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A comparative assessment of five precipitation products in the Saharan desert of Morocco: Sakia El Hamra basin case study

Nafia El-Alaouy · Said El Goumi · Nour-Eddine Laftouhi · Abderrahman Lahrouni · El Houssaine Bouras · Abdelhakim Amazirh · Abdeljalil Gouzrou

Abstract This study evaluates the performance of five satellite precipitation products (GPM IMERG, TRMM 3B42, ERA5, PERSIANN, and CHIRPS) compared to monthly observations from two weather stations (Laayoune and Essmara) over 2001–2017 using statistical metrics including correlation coefficient (CC) and mean square error (MSE). The results reveal notable differences between products. On a monthly timescale, GPM IMERG shows the best overall accuracy with a MSE of 16.8 mm/month. However, TRMM 3B42 exhibits higher temporal correlations with a CC around 0.83. The analysis provides insights into product capabilities and limitations for hydrological monitoring in data-sparse regions. Key findings include the superior performance of latest generation datasets like GPM alongside biases requiring localized calibration. The study delivers an assessment framework to guide integration of multiple satellite estimates for enhanced precipitation quantification and hydroclimatic modeling in water-stressed environments.

Keywords Precipitation products · Saharan Morocco · Accuracy evaluation · Sakia El Hamra Basin

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Introduction

Precipitation is a major component of the hydrological cycle and it is of crucial importance for many sectors, such as agriculture, water resources management, flood forecasting, and climate modeling (Milewski et al., 2015; Moucha et al., 2021; Schilling et al., 2012). However, rainfall is affected by climate change, with a predicted increase in spatio-temporal variability and an accentuation of extreme events such as droughts and floods on a global scale (Langsdorf et al., 2022).

A precise knowledge of the spatio-temporal distribution of precipitation is therefore essential for the understanding of hydrological processes and natural hazards, as well as for adaptation to climate change (Al Bitar et al., 2024; Moucha et al., 2021; Schilling et al., 2012). However, accurate precipitation estimation remains a challenge, especially in mountainous regions where the rugged topography generates a high spatial and temporal variability of precipitation (Bai & Liu, 2018); Satgé et al., 2016; Yang et al., 2017). The networks of ground-based rain gauges are sparse in many regions of the world and do not allow satisfactory spatial coverage (Camici et al., 2018; Fenta et al., 2018; Habib et al., 2012). In addition, the maintenance of in situ measurement networks represents a significant cost (Gebere et al., 2015; Hirpa et al., 2010). Satellite-based precipitation estimation products offer a promising alternative thanks to their extensive spatial coverage and their availability on an almost global scale (Maggioni et al., 2016a, 2016b; Satgé et al., 2016; Sun et al., 2018). Since the launch of the TRMM (Tropical Rainfall Measuring Mission) in 1997, numerous algorithms for restoring rainfall from satellite measurements have been developed (Barnes et al., 1998), for example, IMERG (Integrated Multi-satellitE Retrievals for GPM), CHIRPS (Climate Hazards Group InfraRed Precipitation with Stations), CMORPH (Climate Prediction Center MORPHing technique), GSMaP (Global Satellite Mapping of Precipitation), ERA5 (ECMWF Re-Analysis 5th generation), and PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) (Ashouri et al., 2015; Funk et al., 2015; Hsu et al., 1997). However, due to the differences in the satellite sensors used, the restitution algorithms, the integration of ground data, and the calibration of the biases, these products have variable performances according to the regions of the globe (Guo & Liu, 2016; Sun et al., 2018; Zambrano-Bigiarini et al., 2017). Numerous intercomparison studies have been conducted around the world.

In Africa, Serrat-Capdevila et al. (2016) showed better performances of CHIRPS and CMORPH compared to TRMM 3B42 on the whole continent. In South America, CHIRPS has proven to be more accurate than PERSIANN-CDR (Zambrano-Bigiarini et al., 2017).

In the Amazon basin, the TRMM 3B42 product has proven to be more efficient (Satgé et al., 2016). In Europe, ERA5 has shown a good performance except in summer (Satgé et al., 2019).

In Southeast Asia, GSMaP has proven its ability to estimate precipitation better than CHIRPS (Tan et al., 2020). However, mountainous regions still pose significant challenges. Tan et al. (2020) have shown a significant bias on the Tibetan Plateau using IMERG. This bias is related to altitude and surface roughness. The prior evaluation of satellite products is therefore essential before their use, in particular in areas of rugged terrain (Bai & Liu, 2018; Satgé et al., 2016).

In Morocco, some studies have shown good performance of products such as CHIRPS or TRMM 3B42 on a monthly scale for hydrological applications (El Alaoui El Fels et al., 2022; Karmouda et al., 2022; Tramblay et al., 2016). However, the majority of this work has focused on the north of the country. The sub-Saharan region in the south of Morocco has been little studied, despite an arid climate and significant risks of flash floods (Schilling et al., 2012). This area is characterized by a limited network of rain gauges and a complex topography marked by the Saharan Atlas. Sudden and devastating floods can occur in the wadis and lead to significant damage, as observed in the Aouerga wadi in 2010, and in 2016 around Laayoune city (Nafia et al., 2022).

In this context, the objective of this study is to evaluate the performance of different satellite precipitation products in the Sakia El Hamra basin, located in the sub-Saharan part of Morocco. Five widely used products are analyzed: GPM, TRMM 3B42, ERA5, PERSIANN, and CHIRPS. These data are compared with rainfall observations from two weather stations (Laayoune and Essmara) over the period 2001–2017. The analysis is carried out at monthly time scales in order to determine the most reliable products for hydrological and climatological applications in this region. This study will help to fill the lack of information on the performance of satellite products in the south of Morocco and will enhance our knowledge about monitoring rainfall in this basin with particular hydro-climatic conditions. The results will also make it possible to improve the understanding of the spatio-temporal variability of rainfall and hydrological extremes in the context of climate change, in connection with the resurgence of droughts and flash floods according to the IPCC AR6 report (2022). This research will thus

contribute to a better adaptation in a region very vulnerable to climatic hazards.

Data and methods

Study area

The Sakia El Hamra watershed is located in the Sahara of Morocco, between longitudes 13.45° W and 9.69° W and latitudes 25.52° N and 27.86° N (Fig. 1) with an area of approximately 52,000 km^2; it extends along the Atlantic coast in the region of Laayoune-Boujdour-Sakia El Hamra. The basin is delimited to the north by the Wadi Draâ, to the west by the Atlantic Ocean, to the south and to the east by Algeria and Mauritania (Nafia et al., 2022).

It is crossed by the wadi Sakia El Hamra which originates in the north-east of the basin and flows for about 400 km before emptying into the Atlantic at the level of Laayoune. The climate is arid, with very low average annual rainfall, of the order of 250 mm per year (Nafia et al., 2022). The basin nevertheless presents a risk of flash floods, as observed in some wadis in the region. Its topography is marked by different geological and geographical units that extend from north to south along the coast. The study of this basin is of major interest for the management of water resources and the understanding of extreme hydrological phenomena in this arid and poorly instrumented region of Morocco (Nafia et al., 2022).

Gauged precipitation data

The monthly observed rainfall data used in this study come from the Sahara Hydraulic Basin Agency (ABHS) and cover the period from 2001 to 2017. They were measured by two meteorological stations located in the Sakia El Hamra watershed Laayoune and Essmara. The station of Laayoune, located in the north-western part of the basin, records the rainfall on a flat ground close to the Atlantic Ocean. The
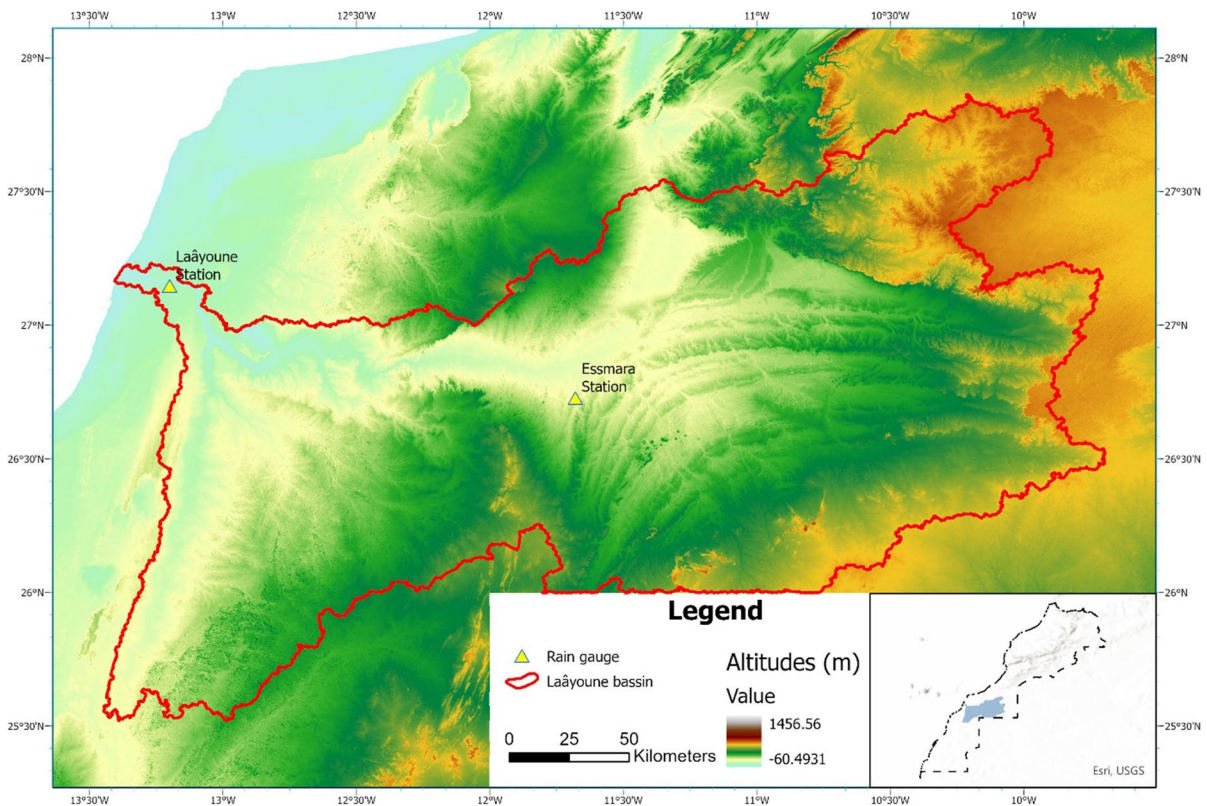

Fig. 1 Location of the Sakia El Hamra Basin and spatial distribution of the gauge stations in the basin

Essmara station is located further east, in a lowland area. In the measurement network being very limited in this arid basin and little instrumented, these two stations constitute the only data sources available for the evaluation of satellite products in this region of southern Morocco. Although sparse, this observed dataset allows a preliminary analysis of the performance of the different satellite precipitation estimation products on the Sakia El Hamra basin.

Satellite-based and reanalysis precipitation products

Five satellite-based precipitation estimation products (Table 1) have been selected to be evaluated in the Sakia El Hamra watershed over the period 2001–2017, including, GPM, TRMM 3B42, ERA5, PERSIANN, and CHIRPS. The daily data of these products were downloaded and then aggregated on a monthly scale in order to be comparable to the monthly observations of the ground stations. A common spatial resolution of 0.1° was adopted for all the products by interpolation of the nearest neighbor, allowing analysis at a regular mesh without modification of the original values (Accadia et al., 2003). Although covering a period of 17 years, the variable availability according to the products generates differences in the length of the time series studied. Despite these limitations, these satellite datasets allow a preliminary evaluation of the performance of the various rainfall estimation algorithms in the particular context of the Sakia El Hamra basin.

The TRMM (Tropical Rainfall Measuring Mission) product was developed by NASA and JAXA as part of the eponymous satellite mission launched in 1997 (Huffman et al., 2007). It is the first product dedicated to the estimation of tropical and subtropical rainfall based on microwave and infrared data. TRMM combines estimates based on different satellite sensors as well as data from ground-based rain gauges (Huffman et al., 2007). Several datasets are available with different latencies and spatio-temporal resolutions. The 3B42 RT version used here provides 3 hourly estimates on a grid of 0.25°.

The precipitation map derived from TRMM satellite (Fig. 2) data reveals a marked variability in interannual precipitation from 2001 to 2017. In January, the rainfall is at its peak with a maximum value of 61.7 mm, indicating a high concentration of rainfall, potentially linked to seasonal climate systems. A gradual decrease is observed until July, when the rainfall reaches its minimum of 3.73 mm. This decrease in rainfall during the first half of the year could be explained by the transition of the winter-summer seasons and by changes in regional atmospheric circulation regimes such as the northward displacement of the Azores anticyclone and the rise in latitude of the Saharan thermal depression. This downward trend in rainfall during the first half of the year could be attributed to the transition of the monsoon seasons or other regional weather phenomena. From August, a gradual increase in precipitation is noted, peaking in October at 33.14 mm. This increase in rainfall during the second half of the year could be explained by the resumption of activity of the Mediterranean and Saharan rain systems, as well as by other meteorological phenomena on a synoptic scale inducing an increase in rainfall (Atlantic depressions, cold drops, etc.). It would be necessary to analyze in depth the potential hydrological and environmental impacts associated with these interannual variations in rainfall patterns, such as flash floods, accentuated water erosion, or the repercussions on the aquatic and terrestrial ecosystems of the Sahara. This increase could be associated with the resumption of monsoon systems or other climatic events that bring increased rainfall. Particular attention should be paid to the analysis of

Table 1 Summary of the satellite-based and reanalysis precipitation products used in this study

| Product	Spatial coverage and resolution	Temporal coverage and resolution	Unit	Data source	References
TRMM	0.25°×0.25°	1998–2015, 3 hourly	mm/day	NASA, JAXA	(Huffman et al., 2007)
GPM	0.1°×0.1°	2014–present, 30 min	mm/day	NASA, JAXA	(Hou et al., 2014)
ERA-5	0.25°×0.25°	1979–present, hourly	mm/day	ECMWF	(Hersbach et al.,2020)
PERSIANN	0.04°×0.04°	2000–present, hourly	mm/day	UC Irvine	(Sorooshian et al., 2000)
CHIRPS	0.05°×0.05°	1981–present, daily	mm/day	USGS, UCSB	(Funk et al., 2015)
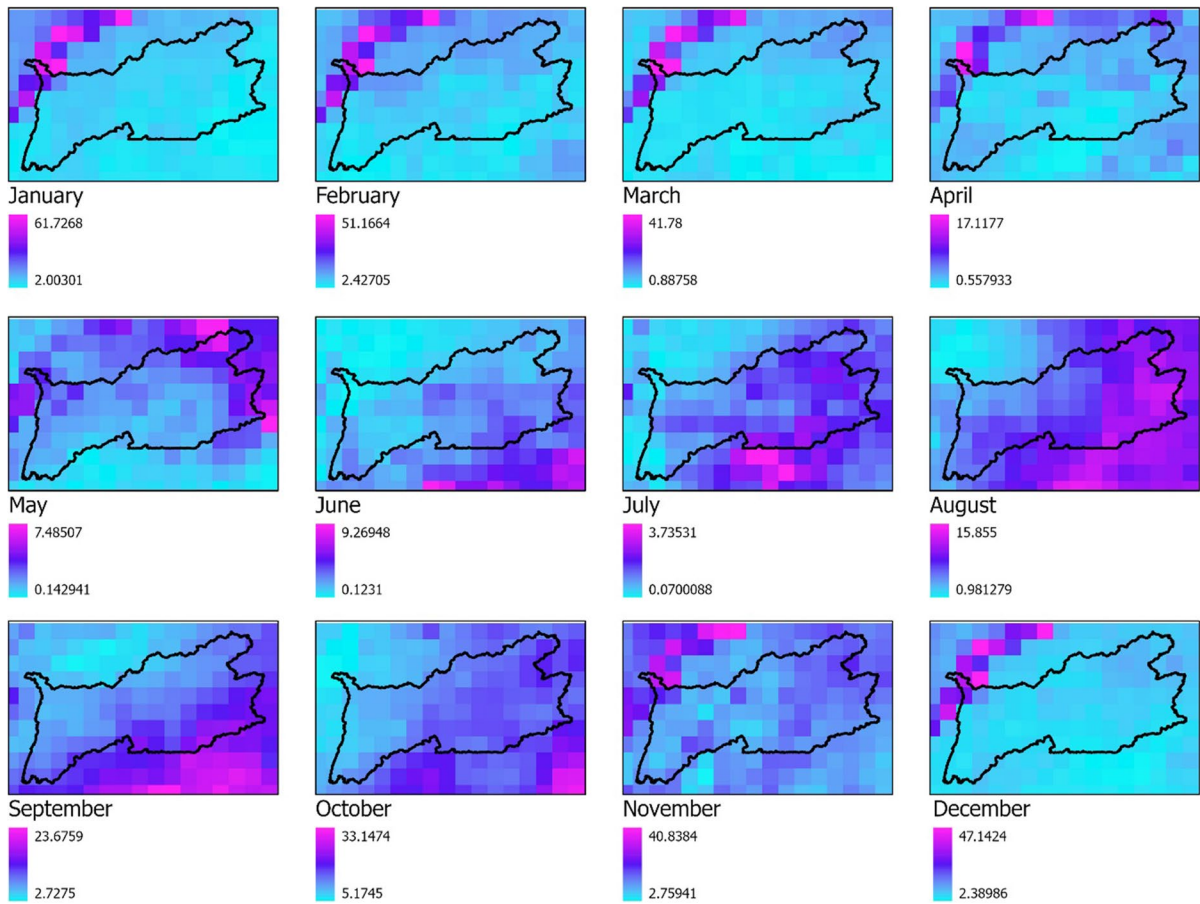
Fig. 2 Distribution of monthly rainfall (mm/month) of TRMM product from 2001 to 2017 in the Sakia El Hamra basin region

the hydrological and environmental impacts associated with these rainfall variations, such as flooding, erosion, and impacts on aquatic and terrestrial ecosystems.

The PERSIANN system (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) was developed at the University of California at Irvine (Hsu et al., 1997). It uses a neural network to estimate rainfall from infrared data from geostationary satellites. PERSIANN provides hourly estimates which are then aggregated at different spatial and temporal scales. The Climatology-Based Cloud Classification version used here (PERSIANN-CCS) integrates a classification of cloud types to improve the estimates.

The PERSIANN precipitation map (Fig. 3) shows distinct precipitation trends over the inter-annual period from 2001 to 2017. In January,

moderate levels of precipitation are observed, with a maximum of 13.65 mm, reflecting a relatively wet winter season. A decrease is then observed, with minimum values in June and July, indicating a pronounced dry season. From August, a significant increase in rainfall is observed, reaching a peak of 25.38 mm, probably due to the establishment of the rainy season. The fluctuation in rainfall levels, with decreasing values in spring and summer, followed by an increase in autumn, highlights the significant seasonal and climatic variations;

The GPM (global precipitation measurement) product is a continuation of TRMM as part of the mission of the same name launched in 2014 (Hou et al., 2014). GPM benefits from an expanded constellation of satellites and improved instruments. It aims to provide more accurate rainfall estimates, especially for moderate and low rainfall.
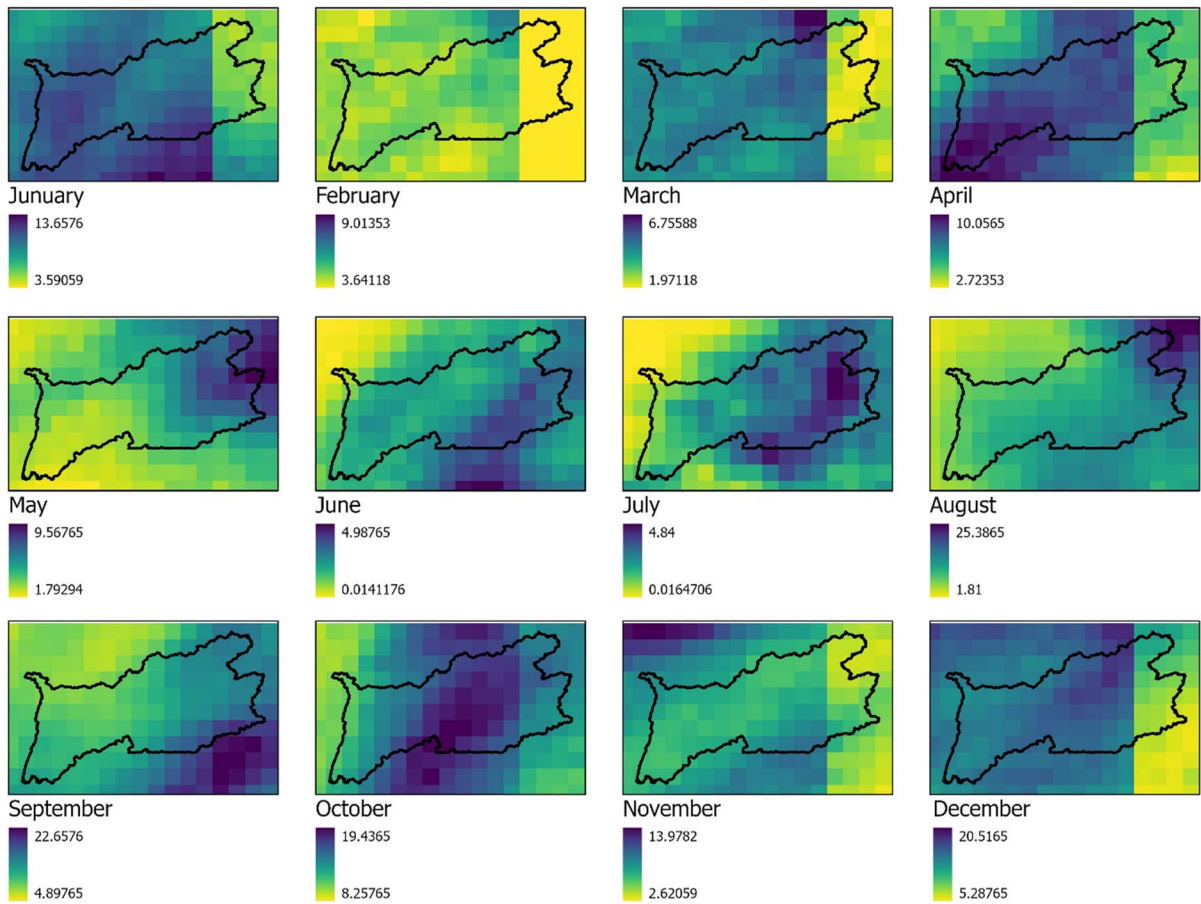
Fig. 3 Distribution of monthly rainfall measured in PERSIANN from 2001 to 2017 in the Sakia El Hamra basin region

IMERG (Integrated Multi-satellitE Retrievals for GPM) is the most advanced level of the product. The final version used here incorporates the most ground observations to correct the product.

The GPM rainfall map illustrates (Fig. 4) a complex dynamics of rainfall distribution over an interannual period from 2001 to 2017. The month of January begins with moderate rainfall, reaching a maximum of 24.82 mm, which suggests a notable rainy activity. A tendency to reduce rainfall is observed until June and July, when it drops to its lowest values, indicating a dry period. This can be attributed to specific seasonal and geographical factors. A significant increase is then noted in September with a peak at 38.46, signaling the return of the wet seasons, perhaps under the influence of the monsoons or other weather systems. The month of December also presents high rainfall, with a maximum of 47.01 mm, concluding the year on a wet note.

CHIRPS (Climate Hazards Group InfraRed Precipitation with Stations) is a product developed by the University of California Santa Barbara and the USGS for drought monitoring applications (Funk et al., 2015). It combines infrared and microwave satellite estimates with data from more than 20,000 rainfall stations. CHIRPS aims to provide a high spatial and temporal resolution product for agricultural and hydrological monitoring. The version 2.0 used here covers the period 1981–almost present with a resolution of 0.05° and a pentadar time step.

The CHIRPS precipitation map (Fig. 5) depicts significant variations in monthly interannual precipitation from 2001 to 2017. In January, a maximum of 32.76 mm is observed, indicating a relatively wet start to the year. The following months, until June, are
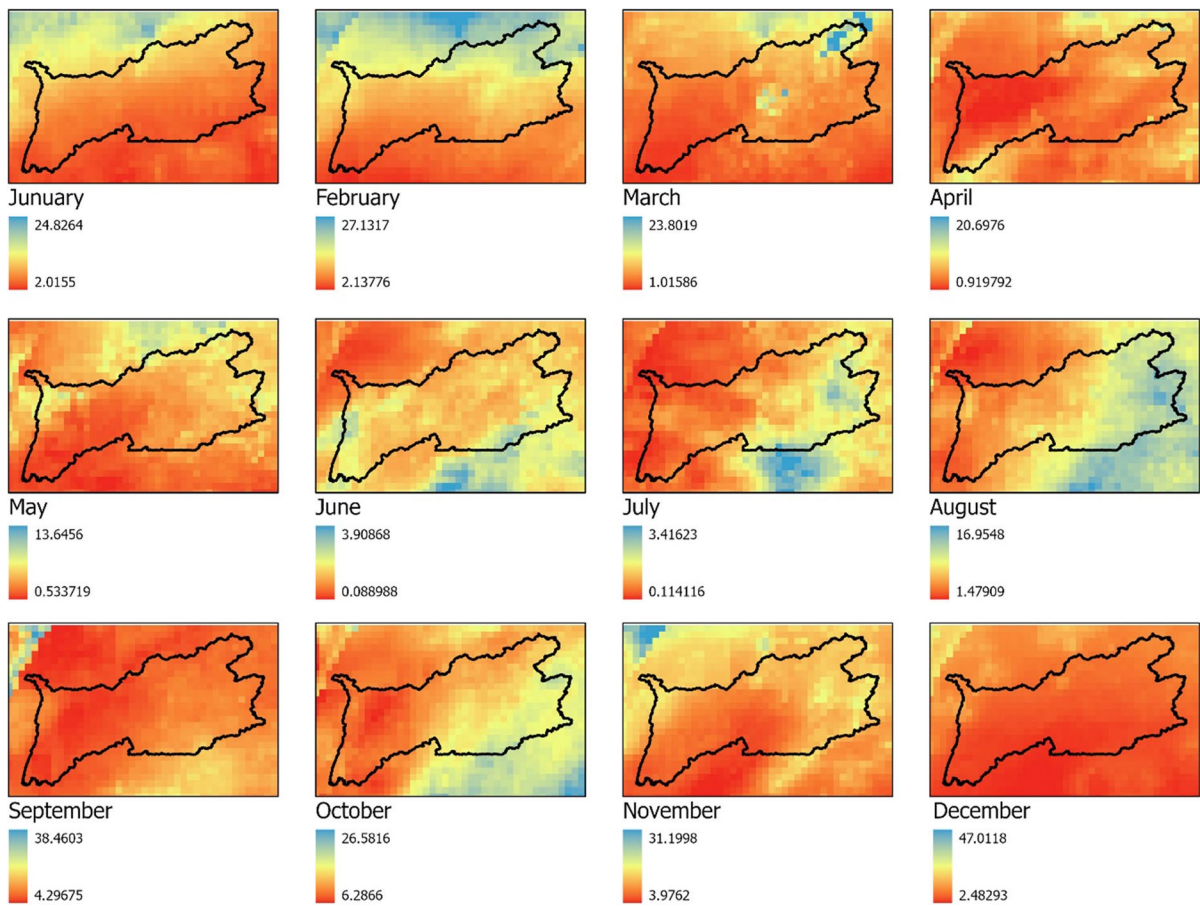
Fig. 4 Distribution of monthly rainfall measured in GPM from 2001 to 2017 in the Sakia El Hamra basin region

characterized by a decrease in rainfall, reaching their lowest point in June with a maximum of 1.08 mm, signaling a dry season. This could be the result of seasonal climatic variations. From September, an increase is noted, with a significant peak in December when the rainfall reaches an impressive maximum of 98.61 mm. This rainfall regime, characterized by a peak in rainfall at the end of the year, seems to indicate the existence of an autumn rainy season in this Saharan region. This seasonality could be linked to recurring meteorological phenomena at this time of the year such as the passage of Mediterranean depressions or tropical storms from the Atlantic. A thorough analysis of regional climatology would make it possible to better understand the underlying synoptic and mesoscale mechanisms responsible for this particular rainfall regime. This pattern suggests a wet season at the end of the year, potentially associated with

specific weather phenomena such as the monsoon or storm systems.

ERA5 is the latest global atmospheric reanalysis produced by the European Center for Medium-term Weather Forecasts (Muñoz-Sabater et al., 2021). It provides numerous atmospheric and terrestrial variables reanalyzed from models and various observations. Regarding precipitation, they are estimated by the ECMWF numerical forecasting model before being readjusted using ground observations. ERA5 improves the spatial and temporal resolution as well as the accuracy of precipitation compared to previous reanalysis.

Evaluation indices

To evaluate the five satellite precipitation products over the study area, first, the raw TRMM, ERA5, PER-SIANN, and CHIRPS products were interpolated to
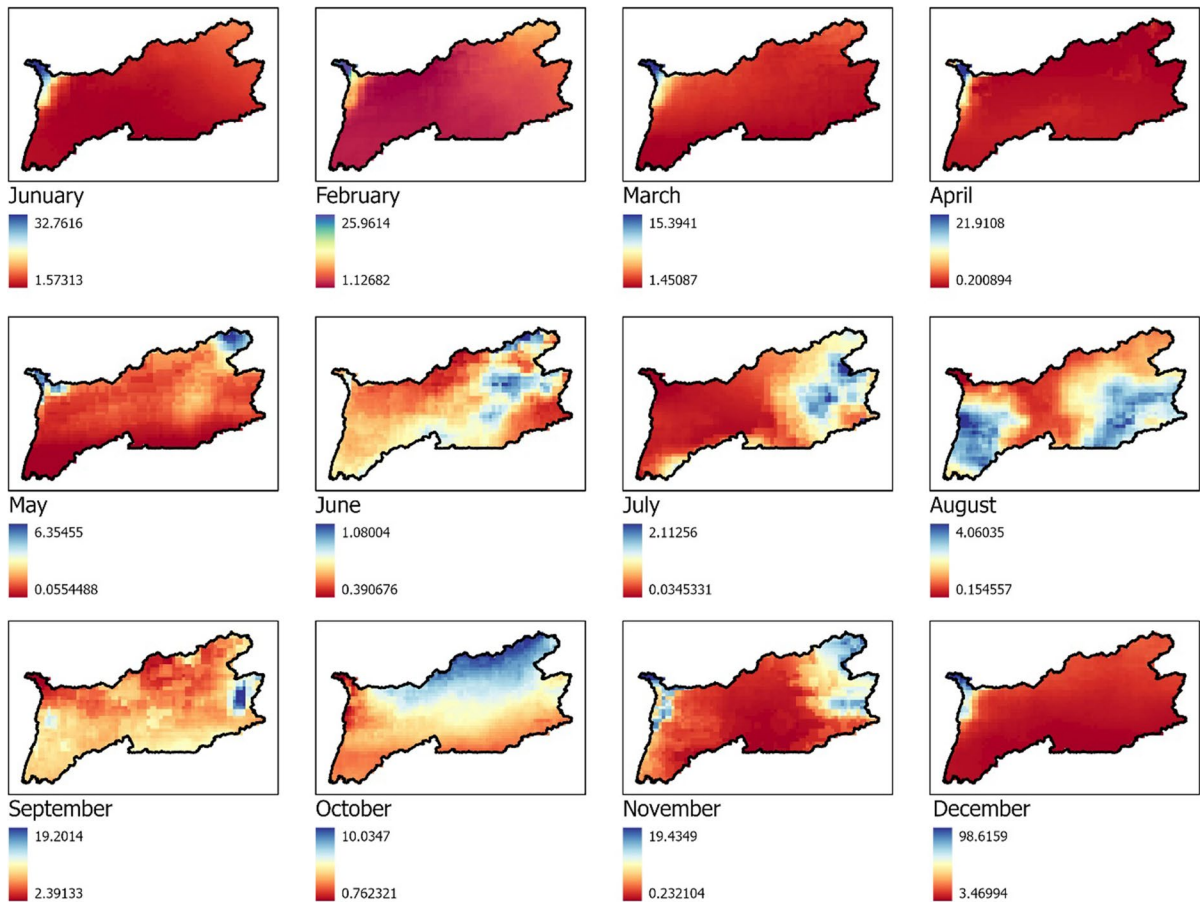
Fig. 5 Distribution of monthly rainfall measured in CHIRPS from 2001 to 2017 in the Sakia El Hamra basin region

0.1° resolution using the bilinear interpolation approach to match the GPM data. The daily datasets were then aggregated to monthly and seasonal time scale to evaluate the accuracy on different time scales. Then, the pixel-to-point approach (Golian et al., 2019; Islam & Cartwright, 2020; Tang et al., 2020; Zhang et al., 2018) was used to extract the precipitation data of the five products (TRMM, ERA5, PERSIANN, CHIRPS, and GPM) at the pixels corresponding to the location of the gauging stations. Four continuous quantitative indices and tow categorical indices of precipitation detection were calculated to evaluate the performances (Table 2). The four continuous indices, namely the correlation coefficient (CC), the mean error (ME), the mean absolute error (MAE), and the mean squared error (RMSE), measure the quantitative accuracy of rainfall estimates. The four categorical indices, i.e., the bias and the fair threat score (ETS), reflect the ability to correctly detect rainy events. The CC represents the correlation between the observed and estimated rainfall. The ME measures the average difference, a negative ME indicating an underestimate and a positive ME an overestimation of precipitation. The MAE and RMSE indicate the magnitude of the differences between observed and estimated values, the RMSE weighting the important errors more. The ETS is an overall detection evaluation score, an optimal value of 1 indicating perfect detection. A reliable product must combine good quantitative accuracy and good precipitation detection capabilities. The rainfall threshold has been set at 0 mm/day for no rainfall, and 0.1 mm/day to 0.25 (WMO) for light rainfall.

Evaluation experimental design

The evaluation of the precipitation products presented above was carried out in terms of monthly and

Table 2 Quantitative and qualitative indices used to evaluate the performance of precipitation products

Evaluation indices	Equation	Range of values	Perfect value
Correlation coefficient (cc)	$CC = \dfrac{\sum_{i=1}^{N}(Si-S)(Gi-G)}{\sqrt{\sum_{i=1}^{N}(Si-S)2}\sqrt{\sum_{i=1}^{N}(Gi-G)2}}$	$(-1, 1)$	1
Mean error (ME)	$ME = \frac{1}{N}\sum_{i=1}^{N}(Si - Gi)$	$(-\infty, +\infty)$	0
Mean absolute error (MAE)	$MAE = \frac{1}{N}\sum_{i=1}^{N} \mid Si - Gi \mid$	$(0, +\infty)$	0
Root mean square error (RMSE)	$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Si - Gi)^2}$	$(0, +\infty)$	0
BIAS	$BIAS = \frac{h+f}{h+m}$	$(0, +\infty)$	1
Equitable threat score (ETS)	$ETS = \frac{h+r}{h+m+f-'}$ $r = \frac{(h+m)(h+f)}{h+m+f+c}$	$(-1/3, 1)$	1

Notation: *N* is the total number of records; S_i and G_i are the estimated and gauged precipitation, respectively; *S* and *G* are their mean values, respectively; and *H*, *M*, *F*, and *C* are the four events indicating whether the satellite has correctly detected an observed rainfall event (as summarized in Table 2), where *H* indicates that the observed rain event has been correctly detected by the satellite; *M* indicates that the satellite has missed the occurring rain event; *F* indicates that the satellite has incorrectly detected the occurring rain event as no-rain; and *C* indicates that there is no-rain and the satellite has detected none. Moreover, *h*, *m*, *f*, and *c* are the numbers of *H*, *M*, *F*, and *C*, respectively

seasonal precipitation at different spatial scales. First, the performance indices were calculated for 2 weather stations in order to obtain the overall accuracy of each product over the entire Sakia El Hamra basin (Brown et al., 2020). Then, the indices were calculated for each station in order to better understand the spatial performance models.

Results and discussion

The satellite precipitation products show distinct patterns in their estimation of monthly rainfall over the Sakia El Hamra basin from 2001 to 2017. TRMM displays high peak rainfall in January followed by a gradual decrease into summer, potentially indicative of seasonal climate influences. In contrast, PERSIANN reveals a winter peak and summer decrease but lower overall rainfall amounts. GPM illustrates complex rainfall dynamics with noticeable spikes in January, September, and December, highlighting both dry and wet periods. Meanwhile, CHIRPS indicates a very wet December but dry June, pointing to possible autumn rainy seasons linked to regional weather phenomena. Finally, though quantitative estimates are unavailable, ERA5 incorporates both model data and ground observations to provide a high-resolution reanalysis. In summary, the products exhibit variability in rainfall distributions, yet all demonstrate capability in capturing expected seasonal and monthly

fluctuations. Further analysis of climatological influences could help explain the differences between products and improve techniques for rainfall estimation in this complex region.

Basic statistics and distribution of the monthly precipitation

During the study period from 2001 to 2017, the average monthly rainfall was analyzed for the Essmara and Laayoune stations, as well as for each satellite product. Figure 6 illustrates their monthly distributions, highlighting seasonal variations and differences between the observed data and satellite estimates. For the Laayoune station, the data reveal that the ERA5 product indicates relatively high average monthly rainfall during the winter months, while the observed data show moderate peaks during these months (Fig. 6). In terms of the distribution of precipitation (Fig. 7), CHIRPS and TRMM seem to be closer to the observed data, indicating a correlation in seasonal patterns. At the Essmara station, an arid climate is evident, with very low average monthly rainfall. Satellite products, in particular PERSIANN and GPM, reflect this trend, although minor variations are observed. ERA5, in particular, seems to indicate slightly higher rainfall during certain months, suggesting a possible overestimation. The analysis of standard deviations reveals that satellite products show variability in rainfall estimates. For example,
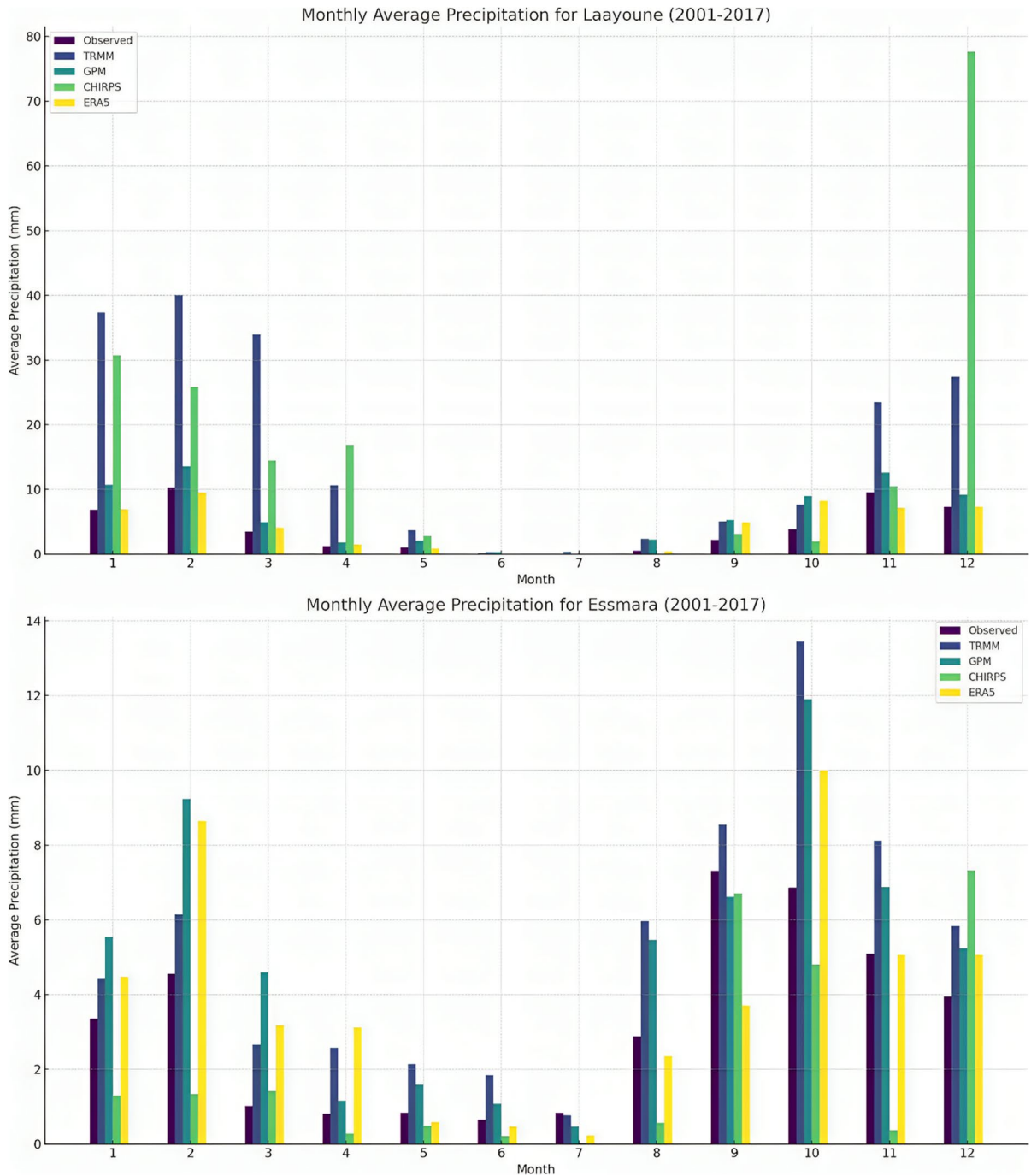
Fig. 6 Monthly average precipitation for Laayoune and Essmara stations over the period 2001–2017

ERA5 displays a higher standard deviation at Laayoune, indicating a greater dispersion of precipitation values. In Essmara, the PERSIANN standard deviation is close to that of the observed data, indicating a relative accuracy in the estimation of rainfall in this arid region. In conclusion, although there are differences between the observed data and the satellite estimates, products such as CHIRPS and TRMM in

Laayoune and PERSIANN in Essmara seem to offer valuable estimates of average monthly rainfall. This information is crucial for understanding the hydrological and climatic dynamics of arid and semi-arid regions.

In Laayoune, the density curves (Fig. 7) reveal a diversity in the estimates of the average monthly rainfall between the observed data and those obtained by satellite products. The observed data present a specific distribution, indicating variability in rainfall levels over the months. At the same time, satellite products, in particular CHIRPS and TRMM, show distinct peaks, suggesting frequent occurrences of

specific precipitation. ERA5 stands out for its wider distribution, indicating a more extensive variety in rainfall estimates. This diversity in the density curves underlines the importance of integrating multiple data sources to obtain a complete and nuanced view of precipitation patterns in Laayoune.

For the Essmara station, the density curves (Fig. 7) are characterized by a notable concentration and uniformity, illustrating the low rainfall typical of this arid region. Satellite products, including PERSIANN and GPM, are in agreement with the observed data, showing similar distributions that confirm the consistency of the estimates under low rainfall conditions.
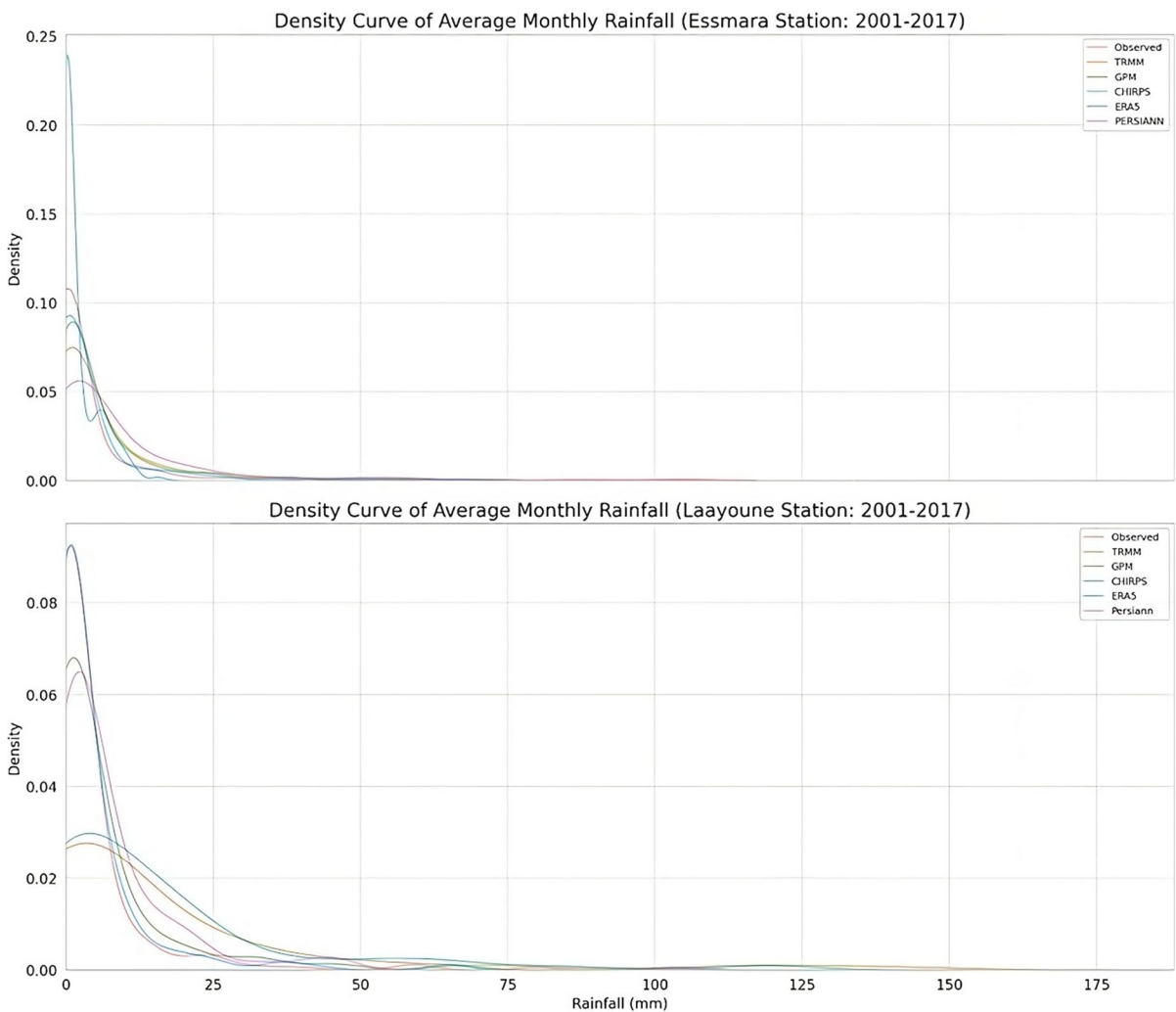

Fig. 7 Density curve of the average monthly rainfall recorded at the gauge stations, as well as density curves of the average monthly rainfall of the different products, observed in the Sakia El Hamra basin from 2001 to 2017

The concentration of the curves indicates that rainfall remains relatively constant and limited throughout the year, reinforcing the identification of Essmara as a region with low rainfall.

Each interpretation offers valuable insights into the distribution and variability of rainfall in the respective regions, contributing to a detailed understanding of local climate patterns and the unique characteristics of each station.

In Laayoune, the data indicate (Table 3) a significant variability in the average monthly rainfall during the period 2001–2017. Days without precipitation are common, as suggested by the minimum value of 0 mm for all data sources. The median rainfall varies from 0.01 (observed data) to 0.26 mm (CHIRPS), highlighting that the majority of months record relatively low rainfall. However, the average and maximum values indicate the occasional presence of higher rainfall days, with TRMM recording the highest average (0.53 mm) and the highest maximum (5.08 mm). The high standard deviation for TRMM also indicates a large variability in daily rainfall, which could be attributed to the sporadic nature of rainfall events in this arid region.

For the Essmara station (Table 4), the average daily rainfall follows a similar trend to that of Laayoune, although with variations. The minimum value of 0 mm also indicates days without precipitation. The rainfall median is generally low for all data sources, indicating that most days receive little rainfall, with PERSIANN and GPM recording slightly higher medians. The average rainfall varies from 0.07 (CHIRPS) to 0.27 mm (PERSIANN), showing a diversity in rainfall estimates. The maximum and the standard deviation of the precipitation also indicate variability in precipitation, with days of greater precipitation being rare but possible.

Evaluation of the precipitation products at the different time scales

Evaluation at the monthly scale

In order to evaluate the five selected precipitation products, several statistical indices were calculated between observed precipitation and different preparation products (Table 5). At the Laayoune station located downstream of the Sakia El Hamra watershed, with a CC of 0.73, TRMM has a relatively good correlation with the observed data, although the mean error (ME) and the mean squared error (RMSE) are high, indicating predictions that are often far from the observations. GPM is distinguished by a high CC of 0.93 and lower error values (ME, MAE, RMSE), indicating remarkable accuracy and correlation with observations. PERSIANN product has a moderate performance with a CC of 0.79 although it effectively detects precipitation events. The CHIRPS product has the lowest CC (0.39) and high errors, highlighting lower correlation and accuracy. Its negative ETS indicates a lower performance than luck in predicting precipitation. With a CC of 0.83, ERA5 shows a good

Table 3 Statistics of average monthly rainfall, collected from Laayoune station and precipitation products, across the Sakia El Hamra basin from 2001 to 2017 (unit: mm)

	Observed	TRMM	GPM	CHIRPS	ERA5	PERSIANN
Minimum	0	0	0	0	0	0
Median	0.006	0.118	0.047	0.261	0.032	0.088
Mean	0.129	0.531	0.199	0.504	0.141	0.243
Maximum	2.663	5.085	3.455	3.975	2.133	3.466
Standard deviation	0.329	0.975	0.423	0.755	0.307	0.392

Table 4 Statistics of average monthly rainfall, collected from Essmara station and precipitation products, across the Sakia El Hamra basin from 2001 to 2017 (unit: mm)

	Observed	TRMM	GPM	CHIRPS	ERA5	PERSIANN
Minimum	0	0	0	0	0	0
Median	0	0.024	0.047	0.018	0	0.084
Mean	0.105	0.171	0.164	0.068	0.13	0.27
Maximum	2.213	3.391	1.813	0.522	2.233	3.308
Standard deviation	0.29	0.37	0.3	0.103	0.337	0.468

Table 5 Indices for evaluating the monthly rainfall of the various products, measured at each gauging station

Station	Product	Correlation coefficient (CC)	Mean error (ME)	Mean absolute error (MAE)	Root mean square error (RMSE)	Bias	Equitable threat score (ETS)
Laayoune	TRMM	0.73	12.15	12.58	26.03	1.39	− 0.03
	GPM	0.93	2.11	2.73	5.52	1.16	− 0.07
	Persiann	0.79	3.49	4.7	8.07	1.66	− 0.01
	CHIRPS	0.39	11.45	13	24.18	1.22	− 0.08
	ERA	0.83	0.38	2.38	5.64	1	− 0.07
Essmara	TRMM	0.68	2.03	3.63	8.51	1.44	− 0.08
	GPM	0.74	1.8	3.12	6.68	1.66	− 0.03
	Persiann	0.62	5.02	5.97	12.25	2.15	− 0.01
	CHIRPS	0.39	− 1.11	3.46	8.11	1.34	− 0.12
	ERA	0.77	0.73	2.5	6.54	1.09	− 0.11

correlation and the lowest ME, indicating remarkable accuracy.

Regarding the Essmara station, TRMM has a good correlation (CC of 0.68) and relatively high errors. The bias indicates an overestimation of rainfall. PERSIANN has the highest bias, indicating a significant tendency to overestimate precipitation. The CC is also lower, indicating a lesser correlation. ERA5 has a good CC and moderate errors. With the lowest CC and a negative ETS, CHIRPS product has a lower performance in terms of correlation and reliability. The negative ME indicates an underestimation of precipitation. The products, although varied in their performance, offer valuable insights to understand the precipitation patterns in the Sakia El Hamra basin. GPM and ERA5 stand out particularly in Laayoune with high precision and correlation, while the performance of the products in Essmara is mixed. The insights derived from this evaluation are crucial to inform the choice of products for specific applications, highlighting the importance of a contextual and detailed evaluation similar to studies in other regions (Yang et al., 2017).

The differences in performance observed between the products can be explained by the algorithms used, the spatial and temporal resolution, and the data sources used for their development. The underlying algorithms, which determine how observations are processed and converted into precipitation estimates, are specific to each product and lead to distinct results. In addition, the resolution at which the estimates are generated, both in space and in time,

influences the ability to accurately represent the distribution of precipitation. Finally, the nature and the quality of the satellite observations, on the ground and of the models which feed these products, also introduce differences in the final estimates (Sun et al., 2018). The differences in the performance of the products can be attributed to the underlying algorithms, the spatial and temporal resolution, and the data sources used in their development.

The boxplots above (Fig. 8) illustrate the variability and the central trend of the indices for evaluating precipitation products compared to observations from gauging stations in the Sakia El Hamra basin from 2001 to 2017. The analysis of these graphs reveals various performances of the products. ERA5 and GPM are distinguished by their high correlation with the observed data and their relatively low errors (ME, MAE, RMSE), indicating superior accuracy and reliability. In particular, ERA5 shows a tendency towards minimal errors, which means that it has fewer false alarms in the prediction of precipitation events. This overestimation could be attributed to PERSIANN's sensitivity to intense rainfall, an aspect that could be explored in future studies to improve the accuracy of the product. TRMM and CHIRPS have higher errors and significant variability in their performance, requiring careful consideration in their application. CHIRPS, in particular, shows a relatively low correlation with the observed data, indicating a potential for improvement in the calibration and validation of the product. In summary, although each product has its inherent
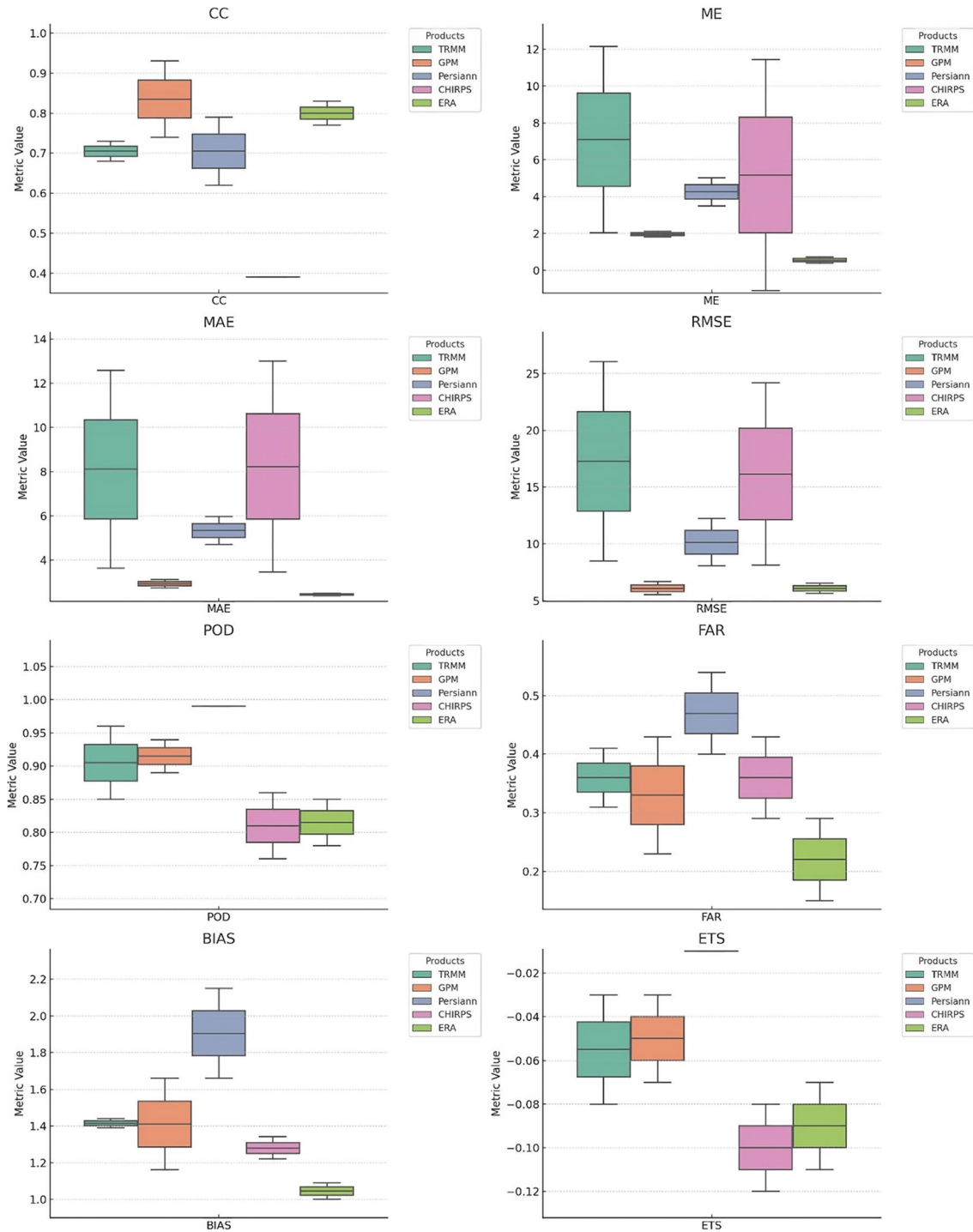
Fig. 8 Boxplot diagrams of the indices for evaluating the monthly precipitation of the products, compared to the observations of the gauges, across the entire Sakia El Hamra basin from 2001 to 2017

strengths and weaknesses, the ERA5 and the GPM prove to be valuable tools for estimating rainfall in the Sakia El Hamra basin, with superior accuracy and reliability. Future research efforts could focus on improving the accuracy of precipitation products, especially in arid and semi-arid regions, where accurate precipitation quantification is crucial for water management and water resource planning.

Evaluation at monthly and seasonal scales

The values of evaluation indices of the satellite products (Figs. 9 and 10) were calculated month by month and season by season for each weather

station. These values are also analyzed on a monthly scale, as illustrated in the previous graphs. Through the annual analysis, it is observed that ERA5 has the highest correlation coefficient (CC) for the majority of the months, except in August and October. The CC values of TRMM, GPM, CHIRPS, and PERSIANN also vary, allowing a thorough comparative analysis.

From September to November, the CC are significantly higher than in other months, indicating an increased accuracy of satellite products during the fall. Regarding the estimation of rainfall, TRMM, ERA5, and PERSIANN tend to overestimate the rainfall for most months, with the exception of
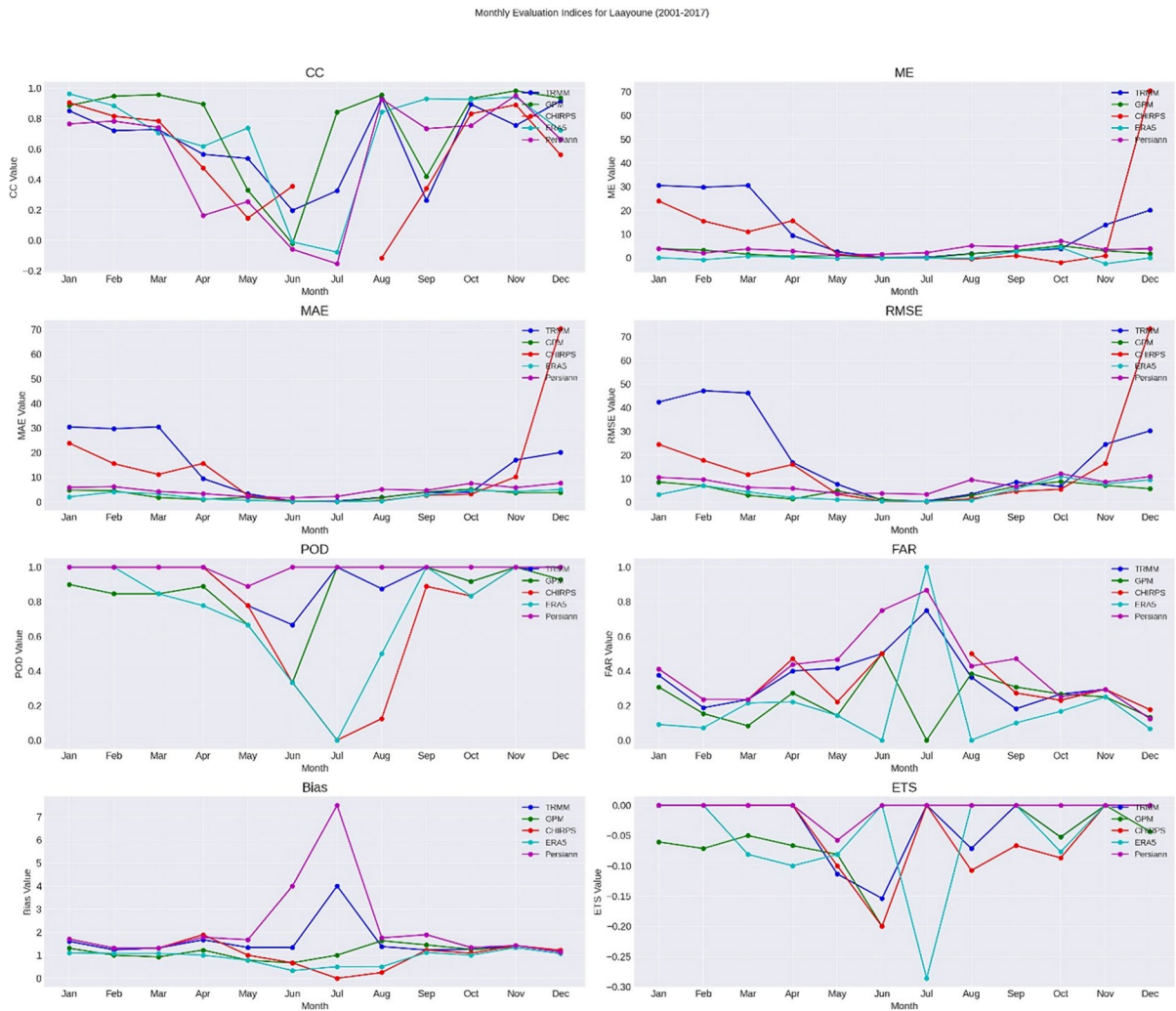

Fig. 9 Monthly evaluation indices precipitation of the various products, compiled from Laayoune station

Fig. 10 Monthly evaluation indices precipitation of the various products, compiled from Essmara station

PERSIANN which presents an underestimation in August. In addition, CHIRPS and GPM show various trends during the different seasons.

The MAE and the RMSE (Fig. 10), which are crucial for assessing the accuracy of rainfall estimates, first increase and then decrease as the year progresses, with peaks observed in July. CHIRPS records the highest MAE and RMSE values from May to September, highlighting a variability in the accuracy of the estimates. In summary, the analysis of the graphs offers a detailed overview of the variable performances of the TRMM, GPM, CHIRPS, ERA5, and PERSIANN satellite products in the estimation of monthly rainfall. These insights are

essential to understand and optimally exploit these satellite products for specific applications, taking into account monthly and seasonal variations.

At the Laayoune station (Fig. 11), the products, particularly TRMM and GPM, show improved performance in summer, characterized by a high ETS, indicating increased accuracy and reliability in estimating rainfall during this season. The analysis of the indices for the Essmara station (Fig. 12) reveals that the ERA5 satellite product excels bias during winter and spring, suggesting an overestimation of rainfall during these periods. On the other hand, products such as TRMM, GPM, CHIRPS, and PER-SIANN improve their performance in the summer,
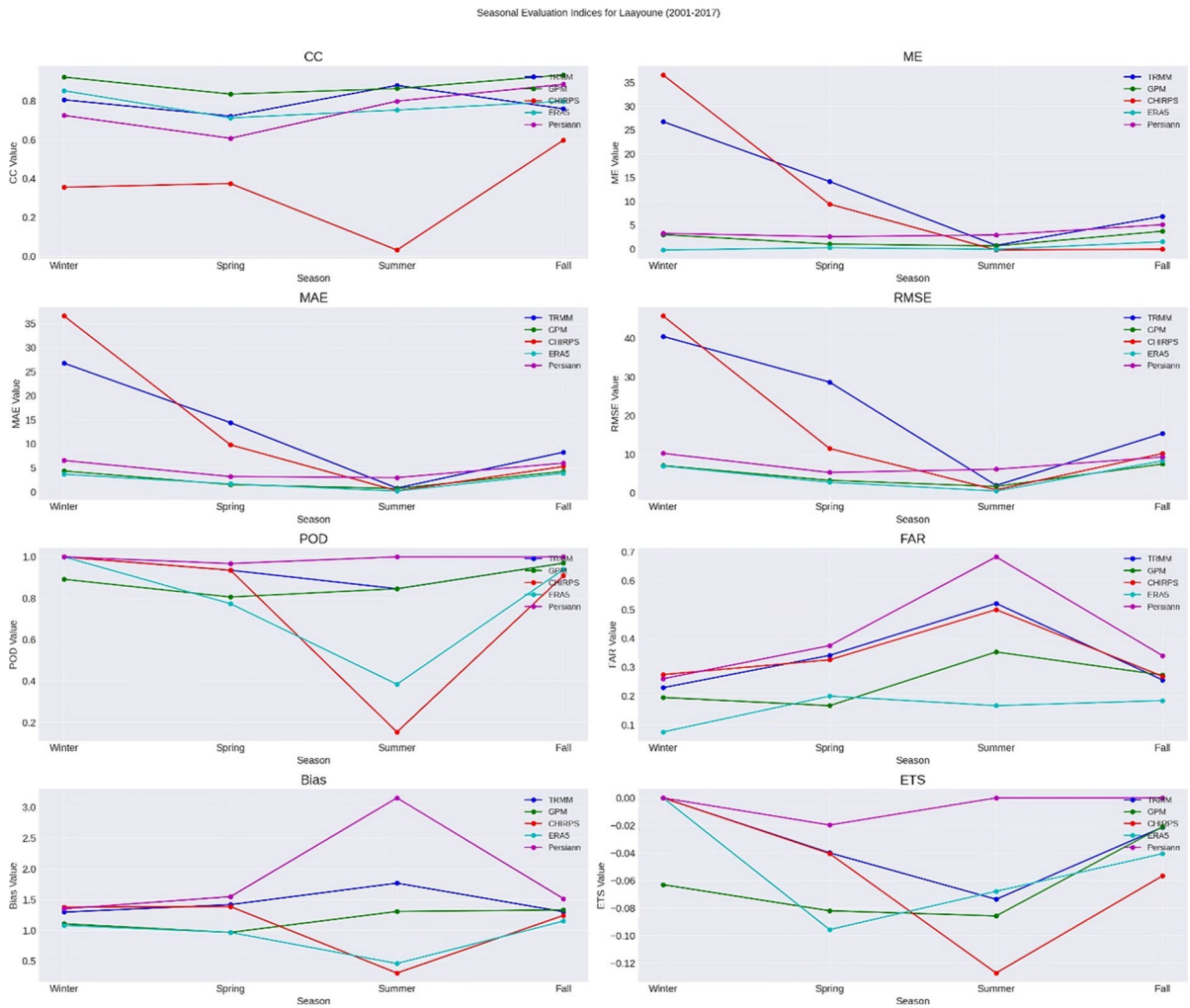
Fig. 11 Seasonal evaluation indices of precipitation products for Laayoune station

as demonstrated by the increase in the ETS, and the reduction of bias.

Discussion

The evaluation of satellite precipitation products over the Sakia El Hamra basin provides important insights into their performance and applicability for hydrological applications in water-scarce regions. The findings indicate significant variability amongst products, consistent with previous comparative assessments globally (Maggioni et al., 2016b; Tian et al., 2007) and regionally across Africa (Ibrahim et al., 2022; Thiemig et al., 2012).

Specifically, GPM and ERA5 demonstrate superior accuracy relative to ground observations, aligning with studies documenting the improved skill of these latest generation products (Xiang et al., 2021). However, significant overestimation biases persist, particularly for rainfall extremes, an issue noted previously for satellite products in arid environments (Jiang et al., 2012; Moazami et al., 2016). This points to the need for localized calibration and bias correction prior to hydrological utilization, as demonstrated for example by Dinku et al. (2018) in enhancing CHIRPS performance in East Africa.

The analysis also highlights important seasonal influences modulating product accuracy, with superior performance during autumn months. Such seasonal variations have been attributed to factors like
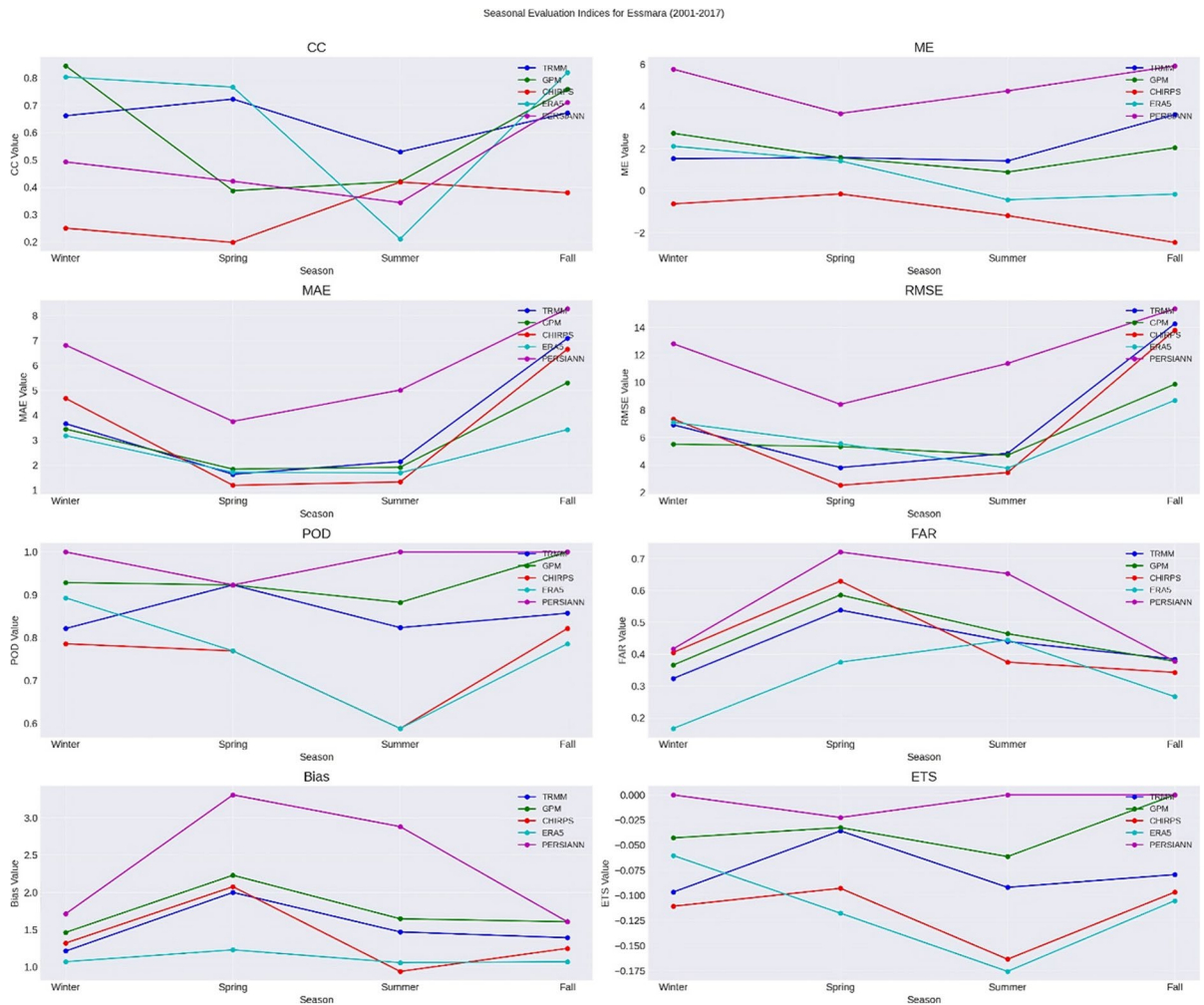
Fig. 12 Seasonal evaluation indices of the precipitation products for Essmara station

storm types and underlying surface characteristics (Gebregiorgis et al., 2017). Adopting dynamic bias correction approaches tailored to different seasons could further optimization (Zhou et al., 2023).

Additionally, the scale dependence of product reliability indicated here reiterates the necessity of multiscale validation spanning daily, monthly, and seasonal timescales (Silva et al., 2022). This provides comprehensive insights into spatiotemporal error characteristics crucial for appropriate hydrological application. For instance, flood modeling requires accurate representation of extreme precipitation, while water balance assessments rely more on correct monthly totals.

Overall, the findings highlight the potential of new-generation satellite precipitation for improved hydroclimatic monitoring in data-sparse regions, while also emphasizing the need for careful, context-specific validation and correction. Combining information from multiple products is recommended to provide more robust precipitation estimates, as demonstrated in previous studies (Thiemig et al., 2012; Yoshimot & Amarnath, 2017). This study thus provides an important framework for guiding optimal exploitation of satellites for water management in arid regions facing increasing water stresses.

Conclusion

This study provides important new contributions to the understanding and evaluation of satellite precipitation products in data-scarce regions with complex terrain. The comprehensive assessment of multiple state-of-the-art products over the hydroclimatically variable Sakia El Hamra basin represents a crucial gap in the literature that this research addresses.

The rigorous validation methodology provides a robust quantification of the capabilities and limitations of each product for hydrological applications. The findings reveal the potential of latest generation datasets like GPM and ERA5, while also highlighting significant biases that require localized calibration and correction.

Key new knowledge includes the characterization of important seasonal influences on product accuracy linked to regional climate factors. This points to the need for dynamic bias adjustment approaches tailored to different periods. The rare multi-temporal analysis also elucidates scale dependence in the products' skill across daily, monthly, and seasonal timeframes.

Overall, this study delivers an evaluation framework to guide optimal integration of multiple satellite estimates for enhancing precipitation quantification and hydroclimatic modeling in water-stressed regions. It also sets the stage for future research directions, including exploring physical drivers of variability, performance assessments across larger spatial domains, and impacts on hydrological simulations from bias-corrected products.

The insights gained contribute significantly to the field of satellite precipitation estimation, especially in complex terrain where ground-based data is limited. They highlight pathways for developing enhanced algorithms and blended products to support water management and climate resilience in vulnerable arid environments.

Declarations

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