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Evaluation of satellite rainfall estimates over Ethiopian river basins

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Abstract

The objective of this study was to evaluate the accuracy of high resolution satellite-based rainfall estimates (SREs) across six river basins within Ethiopia during the major (Kiremt) and minor (Belg) rainy seasons for the years 2003 to 2007. The six regions, the Awash, Baro Akobo, Blue Nile, Genale Dawa, Rift Valley and Wabi Shebele River Basins surround the Ethiopian Highlands, which produces different topographical features, as well as spatial and temporal rainfall patterns. Precipitation estimates for the six regions were taken from three widely used high resolution SREs: the Climate Prediction Center morphing method (CMORPH), Precipitation Estimation from Remotely Sensed Information Using Neural Networks (PERSIANN) and the real-time version of the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B42RT. All three SREs show the natural northwest-southeast precipitation gradient, but exhibit different spatial (mean annual total and number of rainy days) and temporal (monthly) totals. When compared to ground based rain gauges throughout the six regions, and for the years of interest, the performance of the three SREs were found to be season independent. The results varied for lower elevations, with CMORPH and TMPA 3B42RT performing better than PERSIANN in the southeast, while PERSIANN provided more accurate results in the northwest. At higher elevations, PERSIANN consistently underestimated while the performance of CMORPH and TMPA 3B42RT varied.

1 Introduction

High resolution satellite-based rainfall estimates (SREs) provide an alternative source of rainfall data for hydrological applications especially in developing countries, where conventional rain gauges are sparse. The near-real-time availability of the SREs makes them suitable for water resource management applications, however, an over or underestimation in the actual rainfall amount could lead to analysis results that give a false sense of security or a higher false alarm rate.

Given that satellite rainfall estimates are contaminated by sources such as temporal sampling, instrument and algorithm error (Gebremichael et al., 2005), it is important to assess the accuracy of these estimates. Table 1 summarizes recent studies on evaluations of three widely used SREs: Climate Prediction Center morphing method (CMORPH), Precipitation Estimation from Remotely Sensed Information Using Neural Networks (PERSIANN) and Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B42.

The results of these studies indicate that the SREs performance varies with season, region and elevation. For instance, within the United States, Gottschalck et al. (2005) evaluated the performace of PERSIANN and TMPA 3B42RT over the Continental United States (CONUS) and found the performance to be influenced by seasonal precipitation patterns. Their study found that both SREs overestimated precipitation over the central CONUS and mountain west during the spring and summer. However, during the fall and winter months PERSIANN underestimated precipitation in the mountain west and TMPA 3B42RT overestimated. Tian et al. (2007) furthered the work of Gottschalck et al. (2005) by evaluating CMORPH over the CONUS and found that there was an underestimation over the northeast during the summer months, but a severe overestimation over the central CONUS and mountain west during the summer and spring months. Zeweldi et al. (2008) evaluated CMORPH over Oklahoma and found there to be a positive bias during the summer months, but a negative bias during the winter months.

The effect that topography has on the performance of SREs in particular is evidenced by several studies within Table 1. Hong et al. (2007) evaluated the impact that topography might have on the performance of PERSIANN-CCS within the Sierra Madre Occidental (SMO) in western Mexico and found that the bias was affected by the topography. Their study showed that light precipitation events were underestimated in the high elevations and that precipitation in the lower elevation were overestimated. Hirpa et al. (2009) performed an evaluation of CMORPH, PERSIANN and TMPA 3B42RT within the Awash River Basin of Ethiopia and found elevation-dependent trends, with underestimation at higher elevation for CMORPH and TMPA 3B42RT. Bitew et al. (2009) evaluated the performance of CMORPH and PERSIANN-CCS in a small high elevation region of the Ethiopia Highlands and found that both underestimated total rainfall; CMORPH by 32% and PERSIANN-CCS by 49%.

The summarized results of Table 1 bring to light the idea that evaluation studies of SREs must be region specific, and as indicated by Hong et al. (2007) and Hirpa et al. (2009), must take into consideration the elevation in addition to the specific region.

This study aims to evaluate the accuracy of three widely used SREs evaluated in Table 1 across Ethiopia (CMORPH, PERSIANN and TMPA 3B42RT), focusing on smaller regions (river basins). The SREs are compared to ground based rain gauges, which are not without error. This is especially true in mountainous regions, where the challenge for ground based rain gauges is that they are often difficult to physically locate or routinely maintain, making their distribution sparse. To address the spatial representativeness, and random errors, inherent in rain gauge data, the methodology consists of comparing the SREs to rain gauge data on long term averages. This study will perform an intercomparison of the spatial and seasonal patterns of the SREs, a comparison of the spatial pattern of the SREs bias, as well as evaluate the dependence on the bias in the SREs on elevation.

2 Study region and data

2.1 Study region

The Great Rift Valley highlights the complex topography found within Ethiopia (Fig. 1) and splits the center of the country in the northeast and southwest direction by the divergence of tectonic plates. This prominent feature produces the Ethiopian Highlands, which are found on either side of the Great Rift Valley; the highest elevation along these highlands is in excess of 4200 m. The topography on the southeast side of the highlands descends and levels off towards the border between Somalia and Ethiopia. The most mountainous terrain is found to the northwest of the Great Rift Valley and is highlighted by the Blue Nile River.

Figure 1 shows the ground based rain gauges that were available for conducting this study along with the six study regions. The Awash, Baro Akobo, Blue Nile, Genale Dawa, Rift Valley and Wabi Shebele River Basins were chosen based on a threshold of at least 10 rain gauges per river basin, and provides six unique study regions in terms of topography, seasonal precipitation and climate. Table 2 provides drainage area (from Awulachew et al., 2007), the approximate elevation range for the river basin, as well as the elevation range for the rain gauges within the given river basin.

The following is a short discussion focused on Table 2:

- The Awash River Basin, which starts in the highlands of Central Ethiopia, follows the Great Rift Valley towards the northeast. Although this river basin falls fourth on the list in drainage area at approximately 112 696 km^2, Awulachew et al. (2007) reported that the Awash River is considered the most utilized river in Ethiopia. The range of elevation for the rain gauges covers approximately 47% of the total elevation range.

- The Baro Akobo River Basin is the second smallest river basin assessed by this paper with a drainage area of approximately 76 203 km^2. The river basin, located in western Ethiopia, has an elevation ranging from approximately 400 m to 3220 m; the rain gauges used by this study fall within the middle third of the total elevation range. The Ethiopian Highlands are found on the eastern edge of the river basin, with lower lands situated to the west.

- The Blue Nile River Basin is found within the most mountainous region of Ethiopia – the Ethiopian Highlands. Awulachew et al. (2007) identified the Blue Nile River Basin as the most important river basin in Ethiopia, with a significant contribution to land area, total annual rainfall, population and agricultural production. The

199 812 km^2 river basin is the second largest river basin assessed in this study and has elevation ranging from approximately 480 m to 4250 m; the rain gauges cover approximately 57% of the total elevation range.

- The Genale Dawa and Wabi Shebele River Basin, found in south and south eastern Ethiopia, rank as the third largest (171 042 km^2) and the largest (202 697 km^2) river basins in this assessment. The two river basins have similar topography, with their highest elevations (4375 m and 4240 m, respectively) found along the eastern boundary of the Great Rift Valley in the north west corner of each river basin. The topography gently decreases moving to the south east and reaches the lowest elevations of 160 m and 175 m, respectively. The rain gauges cover approximately 41% of the total elevation range for the Genale Dawa River Basin and approximately 65% of the total elevation range for Wabi Shebele.
- The Rift Valley River Basin, located in the southern region of Ethiopia, is the smallest river basin in this assessment at 52 739 km^2. This river basin, which has numerous lakes, has elevation ranging from approximately 455 m to 4175 m. The rain gauges available for use cover approximately 25% of the total elevation range.

2.2 Climate

Ethiopia has three distinct seasons, each with differing precipitation totals. The Belg, approximately defined by March to the end of May, is considered the minor rainy season for most of the river basins, and is generated by weather systems that originate over the Indian Ocean (Seleshi et al., 2004). The Kiremt, approximately defined by June to the end of September, is considered the major rainy season. The seasonal oscillation of the Intertropical Convergence Zone (ITCZ) is the predominant mechanism for the rainfall during the Kiremt (Seleshi et al., 2004; Segele et al., 2008). The Bega is the dry season and is approximately defined by October through the end of February. This season was excluded from the analysis because of the overall low contribution to the mean annual precipitation.

Table 3 provides the mean annual precipitation for each of the river basins, along with the seasonal contribution delivered by the Belg and the Kiremt. The two western river basins, Baro Akobo and Blue Nile, receive the highest precipitation totals at 1465 mm and 1305 mm, respectively. The Kiremt contributes more than half of the annual precipitation to the Baro Akobo River Basin, and 75% to the Blue Nile River Basin.

Genale Dawa and Wabi Shebele River Basins, found in the south east, receive the lowest precipitation totals of the six river basins assessed. Unlike the two aforementioned river basins, these two receive more than half of their precipitation during the Belg. The Kiremt provides the least amount of precipitation for Genale Dawa, where as Wabi Shebele receives the least amount during the Bega.

The Awash and Rift Valley River Basins fall in the middle, when ranking the mean annual precipitation, with 585 mm and 650 mm, respectively. The Kiremt delivers two-thirds of the precipitation to the Awash River Basin and the Belg delivers almost half of the annual precipitation to the Rift Valley River Basin.

2.3 Rain gauge data

Rain gauge data, provided by the Ethiopian Meteorological Agency, was available for 118 stations throughout Ethiopia. More than 75% of the rain gauges in any one basin are defined as a principle (or first class) rain gauge, which is one that has "observations taken by trained observers" (Dinku et al., 2008).

The temporal resolution of the provided rain gauge data was monthly and in assessing the rain gauges with recorded data between 2003 and 2007 it became apparent that there were missing months. More than 70% of the data was available during the 2003 to 2007 Belg for the 8 basins evaluated; only Genale Dawa and Awash had less than 70% of the data (69% and 68%, respectively) for the Kiremt. There was no attempt to fill in the missing data points, and if monthly data for a specific year was missing then it, along with the corresponding satellite data, was excluded from the study. The approach chosen was to assess the data using a five-year average, thereby minimizing the random errors in the data, making a qualitative assessment of the results possible (Hirpa, et al., 2009).

Figure 1 shows that the location of the gauges provided varied spatial representation of the individual river basins. This is evident by comparing the distribution (and number of) gauges within each of the river basins. The Blue Nile, for example, is the most data rich of the river basins evaluated with 37 rain gauges scattered throughout the river basin that cover an elevation range of 2138 m. The maximum elevation difference between any given rain gauge station within this river basin is 192 m, with an average elevation difference of 63 m. The 16 rain gauges within the Awash River Basin cover an elevation of 1 978 m. In stark contrast, the 11 rain gauges within the Baro Akobo River Basin cover an elevation range of only 850 m, or only 30% of the total elevation range.

It is acknowledged here that rain gauges are merely point measurements and it is desired to have a densely populated network in order to compare them with satellite estimates. Although several of the river basins contain a network of rain gauges that represent a large majority of the elevation range within the given river basin, there is typically only one rain gauge within a given 0.25° by 0.25° pixel for comparison with satellite data. However, by averaging the rain gauge observations over a five-year period, we have minimized the spatial representative error in the rain gauge estimates.

2.4 Satellite data

The three high resolution satellite products evaluated in this paper estimate precipitation at the same spatial (0.25° by 0.25°) and temporal (3-hourly) resolution, but achieve the estimates using different means. The morphing method, developed by the Climate Prediction Center (CPC), estimates precipitation using only microwave (MW) data, however, due to the limited space-time resolution and the desire to generate data at a temporal resolution of 3-h, gaps in the MW data need to be estimated. In order to fill the gaps in the MW data, infrared (IR) data is used to generate motion vectors for which time weighted averages of the MW data are generated (Joyce et al., 2004). Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) was developed by the University of Arizona in 1997 to estimate rainfall by using IR data as input to artificial neural networks (ANNs), and when available, ground based data to update the ANNs (Hsu et al., 1997). The Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B42 Real Time (RT) product produces precipitation estimates by converting data from the TRMM Microwave Imager (TMI), Special Sensor Microwave/Sensor (SSM/I) and the real time data from the Advanced Microwave Scanning Radiometer for the Earth Orbiting System (AMSR-E) using the Goddard Profiling Algorithm. In order to provide 3-hourly precipitation estimates, IR data is used to fill in the gaps left by the MW data. Calibration is performed using the TMI sensor (Huffman et al., 2007).

3 Results and discussion

3.1 Spatial precipitation patterns

Figure 2 shows the spatial patterns of annual mean (2003–2007) rainfall and number of rainy days for Ethiopia, according to each SRE. As indicated in Fig. 2a–c, the three SREs show the large natural northwest-southeast rainfall gradient in the region. TMPA 3B42RT and CMORPH exhibit similar spatial patterns of mean annual rainfall (correlation of 0.995), while PERSIANN exhibits slightly different spatial pattern compared to the other SREs (correlation of 0.912). TMPA 3B42RT and CMORPH exhibit similar spatial mean values, whereas PERSIANN underestimates especially in the mountainous northwest region compared to the other SREs.

As indicated in Fig. 2d–f, the three SREs show the northwest-southeast gradient in the number of rainy days in the region. TMPA 3B42RT and CMORPH exhibit similar spatial pattern in the number of rainy days (correlation of 0.999), while

PERSIANN exhibits slightly different spatial pattern compared to the other SREs (correlation of 0.936). PERSIANN gives slightly lower number of rainy days in the mountainous northwest region compared to the other SREs.

3.2 Seasonal rainfall patterns

Figure 3 presents basin-averaged monthly mean (2003–2007) rainfall for each river basin considered in this study, as derived from SREs. The river basins show large variations in their seasonal rainfall patterns and total rainfall amounts. The Blue Nile River basin, located in the northwest, receives large amounts of rainfall (mean annual rainfall = 1370 mm from CMORPH, 911 mm from PERSIANN, 1630 mm from TMPA 3B42RT), with the vast majority (74% to 78%) falling in the Kiremt season (June–September), peaking in July and August. The Baro Akobo River basin, located in the west, also receives large amounts of rainfall (mean annual rainfall = 1578 mm from CMORPH, 1059 mm from PERSIANN, 1762 mm from TMPA 3B42RT) spread over most of the months, with Kiremt contributing half of the total rainfall. The Rify Valley River basin, located in southwest, receives moderate amount of rainfall (mean annual rainfall = 706 mm from CMORPH, 437 mm from PERSIANN, 806 mm from TMPA 3B42RT), with more rain falling in the Belg season (March–May) and the rest evenly distributed across the rest of the months. The Awash River basin, located in the northeast, receives also moderate amount of rainfall (mean annual rainfall = 592 mm from CMORPH, 439 mm from PERSIANN, 717 mm from TMPA 3B42RT), with the vast majority falling in Kiremt (~65%) followed by Belg (~28%). The Wabi Shebele and Genale Dawa River basins receive the smallest rainfall amounts, with the majority falling in the Belg season. For all the six river basins considered, the three SREs exhibit similar shapes of seasonal rainfall pattern, however, TMPA 3B42RT monthly rainfall estimates are consistently higher than CMORPH, which are consistently higher than PERSIANN.

3.3 Spatial pattern of bias ratio

Figure 4 presents the spatial pattern of the mean annual bias ratio (2003–2007) for the three SREs with the bias ratio presented for each of the 0.25° by 0.25° grid cells that contain a rain gauge. CMORPH and TMPA 3B42RT exhibit similar spatial patterns (correlation of 0.978), while PERSIANN exhibits a slightly different pattern (correlation of 0.895 and 0.878, respectively). CMORPH, with a country averaged bias ratio of 0.89, performs better in the northwest portion of the country (0.75 to 1.25), with a tendency to underestimate in the central and southeast (0.50 to 1.00). TMPA 3B42RT has a country averaged bias ratio closer to the ground truth (1.05) but a higher standard deviation when compared to the other SREs. There is a slight overestimation in the northwest (1.00 to 1.25) and a slight underestimation towards the southeast (0.75 to 1.00). PERSIANN exhibits severe underestimation, with a country averaged bias ratio of 0.57. The highest degree of underestimation is found throughout the central part of the country. Similar to the other SREs, PERSIANNs best performance is found towards the northwest.

3.4 Dependence of bias ratio in SREs on elevation

Here, we quantify the bias in the SREs as a function of elevation in the six river basins. Our procedure consists of the following steps. First, we calculated the five-year seasonal mean rainfall at each rain gauge station based on the rain gauge data. Second, we extracted the 0.25° by 0.25° SRE grid cells that contain rain gauges, and calculated the five-year seasonal mean rainfall at each grid cell based on the corresponding SRE data. Third, we calculated the bias in the SREs at each grid cell through the Bias ratio statistic, which is defined as the seasonal mean rainfall of SRE divided by the corresponding seasonal mean rainfall of rain gauge data. A bias ratio greater than one indicates overestimation by SRE, a bias ratio less than one indicates underestimation by SRE, and a bias ratio of one indicates no bias in the SRE. Fourth, we examine the relationship between the Bias ratio at each grid cell and the elevation of the grid cell, for different river basins and two rainy seasons.

Figure 5 displays the bias ratio of SREs as a function of elevation for the main rainy season (Kiremt), for each river basin. Also shown are the fitted lines with their slopes and correlation (*R*) measuring the strength of the fitted lines. The dependence of the Bias ratio of SREs on elevation depends on the river basin. In regions that are dominated by complex topography, and large differences in elevation (Blue Nile and Awash), the Bias ratio of SREs decreases as elevation increases. PERSIANN gives more accurate estimates at lower elevations, while CMORPH and TMPA 3B42RT overestimate. At higher elevations, PERSIANN underestimates rainfall while CMORPH and TMPA 3B42RT give more accurate estimates. In the river basins dominate with less complex topography (Rift Valley and Baro Akobo River basins) elevation does not have a pronounced impact on the Bias ratio of SREs.

In general, at elevations exceeding 1500 m, PERSIANN tends to underestimate in all river basins, while CMORPH and TMPA 3B42RT outperform PERSIANN. Hirpa et al. (2009) came to a similar conclusion for the Awash River Basin alone, and Dinku et al. (2009) found a slight overestimation for CMORPH (bias of 1.11) and TMPA 3B42RT (bias of 1.13) in their assessment for a region of the Ethiopia Highlands that was in excess of 1500 m. At elevations lower than 1500 m, there is a large variation in the performance of the SREs; for example, PERSIANN outperforms CMORPH and TMPA 3B42RT in the Blue Nile River basin, but CMORPH and TMPA 3B42RT outperform PERSIANN in the Genale Dawa River basin for a similar elevation range. Similar results are obtained for the Belg season (see Fig. 6).

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4 Conclusions

The characteristics of precipitation (mean annual total and number of rainy days) as provided by three high resolution SREs has been presented, along with temporal patterns, for six regions that surround the Ethiopian Highlands so as to identify spatial and temporal similarities and differences. The goal was to obtain a better understanding of how these SREs, CMORPH, PERSIANN and TMPA 3B42RT, performed when compared to ground based rain gauges in mountainous regions.

This study has found that all three products capture the varied spatial precipitation pattern over the mountainous northwest, and the homogeneous mean annual precipitation and rainy days in the lower elevation of the southeast. The two MW products (CMORPH and TMPA 3B42RT), are well correlated in both spatial mean annual precipitation and rainy days, with the only IR product (PERSIANN), showing a decrease in correlation coefficient when compared to the two MW products. When comparing the spatial pattern of the two MW products, TMPA 3B42RT records a greater mean annual total; the number of rainy days recorded are nearly identical. Comparing the results of the three SREs to the rain gauges spatially, we found that MW products exhibited similar spatial patterns of the Bias ratio, with each performing better in the northwest, while the IR product underestimated over nearly the entire country.

The three products, regardless of the estimation technique (MW or IR), capture the temporal patterns reported by studies such as Seleshi et al. (2004), with TMPA 3B42RT consistently reporting higher monthly totals than CMORPH, and CMORPH reporting higher monthly totals when compared to PERSIANN.

In our assessment we found that both the MW and IR products were season independent in their performance with respect to elevation, with similar results reported for both the Kiremt and the Belg within each of the six river basins. When the long-term averages of the three SREs were compared to those of the ground based rain gauges, we found that in general PERSIANN has a tendency to underestimate the seasonal precipitation at higher elevations (greater than 1500 m). At lower elevations (less than

1500 m) there was a large variation in the performance – PERSIANN provided more accurate seasonal totals in the three river basins to the northwest (Awash, Blue Nile and Baro Akobo), while CMORPH and TMPA 3B42RT provided more accurate seasonal totals in the river basins to the southeast.

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Table 1. Evaluations on high resolution satellite product.

Rainfall product Evaluated	Region	Main results	Reference
CMORPH TMPA 3B42RT TMPA 3B42	Western Highlands Ethiopia, Africa	Occurrence of rain underestimated by all products Total amount underestimated by TMPA 3B42 (14%); overestimated by TMPA 3B42RT (13%) and CMORPH (11%)	Dinku et al. (2010)
CMORPH TMPA 3B42RT TMPA 3B42	Highlands, Columbia, South America	Occurrence of rain underestimated by all products Total amount underestimated by all products; TMPA 3B42RT (17%), TMPA 3B42 (16%) and CMORPH (9%)	Dinku et al. (2010)
CMORPH PERSIANN-CCS	Berressa Watershed, Ethiopia, Africa	Both underestimate heavy rainfall by 50% Both underestimate total rainfall; CMORPH (32%), PERSIANN-CCS (49%)	Bitew et al. (2009)
CMORPH PERSIANN TMPA 3B42RT	Great Rift Valley, Ethiopia, Africa	TMPA 3B42RT and CMORPH show elevation-dependent trends, with underestimation at higher elevations PERSIANN significantly underestimates at higher elevations. Does not exhibit elevation-dependent trends	Hirpa et al. (2009)
TMPA 3B42 V.6 CMORPH	Mainland China, Asia	Overestimate rainfall less than 1 mm/day Underestimate rainfall greater than 1 mm/day.	Yu et al. (2009)
CMORPH	Oklahoma, United States, North America	Positively biased in summer, negatively biased in winter	Zeweldi et al. (2008)
CMORPH PERSIANN TRMM 3B42	Sierra Madre Occidental, Northwest Mexico, North America	CMORPH and PERSIANN overestimate the precipitation rate and frequency. TRMM 3B42 closely agrees with the rain gauge network.	Nesbitt et al. (2008)
TMPA 3B42 V.6	La Plata Basin, South America	Overestimation by 3%–13% for all sub basins assessed, except one, which underestimated by 1%.	Su et al. (2008)
PERSIANN-CCS	Sierra Madre Occidental, Northwest Mexico, North America	Overestimates precipitation at low elevations, underestimates light precipitation at higher elevations; exhibits elevation-dependant bias	Hong et al. (2007)

Table 1. Continued.

Rainfall product Evaluated	Region	Main results	Reference
CMORPH TMPA 3B42 V6	Continental United States (CONUS), North America	TMPA 3B42 has near zero biases (−1 mm/day to 1 mm/day) for both summer and winter months. CMORPH severely overestimates precipitation over central CONUS; underestimates over the northeast during the summer. Severe underestimation over western and north east during winter months.	Tian et al. (2007)
PERSIANN TMPA 3B42RT	Continental United States (CONUS), North America	PERSIANN overestimate total precipitation over central CONUS and mountain west during spring and summer months. Underestimation over central CONUS and mountain west during fall and winter months. TMPA 3B42RT overestimate total precipitation over central CONUS and mountain west during spring and summer months. Overestimation over mountain west during fall and winter.	Gottschalck et al. (2005)

Table 2. River basin drainage area and topography.

River basin	Drainage Area[1] (km^2)	Range of river basin Elevation (m)		Range of rain gauge Elevation (m)	
		Min	Max	Min	Max
Awash	112 696	0	4175	376	2354
Baro Akobo	75 912	400	3220	1460	2310
Blue Nile	199 812	480	4250	902	3040
Genale Dawa	171 042	160	4375	1066	2840
Rift Valley	52 739	455	4175	1260	2480
Wabi Shebele	202 697	175	4240	295	2940

[1] Drainage area from Awulachew et al. (2007).

Table 3. River basin precipitation characteristics.

River basin	Number of rain gauges	Mean annual precipitation[2] (mm)	Seasonal contribution[2]	
			Belg	Kiremt
Awash	16	585	28%	66%
Baro Akobo	11	1465	29%	52%
Blue Nile	37	1305	16%	75%
Genale Dawa	11	340	56%	12%
Rift Valley	12	650	47%	29%
Wabi Shebele	13	365	51%	31%

[2] Average of CMORPH, PERSIANN and TMPA 3B42RT estimates.

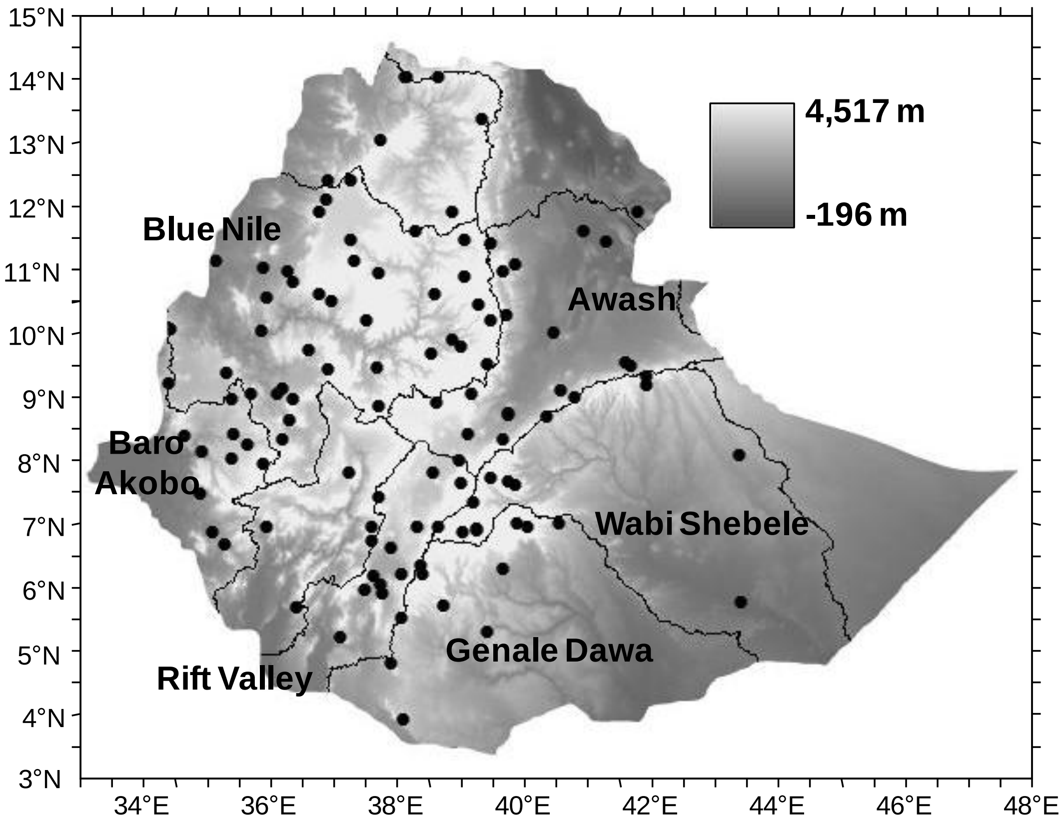


Fig. 1. Six river basins of Ethiopia evaluated and associated rain gauges.

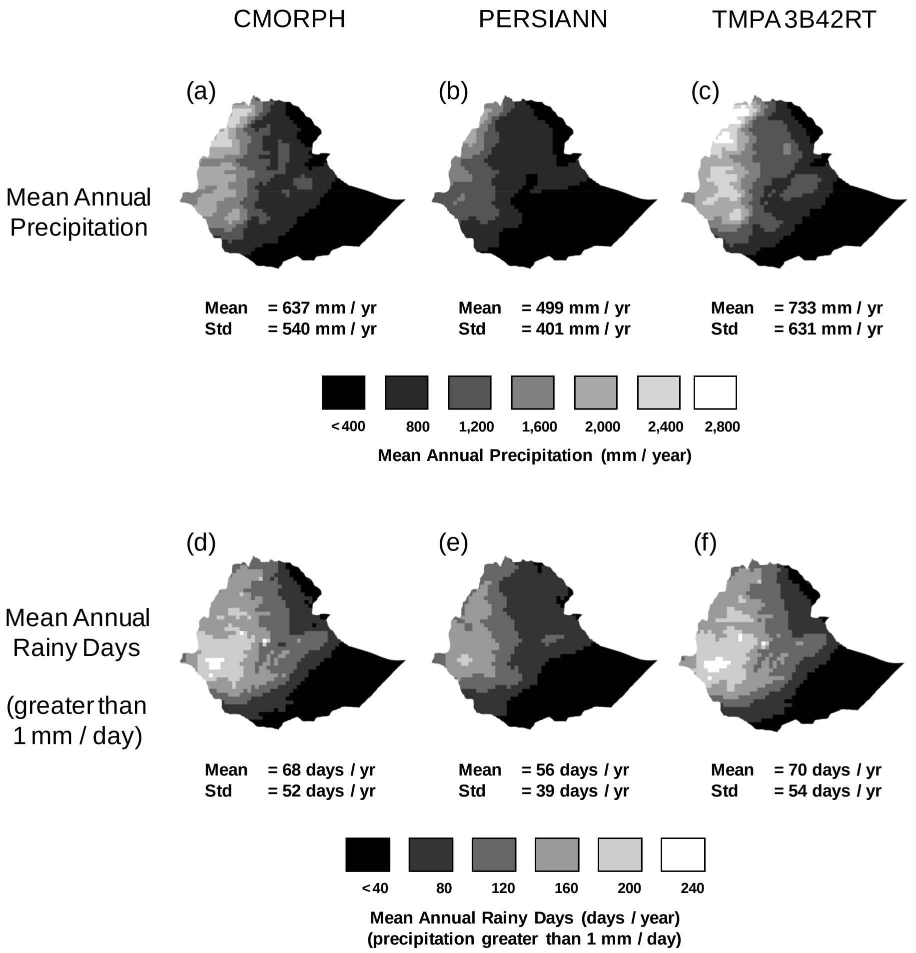
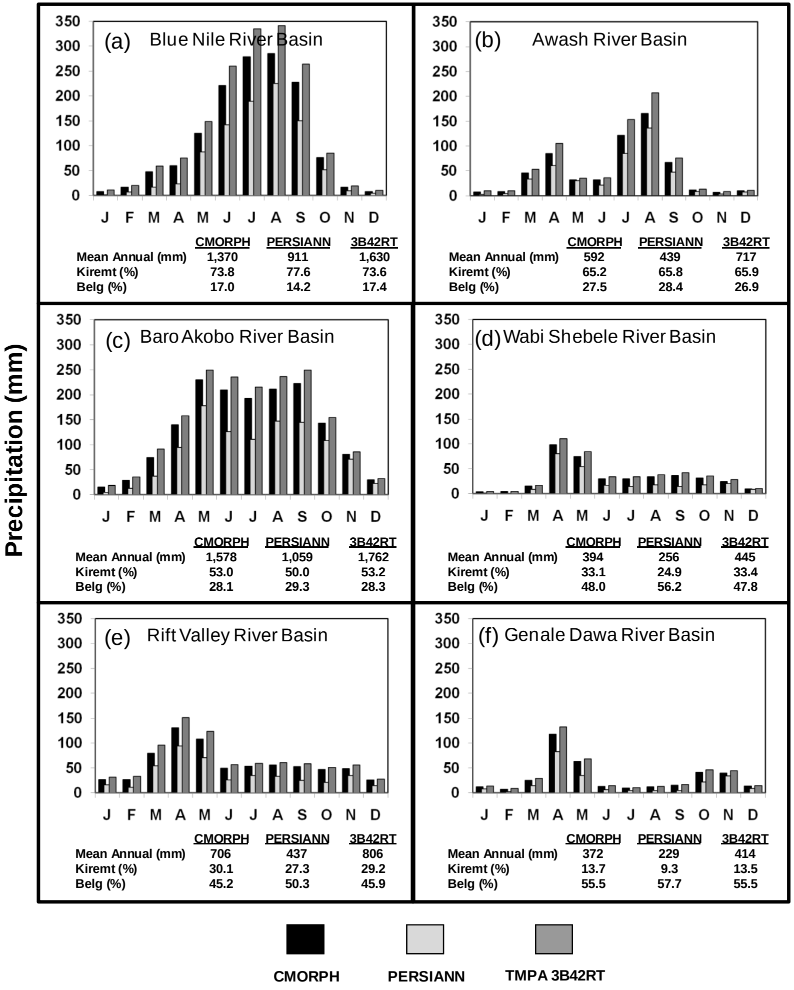


Fig. 2. (a–c) Mean annual precipitation (mm/year), **(d–f)** mean annual rainy days (precipitation greater than 1 mm/day).



(a) Blue Nile River Basin

	CMORPH	PERSIANN	3B42RT
Mean Annual (mm)	1,370	911	1,630
Kiremt (%)	73.8	77.6	73.6
Belg (%)	17.0	14.2	17.4

(b) Awash River Basin

	CMORPH	PERSIANN	3B42RT
Mean Annual (mm)	592	439	717
Kiremt (%)	65.2	65.8	65.9
Belg (%)	27.5	28.4	26.9

(c) Baro Akobo River Basin

	CMORPH	PERSIANN	3B42RT
Mean Annual (mm)	1,578	1,059	1,762
Kiremt (%)	53.0	50.0	53.2
Belg (%)	28.1	29.3	28.3

(d) Wabi Shebele River Basin

	CMORPH	PERSIANN	3B42RT
Mean Annual (mm)	394	256	445
Kiremt (%)	33.1	24.9	33.4
Belg (%)	48.0	56.2	47.8

(e) Rift Valley River Basin

	CMORPH	PERSIANN	3B42RT
Mean Annual (mm)	706	437	806
Kiremt (%)	30.1	27.3	29.2
Belg (%)	45.2	50.3	45.9

(f) Genale Dawa River Basin

	CMORPH	PERSIANN	3B42RT
Mean Annual (mm)	372	229	414
Kiremt (%)	13.7	9.3	13.5
Belg (%)	55.5	57.7	55.5

Fig. 3. Temporal precipitation pattern, 5 year monthly average (2003–2007).

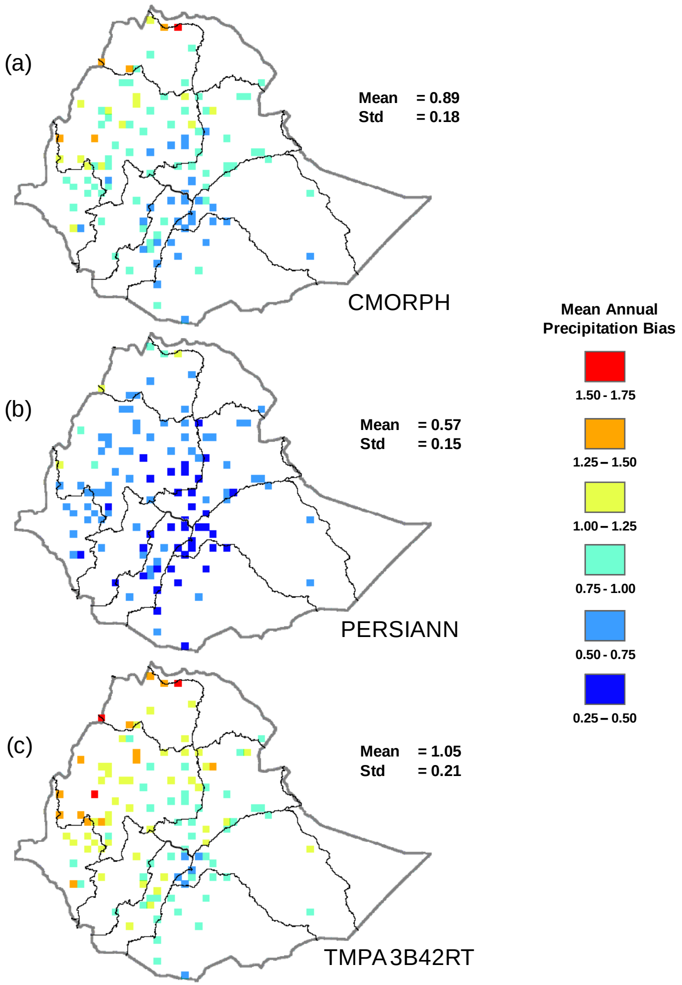


Fig. 4. Mean annual precipitation bias, 5 year average (2003–2007).

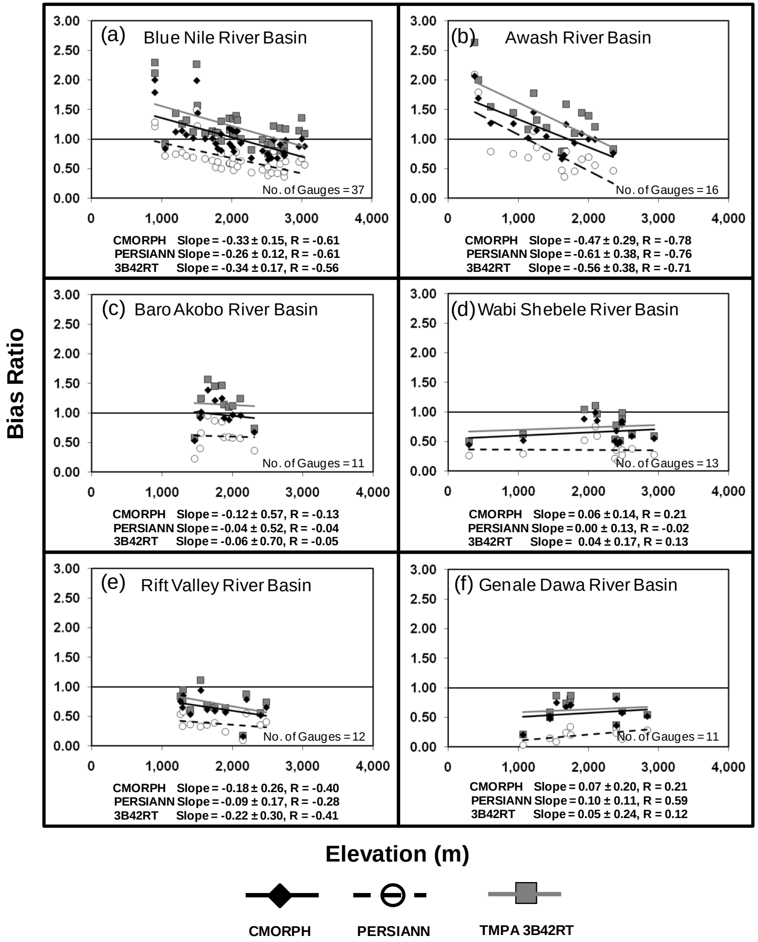


Fig. 5. Bias ratio vs. elevation for the major rainy season (Kiremt). Based on river basins with at least 10 or more rain gauges.

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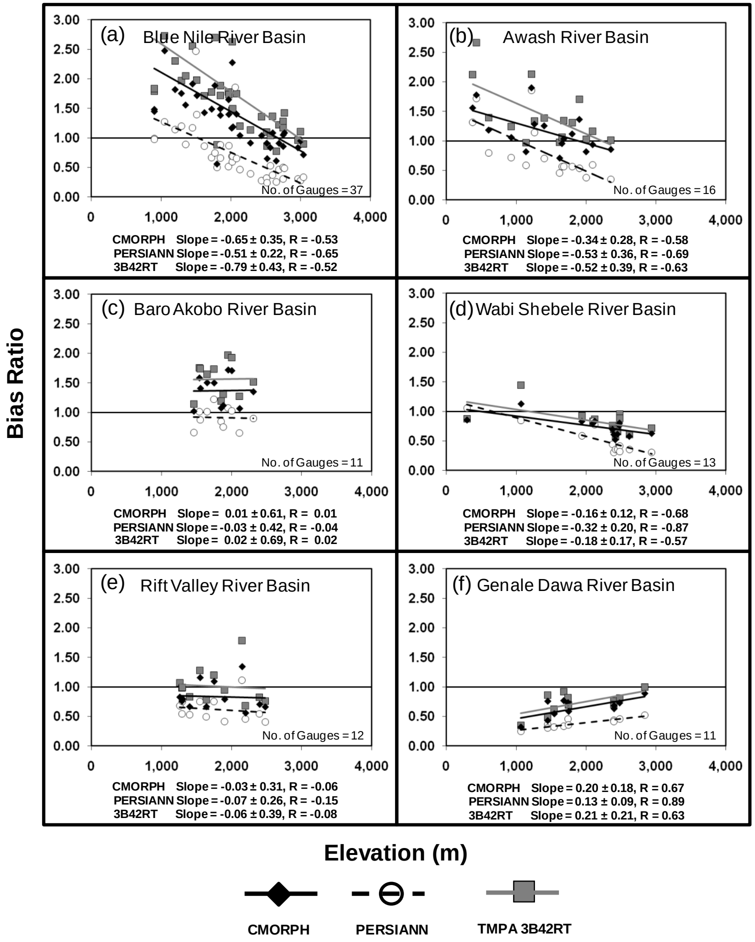

Fig. 6. Bias ratio vs. elevation for the minor rainy season (Belg). Based on river basins with at least 10 or more rain gauges.

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