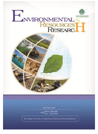

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Evaluation of the TRMM-3B43 V7 rainfall products on a monthly scale in the Northwest of Iran

Kh. Javan*, M.R. Azizzadeh
Assistant Professor, Department of Geography, Urmia University, Urmia, Iran.
Department of Geography, payam-e-Noor University, Tehran, Iran.

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Abstract

Satellite rainfall estimate systems can produce data for areas for which other sources are unavailable. Without referring to ground measurements, satellite-based estimates cannot be used directly before bias correction. This study aims to evaluate the performance of the TRMM-3B43 V7 rainfall products in the Northwest of Iran. The evaluation was carried out using monthly data obtained from 21 meteorological stations during 1998–2015. The monthly and annual spatial distributions of the Pearson correlation coefficient between the station and satellite-based observations as well as the statistical error measure were calculated. The results revealed that the correlations between TRMM 3B43 and rain gauge data were high ($R > 0.80$) in October and small ($R < 0.55$) in August. Moreover, mean annual spatial distribution of R showed that the small values of R occurred in the Northeast and the southern mountainous regions. We found that the TRMM-3B43 V7 overestimated rainfall in the Northeast, in September, October and November (>30 mm) and in December to May (>20 mm). On the contrary, an underestimation was found in the Southwest regions where summer season (June, July & August) is generally characterized by small anomalies in terms of R values. Generally, the satellite products applied in this study underestimate higher rainfall values while showing overestimation for lower rainfall records. The measure of Root Mean Square Error (RMSE) showed that a large spatial variability takes place in September, October and November in most of the stations, particularly when rainfall records is less than 50 mm. Meanwhile, the lowest variability occurred in June, July and August with a slight increase in the Northeast. Our findings imply that satellite products have poor performance for estimating higher rainfalls in the Northwest of Iran on a monthly scale.

Keywords: TRMM-3B43 V7, Rainfall variability, Northwest of Iran

*Corresponding author; kh.javan@ urmia.ac.ir

Introduction

Rainfall is an important component of the global energy and hydrologic cycle; it is one of the main variables predicted in weather forecast models. Moreover, it is a key process in short-term meteorological and long-term climatological studies. Precipitation events are the driving forces behind the hydrological phenomena, such as floods and storms (Pidwirny, 2006). Rainfall is usually measured by the rain gauge stations which can directly and accurately measure climatic variables. Although meteorological stations provide accurate measurements, they are limited at the station level. In most areas, there are no rain gauge networks that can capture the high variability in the space and time of the precipitation systems (Krajewski *et al.,* 2003). Weather radar can provide rainfall information at higher spatial and temporal resolutions; however, it has a number of shortcomings. Radar rainfall estimates are prone to have several sources of uncertainties due to measurement principles, estimation algorithms, and incompletely understood physical processes (Ciach *et al.,* 2007).

In recent years, a number of satellite-based rainfall products with high spatial and temporal resolution have been developed. Satellites obtain information about the distribution and amounts of precipitation both directly and indirectly (Levizzani *et al.,* 2002). Direct observation is made through the passive sensing of the microwave energy absorbed and scattered by hydrometeors and the conversion of these observations into estimates of rainfall rates by accounting for the background radiation from the earth's surface and making assumptions about the size, and distribution of the hydrometeors. Indirect observation is made through sensing infrared radiation emitted by clouds, converting the radiation flux into cloud-top temperatures, making use of empirical correlations of the spatial and temporal coverage of clouds with temperatures below a threshold value and rainfall (Levizzani *et al.,* 2002).

Spatio-temporal rainfall characteristics and validations of the TRMM datasets against rain gauges networks have been performed on a local or regional basis in the Korean Peninsula (Ha *et al.,* 2007), India (Kneis *et al.,* 2014), Greece (Feidas, 2010; Ioannidou *et al.,* 2016; Nastos *et al.,* 2016), Saudi Arabia (Almazroui, 2011), India (Brown, 2006), Bangladesh (Islam & Uyeda, 2005), Nepal (Islam *et al.,* 2010) Ethiopia (Hirpa *et al.,*2010; Worqlul *et al.,* 2014), Angola (Pombo *et al.,* 2015), Eastern Africa (Dinku *et al.,* 2007), The Philippines (Jamandre and Narisma, 2013), Australia (Oke *et al.,* 2009), China (Li *et al.,* 2012; Chen *et al.,* 2013a; Huang *et al.,* 2013; Zhao & Yatagai, 2014; Chen & Li, 2016) and United States (Habib *et al.,* 2009; Wang & Wolff, 2012; Prat & Nelson, 2014; Chen *et al.,* 2013b; Qiao *et al.,* 2014).

In Iran, the evaluation studies and comparison of TRMM have been previously addressed in some studies. Javanmard *et al.* (2010) evaluated the TMPA-3B42 V6 with reference to synoptic rain gauges over Iran from 1998 -2006 and presented some annual, seasonal, monthly and daily comparisons. The study showed the large-scale and local error patterns of TMPA over Iran by focusing on the bias and correlation coefficient measures. Another evaluation study was conducted by Katiraie-Boroujerdy *et al.* (2013) over 32 pixels (0.25°× 0.25°) of Iran. In this study, daily and monthly datasets of CMORPH, PERSIANN, TMPA-3B42 and adjusted PERSIANN (using monthly GPCC data) from 2003 to 2007 were used to perform the evaluation using statistical and categorical measures. The results of the study were consistent with the findings of Javanmard *et al.* (2010) regarding the local patterns of the precision of HRPP and clearly showed the better performance of TMPA-3B42 and adjusted PERSIANN over Iran. Moazami *et al.* (2013) evaluated daily rain rates derived from three satellite precipitation products (PERSIANN, TMPA-3B42V7, & TMPA-3B42RT) using rain gauge observations over Iran. They used statistical and categorical comparison methods to evaluate the satellite rainfall estimates. The results over the entire country indicated that 3B42V7 resulted in better estimates of daily precipitation than those of PERSIANN and 3B42RT. Ghajarnia *et al.* (2015) compared six daily high resolution precipitation data sets (PERSIANN, CMORPH-RAW, CMORPH-CRT, TMPA-RT, TMPA-V7 & APHRODITE) during 2000-2011 in Urmia basin of Iran and considered rain gauge observations as the reference data set. They concluded that APHRODITE and TMPA-V7 presented better estimations while among near real-time products, PERSIANN was able to outperform other estimations. Moazami *et al.* (2016) studied four satellite rainfall estimates (TMPA-3B42V7, TMPA-3B42RT, PERSIANN, & CMORPH) to evaluate a dense rain-gauge network during 2003–2008 over six regions in Iran. The results showed that 3B42V7 led to a better performance in comparison with the other three products over different terrains. The 3B42V7 matched best with the rain-gauge observations, while PERSIANN and 3B42RT overestimated precipitation. However, the CMORPH underestimated the rainfall amount. Erfanian *et al.* (2016) evaluated and calibrated the TRMM rainfall data in different climatic zones in Iran. Their results revealed that the TRMM overestimated rainfall on daily and monthly scales at 68% of stations and the calibration process could improve rainfall estimates in most of the climatic zones. Rasouli *et al.* (2016a) evaluated and calibrated the TRMM rainfall amounts in a six-hour time scale in Lake Urmia Basin. They concluded that TRMM underestimated the rainfall amount. Regression analysis using the F-statistic and significance test of the regression line slope using the t-test represented a significant match of TRMM rainfall with the observed data. Other studies in this field include: Erfanian *et al.* (2013); Erfanian *et al.* (2014); Rasouli *et al.* (2016b), and Javan *et al.* (2017).

To the best of our knowledge, there is still a need to evaluate the long-term satellite data for rainfall in the Northwest of Iran. More specifically, the validation of TRMM derived rainfall with the observed data is absent. The main objective of this study is to examine the performance of rainfall obtained from TRMM 3B43 datasets with reference to the observed rain-gauges amounts based on the data in the northwest of Iran during 1998-2015.

Data and methodology

Study area and datasets

In this study, the TRMM-3B43 V7 rainfall products, with a spatial resolution of 0.25° × 0.25°, were utilized over the Northwest of Iran. Furthermore, monthly rain-gauge data sets from 22 meteorological stations over the studied area were obtained from the database of the Islamic Republic of Iran Meteorological Organization (IRIMO) for the period 1998–2015 (Figure 1). The geographical characteristics (longitude, latitude & altitude) of the meteorological stations along with their statistics (annual mean, maximum, minimum & standard deviation) for the respective monthly rainfall appear in Table 1. The Annual mean rainfall ranges from 228.1 mm in Jolfa station to 633.2 mm in Piranshahr station. Regarding the maximum rainfall, the highest values appear over southwest of the studied area (Table 1). This is very likely due to the orographic effect of border mountains on the air mass coming from the Mediterranean Sea and the Atlantic Ocean.

The Tropical Rainfall Measurement Mission (TRMM) is a joint US-Japan satellite mission for monitoring tropical and subtropical precipitation, and for estimating their associated latent heat. The TRMM was launched in November 1997 to orbit at a low altitude of about 320 km and to cover the entire tropics between 30°N and 30°S twice a day (Kummerow *et al.,* 1998). The TRMM includes a number of precipitation-related instruments, such as precipitation radar, a Visible and Infrared Sensor (VIRS), and a SSM/I like TRMM Microwave Imager (TMI) (Kummerow *et al.,* 2000). However, the TRMM satellite has a poor temporal resolution due to its low sampling frequency. TRMM flies over most tropical locations once or twice a day (Sorooshian *et al.,* 2000).

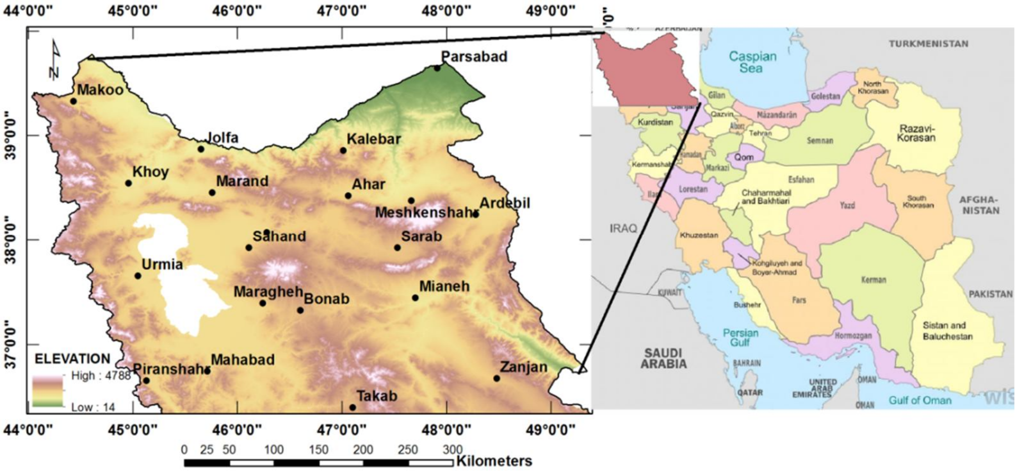

Figure 1. Topography of the study area and geographical distribution of the meteorological stations

Table 1. Geographical Characteristics of the Meteorological Stations, along with the Statistics for the Annual Rainfall

No	Station	Lat (°)	Lon (°)	Alt (m)	Annual mean (mm)	Standard deviation (mm)	Minimum (mm)	Maximum (mm)
1	Ahar	38°26′	47°04′	1390	280.6	57.0	182.9	386.7
2	Ardebil	38°15′	48°17′	1332	270.5	35.6	216.5	343.2
3	Bonab	37°20′	46°04′	1290	261.3	74.7	150.5	456.1
4	Jolfa	38°45′	45°40′	736	228.1	59.3	129.2	349.1
5	Kaleibar	3852′	47°01′	1180	407.4	79.7	298.4	562.0
6	Khoy	38°33′	4458′	1103	270.8	56.3	171.4	395.0
7	Makoo	3920′	44° 26′	1411	319.8	74.14	185.7	445.0
8	Mahabad	36°45′	4543′	1351	372.2	90.2	237.0	578.1
9	Maragheh	37°24′	46°16′	1477	251.0	59.4	166.1	395.8
10	Marand	38°28′	45°46′	1550	378.6	80.0	230.6	486.9
11	Mianeh	37°27′	47°42′	1110	266.2	57.8	170.0	376.0
12	Meshkinshahr	38°23′	47°40′	1568	386.6	83.6	268.4	542.7
13	Urmia	37°40′	45°03′	1328	282.8	70.9	167.2	427.6
14	Parsabad	39°39′	47°55′	32	281.7	62.6	187.0	407.5
15	Piranshahr	36°40′	45°08′	1455	633.2	130.9	404.9	885.2
16	Saghez	36°15′	46°16′	1522	407.6	99.5	272.5	582.6
17	Sahand	37°56′	46°07′	1641	203.9	30.0	156.0	271.9
18	Sarab	37°56′	47°32′	1682	244.1	41.7	176.6	309.4
19	Tabriz	28°05′	46°17′	1361	244.2	42.9	171.4	311.0
20	Takab	3624′	47°06′	1817	298.3	63.7	175.7	395.8
21	Zanjan	36°41′	48°29′	1663	291.4	66.6	167.6	400.8

The TRMM 3B43 Version-7 (V7) is a standard monthly rainfall product which is derived after averaging the TRMM-3B42 V7rainfall products. This product is widely used for the climatological applications (Kummerow *et al.,* 1998; Rosenfeld, 1999; Huffman *et al.,* 2007; Huffman *et al.,* 2010; Cecil *et al.,* 2014). Wherever feasible, TRMM -3B42 combines precipitation estimates from multiple satellites as well as gauge analyses (Huffman *et al.,* 2007).

The purpose of the 3B42 class of algorithms (Huffman *et al.,* 2007) is to produce TRMM-adjusted merged-infrared (IR) precipitation data. The algorithm consists of two separate steps. The first step uses the TRMM VIRS and the TMI orbit data (TRMM products 1B01 & 2A12), and the monthly TMI/TRMM Combined Instrument (TCI) calibration parameters (from TRMM product 3B31) to produce monthly IR calibration parameters. The second step uses these derived monthly IR calibration parameters to adjust the IR precipitation data, which consists of GMS, GOES-E, GOES-W, Meteosat-7, Meteosat-5, & NOAA- 12 data. The final gridded Version 6 of the 3B42 product (henceforth simply referred to as TRMM) is a 0.25° grid-mesh dataset based on multi-satellite precipitation analysis (Huffman *et al.,* 2004). The TRMM spatial coverage extends from 50° S to 50° N.

Methodology and statistical measures

The monthly precipitation of gauge observations was used as reference data to evaluate the satellite products. In order to evaluate the performance of TRMM-3B43, Pearson correlation coefficient (R), Bias, relative Bias (RBias) and root mean square error (RMSE) statistic metrics were used in the study. RBias and R are dimensionless, while Bias and RMSE are in mm. The correlation coefficient (R) is used to assess the agreement between the TRMM rainfall estimation and rain gauge observation. The value of R is between −1 and +1. R is defined as follows:

$$R = \frac{\sum_{i=1}^{N}(P_{Si}-\bar{P}_S)\left((P_{Oi})-(\bar{P}_O)\right)}{\sqrt{\sum_{i=1}^{N}(P_{Si}-\bar{P}_S)^2}\sqrt{\sum_{i=1}^{N}(P_{Oi}-\bar{P}_O)^2}} \quad (1)$$

where P_{Si} is the value of TRMM rainfall estimation for the i^{th} month, P_{Oi} is the value of rain gauge observation, N is the number of months, $\bar{P}_S$ is the average value of TRMM rainfall estimation over the desired period, and $\bar{P}_O$ is the average value of rain gauge observations.

The root mean square error (RMSE) is used to measure the average error magnitude. A value of RMSE equal to zero means that there is no error between the estimated and the observed data and the error increases with increasing values of RMSE.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_{Si}-P_{Oi})^2} \quad (2)$$

Bias is defined as the average difference between satellite estimates and rain gauge observations. The value of Bias can be positive as well as negative; positive Bias indicates overestimation of rainfall amount, while a negative Bias indicates underestimation of this amount. The Bias is defined as follows:

$$Bias = \frac{\sum_{i=1}^{N}(P_{Si}-P_{Oi})}{N} \quad (3)$$

Relative bias (RBias) describes the systematic error of the satellite precipitation. Similar to Bias, positive and negative values of RBias indicate the overestimation and underestimation of rainfall amount respectively.

$$RBias = \frac{\sum_{i=1}^{N}(P_{Si}-P_{Oi})}{\sum_{i=1}^{N}P_{Oi}} \times 100\% \quad (4)$$

Results and discussion

Comparison of the monthly rainfall

Monthly rainfall (mm) estimated by TRMM is compared with the rain-gauge data (Figure 2a). The rainfall of each month is averaged over 1998–2015, both from the TRMM data and from all the analyzed stations. The TRMM follows the annual cycle well, with high overestimations in the wet months (during November to May) and low overestimations in the dry months (from June to October). The correlation coefficient (R) of the rainfall between the TRMM and the rain-gauge data obtained each month is displayed in Figure 2b. The correlation coefficient is significant for all months; it lies between 0.69 and 0.93, with an average of about 0.81. This indicates that there is a good correlation between the two data sources, even though the TRMM overestimates the monthly rainfall in the entire study area (Figure 2a).

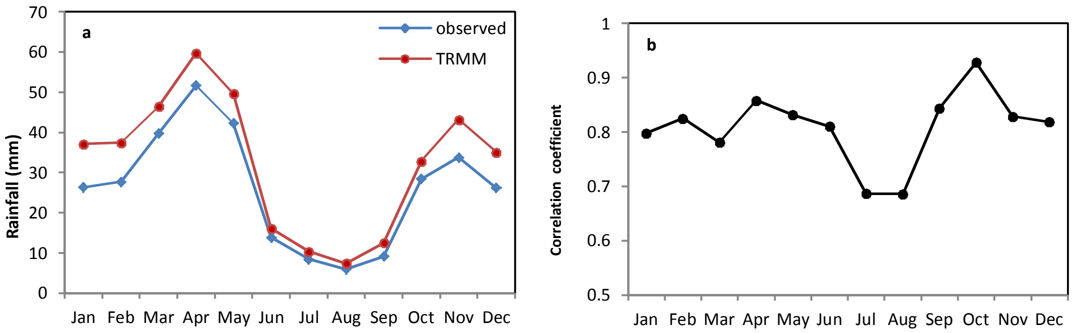

Figure 2. a. The average monthly rainfall of TRMM and rain gauge stations. b. The monthly correlation coefficient (R) between TRMM and the rain gauges over 1998–2015.

To evaluate rainfall estimates of TRMM, the scatter plot of monthly rainfalls, obtained from TRMM and rain-gauge data, is presented in Figures 3-6. The evaluation is performed over an 18-year period from 1998 to 2015 and considers the impact of monthly changes on TRMM estimations. Each mark in these figures represents an average value of monthly rainfall at each selected station over the study area. According to Figures 4-6, TRMM has a good agreement with the observed data for all of the months. Through this analysis, it became clear that TRMM overestimates the rainfall in some months and areas, and underestimates in other months and areas for the northwest of Iran. These results are consistent with the overestimations of rainfall in the annual dataset, autumn, winter and spring seasons and underestimations in the summer season in Iran (Moazami *et al.,* 2016; Erfanian *et al.,* 2016).

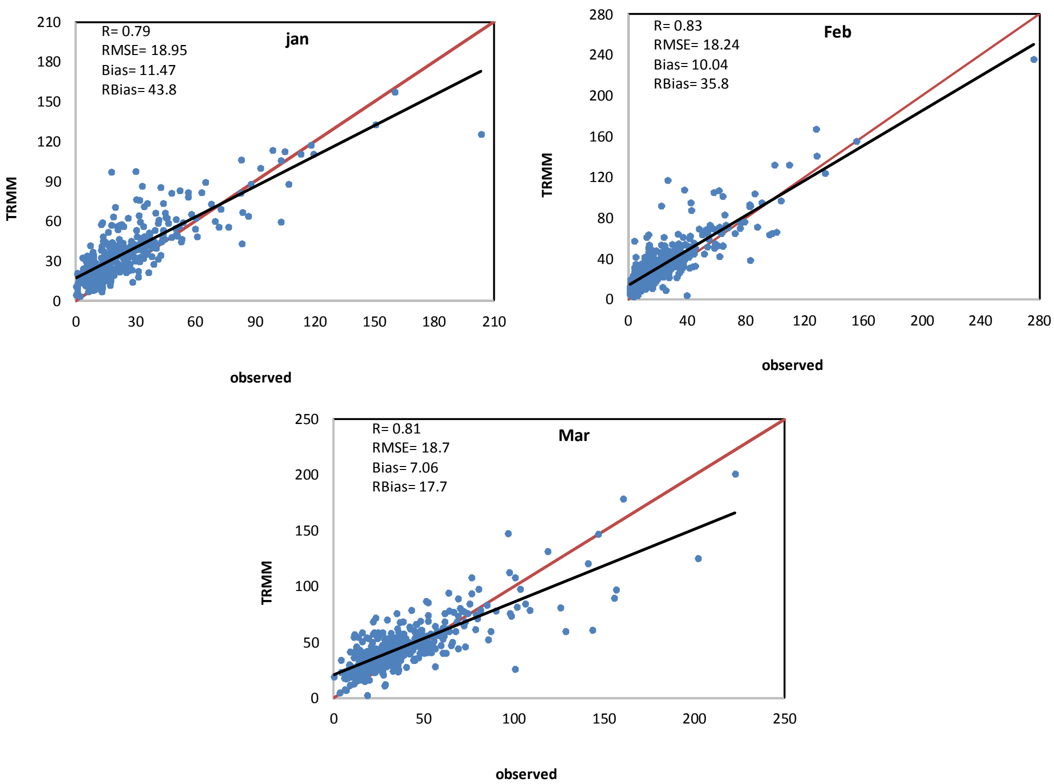

Figure 3. Scatter plot of monthly rainfall estimated in winter by TRMM (mm) and observations (mm) during 1998–2015.

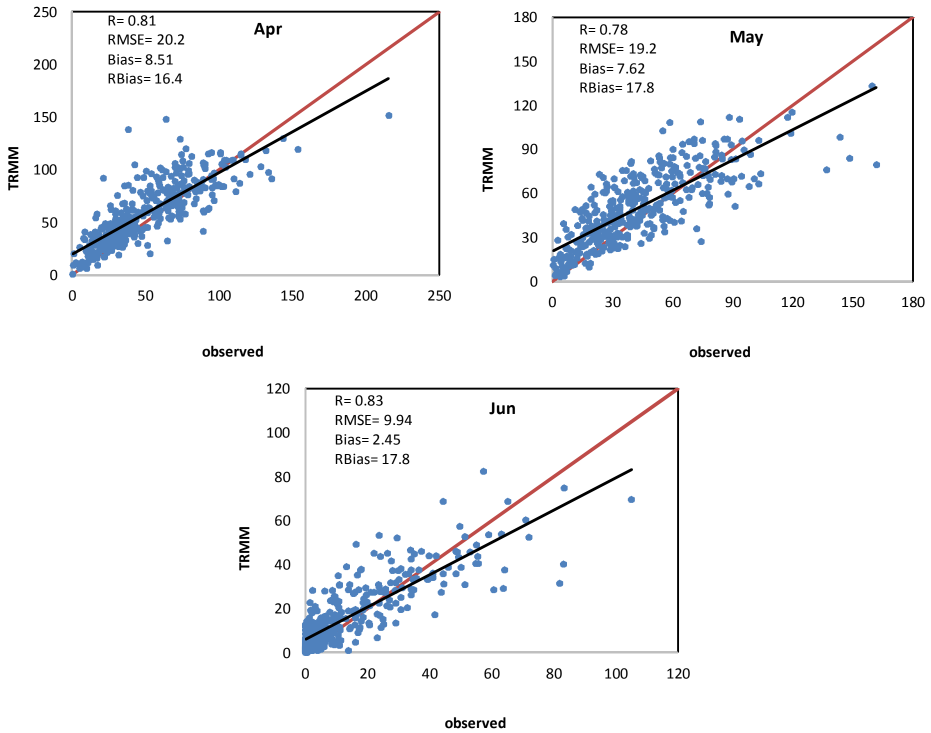

Figure 4. Scatter plot of monthly rainfall estimated in spring by TRMM (mm) and observations (mm) during 1998–2015.

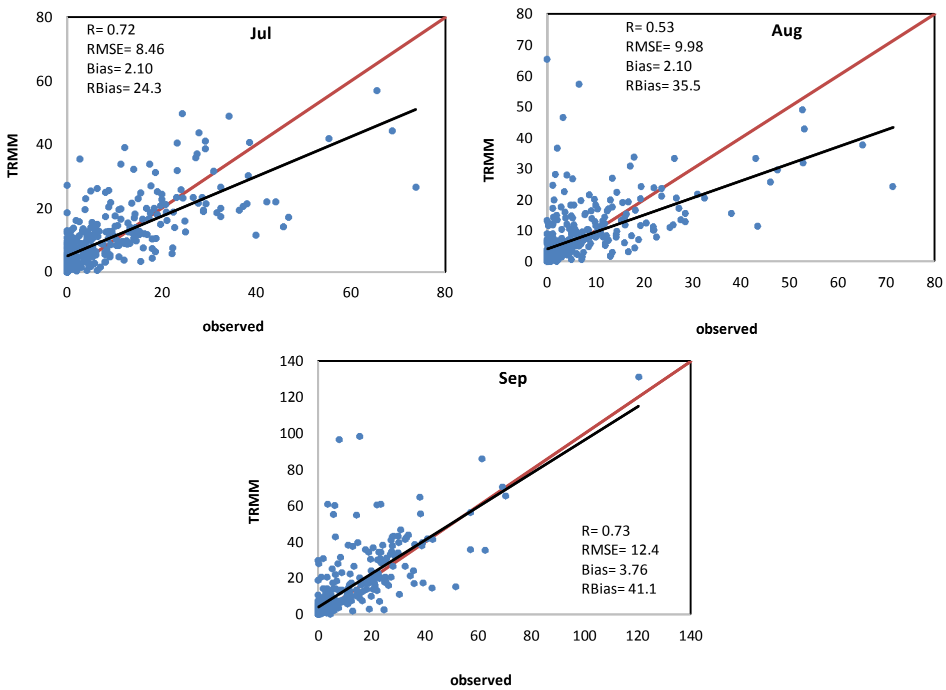

Figure 5. Scatter plot of monthly rainfall estimated in summer by TRMM (mm) and observations (mm) during 1998–2015.

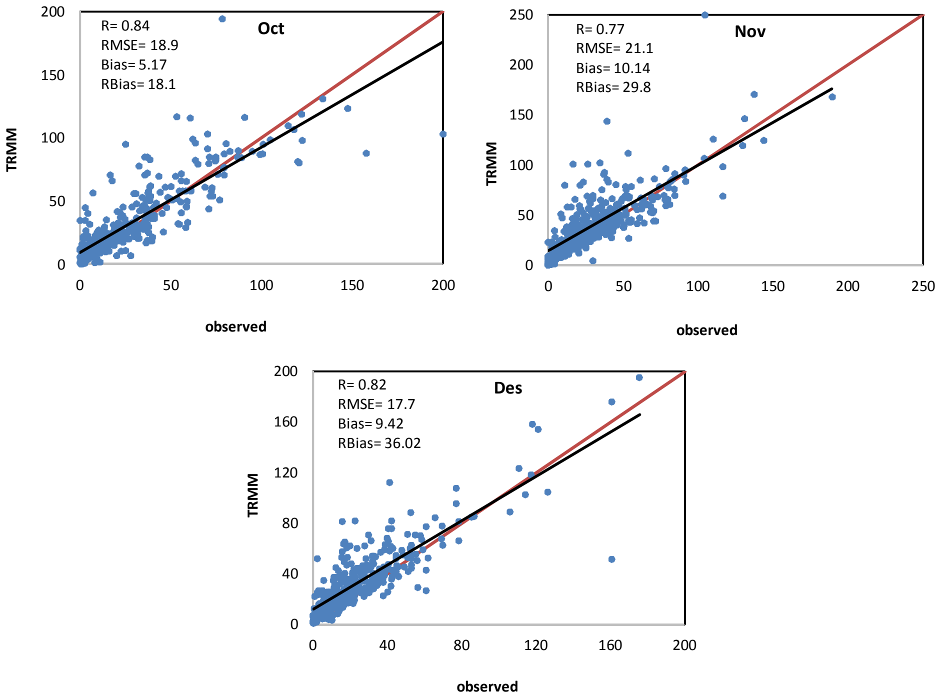

Figure 6. Scatter plot of monthly rainfall estimated in autumn by TRMM (mm) and observations (mm) during 1998–2015.

Correlations between TRMM 3B43 and rain gauge datasets

The spatial distribution of the Pearson correlation coefficient (R) between the total amount of rainfall of the two examined datasets is illustrated in Figure 7, which appear to have high correlations, indicating that the TRMM 3B43 and the rain gauge datasets have a good correlation on a monthly basis. More specifically, during October the correlation coefficient is high (>0.90, statistically significant at 95%) in the northwest of Iran, with minor exceptions in the northeast and the Parsabad Plain. In other months such as August, the correlation coefficient is small across the studied area. The general lack of meteorological stations at high altitudes is the likely cause of the anomalies observed in the correlation of the two examined data bases. If that is the case over highlands and mountainous regions, TRMM 3B43 estimations will be most useful for filling the existing spatial gap due to the scarcity of rain gauges. Figure 8 depicts the mean annual spatial distribution of correlation between the space-borne products and rain gauge datasets. As shown in Figure 8, small correlations occur in the northeast and the south mountainous regions.

Statistical Error Measures

To address the spatial distribution of bias values, the monthly averaged value of bias at each selected station over the study area is represented in Figure 9. The TRMM 3B43 datasets, during January, February and December, overestimate (>20 mm) the rain-gauge data sets over the northeast. On the contrary, high underestimation is demonstrated over the southeast (Piranshahr). In March, a similar pattern is illustrated as in January, February and December, but the underestimation is higher than those months. During May, high underestimation extends from northeast to the central part of the study area. Small positive anomalies exist within summer months (June, July & August) while in autumn months (September, October & November) high positive anomalies (>30 mm) is demonstrated over the northeast (especially in Ardebil). Moreover, a high negative anomaly exists in March over the southwest of the study area (Fig. 9). Generally, it seems that

TRMM3B43 indicates an underestimation at higher rainfall values and an overestimation at lower rainfall values. These findings are in agreement with those of Moazami *et al.* (2016), who performed validation of four space-borne precipitation products, namely TMPA-3B42V7, TMPA-3B42RT, PERSIANN, and CMORPH with rain gauge data sets. All three products show some underestimation at higher rainfall accumulations. However, TMPA-3B42V7 datasets look slightly better than the other three, indicating a better correspondence with the rain-gauge than the others. There is a general agreement between the rain-gauge precipitation and the satellite products with a better agreement at lower rainfall accumulations against some underestimation at higher rainfall accumulations.

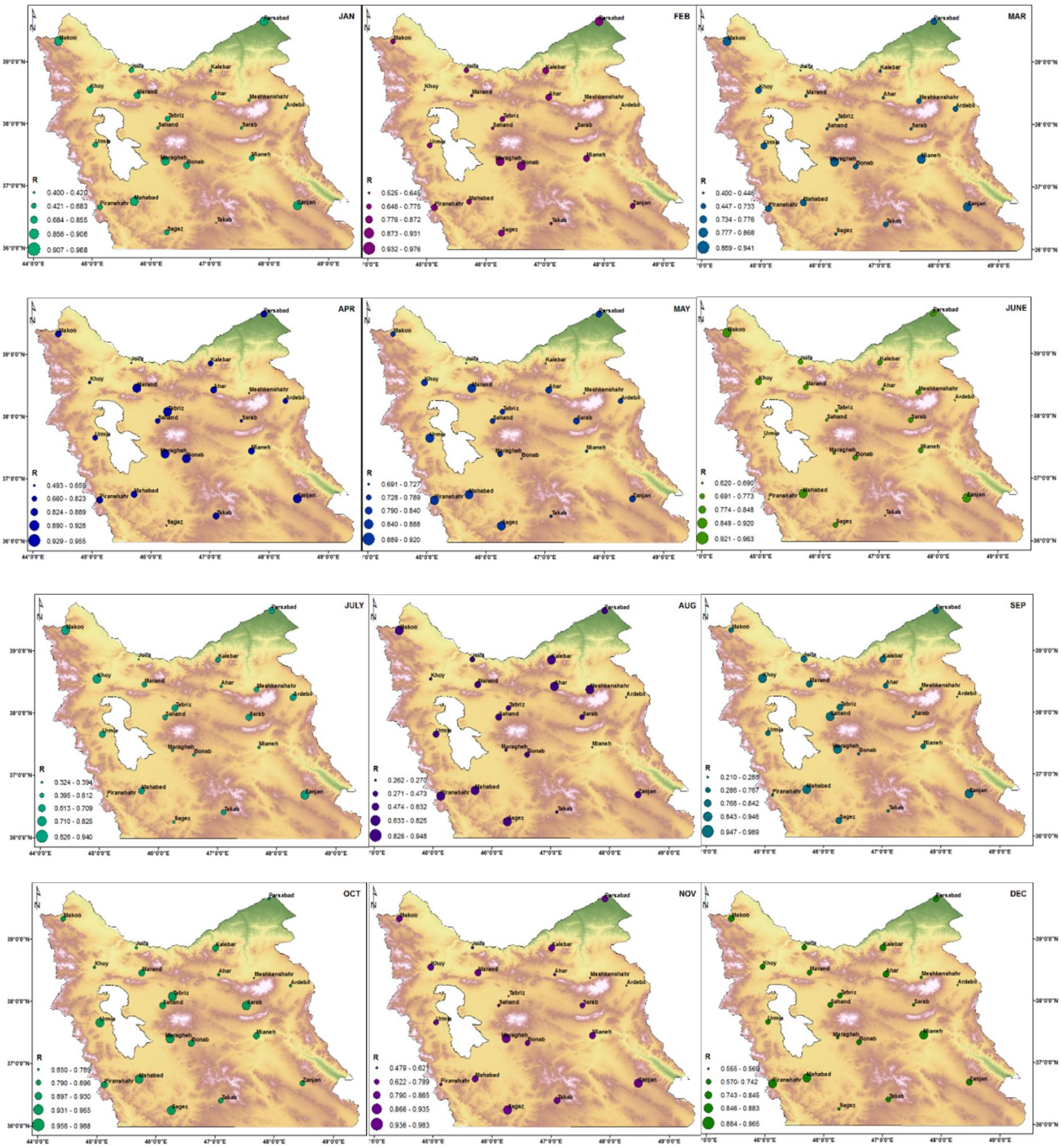

Figure 7. Mean monthly spatial distribution of the Pearson correlation coefficient between TRMM (3B43) and observations in the northwest of Iran over 1998–2015.

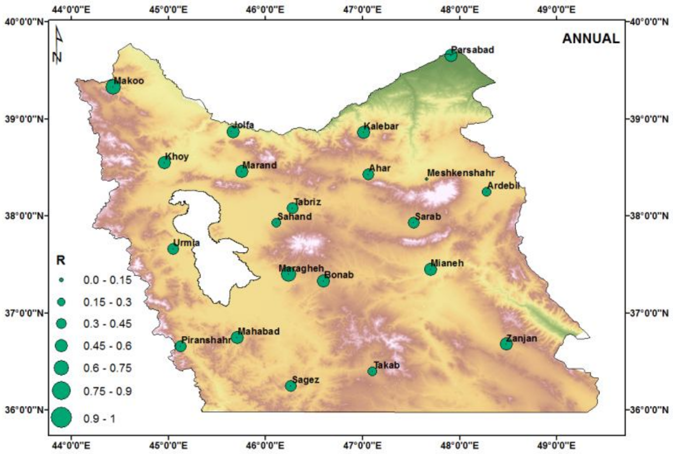

Figure 8. Mean annual spatial distribution of the Pearson correlation coefficient between TRMM (3B43) and rain gauge data base in the northwest of Iran for the period 1998–2015.

Furthermore, RMSE is computed to estimate the average error magnitude of the satellite precipitation products. The mean monthly spatial distribution of the RMSE between the TRMM3B43 and rain gauge datasets over the northwest of Iran are presented in Figure 10. RMSE shows large spatial variability in September, October and November taking values from 5 mm over the central parts to 40 mm over the northeast and southwest of the study area, while the lowest values (< 3 mm) appear in summer months (June, July & August) with small increases over northeast (< 25 mm). During January, February and December, high values which are greater than 30 mm exist over the northeast and small values (< 10 mm) exist over the northwest of the study area. In March, the high values of RMSE can be seen in the southwest, which receives the highest rainfall amounts. The spring months (April & May) demonstrate high values of rainfall (>30 mm) over the northeast (especially in MeshkinShahr). Generally, the highest values of RMSE imply the poorest estimations of TRMM 3B43.

Table 2 lists the monthly averaged values of all the performance metrics for the total months all over the northwest of Iran. Regarding this table, we found that the mean TRMM precipitation ranges from 7.38 mm (in August) to 59.7 mm (in April), while the mean rain-gauge precipitation ranges from 5.97 mm (in August) to 51.6 mm (in April) for the northwest of Iran. The correlations appear to be high (0.84) during October, against relatively low correlations (0.53) during August. The RMSE ranges from 8.46 mm (in July) to 21.1 mm (in November). It seems that there are high values of RMSE at higher precipitation and small values at lower precipitation. The monthly averaged values of Bias ranges from 2.1 mm (in July and August) to 11.5 mm (in January). The relative bias (RB) as one of the verification metrics used in this study ranges from 16.4% (in April) to 43.8% (in January). The overestimation over the northwest of Iran in January is more pronounced (> 40%).

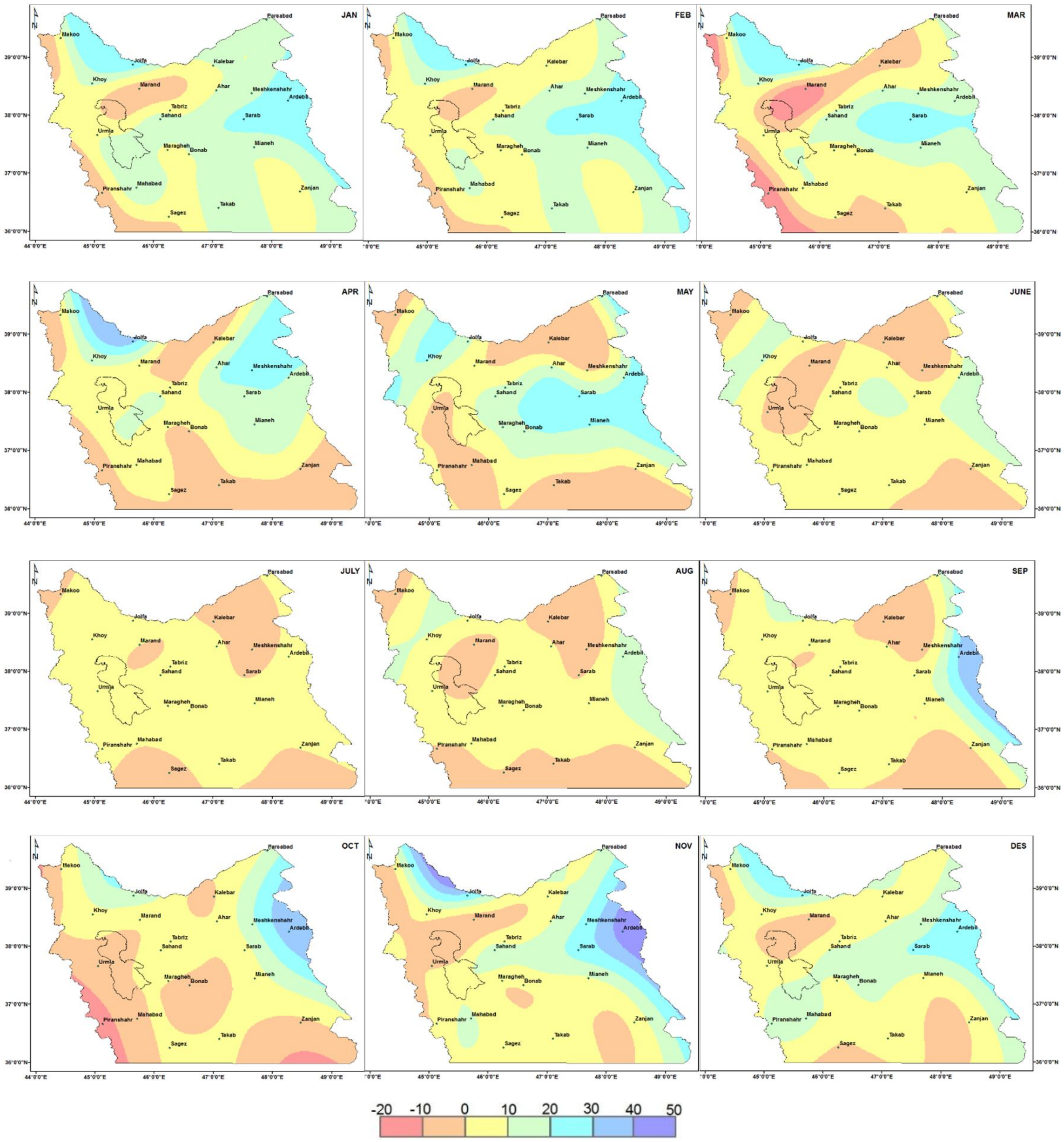

Figure 9. Mean monthly spatial distribution of Bias value between TRMM (3B43) and rain gauge data base in the northwest of Iran for the period 1998–2015.

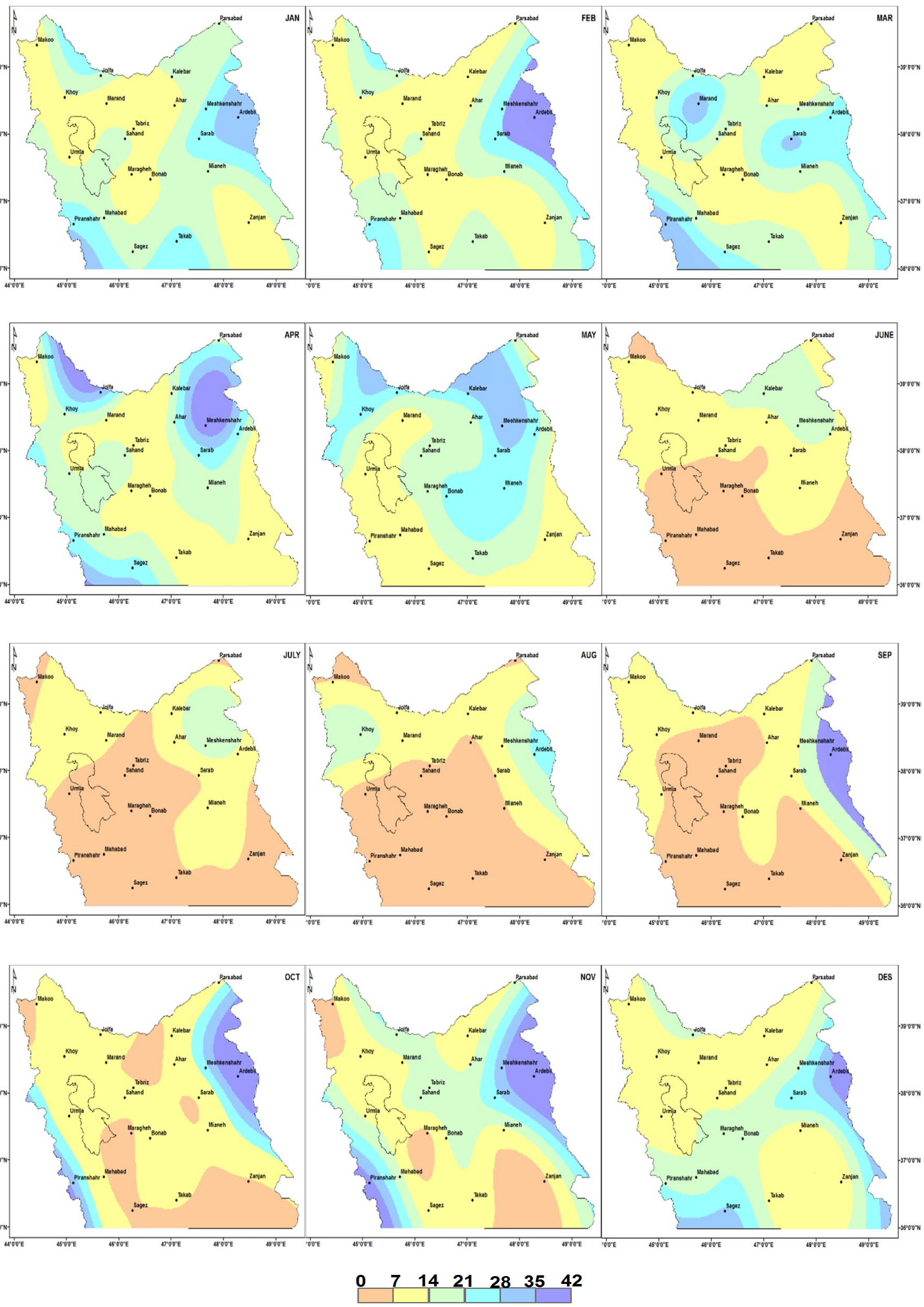

Figure 10. Mean monthly spatial distribution of RMSE value between TRMM (3B43) and rain gauge data base in the northwest of Iran over1998–2015.

Table 2. Monthly Averages of Evaluation Criteria at all Stations in the Study Area Over 1998–2015

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TRMM (mm)	37.1	37.4	46.4	59.7	49.7	16.1	10.3	7.38	12.5	32.8	43.1	35
Rain gauge (mm)	26.3	27.7	39.7	51.6	42.3	13.8	8.44	5.97	9.18	28.4	33.8	26.6
RMSE (mm)	18.9	18.2	18.7	20.2	19.2	9.94	8.46	9.98	12.4	18.9	21.1	17.7
Bias (mm)	11.5	10.04	7.06	8.51	7.62	2.45	2.10	2.10	3.76	5.17	10.1	9.42
RBias (%)	43.8	35.8	17.7	16.4	17.8	17.8	24.3	35.5	41.1	18.1	29.8	36.02
R	0.79	0.83	0.81	0.81	0.78	0.83	0.72	0.53	0.73	0.84	0.77	0.82

Conclusion

Satellite rainfall products are increasingly useful data sources for hydrological applications because of their ability to provide continuous coverage of large areas with relatively good temporal resolution. However, due to the indirect nature of satellite products, their estimates tend to make larger errors in comparison to ground-based radar and rain-gauge precipitation recording. This study investigated the performance of TRMM-3B43 V7 products in the northwest of Iran. The evaluation was carried out with respect to the rain gauge data base over the period 1998–2015. Monthly rainfall collected at 21 stations over northwest of Iran was utilized as ground-based observations. The results indicated that the TRMM3B43 products were capable of estimating spatial distribution of monthly rainfall in the region. Correlation coefficient (R) between TRMM and rain-gauge was high in October (R> 0.90) and small in August (R < 0.70). Mean annual spatial distribution of correlation showed that small correlations occurred in the northeast and the south mountainous regions. This indicated that there was a good relationship among the two measurements even though TRMM-3B43 overestimated the rainfall amount compared to the observed data. The overestimation was indicated over the northeast. On the contrary, an underestimation was found in the southwest region where summer season (June, July & August) is generally characterized by small anomalies in terms of R values. Generally, the findings of the performed validation indicated an underestimation at higher precipitations and an overestimation at lower precipitations.

The RMSE values showed a large spatial variability in September, October and November in values less than 50 mm over the majority of the study area, while the lowest values (< 3 mm) were recorded in June, July, and August with small increases over northeast. Generally, the highest values of RMSE implied the poorest estimations of TRMM 3B43.This result implied that satellite products have a poor performance in estimating high monthly precipitation totals over the northwest of Iran. This indicates that TRMM rainfall amounts should be corrected or calibrated, and that the calibration process could improve rainfall estimates in the northwest of Iran.

However, we should note that the instruments on TRMM which was launched in 1997 to study rainfall for weather and climate research were turned off after over 17 years of productive data gathering and the spacecraft re-entered the Earth’s atmosphere in 2015.

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