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Evaluation of Satellite Rainfall Estimates in the Pra Basin of Ghana

Collins Owusu [1] · K. A. Adjei [1] (iD) · S. N. Odai [1]

Abstract

Availability of gauged rainfall data in most developing countries at good resolution is usually a challenge since meteorological stations are usually located near urban areas. In cases where data is available some stations may still have a lot of missing values. However, in recent times, satellite derived rainfall estimates provide an alternate source of rainfall data in areas where conventional rainfall measurements are not readily available. This study evaluated the accuracy of three satellite rainfall products, TMPA 3B42RT, TMPA 3B42 and CMORPH, in the Pra basin of Ghana. Using the point-to-pixel method, data extracted from $0.25° × 0.25°$ satellite grids were compared with gauged rainfall measurements and analyzed using correlation coefficient (r), bias and percent bias (%Bias) as the performance evaluation methods. Seven (7) gauge stations with no missing data for the period 2003–2008 were used in the evaluation. The results, following the analysis of the data at daily, monthly, annual and seasonal timescales, showed that TMPA products performed better on all timescales considered. CMORPH on the other hand showed overestimation at all gauge locations. The TMPA 3B42 was seen to be the best amongst the three products. The overall rainfall in the basin was well depicted by the TMPA 3B42 and 3B42RT. Although there was not a perfect match between the 3B42RT and 3B42 products and the gauged rainfall, these products can be used to supplement gauged rainfall measurements in the basin and in estimation of rainfall in ungauged basins with similar characteristics.

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1 Introduction

Rainfall is a vital component of the hydrological cycle. It is an important atmospheric input into land surface hydrologic models. Rain gauges provide direct point measurements whose accuracy will result in reliable rainfall-runoff models. To achieve a satisfactory prediction from rainfall-runoff models, a network of well distributed rain gauges is required. Availability of a dense network of rain gauges is quite rare in developing countries like Ghana due to the limited budget allocated to meteorological agencies (Adjei et al. 2011). Even in cases where there are areas with relatively dense gauge network there still exist the challenge of unreliable records, large proportion of missing values and limited access to available data (Dinku et al. 2007).

Satellite-based Rainfall Estimation (SRFE) products have a huge potential as an alternative source of data in regions where conventional rainfall measurements are not readily available or inadequate due to their high spatial and temporal resolution. Satellite-based rainfall estimation instruments collect data mainly at the thermal infrared (TIR) and passive microwave (PMW) wavelengths which are used to estimate rainfall rates (Kidd et al. 2012; Qin et al. 2014). The satellite systems are divided into two: geosynchronous earth orbit (GEO) satellites and low earth orbit (LEO) satellites. The GEO satellites use thermal infrared (TIR) sensors (Qin et al. 2014) and have revisit times of 15–30 min (Bitew and Gebremichael 2011), while the LEO satellites have passive and active microwave (MW) sensors. Many satellite rainfall retrieval/estimation algorithms have been developed to estimate rainfall by using either TIR or MW or a combination of both to take advantage of their strengths.

The Tropical Rainfall Measuring Mission (TRMM) Multisatellite Rainfall Analysis (TMPA) method (Huffman et al. 2007) uses both MW and TIR. This method creates an estimate that contains MW-derived rainfall estimates when and where MW data are available, and uses MW data to calibrate the IR-derived estimates when MW data is not available. The TMPA produces two versions of rainfall products: near-real-time version (3B42RT) and post-real-time research version (3B42). The 3B42 uses monthly rain gauge data for bias adjustment. The Climate Prediction Center (CPC) Morphing technique (CMORPH) method (Joyce et al. 2004) uses rainfall estimates that have been derived from low orbit satellite microwave observations exclusively. TIR imagery is used to interpolate between two PMW-derived rainfall intensity fields but not for rainfall estimate.

Satellite-based rainfall products have their own shortcomings since they are not direct estimates of rainfall. Some sources of error include gaps in revisit times, poor relationship between rainfall rate and satellite signals, and atmospheric effects (Bitew and Gebremichael 2011). It is therefore crucial to evaluate the accuracies of these products by comparing them with rain gauge data or based on their ability to simulate streamflow in a rainfall runoff model. The first method is considered in this study. Little work has been done to evaluate the suitability of satellite-based rainfall data in Ghana. A study by Adjei et al. (2011) in the Black Volta basin of Ghana compared rain gauge measurements with TRMM satellite rainfall estimates and the prospect of using the satellite estimates to complement ground measured rainfall.

The Pra basin in Ghana (Fig. 1) is an area where satellite-based rainfall could be very vital since the distribution of reliable rain gauge stations is skewed to the upper part of the catchment (Fig. 2) and also not well distributed. This study, therefore, evaluates how well TMPA 3B42, TMPA 3B42RT and CMORPH rainfall estimates compares with rain gauged ones in the Pra basin of Ghana.
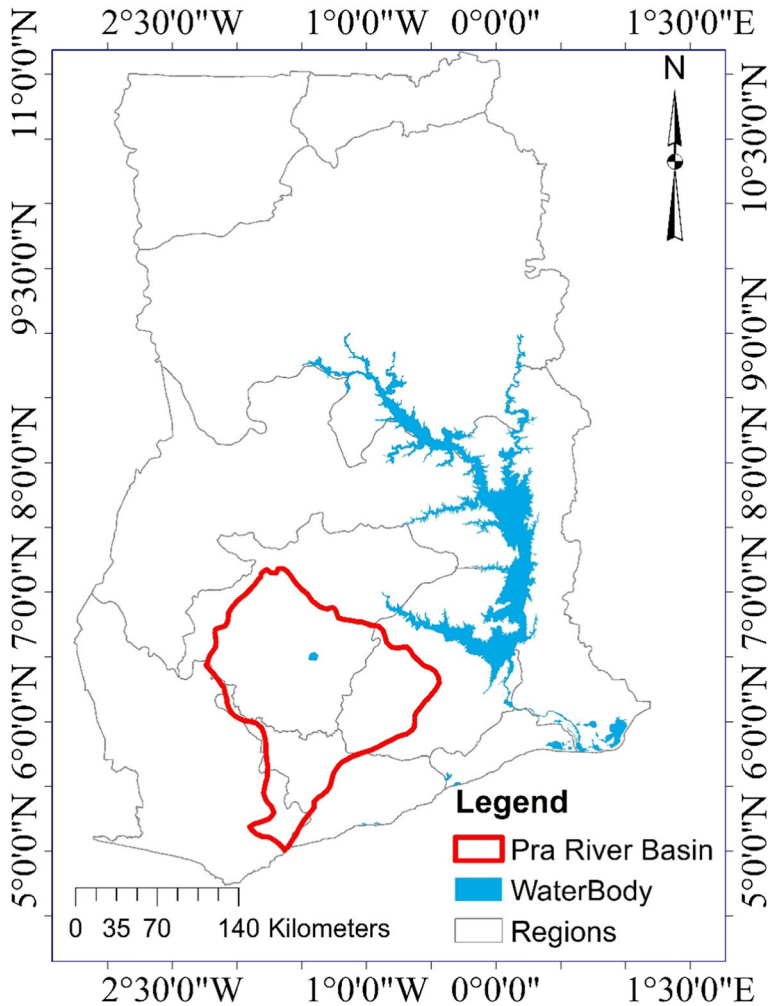
Fig. 1 Location map of the study area

2 Materials and Methods

2.1 Description of Study Area

The Pra Basin is located between latitudes 5°N and 7° 30'N, and longitudes 2° 30'W and 0° 30'W, in south-central Ghana. The total area of the basin is approximately 23,330 km² (Fig. 1). The topography is characterized by fairly flat land in the south with few mountains in the middle to northern sectors of the basin. The peak elevations in the basin are situated in the north and eastern borders with elevations of up to 800 m above sea level. Vegetation of the basin is of moist semi-deciduous forest type. The main land cover types in the basin are agricultural land (60%), forest (30%), grassland and human settlement (10%). The basin is also characterized by isolated forest reserves and large commercial tree plantations (WRC 2012). The basin has two rainy seasons: a major season (March to July), and a minor season
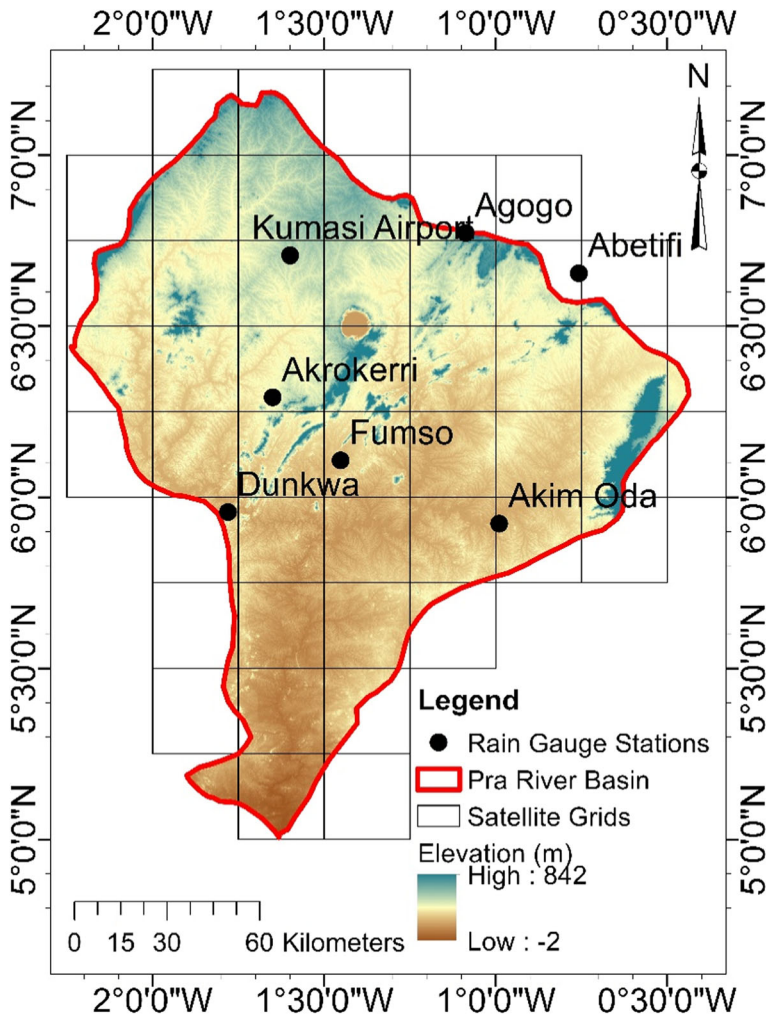
Fig. 2 Spatial distribution of gauge stations and satellite grids

(September to November) (Owusu and Waylen 2013) as cited by (Nkrumah et al. 2014). The annual rainfall ranges from 1300 mm to 1900 mm with a mean of 1500 mm. The relative humidity ranges between 70%- 80% and the average maximum and minimum temperatures are 31 °C and 21 °C, respectively (Akrasi and Ansa-Asare 2008).

2.2 Data Sources and Processing

2.2.1 Gauged Rainfall Data

Ground measured daily rainfall data (Table 1) for the study period 2003–2008 obtained from the Ghana Meteorological Agency (GMET) was used as a reference to assess the accuracy of satellite-derived rainfall estimates (Table 2). The choice of the study period was based on a common time between gauges and the SRFEs where the selected gauges had no missing data.

Using Thiessen polygon analysis of the rain gauge network in and around the Pra basin, 22 gauge stations were found to have influence on the basin. Of the 22 stations identified, some had several years of missing data and others had very short durations. Seven out of the 22 stations (Table 1) were found to have no missing data for the period under study, and were therefore used in the analysis. Locations and distributions of the 7 stations can be seen in Fig. 2.

2.2.2 Satellite Rainfall Data

The TMPA 3B42 and 3B42RT (version 7) (Table 2) have 3-h temporal resolution and a 0.25° × 0.25° spatial resolution (Fig. 2) in a global belt extending from latitude 50°S to 50°N. The 3B42RT is the near-real-time experimental version and the 3B42 is the post-real-time research version which is adjusted by monthly rain gauge data. 3B42RT is released in about 9 h after real time and 3B42 in about 10–15 days after the end of each month. The TMPA data used in this study was acquired using the Interactive Online Visualization and Analysis Infrastructure (Giovanni) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

   The Climate Prediction Center morphing method (CMORPH) (Table 2) rainfall estimates are available on 0.07277° × 0.07277° spatial resolution over the global 60°S to 60°N in 30 min temporal resolution. The 0.25° × 0.25° and 3-h resolution version was used in this study. The CMORPH dataset was obtained from the Climate Prediction Center, National Weather Service, NOAA, U.S. Department of Commerce.

2.2.3 Data Processing

The TMPA data was exported in ASCII format from the source which was then processed with a text editor. The accumulated rainfall for the 3-h 0.25° × 0.25° grids were imported to a spreadsheet after processing. Daily accumulated rainfall was then computed for each grid for a particular day by summing the 3-h rainfall from 9 am on that day to 9 am the next day in accordance with the time span used by GMET in measuring daily rainfall in Ghana. The 0.25° × 0.25° grid map was plotted together with the rain gauge locations. Comparison of the satellite rainfall estimates with gauge measurements was carried out using the point-to-pixel method. Rainfall data observed from selected stations were compared with respective satellite rainfall estimate for the grid within which the stations were located. This method was used in a study conducted by Thiemig et al. (2012) in which they validated Climate Prediction Center (CPC) morphing technique (CMORPH), the Rainfall Estimation Algorithm, version 2

Table 1 List of rain gauges used in the study

Station	Location	Latitude	Longitude	Elevation (m)	Type
1	Abetifi	6.67	−0.75	594.7	Synoptic
2	Agogo	6.78	−1.08	457.5	Other
3	Akrokeri	6.30	−1.65	261.4	Other
4	Dunkwa	5.97	−1.78	158.6	Other
5	Fumso	6.12	−1.48	147.1	Other
6	Kumasi Airport	6.72	−1.60	286.3	Synoptic
7	Akim Oda	5.93	−0.98	139.4	Synoptic

Table 2 List of satellite rainfall products used in the study

No.	Name	Resolution		Latency	Corrected by gauges
		Spatial	Temporal		
1	TMPA 3B42	0.25°	3 h	10–15 days	Yes
2	TMPA 3B42-RT	0.25°	3 h	9 h	No
3	CMORPH	0.25°	3 h	18 h	No

(RFE2.0), Tropical Rainfall Measuring Mission (TRMM) 3B42, Goddard profiling algorithm, version 6 (GPROF 6.0), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), Global Satellite Mapping of Precipitation moving vector with Kalman filter (GSMap MVK) satellite products over four basins in Africa.

The CMORPH 3-h 0.25° × 0.25° grids were downloaded in net CDF file format. The files for each year were combined into one file by using NCO software (net CDF Operators). The final net CDF files were imported into a spreadsheet using NetCDF4Excel. The summary of the methodology used in this study is shown in Fig. 3.

2.3 Performance Assessment

To assess how well the satellite rainfall products performed against the rain gauge measured values quantitatively, the following set of performance statistical methods were used: correlation coefficient (r), bias and percent bias (%Bias) (Eqs. 1–3). Statistics were calculated for daily, monthly, yearly and seasonal time series.
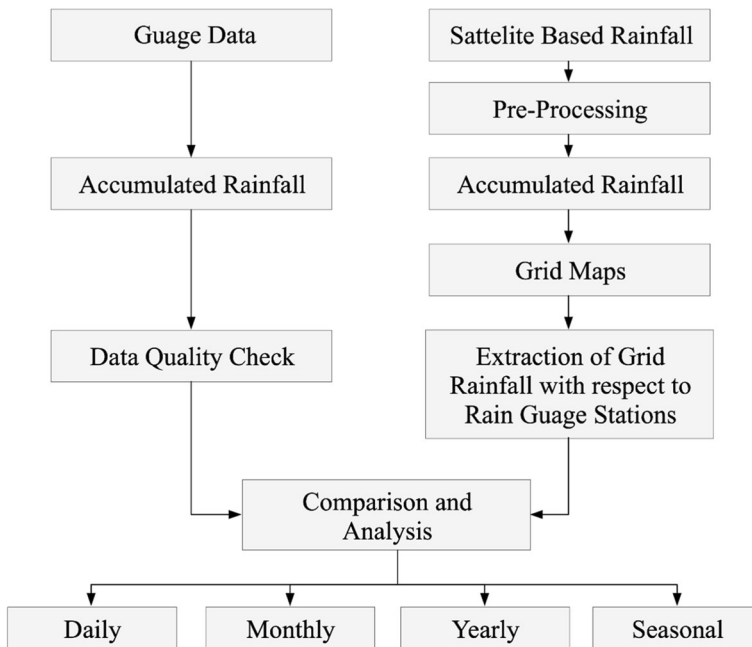
Fig. 3 Flowchart of methodology of rainfall analysis

$$Correlation\ coefficient = \frac{\sum_{i=1}^{n}\left(G_i - \overline{G}\right)\left(S_i - \overline{S}\right)}{\sqrt{\sum_{i=1}^{n}\left(G_i - \overline{G}\right)^2} \times \sqrt{\sum_{i=1}^{n}\left(S_i - \overline{S}\right)^2}} \qquad (1)$$

$$Bias\ (mm) = S_i - G_i \qquad (2)$$

$$pBIAS = \frac{\sum_{i=1}^{n}(S_i - G_i)}{\sum_{i=0}^{n} G_i} \times 100 \qquad (3)$$

where: S is the satellite estimated value; G is the rain gauge value; n is the number of samples; $\overline{S}$ is the mean satellite estimated value; and $\overline{G}$ is the mean rain gauge value.

The correlation coefficient measures the strength of the linear relationship between the gauge observations and the satellite estimates. The percent bias measures the average tendency of the satellite estimates to be larger or smaller than the average gauge values (Yapo et al. 1996). Positive and negative values indicate overestimation and underestimation, respectively.

3 Results and Discussion

3.1 Daily Rainfall Analysis

Coefficient of correlation (R) and percent bias (%Bias) were computed for the TMPA 3B42, TMPA 3B42-RT and CMORPH products. All the satellite products considered showed a moderate positive linear relationship ranging from 0.31 to 0.58 (2192 comparison pairs per station) on a daily time scale (Fig. 4). CMORPH performed the best, with a maximum R of 0.58 and a mean value of 0.51. The results obtained are similar to findings by Chen et al. (2014) who evaluated high resolution precipitation estimates from satellites in Beijing. Yong et al. (2012) and Dinku et al. (2010) also showed similar ranges of R obtained for both TMPA 3B42 and TMPA 3B42-RT.

CMORPH had a relatively high tendency (Fig. 5) of overestimating the rainfall (32–44%). Similar overestimation characteristics of the CMORPH were also observed in the study by Cohen Liechti et al. (2012) over the Zambezi river basin and Chen et al. (2014) in Beijing. On the contrary, studies by Romilly and Gebremichael (2011) and Moazami et al. (2016) reported that CMORPH always underestimated gauged rainfall measurements. However, their studies were conducted over complex high-terrain areas, and in different climatic conditions compared to the area under study. TMPA 3B42 and TMPA 3B42-RT recorded maximum 14.2% and 17% tendencies of overestimation, respectively, at 6 out of the 7 stations considered. This tendency of TMPA 3B42 and 3B42-RT to overestimate gauged rainfall measurements were also observed in previous similar studies (Yong et al. 2012; Dembélé and Zwart 2016; and Sahlu et al. 2017). Although the satellite products did not perform very well on a daily timescale at the station level, a scatter plot of the average daily rainfall from all 7 stations versus the average from each of the satellite rainfall estimates (Fig. 6) showed a good correlation with values between 0.72 and 0.76. Similar results were also reported in studies by Su et al. (2008) and Yong et al. (2012). This shows that the average daily rainfall in the basin is well represented by all the satellite products reviewed.
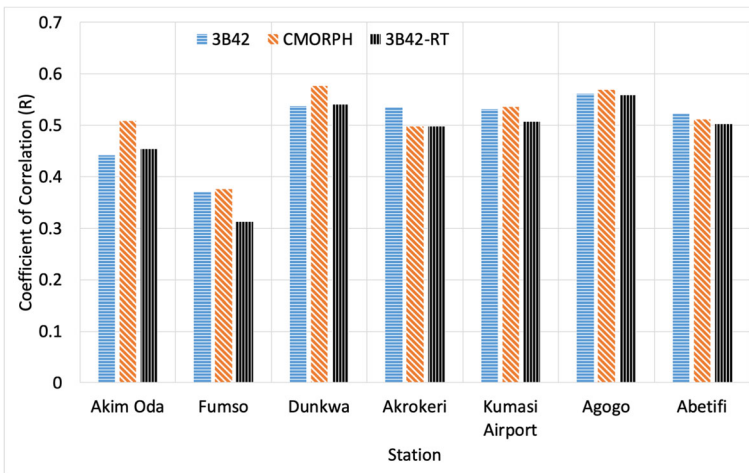
Fig. 4 Correlation coefficient (R) between the daily rainfall records obtained from the SRFEs and the rain gauges for the study period at the various stations

3.2 Monthly Rainfall Analysis

Coefficient of Correlation (R) was computed for all the monthly rainfall at the 7 selected stations. An analysis was carried out to assess if there was any relationship between the elevation of the stations and the computed R for each of the satellite products. A study conducted by Romilly and Gebremichael (2011) in some basins in Ethiopia revealed that bias in satellite rainfall estimates depended on elevation. However, no clear relation (Fig. 7) was observed between the correlation coefficient and the elevations of the stations in this study. This assertion is also confirmed by the results of a similar study by Adjei et al. (2011) in a similar basin in Ghana.

The computed R for all the stations and satellite products ranged from 0.50 to 0.91 (144 monthly observations) and showed a moderate to strong positive linear relationship between the SRFEs and rain gauge values on a monthly time scale. The TMPA 3B42 had a very strong
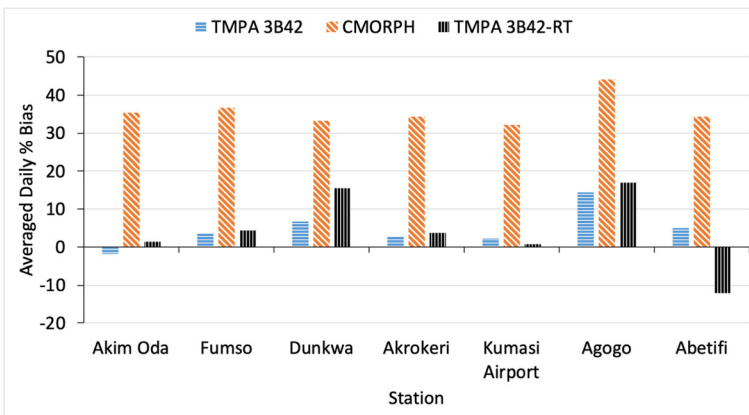

Fig. 5 Average percent bias (% Bias) of daily rainfall obtained from the SRFEs and the rain gauges for the study period
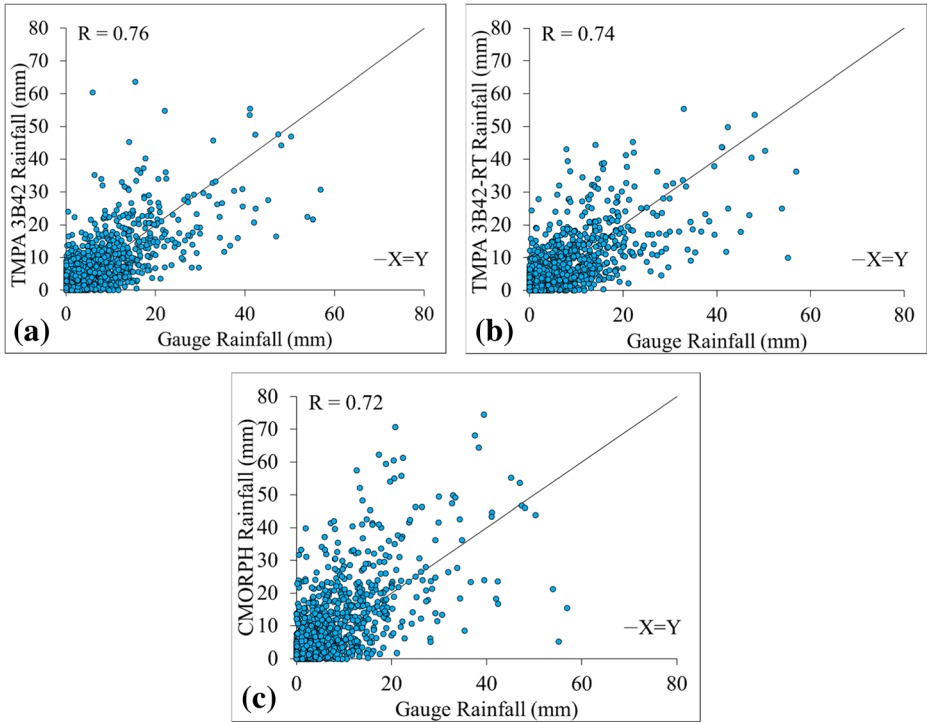
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Fig. 6 Plot of averaged daily rainfall (mm) from all 7 stations obtained from SRFEs versus rain gauges: **a** TMPA 3B42; **b** TMPA 3B42-RT and (**c**) CMORPH, 2003–2008 [Coefficient of Correlation (R)]

linear relationship with the gauged rainfall with R ranging from 0.70 to 0.91. The study of the TMPA 3B42 by Adjei et al. (2011) in the Black Volta basin of Ghana also showed similar
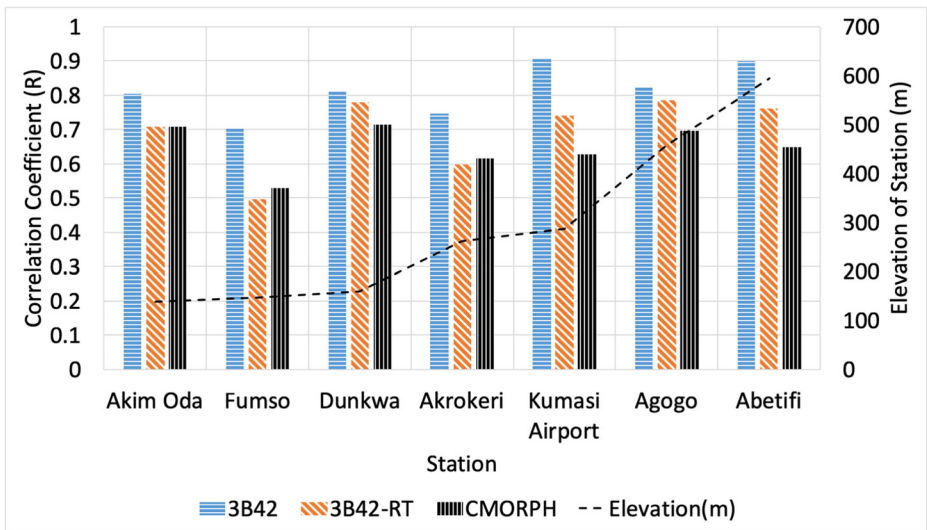

Fig. 7 Correlation coefficient (R) between the accumulated monthly rainfall records obtained from the SRFEs and the rain gauges for the study period at the various stations and a plot of the elevations of the various stations

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range of R with a maximum of 0.88. TMPA 3B42-RT (0.50–0.79) and CMORPH (0.53–0.72) showed a moderate to strong linear relationships, although the CMORPH tended to mostly overestimate the rainfall at all 7 stations. Analysis (Fig. 8) of the correlation between average accumulated monthly rainfall from all the stations in the basin showed a very good performance for all satellite products. The TMPA 3B42 showed an excellent performance with an R of 0.95. This strong performance was also reported in the study by Adjei et al. (2011). CMORPH showed the weakest correlation but still had a strong positive correlation (Fig. 8c) of 0.72. However, the high tendency of CMORPH to overestimate the recorded rainfall was again observed as it overestimated the rainfall in 42 out of the total 72 months analyzed.

A plot of the average monthly error bias for all the 7 stations was carried out to see the extent of overestimation or underestimation by the SRFEs (Fig. 9). The total number of months for which rainfall was overestimated by the satellite products far exceeded that of underestimation. TMPA 3B42 and 3B42-RT had an average overestimation of 5.09 mm and 4.94 mm, respectively, while CMORPH grossly overestimated the measured rainfall with an average bias of 40.25 mm. All the satellite products considered in this study on the average overestimated the monthly gauged rainfall in the basin. On the contrary, previous studies (Adjei et al. 2011; Dembélé and Zwart 2016) showed that the TMPA products on the average underestimate the monthly rainfall. The differences in findings with respect to the monthly bias can be attributed to differences in climatic zones resulting in different characteristics in the accumulated rainfall.
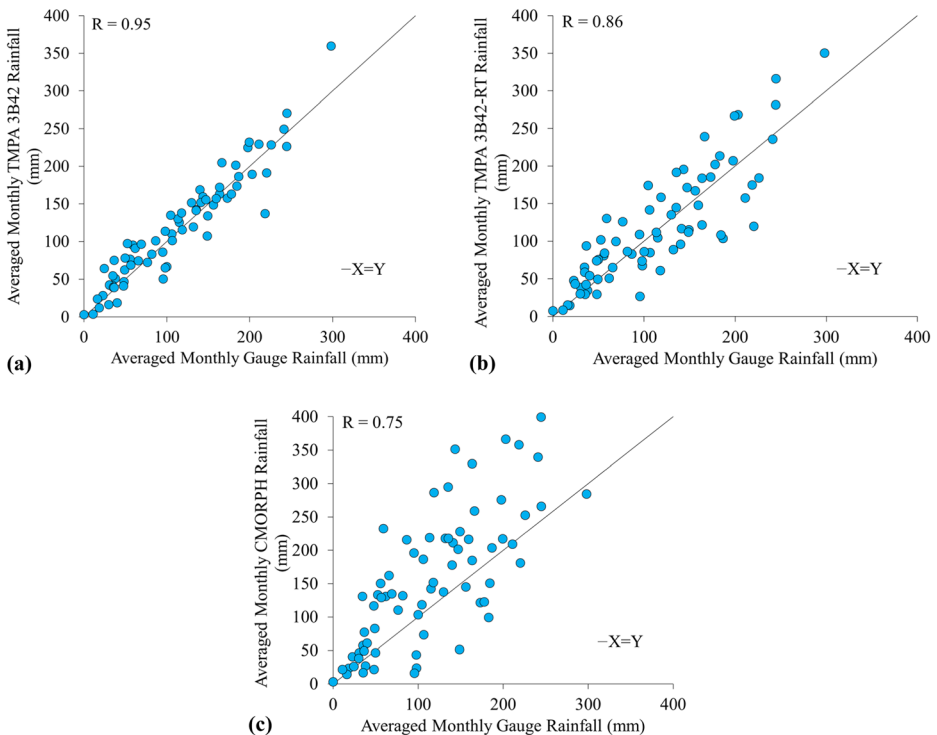

Fig. 8 Plot of average monthly rainfall (mm) from all 7 stations obtained from SRFEs versus rain gauges: **a** TMPA 3B42; **b** TMPA 3B42-RT; and (**c**) CMORPH, 2003–2008 [Coefficient of Correlation (R)]

The average monthly rainfall of the basin was well represented by the TMPA 3B42 (Fig. 10a), followed by the TMPA 3B42-RT (Fig. 10b). CMORPH overestimated the average monthly rainfall except in the transition months of July and August where it was underestimated (Fig. 10c).

3.3 Seasonal Rainfall Analysis

The basin falls within the southern sector of Ghana which has two wet seasons: a major season from March to July, and a minor season from September to November. A total of 24 out of the 72 months analyzed for each station were in the dry season. All the satellite
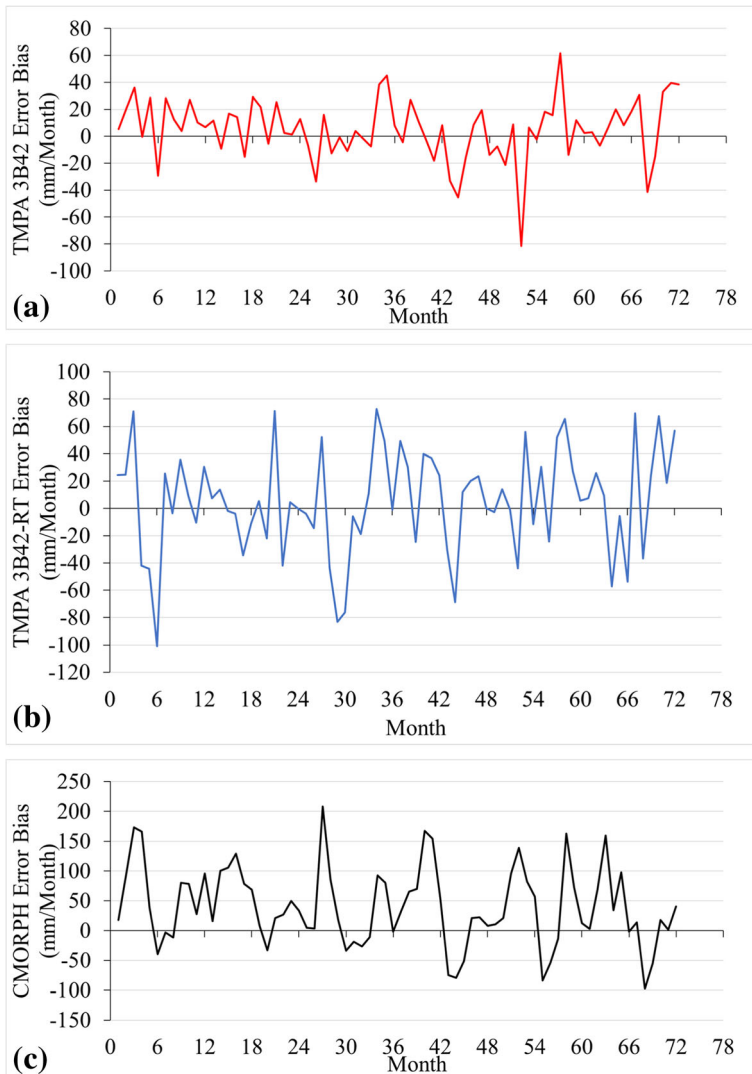

Fig. 9 Monthly averaged bias of SRFEs for the 7 rain-gauge stations: **a** TMPA 3B42; **b** TMPA 3B42-RT; and (**c**) CMORPH, 2003–2008
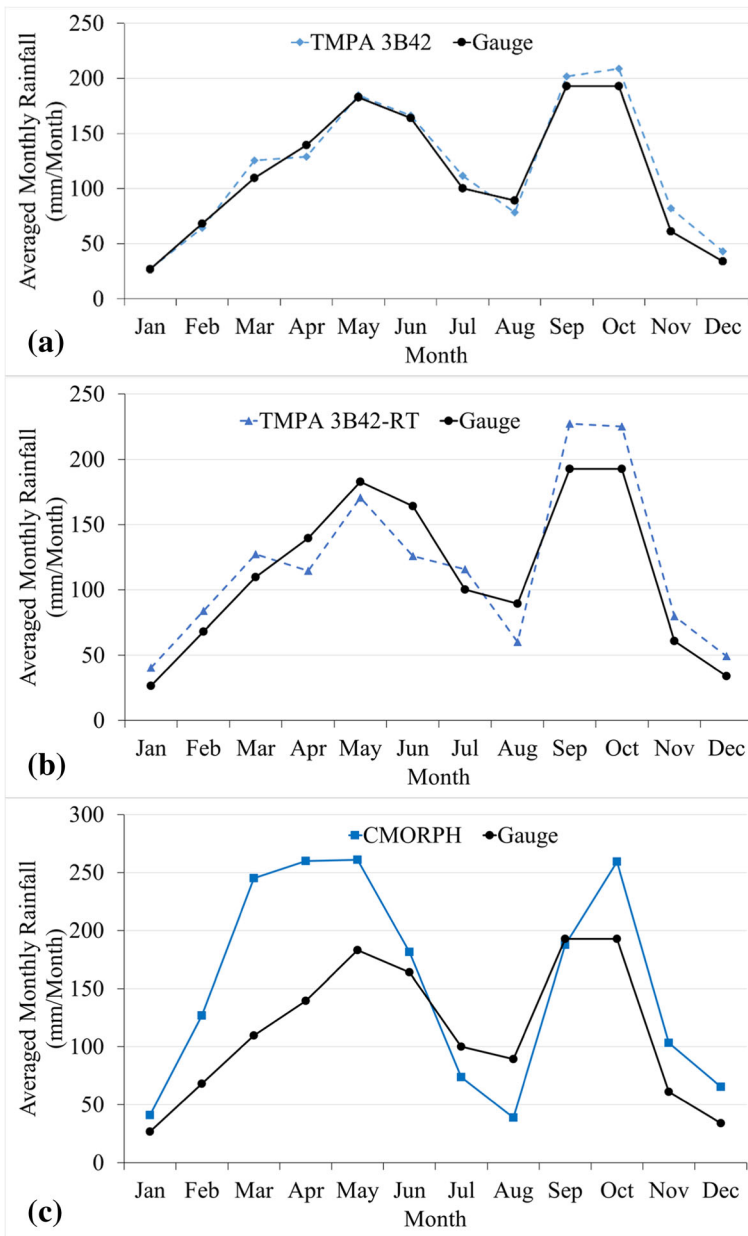
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Fig. 10 Averaged monthly rainfall (mm) obtained from SRFEs and rain gauges: **a** TMPA 3B42; **b** TMPA 3B42-RT; and (**c**) CMORPH, 2003–2008

products were able to represent the bimodal rainfall pattern in the basin (Fig. 11), although CMOPRH was seen to significantly overestimate the rainfall in the major wet season.

With the assumption that overestimation or underestimation within 0–10 mm bias is acceptable, the number of months of bias falling within different bias ranges was computed. Percentage of the number of months falling within the acceptable ±10 mm
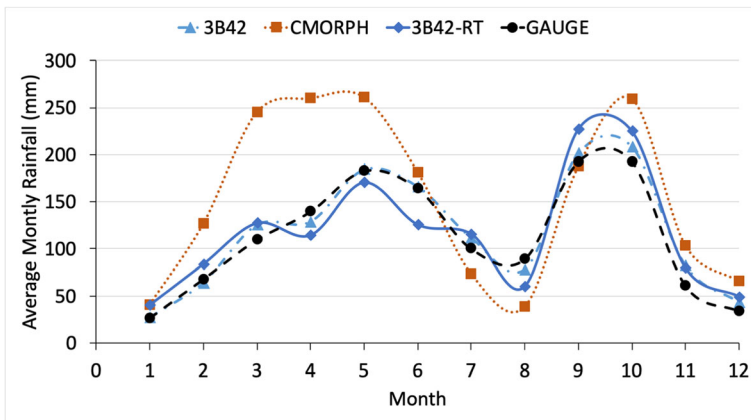
Fig. 11 Annual variation of mean monthly rainfall of SRFEs and Gauge data, 2003–2008

was plotted for each season and station (Fig. 12). All the SRFEs relatively perform better in the dry season compared to the rainy season when the monthly accumulated rainfall with ±10 mm of the gauged values were compared (Fig. 13). The study by Adjei et al. (2011) also reported better performance of the TMPA in the dry season compared to the wet season.

3.4 Annual Rainfall Analysis

The average annual rainfall and bias ratio for each year was computed to see how the annual rainfall estimated by the SRFEs compared with the gauged data (Table 3).

TMPA 3B24 mostly overestimated the annual rainfall, with a maximum overestimation of 12.47%, minimum of 3.5% and a mean of 8.23% overestimation. On the underestimation side, it showed a maximum of 4.25% in year 2006 and a minimum of 0.1% in 2007. TMPA 3B42 is more likely to overestimate the annual rainfall. TMPA 3B42-RT also showed a similar trend, with a maximum of 30.66% overestimation, minimum of 1.78% and a mean of 22%. It showed an underestimation only in year
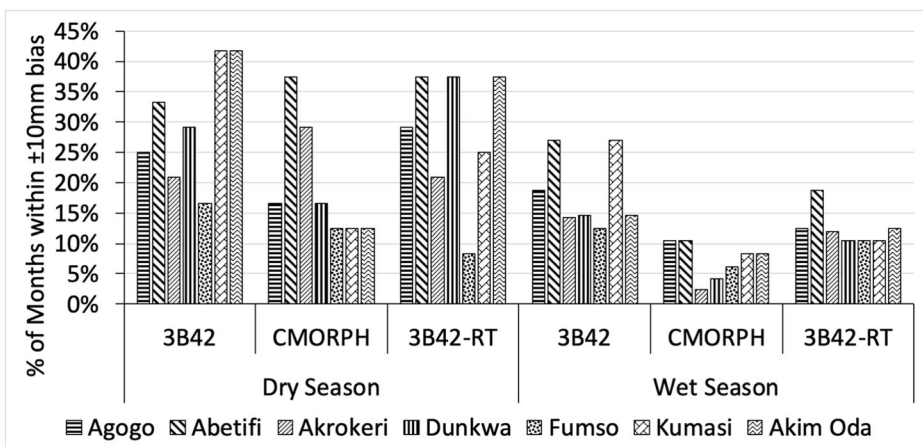

Fig. 12 Comparison of performance of SRFEs for different seasons and stations, 2003–2008
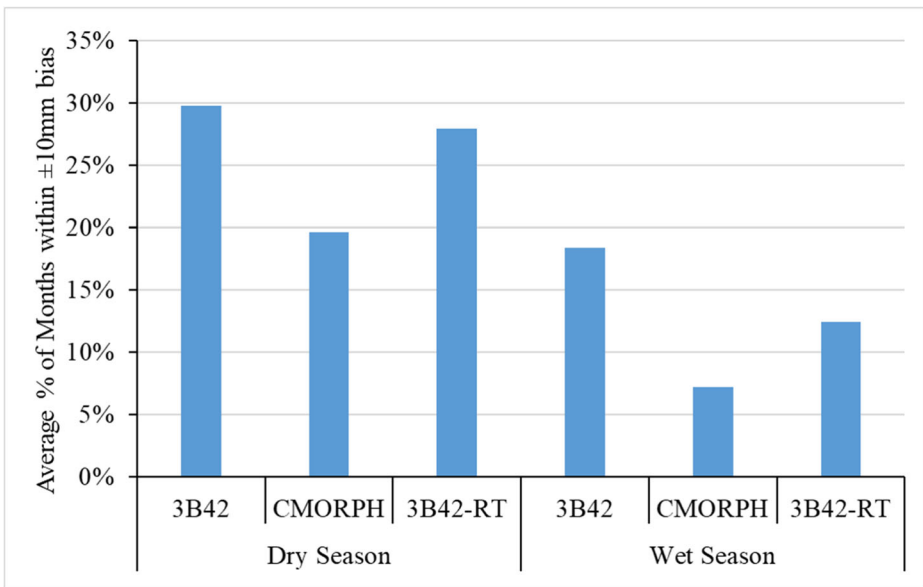
Fig. 13 Overall performance of SRFEs for different seasons, 2003–2008

2005 with a value of 2.03%. CMORPH significantly overestimated the annual rainfall with no underestimation. It showed a maximum of 66.9% and a minimum of 35.99% with a mean of 53.10%.

4 Conclusions

Comparison of satellite products with gauge data showed that the performance of all the satellite products on a daily time scale was not very good with correlations coefficients below 0.6. However, the performance, on the monthly timescale, was far better with correlation coefficient ranging between 0.5–0.91. This showed a moderate to strong positive linear relationship between satellite rainfall estimates and gauge measurements. Despite the positive correlation, CMORPH frequently overestimated at all time scales. Seasonal analysis of the products also showed bias in estimation. On an annual timescale, the performance of the 3B42 was at 12.5% maximum overestimation and 4.3% underestimation when compared with

Table 3 Comparison of SRFE and Rain Gauge (RG) performances in the estimation of annual rainfall, 2003–2008

Year	Gauge (mm)	3B42 (mm)	Bias Ratio (%)	CMORPH (mm)	Bias Ratio (%)	3B42-RT (mm)	Bias Ratio (%)
2003	1203.31	1353.38	12.47	1921.16	59.66	1224.76	1.78
2004	1375.63	1481.27	7.68	1980.34	64.57	1363.37	13.30
2005	1229.29	1272.26	3.50	1636.45	35.99	1178.86	−2.03
2006	1393.01	1333.83	−4.25	1784.73	48.32	1505.53	25.12
2007	1506.21	1504.68	−0.10	2008.33	66.90	1673.98	39.11
2008	1445.36	1579.17	9.26	1727.46	43.56	1572.29	30.66

annuals computed from gauged measurements. The 3B42-RT also showed a maximum overestimation of 30% while the CMORPH significantly overestimated with a mean of 53.1%. TMPA 3B42 was found to be the best product closely followed by the TMPA 3B42-RT. CMORPH is not recommended for use in the basin since the percentage of overestimation is extremely high for the basin. The satisfactorily performance of TMPA 3B42 can be attributed to the adjustment of the estimates using monthly rain gauge data from stations across the globe. The poor performance of the CMORPH can be attributed to the fact that its estimates are based entirely on infrared sensors as compared to the TMPA products which are estimates from a combination of both infrared and microwave sensors. Overall, TMPA products are recommended to be used in other ungauged basins with similar characteristics as the Pra basin.

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