

Evaluation of the Accuracy of Satellite Precipitation Data Compared to Station Observations in Northeastern Iran

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(Received: 31 Jan 2026, Revised: 18 Feb 2026, Accepted: 25 Feb 2026, Published online: 25 Feb 2026)

Abstract

This study aimed to evaluate the performance of three satellite precipitation products—CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data), PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks), and TRMM (Tropical Rainfall Measuring Mission)—in representing precipitation patterns across northeastern Iran during the 2001–2010 period. For this purpose, data from six selected synoptic meteorological stations obtained from the Iranian Meteorological Organization were compared with satellite-derived datasets accessed through the Google Earth Engine platform. The products were evaluated at daily, monthly, and annual time scales. At the daily scale, statistical indicators including the correlation coefficient (R), root mean square error (RMSE), and bias were calculated. Additionally, independent-samples t-tests were applied to examine differences in monthly mean precipitation, and annual precipitation zoning during dry and wet years was conducted within a Geographic Information System (GIS) framework. All computations related to the Taylor diagram and statistical metrics were carried out using R, while independent-sample t-test analyses were performed in SPSS. The results demonstrated that the performance of satellite products is strongly dependent on temporal scale and climatic conditions. At the daily scale, TRMM showed the highest agreement with ground observations and outperformed CHIRPS and PERSIANN in terms of accuracy. Despite its higher spatial resolution, CHIRPS exhibited weak performance in estimating daily precipitation over the study area. At the annual scale, TRMM performed more reliably, particularly during dry years, whereas all three products tended to underestimate precipitation during wet years. Furthermore, the highest estimation accuracy for all three satellite products was jointly observed at the Torbat-Heydariye station. At the monthly scale, although TRMM occasionally demonstrated relatively better performance, statistically significant differences between satellite-derived and station data were detected in 83% of the stations. Overall, the findings indicate that the selection of satellite precipitation products should be tailored to temporal scale, topographic characteristics, and regional climatic conditions. Regional validation is therefore essential prior to application in water resource management and climatological studies in dry and semi-arid regions.

Keywords: CHIRPS, PERSIAN, Precipitation, TRMM, Northeast Iran.

Cite this article: Salahi, B. and Shahi, A. (2025). Evaluation of the Accuracy of Satellite Precipitation Data Compared to Station Observations in Northeastern Iran. *Nivar*, 49(Special Issue (S1)), 73-89. doi: 10.30467/nivar.2026.573075.1368

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1. Introduction

Precipitation is one of the most critical meteorological variables, playing a fundamental role in the Earth's water and energy balance. Accurate measurement of precipitation is essential for effective water resource management and climate hazard analysis (Kim et al., 2017). Although ground-based station measurements provide the most precise observations, limitations in station density and spatial coverage, maintenance costs, and accessibility challenges—particularly in arid and semi-arid regions—introduce uncertainties in precipitation monitoring (Gholami et al., 2023). In this context, remote sensing technology, offering extensive spatial and temporal coverage, has emerged as a complementary tool for monitoring atmospheric variables (Kumar et al., 2013). In recent years, global-scale precipitation estimation methods using satellite-derived products with high temporal and spatial resolutions have been developed as alternatives to ground observations and have been analyzed in numerous studies (Jiang et al., 2016).

Over the past decades, several satellite precipitation products have been developed, among which the most widely used include CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data), PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks), and TRMM (Tropical Rainfall Measuring Mission) (Satgé et al., 2019; Serrat-Capdevila et al., 2016; Funk et al., 2015). Each of these datasets is based on different algorithms and data sources. For instance, CHIRPS combines satellite and ground-based data (Funk et al., 2015), PERSIANN relies on artificial neural networks for precipitation estimation (Satgé et al., 2019), and TRMM is derived from radar and spaceborne observations (Serrat-Capdevila et al., 2016). Evaluations at various spatial and temporal scales have indicated that the performance of these products is heterogeneous and strongly dependent on regional climatic and topographic conditions (Zambrano-Bigiarini et al., 2017; Gebrechorkos et al., 2024).

International studies have shown that CHIRPS performs well in reproducing the annual precipitation cycle and spatial patterns across

many tropical and semi-arid regions (Bayissa et al., 2017; Morales-Velázquez et al., 2021; Das et al., 2022), although its accuracy may decrease at daily scales in some areas. Similarly, assessments of TRMM have demonstrated its ability to capture temporal precipitation variations effectively, particularly at monthly and annual scales (Masoodian et al., 2016; Miri, 2016). In contrast, PERSIANN's performance has been reported to vary depending on the climatic regime, occasionally underestimating precipitation in arid regions (Katiraie Boroujerdy, 2016). Recent global studies have further assessed satellite precipitation products with higher resolution and advanced algorithms, such as GPM-IMERG. For example, da Silva et al. (2023) evaluated GPM products in Chile during 2015–2020, identifying IMERG Early as the most accurate product. Acosta-Reyes et al. (2024) assessed the spatial and temporal accuracy of IMERG in Mexican states for 2001–2020, reporting notable correlation and RMSE metrics. Rodríguez et al. (2024) also evaluated IMERG products in Colombia during 2001–2019, highlighting their high accuracy at the monthly scale.

In Iran, numerous studies have evaluated these datasets. Findings indicate that although products such as CHIRPS and ERA5 exhibited acceptable correlations with station data across many regions (Gholami et al., 2023; Bahrami & Darand, 2025), their accuracy was not uniform and varied with climatic conditions and topography. Moreover, satellite products' performance differed across temporal scales, generally exhibiting higher uncertainties at shorter time scales, such as daily observations (Mianabadi et al., 2022). Recent studies using advanced datasets and newer products provide additional evidence regarding their precipitation representation. For instance, Ordooni et al. (2021) compared GPM-IMERG products with rain gauge measurements in the Gorgan-Rud basin, confirming their accuracy. Sharafati and Shobeiri (2022) analyzed CHIRPS data across 68 Iranian stations and found that in 41% of the stations, more than 60% agreement with observations was observed. Additionally, Shahi and Salahi (2025) evaluated the ability of satellite products to represent extreme precipitation events in northwestern Iran over two

decades, reporting high accuracy for GPM-IMERG and AQUA-AIRS data.

Despite these studies, a simultaneous and multi-scale evaluation of CHIRPS, TRMM, and PERSIANN in northeastern Iran, particularly focusing on dry and wet years, has not yet been comprehensively reported. Northeastern Iran, characterized by diverse topography, high precipitation variability, and relatively sparse ground stations, is a sensitive region for precipitation monitoring. Therefore, regional validation of these products is essential for applications in water resources and climate studies.

In this study, considering the temporal overlap of satellite and station data and the availability of reliable datasets, the period from 2001 to 2010 was selected for analysis. The primary objective is to assess the accuracy and reliability of three satellite precipitation products—CHIRPS, TRMM, and PERSIANN—in representing precipitation in northeastern Iran at daily, monthly, and annual scales. The novelty of this research lies in providing an integrated multi-scale evaluation framework and examining the performance of these products under contrasting climatic conditions, including dry and wet years.

2 .Data and Methods

2-1. Location of the Study Area

The study area for this research is located in northeastern Iran, spanning latitudes from 35° to 37° N and longitudes from 57° to 61° E. It includes the provinces of North Khorasan and Razavi Khorasan. Six meteorological stations within this region were selected for the study (Figure 1) based on multiple criteria, including topographic variability, diversity of rainfall patterns, inter-station distances, and the availability of complete historical records. Despite certain temporal and spatial limitations, the selected dataset adequately represents the climatic conditions of the region, ensuring the scientific reliability of the findings. These six stations were considered the most reliable and homogeneous subset for comparison with satellite data. The selection was guided by data quality and consistency criteria, in accordance with approaches used in previous reputable studies (Awatade et al., 2018; Ali et al., 2017; Akinyemi et al., 2020). In these studies, a limited number of homogeneous stations was used to ensure valid assessments under data constraints—for instance, Awatade et al. (2018) analyzed six stations over 11 years, Ali et al. (2017) studied six stations over 10 years, and Akinyemi et al. (2020) also relied on six stations to perform accurate and reliable analyses of satellite precipitation data. Accordingly, the selection of six stations in this study, following established scientific standards, ensures the validity of the evaluations and comparisons with satellite-derived precipitation data.

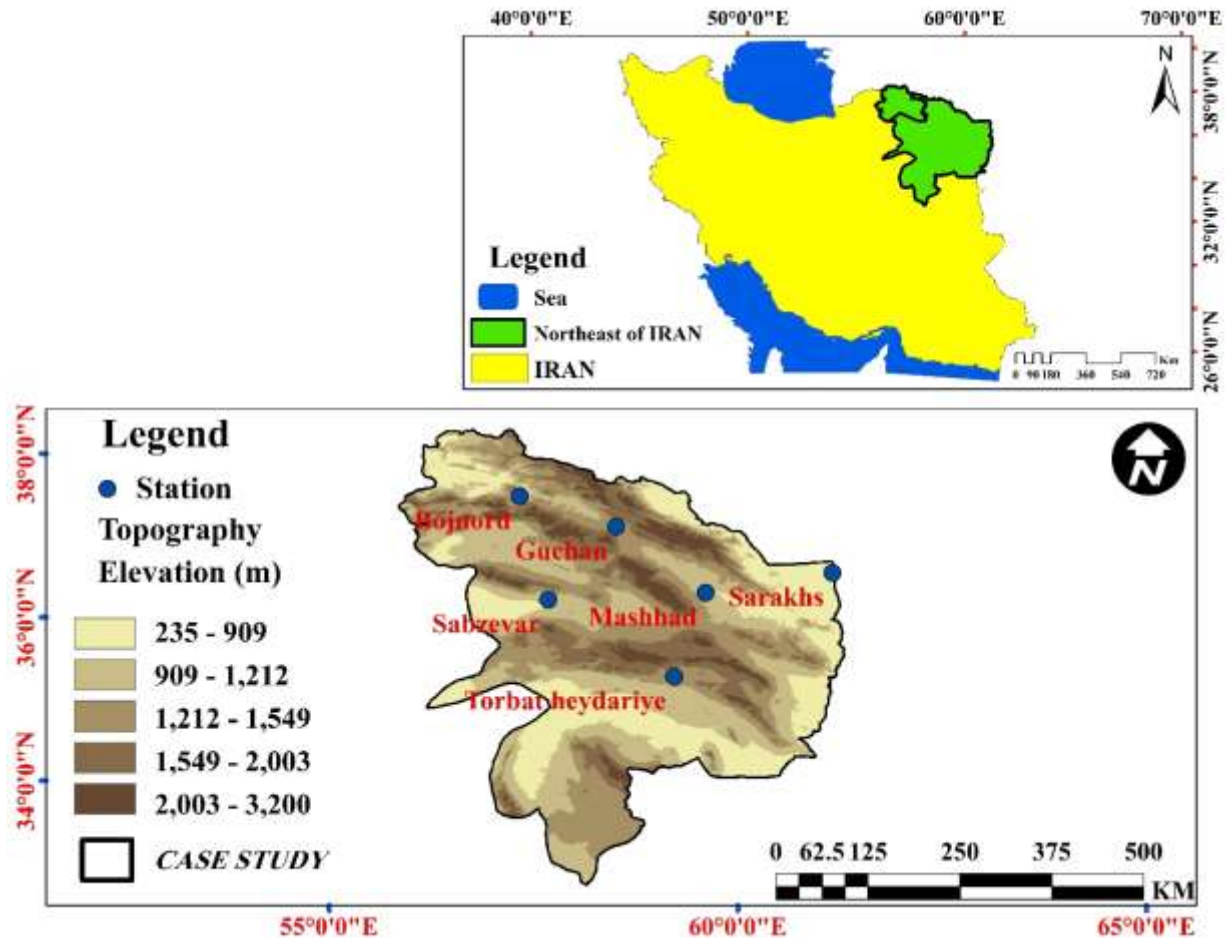


Figure 1. Geographical location, topography, and stations of the study area

2-2. Data

In this study, daily precipitation data from six selected synoptic meteorological stations in northeastern Iran for the period 2001–2010 were used. Station data were obtained from the Iranian Meteorological Organization (IRIMO) database (www.irimo.ir), with daily accumulated precipitation values recorded in millimeters (mm). In addition to ground-based data, three satellite precipitation products—CHIRPS, TRMM, and PERSIANN—were independently evaluated. Key characteristics of these datasets are presented in Table 1. Satellite precipitation data (CHIRPS, TRMM, and PERSIANN) were obtained through the Google Earth Engine (GEE; <https://earthengine.google.com>) platform. For each product, the data were clipped to the study area (57° – 61° E longitude and 35° – 37° N latitude). When necessary, the data were aggregated to daily totals to match the temporal resolution of ground-based observations. For

each meteorological station, the nearest satellite grid cell was identified to ensure spatial consistency, enabling accurate comparison between satellite-derived and in-situ precipitation data. These procedures ensure the reliability and accuracy of the satellite product validation.

CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data)

CHIRPS provides quasi-global precipitation data at 0.05° (~ 5.4 km) spatial resolution with daily, pentad, and monthly temporal resolution. The dataset has been available since 1981, reporting precipitation in millimeters (mm). CHIRPS integrates infrared satellite imagery with ground station data to improve precipitation estimation accuracy. In the study area, CHIRPS covers approximately 3,200 grid cells, and each meteorological station was matched with the nearest grid cell to ensure spatial consistency.

TRMM (Tropical Rainfall Measuring Mission – TMPA 3B42)

The TRMM 3B42 product provides precipitation estimates at 0.25° (~25 km) spatial resolution and three-hourly temporal resolution, which were aggregated to daily totals for this study. TRMM has been available from 1998 to 2019 and reports precipitation in millimeters (mm). The dataset combines radar, passive microwave, and infrared satellite observations from multiple platforms. In the study area, TRMM covers approximately 128 grid cells. Due to the coarser spatial resolution compared to CHIRPS, some stations may fall within the same grid cell; in such cases, station data were compared with the corresponding grid cell value.

PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks)

PERSIANN provides precipitation data at 0.25° spatial resolution with daily or sub-daily temporal resolution, depending on the product version. The dataset has been available since 1983 and reports

precipitation in millimeters (mm). Its algorithm relies on artificial neural networks to estimate precipitation from infrared satellite imagery. Within the study area, PERSIANN covers approximately 128 grid cells, and, similar to TRMM, some stations may fall within the same grid cell.

Although the initial objective was to evaluate a 30-year period, overlapping temporal coverage among the satellite products, gaps in station data, and data quality inconsistencies limited the analysis. Attempts to use a 20-year period encountered similar constraints. After careful assessment, only a continuous 10-year period (2001–2010) was deemed complete and consistent enough to allow reliable analysis. This period aligns with recent international studies that validated satellite precipitation products using a similar number of stations over approximately 10 years (Toté et al., 2015; Ali et al., 2017; Tedla et al., 2024). Therefore, the 2001–2010 period was selected as the most stable and consistent interval for meaningful comparison between ground-based and satellite-derived precipitation data in this study.

Table 1. General information of selected satellites

| Row | Name of the satellite | Time Period | Spatial resolution (degrees) | Time Resolution | Unit |
|-----|-----------------------|-------------|------------------------------|-----------------|---------------------|
| 1 | TRMM (3B42 V7) | 1998-2019 | 0.25 | daily | Millimeters per day |
| 2 | CHIRPS | 1981-2021 | 0.05 | daily | Millimeters per day |
| 3 | PERSIAN-CDR | 1983-2020 | 0.25 | daily | Millimeters per day |

2-3. Measurement

Daily precipitation data from six synoptic meteorological stations and three satellite products (CHIRPS, TRMM, and PERSIANN) were examined for missing values and overall completeness. Daily data from both stations and satellites were aggregated to monthly and annual totals by summing daily precipitation values. Annual averages over the 10-year period (2001–2010) were calculated for each station to identify wet (above-normal) and dry (below-normal) years. Representative wet and dry years were

selected based on the years with maximum and minimum annual precipitation recorded across all stations in the study region. The performance of satellite-derived precipitation was assessed using a combination of Taylor diagrams and three statistical metrics: correlation coefficient (r), bias, and root mean square error (RMSE). The correlation coefficient quantified the temporal agreement between satellite estimates and ground-based observations. Bias indicated systematic overestimation or underestimation by the satellites, while RMSE measured the overall magnitude of errors, emphasizing larger

deviations. For spatial analysis, annual precipitation data for the selected wet and dry years were interpolated using a weighted inverse distance method (IDW) in a geographic information system (GIS) to create precipitation zoning maps. Annual precipitation maps derived from satellite data and ground-based measurements were compared to evaluate the spatial performance of each satellite product. To assess monthly performance, satellite and station datasets were aggregated to monthly averages over the 10-year period. Independent samples T-tests were conducted for each month (January–December) to determine statistically significant differences between satellite estimates and station observations. This approach allowed evaluation of satellite performance at both monthly and annual scales while minimizing distortions caused by atypical annual variability. The computations associated with the Taylor diagram and statistical metrics were performed using the **R** software environment, while independent-sample t-test analyses were conducted in **SPSS**.

The Taylor diagram is a graphical tool that simultaneously evaluates correlation coefficients, standard deviations, and root mean square errors (Taylor, 2001). In this representation, observational data serve as a reference point along the horizontal axis, while the angular dimension illustrates the correlation between observed and simulated values. Standard deviation values are denoted by concentric circles centered around the origin, whereas RMSE values are depicted as concentric circles relative to the reference point. These three statistical metrics are interconnected through an equation (1), where R represents the correlation coefficient between simulated and observed data, E' denotes the root mean square error, and σ_f^2 and σ_r^2 correspond to the variances of simulated and

observed data, respectively. The Taylor diagram is constructed based on the resemblance of equation (1) to the trigonometric relationship involving cosine (2) (Babaeian et al., 2021).

$$E'^2 = \sigma_f^2 + \sigma_r^2 - 2\sigma_f\sigma_rR \quad (1)$$

$$c^2 = a^2 + b^2 - 2ab\cos\phi \quad (2)$$

3. Results

The accuracy of satellite-derived precipitation was first evaluated by comparing daily precipitation data from the CHIRPS, TRMM, and PERSIANN products with observations recorded at six synoptic meteorological stations in northeastern Iran. A Taylor diagram was employed to assess the agreement between satellite estimates and ground observations in terms of correlation, standard deviation, and overall error structure. The results indicate that TRMM demonstrated relatively superior performance compared to the other satellite products. Across all stations, TRMM exhibited a correlation coefficient of approximately 0.4, a standard deviation below 0.5, and a root mean square error (RMSE) of less than 1. In contrast, CHIRPS and PERSIANN showed comparable performance to each other, with only minor differences in statistical indicators. At the daily scale, no significant spatial variation in satellite performance was detected among the six stations, suggesting relatively consistent accuracy across the study area. At Torbat-Heydariye and Guchan stations, the outputs of all three satellite products closely matched observational data. At Mashhad and Sabzevar stations, CHIRPS and TRMM demonstrated similar performance. Among all stations, Torbat-Heydariye exhibited the highest overall agreement between satellite-derived and observed precipitation (Figure 2).

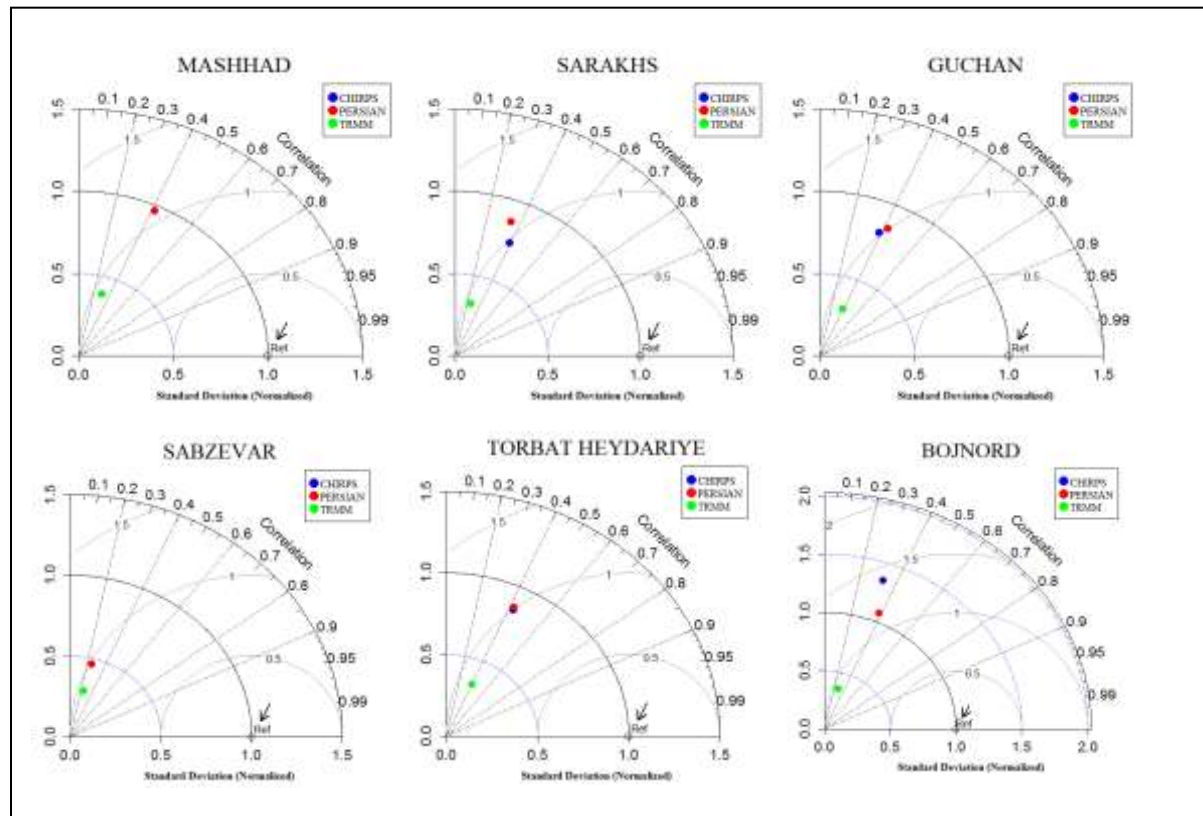


Figure 2. Taylor diagram for six synoptic stations in the northeastern region of Iran in 2001-2010

To strengthen the robustness of the evaluation, three additional statistical metrics—correlation coefficient (r), bias, and RMSE—were calculated (Table 2). The statistical results confirmed the findings derived from the Taylor diagram and further emphasized the superior performance of TRMM. RMSE, considered the primary indicator of overall estimation error, consistently showed lower values for TRMM across all stations. Bias

analysis revealed systematic differences among the products. TRMM tended to underestimate precipitation at all synoptic stations. In contrast, CHIRPS and PERSIANN showed overestimation at Bojnord and Mashhad stations. At Guchan, Sabzevar, and Torbat-Heydariye stations, bias values were negligible or close to zero, indicating relatively balanced estimates at these locations.

Table 2. Validation results of satellite precipitation datasets based on correlation, RMSE, and Bias

| Station | Dataset | Bias | RMSE | R | Bias_Type | Absolute_Bias |
|---------|----------|-------|------|------|-----------------|---------------|
| Bojnord | CHIRPS | 0.43 | 3.71 | 0.33 | Overestimation | 0.43 |
| | PERSIANN | 0.22 | 3.07 | 0.38 | Overestimation | 0.22 |
| | TRMM | -0.41 | 2.6 | 0.3 | Underestimation | 0.41 |
| Guchan | CHIRPS | 0 | 3.19 | 0.38 | negligible bias | 0.02 |
| | PERSIANN | 0 | 3.16 | 0.42 | negligible bias | 0.001 |

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|-----------------|----------|-------|------|------|-----------------|------|
| | TRMM | -0.58 | 3 | 0.4 | Underestimation | 0.58 |
| Mashhad | CHIRPS | 0.17 | 2.7 | 0.41 | Overestimation | 0.17 |
| | PERSIANN | 0.17 | 2.7 | 0.41 | Overestimation | 0.17 |
| | TRMM | -0.38 | 2.43 | 0.3 | Underestimation | 0.38 |
| Sabzevar | CHIRPS | 0 | 3.15 | 0.25 | negligible bias | 0.04 |
| | PERSIANN | 0 | 3.15 | 0.25 | negligible bias | 0.04 |
| | TRMM | -0.22 | 3 | 0.24 | Underestimation | 0.22 |
| Sarakhs | CHIRPS | 0 | 2.33 | 0.39 | negligible bias | 0.05 |
| | PERSIANN | 0.15 | 2.53 | 0.34 | Overestimation | 0.15 |
| | TRMM | -0.37 | 2.3 | 0.25 | Underestimation | 0.37 |
| Torbat-Heydarie | CHIRPS | 0 | 2.66 | 0.43 | negligible bias | 0.06 |
| | PERSIANN | 0 | 2.7 | 0.42 | negligible bias | 0.07 |
| | TRMM | -0.39 | 2.47 | 0.4 | Underestimation | 0.39 |

Analysis of annual precipitation during the 2001–2010 period identified 2003 as a representative wet year and 2008 as a representative dry year. These benchmark years were selected based on annual precipitation extremes observed consistently across all stations. Using annual precipitation data from CHIRPS, TRMM, PERSIANN, and ground observations, spatial precipitation zoning was performed through interpolation (Figures 3 and 4). In the dry year (2008), annual precipitation derived from TRMM closely matched station observations. The similarity between the interpolated precipitation maps generated from TRMM and those derived from ground-based data indicates strong spatial consistency and high reliability of TRMM under dry conditions. In contrast, CHIRPS and PERSIANN exhibited weaker spatial agreement with observed data during this year (Figure 3). For the wet year (2003), all three satellite products showed limited spatial resemblance to observational precipitation patterns. The discrepancies between satellite-derived and observed annual precipitation maps suggest reduced reliability of these products during wetter conditions in northeastern Iran. Overall, spatial

patterns of precipitation in both wet and dry years revealed a clear north-to-south decreasing gradient across the study area. Observational data confirmed that Guchan and Bojnord stations consistently recorded higher annual precipitation amounts compared to other stations, highlighting significant regional variability (Figure 4).

To further examine precipitation variability, monthly mean precipitation was analyzed for both observational and satellite datasets over the 10-year period. The results show a pronounced seasonal pattern, consistent with the climatic characteristics of northeastern Iran. Precipitation is predominantly concentrated during the cold season (autumn and winter), while summer months exhibit minimal rainfall.

Monthly comparisons between observational data and satellite products indicate that performance varies seasonally. Satellite products generally demonstrate improved agreement with observations during low-precipitation months, whereas discrepancies increase during peak rainfall periods. This seasonal behavior partly explains the reduced performance of satellite products during the representative wet year.

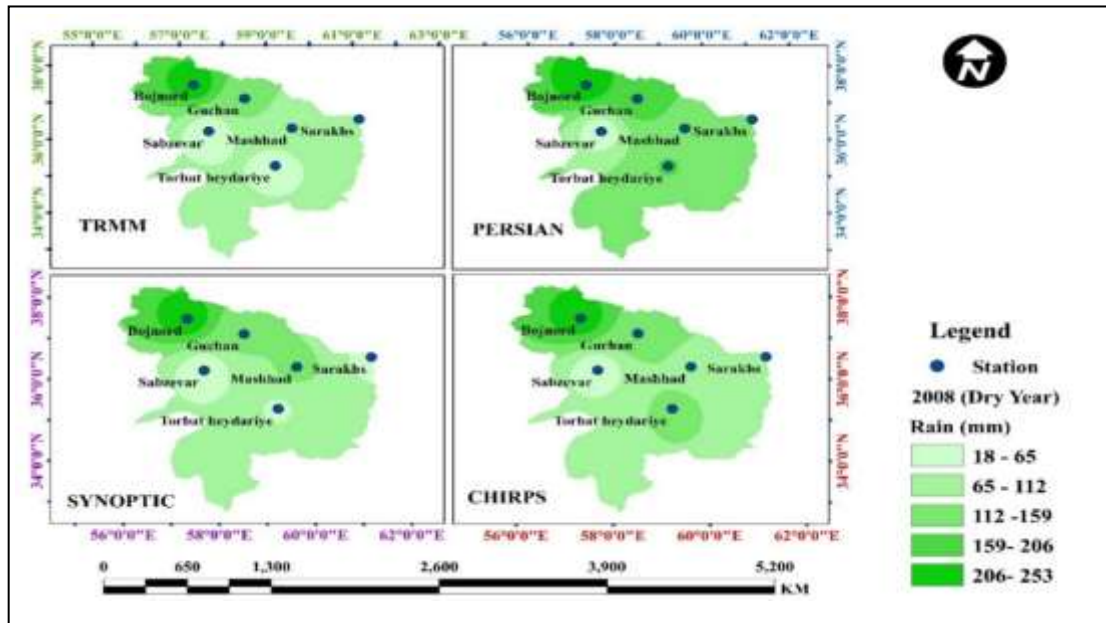


Figure 3. Zoning of annual precipitation in the northeastern region of Iran in 2008 based on satellites and meteorological stations

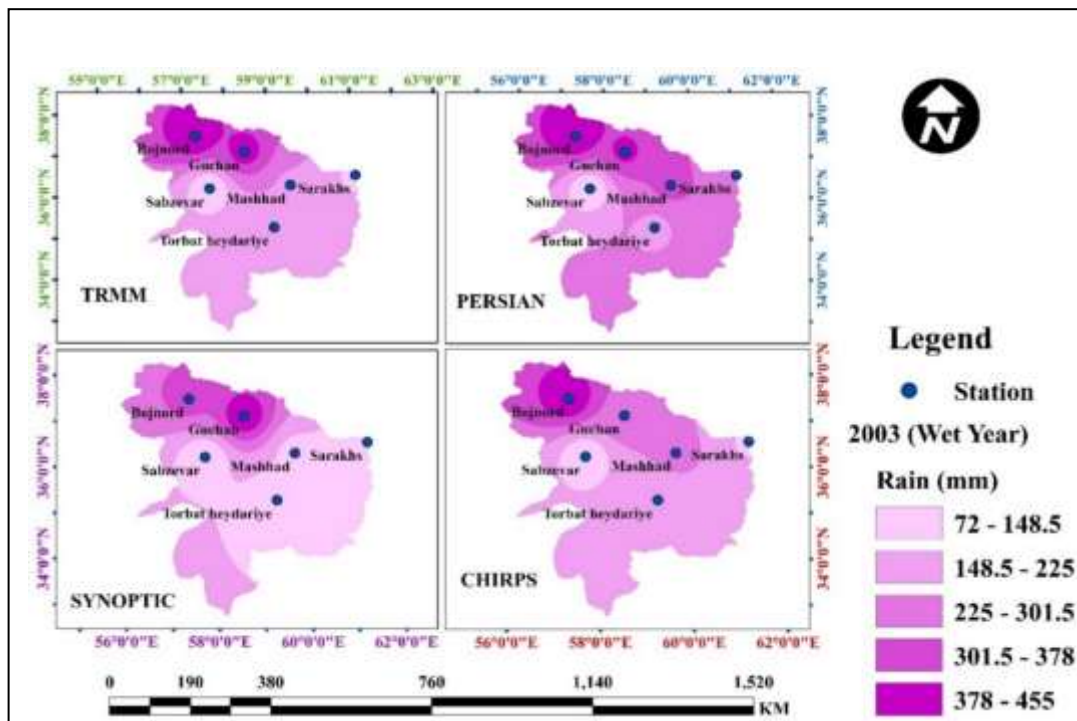


Figure 4. Zoning of annual precipitation in the northeastern region of Iran in 2003 based on satellites and meteorological stations

A comparative analysis of average monthly precipitation at Mashhad station revealed that the station data (18.26 mm) and CHIRPS satellite data (23.44 mm) differed by approximately 5 mm. Based on the t-test results (p-value = 0.54), this difference was not statistically significant, suggesting that CHIRPS performed adequately in representing precipitation for this location. Similarly, when evaluating the PERSIANN satellite data, the average precipitation reported by the satellite also showed a 5 mm difference compared to station observations. However, the p-value (0.54) further confirms that there was no statistically significant variation between the two datasets, which indicates that PERSIANN was moderately accurate in capturing precipitation levels at Mashhad station. In contrast, the TRMM

satellite data, which showed an average precipitation of 6.46 mm, exhibited a substantial difference of 12 mm compared to the station's recorded average of 18.26 mm. The t-test results (p-value = 0.038) confirmed that this difference was statistically significant, highlighting TRMM's reduced accuracy in representing monthly precipitation for Mashhad station. Both CHIRPS and PERSIANN satellites demonstrated better performance than TRMM by recording averages that closely aligned with station data and without significant statistical discrepancies. TRMM showed the largest deviation from station data alongside a relatively high standard deviation, as well as a statistically significant difference confirmed by the t-test (Table 3).

Table 3. Results the t-test for comparing the monthly precipitation of the satellite and the station (Mashhad)

| Group | Average | Standard deviation | T | p-value |
|------------------|---------|--------------------|------|---------|
| Mashhad station | 18.26 | 16.8 | -0.6 | 0.54 |
| CHIRPS Satellite | 23.44 | 24.18 | | |

| Group | Average | Standard deviation | T | p-value |
|-------------------|---------|--------------------|------|---------|
| Mashhad station | 18.26 | 16.8 | -0.6 | 0.54 |
| PERSIAN satellite | 23.4 | 24 | | |

| Group | Average | Standard deviation | T | p-value |
|-----------------|---------|--------------------|---|---------|
| Mashhad station | 18.26 | 16.8 | 2 | .038 |
| TRMM Satellite | 6.46 | 5.77 | | |

At Sarakhs station, the ground station recorded an average precipitation of 15 mm, while the CHIRPS satellite estimated it at 17 mm, resulting in a modest difference of 2 mm. Despite this numerical gap, the t-test yielded a t-statistic of -0.23 and a significance level of 0.8, demonstrating no statistically significant disparity between the data from the two sources. Hence, it can be inferred that the satellite data closely align with the ground measurements, and the minor discrepancy is not statistically meaningful. Similarly, at this station, the average precipitation recorded by the ground station and the PERSIANN satellite was 15 mm and 20 mm, respectively, reflecting a difference of 5 mm. However, the t-test results, with a t-statistic of 0.6 and a p-value of 0.53, again indicate no

significant difference. Additionally, the standard deviation difference of 4 mm falls within acceptable limits, suggesting that the PERSIANN satellite provided relatively accurate performance for this station. In contrast, an analysis comparing the average precipitation between the ground station and the TRMM satellite revealed a statistically significant difference in their data (t=2.4, p-value=0.031). Furthermore, the considerable disparity in standard deviation between the two sources (11 mm) highlights inconsistencies in the data dispersion. This divergence suggests reduced accuracy in the TRMM satellite's measurements for Sarakhs station (as detailed in Table 4).

Table 4. Examining the difference in the average monthly precipitation in ground and satellite data at the Sarakhs station

| Group | Average | Standard deviation | T | p-value |
|------------------|---------|--------------------|-------|---------|
| Sarakhs station | 15.69 | 15.58 | -0.23 | .82 |
| CHIRPS Satellite | 17.29 | 18.27 | | |

| Group | Average | Standard deviation | T | p-value |
|-------------------|---------|--------------------|-------|---------|
| Sarakhs station | 15.69 | 15.58 | -0.63 | 0.53 |
| PERSIAN satellite | 20.33 | 19.89 | | |

| Group | Average | Standard deviation | T | p-value |
|-----------------|---------|--------------------|-----|---------|
| Sarakhs station | 15.69 | 15.58 | 2.4 | 0.031 |
| TRMM Satellite | 4.4 | 4.2 | | |

At the Bojnord station, a comparison of average precipitation values—22 mm from the station data and 35 mm from the CHIRPS satellite—reveals a notable difference in their means (13 mm). However, a t-test with a statistic of 1.27 and a significance level of 0.22 indicates that this difference is not statistically significant. The disparity in standard deviation between the two sources (16 mm) suggests variation in data dispersion. Nonetheless, due to the lack of statistical significance, it cannot be conclusively stated that there is a real difference in precipitation measurements. Hence, the satellite data aligns reasonably well with the station records at this scale. When comparing the station

data (22 mm) with PERSIANN satellite estimates (29 mm), the difference in average precipitation is 7 mm, with a standard deviation of 8 mm. The corresponding t-value (0.77) and p-value (0.4) confirm that this difference is not statistically significant. This indicates that the PERSIANN satellite data performed adequately at this station. In contrast, the comparison between the station data (22 mm) and TRMM satellite values (9 mm) shows a more substantial difference in both mean (13 mm) and standard deviation (10 mm). With $t=2.36$ and a p-value of 0.027, this difference is statistically significant, highlighting lower accuracy of TRMM satellite data at this station (Table 5).

Table 5. Statistical comparison of satellite and station precipitation data with the t-test for Bojnord station

| Group | Average | Standard deviation | T | p-value |
|------------------|---------|--------------------|-------|---------|
| Bojnord station | 22.31 | 16.92 | -1.27 | 0.22 |
| CHIRPS Satellite | 35.25 | 31 | | |

| Group | Average | Standard deviation | T | p-value |
|-------------------|---------|--------------------|-------|---------|
| Bojnord station | 22.31 | 16.92 | -0.77 | 0.44 |
| PERSIAN satellite | 29 | 25 | | |

| Group | Average | Standard deviation | T | p-value |
|-----------------|---------|--------------------|------|---------|
| Bojnord station | 22.31 | 16.92 | 2.36 | 0.027 |
| TRMM Satellite | 9.72 | 7.31 | | |

At Torbat-e-Heydariye station, the comparison between precipitation data from ground observations and satellite datasets reveals varying levels of agreement. For the CHIRPS satellite

data, although the difference in standard deviation is relatively small (3 units), the statistical analysis results in a t-value of 0.26 and a p-value of 0.8. These metrics suggest that the

difference in average monthly precipitation between the station and the satellite data is not statistically significant, demonstrating that CHIRPS performed reasonably well in approximating the precipitation values, with a relatively favorable similarity observed. Similarly, the PERSIANN satellite data showed a standard deviation difference of 3 mm, yielding a t-statistic of 0.28 and a p-value of 0.77. Since this p-value exceeds the significance threshold of 0.05, the discrepancy in average monthly precipitation is deemed statistically insignificant. This reflects a commendable alignment between

station data and PERSIANN satellite measurements. However, the TRMM satellite data presented a more considerable disparity, with a standard deviation difference of 12 mm, leading to a t-value of 2.2 and a p-value of 0.04. As this p-value falls below the critical threshold of 0.05, the difference in mean precipitation is statistically significant. This indicates that TRMM satellite data performed poorly in capturing precipitation patterns at this station, failing to reliably represent the observed values (as summarized in Table 6).

Table 6. Analysis of monthly precipitation differences based on the t-test (Torbat-Heydariye station)

| Group | Average | Standard deviation | T | p-value |
|--------------------------|---------|--------------------|-------|---------|
| Torbat Heydariye Station | 18.24 | 17.74 | -0.26 | 0.8 |
| CHIRPS Satellite | 20.27 | 20 | | |

| Group | Average | Standard deviation | T | p-value |
|--------------------------|---------|--------------------|-------|---------|
| Torbat Heydariye Station | 18.24 | 17.74 | -0.28 | 0.77 |
| PERSIAN satellite | 20.47 | 20.36 | | |

| Group | Average | Standard deviation | T | p-value |
|--------------------------|---------|--------------------|-----|---------|
| Torbat Heydariye Station | 18.24 | 17.74 | 2.2 | 0.04 |
| TRMM Satellite | 6.32 | 6 | | |

At Guchan station, the analysis reveals a minimal difference in standard deviation (2 mm) alongside a very low t-statistic (0.071) and a high p-value (0.94). These findings suggest that the mean precipitation measured by CHIRPS station data and satellite data exhibit negligible differences, rendering any statistical comparison entirely insignificant. This reflects highly favorable performance of satellite data in accurately representing ground-based measurements at this location. Essentially, the satellite data closely align with station data, underscoring their reliability and similarity. Further evaluation shows that precipitation values recorded by PERSIANN satellite and station data at Guchan station are nearly identical, with no statistically significant variation. This level of agreement represents an exceptional consistency between

satellite-derived and ground-measured data, highlighting the high accuracy and dependability of satellite observations at this site. Conversely, examining TRMM satellite data at the same location produces contrasting results. Despite a statistically significant difference in mean precipitation (26 mm for station data versus 8 mm for TRMM data at a 5% significance level), the considerable disparity in dispersion (standard deviation) suggests variability in fluctuations between the two datasets. This divergence indicates a marked inadequacy in the reliability of TRMM satellite performance at Guchan station (Table 7).

Table 7. Assessment of the consistency of satellite data with a station using the t-test (Guchan station)

| Group | Average | Standard deviation | T | p-value |
|------------------|---------|--------------------|-------|---------|
| Guchan station | 26.64 | 22.64 | 0.071 | 0.94 |
| CHIRPS Satellite | 26 | 25 | | |

| Group | Average | Standard deviation | T | p-value |
|-------------------|---------|--------------------|-------|---------|
| Guchan station | 26.64 | 22.64 | 0.003 | 1 |
| PERSIAN satellite | 26.61 | 26.43 | | |

| Group | Average | Standard deviation | T | p-value |
|----------------|---------|--------------------|-----|---------|
| Guchan station | 26.64 | 22.64 | 2.6 | 0.022 |
| TRMM Satellite | 8.83 | 6.9 | | |

At Sabzevar station, although the average precipitation data differs by approximately 1.6 mm, the t-test does not reveal any statistically significant disparity between the station's measurements and the CHIRPS satellite data. This indicates a satisfactory alignment between the satellite and ground data, suggesting the satellite's performance has been relatively reliable, with deviations falling within the natural variability of the dataset. Specifically, a minor mean precipitation difference of 1.64 mm yielded a p-value of 0.79, confirming statistical insignificance. Moreover, the close resemblance in standard deviations highlights the stable behavior of data distribution, further supporting

the good performance of the PERSIANN satellite data at this station, which aligns well with ground observations. In contrast, while the mean precipitation difference between the station and TRMM satellite data is relatively larger at 7 mm, this variation remains statistically insignificant (p-value = 0.14, higher than the threshold of 0.05). However, the noticeable discrepancy in standard deviation points to differing patterns of data dispersion. Overall, the satellite data at Sabzevar station demonstrates moderate accuracy, with results regarded as mostly reliable but requiring careful interpretation (Table 8).

Table 8. Significant difference in mean monthly precipitation between two data sources (Sabzevar station)

| Group | Average | Standard deviation | T | p-value |
|------------------|---------|--------------------|-------|---------|
| Sabzevar station | 12 | 14 | -0.26 | 0.79 |
| CHIRPS Satellite | 13.65 | 12.56 | | |

| Group | Average | Standard deviation | T | p-value |
|-------------------|---------|--------------------|-------|---------|
| Sabzevar station | 12 | 14 | -0.26 | 0.79 |
| PERSIAN satellite | 13.64 | 12.91 | | |

| Group | Average | Standard deviation | T | p-value |
|------------------|---------|--------------------|-----|---------|
| Sabzevar station | 12 | 14 | 1.5 | 0.14 |
| TRMM Satellite | 5.38 | 5.41 | | |

Based on numerous studies conducted in different regions of the world and over various time periods, satellite precipitation products exhibit spatial dependency and their accuracy varies depending on the specific variable under

consideration. In other words, prior to utilizing satellite data for any variable in a given region, a thorough evaluation using statistical metrics is essential, and the best-performing product should be selected based on comparative assessments.

The results of this study indicate that high spatial resolution alone does not guarantee accurate estimates, and a satellite with finer resolution

may not necessarily provide more reliable results compared to satellites with coarser resolution.

4. Conclusion

This study evaluated the performance of three satellite-based precipitation products—CHIRPS, PERSIANN, and TRMM—over the period 2001–2010 at six synoptic stations in northeastern Iran, demonstrating that the accuracy and reliability of these products strongly depend on both the temporal scale and the climatic conditions of the region. On a daily scale, TRMM exhibited the highest consistency with ground-based observations, effectively capturing precipitation patterns, while CHIRPS and PERSIANN showed relatively weaker performance. At the annual scale, TRMM proved more accurate, particularly during dry years, although all three products tended to underestimate precipitation during wet years. At the monthly scale, although TRMM occasionally performed better, substantial discrepancies with station data were observed at most stations. These variations are primarily attributed to differences in data retrieval algorithms, spatial and temporal resolution, and the region's complex topography and climatic variability. The results align with the findings of Payfeshordeh et al. (2022), confirming the superior accuracy of TRMM compared to CHIRPS and PERSIANN. Moreover, the observed daily-scale errors for CHIRPS are consistent with the study by Mianabadi et al. (2022). However, the findings differ from those of Khanmohammadi et al. (2022), in which TRMM performance in northeastern Iran was reported as weak on a daily scale but improved at the monthly scale. Independent t-test results on monthly mean data indicated that CHIRPS and PERSIANN did not show significant differences from ground-based measurements at most

stations ($p > 0.05$), demonstrating acceptable accuracy in reproducing monthly precipitation, whereas TRMM exhibited statistically significant differences at some stations ($p < 0.05$), confirming its lower accuracy. The relatively high standard deviation observed at certain stations reflects the climatic characteristics of the region—virtually no rainfall during the warm months and intense precipitation during the cold months—and is not attributable to computational error. Global studies indicate that satellite precipitation products exhibit spatial dependence and that their accuracy is influenced by multiple factors. Therefore, statistical evaluation of satellite data for each variable and location prior to application is essential to select the most suitable product. High spatial resolution alone does not guarantee greater accuracy; performance must be interpreted in light of differences in retrieval algorithms, spatial/temporal resolution, and data sources (blended versus solely satellite-based). In this study, the use of statistical indices—including correlation coefficient (R), bias, RMSE, and bias direction—highlights these differences and emphasizes the importance of selecting satellite products according to temporal scale, topographic complexity, and reference station density. In conclusion, this research underscores the necessity of cautious and informed application of satellite-based precipitation data in regions characterized by complex topography and semi-arid climate. The findings provide valuable guidance for selecting appropriate satellite products for water resource management and climatological studies in dry and semi-arid regions of Iran.

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