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A Three-Step Approach for Bias Adjustment of Satellite-Based Daily Precipitation Data

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Abstract

The study aims to propose and evaluate a simple approach to adjust daily satellite gridded data by considering ground-based data (i.e., from rain gauges). The corresponding algorithms were written in Python and a model was developed for that aim. The model can analyze any gridded satellite data over any geographic region of the world, this study presenting the application and evaluation of the model for mainland Portugal. Moreover, the recently-released (late 2020) PERSIANN-CCS-CDR product was selected for the study, having in attention that the referred satellite product provides relatively long-term precipitation records (1983-present) with high spatiotemporal resolution (0.04º x 0.04º spatial and 3-hourly temporal). The present comparison study was performed at both pixel (0.04º) and watershed scales. Regarding the latter spatial scale, three watersheds in mainland Portugal were chosen for the corresponding analysis. Overall, the satellite and the rain gauge datasets agree well at the monthly time level. The obtained results show differences between the two datasets at the daily time level, but the adjusted daily PERSIANN-CCS-CDR data are in good agreement with the corresponding rain-gauge data at both grid and watershed scales.

Keywords: Precipitation; Satellite product; PERSIANN-CCS-CDR; Bias adjustment; Portugal

1. INTRODUCTION

Complete and reliable daily precipitation data are crucial for hydrological studies on assisting water resources management decision-making processes. Traditionally, the precipitation records are obtained from ground-based rain-gauge stations, in which gaps in the data series are very frequent. Compared to the rain-gauge data, satellite-based precipitation products provide data that are more spatially homogeneous and temporally complete. However, the satellite products are just estimations that have various sources of uncertainty (Bui et al., 2019).

A preliminary bibliographic survey on related works shows that the PERSIANN family of global satellite precipitation data has attracted the attention of many researchers around the world, possibly because PERSIANN family offers several products at different spatial and temporal scales. The above-mentioned acronym stands for Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks. The PERSIANN family has been developed at the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California. It offers three main products: PERSIANN, PERSIANN-CCS (Cloud Classification System), and PERSIANN-CDR (Climate Data Record). A good review of the products has been presented by Nguyen et al. (2018). In short, the PERSIANN algorithm (Hsu et al., 1997) is based on the geostationary longwave infrared imagery to estimate hourly precipitation at each 0.25º x 0.25º pixel. The corresponding precipitation data are available for the period from 2000 to the present. PERSIANN-CCS product (Hong et al., 2004) utilizes more information from the infrared cloud images, compared to PERSIANN, and provides hourly precipitation data at a high spatial resolution of 0.04º x 0.04º for the period 2003-present. It should be noted that the two above-mentioned products are available at a time lag of, respectively, 2 days and about 1 h, intending to serve the needs for decision-making at short time lags. PERSIANN-CDR (Ashouri et al., 2015) uses a modified PERSIANN algorithm to provide long-term (1983-present) 3-hourly data at each 0.25º pixel. The bias in the PERSIANN-CDR estimates is reduced by considering monthly 2.5º precipitation data from the Global Precipitation Climatology Project.

The performance of the above-referred products has been investigated by many researchers. For example, Shen et al. (2010) evaluated PERSIANN data on a 0.25º grid over China using 3-year rain-gauge data (2005-2007). The results show that the correlation between the two datasets is 0.3-0.6 for 3-hourly precipitation over eastern China, while it is less than 0.4 when moving towards the west of China. In other words, PERSIANN data shows better performance (in terms of the correlation coefficient) over regions with wet climatology (i.e., the eastern part of China). The results at daily time-scale show mostly a higher correlation between the two datasets, compared to the sub-daily data. Gao and Liu (2012) evaluated the overall performance of PERSIANN data over the Tibetan Plateau (in China) by considering 6-year daily rain-gauge records from 2004 to 2009. A downscaling method was adopted to obtain the satellite-based precipitation time series at the location of the rain-gauge stations. A conclusion was that PERSIANN underestimates precipitation at low elevations (< 3500 m) and overestimates at high elevations. Recently, Salmani-Dehaghi and Samani (2019) assessed monthly precipitation data from PERSIANN family products over a province of Iran by considering the corresponding rain-gauge data during 2003-2015. The results show that monthly PERSIANN-CDR data performs better than the two other above-referred products. However, all products mostly underestimate the precipitation in different spatial scales over the study area. More recently, Alnahit et al. (2020) evaluated PERSIANN and PERSIANN-CDR products over two small watersheds (126 and 274 km^2) in the Seneca River basin (located in the USA) by considering the corresponding rain-gauge data (2001–2014). The comparison at the watershed scale indicates that the PERSIANN-CDR has better performance at both daily and monthly levels in terms of coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), and Percent bias (PBIAS). Alnahit et al. (2020) also evaluated PERSIANN and PERSIANN-CDR products using streamflow modeling. The corresponding results were compared with monthly observed streamflow values. The obtained results for PERSIANN-CDR data indicate a “good” performance of the product for the validation period of the hydrological model, while the corresponding results for PERSIANN show “unsatisfactory” performance. Gunathilake et al. (2020) assessed PERSIANN family products in daily streamflow modeling at Upper Nan River basin in northern Thailand. The corresponding results indicate the better performance of PERSIANN-CDR data (in terms of R^2 and NSE) than the two other products for both calibration (2003-2006) and validation (2007-2010) periods.

It should be mentioned that, in the literature, a bigger interest in the research on the PERSIANN-CDR product over the two other products may be found, possibly because of the better performance reported for that product. Nevertheless, the analysis of those research studies indicates that the performance of PERSIANN-CDR data varies in different geographic regions of the world. Some of these works are summarized below.

Duan et al. (2016) evaluated the accuracy of the PERSIANN-CDR gridded-data in the Adige River basin, located in Italy, at different temporal scales (daily, monthly and yearly). The corresponding comparison study was performed at the grid- and watershed-scale by considering the rain-gauge data from 2000 to 2010. The results show a poor correlation (about 0.3) between the PERSIANN-CDR and rain-gauge data at the daily scale, but a good correlation (0.75-0.95) for the monthly and yearly precipitation data (derived from, respectively, daily and monthly data). Alijanian et al. (2017) assessed the performance of the PERSIANN-CDR data over Iran for a ten-year period (2003–2012). The best correlation between daily satellite-based data and ground-based data (0.82) was observed in the south of Iran region (shore of the Persian Gulf) with a very hot and humid climate, while the lowest correlation (0.32) corresponded to the moderate and rainy regions (shore of the Caspian Sea in the north of Iran). Further, the monthly rainfall patterns were captured well by the PERSIANN-CDR data in different climate zones of the country (correlations: 0.72-0.85). Baez-Villanueva et al. (2018) analyzed the PERSIANN-CDR daily-data from 2001 to 2015 over three different watersheds in Latin America (in Brazil, Chile and Colombia). The analysis was mainly based on comparing the time series of the rain-gauge data with the corresponding grid-cell PERSIANN-CDR data (i.e., point to pixel analysis). The results show a better performance of the PERSIANN-CDR data, in terms of the modified Kling-Gupta Efficiency index, at the Chilean watershed than that at two other watersheds considered. El Kenawy et al. (2019) evaluated the performance of the PERSIANN-CDR daily-data over six countries in the Middle East for the period of 2000-2013. The Spearman’s rank correlation was calculated to assess the agreement between the rain-gauge and PERSIANN-CDR datasets. The corresponding results show different correlations (0.45-0.83) between two datasets at the country level.

Recently, late 2020, CHRS released the so-called PERSIANN-CCS-CDR product (Sadeghi et al., 2019). The method mainly combines the algorithms used in PERSIANN-CCS and PERSIANN-CDR and provides precipitation records from 1983 to the present with high spatiotemporal resolution (0.04^o x 0.04^o spatial and 3-hourly temporal). The new product is attractive since the high spatial resolution of the product makes it adequate for use in the hydrological studies of small catchments. Moreover, the corresponding long-term data records are useful for the calibration of the hydrological models using historical events.

To the best of the authors’ knowledge, there is not much information about the performance of PERSIANN-CCS-CDR product. Hence, this study analyzes this product over Portugal by considering the corresponding rain-gauge data (provided by APA, Agência Portuguesa do Ambiente, Portuguese Environmental Agency). For this aim, a Python script was developed to download, extract and analyze the data, taking into account that any satellite-based gridded data can be evaluated by considering the corresponding point rain-gauge records. The main objectives of the study are as follows:

i. Point to pixel comparison between rain-gauge and PERSIANN-CCS-CDR datasets;
ii. Comparing two precipitation datasets at the watershed scale;
iii. Introducing and applying a simple approach to reduce the possible differences between two datasets.

2. STUDY AREA AND DATA

Mainland Portugal, with an area of about 92212 km^2, is located in the Southwestern end of Europe. It is bordered by the Atlantic Ocean (West and South) and Spain (North and East); and is largely influenced by the Mediterranean and Atlantic climatic zones. Overall, the south of Portugal is warmer and drier than the north. Moreover, the distribution of average annual precipitation, shown in Figure 1 (left), indicates high precipitation (>1000 mm/year) in the northwest regions of the country and lower precipitation when moving towards south and east (mostly 500-1000 mm/year). The topography of Portugal, shown in Figure 1 (right), is steeper to the north and flatter to the south. The corresponding elevation ranges from the sea level to about 1950 m.

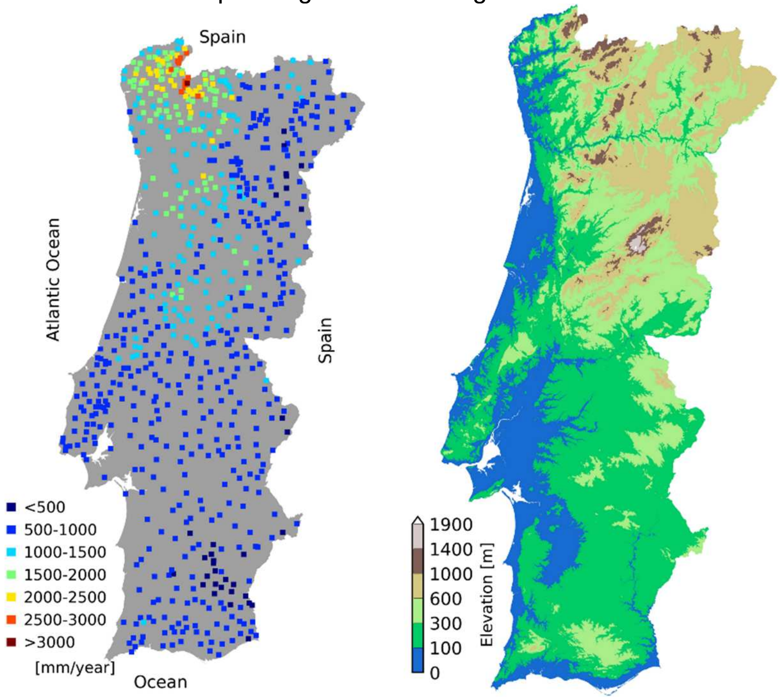

Figure 1. Distribution of average annual precipitation at mainland Portugal (left) and Portugal topographic map (right).

Figure 2 shows the percentage of the available daily rain-gauge data at each hydrological year from 1983 to 2020. Although 789 rain-gauge stations have been registered in the APA public-database (*https://snirh.apambiente.pt/index.php?idMain=*), 125 stations did not report any daily precipitation during the referred period (1983-2020). Therefore, those stations were excluded from the present analysis. The percentage of 100 indicates that all the studied stations (789-125=664) present the daily precipitation for all days of the corresponding hydrological year. It should be noted that the present analysis doesn't consider the operational interval (i.e., start date or/and end date) of rain gauges. Nevertheless, from Figure 2, one can see that the number of missing data is significant during 2009-2014. Hence, this study is focused on the data before 2009 (26 hydrological years) as treating missing rain-gauge data is not relevant to the scope of this study.

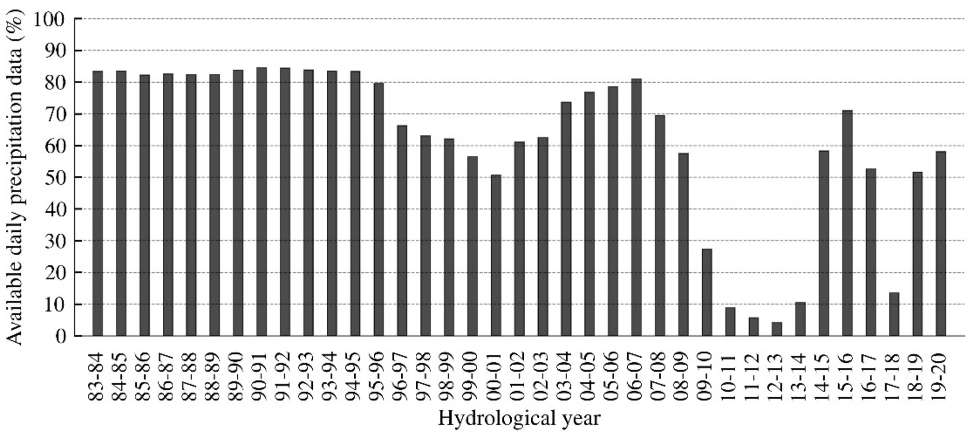

Figure 2. Percentage of the available daily rain-gauge data at each hydrological year over mainland Portugal.

It is to be noted that daily precipitation reported by APA corresponds to a 24 h period beginning at 09:00 AM of each day. It means that APA data is not directly comparable with the daily PERSIANN-CCS-CDR data that goes from 00:00 to 23:59 of the given date. To overcome the issue, at first, the gridded 3-hourly PERSIANN-CCS-CDR data were extracted from the CHRS database (*https://chrsdata.eng.uci.edu/*). Then, the new daily data (correspondent to APA methodology) were obtained by the accumulation of the 3-hourly data for each day from 09:00 AM to the same hour of the next day. Figure 3 shows the percentage of the corresponding adjusted-daily (hereafter daily) PERSIANN-CCS-CDR data available during 1983-2009. The percentage of 100 indicates that all the 0.04-degree grid cells (5821 cells covering the mainland Portugal) present the daily precipitation for all days of the hydrological year. To note that PERSIANN-CCS-CDR product has also missing 3-hourly records over the study area. Therefore, for the present analysis, the corresponding days were considered as the days with missing data and excluded from the analysis. As can be perceived from Figure 3, during the study period, the number of missing daily data is maximum in 1988-1989 (28%) and reaches zero with time.

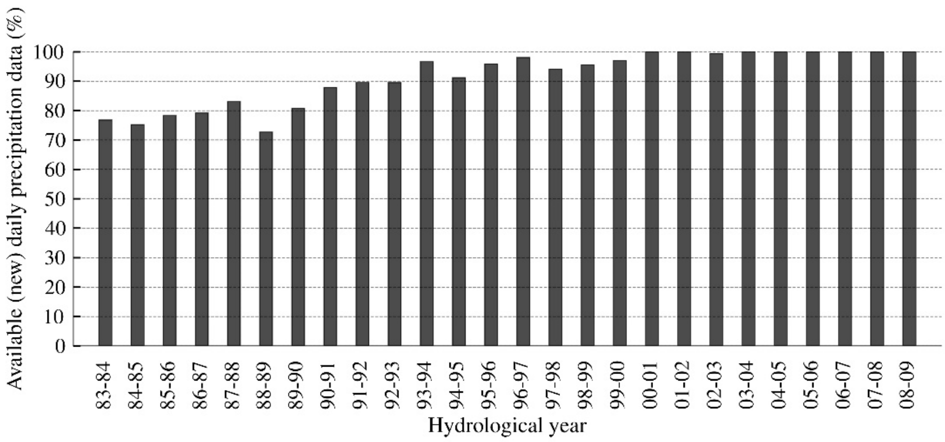

Figure 3. Percentage of the available daily PERSIANN-CCS-CDR data (obtained from 3-hourly data) at each hydrological year over mainland Portugal.

3. METHOD

3.1 Point to Pixel Analysis

The PERSIANN-CCS-CDR product is developed in the gridded format with a fairly fine resolution (0.04º ~ 4 km). In correspondence, the point to pixel analysis is done for each 0.04º pixel that includes a rain-gauge station (gauged pixel). Therefore, the precipitation data at a rain-gauge station is directly compared with the corresponding grid-cell (pixel) data at both daily and monthly time levels. Ideally, there should be 26-year data records for each dataset, but due to the missing data at both the rain gauge and PERSIANN-CCS-CDR datasets mentioned before, the comparison was performed between the data pairs. Concerning the monthly precipitation, the accumulation of the daily values was computed for each dataset for the complete months. A month is considered complete if it contains no missing daily data. The incomplete months were then neglected from the comparison. Figure 4 presents the number of data pairs for each gauged pixel in the percentage form. It is to be noted that the percentage of 100 indicates that the comparison was performed using all the expected daily and monthly data (i.e., 9497 days or 312 months) for each dataset.

3.2 Watershed-Scale Analysis

To achieve the goal of comparing the two precipitation datasets at the watershed scale, the time series of the spatially-averaged (mean) daily precipitation over each watershed was computed using both datasets and evaluated at daily and monthly time levels. For that aim, 16 watersheds (on a total of 17) in mainland Portugal were selected. The small and littoral watershed excluded, named Ribeiras do Alentejo, has no rain gauge data for the study period. To compute the mean value using the rain-gauge data, the Thiessen polygons defining the area of influence of the rain gauges on each of those watersheds were created. For the present evaluation, any station with a missing daily value was neglected from the averaging at the corresponding day. In this case, the precipitation record at each station is given a weight correspondent to the ratio of the area of the corresponding polygon to the total area of the polygons with available data. Moreover, a nominal criterion was defined in which the mean daily precipitation is computed if the area corresponding to the available rain-gauge data is at least 75% of the watershed area. Concerning the PERSIANN-CCS-CDR data, for each watershed, the arithmetic mean was calculated using daily data at the 0.04º pixels representing the watershed. The criterion of 75% of the watershed area, mentioned above, was also adopted for the gridded data to overcome the issue related to the missing data. Finally, the complete monthly precipitation values were also computed for each dataset.

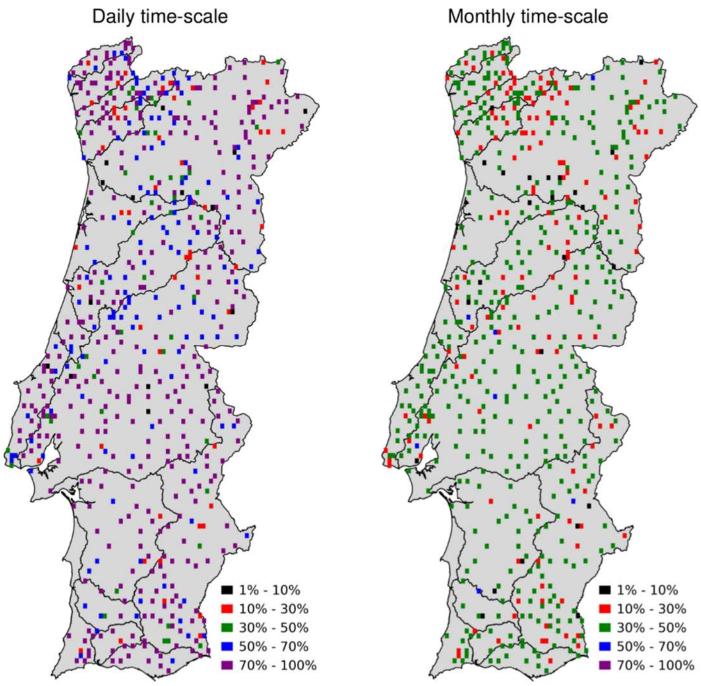

Figure 4. Number of daily/monthly data pairs at each gauged pixel. Note that 100% indicates all the expected values for the study period (i.e., 26 years = 9497 days = 312 months).

3.3 Adjustment of the PERSIANN-CCS-CDR Data

This study proposes and evaluates an approach for improving the quality of the PERSIANN-CCS-CDR data over mainland Portugal. The approach is mainly based on minimizing the difference between the satellite-based and gauge-based data over a common area.

Figure 5 (left) shows the distribution of the Portuguese rain-gauge stations over a grid with a resolution of 0.04º (latitude and longitude). As expected, in this case, there are many cells/pixels (inside the territory of mainland Portugal) that do not contain any rain-gauge station (i.e., reference data). Therefore, to overcome the issue, the differences between the two satellite- and gauge-based datasets were obtained by considering a 0.4º pixel grid frame. As shown in Figure 5 (right), every 0.4º pixel includes several rain-gauge stations, helping to compute the mean daily precipitation over the pixel for the days when there are some missing data.

In short, a three-step approach is proposed to adjust daily PERSIANN-CCS-CDR data at both gauged and ungauged 0.04º pixels as follows:

- The mean of the daily rain-gauge values is computed over each 0.4º pixel by considering the corresponding Thiessen polygons. Concerning the PERSIANN-CCS-CDR data, the arithmetic mean of the data is calculated. It is to be noted that the available data should cover at least one-third of the 0.4º pixel area.
- The difference between the two mean precipitation values is calculated at each 0.4º pixel. On some days, the mean precipitation might not be computed due to the corresponding missing values being exceeded. In this case, the difference between the two datasets at the target 0.4º pixel is estimated (using Inverse Distance Weighting interpolation technique) considering the differences between the two datasets at the neighboring 0.4º pixels.
- The difference between the two mean values at each 0.4º pixel, mentioned in the previous step, is added/subtracted to/from the corresponding 0.04º pixels PERSIANN-CCS-CDR data.

3.4 Evaluation Indicators

For this work, two evaluation indicators were selected to determine the relationship between the two datasets. (i) The correlation between the two series of precipitation data was computed using Eq. [1]. The correlation coefficient has a value between -1 and +1, where +1 indicates a perfect positive linear correlation, 0 means no linear correlation, and −1 is a total negative linear correlation. (ii) Root-mean-square error (RMSE) was calculated using Eq. [2] to quantify the difference between the two datasets. It varies from the optimal value of 0 to a large positive value.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad [1]$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}} \quad [2]$$

where, x and y represent two datasets; *n* denotes the number of data pairs and the overbar indicates mean quantities.

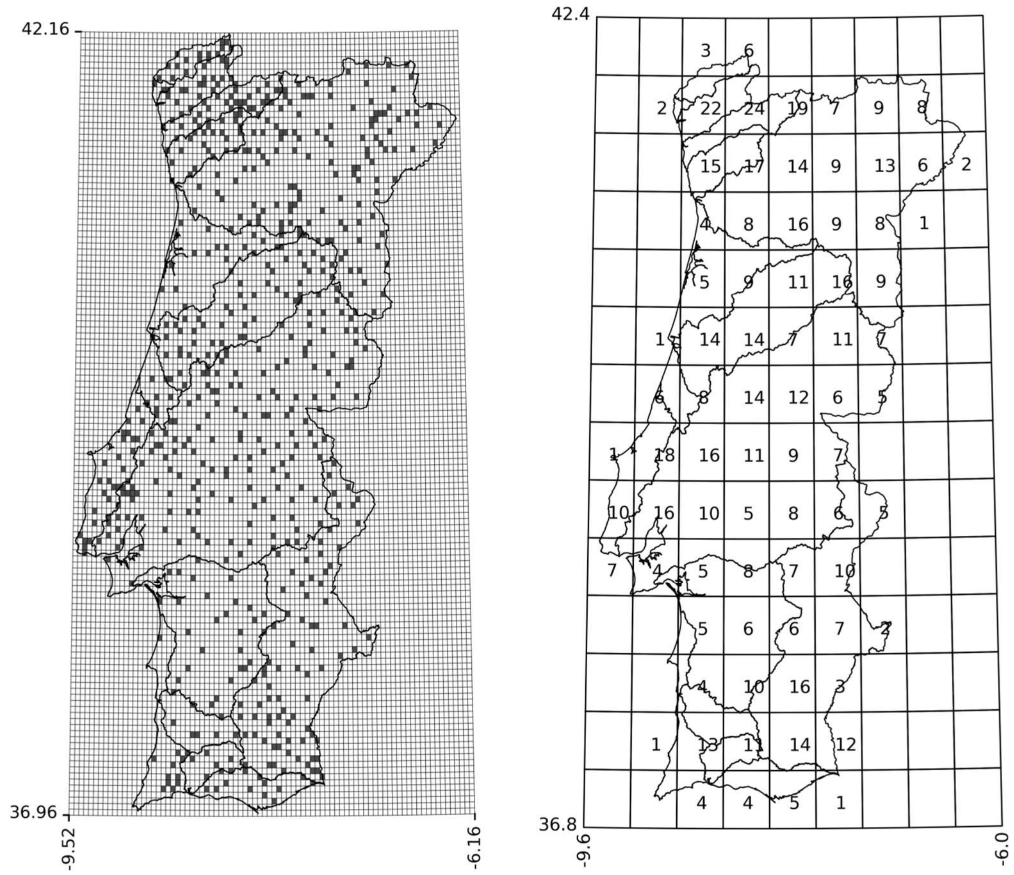

Figure 5. Distribution of the rain-gauge stations over mainland Portugal with two different grid systems: (left) 0.04º and (right) 0.4º. Note that the black squares on the left sub-figure represent the 0.04º pixels supported by at least one rain-gauge station. The numbers on the right sub-figure represent the number of Portuguese rain-gauge stations located at each 0.4º x 0.4º pixel.

4. RESULTS

Figure 6 presents the results of the point to pixel comparison between the two datasets at daily and monthly time levels over mainland Portugal. The corresponding results at the daily time scale indicate that, although the correlation coefficient varies from 0.07 to 0.35 over the country, the correlation between the two daily datasets is about 0.15 in most of the stations. At the monthly time level, the two datasets are in good correlation (mostly 0.6-0.97). It is noteworthy to recall here that PERSIANN-CCS-CDR uses the alghorithms employed in PERSIANN-CCS and –CDR in which the CDR data are bias-adjusted data using monthly data from Global Precipitation Climatology Project. Concerning the RMSE between the two datasets, at both time levels considered, the error is maximum for the northern Portugal region and it decreases when moving to the south.

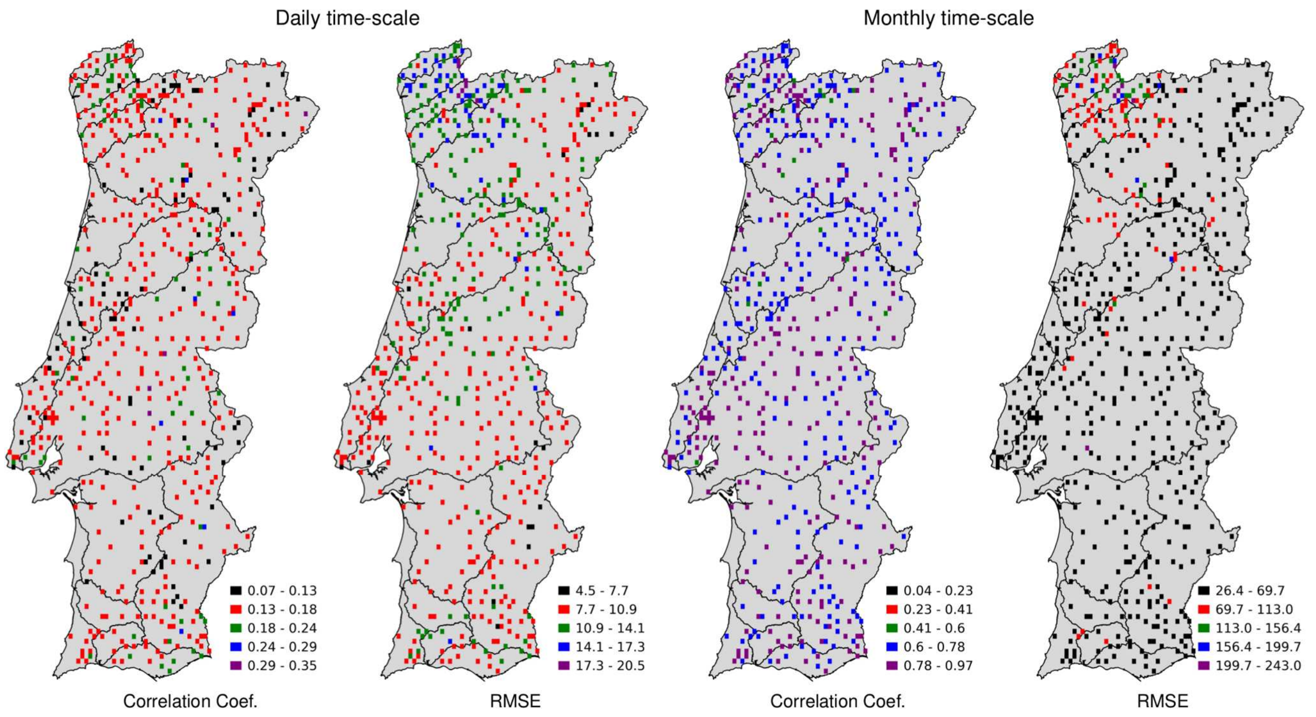

Figure 6. Point to pixel (0.04º) comparison (correlation coefficient and RMSE) between the two datasets (1983-2009) over mainland Portugal.

Figure 7 presents the results of the comparison between the two datasets at the watershed scale. As referred before, 16 watersheds were selected for this study. The obtained results show that the correlation between the two datasets is higher at the monthly time level than that at the daily level. Moreover, the correlation between the two datasets is slightly higher at the watershed scale compared to the pixel scale. For example, the correlation coefficient is about 0.24 and 0.87 (respectively at daily and monthly time-scale) over the Mondego watershed, whereas the point to pixel comparison over the Mondego shows a mean correlation value of about 0.15 and 0.7. Finally, the high differences between the two datasets are observed near the northern border of Portugal with Spain, where mostly high annual precipitation was reported.

Overall, according to the obtained results, PERSIANN-CCS-CDR data are not in agreement with those from the Portuguese rain-gauge stations at the daily time level, meaning that the above-referred satellite-based precipitation data could not be considered as a supplementary or surrogate source of the observational data in the hydrological studies over Portugal. Therefore, this study was aimed to assess a proposed adjusting precipitation data process.

For this work, the adjustment of the daily PERSIANN-CCS-CDR data using the approach presented in subsection 3.3 was performed over three watersheds (Douro, Mondego and Sado) for the period 1983-2009. The watersheds were chosen from Northern, central and southern Portugal to be mostly representative of the different precipitation characteristics. Figure 8 pictures temporal variations of the mean daily precipitation (using rain-gauge data and both direct and adjusted PERSIANN-CCS-CDR) over the selected watersheds from October 1983 to March 1984. One can see the differences and relative mismatch between the PERSIANN-CCS-CDR and rain-gauge datasets, while the adjusted PERSIANN-CCS-CDR data are in good agreement with the rain-gauge data. The above-referred agreement was also confirmed when the comparison is done for a longer period (i.e., 26 years) as shown in the corresponding scatterplots presented in Figure 9. The correlation coefficient significantly increased from 0.21-0.3 to 1 by adjusting the daily PERSIANN-CCS-CDR data. Moreover, the RMSE between the two mean daily time-series sharply decreased from 6.92 to 0.49 mm for Douro, 7.64 to 0.57 mm for Mondego and 6.98 to 0.44 mm for Sado. It is to be noted that all the available satellite-based data could be adjusted using the approach presented.

The improvement in the quality of the daily PERSIANN-CCS-CDR data was also evaluated by the point to pixel comparison over the three selected watersheds. The corresponding results, presented in Figure 10, show a mean correlation coefficient of about 0.8 between the adjusted PERSIANN-CCS-CDR data and rain-gauge data. It is noteworthy to mention that the coefficient was about 0.15 before adjusting the data. Moreover, the difference between the two daily datasets (in terms of RMSE) decreased in all the stations with area of influence over the above-referred watersheds.

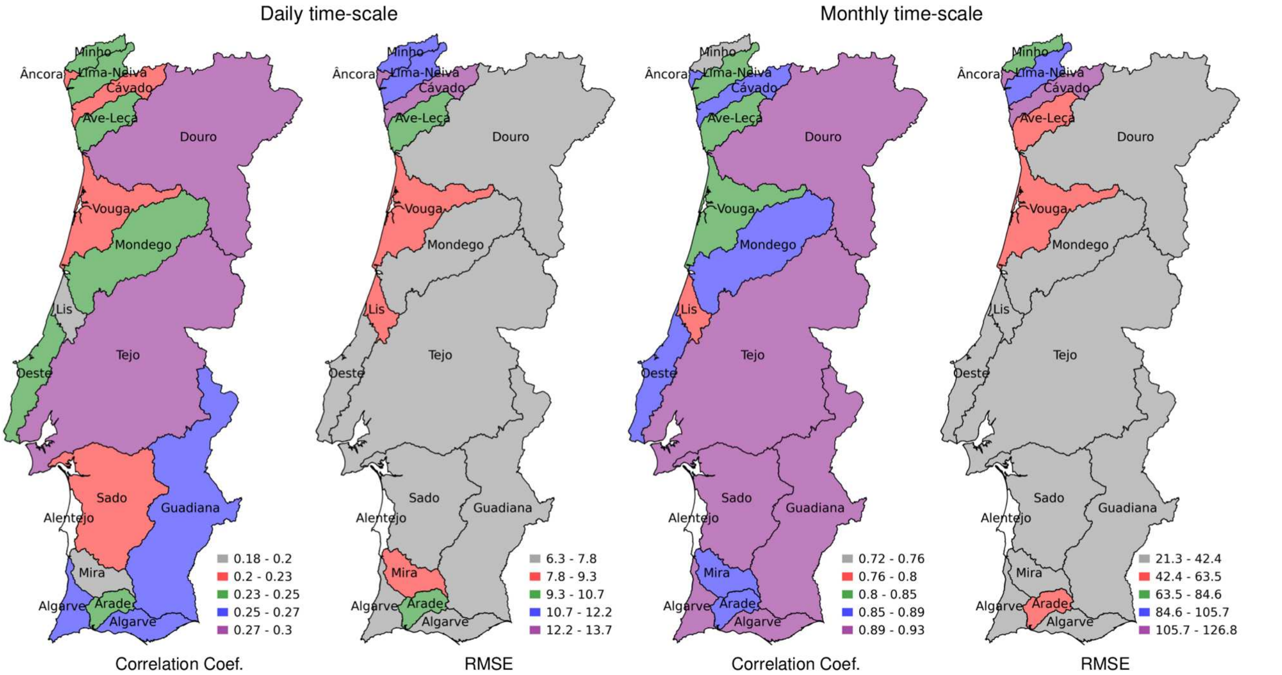

Figure 7. Comparison (correlation coefficient and RMSE) between the two datasets (1983-2009) at the watershed scale over mainland Portugal.

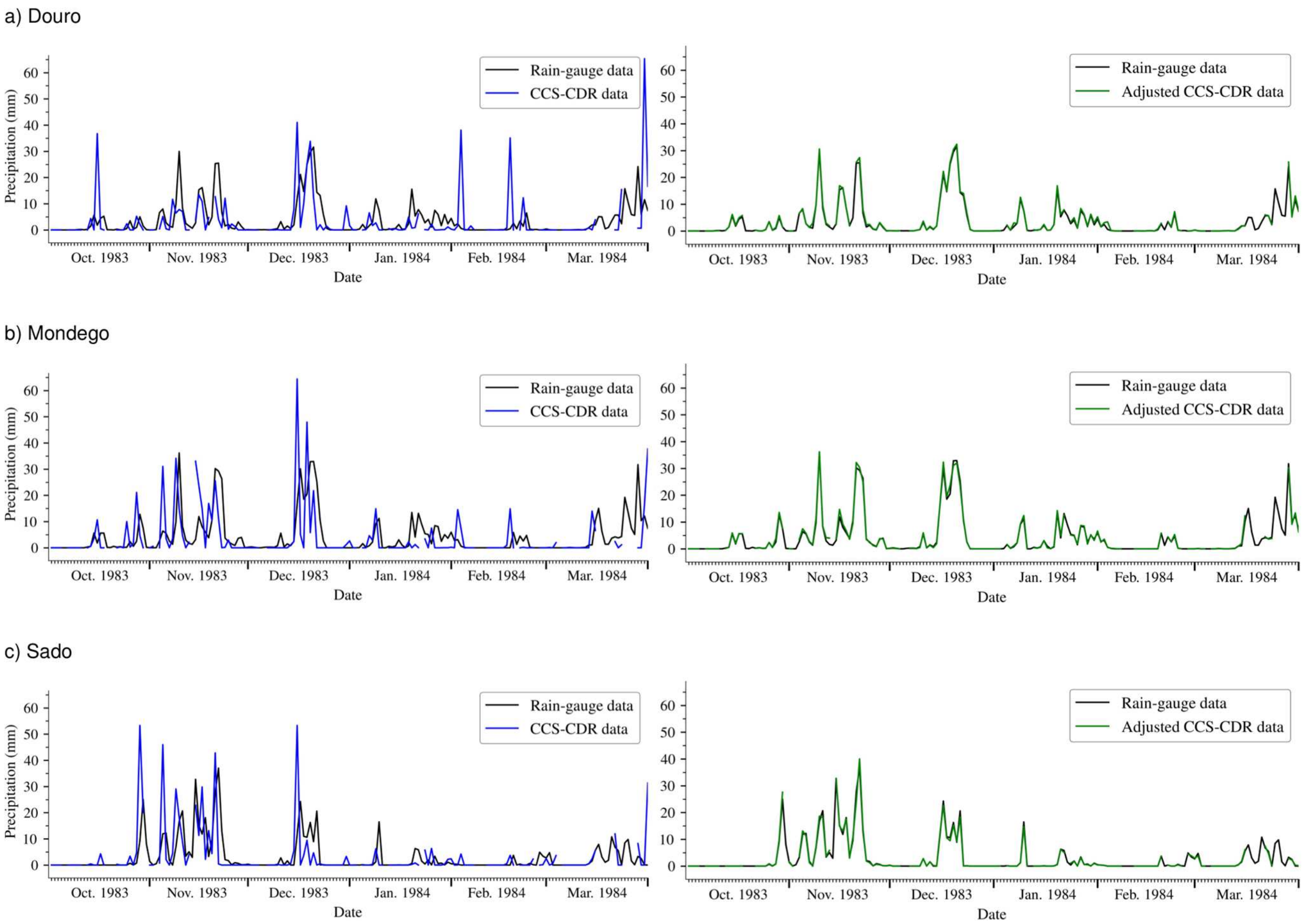

Figure 8. Time series of the mean daily precipitation (derived from the rain-gauge, PERSIANN-CCS-CDR, and adjusted PERSIANN-CCS-CDR data) for 10/1983-03/1984 over Douro, Mondego and Sado watersheds.

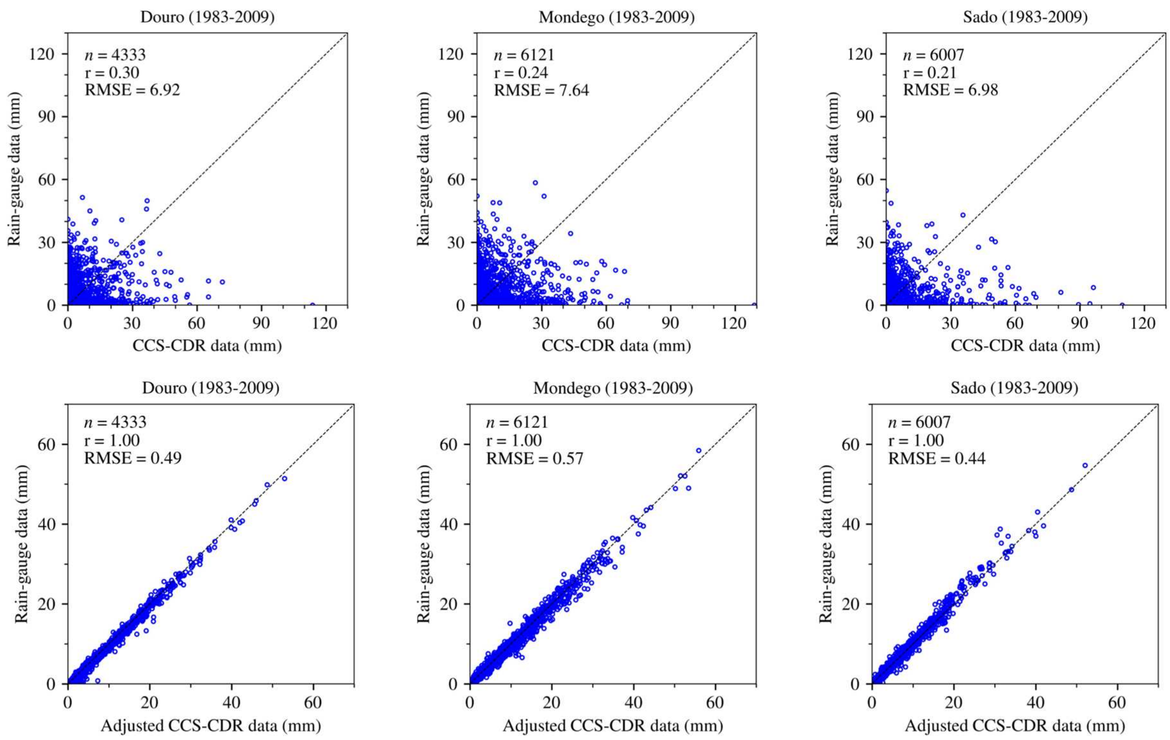

Figure 9. Scatterplots of the mean daily precipitation from the rain-gauge, PERSIANN-CCS-CDR, and adjusted PERSIANN-CCS-CDR data for 26 years (1983-2009) over Douro, Mondego and Sado watersheds.

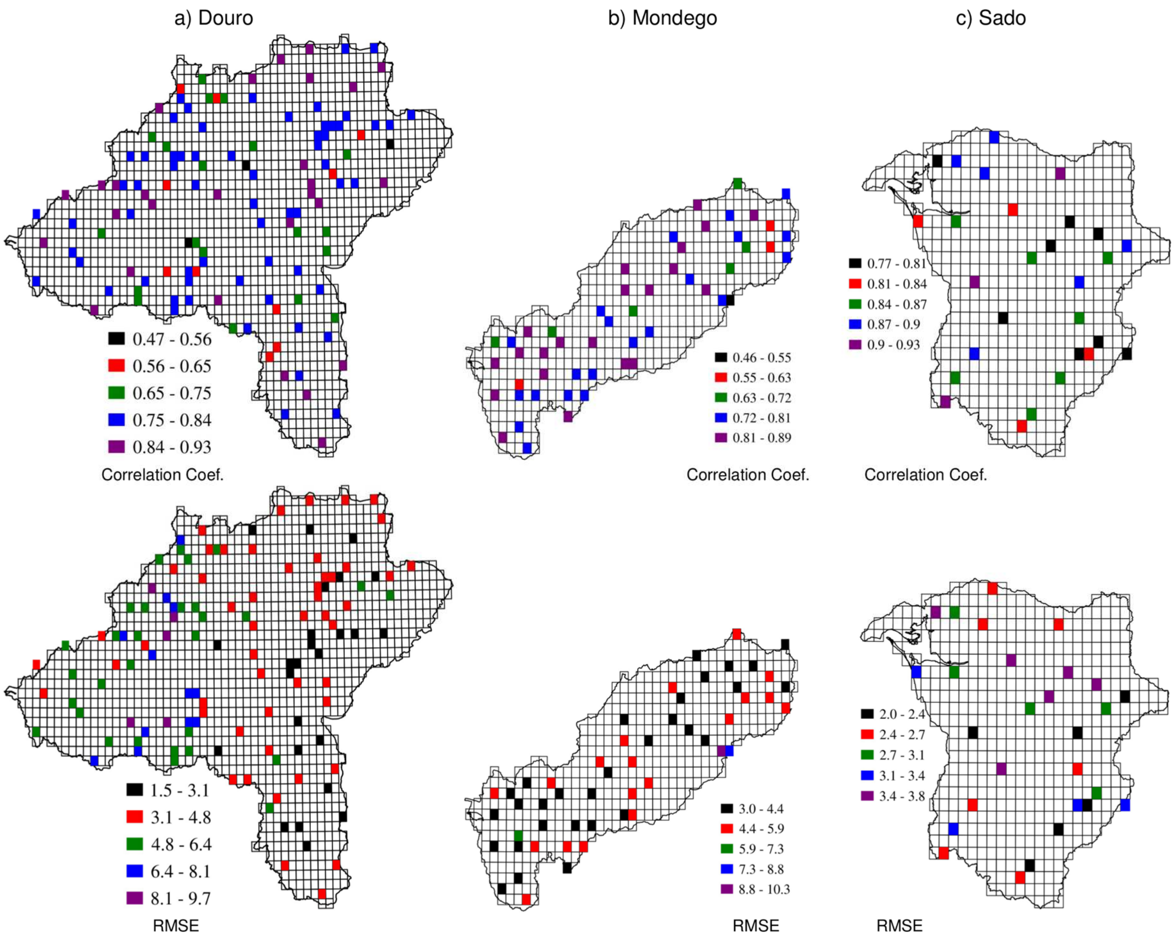

Figure 10. Point to pixel (0.04º) comparison (correlation coefficient and RMSE) between the adjusted daily PERSIANN-CCS-CDR and rain-gauge data during 1983-2009 over Douro, Mondego and Sado watersheds.

5. CONCLUSIONS

The study firstly evaluated the performance of the PERSIANN-CCS-CDR precipitation product through comparison with data from 664 rain gauges, during 1983-2009, over mainland Portugal.

A point to pixel analysis of daily and monthly precipitation was performed on a 0.04º grid over the entire country. The higher difference (in terms of RMSE) between the two datasets were observed at the rain-gauge stations located in northwestern Portugal, which receives higher precipitation compared to the rest of the country. Moreover, the correlation between the two daily datasets mostly varies between 0.13 and 0.18. At the monthly time level, the correlations increased to the range of 0.6-0.97 in most parts of the country.

An Increase in the spatial scale for the analysis (from pixel to the watershed) resulted in improving the agreement between the two datasets at both daily and monthly time levels. The spatially-averaged precipitation time series were estimated for 16 watersheds using both datasets. The corresponding correlation coefficients between the two monthly time series are between 0.72 and 0.93. Concerning the daily time level, the correlation coefficients are in the range of 0.18-0.3.

The study evaluated (as the goal of the paper) a simple approach proposed to adjust the PERSIANN-CCS-CDR precipitation data at the daily time-scale by considering the rain-gauge data. The presented approach was applied on three watersheds located in the northern, central and southern part of mainland Portugal. The comparison between the adjusted daily PERSIANN-CCS-CDR and rain-gauge data shows a very good agreement between the two datasets at both pixel and watershed scales. For example, at the watershed scale, the correlation coefficient increased from 0.21-0.3 to 1 and RMSE decreased from 6.92-7.64 to about 0.5 mm. At the pixel scale, the new correlation coefficients mostly vary between 0.72 and 0.93, showing the improvement of the PERSIANN-CCS-CDR data quality over the study area.

Overall, the study suggests evaluating the PERSIANN-CCS-CDR product locally and, if (most often) necessary, performing the adjustment procedure.

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