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Assessment of Multi-Satellite Precipitation Products over the Himalayan Mountains of Pakistan, South Asia

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Abstract: Performance assessment of satellite-based precipitation products (SPPs) is critical for their application and development. This study assessed the accuracies of four satellite-based precipitation products (PERSIANN-CDR, PERSIANN-CCS, PERSIANN-DIR, and PERSIANN) using data of in situ weather stations installed over the Himalayan Mountains of Pakistan. All SPPs were evaluated on annual, seasonal, monthly, and daily bases from 2010 to 2017, over the whole spatial domain and at point-to-pixel scale. The assessment was conducted using widely used evaluation indices (root mean square error (RMSE), correlation coefficient (CC), bias, and relative bias (rBias)) along with categorical indices (false alarm ratio (FAR), probability of detection (POD), success ratio (SR), and critical success index (CSI)). Results showed: (1) PERSIANN and PERSIANN-DIR products efficiently traced the spatio-temporal distribution of precipitation over the Himalayan Mountains. (2) On monthly scale, the estimates of all SPPs were more consistent with the reference data than on the daily scale. (3) On seasonal scale, PERSIANN and PERSIANN-DIR showed better performances than the PERSIANN-CDR and PERSIANN-CCS products. (4) All SPPs were less accurate in sensing daily light to medium intensity precipitation events. Subsequently, for future hydro-meteorological investigations in the Himalayan range, we advocate the use of monthly PERSIANN and PERSIANN-DIR products.

Keywords: PERSIANN family; satellite; precipitation; assessment; Himalayan Mountains; South Asia

1. Introduction

Precipitation is a core part of the global energy and water cycle. It is a source of fresh water and a moderator of our climate system; however, it may also cause devastating storms and droughts [1]. Therefore, it is critical to monitor and measure the amount and spatial distribution of precipitation as well as its variability over time. Moreover, accurate and uninterrupted information of precipitation at different spatial and temporal scales is critical for different agricultural, environmental, hydrological, meteorological, and societal applications. Traditional ground-based instruments (weather stations and radars) are considered as the most reliable sources of precipitation measurements [2]. However, the main difficulties in accessing the uninterrupted measurements of precipitation for many applications in mountainous and remote areas are the rugged topography and an inequitable distribution of weather stations [3–6]. The Himalayan Mountains also have similar constraints on obtaining precipitation data due to sparse or non-uniform installation of meteorological stations. Therefore, it is imperative to investigate additional reliable and uninterrupted sources of precipitation information.

In the past, many satellite-based precipitation products were launched to provide continuous and reliable information on precipitation. Satellite-based products can provide worldwide estimates of precipitation at acceptable spatial and temporal scales. Previously, several satellite-based precipitation products (SPPs) were introduced [7–10]. The latest SPP precipitation estimating algorithms are capable of providing continuous precipitation information at fine spatial and temporal resolutions, using data from either infrared (IR) or microwave (MW) sensors. They are also capable of blending the information from both IR and MW sensors to produce global precipitation estimates. Such SPPs include IMERG, TRMM, CMORPH, and PERSIANN family products. Previously, numerous researchers have investigated the evaluation assessments of IMERG, TRMM, and CMORPH satellite-based precipitation products. However, the performance of the PERSIANN family of products, particularly their inter-comparison, with reference to the in situ measurements in Pakistan's mountainous terrain, is not well characterized. Therefore, this study focuses on the assessments and inter-comparisons of the performance of the PERSIANN family of products.

The Center for Hydrometeorology and Remote Sensing (CHRS) [11] at the University of California, Irvine (UCI), developed the [12–14] (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) PERSIANN system, which uses neural network function classification/approximation procedures to calculate an estimate of rainfall rate at each $0.25° \times 0.25°$ pixel of an infrared brightness temperature image provided by geostationary satellites. PERSIANN-CDR [15–17] offers daily worldwide rainfall information at a 0.25° grid scale. PERSIANN-CCS [18–20] is a cloud segmentation technique with customizable thresholds. The variable threshold approach, in contrast to the classic constant threshold strategy, allows for the detection and separation of specific cloud patches. PERSIAANN-CDR is the only post-real-time product in the CHRS data portal due to its reliance on high frequency sampled IR photography. PDIR-Now [21] has a number of advantages over other near-real-time precipitation datasets, including its relatively short latency from the moment of rainfall incidence (15–60 min).

Although Satellite-based Precipitation Products (SPPs) provide sustainable information, their information changes with respect to area and time [22,23]. Therefore, uncertainly analysis of satellite products is necessary to check their accuracy before their direct application. It is also a very important factor to determine which satellite products should be used for water conservation in the field. Several studies compared satellite-based precipitation products with gauge-based rainfall to reduce uncertainty and help determine the appropriate use of satellite products for water conservation [24–28]. Despite the fact that SPPs provide continuous data of precipitation, the accuracy of those datasets varies greatly from region to region. It is essential to check their accuracy prior to their direct application [29]. Several scientists have evaluated the error characteristics of SPPs in many areas, including Africa [24,30], South America [25,31], Nigeria [32], Austria [6], China [33], Europe [12,25], Iran [17], India [10,34], United Arab Emirates [35], Taiwan [23], Brazil [36], and Pakistan [2,37,38]. Hamza et al. [38] used both PERSIANN-CDR over the Hindukush Mountains along with other products (IMERG, TRMM and SM2-rain); he concluded that the PERSIAAN-CDR performance is more satisfactory then TRMM-3B42V7 and SM2Rain-ASCAT.

Although different SPPs [2,19] have been used to assess the uncertainty of PERSIANN-CDR, SM2-Rain, CHIRPS, and IMERG in Pakistan, the evaluation assessment of the PERSIANN family (PERSIANN, PERSIANN-CCS, PERSIANN-CDR, and PERSIANN-DIR) have not yet been performed, especially on the mountainous terrain of the Himalaya. The

Himalaya is a large crescent-shaped mountainous range that runs over 2500 km from the southern end of the Indus Valley, past Nanga Parbat in the west, to Namcha Barwa in the east, and from the Indus Valley's southern end to Namcha Barwa in the east. The range is 350 km wide in the west and 150 km wide in the east. The Indus River, which starts near the holy mountain of Kailash in Western Tibet and represents the range's true western boundary, runs south and east of the Pakistani Himalaya [39]. Three of Pakistan's provinces are bordered by the Himalaya. The Nanga Parbat massif and its surrounding valleys, Azad Jammu and Kashmir, and the Khyber Pakhtun Khwa (KPK) southeast corner include the western portion of the Himalaya in Pakistan. The literature review revealed that the topography of the study area varies significantly, which hinders the continuous measurement of precipitation data. Therefore, this study is designed to assess the performance of SPPs of the PERSIANN family over the Himalayan Mountains of Pakistan, South Asia. This will be the first uncertainty analysis of the four latest PERSIANN family precipitation productions in the Himalayan range of Pakistan. The results of this assessment will be very beneficial to algorithm developers, SPPs data users, and Pakistani policymakers.

2. Materials and Methods

2.1. Study Area

The Himalayan mountainous range in Pakistan (Figure 1), which serves as a physical and cultural barrier between South and Central Asia, was selected for the performance assessment of four PERSIANN family SPPs (PERSIANN, PERSIANN-CDR, PERSIANN CCS, and PDIR). This range covers the majority of northern Pakistan [40] and stretches approximately 200 miles (320 km) in the northern parts of the country. The hydrology and glaciology of South Asia, particularly the water resources of Pakistan, are significantly influenced by the precipitation patterns over this mountainous domain [41]. Figure 2 displays spatial variation of mean yearly precipitation over the selected study area.

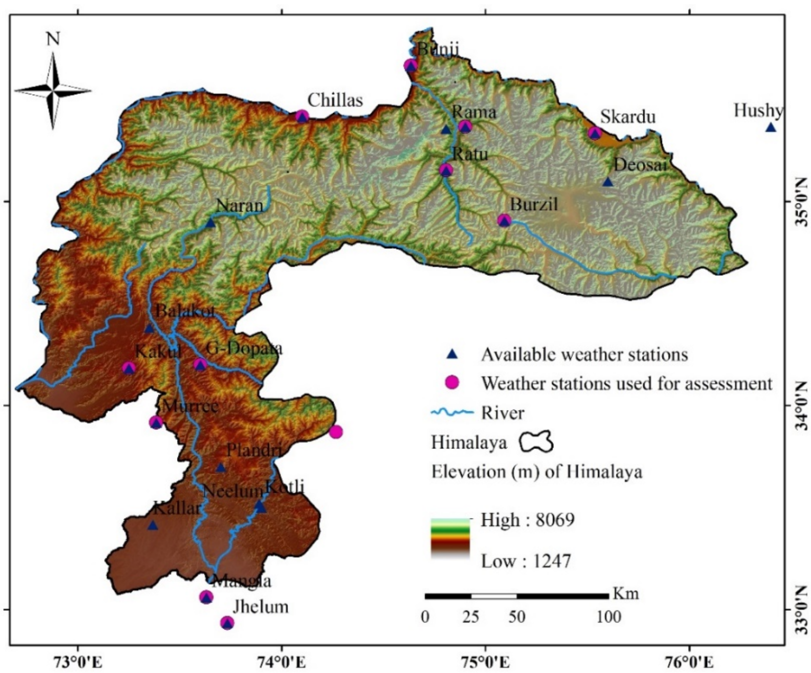


Figure 1. Locations of specified weather stations and a topographic map of the research region.

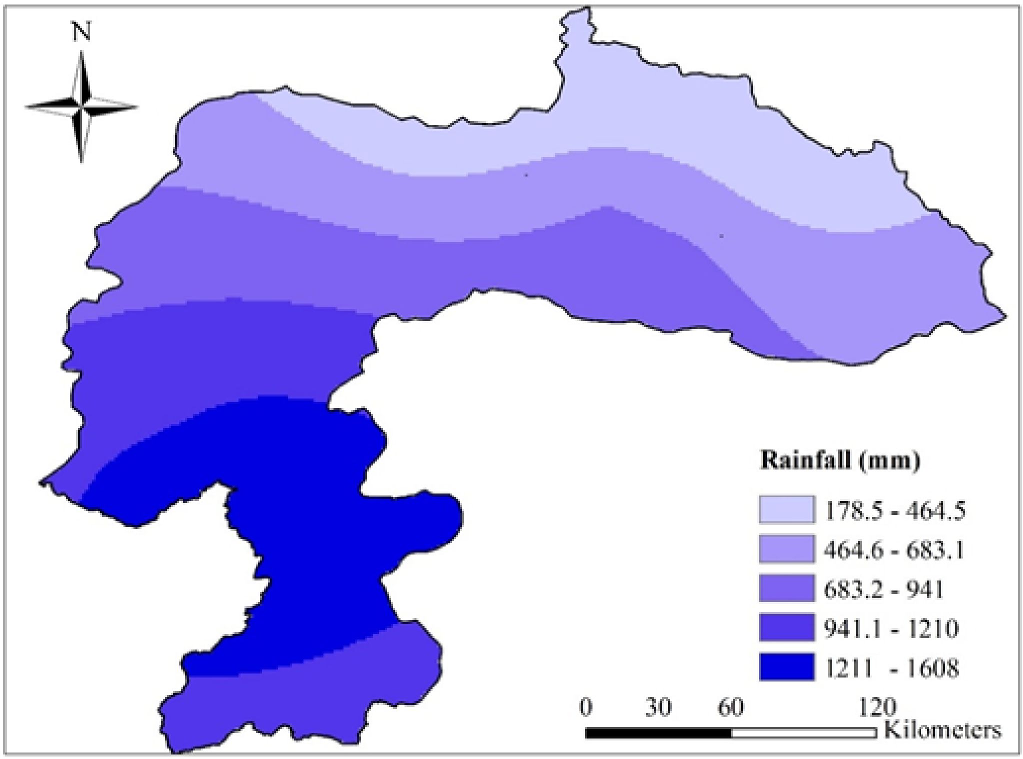


Figure 2. Spatial variability of average annual observed precipitation (from 2010 to 2017) over the Himalayan Mountains of Pakistan.

2.2. Datasets

The Pakistan Meteorological Department (PMD) provided daily precipitation datasets from 21 meteorological stations located inside and around the Himalayan range. However, continuous and reliable data from only 12 in situ stations were available from 2010 to 2017. Because of missing values (more than 10%) in daily precipitation data of nine stations, they were excluded in this assessment. Figure 1 depicts the positions of all weather stations installed in this area, including the locations of weather stations considered for this assessment. Table 1 describes the salient characteristics of in situ weather stations considered for this assessment. Previously, datasets of the same weather stations were used in several hydro-climatic investigations [33,42,43]. The spatial resolution of two PERSIANN family products (PERSIANN and PERSIANN-CDR) is 0.25° × 0.25°, covering 60° S to 60° N in latitude. The PERSIANN-CDR product offers a reliable, high-resolution, and long-term global precipitation database for assessing daily precipitation variations and trends. This product was developed using GridSat-B1 infrared data, and the algorithm of the product was revised using the Global Precipitation Climatology Project (GPCP) monthly product. The public can access the PERSIANN-CDR [11] product as an effective climate data record from the NOAA NCDC CDR Program website. The PERSIANN-CSS system has a spatial resolution of 0.04° × 0.04° and also covers latitude of 60° S to 60° N. Cloud-patch features can be classified using the PERSIANN-CCS algorithm, which uses satellite data to assess cloud height, areal extent of precipitation, and textural variability [20]. The PDIR is a real-time and high-resolution satellite-based precipitation product. The advantage of PDIR-Now over other near-real-time precipitation datasets is its reliance on high frequency sampled IR imagery; as a result, PDIR-Now has a very small latency from the moment of the precipitation event (15–60 min). PDIR-Now additionally corrects for the errors and uncertainties associated with the usage of IR images using a variety of methods, the most notable of which is the dynamic shifting of (Tb-R) curves using rainfall climatology. The latency of PDIR-Now makes it ideal for near-real-time applications. PDIR-minimal, due to the low latency, is now suited for near-real-time hydrologic applications, such as flood forecasting and flood inundation mapping. In addition, the calibrated PDIR product estimates can be used to reconstruct historical precipitation estimates with high spatiotemporal resolution.

Table 1. Salient features of weather stations used in this assessment.

Sr. No.	Station	Latitude (°)	Longitude (°)	Elevation (m)
1	Astore	35.37	74.9	2168
2	Bunji	35.67	74.63	1470
3	Burzil	34.91	75.09	4030
4	Chillas	35.42	74.1	1251
5	G-Dopata	34.2	73.6	813.5
6	Jhelum	32.93	73.73	287.2
7	Kakul	34.18	73.25	1309
8	Murree	33.92	73.38	2127
9	Ratu	35.15	74.81	2920
10	Skardu	35.34	75.54	2316.5
11	Mangla	33.06	73.63	283.3
12	Rawalkoat	33.87	74.27	1677

For this assessment, freely available daily estimates of four PESIANN family products (PERSIANN, PERSIANN-CDR, PERSIANN-CCS, and PDIR) were downloaded for the same study period (2010–2017). All satellite-based products were obtained from the CHRS data gateway ("https://chrsdata.eng.uci.edu/"). Daily data of all SPPs were accumulated to get the monthly, seasonal, and annual time series datasets. Several studies [3,28,44] used a similar procedure to acquire the monthly, seasonal, and annual estimates of SPPs.

2.3. Methods

The uncertainty in the estimates of four SPPs (PERSIANN, PERSIANN-CDR, PERSIANN-CCS, and PDIR) was assessed against the observation of in situ weather stations. Following the method of [27], only those grids of SPP containing at least one weather station were considered for this assessment. The data from ground-based weather stations are on a point-scale, whereas the spatial resolutions of gridded products are 0.25° (for PERSIANN-CCS and PERSIANN-CDR) and 0.04° (for PERSIANN and PDIR-Now). Therefore, a straightforward grid-to-point matching method is used to complement the SPPs with weather stations: the grid of SPPs whose center position is nearest to the weather station is matched to this station. Generally, the up-scaling of the in situ gauge-based point data to the grid scale used the simple averaging method or spatial interpolation techniques in the assessment studies of SPPs with reference to the gauge-based observations. Literature reviews revealed that the use of non-geostatistical spatial interpolation methods may result in some discrepancies in mountainous terrain because of the errors associated with interpolation techniques, weather station density, and some other systematic issues [38]. Therefore, simple averaging of the observations of in situ gauge-based data was considered for those stations where two or more than two stations were installed in a single grid. This approach was also used in several previous studies [6,12,14]

The performances of considered SPPs were compared with each other at different temporal (annual, seasonal, monthly, and daily) and spatial (point-to-pixel and entire domain) scales. Using Kriging with an external drift (KED) technique [39], a spatial variability map of annual average precipitation was generated for the study area.

The capability of each SPP to signify the spatial distribution of measured precipitation in the Himalayan Mountains was evaluated. The evaluation indices (root mean square error (RMSE), bias, relative bias (rBias), and correlation coefficients (CC)), along with categorical indices (probability of detection (POD), critical success index (CSI), false alarm ratio (FAR), and success ratio (SR)), have been applied in several assessments of SPP in different topographic and climatic regions of the world [28]. In this study, all of these assessment and categorical indices were used to evaluate the accuracies and skills of SPPs. The skill of all PERSIAN family products to represent the temporal variability of precipitation over the rugged topography was also assessed by associating their daily temporal variability to variance in the measurements of reference stations.

The CC (dimensionless) was used to assess the direct relationship between the gauges data and the estimates of SPPs over the Himalayan range. The bias (mm/time) was calculated to determine whether the precipitation magnitude was overestimated or underestimated. The rBias (%) was calculated to assess the divergence between the gauge-based and satellite-based datasets. Based on gauge data, we calculated RMSE to check how much inaccuracy (mm/time) was present in remotely sensed estimates. Equations of considered evaluation indices are given below:

$$\mathrm{CC} = \frac{\sum_{i=1}^{n}(Gi - G)(Si - S)}{\sqrt{\sum_{i=1}^{n}(Gi - G)^2} \times \sqrt{\sum_{i=1}^{n}(Si - S)^2}} \tag{1}$$

$$\mathrm{rBias} = \frac{\sum_{i=1}^{n}(Si - Gi)}{\sum_{i=1}^{n} Gi} \times 100 \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (Si - Gi)^2} \tag{3}$$

$$\mathrm{BIAS} = \frac{\sum_{i=1}^{n}(Si - Gi)}{n} \tag{4}$$

wre Gi denotes the in situ reference data, mean of the reference data is symbolized by G, and Si and S characterize the satellite data and mean of the satellite data, respectively. The total number of observations are denoted by n. If the estimated value of CC for any product is 1, bias and RMSE are zero, then that product's estimation capability is considered perfect. Some researchers have documented the acceptable ranges of rBias (−10%–10%) and CC ($\geq$0.7) for the use of satellite-based estimates in hydro-climatic studies.

$$\mathrm{POD} = \frac{H}{H + M} \tag{5}$$

$$\mathrm{FAR} = \frac{F}{H + F} \tag{6}$$

$$\mathrm{CSI} = \frac{H}{H + M + F} \tag{7}$$

In the above equations, H indicates the occurrence of precipitation occasions correctly reported by the reference gauging stations as well as by the satellite-based products, F shows the false representation of precipitation occurrence by satellite, and M indicates the precipitation occurrence recorded by gauges but missed by satellite products. The threshold value of the critical success index and probability of detection is one, and for FAR is zero.

To provide a better comparison of the performances of PERSIANN family, the PDF of all satellite-based daily precipitation estimates with reference to the in situ data at difference intensities was determined. This was done by following previous performance evaluations of SPPs [38]. Furthermore, a summary of the agreement between the daily and monthly gauge-based and satellite-based precipitation data was elaborated in the Taylor diagrams (Taylor (2001)). Taylor diagrams were used in several previous assessments of SPPs in different areas.

3. Results

3.1. Potential of PERSIANN Family Products to Monitor the Spatial and Temporal Variability of Precipitation

A comparison of daily precipitation amounts obtained from four SPPs and in situ weather stations is shown in Figure 3. In the whole study region, significant spatial variability in the amount of precipitation was found, which could be linked to the complicated mountainous topography. According to all data sources, the low altitude parts (southern part of the study domain) received more precipitation. Results revealed that the PERSIANN-DIR product outperformed other SPPs in the southern part of the Himalayan region. At higher elevations, the PERSIANN family of products struggled to correctly predict the amount of precipitation. All products showed an overestimation of precipitation magnitude in the northern areas of the study domain. Over the middle and southern parts, however, the spatial variability of precipitation was adequately represented by all SPPs.

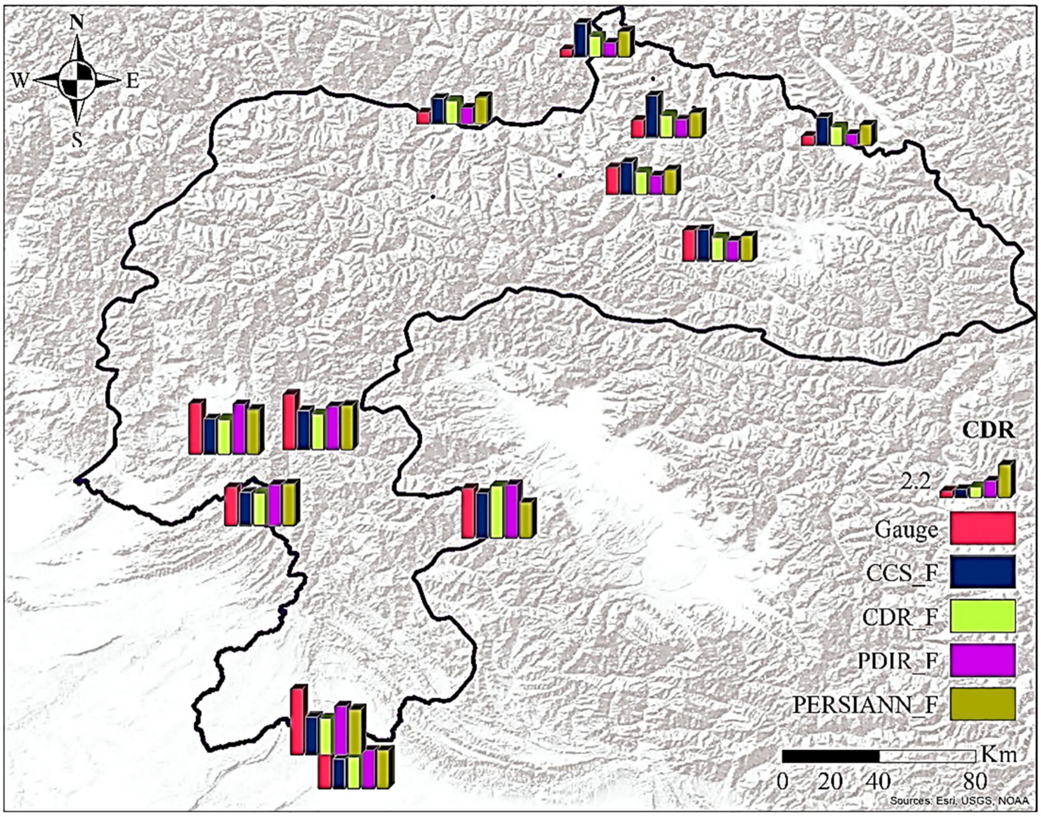


Figure 3. Spatial variability of average daily precipitation acquired from the reference weather stations and four PERSIANN family products (PERSIANN, PERSIANN-CDR, PERSIANN-CCS, and PDIR).

Comparison of the daily precipitation measurements acquired from the in situ stations and PERSIANN family products is depicted in Figure 4. For the period from 2010 to 2017, the time series of precipitation were obtained using the moving average of daily data from available in situ gauges and all of the PERSIANN SPPs. Previously, several researchers have used a similar method to compare the capability of SPPs to track the time-based variability of precipitation over different regions of the world [20,23,27–31]. According to the statistics shown in Figure 4, two distinct periods of high precipitation were found in a year. Overall performance of the PERSIANN product to signify the temporal variability of average daily reference precipitation was better than its other family products. However, this product slightly underestimated the magnitudes of precipitation during both peaks (in March and September); conversely, it overestimated the magnitudes of precipitation in April and October. Although PERSIANN-CDR and PDIR SPPs were in better agreement with the gauge data in terms of capability to monitor the precipitation's temporal variability, they showed uncertainties in the estimations of precipitation magnitudes. The PDIR product showed overestimation of precipitation during the winter season, whereas it showed substantial underestimation of precipitation magnitude throughout the summer season. The CDR product showed substantial underestimation of precipitation magnitude during the entire year. The CCS product totally failed to track the temporal variability of observed precipitation.

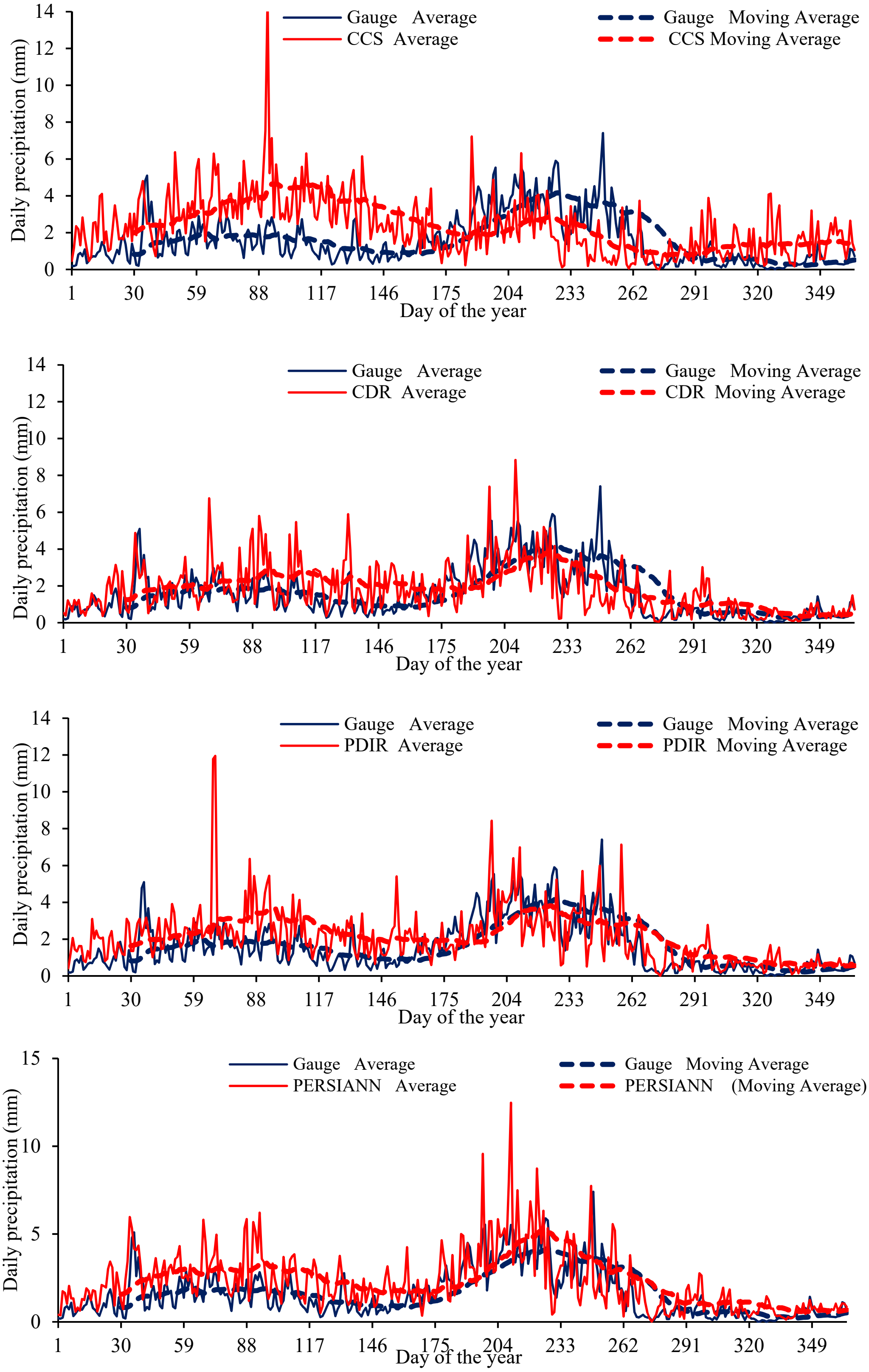


Figure 4. Temporal inconsistency of daily average precipitation amount acquired from the reference weather stations and SPPs of the PERSIANN family.

3.2. Performance of PERSIANN Family Products at the Monthly Scale

The monthly performances of four SPPs (PERSIANN, PERSIANN-CDR, PERSIANN-CCS, and PDIR) are summarized in Figure 5 (Taylor diagram). The normalized areal average data from weather stations and SPPs were used to create the Taylor diagram. Except for CCS, all SPPs displayed good agreement with the in situ monthly data. The correlation coefficients of PERSIANN, CDR, and PDIR were higher than 0.70; however, the correlation coefficient of the CCS product was less than 0.50. The PERSIANN showed best performance in terms of RMSE (lower than 0.50), whereas the RMSE values of PDIR, CDR, and CCS were greater than 0.50, which indicated higher uncertainties in the monthly estimates of these products. The SD values of all PERSIANN family SPPs were similar to the SD value of the in situ measurements.

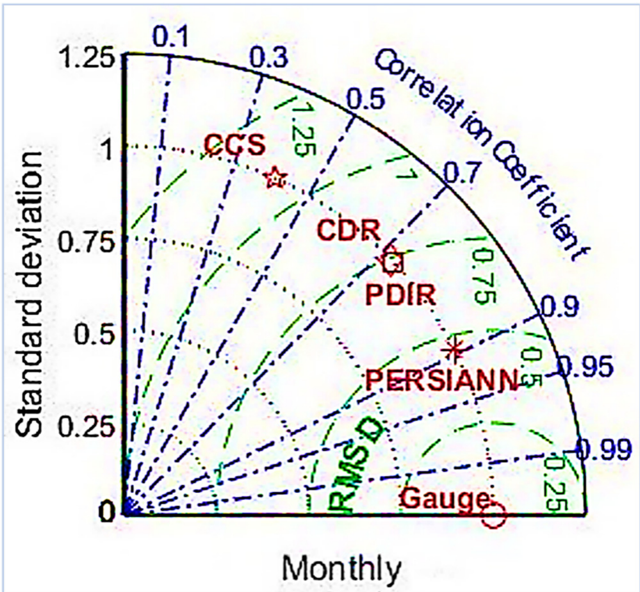


Figure 5. Taylor diagram illustrating the performance of all PERSIANN family SPPs, at a monthly scale. Partial-circular lines (shown in green) represent RMSE values, whereas straight blue lines represent CC values.

Figure 6 depicts variations in calculated CC, RMSE, bias, and rBIAS values for PERSIAN family SPPs. These variations in all four statistical indices were obtained using the monthly estimates of all SPPs against the observations of respective stations. The box interval of CC for PERSIANN showed higher variability in the agreement between the reference data and satellite-based data. In terms of bias and rBIAS, PDIR and CDR showed better performances than CCS and PERSIANN products, as indicated by the smaller variations in their box lengths.

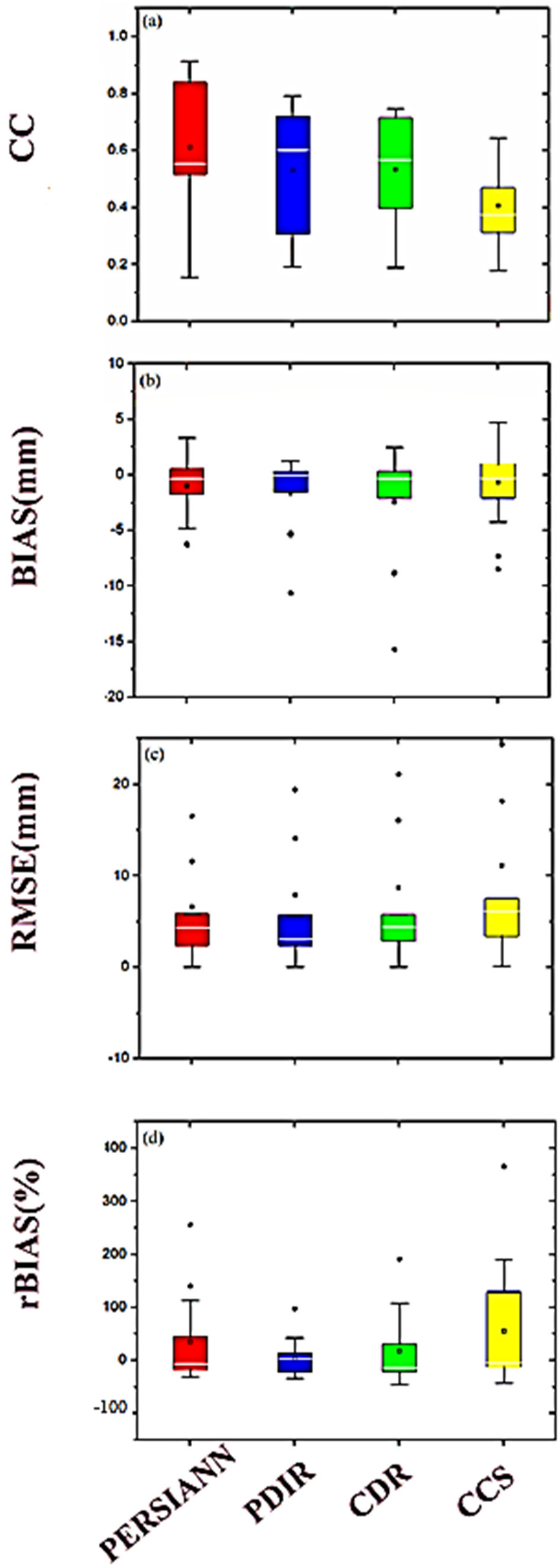


Figure 6. Box blots of assessment indices (**a**) CC, (**b**) RMSE, (**c**) bias, and (**d**) rBIAS estimated for PERSIANN family SPPs at a monthly scale over the Himalayan range of Pakistan. The mean values are shown by small squares, whereas the median is represented by horizontal lines within the boxes. The linear trend of the mean values is shown by the white lines.

3.3. Performances of PERSIANN Family Products on Daily Estimations

Figure 7 summarizes performances of PERSIAN family satellite-based precipitation products against the reference daily data. The CC values for PERSIANN, CCS, PDIR, and CDR were 0.15, 0.15, 0.28, and 0.28, respectively. This indicated that there were discrepancies between the daily reference data and estimates of the PERSIANN family's products. Poor performances of all PERSIANN family products were also revealed by higher values of RMSE (>1.0), as shown in Figure 7.

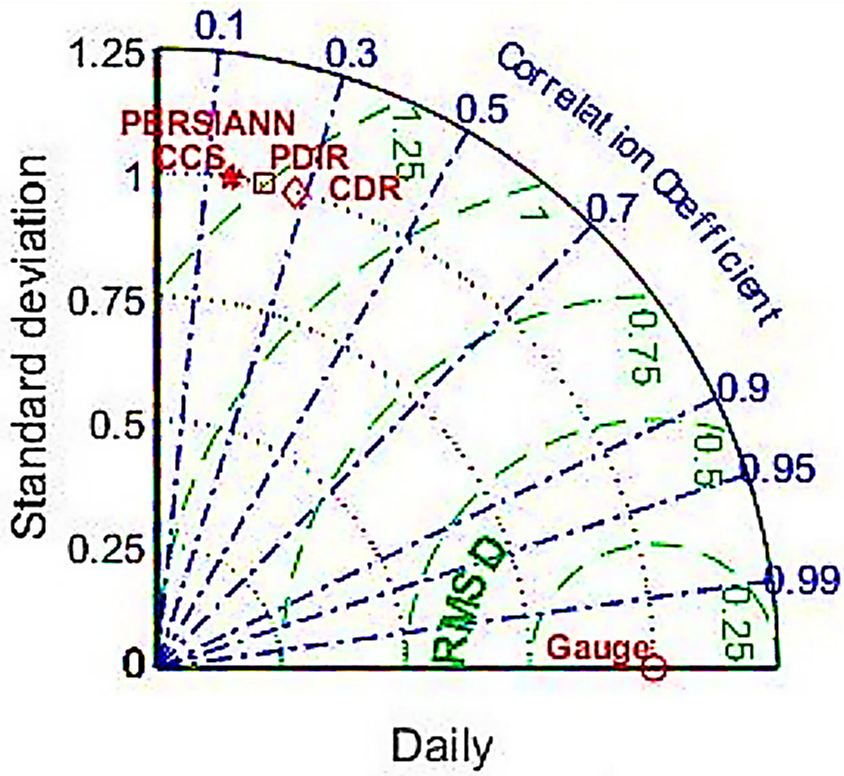


Figure 7. Performances of daily estimates of PERSIANN, CDR, CCS, and PDIR products depicted in a Taylor diagram.

Figure 8 illustrates the dissimilarity in assessed values of evaluation indices for four satellite products (PERSIANN, PERSIANN-CDR, PERSIANN-CCS, and PDIR). The RMSE of each SPP showed the least fluctuation when compared with the other evaluation indices (CC, BIAS, and rBIAS). Furthermore, as demonstrated by the length of the box, the PERSIANN showed the highest variation in the values of CC. As compared to the performances of other SPPs in the Himalayan range, the discrepancy in the calculated values of BIAS and rBIAS for PDIR product revealed its relatively better performance, as specified by the box extents of BIAS and rBIAS. PERSIANN-CCS had the highest volatility in terms of RMSE, as evidenced by the size of the box extent.

The influence of elevation on the performances of PERSIANN family products (in terms of CC, BIAS, rBIAS, and RMSE) is shown in Figure 9. The correlation between the in situ datasets and the estimates of PERSIANN family products decreased with an increase in elevation. With the increase in elevation, the CC and RMSE values of all products decreased, whereas the values of rBIAS showed a direct relationship with the altitude.

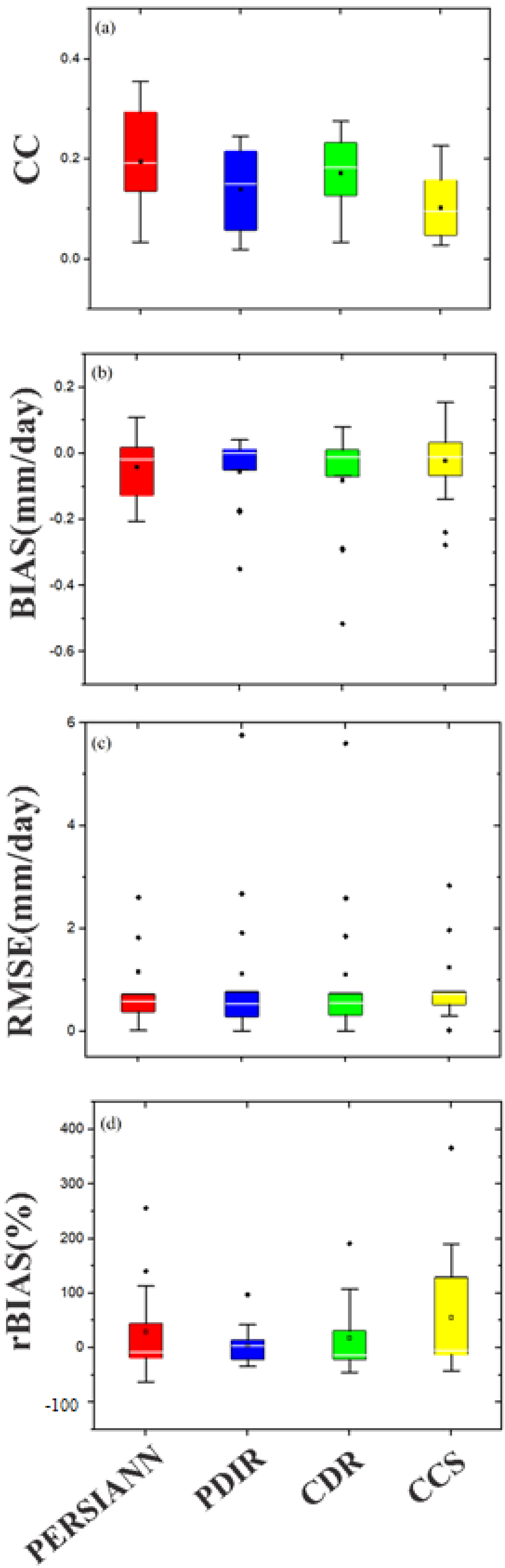


Figure 8. Box plots of (**a**) CC, (**b**) BIAS, (**c**) rBIAS, and (**d**) RMSE estimated for daily estimations of PERSIANN, PERSIANN-CDR, PERSIANN-CCS, and PDIR products against in situ data over the Himalayan range of Pakistan.

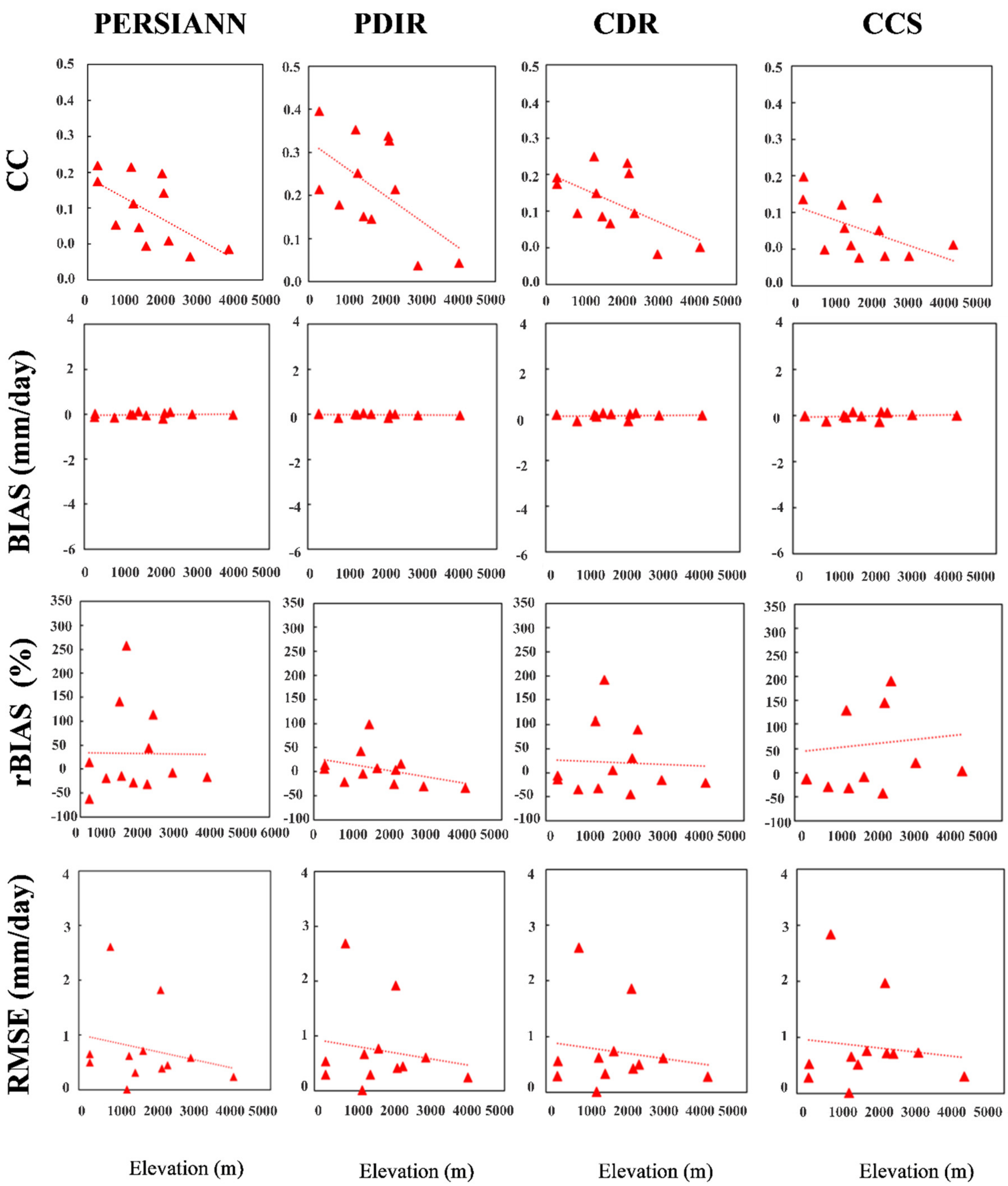


Figure 9. Effect of elevation on the values of CC, BIAS, rBIAS, and RMSE estimated for all PERSIANN family SPPs on daily scales.

Figure 10 shows the impact of precipitation intensity on the performances of the SPPs, in terms of RMSE, CC, BIAS, and rBIAS. Results showed that the agreements between the estimates of all PERSIANN family products and reference data were in direct proportion with the precipitation rates, as indicated by higher values of CC at higher precipitation rates (Figure 10). The values of BIAS (rBIAS) decreased with the increase in precipitation rate; conversely, the values of RMSE increased with the increase in precipitation intensity.

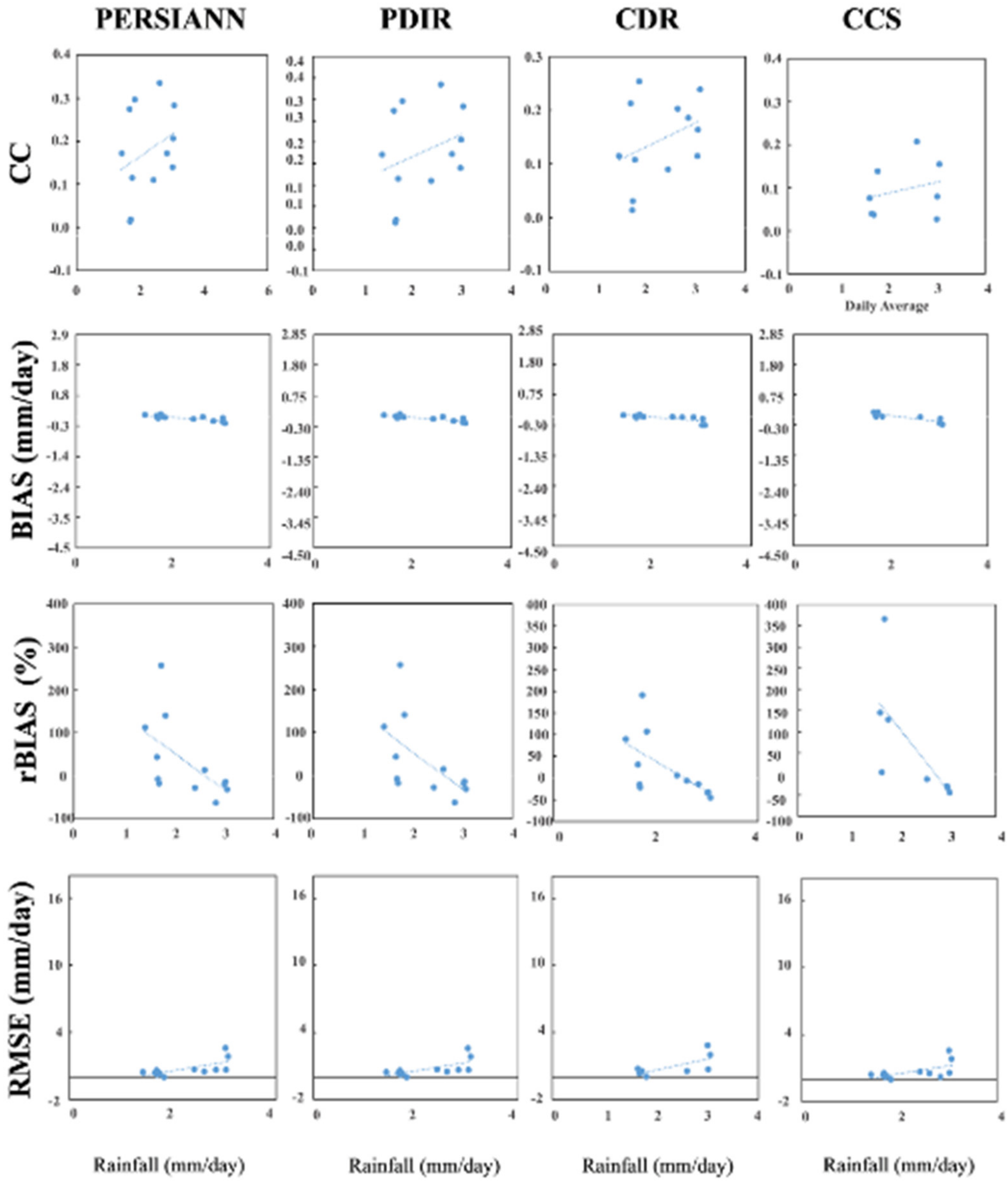


Figure 10. The effect of precipitation intensity on the evaluation indices. The metrological stations are indicated by blue markers, and the linear regression fitting lines are indicated by dotted lines.

Figure 11 presents the spatial discrepancies in the assessed values of CC, rBIAS, and RMSE for all PERSIAN family products with reference to in situ data. The spatial variability of CC for the CCS product revealed that the relationship between the estimates of this product and the reference data was very weak. A map of rBIAS for CCS product indicated that the estimates of this product were more biased with the measurements of in situ data over higher elevations. Significant errors in the estimations of the CCS product were indicated by the spatial patterns of RMSE for this product. Generally, agreements between the estimates of PERSIANN and PDIR products and the observations of in situ stations were relatively better than the other two products, as indicated by the spatial patterns of rBIAS for PDIR and CDR products (Figure 11). Overall performance of the CDR product in terms of rBIAS and RMSE was better than all other products of the PERSIANN family.

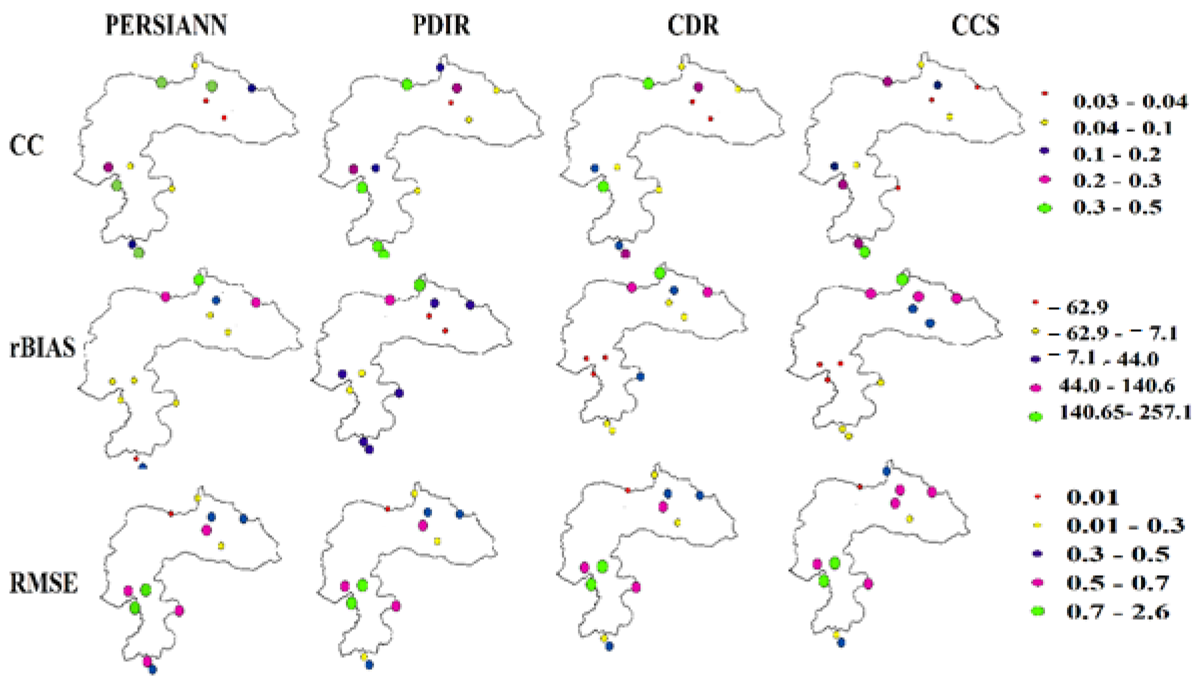


Figure 11. Performance assessment of four SPPs at a daily scale.

3.4. Evaluation of SPPs at a Seasonal Scale

Figure 12 shows seasonal discrepancies in CC, RMSE, BIAS, and rBIAS estimated for all SPPs (PERSIANN family products). Generally, all SPPs displayed higher variations in CC during the spring season [45–48]., as indicated in Figure 12a. The agreement between the estimates of the CCS product and reference data was comparatively poor in all seasons, excluding the winter season. The CCS product showed significant overestimation of precipitation magnitude in the spring season, as shown by box plots of rBIAS (Figure 12b). The PERSIANN product showed higher variaitions in the estimated values of CC in all seasons. The uncertanities in the estimates of all PERSIANN family products were lower in the autumn season, as indicated by the box intervals of rBIAS and RMSE.

Figure 13 displays the comparisons of the rBIAS determined for all SPPs against the measurements of the weather stations, based on seasonal total precipitation amounts over the Himalayan range of Pakistan [49]. Generally, all SPPs showed underestimations of precipitation over this mountainous domain, except the CCS product, which showed significant overestimation of the precipitation magnitude in the spring season. In the winter season, the CDR product showed significant underestimation (30%) of observed total precipitation, followed by PDIR and CCS (more than 10%). The underestimation of the PERSIANN product during the winter season was within acceptable limits (10%). In the spring season, the underestimations of PERSIANN, PDIR, and CDR were less than 10%, which indicates their better performances. CDR shows slight underestimation, whereas PDIR was unable to perform in the spring season, with almost a zero value of rBIAS. CCS shows maximum overestimation in the spring season. CCS shows maximum underestimation in summer, followed by PDIR and CDR. In the autumn season, all satellite-based products showed underestimation of precipitation magnitudes. Overall, the performance of PERSIANN and CDR in terms of rBIAS are acceptable in all seasons.

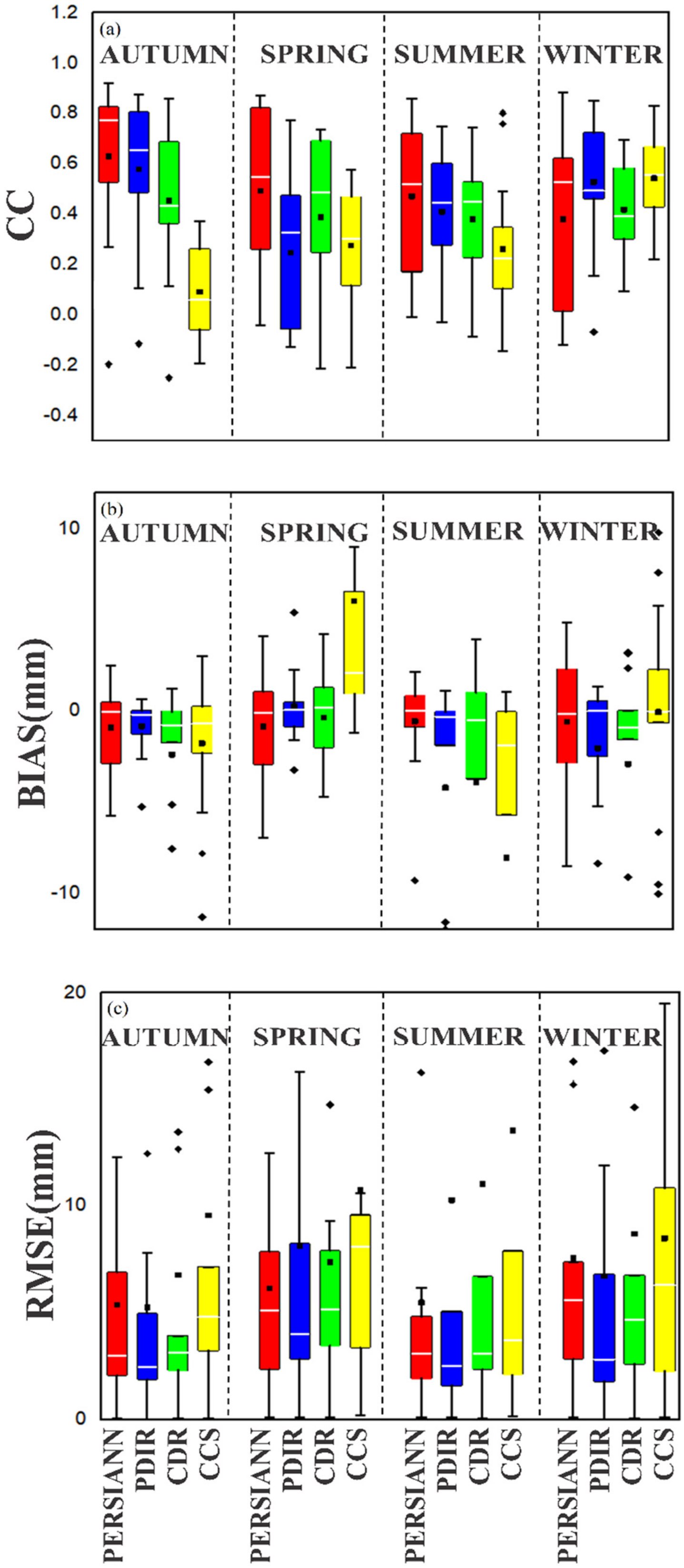


Figure 12. Box plots of the assessment indices (**a**) CC, (**b**) BIAS, and (**c**) RMSE for all PERSIANN family products at a seasonal scale. The mean and median values are shown by small squares and horizontal lines inside the boxes, respectively. The linear trend of mean values is depicted by the white lines.

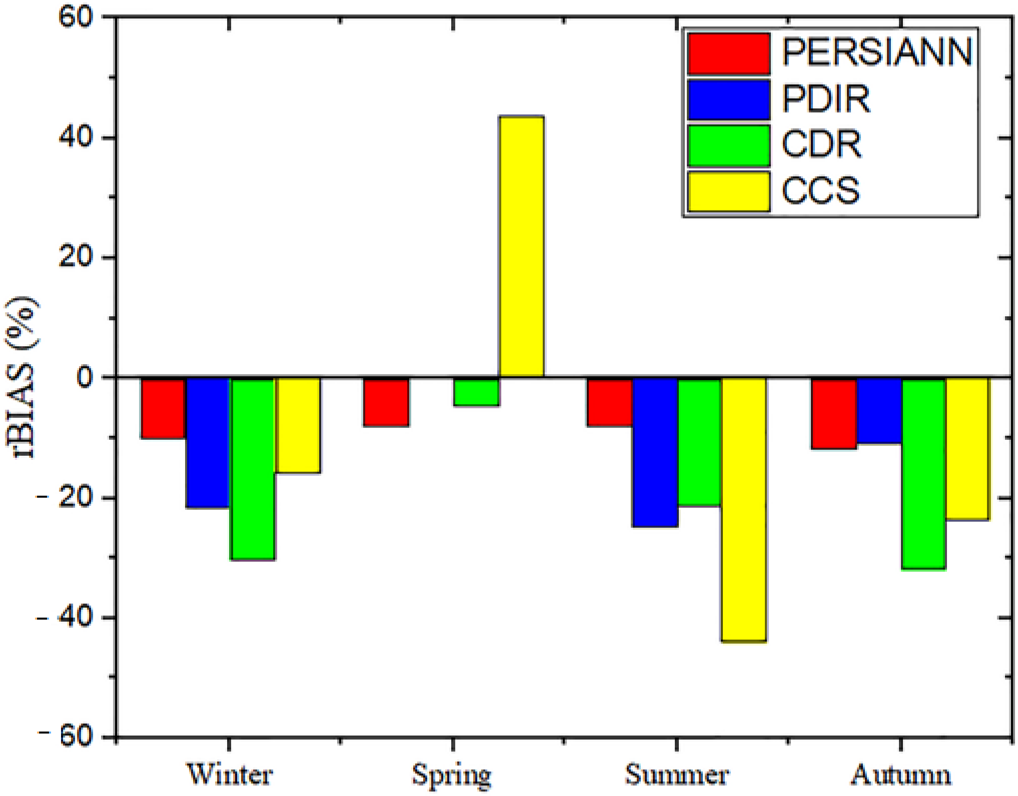


Figure 13. Values of rBias (%) of four PERSIANN family precipitation products estimated on a seasonal scale for the entire research area.

3.5. Ability of PERSIANN Family Products to Capture the Amount of Precipitation Events

Figure 14 depicts the assessment of four SPPs in terms of their ability to capture occurrence of precipitation events over the study area. Roebber [32] presented a performance diagram to graphically summarize the estimated values of the categorical indices (POD, SR, CSI, and Bias). The Roebber Performance Diagram (or simply performance diagram) was used in several previous investigations of SPPs in different countries [33].

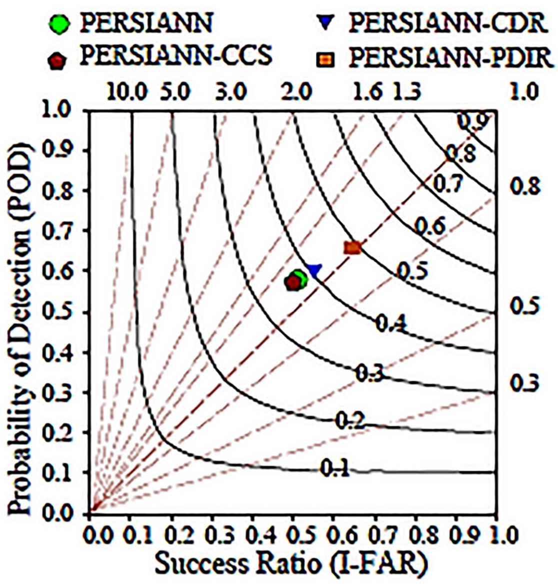


Figure 14. Ability of PERSIANN family products (PERSIANN, PERSIANN-CDR, PERSIANN-CCS, and PDIR) to assess the occurrence of daily precipitation events over the Himalayan range of Pakistan.

The estimated values of POD for the PERSIANN, CDR, CCS, and PDIR were 0.45, 0.56, 0.46, and 0.62, respectively. The highest value of POD was obtained for the PDIR, which revealed that this products' skill to assess the rate of precipitation events was better than other products of its family. The higher SR value of this product also confirms this finding.

Performance diagrams (Figure 15) show the precipitation detection abilities of SPPs on a seasonal scale. The performance of PDIR was better than other products, as indicated by higher values of POD in all seasons for this product. In contrast, CCS product performed poorly in all seasons. The performance of PERSIANN was satisfactory in all seasons, except winter. The CDR product performed better in spring and summer then in autumn and winter.

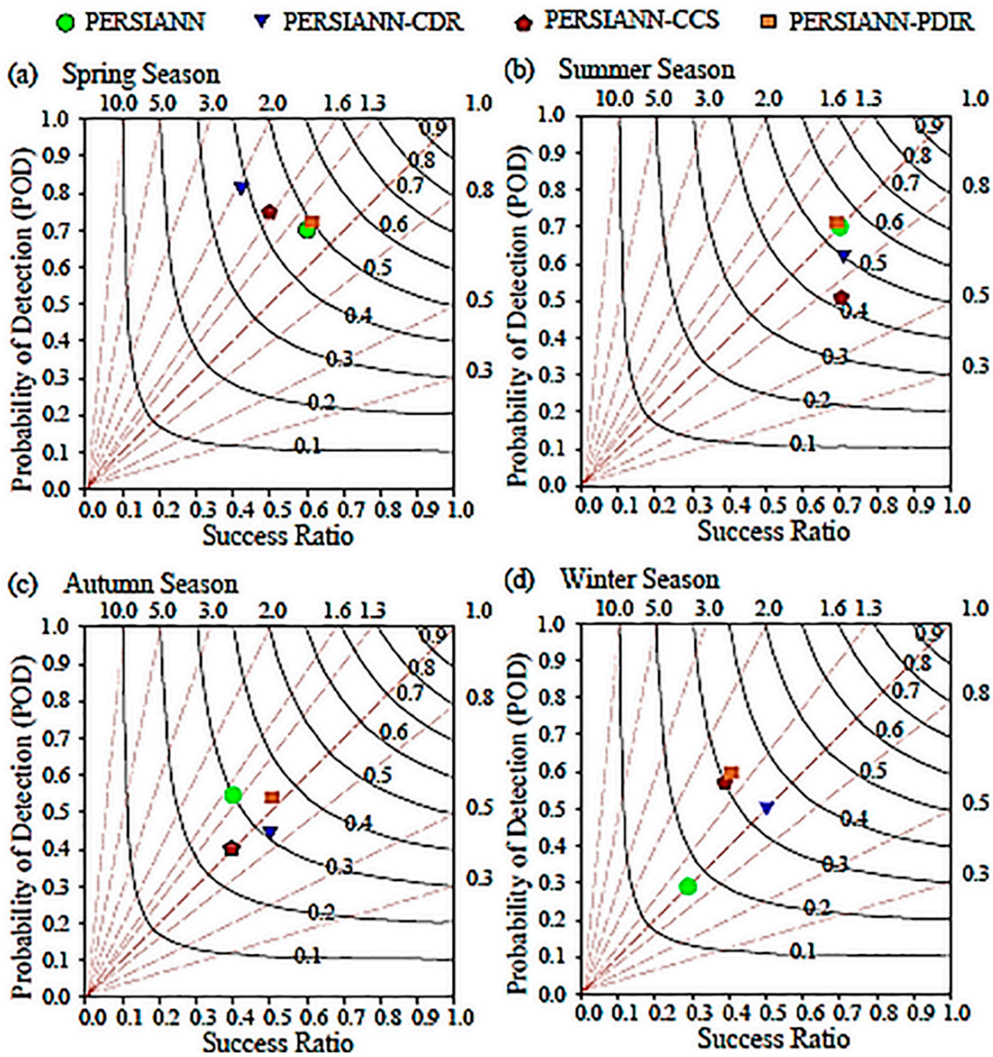
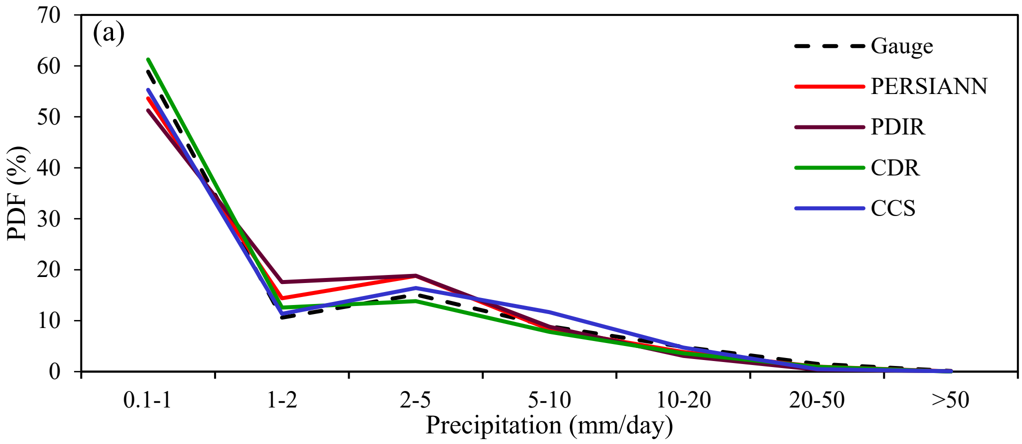
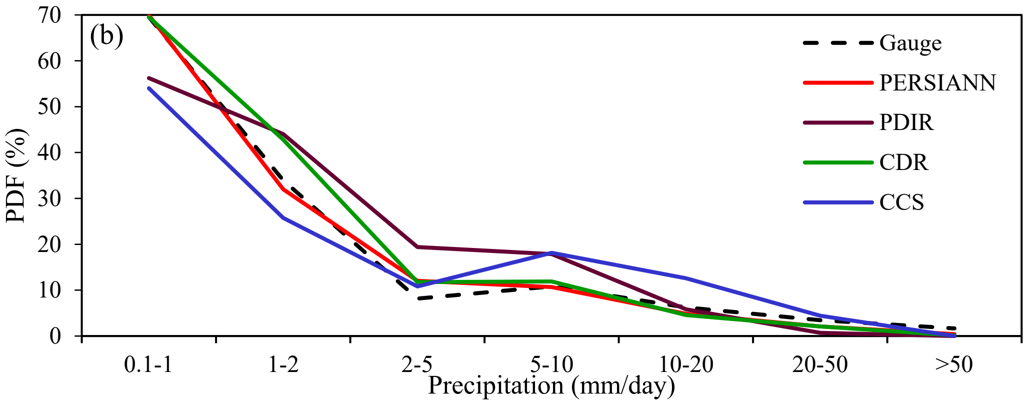


Figure 15. Ability of all PERSIANN's family SPPs to capture seasonal basis precipitation over the study area is represented by a performance diagram. Straight lines represent the BIAS values, whereas the curved line represents the CSI. The performance of all SPPs is described in four seasons spring, summer, autumn and winter in figures (**a**–**d**) respectively.

The probability density function (PDF) of daily precipitation estimates from satellite products was estimated (as shown in Figure 16) with reference to the in situ weather stations installed in Himalayan Mountains. The higher concentration of light precipitation was revealed by evaluating daily data obtained from the reference gauges. Light precipitation events, with intensity less than 2 mm/day, were more frequent (72.0%) in this region. CDR showed overestimation of light intensity (<2 mm/day) events, whereas PERSIANN and PDIR showed underestimation of light intensity events. All of the PERSIANN family products showed underestimations of medium intensity (10 mm/day) precipitation events, which revealed that these products are unreliable for the estimation of such events.

In the winter season, almost all SPPs showed underestimation of light precipitation events. In the case of the spring season, the PERSIANN product performed the best in terms of PDF for light to medium intensity precipitation events, according to the results. All products were unable to perform well in the summer season, as indicated by over and underestimations of almost all events. However, all products showed better performance as compared with the reference data in the autumn season.





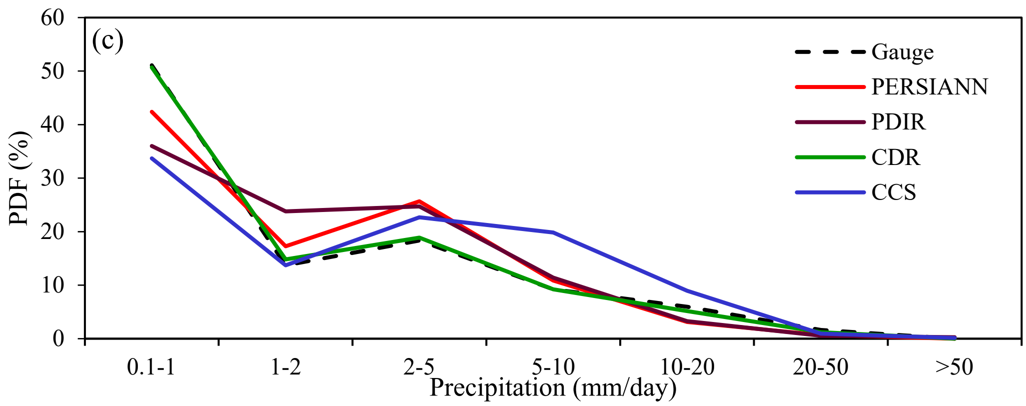


Figure 16. *Cont.*

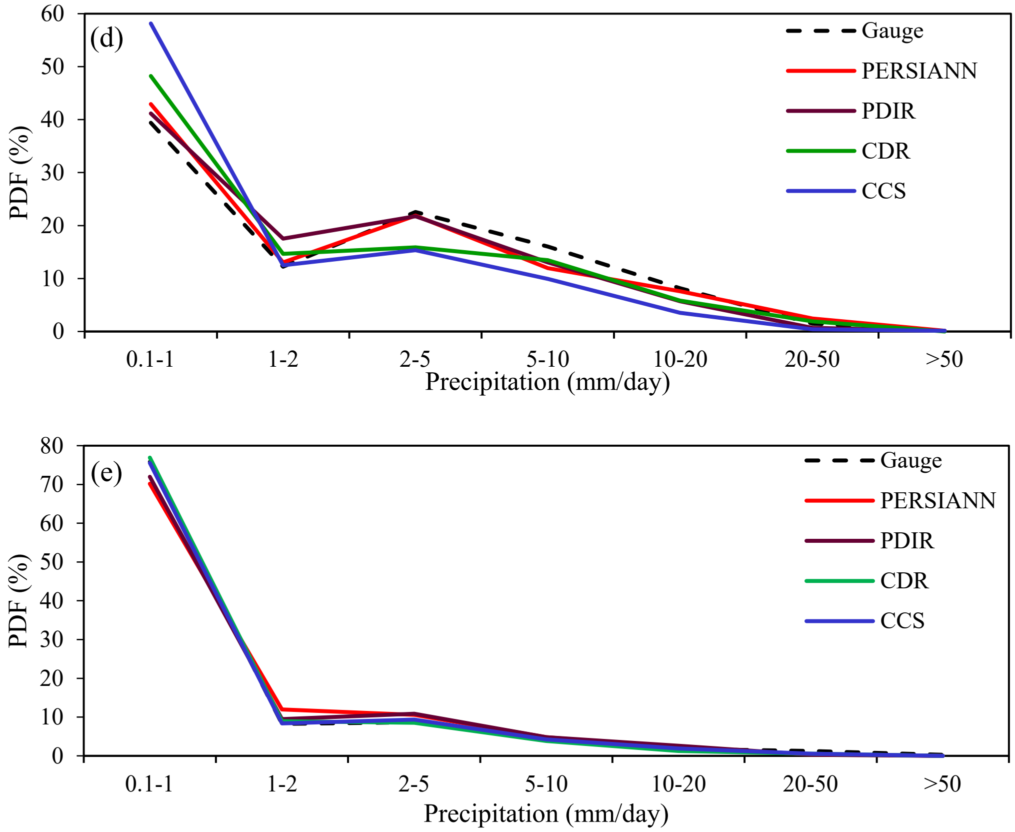


Figure 16. Probability density functions of PERSIANN, PERSIANN-CDR, PERSIANN-CCS, and PDIR products estimated against (**a**) daily, (**b**) winter season, (**c**) spring season, (**d**) summer season, and (**e**) autumn season observations over the Himalayan range.

4. Discussion

Using several statistical indicators, the accuracies of four satellite-based precipitation products (PERSIANN, PERSIANN-CDR, PERSIANN-CCS, and PDIR) were evaluated over the Himalayan Mountains of Pakistan. Many researchers have previously evaluated the performances of these SPPs in different climatic and topographic conditions. Previous studies have shown that regional climate system and topography can substantially influence the performance of satellite-based precipitation products [2,3,6,20,38,49,50]. In Malaysia [51], for example, the PERSIANN-CDR product's performance was compared to that of other satellite-based products [37]. It was found that the regional climatology and precipitation retrieval technique both had a significant impact on the accuracy of this product. Hamza [52] examined the performance of PERSIANN and SM2Rain products over the Hindu Kush Mountains and found that the values of BIAS and RMSE were considerably influenced by regional precipitation patterns, seasonality [53], and elevation

The current investigation also found that the climatic and topographic conditions had a substantial impact on assessment of the studied satellite products, which was comparable with previous findings in the mountainous regions [3,17,25,38]. The PERSIANN-CCS product was unable to perform better in comparison with other satellite products. The skills of PERSIANN and PERSIANN-CDR were in better agreement with in situ gauge data as compared to the PERSIANN-CCS product, which was confirmed by previous study in a similar topographic region [6,19]. Moreover, at 5% significance level, the dependence of correlation coefficients of all SPPs on the elevation and precipitation intensity was non-significant.

The assessments of PERSIANN and PERSIANN-CDR showed their better performance in terms of their ability to capture spatial and temporal variations of observed precipitation in the study area, which completely matched the results of [38]. Overall, the monthly scale estimates outperformed the daily scale estimates, which was in line with earlier research. In terms of CC, PERSIANN-CCS failed to perform on the seasonal scale. Despite the moderate CC values for PERSIANN, PDIR, and PERSIANN-CDR, the accuracies of all of these products were uncertain on the seasonal scale.

Generally, the low intensity precipitation events (less than 2 mm/day) are more common (>65% annually) in the Himalayan Mountains. Overall performance of the PERSIANN product, in terms of capability to detect the low intensity precipitation events, was better than other PERIANN family products. All PERSIANN family products showed better detection skills in the autumn season. However, the uncertainty of remote sensing data (Huang et al. [23], Shen et al. [54]) may also affect the research results.

Because sub-daily data were not available in the study area, the lowest temporal scale used in this study to evaluate the performances of four SPPs was daily resolution. At the sub-daily resolution, Shen et al. [54] found a significant difference in the performance of SPPs. Therefore, the findings of comparing four SPPs at the sub-daily scale, as well as the conclusions drawn from those comparisons, may be somewhat different from those drawn at the daily scale. Moreover, the uncertainty of remote sensing data [23,54,55] may also affect the research results.

5. Conclusions

Uncertainties in the daily, monthly, seasonal, and annual estimates of four satellite-based precipitation products of the PERSIANN family (PERSIANN, PERSIANN-CDR, PERSIANN-CCS, and PDIR) were assessed using the measurements of in situ weather stations installed in the Himalayan Mountains of Pakistan. Assessment of SPPs was carried out from January 2010 to December 2017. Following are the conclusions of this research:

- The PERSIANN and PDIR products reliably tracked precipitation in Pakistan's Himalayan range. However, the spatial variability of precipitation over the study area was difficult to reproduce using PERSIANN-CCS and PERSAINN-CDR products.
- The PERSIANN result accurately reproduced the temporal variability of the observed precipitation over the study area. All other products, including PERSIANN-CDR, PERSIAN-CCS, and PDIR, were unable to capture the precipitation's temporal variability.
- PERSIANN-CDR and PERSIANN-PDIR exhibited significant underestimation (−20.10% and −13.00%, respectively) of precipitation amounts, whereas PERSIANN and PERSIANN-CCS showed slight underestimation (−8.05% and −5.37%, respectively) of precipitation amounts over the study domain.
- On a monthly scale, all SPPs in the PERSIANN family performed better than on the daily scale.
- Generally, the liner agreement between the reference data and satellite-based data decreased with an increase in altitude. This revealed that the capabilities of SPPs to accurately represent the precipitation amounts at higher altitudes were poor.
- The linear agreement between the reference data and the satellite-based data were higher at higher precipitation intensities.
- PERSIANN and PDIR products exhibited good agreement with the reference data in all seasons; however, the overall performances of PERSIANN-CDR and PERSIANN-CCS were poor in all seasons.
- In terms of probability of detection, the PDIR outperformed all other family products.

The results of this assessment showed that the precipitation products PERSIANN and PDIR outperformed their counterparts, PERSIANN-CCS and PERSIANN-CDR, in the Pakistani Himalayan region. The correlation coefficient (CC) for PERSIANN and PDIR products was >0.70 on a monthly basis, and rBIAS was also within the acceptable range (±10%). As a result, we advocate the use of monthly estimates of PERSIANN and PDIR products for hydro-climatic studies in this region.

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