashemi et al., 2020). Increasing the density and the distribution area of observational stations can directly weaken this altitude effects. We also note uncertainties that may arise from the re-gridding of the remotely sensed datasets in order to pair with the in-situ gauge data. In addition, the assumption of normal distribution when analyzing extremely high daily precipitation can also lead to uncertainty. Generally, the non-normal (skewed) distribution of precipitation is caused by the zero rainfall events at single site (Kumar et al., 2009; Semenov, 2008; Sloughter et al., 2007). An associated problem is the quantity and reliability of the data used to fit the distribution. Different probability distributions are used to describe the observed time series of daily precipitation, then different extreme values may be obtained (Angelidis et al., 2012). This study provides a foundation from which further studies can be carried out to explore these aspects in more detail.

In the future, more studies are needed to validate the method and data in regions with complex topography and climatic conditions, and to further improve the retrieval algorithm. This will greatly benefit hydrological applications, especially in areas with sparse and irregular observation networks. Furthermore, no products used in this study accurately represent extreme precipitation events, thus, it is necessary to improve the ability of all of these products to capture extreme events.

Acknowledgments

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Conflicts of Interest

The authors declare no conflicts of interest.

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Table and figure captions

Table 1. The precipitation products used in this study.

Figure 1. The Upper Brahmaputra River Basin originates from the Tibetan Plateau (TP) with the spatial distribution of nine meteorological stations from the China Meteorological Administration (CMA) and 166 rain gauges from Ministry of Water Resources (MWR), China. The green arrow indicates the direction of the westerlies, the Indian monsoon and the East Asian monsoon. The elevation data was obtained from the SRTM DEM datasets (www.earthexplorer.usgs.gov).

Figure 2. The flowchart used to produce the spatio-temporal continuous precipitation dataset (*P_int*).

Figure 3. The spatial distribution of *P_int* (mm) averaged from 1981 to 2016 (a. annual; b. seasonal).

Figure 4. The spatial distribution of different precipitation products during the warm season (May to October) and the cold season (November to April) averaged from 2008 to 2016.

Figure 5. Variations in basin-averaged precipitation from multi-year monthly mean values (top), annual values (middle) and monthly values (bottom) for the different products.

Figure 6. A comparison of the probability distribution function (PDF) between all the monthly observations and different precipitation products in the warm seasons (May to October in 2014 and 2016).

Figure 7. As for Figure 6 but with scatter plots.

Figure 8. A validation of *P_int* against short time series by comparing with daily gauge-averaged precipitation from May to October in 2014 and 2016.

Figure 9. A validation of *P_int* (mm) against short time series: spatial distribution of the observations and corresponding grids in *P_int* from May to October in 2014 and 2016.

Figure 10. A validation of *P_int* against a long time series: (a). PDF and scatter plots for monthly precipitation at nine CMA stations, (b). station-averaged monthly precipitation from 1981 to 2016.

Figure 11. A trend analysis of the annual and seasonal precipitation (a: annual; b: spring; c: summer; d: autumn; e: winter) over 36 years (1981-2016) between *P_int*, GLDAS, ITP-Forcing and MERRA2. The triangles represent the observed trend of the corresponding meteorological stations.

Figure 12. The number of meteorological stations (total of nine) which present the same trends as the different precipitation products, according to Figure 11.

Figure 13. A comparison of extreme events, as captured by different precipitation products.

Figure 14. An evaluation of simulated daily discharge at Nuxia station from 2008 to 2016 forced by different precipitation products. All the discharge values have been normalized.

Table 1. The precipitation products used in this study.

Precipitation products	Time range	Temporal resolution	Spatial resolution
CMA gridded data	2008-2016	hourly	0.1°×0.1°
GLDAS	1981-2016	3-hour	0.25°×0.25°
ITP-Forcing	1981-2016	3-hour	0.1°×0.1°
MERRA2	1981-2016	hourly	0.5°×0.625°
TRMM	1998-2016	3-hour	0.25°×0.25°

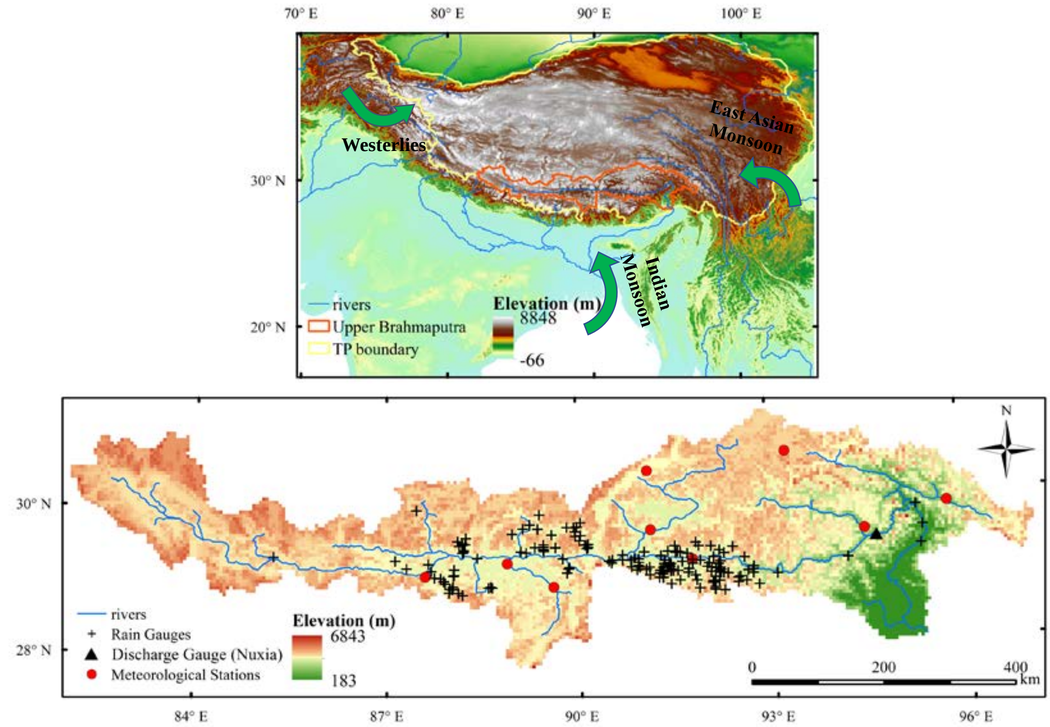

Figure 1. The Upper Brahmaputra River Basin originates from the Tibetan Plateau (TP) with the spatial distribution of nine meteorological stations from the China Meteorological Administration (CMA) and 166 rain gauges from Ministry of Water Resources (MWR), China. The green arrow indicates the direction of the westerlies, the Indian monsoon and the East Asian monsoon. The elevation data was obtained from the SRTM DEM datasets (www.earthexplorer.usgs.gov).

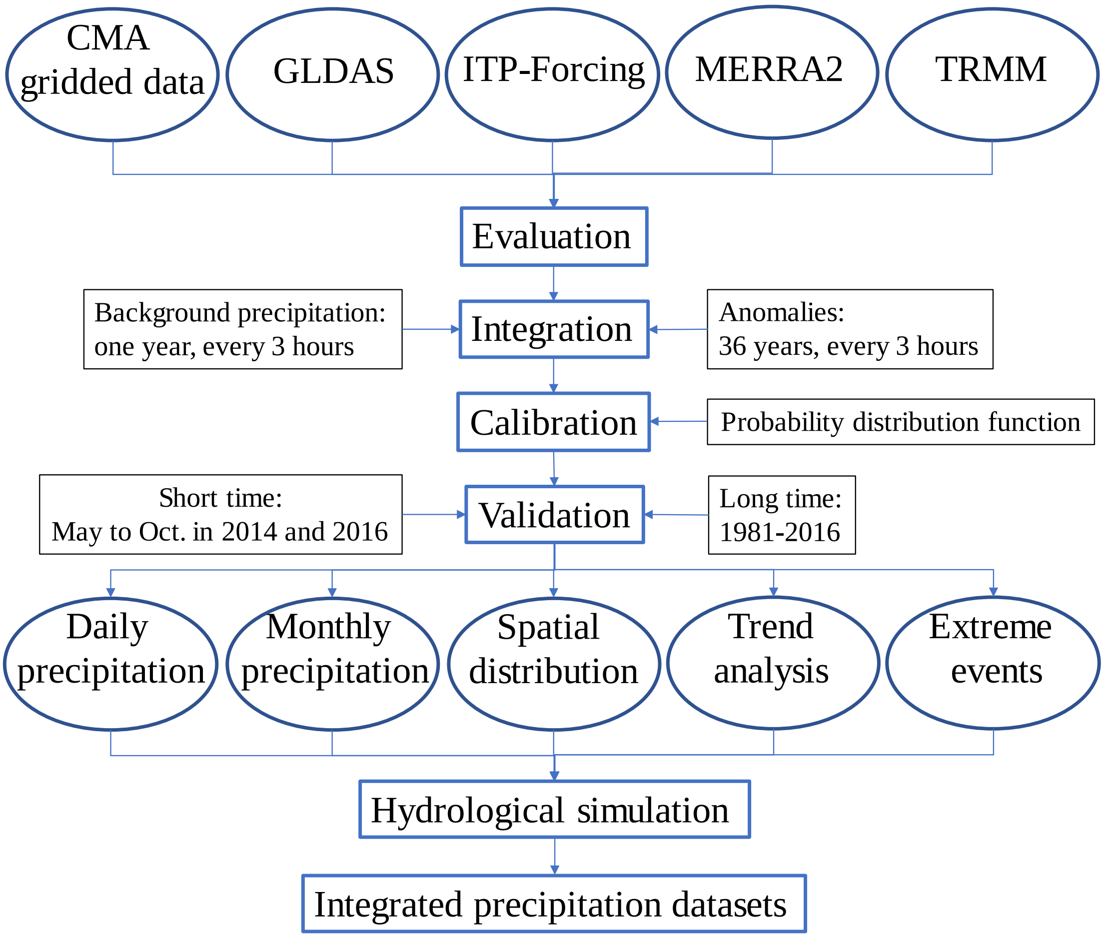

Figure 2. The flowchart used to produce the spatio-temporal continuous precipitation dataset (*P_int*).

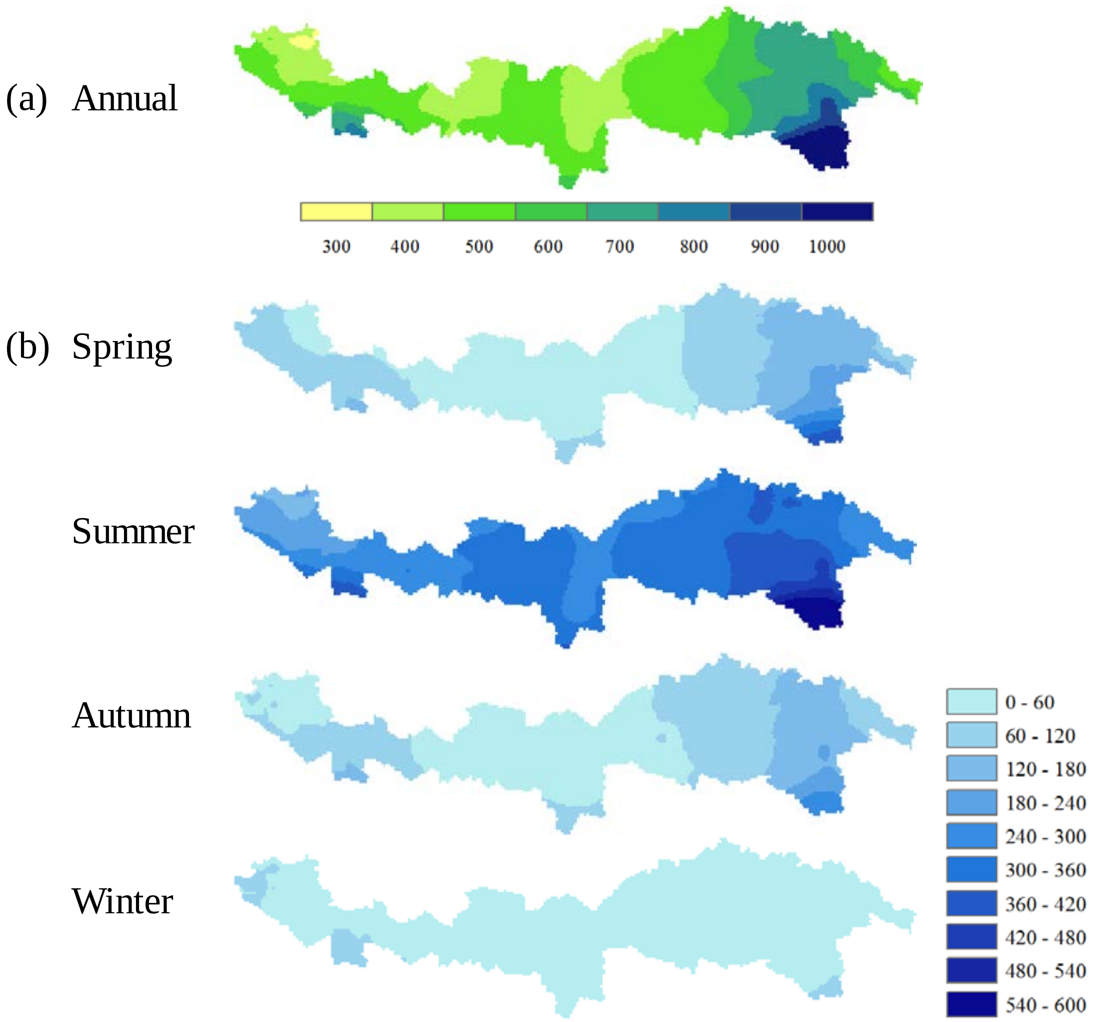

Figure 3. The spatial distribution of *P_int* (mm) averaged from 1981 to 2016 (a. annual; b. seasonal).

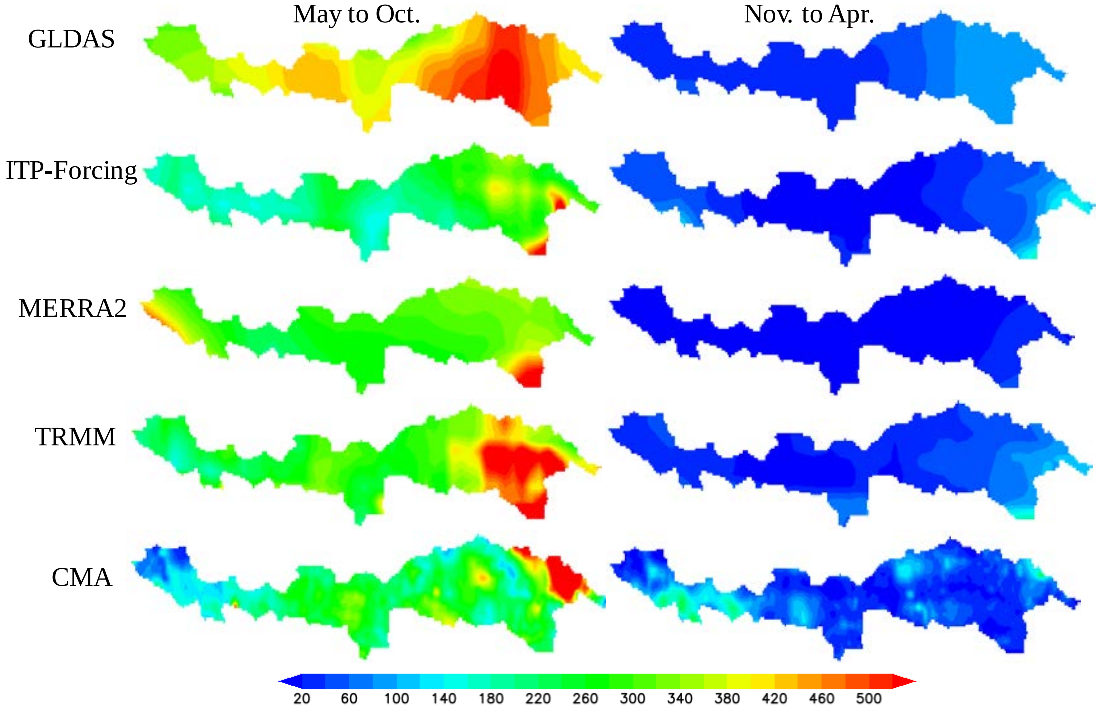

Figure 4. The spatial distribution of different precipitation products during the warm season (May to October) and the cold season (November to April) averaged from 2008 to 2016.

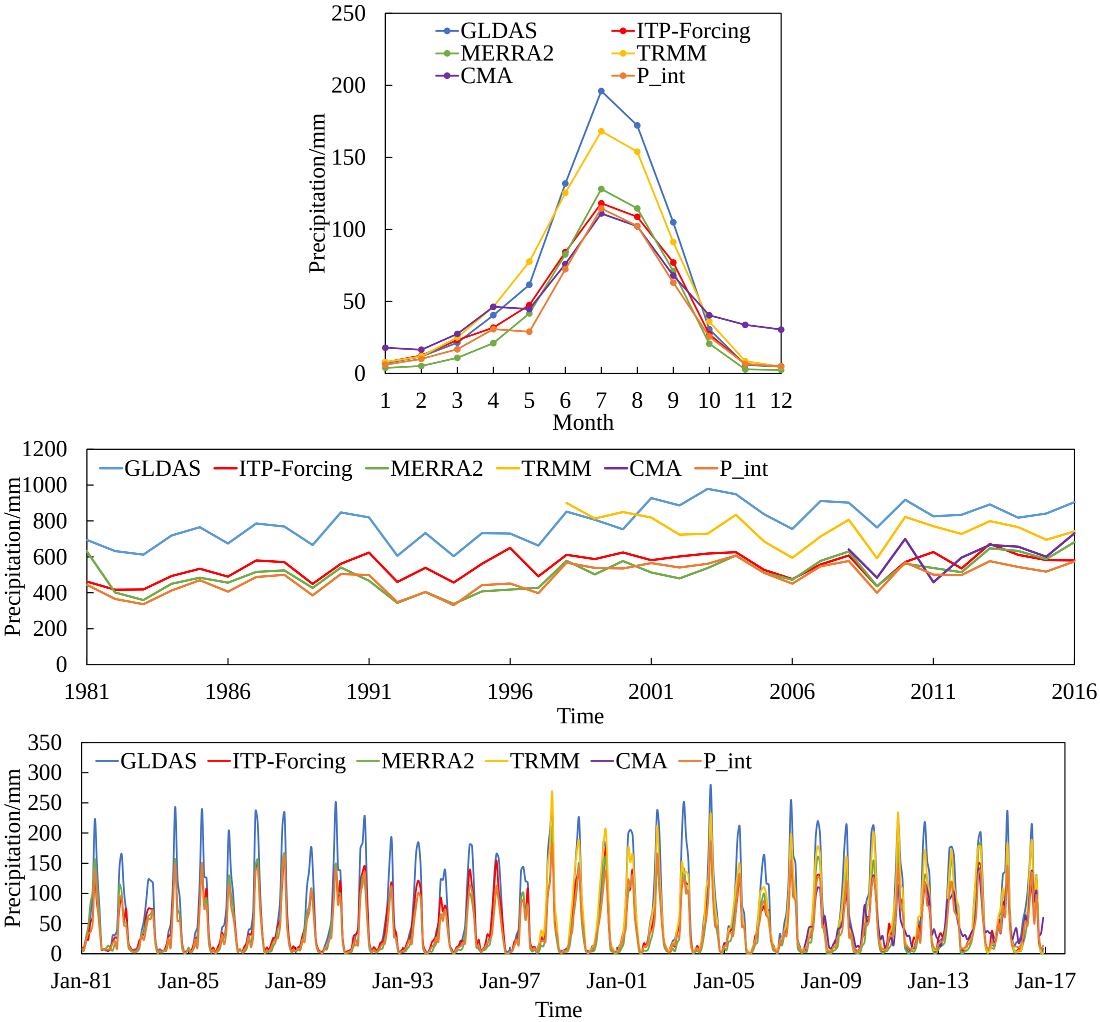

Figure 5. Variations in basin-averaged precipitation from multi-year monthly mean values (top), annual values (middle) and monthly values (bottom) for the different products.

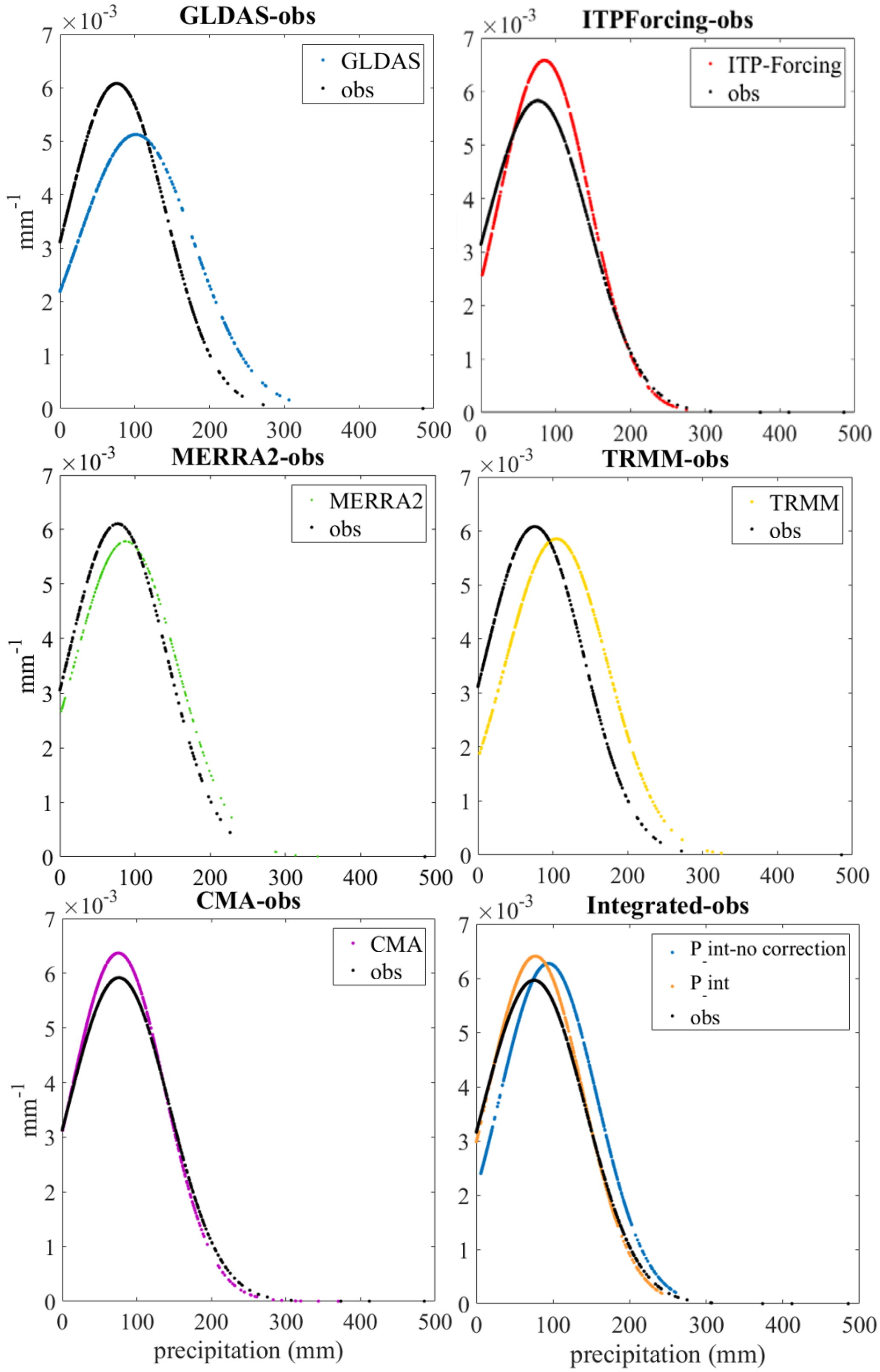

Figure 6. A comparison of the probability distribution function (PDF) between all the monthly observations and different precipitation products in the warm seasons (May

to October in 2014 and 2016).

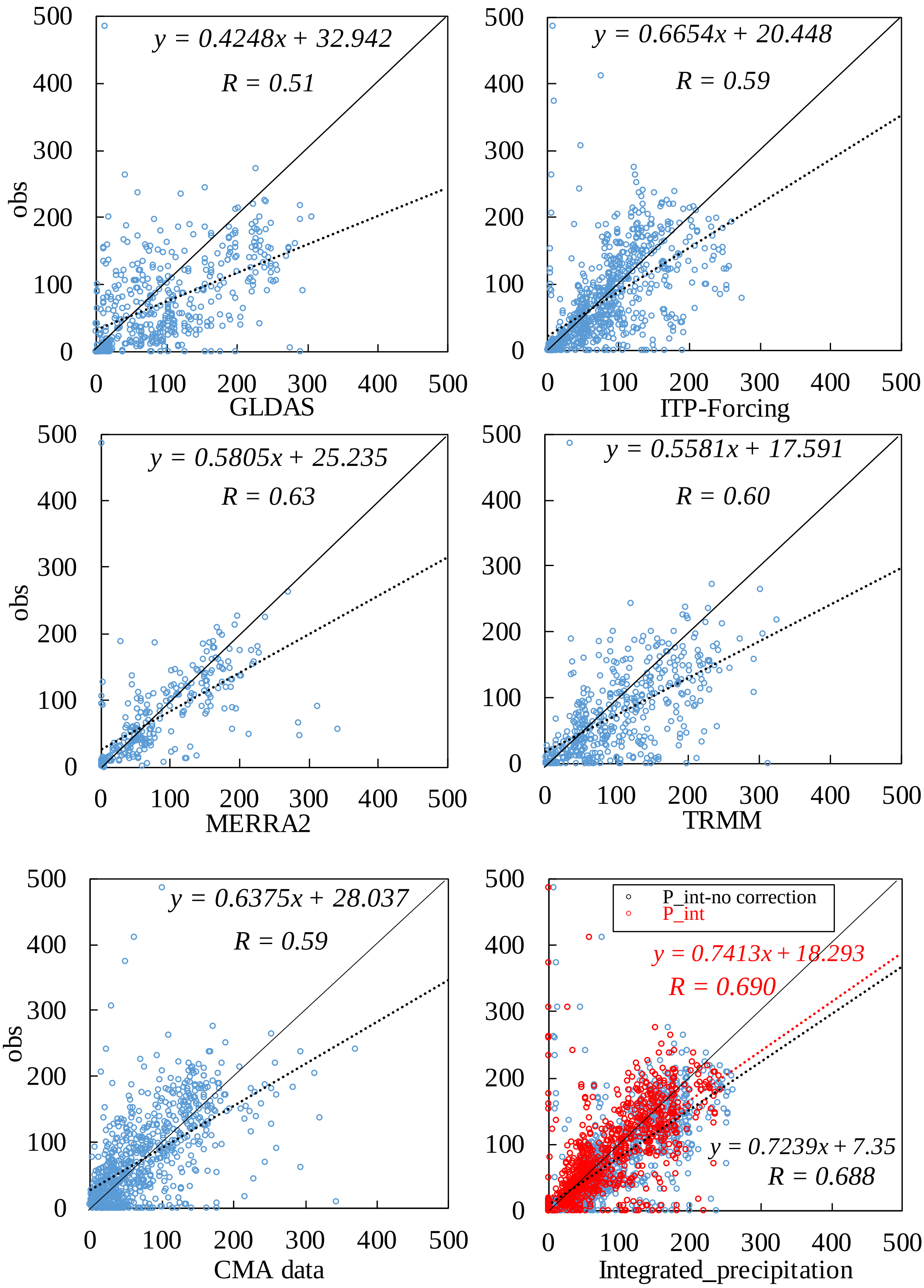

Figure 7. As for Figure 6 but with scatter plots.

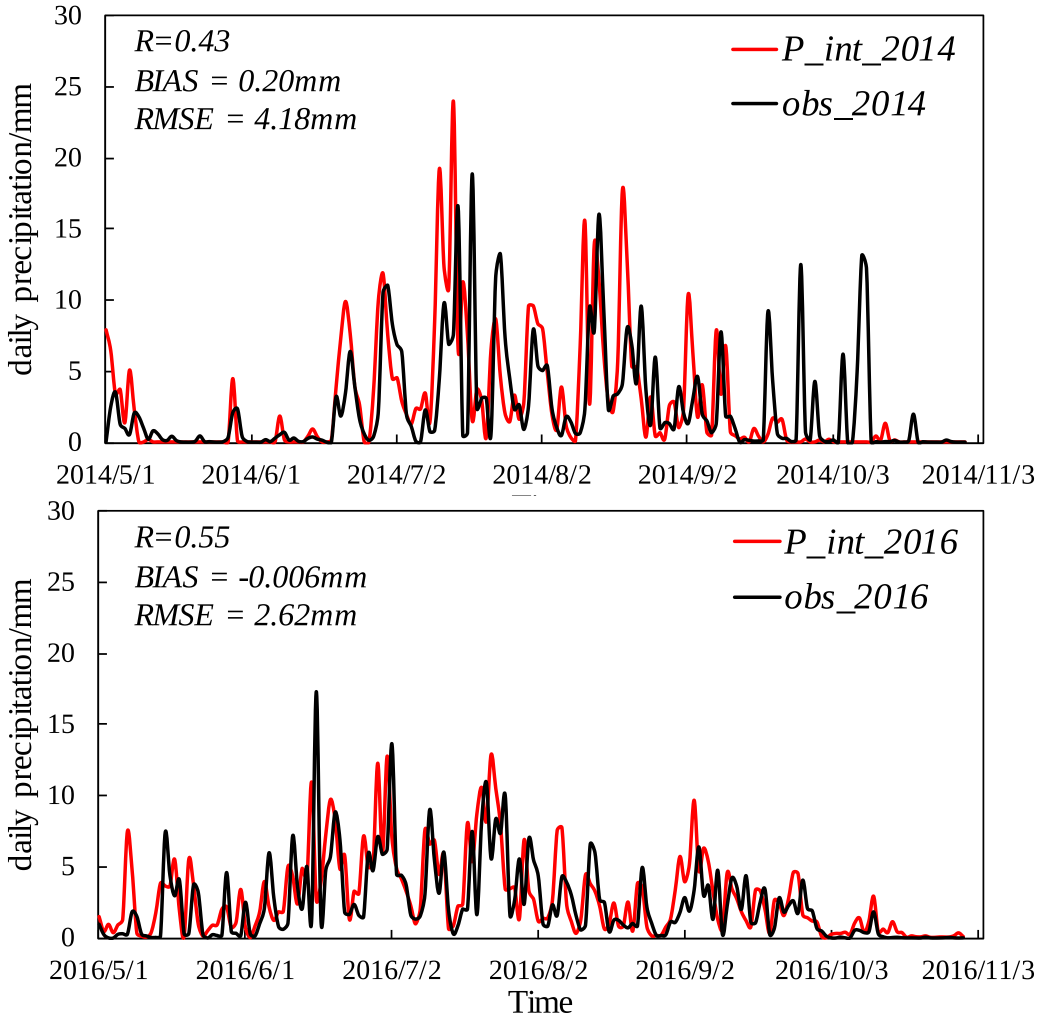

Figure 8. A validation of *P_int* against short time series by comparing with daily gauge-averaged precipitation from May to October in 2014 and 2016.

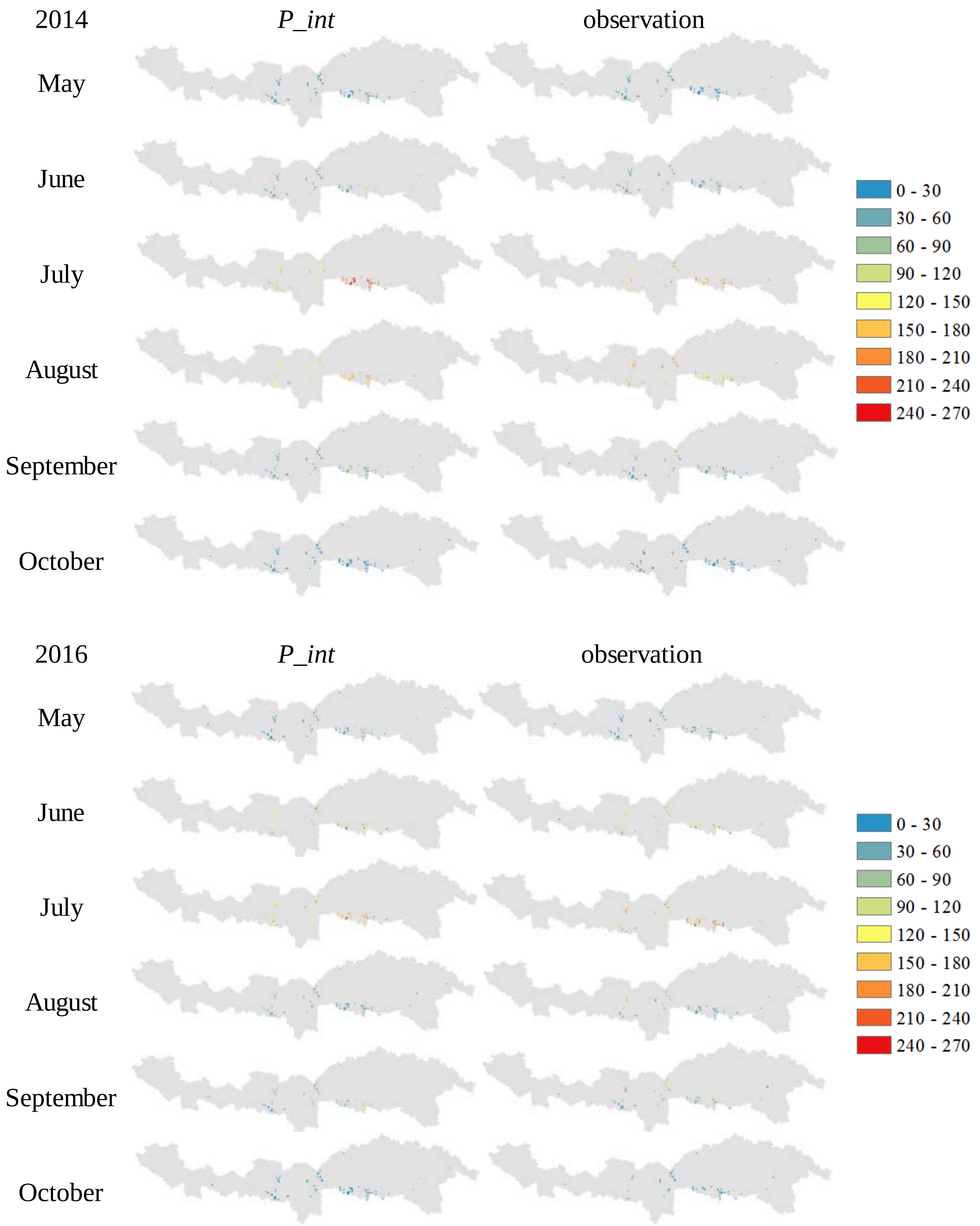

Figure 9. A validation of *P_int* (mm) against short time series: spatial distribution of the observations and corresponding grids in *P_int* from May to October in 2014 and 2016.

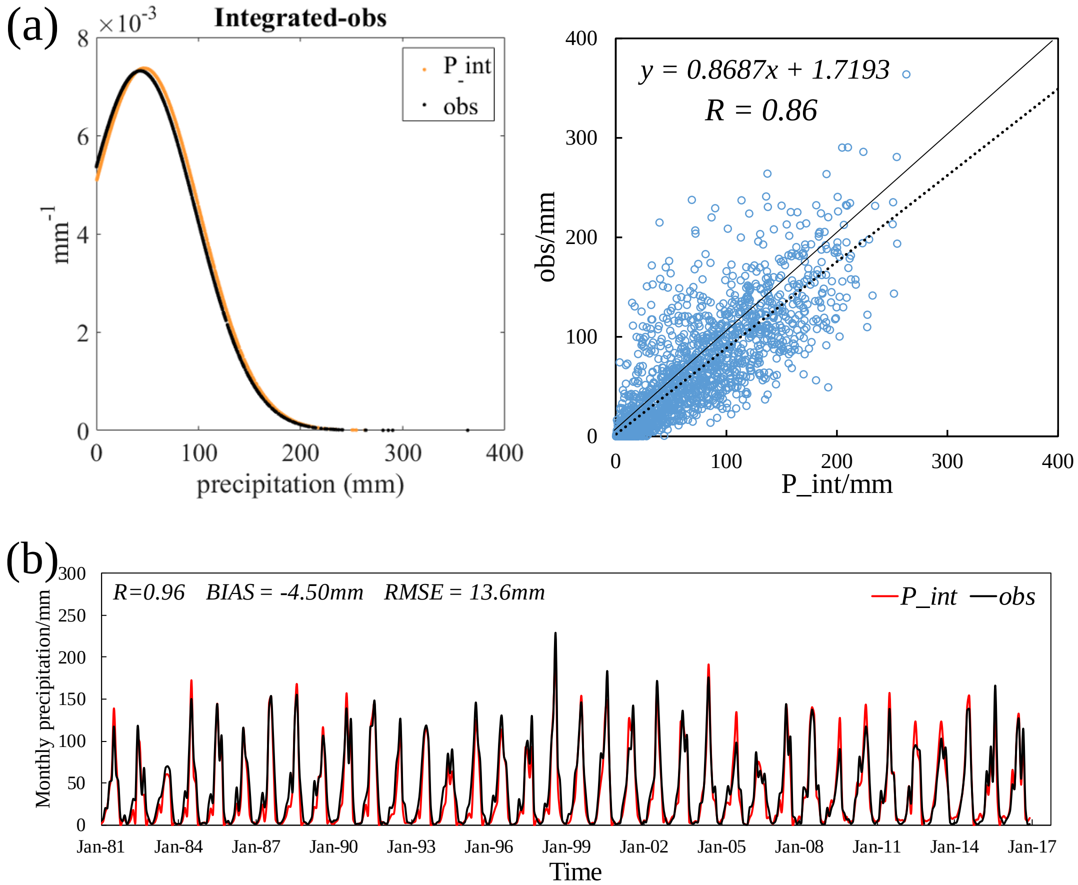

Figure 10. A validation of *P_int* against a long time series: (a). PDF and scatter plots for monthly precipitation at nine CMA stations, (b). station-averaged monthly precipitation from 1981 to 2016.

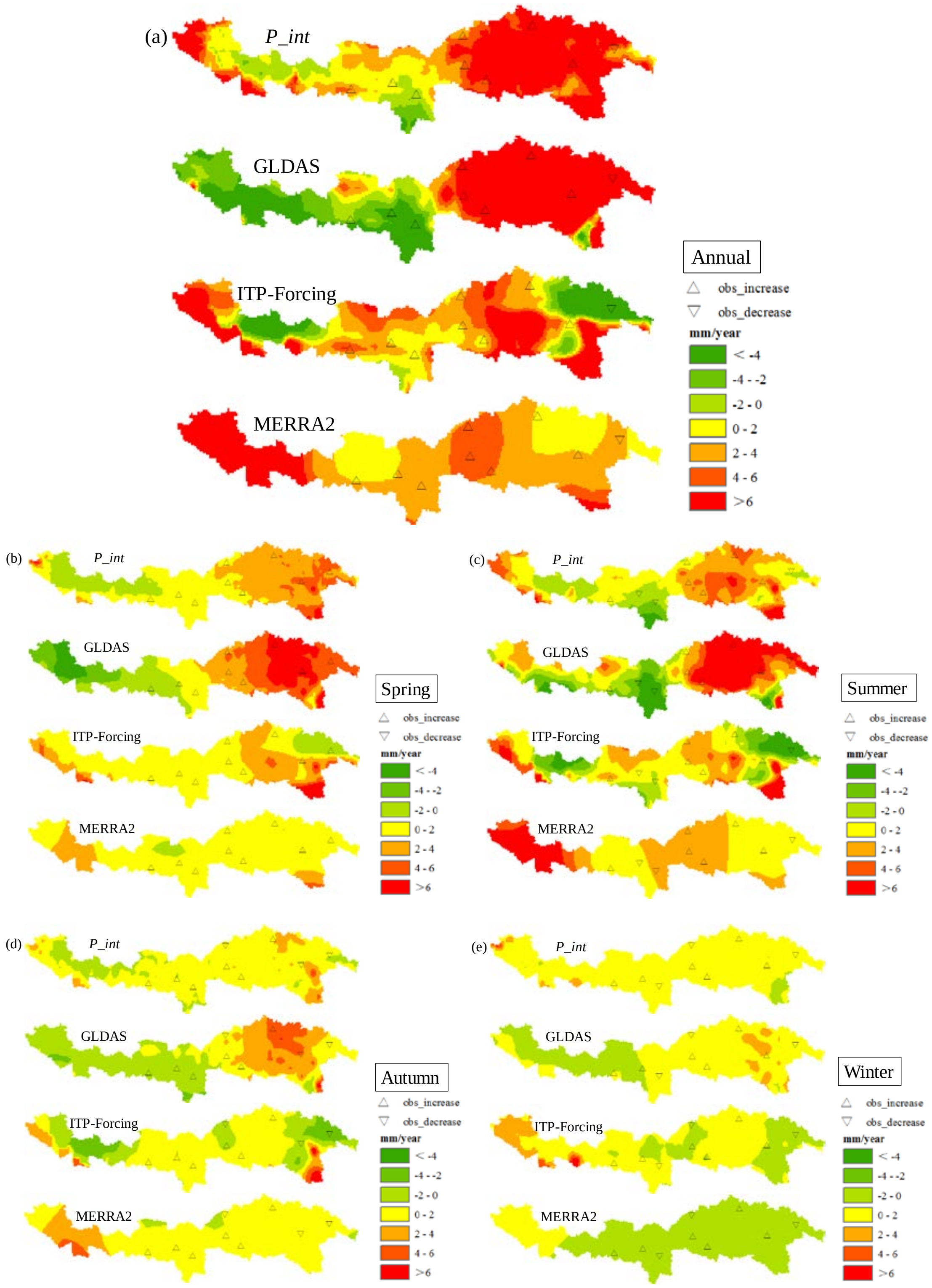

Figure 11. A trend analysis of the annual and seasonal precipitation (a: annual; b: spring; c: summer; d: autumn; e: winter) over 36 years (1981-2016) between *P_int*, GLDAS, ITP-Forcing and MERRA2. The triangles represent the observed trend of

the corresponding meteorological stations.

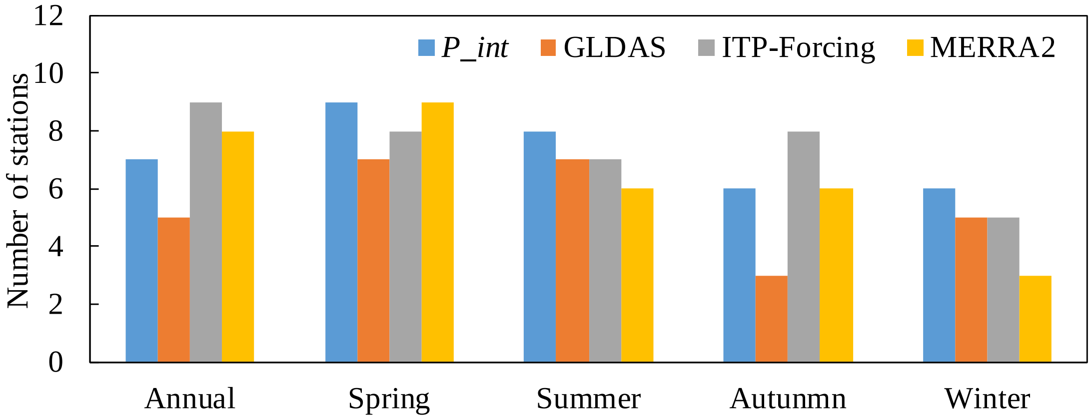

Figure 12. The number of meteorological stations (total of nine) which present the same trends as the different precipitation products, according to Figure 11.

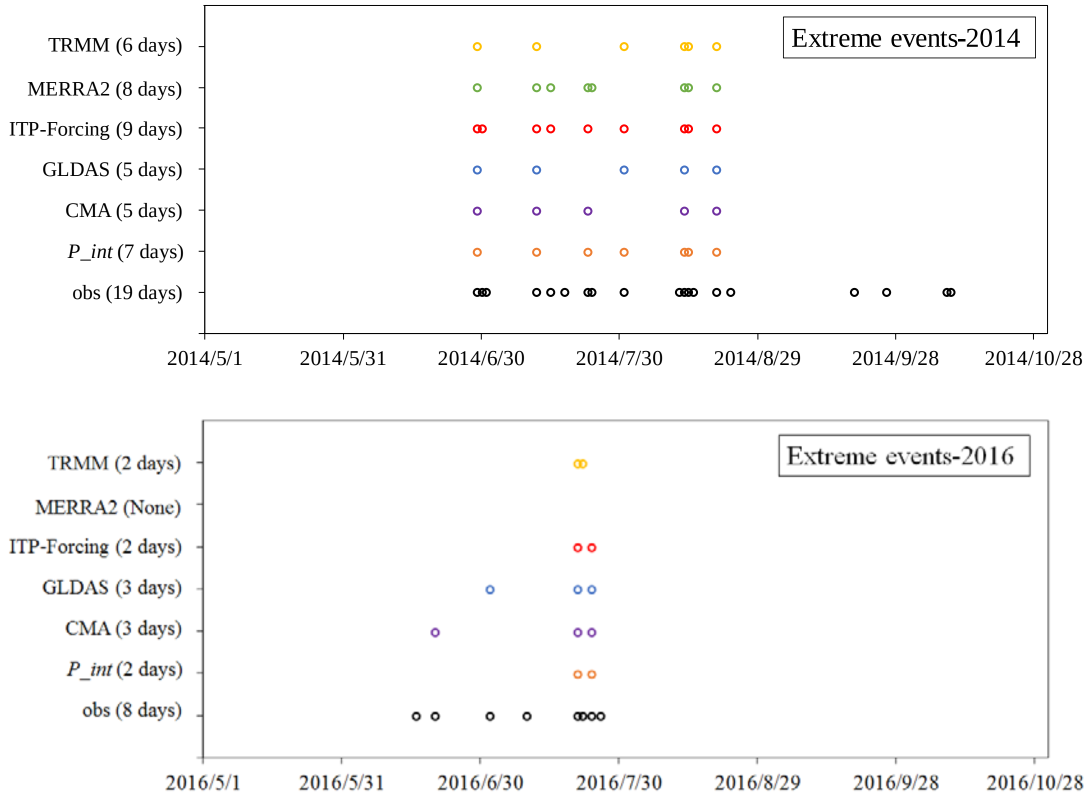

Figure 13. A comparison of extreme events, as captured by different precipitation products.

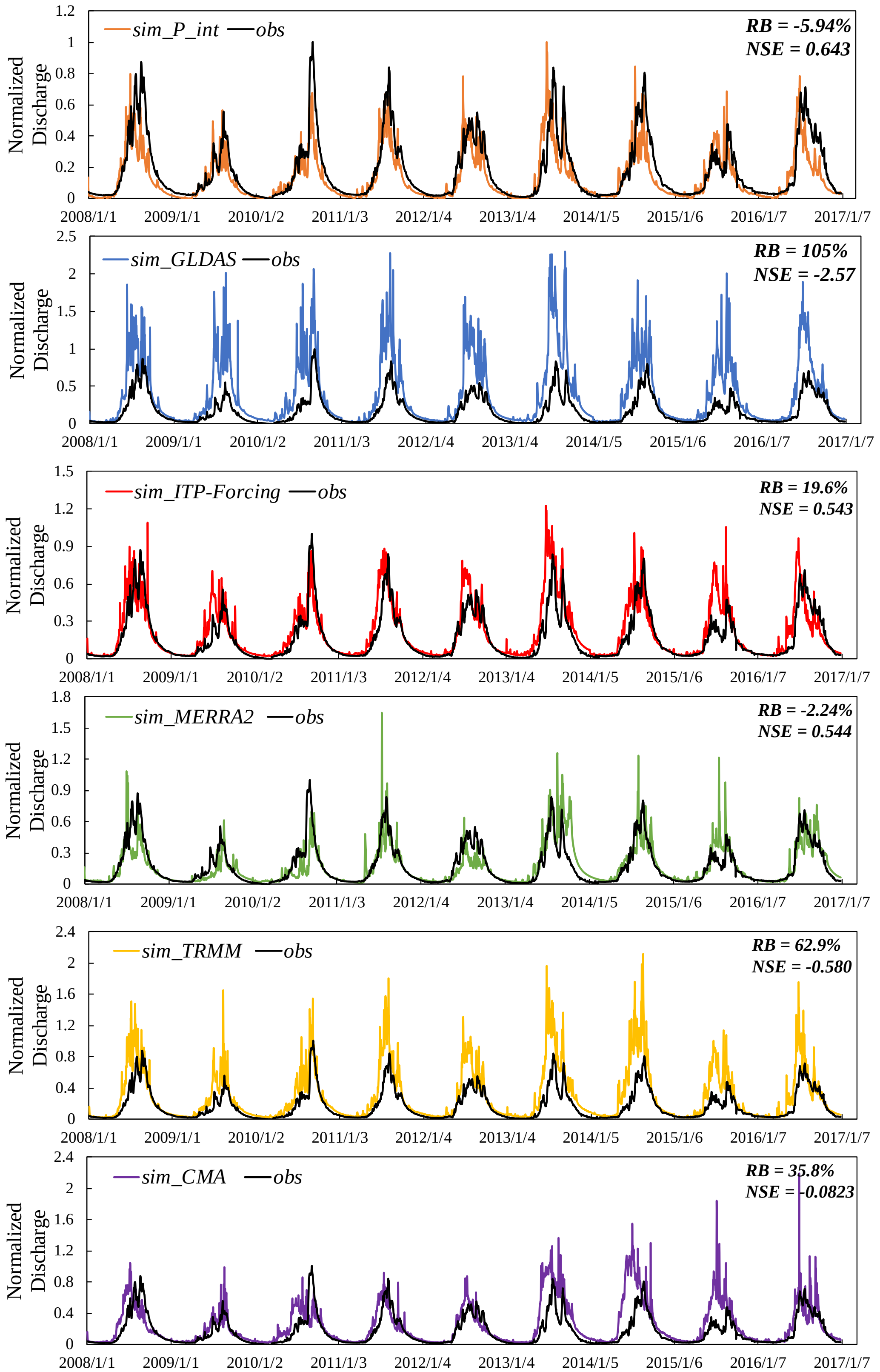

Figure 14. An evaluation of simulated daily discharge at Nuxia station from 2008 to 2016 forced by different precipitation products. All the discharge values have been

normalized.