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Water Cycle

Evaluation of satellite-based (CHIRPS and GPM) and reanalysis (ERA5-Land) precipitation estimates over Eritrea

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Abstract

Availability of long-term and spatially high-resolution precipitation data is important for sustainable water resource management, drought monitoring and hydrological analysis. In Eritrea, in-situ precipitation measurements are too sparse to represent the highly variable rainfall on the ground. Thus, as alternative data sources, satellite-based (CHIRPS and GPM) and reanalysis (ERA5-Land) products were evaluated against 40 stations within the study period (1992–2018). The performance evaluation was made for monthly precipitation totals along the different elevations, agroecological zones and seasons. Overall, these products captured the seasonality of precipitation over the country's different zones. GPM performed well in all zones of the country ($r_s > 0.42$, RMSE = 44.0 mm), except for the arid highlands ($r_s = 0.19$, RMSE = 56.4 mm) during the summer season. The performance of GPM did not exhibit a distinct pattern with respect to elevation, amount, and nature of rainfall. CHIRPS demonstrated better estimates over areas where rainfall is of a convective nature during the summer period. These areas include the moist highlands ($r_s = 0.4$, RMSE = 47.1), arid lowlands ($r_s = 0.48$, RMSE = 39.0), arid highlands ($r_s = 0.31$, RMSE = 48.1) and semi-desert ($r_s = 0.38$, RMSE = 20.1) regions. However, there were no significant correlations over the sub-humid regions in the winter period ($r_s = 0.19$, RMSE = 25.8), as rains originate from "warm" clouds. ERA5-Land highly underestimated the summer and spring rainfalls in all parts of the country. The summer percentage bias (PBIAS) of this product ranged between −22.6 and −80.1. Therefore, GPM could primarily be considered as an alternative rainfall data source for the summer and spring seasons over Eritrea. CHIRPS can also be used as a potential data source specifically for the areas with convective rainfall during the summer and spring seasons. However, ERA5-Land needs further improvement to represent precipitation in Eritrea.

Keywords: CHIRPS, GPM, ERA5-Land, Eritrea

1 Introduction

Understanding precipitation variability in Eritrea is crucial because precipitation is the major water source for agriculture, industry, and domestic water supply. Precipitation is highly variable in Eritrea owing to its semi-arid location, diverse topographic features, and proximity to the Red Sea. As a result, sparse coverage and inconsistent ground-based rainfall observations cannot provide the actual rainfall distribution over the country. Hence, satellite-derived and reanalyses rainfall products are considered alternative sources for a high-resolution and temporally continuous gridded precipitation dataset.

Several satellite-based rainfall products are available with different time span and spatial resolutions. These include: i) Climate Prediction Centre (CPC) Merged Analysis of Precipitation (CMAP) – a monthly global precipitation with 2.5° resolution that has been constructed from an analysis of gauge data and satellite-derived precipitation estimates since 1979 (Xie and Arkin, 1997); ii) Global Precipitation Climatology Project (GPCP) – monthly analysis of surface precipitation which started in January 1979 with 2.58° resolution (Adler et al., 2003); iii) African Rainfall Climatology version 2 (ARC2) – daily precipitation estimates centred over Africa at 0.1° spatial resolution dating back to 1983 (Novella and Thiaw, 2013); iv) Tropical Applications of Meteorology using Satellite and ground-based observations (TAMSAT) rainfall estimate – decadal (10-day) rainfall estimates for all of Africa at high spatial resolution (0.0375°) starting in 1983 (Maidment et al., 2014); v) Global Precipitation Measurement (GPM) mission (Hou et al., 2014) – the next generation of global precipitation products with halfhourly temporal and 0.1° spatial resolutions which started in 1992; it is built upon the success of Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al., 1998; Huffman et al., 2007); vi) Climate Hazards Group Infrared Precipitation with station (CHIRPS) – pentadal (5-day) and 0.05° spatial resolution rainfall products since 1981 (Funk et al., 2015).

Reanalyses are also an alternative data source for global precipitation. Reanalysis systems merge the available observations with the background model forecast, which uses laws of physics to generate uniform gridded data. Globally, one of the leading reanalysis prod-

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ucts is ERA5 (Hersbach et al., 2020), produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) since 1950. High resolution surface data are generated from ERA5 by means of the land-surface model H-TESSEL; the resulting dataset ERA5-Land has a spatial resolution of 0.09° and currently dates back to 1981 (Muñoz-Sabater et al., in review).

In this study, we focus on the evaluation of the satellite-based (CHIRPS and GPM) and reanalysis (ERA5-Land) datasets since they cover a relatively long-time span, have high resolution, and are the most recent products. Compared to GPM and ERA5-Land, CHIRPS has been better evaluated and more widely used, mainly because it was released earlier. Overall, the evaluation of CHIRPS indicated that it performs best in areas where precipitation is predominantly convective in nature, since long duration cold cloud-top temperatures are within the threshold of the satellite algorithm (Dinku et al., 2007; Paredes-Trejo et al., 2017; Saeidizand et al., 2018; Al-Falahi et al., 2020). This has been demonstrated in the highland region of Yemen (Al-Falahi et al., 2020); India (Prakash, 2019); the southern coastal lowlands of Iran (Saeidizand et al., 2018); Argentina (Rivera et al., 2018); Cyprus (Katsanos et al., 2016); and Venezuela (Paredes-Trejo, 2016). Conversely, CHIRPS showed some limitations in estimating orographic rainfall since the fixed threshold value identifies warm orographic clouds as non-precipitating, as reported in Northeast Brazil (Paredes-Trejo et al., 2017) and the western Amazon (Cavalcante et al., 2020; Mu et al., 2021), where it underestimated the values of rainfall and extreme rainfall indices. The same underestimation was observed for mountainous regions of China (Bai et al., 2018) and eastern Africa (Dinku et al., 2018).

In the East Africa countries (Ethiopia, Kenya, Somalia, Uganda, Rwanda, and Tanzania) CHIRPS performed best over the northern half of the Ethiopian highlands during the boreal summer and in southern and western parts of Tanzania. However, CHIRPS showed lower correlation values mainly over the southern half of Ethiopia, most of Somalia, the highlands and coastal regions of Kenya and Tanzania, and most of Uganda and Rwanda (Dinku et al., 2018; Maidment et al., 2017). This could be a result of warm coastal and orographic rainfall processes that produce rainfall at relatively warmer cloud-top temperatures beyond the thresholds of the satellite-based precipitation products (Dinku et al., 2018).

The objective of this study is, therefore, to evaluate CHIRPS, ERA5-Land, and GPM against ground-based rainfall observations from 40 stations across Eritrea. This research is novel in Eritrea, since such evaluation has not been done for the satellite-based and reanalysis products. In addition, GPM is a newly released product and not much validation work has been done relative to the independent precipitation measurements. Hence, this paper is organised as follows: Section 2 presents a description of the study area with respect to topography, agroecological zones and seasons. In addition, this section presents the data source, and methods employed to undertake the analysis. Section 3 discusses the results regarding interannual precipitation variability, and the performance of CHIRPS, GPM, and ERA5-Land spatially (along with the different altitude ranges and agroecological zones) and temporally within the four seasons. Finally, Section 4 highlights the conclusion and recommendations drawn from the study.

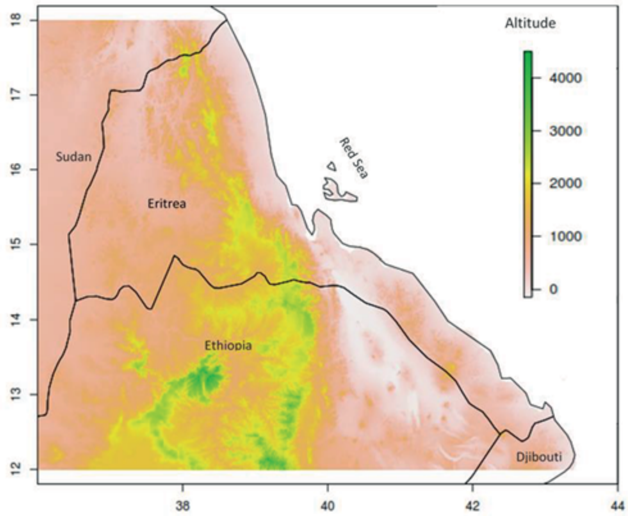

Figure 1: Topographic map of Eritrea.
The national boundary is not authoritative in all the maps.

2 Study area, data, and methods

2.1 Description of the study area

I. Eritrea has three distinct topographic features: i) central highlands with an elevation range from 1,500 to 3,000 m; ii) western lowlands with a semi-arid climate and flat-to-rolling plains with an elevation range between 500 and 1,500 m; and iii) eastern lowlands with a flat desert area bordering the Red Sea with an elevation change from 100 m below sea level to 500 m above (Fig. 1).

II. Agroecological zones: Eritrea is situated in the Horn of Africa with climate ranging from hot and arid adjacent to the Red Sea to temperate in the highlands and isolated micro-catchments area in the sub-humid zone. Eritrea has six agroecological zones, each having a homogenous climate, landform, soil, and vegetation (FAO, 1997). The specific description of these zones, based on the FAO (1997) characterisation, is presented below (Fig. 2).

III. Seasons: Eritrea can be divided into two regimes based on its seasonal precipitation: i) the highlands and western lowlands that receive rainfall mainly during the summer season (JA); and ii) the eastern escarpment and eastern lowlands, where rainfall occurs dominantly during the winter period (DJF). Flohn (1963) first noted these peculiar rainfall regimes in

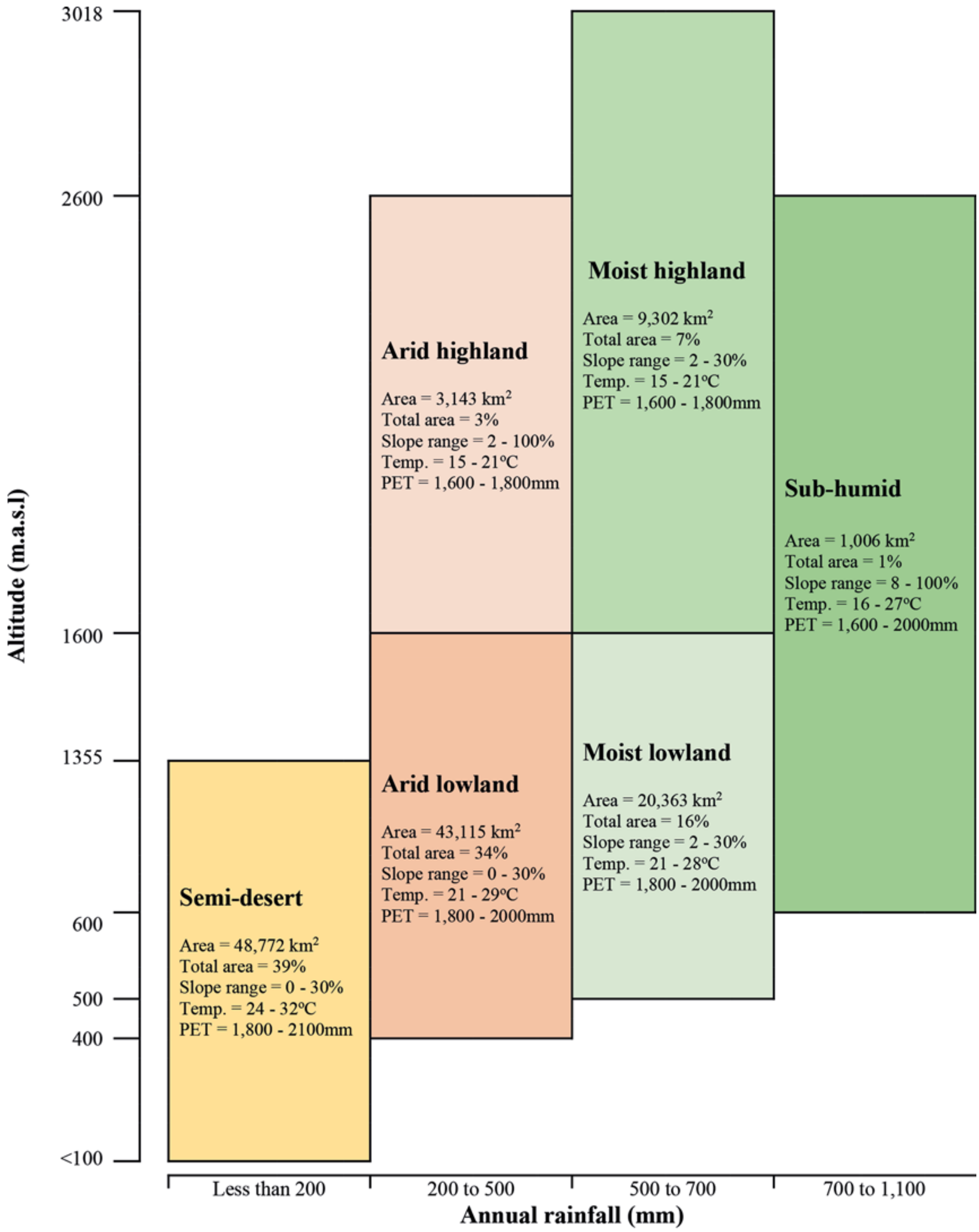

Figure 2: Specific description of the six agroecological zones of Eritrea. Temp denotes air temperature (°C) and PET represents potential evapotranspiration (mm).

which the highlands of Eritrea received more than 90 per cent of the annual rainfall in the summer period, while 20 km to the east, winter rains yielded about 90 per cent of the annual amount. The four seasons with respect to their nature of rainfall and associated atmospheric circulation are described below:

(a) Summer (JA): the main rainy period for the highlands and western lowlands of the country occurs when the Intertropical Convergence Zone (ITCZ) moves to its northernmost position over Eritrea (Hastenrath, 1991; Segele et al., 2009). The rainfall is largely convective in origin, where the equatorial westerlies converge with the diurnal sea breeze from the Red Sea along with an overlaying easterly flow (Flohn, 1963).

(b) Autumn (SON): several rainfalls occur as an extension of the summer season, mainly in the month of September, but for the most part it is a dry season in the highlands and western parts of the country.

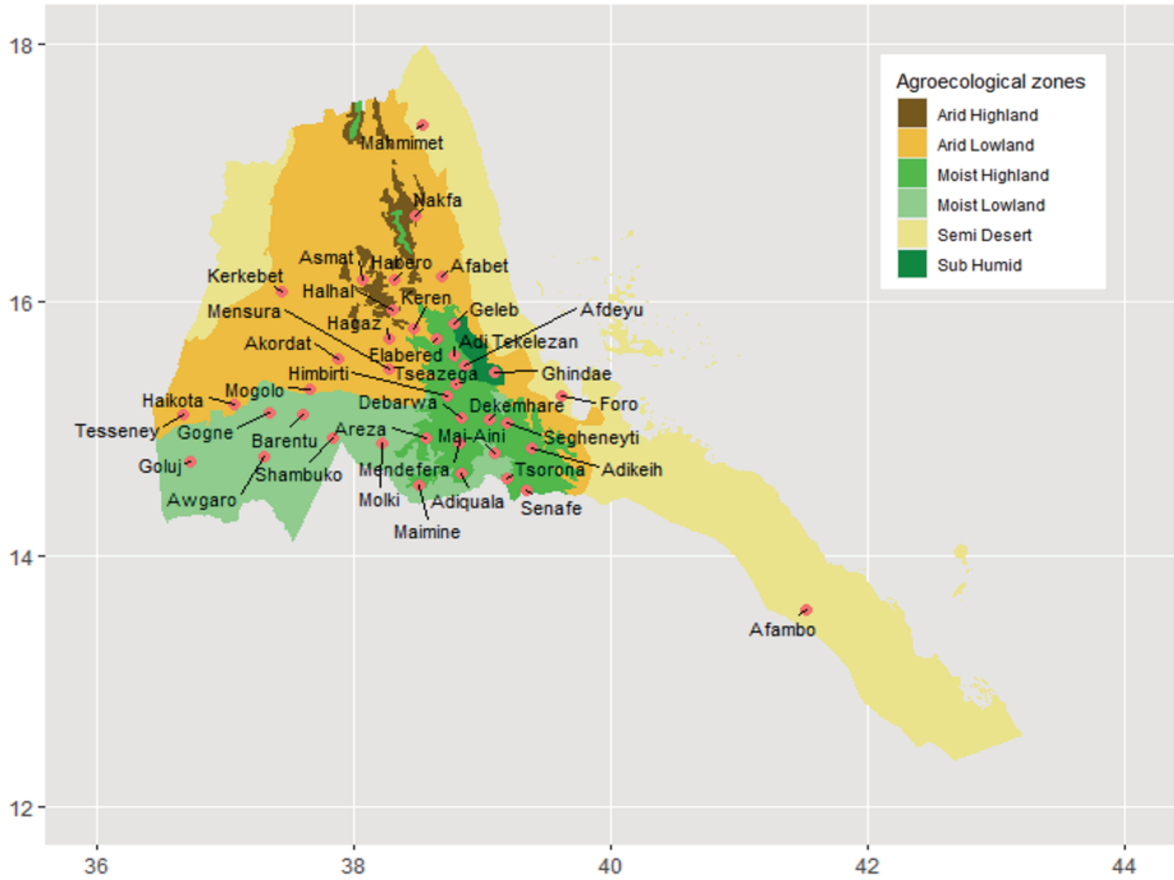

Figure 3: Location of rainfall stations within the respective agroecological zones of Eritrea.

(c) Winter (DJF): a rainfall season dominantly in the eastern lowlands and eastern escarpment where, due to local daytime circulations, stratocumulus clouds are constantly driven towards the eastern escarpment and drizzle heavily from these stable, "warm" clouds (Flohn, 1963).

(d) Spring (MAM): "small-rainfall" from deep and cloudy convection, mainly over the highlands, that is produced by an interaction between travelling upper troughs in the westerlies and shallow tropical disturbances steered towards the north. During this season, elongated Cirro- and Altostratus "streets" of the subtropical jet are frequently observed (Flohn, 1963).

2.2 Data sources

2.2.1 Rain-gauge precipitation

Monthly precipitation data (1992–2018) from 40 stations across the country were considered, which represent all the elevations, agroecological zones and rainfall seasons of Eritrea. Rainfall was recorded, using manual rain gauges, by the respective Ministry of Agriculture sub-zone offices within the six administrative zones of the country (Fig. 3). At national level, the Ministry of Agriculture compiles and verifies the quality of the stations' rainfall dataset. Data quality control is manually checked for erroneous data (e.g., negative values and extreme outliers) against the respective station log sheets. In addition, Asmara city's rainfall was recorded by Asmara International Airport Meteorological Services.

2.2.2 CHIRPS precipitation estimates

As described above, CHIRPS is a 30+ year quasi-global rainfall dataset ranging from 1981 to the near present. It covers 50° S–50° N (and all longitudes) with high resolution (0.05°) and is blended with in-situ station data to create a gridded rainfall time series (Funk et al., 2015). The CHIRPS dataset was released by the Climate Hazards Group at the University of California, Santa Barbara. The different temporal resolution datasets are publicly available: ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/.

The major inputs for the creation of CHIRPS include: i) pentadal (five-day) precipitation climatology (CHPClim), which is a combination of satellite observations and average precipitation from stations, representing the spatial component; ii) quasi-global geostationary thermal infrared (TIR) satellite observations, representing the temporal component; iii) satellite precipitation data from the Tropical Rainfall Measuring Mission (TRMM) 3B42 product; iv) atmospheric model rainfall fields; and v) in-situ precipitation observations. First, the percentage of Cold Cloud Duration (CCD) is calculated during the pentad when the infrared (IR) observations indicate cold cloud tops (< 235°K, likely rainfall clouds). Then, the percentage of CCD is converted to IR Precipitation (IRP) pentad rainfall estimates using a local regression model developed between CCD and TRMM 3B42 precipitation pentads. To avoid bias, the IRP pentads are expressed as a per cent of normal by dividing the values by their long-term (1981–2012) IRP means. Then, the per cent of normal IRP pentad is multiplied by the corresponding CHPClim pentad to produce the Climate Hazards Group IR Precipitation (CHIRP) (Funk et al., 2014).

In the last step, station data are blended with the CHIRP data to produce the final product, CHIRPS. The blending process is carried out at pentadal and monthly timescales. The blending procedure is a modified inverse distance weighting algorithm with the five nearest station observations used to calculate an adjustment ratio for the CHIRP value. Each station is assigned a weight proportional to the square of its expected correlation. Closer stations receive higher weights. These five weights are then scaled to a sum of 1 and used to blend the station data into a single modifier (ratio) that can be used to adjust the CHIRP estimates (Funk et al., 2014). In this study, the monthly CHIRPS precipitation dataset has been downloaded for the corresponding stations across Eritrea.

2.2.3 Global Precipitation Measurement (GPM)

GPM is a high resolution (half-hourly and 0.1°) advanced precipitation measurement from a constellation of research and operational microwave sensors. It is built upon the 17-year success of the TRMM and specifically designed with sensors to provide more accurate and instantaneous precipitation estimates, particularly for light rainfall and falling snow (Hou et al., 2014; Skofronick-Jackson et al., 2018).

The monthly precipitation dataset (1992–2018) has been extracted and compiled for the corresponding stations across Eritrea. The GPM precipitation dataset (v2020) is publicly available: https://gpm.nasa.gov/data/directory.

2.2.4 ERA5-Land precipitation

ERA5-Land (Muñoz-Sabater et al., in review) is the land component of the latest global reanalysis dataset provided by ECMWF (2019): ERA5 (Hersbach et al., 2020). It has a high spatial (9 km) and temporal (hourly) resolution, currently starting in 1981 (an extension back to 1950 is underway). In this study, an hourly resolution ERA5-Land reanalysis precipitation has been extracted and aggregated to monthly resolution. The ERA5-Land dataset is publicly available: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=form.

2.3 Methods

2.3.1 Interannual variability analysis

The interannual precipitation variability is described using box plots, where the statistical distribution is described with median, interquartile range, outer range, and extremes (beyond the 90^{th} percentile). This enables a visualisation and comparison of the seasonal distribution and interannual variability among the station, CHIRPS, GPM, and ERA5-Land datasets. Moreover, the similarity of seasonality and interannual precipitation variability is a prerequisite for further analyses.

2.3.2 Statistical analysis

Independently, the monthly CHIRPS, GPM, and ERA5-Land datasets were evaluated against the observed rainfall records (1992–2018) across Eritrea. First, we evaluated the seasonal sums for the respective agroecological zones and then on a station level. Pairwise statistical comparisons were made to evaluate the performance of these rainfall products in estimating the observed precipitation. We used Spearman's rank correlation, the root mean squared error (RMSE) and the percentage bias (bias divided by the observed value) to evaluate the datasets. A spatial performance was assessed by making stratification with respect to elevation and agroecological zones of the country. Similarly, temporal performance was validated with seasonal averages.

Previously, the station rainfalls from Asmara, Massawa and Asseb were blended in the CHIRPS dataset. Therefore, we exclude them from all pairwise correlation analysis with CHIRPS as well as GPM and ERA5-Land for consistency, and to make sure that the datasets are independent.

3 Result and discussion

3.1 Interannual precipitation variability

Overall, the rainfall products (CHIRPS, GPM, and ERA5-Land) captured the seasonality of precipitation over the different zones of the country. Dominantly, summer rainfall covers the main rainfall season for most areas (Fig. 4). The median, interquartile range (IQR), outer ranges (10^{th} and 90^{th} percentile), and extreme rainfall values for each rainfall product with respect to the observed rainfall are described below, mainly focusing on the summer rainfall.

Seasonal rainfall variability is well depicted by CHIRPS with overestimation of median and IQR measurements mainly during the summer season in all agroecological zones. However, CHIRPS showed underestimation of IQR in the sub-humid zone during the winter season. Extreme rainfall values are denoted by the points above the vertical lines (90^{th} percentile). CHIRPS also underestimated both the 90th percentiles and extreme rainfall during the summer season: the maximum

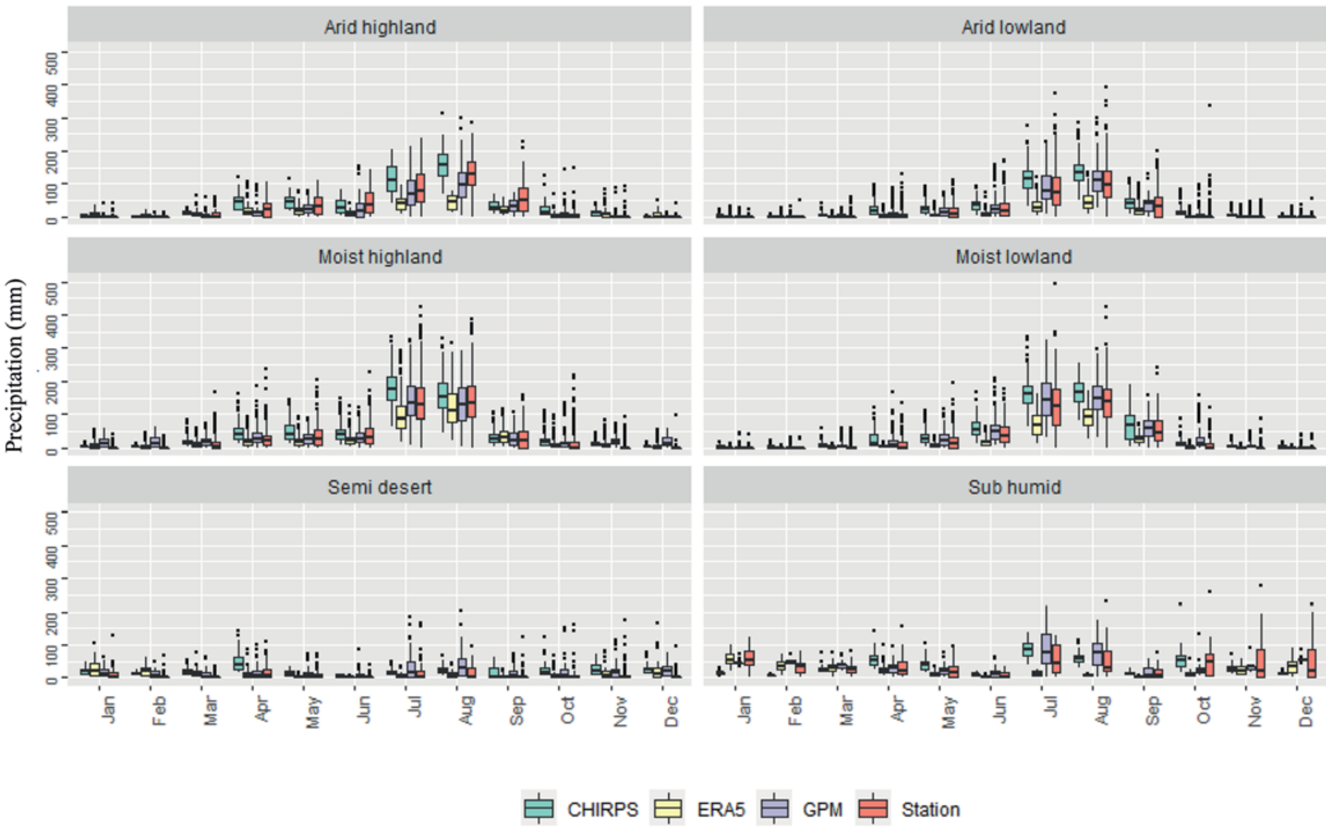

Figure 4: Interannual precipitation variability over the six agroecological zones of Eritrea for the study period (1992–2018).

average monthly rainfall on record (500 mm) during the study period (1992–2018) depicted by CHIRPS was 350 mm in July, over the moist lowlands.

GPM accurately captured the seasonality of precipitation and showed reasonably similar median and IQR values over the moist highlands, arid highlands, moist lowlands and arid lowlands. However, in the semi-desert and sub-humid regions, GPM indicated a wider IQR and slight overestimation of the summer rainfall. Generally, GPM showed good estimation of the 90th percentiles of rainfall during the summer season, except for the semi-desert and sub-humid regions. Overall, maximum rainfall values were mostly recorded during the summer periods except for the sub-humid zone, where the maximum rainfalls occurred in the winter period. The maximum rainfall records were generally underestimated by GPM. The maximum GPM-predicted value reached 325 mm in July for the moist highlands, where the corresponding observed maximum value was 425 mm.

ERA5-Land depicts the seasonality of precipitation. However, it highly underestimated the corresponding observed rainfall in all the agroecological zones, except in the moist highlands, where it presented a relatively accurate prediction and a coherent pattern with the rainfall season. Similarly, ERA5-Land underestimated all the median, IQR, and maximum rainfall values in all the seasons across the country.

In summary, GPM performed better in capturing the seasonality and depicting the interannual precipitation variability than CHIRPS estimated. ERA5-Land highly underestimated the observed rainfall in all the agroecological zones and only performed relatively well in the moist highlands.

3.2 CHIRPS evaluation

The summer season (Jul–Aug) accounts for the main rainfall in all agroecological zones of the country, but it has a lower contribution in the sub-humid (25 %) and semi-arid regions (28 %) (Fig. 5). On average, the summer rainfall period accounts for more than 67 % of the total annual rainfall in most areas of the country. Overall, CHIRPS overestimated the seasonal rainfalls in all agroecological zones and particularly in the semi-desert area (Fig. 5).

CHIRPS performed well across the agroecological zones of Eritrea, where the rainfall is convective in nature during the summer season (Table 1). These agroecological zones include the moist highlands (r_s = 0.4, RMSE = 47.1), arid lowlands (r_s = 0.48, RMSE = 39.0), arid highlands (r_s = 0.31, RMSE = 48.1) and semi-desert (r_s = 0.38, RMSE = 20.1) regions (Fig. 6). However, the performance of CHIRPS was lower in the moist lowlands (r_s = 0.1, RMSE = 62.2) and sub-humid regions (r_s = 0.21, RMSE = 36.7). In winter,

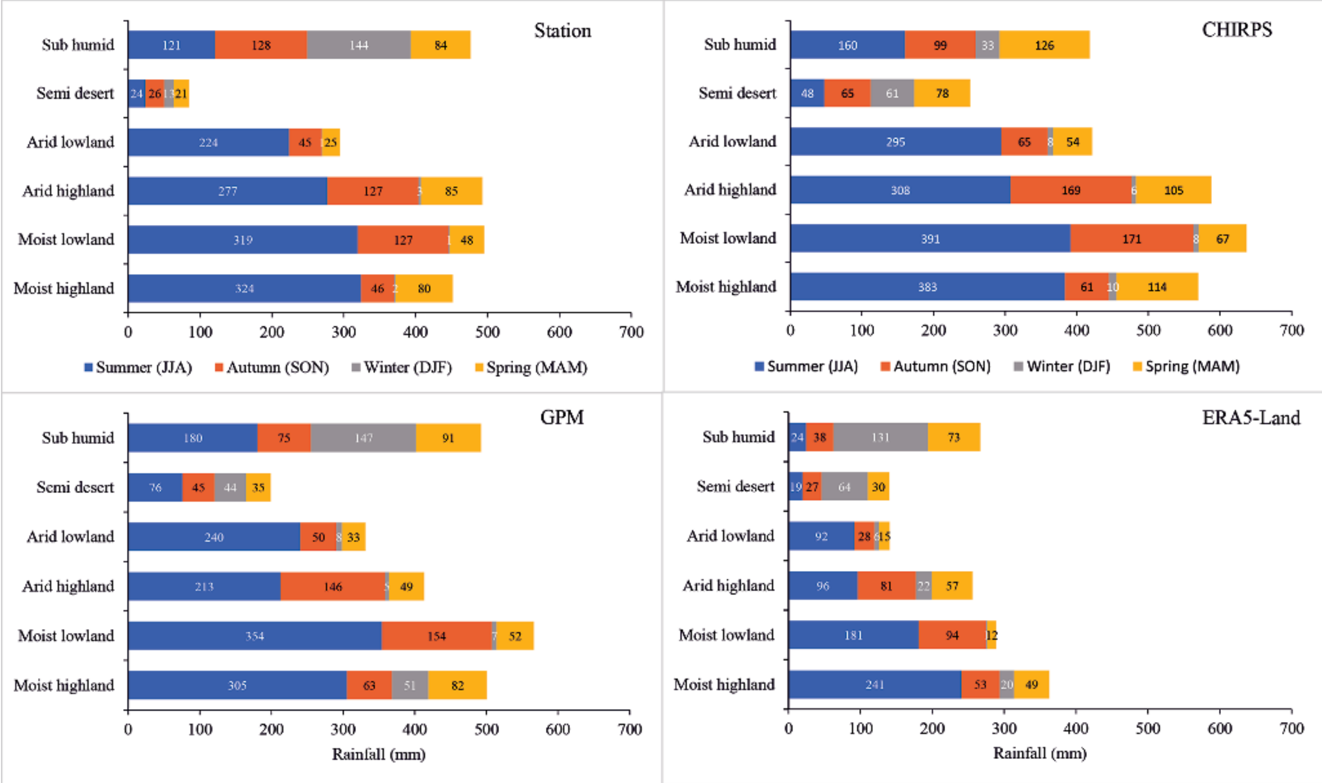

Figure 5: Seasonal rainfall for the different agroecological zones for the period from 1992 to 2018. The station and three precipitation products represent the mean value for the respective agroecological zone.

CHIRPS performed poorly in the sub-humid (r_s = 0.19, RMSE = 25.8) and semi-desert (r_s = 0.051, RMSE = 8.95) regions, since the rainfall is from "warm" clouds created due to local daytime circulations.

Despite the elevation differences, significant correlation and low bias were found in the regions in which the rainfall is convective. These areas mainly incorporate the western arid lowlands and the moist highlands (Fig. 6). In turn, this finding substantiated that in the summer season the westerly wind is the moisture-bearing wind to the central highlands of Eritrea (Fessehaye et al., 2021). As it was also reported by Segele et al. (2009), summer rainfall in the Horn of Africa is associated with enhanced westerlies across western and central Africa.

Regionally, CHIRPS performed best over the northern half of the Ethiopian highlands during the boreal summer. However, CHIRPS showed lower correlation values mainly over the southern half of Ethiopia. This could be a result of warm orographic rainfall processes that produce rainfall at relatively warmer cloud-top temperatures (Dinku et al., 2018). Globally, similar findings have been reported for the satellite-based rainfall estimates and demonstrate high performance in areas where rainfall is predominantly convective in origin. Naturally, convective clouds have long duration cold cloud-top temperatures within the threshold of the satellite algorithm and enable CHIRPS' peak performance (Dinku et al., 2007; Paredes-Trejo et al., 2017; Saeidizand et al., 2018; Al-Falahi et al., 2020). However, satellite-based products underestimated rainfall from "warm" clouds since the temperature of such clouds was higher than the threshold used by the satellite algorithms (Dinku et al., 2018).

The "small rainfall" in spring also substantially contributed to the annual rainfall in different zones of the country (Table 2). CHIRPS performed well in estimating this rainfall in the moist highlands (r_s = 0.6, RMSE = 15), moist lowlands (r_s = 0.33, RMSE = 12), arid highlands (r_s = 0.39, RMSE = 15.5), and arid lowlands (r_s = 0.37, RMSE = 9.4). This is because this season favours deep and cloudy convection (Flohn, 1963; Habtemichael and Pedgley, 1974).

3.3 GPM evaluation

GPM showed the best estimations of seasonal rainfalls in all agroecological zones but overestimated the semi-desert rainfall (Fig. 5). GPM was accurate in all zones of the country (r_s > 0.42, RMSE = 44.0 mm), except in the arid highlands (r_s = 0.19, RMSE = 56.4) during the summer season (Table 1). The error analysis showed that GPM estimated RMSE (<60), where the performance of GPM was good. In contrast, higher RMSE values were recorded mainly on the lower section of the moist lowlands (60–80) (Fig. 7). GPM showed varied percentage biases (PBIAS) with an extreme overestimation only in the semi-desert zone (144) during the summer season.

Moreover, the correlation of GPM with station rainfall was significant during both autumn and spring in all

Table 1: Satellite-based (CHIRPS and GPM) and reanalysis (ERA5-Land) performance evaluation averaged per agroecological zone and season.

Agroecological zone	Parameters	CHIRPS				GPM				ERA5-Land			
		Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
		JA	SON	DJF	MAM	JA	SON	DJF	MAM	JA	SON	DJF	MAM
Moist highlands	Correlation (r_s)	***0.4***	***0.3***	–	***0.6***	***0.4***	***0.26***	–	***0.49***	***0.39***	***0.31***	–	***0.57***
	RMSE (mm)	47.1	13.8	–	15	48.5	15.3	–	16.2	45.6	14.9	–	14.9
	PBIAS (%)	20	22.5	–	53	−2.8	24.3	–	9.8	−22.6	7.8	–	−33.9
Moist lowlands	Correlation	0.1	***0.33***	–	***0.33***	***0.41***	***0.34***	–	***0.44***	***0.39***	***0.36***	–	***0.27***
	RMSE (mm)	62.2	15.4	–	12	58.1	16.8	–	11.3	55.7	15	–	11.9
	PBIAS (%)	22	41.1	–	77	12.5	41	–	38.9	−40.3	−51.1	–	−67
Arid highlands	Correlation (r_s)	***0.31***	0.15	–	***0.39***	0.19	***0.49***	–	***0.33***	***0.27***	***0.36***	–	***0.44***
	RMSE (mm)	48.1	21.2	–	15.5	56.4	18.5	–	16.3	41	19.5	–	14.6
	PBIAS (%)	23.3	−5.2	–	43.4	−17.9	−29.1	–	−33.2	−61.5	−39.3	–	−23.2
Arid lowlands	Correlation (r_s)	***0.48***	***0.29***	–	***0.37***	***0.4***	***0.34***	–	***0.34***	***0.43***	***0.29***	–	***0.22***
	RMSE (mm)	39.0	15.6	–	9.4	45.5	16	–	10.4	41.7	15.9	–	9.58
	PBIAS (%)	31.7	34.2	–	114	6.6	4.3	–	27.1	−57.4	−41.9	–	−43
Semi-desert	Correlation (r_s)	***0.38***	***0.42***	−0.05	0.15	***0.41***	0.25	−0.081	***0.29***	***0.34***	***0.36***	0.14	0.17
	RMSE (mm)	20.1	15.5	8.95	14.4	28.9	16.1	9.05	12	22.5	17.4	12.5	11.4
	PBIAS (%)	38.8	62.2	223	178	144	45	168	37.2	−44.7	−29.5	278	4.9
Sub-humid	Correlation (r_s)	0.21	***0.48***	0.19	0.31	***0.47***	0.35	0.15	***0.42***	***0.45***	0.2	0.37	0.19
	RMSE (mm)	36.7	27.5	25.8	20.8	39.1	29.3	25.9	18.1	34.2	32.9	23.8	18.8
	PBIAS (%)	37.9	−17.1	−77.1	51	52.4	−37.1	2	8.5	−80.1	−67.9	−8.7	−13.1

NB.

- Bold and italic correlations indicate statistically significant values at 95 % level of significance.
- For consistency the summer rainfall accounts the main rainfall months during July and August only.

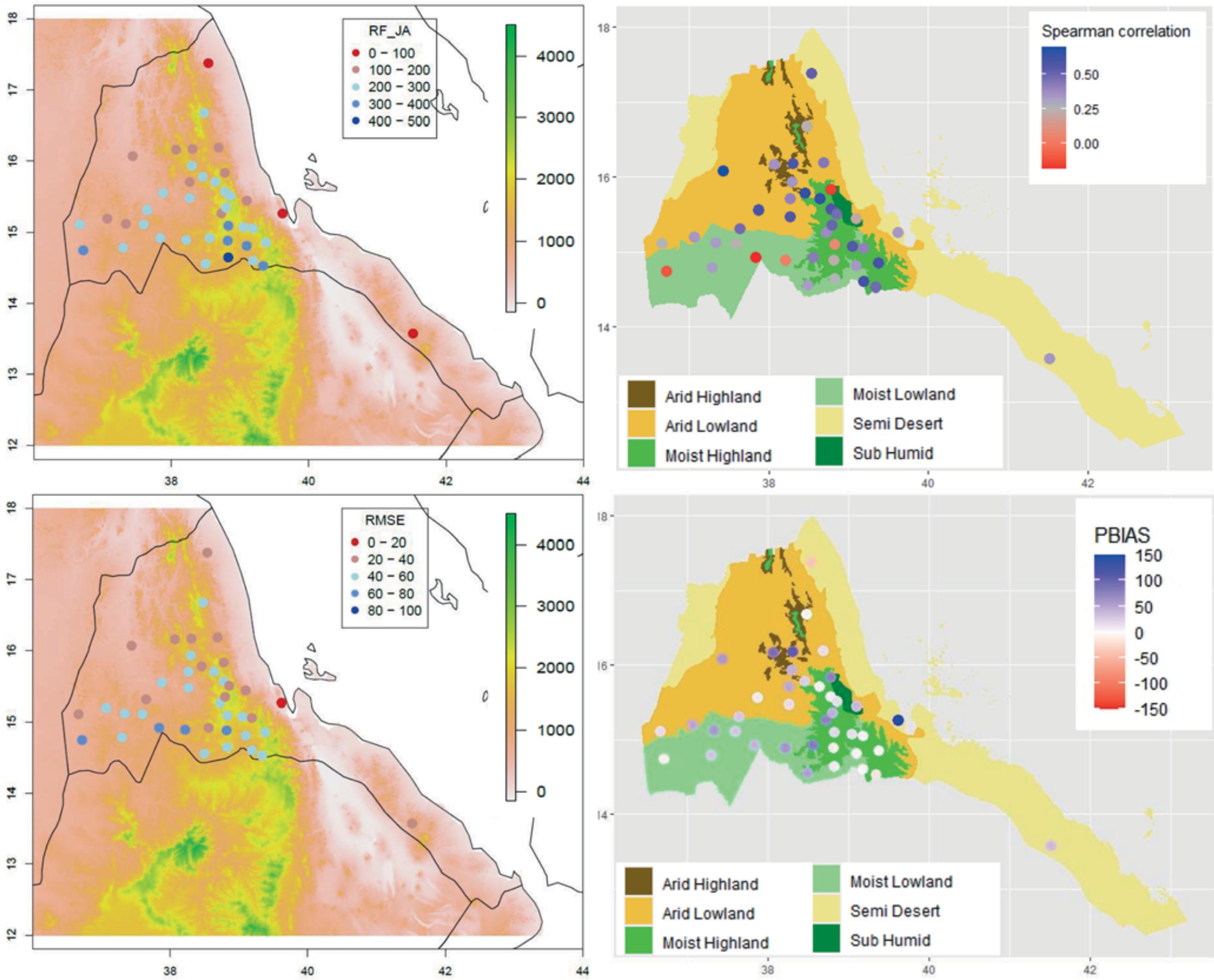

Figure 6: Pairwise statistical analysis between observed and CHIRPS data for the summer season (1992–2018). RF denotes rainfall (mm), RMSE = root mean squared error (mm), and PBIAS = percentage bias (%).

agroecological zones (Table 1). Note that the autumn rainfall mainly occurs until mid-September, as an extension of the summer rainfall. In spring, GPM demonstrated high performance in all parts of the country with significant correlation and low RMSE (<18.1). The correlations between GPM and station data were not statistically significant in the semi-desert ($r_s = -0.081$, RMSE = 9.05) and sub-humid regions ($r_s = 0.15$, RMSE = 25.9) during the winter period (DJF) (Table 1). Similar results have been reported in Saudi Arabia: for seasonal-based evaluation of GPM, the precipitation products exhibited better performance in spring and summer, while having relatively lower accuracy and higher biases in autumn and winter (Mohammed et al., 2020). Unlike for CHIRPS, the performance of GPM does not seem to be influenced by or exhibit a distinct pattern with respect to elevation, amount, and nature of rainfall (convective or orographic). This could be because GPM uses microwave sensors for measuring precipitation and radiative signatures, which are more directly linked to the precipitating particles (Hou et al., 2014). In contrast, CHIRP estimated precipitation with IR sensors inferred from cloud-top radiances that could be influenced by the nature of the clouds (orographic or convective).

3.4 ERA5-Land evaluation

Generally, ERA5-Land underestimated the seasonal rainfall in almost all parts of the country (Fig. 5). However, a few stations show slight overestimation in the moist highlands (Fig. 8). ERA5-Land exhibited significant correlation, mainly in the highlands and western lowlands of the country (Fig. 9). As different researchers reported, reanalysis products showed large biases in regions where there were few observation inputs for the model forecast and data assimilation (Sahlu et al., 2017; Gleixner et al., 2020).

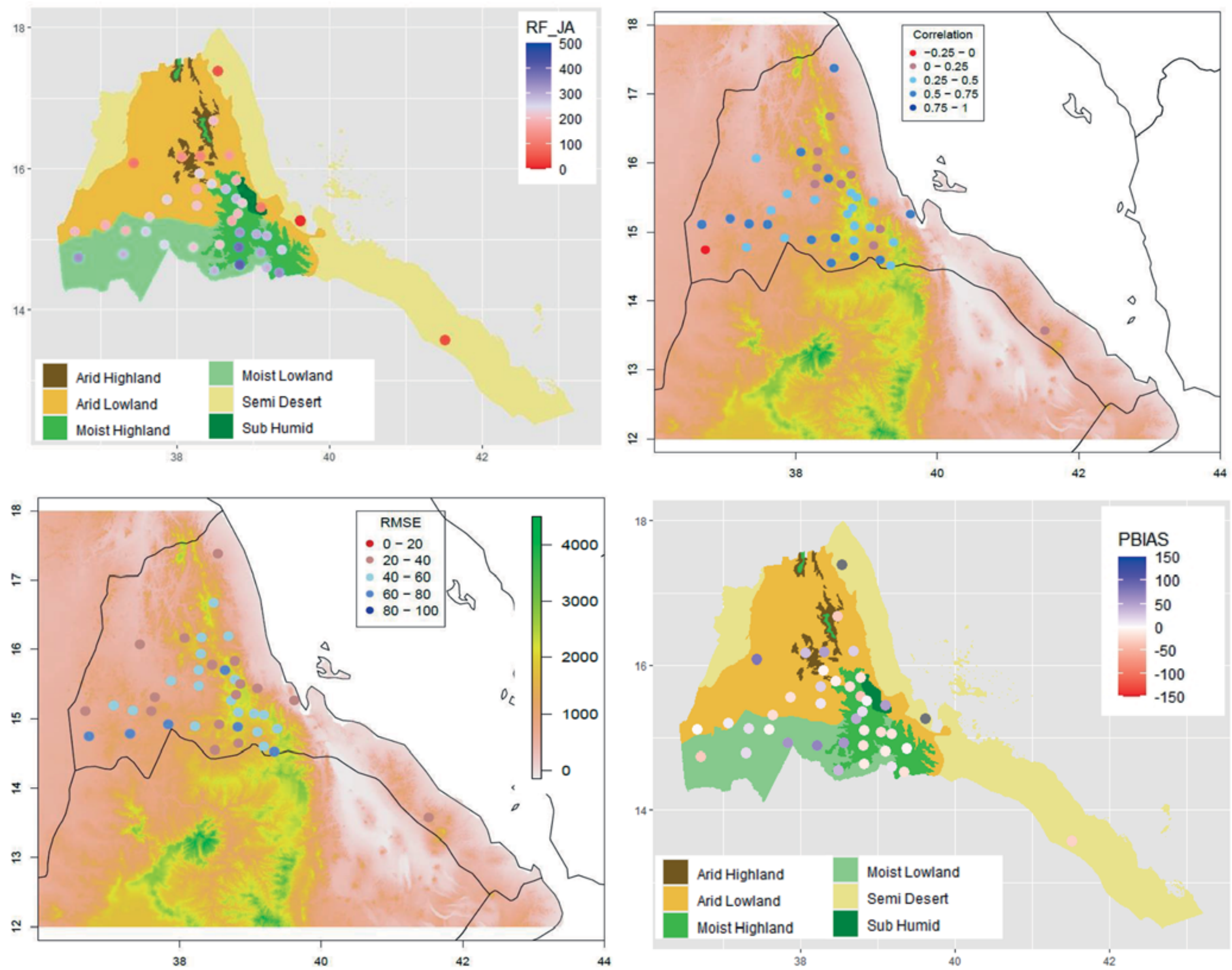

Figure 7: Pairwise statistical analysis between observed and GPM data for the summer season (1992–2018).

In East Africa, the evaluation of ERA5 and its predecessor ERA-interim indicated that the seasonality of precipitation was well captured, but temporal and spatial correlation with observations were low (Diro et al., 2009; Gleixner et al., 2020). It was reported that ERA5 has greatly improved in comparison to its predecessor (Gleixner et al., 2020); however, ERA5-Land still shows underestimation and needs further improvement to represent Eritrean precipitation.

Overall, GPM could primarily be considered as an alternative rainfall data source for the summer and spring seasons over Eritrea, relative to CHIRPS and ERA5-Land. Recently, similar results have been reported in Iran that indicate GPM outperforms CHIRPS and ERA5 in capturing the spatial distribution of precipitation and meteorological drought events across the country (Kiany et al., 2021).

Finally, it is important to look back and assess how rainfall products agree with Flohn's (1963) observation that the highlands of Eritrea receive more than 90 per cent of the annual rainfall in the summer period, while in the east, winter rains yield about 90 per cent of the annual precipitation. In the study period, the station summer rainfall in the highlands account for 72 % of the annual rainfall (Fig. 5). However, the rainfall products – CHIRPS (67 %), GPM (66 %) and ER5-Land (61 %) – all show lower percentages of summer rainfall. In contrast, the eastern winter (DJF) rainfall from station records covers 30 % of the annual rainfall, which is not in agreement with Flohn's observation. Similarly, GPM (30 %) and ER5-Land (49 %) reproduced the winter rainfall relatively consistently with the observed rainfall. However, CHIRPS highly underestimated the percentage of the winter rainfall (8 %) because the eastern winter rains are from "warm" clouds (Dinku et al., 2018).

4 Conclusions and recommendations

The evaluation of the satellite-based (CHIRPS and GPM) and reanalysis (ERA5-Land) products in Eritrea demonstrates that their performance varies over the different agroecological zones, topography and seasons. Overall, the interannual precipitation variability

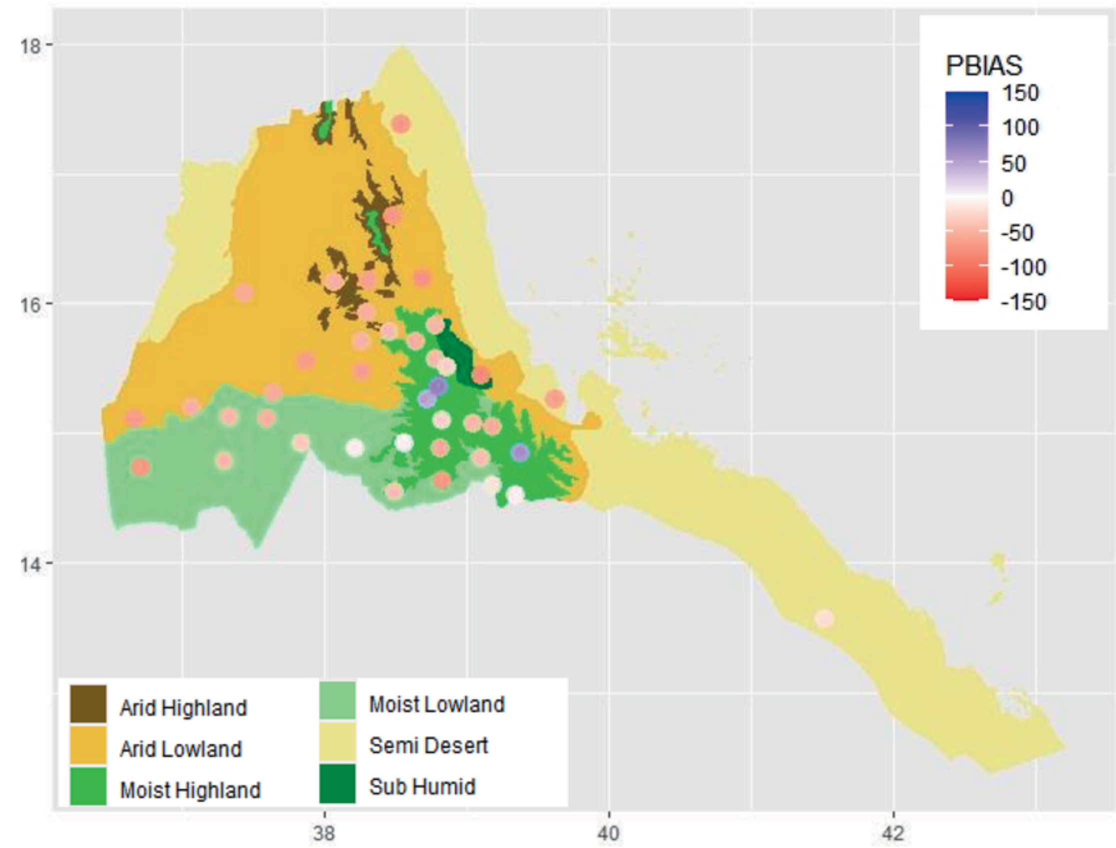

Figure 8: Percentage bias between observed rainfall and ERA5-Land estimates for the summer season (Jul–Aug) during the study period (1992–2018).

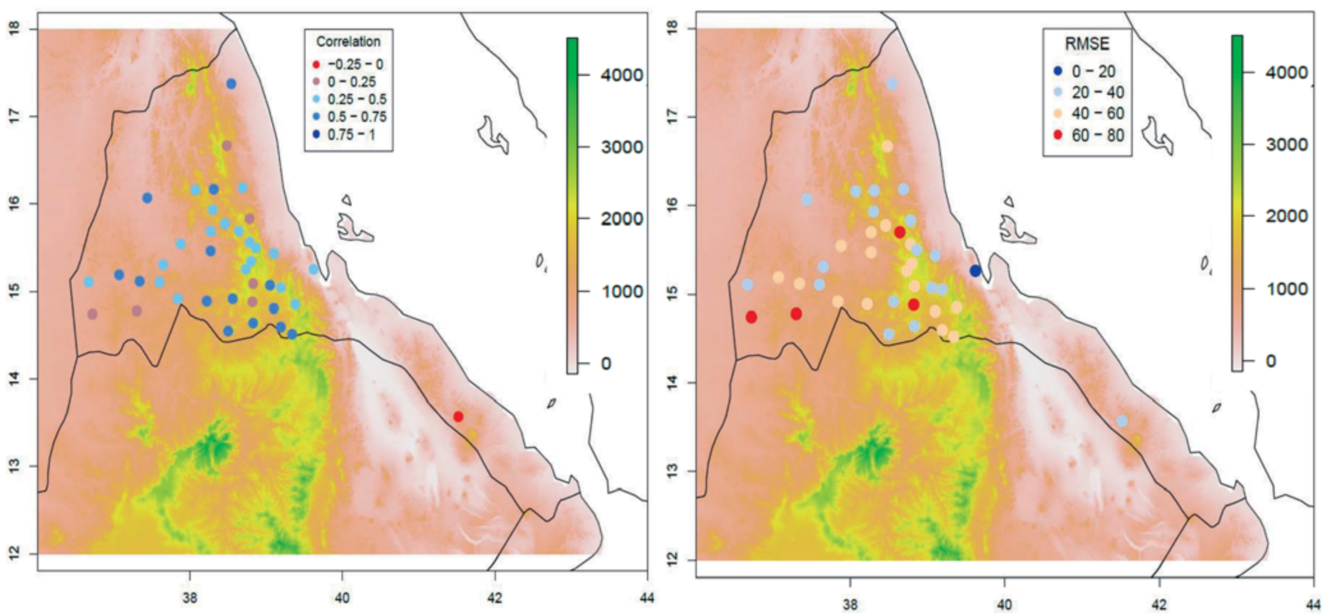

Figure 9: Pairwise correlation analysis between observed rainfall and ERA5-Land estimates for summer season (Jul–Aug) during the study period (1992–2018).

across the country and its seasonality is captured by all the satellite-based (CHIRPS and GPM) and reanalysis (ERA5-Land) rainfall products. CHIRPS primarily demonstrates better estimates over the areas where the rainfall is convective in nature. However, no significant correlations were found over the region with rainfall from “warm” clouds. This is mainly because convective clouds have long-duration cold cloud-top temperatures within the threshold of the satellite algorithm but not “warm” clouds.

The performance of GPM does not seem to be influenced by the elevation, amount, and nature of rainfall (convective or orographic). Overall, GPM performed well in all zones of the country, except for the arid highlands during the summer season. However, the correlation of GPM with station rainfall is not statistically significant in the semi-desert and sub-humid regions during the winter period (DJF). ERA5-Land highly underestimates the summer and spring rainfalls in all parts of the country.

In summary, GPM can primarily be considered as an alternative rainfall data source for the summer and spring seasons across the country. CHIRPS should mainly be used as a potential data source for the areas identified with convective rainfall during the summer and spring seasons. In due course, it is recommended to assimilate Eritrea’s existing observed rainfall data with the CHIRPS and ERA5-Land products, so that they could provide accurate, long-term, and high-resolution rainfall data across the country.

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