



Performance Evaluation of Three Satellites-Based Precipitation Data Sets Over Iran

Morteza Miri¹ · Reyhaneh Masoudi² · Tayeb Raziei³

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Abstract

The present study aims to evaluate the performance of daily and monthly precipitation data relative to GPM-IMERG, TRMM_3B42 and PERSIANN satellite-based precipitation estimations against historical data for the period 2014–2017 as observed at 70 synoptic stations distributed over Iran. The coefficient of determination (R -squared), root mean square error and the Nash–Sutcliffe model efficiency coefficient were used to evaluate the performance of the used data sets against observed precipitation records at the considered stations. The statistics showed that the considered data sets are generally less successful in estimating daily precipitation at nationwide as the estimation errors were found high at almost all the studied stations. The errors of daily precipitation estimation of GPM-IMERG, TRMM_3B42 and PERSIANN-CDR data sets showed that although there is a considerable similarity between the estimated precipitation by the three data sets, especially between the TRMM_3B42 and GPM-IMERG, the accuracy of GPM-IMERG daily precipitation over Iran is higher than that of TRMM_3B42 and PERSIANN-CDR. The highest R^2 value for GPM-IMERG, TRMM_3B42 and PERSIANN-CDR remotely sensed daily precipitation is equal to 0.6, 0.46, and 0.37, respectively. Similarly, on the monthly time scale, the GPM-IMERG, with an average R^2 value of 0.83 over the country, performs better than the other two data sets. The TRMM_3B43 with mean nationwide $R^2 = 0.80$ also showed comparative performance with GPM-IMERG, but the PERSIANN-CDR data set with an average R^2 value of 0.4 over the stations is not as accurate as the GPM-IMERG and TRMM_3B43.

Keywords Remote sensing data · GPM-IMERG · TRMM_3B43 · PERSIANN-CDR · Performance statistics · Precipitation

Introduction

Precipitation is one of the main inputs in hydrological systems, and therefore, knowledge on areal precipitation characteristics plays an important role in understanding the cycle and management of water resources (Su et al. 2008; Qi et al. 2016). The amount, intensity and time distribution

of rainfall can be obtained from various sources of data such as meteorological stations, weather RADAR, LiDar and meteorological satellites. Rainfall is typically measured by rain gauges and weather RADARs, which are the most reliable sources of rainfall data for a given location (Miri et al. 2016; Gairola et al. 2015). However, the satellite's measurements are affected by systematic errors such as losses due to wetting, evaporation and aerodynamic effects (Porcu et al. 2014; Blacutt et al. 2015). Moreover, precipitation estimates by satellites have some uncertainties due to the influence of various factors such as algorithm limitations and rainfall estimation sensor, surface type and land use and land cover (Hong et al. 2006; Tang et al. 2015). On the other hand, the low density of meteorological stations, especially in mountainous and desert regions of the world, induced by economic or geographical constraints, has limited installation and use of

✉ Morteza Miri
mmiri@ut.ac.ir

¹ Department of Geography, University of Tehran, Tehran, Iran

² Department of Reclamation of Arid and Mountainous Zones Regions, Faculty of Natural Resources, University of Tehran, Tehran, Iran

³ Soil Conservation and Watershed Management Research Institute, Tehran, Iran

meteorological stations at the global and regional scales (Gairola et al. 2015; Mishra et al. 2011). Due to the lack of data caused mainly by the aforementioned problems, a deep understanding and knowledge on the spatial and temporal characteristics of rainfall are lacking in many parts of the world (Blacutt et al. 2015). To overcome these problems, rainfall measurements by remote sensing techniques are a potential alternative when ground-based and radar observations are unavailable (Jiang et al. 2016).

So far, many remotely sensed precipitation data sets have been developed, including the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN; Sorooshian et al. 2000, 2002), global land data assimilation system (GLDAS; Rodell et al. 2004), a method that Produces Global Precipitation Estimates from Passive Microwave and Infrared Data at High Spatial and Temporal Resolution (CMORPH; Joyce et al. 2004), Global Satellite Mapping of Precipitation and Moving Vector with Kalman filter (GSMaP-MKV; Ushio et al. 2009) and Climate Hazards Group Infrared Precipitation with Station data (CHIRPS; Funk et al. 2015). In recent decades, the satellite techniques of precipitation estimation have been significantly improved, making quantitative description of the spatiotemporal variation of precipitation possible over the globe (Porcu et al. 2014). The Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM-IMERG) (Kummerow et al. 1998; Hou et al. 2014) are the most recently launched satellite precipitation estimators that are used worldwide. Nowadays, the estimated precipitation by satellites is widely used for various purposes such as weather monitoring, surveillance and forecasting, climate modeling and hydrological studies (Oliveira et al. 2016).

To compare precipitation amount estimated by satellites with the ground-truth precipitation observations (e.g., rain gauges), Feidas (2010) evaluated the accuracy of six satellite databases over Greece, demonstrating that the TRMM 3B43 has a good performance at 0.5°, 1.5° and 2.5° spatial resolutions. Li et al. (2013) investigated the accuracy of daily, monthly and annual precipitation estimations of TRMM, PERSIANN and CMORPH against observation in Yangtze River basin using statistical indices such as the sum of squared error and skewness for the period 2008–2012. The results indicated that the TRMM overestimates and the PERSIANN and CMORPH underestimate rainfall over the basin.

Many studies have compared precipitation estimation by the latest generation of satellites (i.e., GPM-IMERG) with the previous generations such as TRMM at different time scales and have pointed to the performance improvement of the GPM-IMERG in relation to the previous satellites such as TRMM, CMORPH and GSMaP-MKV (Ning et al.

2016; Satgé et al. 2017; Wei et al. 2017; Prakash et al. 2018; Lu and Yong 2018). By reviewing the accuracy of the estimated GPM-IMERG and TRMM rainfall data at daily, monthly and seasonal scales, Tan and Santo (2018) stated that the total rainfall estimated for Singapore by the GPM-IMERG is slightly accurate than that estimated by the TRMM. Beck et al. (2019) have statistically investigated the accuracy of 26 gridded and satellite-based precipitation databases in the USA for the period 2008–2017 and showed that the GPM-IMERG is more accurate than TRMM. Gebregiorgis et al. (2018) also stated that the GPM-IMERG has considerably improved regarding its previous generation, and in many cases, its result is more accurate than the TRMM estimates. Many other researchers have also evaluated the performance of remotely sensed precipitation estimations all over the world (Collischonn et al. 2008; Seyyedi 2010; Ochoa et al. 2014; Skok et al. 2016), including Iran (Shirvani and Fakharzadeh Shirazi 2014; Miri et al. 2016; Dezfooli et al. 2016; Erfanian et al. 2016), mostly considering the monthly and annual total rainfall estimates for the comparison analysis.

Sharifi et al. (2016) compared Era-Interim, TRMM and GPM-IMERG daily precipitation data sets in four climate zones of Iran and stated that although the three databases underestimate the rainfall values at daily time scale, the GPM-IMERG outperforms the TRMM and Era-Interim data sets. Alibakhshi et al. (2017) compared the GPM-IMERG and TRMM rainfall data with the recorded rainfall over the Kashafrood basin in northeastern Iran and indicated that the TRMM is generally more accurate than the GPM-IMERG.

As indicated by the above literature reviewed, the performance of rainfall estimation by the remotely sensed data has been successfully evaluated worldwide. Nevertheless, as mentioned above, a few studies have attempted to evaluate performance of some remotely sensed precipitation data sets in a catchment or over a limited area of Iran. Due to the topographic complexity, the wide latitudinal and longitudinal extension, and possessing diverse climates (Raziei et al. 2014), it is obvious that the performance of any data set may vary across Iran. Hence, it is necessary to assess the performance of the available satellite-based precipitation data sets over such a large country, having different climates and landscape features. The results of such a performance evaluation may provide useful insights to improve the remotely sensed algorithm used for rainfall estimation (Alimohammad et al. 2014). Hence, the remotely sensed precipitation data sets should be evaluated at local and national scale before being used as an input in any studies. Accordingly, the main propose of the present study is to evaluate the performance of GPM-IMERG, TRMM_3B42, TRMM_3B43 and PERSIANN daily and monthly precipitation data sets over Iran.

Data and Methods

Data

Observational Data

In this study, daily and monthly total precipitation records from 70 synoptic stations relative to the Islamic Republic of Iran Meteorological Organization (IRIMO) as well as the GPM-IMERG, TRMM_3B42, and PERSIANN satellite precipitation measurements for the period March 2014 to December 2017 were used. As shown in Fig. 1, except the desert areas of central-eastern Iran, the used stations are relatively well distributed across the country, thus making performance evaluation of the used satellite-based precipitation data sets possible in different geographical areas of Iran being characterized with different climates and geographical features.

TRMM

TRMM was launched on November 28, 1997, by a collaboration between the USA and the Japan space agencies. The TRMM sensors include the precipitation radar, the microwave imager and the visible and infrared scanners. The products of TRMM satellite are classified into three levels, and the level 3 products are called climate products. The TRMM climate products are currently available on three hourly (TRMM_3B42RT) and (TRMM_3B42.V7), daily (TRMM_3B42RT_Daily.V7) and (TRMM_3B42_Daily.V7), and monthly (TRMM_3B43.V7) time scales for the tropical region and the mid-latitudes of the earth (50° south to 50° north). The spatial resolution of TRMM is $0.25^{\circ} \times 0.25^{\circ}$ in latitude and longitude, spanning from 1998 to 2019. After more than 17 years of productive data gathering, the mission of TRMM satellite ended up on April 8, 2015, and the spacecraft returned the Earth's

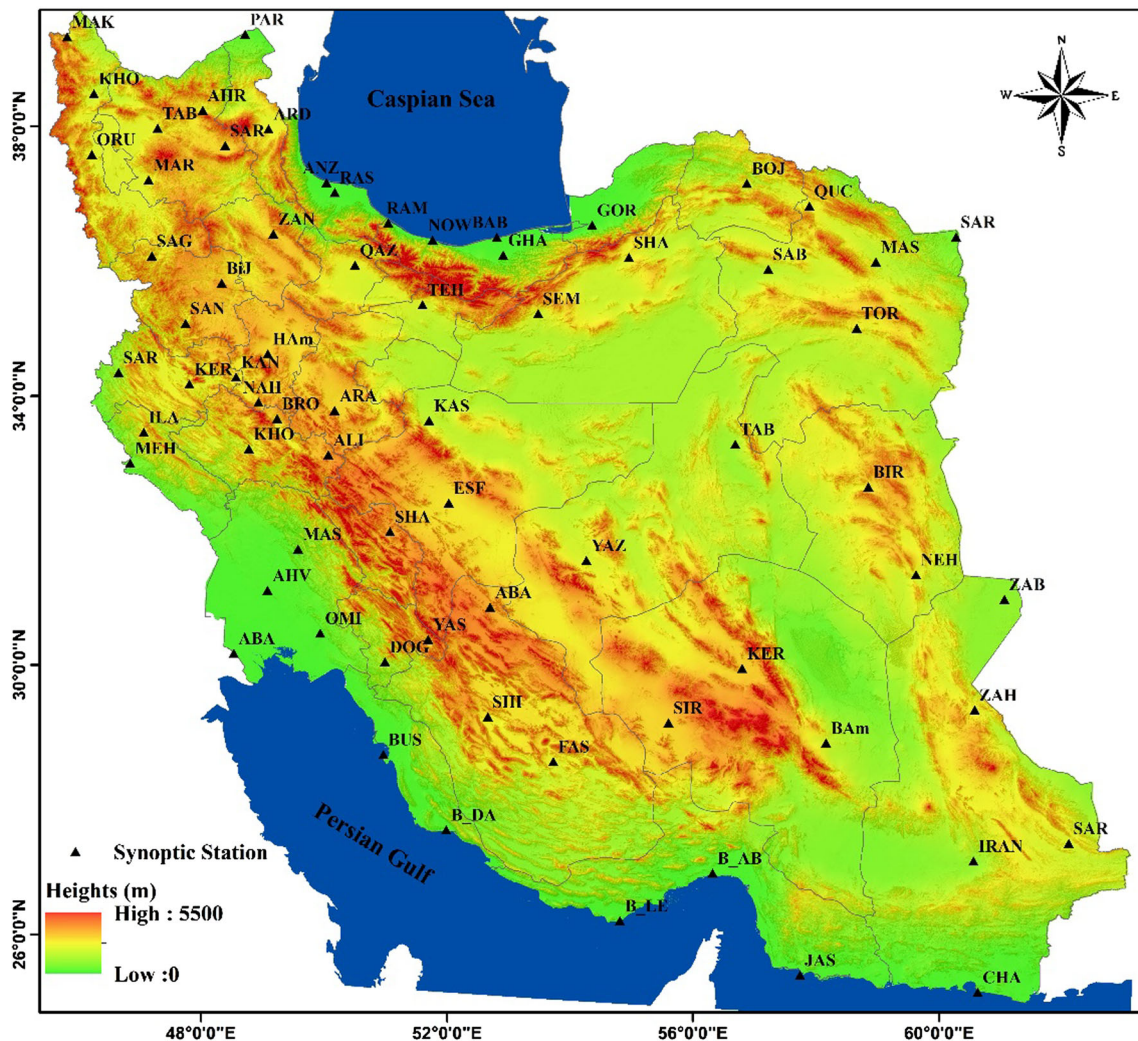


Fig. 1 Spatial distribution of the meteorological stations used over the topographic map of Iran

atmosphere on June 15, 2015, over the South Indian Ocean. The terminal phase began when fuel was exhausted in July 2014. On October 7, 2014, the satellite descended to an altitude that precluded useful TRMM Precipitation Radar data, with a brief revival as TRMM descended past the original altitude of 350 km. Meanwhile, the TRMM Microwave Imager (TMI) continued to function with slowly changing characteristics until it was shut down on April 8, 2015, as part of the decommissioning, or “passivation” of the satellite. Nonetheless, in parallel with IMERG, the multi-satellite TMPA products will continue to be produced through mid-2019 (Miri 2016; Huffman 2018; Fang et al. 2019). For this research, the daily (TRMM 3B42.V7) and monthly (TRMM 3B43.V7) precipitation products for the period spanning from March 2014 to December 2017 were used. The TRMM Products briefly described above were retrieved from <https://pmm.nasa.gov/data-access/downloads/TRMM>.

GPM-IMERG

Given the successful mission of TRMM sensor ended on April 2015, a year before its fuel ran out and fell, NASA and the Japan space exploration agency launched the Global Precipitation Measurement Mission (GPM-IMERG) sensor to space on February 27, 2014, to measure the global precipitation at fine temporal and spatial resolution. It is an international network of different satellites, such as the TMPA, CMORPH and the PERSIANN, providing accurate measurements of global rain and snow observations, using two-frequency radar and multichannel microwave imaging. The final products of this satellite have been available to researchers and users since June 01, 2000, with a half-hour delay at hourly time scale. The GPM-IMERG data cover half-hourly, daily and monthly total precipitation with the spatial resolution of 0.10° in latitude and longitude (Huffman et al. 2015). For this research, the daily (GPM_3IMERGDF) and monthly (GPM_3IMERGM) precipitation products for the period spanning from March 2014 to December 2017 were used. The GPM-IMERG product is available at <https://pmm.nasa.gov/data-access/downloads/gpm>.

PERSIANN

PERSIANN is an algorithm that is based on the use of remote sensing data and the artificial neural network approach, which was developed at the University of Arizona in 1999 (Sorooshian et al. 2000). In this model, first, the cloud-top brightness temperature is estimated in each of the network cells. Then, using the passive microwave data, the cloud-top brightness temperature data are calibrated with the probability-matching method and the precipitation

rate per hour is estimated. In fact, the system uses the neural network function approximation method and the infrared image brightness temperature to estimate the precipitation rate in each cell with 0.25° spatial resolution, which is provided by the geosynchronous satellite every 30 min (Sorooshian et al. 2000). Currently, the precipitation data of this model are available to the users with a spatial resolution of $0.25^\circ \times 0.25^\circ$ in latitude and longitude at monthly, daily and hourly (1, 3 and 6 h) time scales for an area between 60° north and 60° south. In this study, the PERSIANN-CDR precipitation product was used, which is generated employing the PERSIANN algorithm and GridSat-B1 infrared data which is adjusted using the GPCP precipitation product. The PERSIANN-CDR product was downloaded from <http://chrsdata.eng.uci.edu>.

Methodology

In the present study, three statistical tests were used to evaluate the performance of daily and monthly precipitation measurements of the GPM-IMERG, TRMM_3B42.V7 and TRMM_3B43.V7 and the PERSIANN-CDR against observation at 70 synoptic stations distributed over Iran (Fig. 1, see “Appendix” for details about the names and the coordinates of the mentioned stations).

The time series of GPM-IMERG, TRMM_3B42.V7 and TRMM_3B43.V7, and PERSIANN-CDR precipitation measurements corresponding to the nearest grid point to each station were extracted and compared with the observed precipitation using several performance evaluation statistics commonly used in comparative analyses such as comparing the model estimation with the ground-truth observation (Moriassi et al. 2007). However, for the sake of brevity, among the used statistics, only the R -squared (R^2), the Nash–Sutcliffe model efficiency coefficient (EF) and the root mean square error (RMSE) as formulated in Eqs. 1–3 are presented herein. R -squared (R^2) is a statistical measure that represents the proportion of the variance for a dependent variable that is explained by an independent variable or variables in a regression model. R -squared explains to what extent the variance of one variable explains the variance of the second variable. EF comparatively determines the relative magnitude of the residual variance to the measured data variance, and with the residual variance equal to the observed data variance, it results in $EF = 1.0$; contrarily, when EF equals zero or is negative, this indicates that the observed mean (O) is as good as or better predictor than the model. The RMSE characterizes the variance of the errors; the smaller the RMSE, the better the model’s performance.

$$R^2 = \frac{\sum_{i=1}^n O_i p_i}{\sqrt{\sum_{i=1}^n O_i^2 \sum_{i=1}^n p_i^2}} \quad (1)$$

$$EF = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (o_i - p_i)^2} \quad (3)$$

In the above equations, p_i is the predicted value (satellite measurement), o_i is the observed value, \bar{o}_i is the mean of the observed value, \bar{p}_i is the mean of the predicted value, and N is the number of data or the length of the time series.

Finally, the long-term annual total precipitation of observation and the three satellites-based measurements were mapped using the inverse distance weighting (IDW) method to illustrate how the satellite-based measurements covary with the map of observed annual total precipitation.

Result

As indicated earlier, the performance of the three satellites-based precipitation data sets over Iran was evaluated at both daily and monthly time scales as presented below.

Data Sets Performance at the Daily Time Scale

Figure 2 shows the spatial variations of the statistics used to evaluate the accuracy of the GPM-IMERG, TRMM_3B42 and PERSIANN-CDR daily precipitation data sets over Iran as compared with the observations at the stations distributed across the country. As it can be seen, the higher R^2 values in Fig. 2a indicate a better performance of GPM-IMERG when compared to the R^2 values of the TRMM_3B42 and PERSIANN-CDR data sets in Fig. 2b, c. In Fig. 2a, 19% of the stations show R^2 values between 0.51 and 0.66, but the R^2 values of TRMM_3B42 and PERSIANN-CDR are higher than 0.50 in only one and two stations, respectively (Fig. 2b, c). Despite the observed differences in R^2 values of the three precipitation data sets, their spatial behavior is similar, especially in areas characterized by the highest and lowest R^2 values. Based on the R^2 indicator, the GPM-IMERG, TRMM_3B42 and PERSIANN-CDR data sets have the highest accuracy in western Iran, particularly in the middle of the Zagros Mountains and southern Iran, whereas the least accuracy is observed in the coastal areas of the Caspian Sea in northern Iran.

In other regions of Iran, although the R^2 value for the GPM-IMERG is higher than that for the TRMM_3B42 and PERSIANN-CDR; however, the R^2 value is less than 0.5 for all the three data sets, being statistically significant at

0.05 significant level. Therefore, based on R^2 indicator, except the central Zagros and some locations in southern regions, the reliability of the satellite-based daily precipitation data sets considered herein is low and might not be considered as a good proxy for decision making. This is especially much pertinent for the coastal areas of the Caspian Sea and eastern Iran where the coefficient of determination between the estimated and observed precipitation is the lowest (Fig. 2).

The spatial patterns of the other used indicators are consistent with the R^2 statistic. Based on the EF indicator, GPM-IMERG is more efficient than the other two data sets. The highest values of this indicator were also observed in the central Zagros and southern regions of Iran, and the lowest EF values are seen in the coastal areas of northern Iran. In other regions of Iran, the value of this indicator is less than 0.30, and notably, in some areas, the EF values are negative for TRMM_3B42 and PERSIANN-CDR. In general, the EF values over Iran are low, indicating that the daily precipitation of GPM-IMERG, TRMM_3B42 and PERSIANN-CDR data sets is not suitable for analyzing daily precipitation, particularly daily extreme precipitation events in Iran (Fig. 2).

The spatial pattern of the RMSE for the estimated precipitation by the three data sets resembles the spatial behavior of the other statistics. According to this indicator, the maximum deviation of the remotely sensed daily precipitation is observed in the coastal areas of northern Iran, the central Zagros Mountains and the northwest of Iran. The high values of RMSE on the northern coast of the Caspian Sea could be attributed to the fact that the satellites are not able to estimate extreme precipitation in these areas. In contrast, the lowest RMSE value was obtained for the central and southeastern parts of Iran, which might be due to the higher frequency of zero daily precipitation recorded by both the stations and the satellites. However, based on the EF and R^2 indicators, it can be concluded that the accuracy of the data sets in these areas is low (Fig. 2).

Data Sets Performance at the Monthly Time Scale

Figure 3 shows the accuracy of the monthly precipitation data sets in comparison with the observations at the synoptic stations considered. The spatial variation of the estimated R^2 values between the precipitation estimated by the satellites and observed total precipitation at the station's locations indicates the higher accuracy of the GPM-IMERG as compared to the TRMM_3B43 and PERSIANN-CDR, and also the higher accuracy of the TRMM_3B43 than the PERSIANN-CDR in different parts of Iran. The values of R^2 for the GPM-IMERG and TRMM_3B43 are more than 0.8 in most parts of Iran. In other words, the estimated precipitation of GPM-IMERG

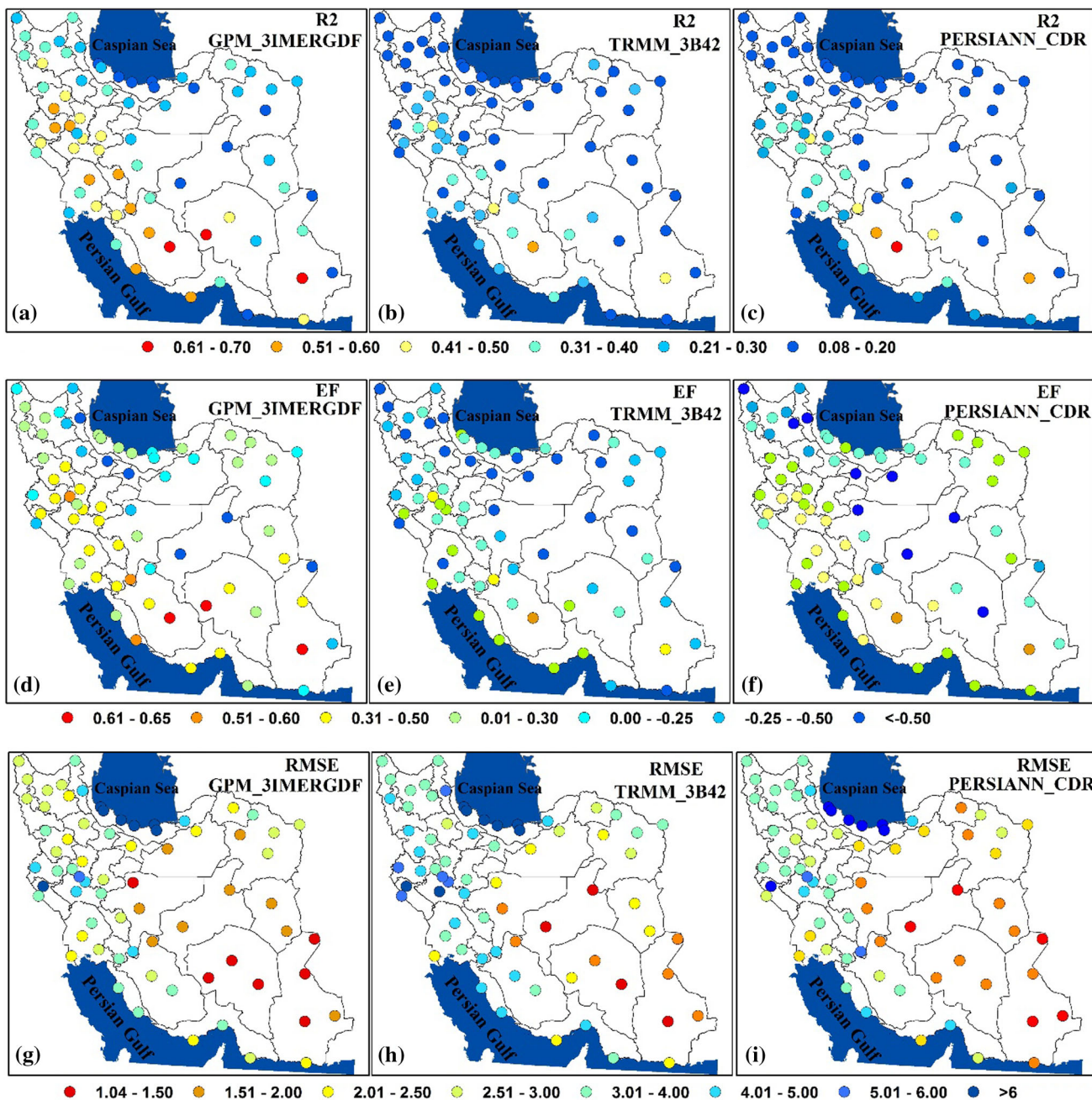


Fig. 2 Spatial variation of R^2 , EF and RMSE indicators over Iran, resulted from a pairwise comparison between daily observed precipitation and the GPM-IMERG, TRMM_3B42 and PERSIANN-CDR daily precipitation retrieved for the closest grid point to the stations

and TRMM_3B43 describes more than 80% of the precipitation variance in most of the studied stations. As seen, the R^2 values of some of the stations in western and southwestern Iran may reach 0.9 and beyond, which indicates a good relationship between the estimated and observed precipitation in these areas.

The lower range of the R^2 values for the considered data sets at monthly time scale is between 0.4 and 0.5 which were observed only in about 4% of the stations, located in the southern Alborz hillsides as well as in Yazd station in

central Iran. The R^2 values for the other stations are more than 0.5. For the PERSIANN-CDR precipitation data set, the highest R^2 is 0.9 which is observed in 24% of the stations. However, the R^2 value is greater than 0.8 for 55% of the stations and between 0.5 and 0.8 for 21% of the stations.

There is also a notable discrepancy between the spatial distribution of R^2 values of the PERSIANN-CDR and the other two data sets, mostly induced by the higher R^2 values of GPM-IMERG and TRMM_3B43 in the coastal regions

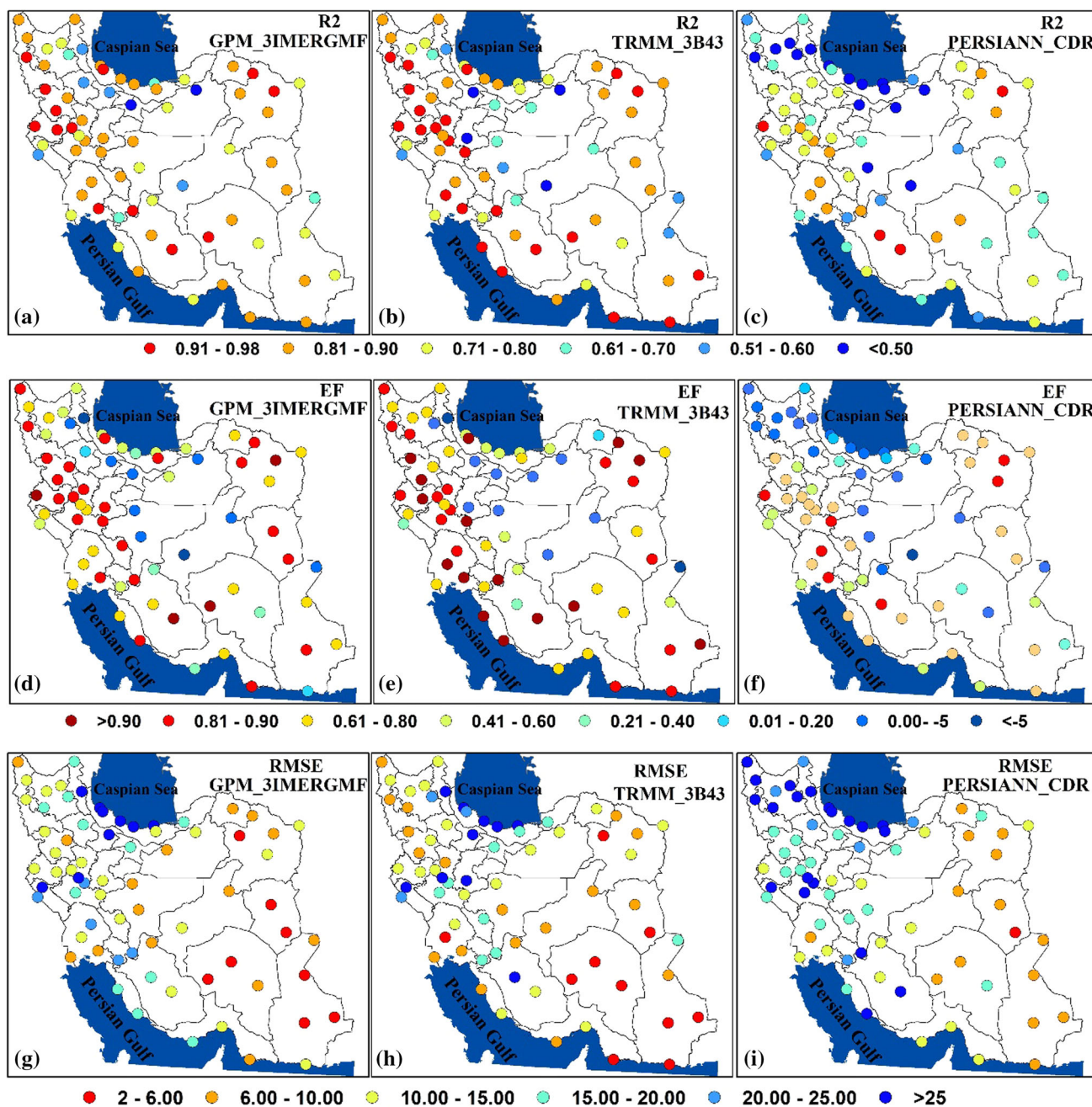


Fig. 3 Spatial variation of R^2 , EF and RMSE indicators over Iran, resulted from a pairwise comparison between monthly observed precipitation and the GPM-IMERG, TRMM_3B43 and PERSIANN-CDR monthly precipitation retrieved for the closest grid point to the stations

of northern Iran, where the R^2 values of the PERSIANN-CDR data set are as low as 0.5. The spatial behavior of the EF indicators (Fig. 3) is consistent with the maps of R^2 indicator, and in most parts of Iran, it is between 0.5 and 0.97 for both GPM-IMERG (70% of stations) and TRMM_3B43 (75% of stations).

In some stations, particularly in western and south-western regions of Iran, where the R^2 value is the highest,

the EF Index also exceeds 0.8, indicating the good relationship between observation and GPM-IMERG and TRMM_3B43 precipitation data sets. The lowest value of the efficiency factor for TRMM_3B43 and GPM-IMERG was observed in the stations located in the central and southern Alborz hillsides, which indicates the poor relationship between the estimated precipitation and the observational data. As is seen, the efficiency factor of the

PERSIANN-CDR data set is not consistent with the R^2 values of the other two data sets over different parts of Iran. As for GPM-IMERG and TRMM_3B43, the higher EF values ranging between 0.5 and 0.9 were mostly observed in the western and southwestern parts of Iran, taking into account almost 55% of the studied stations. The lowest EF values were also observed in the central regions, the southern Alborz hillsides and the northern coasts of Iran. According to the map of EF indicator, although the PERSIANN-CDR monthly precipitation data have a moderate or lower accuracy in some regions, a good relationship was found between the PERSIANN-CDR monthly precipitation and the observation in most regions of Iran, especially in the west, southwest and northeast of Iran (Fig. 3).

Spatial Representativeness of the Used Data Sets

Figure 4 depicts the spatial patterns of the long-term mean annual precipitation of the remotely sensed data sets used as well as the observation computed for the studied period (2000–2017). As shown, the GPM-IMERG and TRMM better mimic the spatial pattern of the mean annual observed precipitation, whereas noticeable inconsistency between the PERSIANN-CDR and the observation considering both the spatial behavior and the precipitation amount was observed. Therefore, as shown in Fig. 4, there is a remarkable similarity between the GPM-IMERG and TRMM as well as between these two data sets and the observation regarding both the spatial distribution and magnitude of the precipitation; particularly, the GPM-

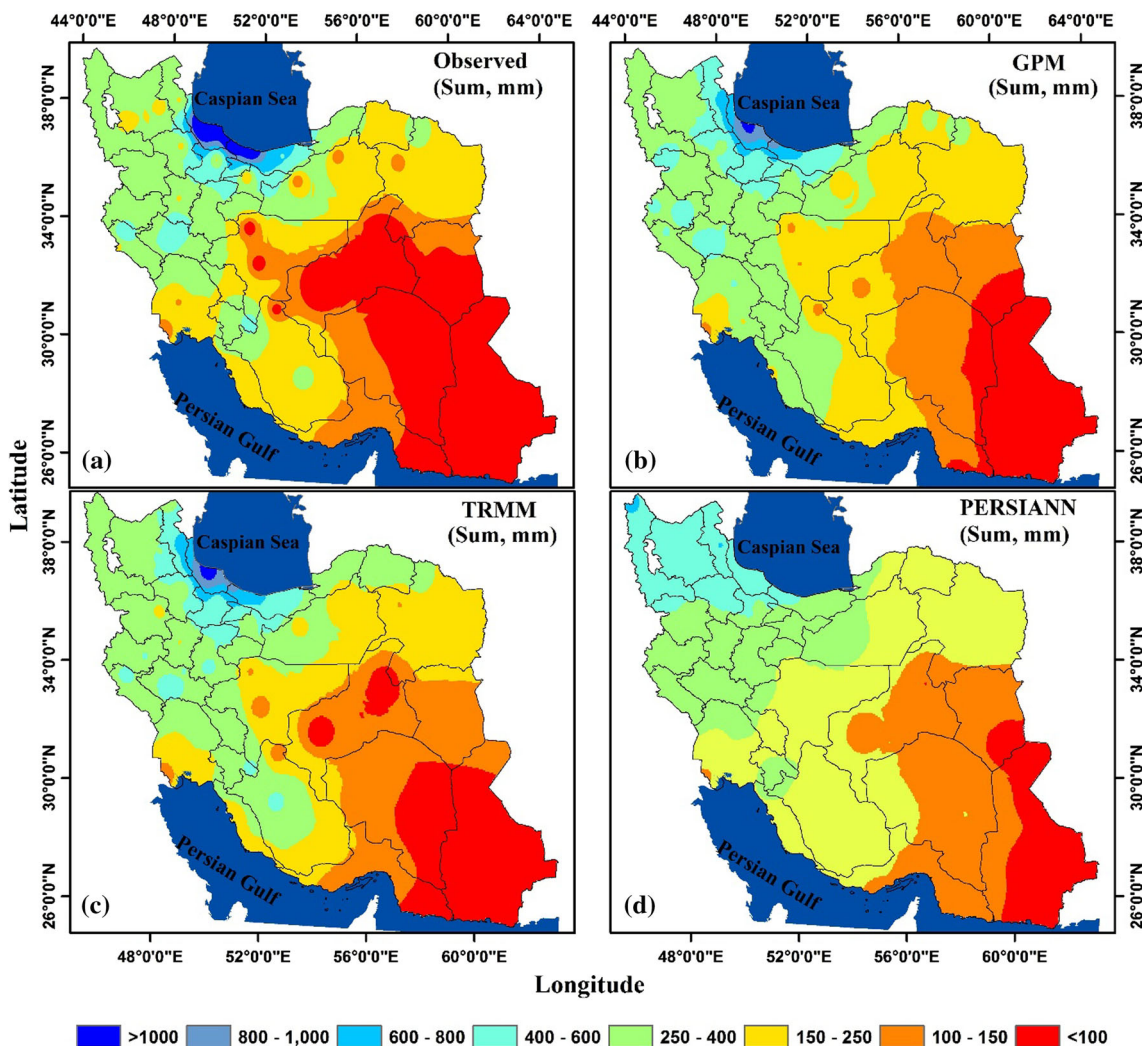


Fig. 4 Spatial distribution of the long-term annual precipitation corresponding to the observation, the TRMM, GPM-IMERG and PERSIANN-CDR data sets computed for the period 2014–2017

IMERG and TRMM well represent the areas characterized with low and high precipitation amounts in the country. However, as illustrated in Fig. 4, obviously the PERSIANN-CDR data set underestimates the precipitation amount almost all over the country, especially in northern Iran featured with the highest precipitation amount in the country. Nevertheless, it seems that the PERSIANN-CDR precipitation estimation is closer to the observation in some areas including the hyper-arid climate of southeastern Iran. Although the GPM-IMERG and TRMM showed better performance in representing the spatial pattern of the mean annual precipitation of Iran and the associated cores of high and low precipitation, however, they are unable to closely estimate the precipitation amount in different parts of the country, especially in the humid areas of northern Iran featured with as high as 1000 mm of precipitation as illustrated by the map of observed precipitation, and 990, 740 and 600 mm by GPM-IMERG, TRMM and PERSIANN-CDR data sets, respectively.

Conclusion

This study statistically evaluated the performance of the GPM-IMERG, TRMM_3B42.V7 and 3B43.V7, and PERSIANN-CDR remotely sensed data sets in estimating daily and monthly precipitation across Iran. The results showed that the accuracy of the GPM-IMERG in estimating daily precipitation is inappropriate almost all over the country; however, it exhibits a moderate accuracy in some areas including western Iran, i.e., the middle of the Zagros ranges. It showed very poor performance over the coastal areas of the Caspian Sea as well as the central areas of the country. The results suggest that the performance of GPM-IMERG data set is decreased from west to the east and from the south to the north of the country. According to EF indicator, the GPM-IMERG daily precipitation data are not accurate enough at the country level and thus, it is not suited for analyzing extreme daily precipitation events. It was also found that the GPM-IMERG tends to overestimate daily precipitation in many parts of Iran; however, the magnitude of the underestimation of GPM-IMERG database is much higher than the magnitude of its overestimations in Iran. Comparable performance between GPM-IMERG and TRMM_3B42 was also found as indicated by the statistics considered in the study. As for GPM-IMERG, the TRMM_3B42 performs better in western Iran, especially along the Zagros Mountains, while it performs the worst in the Caspian region. Although the accuracy of TRMM_3B42 data set in western Iran is somewhat appropriate and acceptable, the EF statistic showed that

this database could not predict the rainfall extremes in Iran as accurate as of the GPM-IMERG database. The highest observed TRMM_3B42.V7 rainfall underestimation was observed in the Caspian Sea region, which was also the case for GPM-IMERG data set. The comparison of the PERSIANN-CDR daily precipitation with the observational data set indicates that it is the least accurate data set in Iran as compared with the GPM-IMERG and TRMM_3B42 data sets.

The results of the present study revealed that the performance of the three used data sets is increased when their monthly precipitation estimations were compared with the monthly observed precipitation over Iran. As with the case of the daily time scale, the performance of the GPM-IMERG was found better than that of TRMM_3B43 and PERSIANN-CDR. In contrast to the daily time scale, it was found that the PERSIANN-CDR data set has reasonable accuracy in most areas of Iran. However, in some areas such as the coastal areas of northern Iran and in some locations of central-northern Iran (Shahrood and Qazvin stations), these satellites estimate the amount of precipitation much more or much less than the actual observed precipitation amount. The underestimation of rainfall at the stations in northern Iran can be attributed to the low power of the satellite in distinguishing between atmospheric conditions over the land and the water body and therefore underestimates rainfall in these areas. However, the complex topographic conditions in the Caspian Sea area (rapid elevation changes in short distances from the sea coast to the mountain crests) can also add to this complexity and reduce the ability of the satellite to accurately estimate rainfall in the area. The lower accuracy of the three used data sets in the coastal areas of northern Iran has been already reported by similar recent studies using the CRU (Miri et al. 2016), GPCC (Miri et al. 2017) and ECMWF (Raziei and Sotoudeh 2017) data sets. Overall, it can be stated that all the three used databases underestimate precipitation in the southern Caspian Sea coast in northern Iran and overestimate precipitation in the northwest and west of Iran. Finally, it can be stated that although the accuracy of the daily rainfall data of the three databases is not high enough in Iran, though it is moderate in some regions, however, the accuracy of the monthly precipitation estimations by the three remotely sensed data sets, especially the GPM-IMERG, is relatively high and they well represent the spatial distribution of the observed precipitation over Iran. Hence, the good agreement between the observed monthly precipitations and the precipitation estimations by the GPM-IMERG, TRMM_3B43 and PERSIANN-CDR over Iran promises for further improvements in satellite technology, increasing the accuracy of

satellite precipitation estimation over the country. Excepting a few cases in which the GPM-IMERG and TRMM were not been able to accurately predict the monthly extreme precipitation in some scattered stations in Iran, it can be stated that these two data sets provide excellent precipitation estimations in almost all studied stations at

Appendix

Table 1 shows the names and the coordinates of the used meteorological stations depicted in Fig. 1. Only the initial letters of each station name are displaced in Fig. 1.

Table 1 The names and the coordinates of the meteorological station

Name_station	Long	Lat	Name_station	Long	Lat	Name_station	Long	Lat
Maku	44.39	39.38	Mehrabad	51.31	35.69	Nehbandan	60.03	31.54
Parsabad	47.78	39.60	Semnan	53.42	35.59	Zabol	61.54	31.09
Orumiyeh	45.06	37.66	Mashhad	59.63	36.24	Zahedan	60.90	29.47
Khoy	45.00	38.56	Sabzevar	57.65	36.20	Kerman	56.96	30.26
Tabriz	46.24	38.12	Torbat-e Heydariyeh	59.22	35.27	Sirjan	55.68	29.47
Ahar	47.07	38.43	Kermanshah	47.15	34.35	Bam	58.35	29.10
Sarab	47.53	37.93	Kangavar	47.98	34.50	Yazd	54.29	31.90
Maragheh	46.15	37.35	Sarpol-e-Zahab	45.87	34.45	Shiraz	52.60	29.56
Ardebil	48.33	38.22	Saqez	46.31	36.22	Abadeh	52.62	31.20
Bandar-e-Anzali	49.46	37.48	Sanandaj	47.01	35.25	Yasuj	51.56	30.70
Rasht	49.62	37.32	Bijar	47.62	35.89	Dogonbadan	50.82	30.35
Ramsar	50.68	36.90	Hamedan (Airport)	48.53	34.87	Abadan	48.21	30.38
Nowshahr	51.47	36.66	Nahavand	48.41	34.14	Ahvaz	48.74	31.34
Babolsar	52.65	36.72	Tabas	56.95	33.60	Omidiyeh (Aghajari)	49.69	30.74
Gharakhil	52.77	36.45	Kashan	51.48	33.97	Masjedsoleyman	49.24	31.98
Gorgan	54.41	36.91	Ilam	46.40	33.59	Bushehr (Airport)	50.82	28.96
Bojnurd	57.30	37.49	Khorramabad	48.28	33.44	Fasa	53.72	28.90
Zanjan	48.52	36.66	Borujerd	48.76	33.92	Bandar-e-Dayyer	51.93	27.83
Qazvin	50.05	36.25	Aligudarz	49.70	33.41	Saravan	62.32	27.39
Shahrud	55.09	36.42	Birjand	59.28	32.89	Iranshahr	60.72	27.23
Quchan	58.45	37.12	Isfahan (Airport)	51.86	32.74	Bandarabbas	56.37	27.21
Sarakhs	61.15	36.54	Shahrekord	50.84	32.29	Bandar-e-Lengeh	54.83	26.53
Arak	49.78	34.07	Mehran	46.18	33.11	Chabahar	60.65	25.28
						Jask	57.77	25.64

monthly time scale. Given the relatively good precipitation estimation at most of the Iranian stations, as well as being up to date and real time and proving a very good spatial and temporal coverage, the considered data sets can be used as alternative sources of information for various climatological and hydrological studies in Iran. Nonetheless, it is also worth mentioning that the performance evaluation of the present study is valid at the considered stations and any generalization of the achieved results to the surrounding stations should be done with caution when required, particularly in coastal areas and the places with a very complex topography.

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