Interactive comment on "Comparing TRMM 3B42, CFSR and ground-based rainfall estimates as input for hydrological models, in data scarce regions: the Upper Blue Nile Basin, Ethiopia" by A. W. Worqlul et al.

DETAILED RESPONSES TO ANONYMOUS REFEREE #2

We would like to thank the Anonymous Referee #2 for his/her comments. The comments are excellent and helped us to improve the manuscript significantly.

In the rewritten paper, which is attached as part of this review, we have used the comments to our advantage and strengthened our manuscript in order to increase clarity and readability for potential readers. In addition, we have clarified the text over which the reviewers were misinformed. Each of the comments is addressed below. Changes in the original manuscript are highlighted in blue for visibility.

Comment 1 (beginning):

This paper provides a study on the comparison of TRMM 3B42, CFRS and ground-based rainfall estimates over Ethiopia with direct comparison of TRMM and CFRS with gauge observation as well as comparison through hydrologic response to stream flow. As we know, many related research about the evaluation of satellite-based precipitation products have been published. But from the paper, the authors did not mention the recent progress, especially recent literature with dense gauge over Ethiopia. Also, little description about the TRMM product is given, and the cited papers are about the old Version 6 TRMM, not the latest Version 7. In addition, the methodology of comparison is not sound enough.

Response 1 (beginning):

Based on the comment of the reviewer explaining that our literature was outdated, we have included two new subtopics to describe TRMM data more under section 2.3 ***Satellite data*** and we have modified the methodology and the result is included under section 3.2.3. ***Validation of***

CFSR rainfall estimate by gauged rainfall parameters. The comments on this part of the manuscript were extremely helpful and we thank him for his contribution to our paper.

In the introduction part, we have included the following paragraph to include some of the recent researches on page 2084 after line 20.

The performance of TRMM 3B42 version 6 has been evaluated over Iran by Javanmard et al. (2010), over Nzoia River Bain in Kenya by Ouma et al. (2012), over USA by Tian et al. (2007) and over Ethiopia by (Dinku et al., 2007) among others, and the result indicated the importance of TRMM rainfall estimate in rainfall data scares regions. The improved version 7 of TRMM 3B42RT which is near-real time and the research version 3B42 adjusted for monthly gauged rainfall (Chen et al., 2013; Moazami et al., 2014; Xue et al., 2013) has also performed well in capturing the gauged rainfall amounts and pattern. According to Romilly and Gebremichael (2011) the near-real time version 3B42RT has performed well in capturing the five year averaged gauged rainfall in Ethiopia compared to Precipitation Estimation from Remotely Sensed Information Using Neural Networks (PERSIANN) and Climate Prediction Center morphing method (CMORPH) rainfall estimates. Chen et al. (2013) after comparing the real-time and research products with gauged rainfall data in the Mainland China indicated that, the research version 3B42 has much better performance than the real-time product 3B42RT.

Inserted on page 2087 before line 1:

2.3. Satellite data

The two satellite rainfall estimates used in this study are TRMM product 3B42 version 7 and CFSR. The TRMM-3B42 estimates are produced in four steps (Dinku et al., 2010; Huffman et al., 2007): (i) the PM estimates are adjusted and combined, (ii) TIR precipitation estimates are created using the PM estimates for calibration, (iii) PM and TIR estimates are combined, and (iv) the data is rescaled to monthly totals where by gauge observations are used indirectly to adjust the satellite product (Huffman et al., 2007). The near-real time version 3B42RT is produced at the end of the third procedure, this data does not include gauge information (Huffman and Bolvin, 2013; Ouma et al., 2012). The product TRMM 3B42 has been available since 1998 with a spatial resolution of approximately 27 km at the equator and with a temporal resolution of 3 hour. The CFSR was designed and executed as a global, high-resolution coupled atmosphere–ocean–land surface–sea ice system to provide the best estimate of the state of these coupled domains for the study period (Saha et al., 2014). The new feature in CFSR includes: the first reanalysis system in which the guess fields are taken as the 6-h forecast from a coupled atmosphere–ocean climate system with an interactive sea ice component; and it assimilates satellite radiances and humidity values (Wang et al., 2011). The CFSR global atmosphere data has a spatial resolution of approximately 38 km and the data is available from 1979 (Saha et al., 2010).

The methods are modified as follows and the result is included under section 3.2.2 on page 2094 after line 14:

2.4. Methods

The study comprises of two parts, in the first part, the satellite rainfall estimates (TRMM and CFSR) are compared with gauged rainfall data within the satellite grid box. Then a monthly comparison is done using a standard statistics (i.e., coefficient of determination and bias). The areal rainfall of the gauged data and satellite grids are estimate by using inverse distance interpolation. Next, the high-resolution satellite rainfall products (CFSR and TRMM) and gauged rainfall daily data are used as an input to two watershed models HBV-IHMS and PED for daily stream flow simulation in the Gilgel Abay and Main Beles basins. The model parameters are used to fit the observed flow through model calibration. The model calibration period ranges from 1994 to 2003 and the model is validated from 2004 to 2006 for gauged rainfall, CFSR and TRMM data. The performance of the calibrated model is evaluated by the Nash-Sutcliffe Coefficient (NSE), percent bias (PBIAS), and coefficient of determination (R^2). In addition, the calibrated and validated model parameter sets of the gauged rainfall are used to evaluate the performance of CFSR and TRMM rainfall estimate in capturing the observed flow. The hydrological models HBV and PED are described below:

The result of validating the satellite data with the gauged model parameter sets is inserted on page 2095 after line 14:

3.2.3. Validation of CFSR rainfall estimate by gauged rainfall calibrated and validated parameters

The optimized model parameter sets of the gauged rainfall are used to validate the performance of CFSR rainfall estimate by predicting the observed flow of study watersheds. This is achieved by rerunning the calibrated and validated gauged rainfall model by CFSR rainfall estimate, while keeping the optimised gauged rainfall model parameters. The performance of the simulated flow has captured the observed flow pattern with R-square in between 0.6 and 0.74 for both watersheds and both models but there are a larger volume difference between the simulated and observed flow. The NSH value ranges between 0.4 and 0.5 for Gilgel Abay simulated by PED and HBV models, respectively and it ranges between 0.0 and 0.2 when Main Beles is simulated by PED and HBV, respectively. The performance of CFSR data for Gilgel Abay was better than the result of Main Beles, this is associated with the quality of gauged rainfall data in the Gilgel Abay watershed, which lead to a reliable calibrated model parameter sets. Main Beles which has scarce gauged rainfall observations the calibration model parameters seems not quite representative of the watershed and leads to poor performance of CFSR data while simulated with gauged rainfall parameters.

Comment 2

T. G. Romilly and M. Gebremichael published a paper "Evaluation of satellite rainfall estimates over Ethiopian river basins" with much denser gauges network over Ethiopia. In this paper, the TRMM product shows good performance when compared with gauge observations. The authors *did not compare the results in this paper with previous study and explain what/why are the same and different. The results presented in previous study seem more believable than current study. Recent literature: [1] Romilly T G, Gebremichael M. Evaluation of satellite rainfall estimates over Ethiopian river basins [J]. Hydrology and Earth System Sciences Discussions, 2010, 7: 7669-7694. [2] Gebregiorgis A S, Moges S A, Awulachew S B. Basin Regionalization for the Purpose of Water Resource Development in a Limited Data Situation: Case of Blue Nile River Basin, Ethiopia[J]. Journal of Hydrologic Engineering, 2012, 18(10): 1349-1359. [3] Evaluation through Independent Measurements: Complex Terrain and Humid Tropical Region in Ethiopia.*

Response

The impression given in the above comment that Ethiopia has a dense network of rain gauges is not in accordance with the cited paper of Romilly and Gebremichael (2011). Here we cite verbatim (Romilly and Gebremichael, 2011).

> "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^o by 0.25^o 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"

In addition the following proves that the rain gauge network in Romilly and Gebremichael (2011) is not dense. These two authors compare 118 gauged data with satellite rainfall estimate using PERSIANN and TRMM 3B42RT in six major basins in Ethiopia. Out of 118 stations, 37 of them fall under Blue Nile basin of area 176,000 km^2 (which is approximately one station for 4500 km^2 of area).

We are therefore not sure why based on the above; the reviewer writes that "The results presented in previous study seem more believable than current study." Our network of rain gauges was much denser than in the above study. Moreover five year average data are unusable in hydrologic models (which as stated clearly in the title was the main purpose of this manuscript).

The TRMM 3B42RT is a real-time product which was used by Romilly and Gebremichael (2011), the data that we used is post-real-time research version 3B42 adjusted for monthly rain gauged data (Moazami et al., 2014;Xue et al., 2013;Chen et al., 2013). It is assumed that 3B42 will supersede the 3B42RT estimates (Huffman and Bolvin, 2013). Of course, 3B42 has performed well in different parts of the world; it has captured the most prominent seasonal futures of precipitation in Pacific-Andean region in western South America Ochoa et al. (2014). Javanmard et al. (2010) indicated that 3B42 data has captured well the spatial distribution of gauged rainfall pattern and amounts over Iran.

But for our case, the performance of 3B42 is poor this could be associated with the data used for bias correction as Haile et al. (2013) indicated after personal communication with TMPA research team, that gauged rainfall data of the Upper Blue Nile Basin area was not made available to them when the bias adjustment was conducted. Bitew et al. (2012) and Bitew and Gebremichael (2011) validated the suitability rainfall products as input to hydrological model in the Ethiopian highland, they reported that 3B42 failed to perform well compared to the satellite-only product 3B42RT.

The second recommended paper by the referee #2 of (Gebregiorgis et al., 2012) has no relevancy with our paper, there might be some type mistake. Their study is not about evaluation of satellite rainfall but rather it is about hydrological characterization of the river basin into hydrologically homogenous regions to explain hydrological variables such as extreme and annual flows. The impression given in the above comment that "*The authors did not compare the results in this paper with previous study and explain what/why are the same and different.*" Here we cite verbatim (Gebregiorgis et al., 2012).

> “This paper discusses regionalization of the Blue Nile River Basin (BNRB) by using statistical techniques and describes the selection of best-fit distribution models to estimate the flood frequency of the basin; such undertakings have not been made before.” (Gebregiorgis et al., 2012).

The third paper recommended by the referee #2 (Bitew and Gebremichael, 2010) focuses on the evaluation of satellite rainfall products with 22 ground rainfall observation stations in a two 5 by 5 km grid boxes. The ground rainfall data is collected for 39-days by a field complain. They used satellite rainfall products of PERSIANN-CSS and CMORPH which is actually different from what we have used TRMM 3B42 and CFSR data. Since they have used a different satellite rainfall estimate it is difficult to compare it with our result and in addition the length of their study is just for 38 days and that does not describe whether the satellite data is capturing the annual rainfall patterned or not.

Comment 3:

A lot of study about the performance of latest V7 TRMM products have been published, but the authors have not mentioned in the papers, and the authors did not explain why the TRMM 3B42V7 shows poor performance over the study area. The authors seem to give an experimental report without scientific interpretation. Recent literature about V7 TRMM products, for example: [1] Saber Moazami, et al, 2014: Comprehensive evaluation of four high-resolution satellite precipitation products over diverse climate conditions in Iran. Hydrological Sciences [2] Yong, B., et al, 2015: Global view of real- time TRMM Multi-satellite Precipitation Analysis: implication to its successor Global Precipitation Measurement mission, Bull. Amer. Meteor. Soc [3] Chen, S., et al, 2013: Evaluation of the Successive Version-6 and Version-7 TMPA Precipitation Estimates over the Continental United States. Water Resour. Res.doi: 10.1002/2012WR012795. [4] Chen, S., et al, 2013: Similarity and Difference of the two Successive V6 and V7 TRMM Multi- satellite Precipitation Analysis (TMPA) Performance over China. Journal of Geophysical Research. Doi: 10.1002/2013jd019964. [6] Huffman, G. J., and D.

T. Bolvin (2013), TRMM and Other Data Precipitation Data Set Documentation, Lab. For Atmos., NASA Goddard Space Flight Cent. And Sci. Syst. And Appl. [7] Huffman, G. J., D. T. Bolvin, E. J. Nelkin, and R. F. Adler (2011), Highlights of version 7 TRMM multisatellite precipitation analysis (TMPA), paper presented at the 5th International. Precipitation Working Group Workshop, Workshop Program and Proceedings, 11–15 Oct., Hamburg, Germany, edited by C. Klepp and G. Huffman, Reports on Earth Syst.Sci., 100/2011, Max-Planck-Institut fC urMeteorologie, pp.

109–110.

Response 3

The emphasis of our manuscript is on the suitability of using the rainfall products (and not only TRIMM) for input to hydrological models in places where there is not a dense rain gauge network and the bias correction can therefore be poor. The reviewer is correct that for completeness we should have included the papers cited above; therefore:

We have modified the paragraph under page 2091 line 13 to21 as follows for clarity:

A study by Romilly and Gebremichael (2011) indicated that, the near-real time product 3B42RT performed better than PERSIANN rainfall estimate in capturing the gauged rainfall with an average bias ratio of 1.05 for Ethiopia. Apparently, the TRMM 3B42 bias is adjusted with monthly gauged rainfall data, and as a result, has performed well in many parts of the world (Javanmard et al., 2010; Moazami et al., 2014; Ouma et al., 2012). But, Dinku et al. (2008) and Haile et al. (2013), in the Ethiopian highlands, have indicated a consistent result with our study. Bitew et al. (2012) also indicated that, 3B42RT rainfall estimate has a smaller bias compared to the PERSIANN and 3B42 rainfall estimates. Haile et al. (2013) after personal communication with TMPA research team indicated that gauged rainfall data of the Upper Blue Nile Basin was not made available to them when the bias adjustment was conducted. Likely, the additional adjustment of 3B42RT with gauged data seems not working for our study site. Therefore, further adjustment has to be done to use TRMM 3B42 rainfall products in the Blue Nile Basin. Since TRMM 3B42 data did not capture the temporal pattern of the gauged rainfall, TRMM data is not used to capture the observed flow though hydrologic model calibration.

Comment 4:

The authors use the Thiessen Polygon to define a large area (the grid of TRMM) for comparison of TRMM and gauge observations, this method would give misleading results about the performance of TRMM products. Since the gauge network is too sparse, the authors should compare the TRMM product with gauge observations based on the grids that were overlapped by gauge. In addition, the spatial resolution of TRMM and CFSR is quite different; the authors should consider the scale problem and cannot give simple conclusion that CFRS has better performance than TRMM.

Response 4:

We have accepted the comment, we have used inverse distance interpolation to estimate the areal rainfall of gauged and satellite data, the model calibration is done again with the rainfall interpolated by inverse distance. We have also compared the satellite rainfall estimates (TRMM and CFSR) with the ground rainfall observation data within the satellite gauged box. Now Table 1, Table 2, Table 3 and Figure 1 to 10 are modified after gauged, CFSR and TRMM rainfall estimates are interpolated by inverse distance method.

The following paragraph is included under page 2090 and above line 16

> The satellite rainfall estimate of TRMM and CFSR data are compared with the gauged rainfall inside the satellite grid box. Figure 1 shows the correlation coefficient and bias of gauged rainfall vs. TRMM and CFSR data. The result indicated that CFSR data capturing 89 to 92% of the gauged rainfall pattern and TRMM captured 28 to 55% of the gauged rainfall pattern. The bias calculated as a ratio of annual mean of satellite rainfall estimate to the gauged data indicated 0.97 and 1.16 for TRMM and CFSR data respectively.

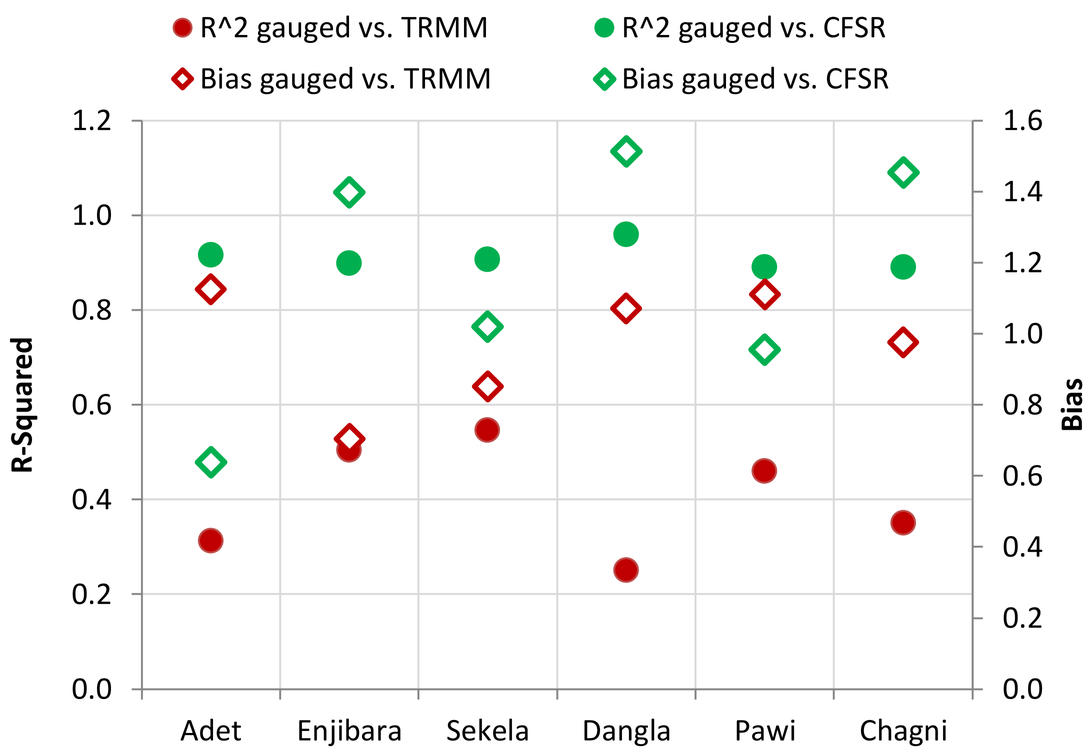


Figure 1: Long-term average monthly R-square and Bias of TRMM and CFSR rainfall estimate vs. ground rainfall observation stations within the satellite grid box.”

Comment 5

For the hydrology modeling, the authors calibrate the hydrology models with TRMM, CFSR ,and gauge, respectively, and then use very quit different parameters for simulation during validation, and thus for comparison based on simulated flow. Results with such experiment would be unbelievable and don’t make senses, because event the poor precipitation input can lead to good simulated flow if some important parameters are manfully tuned to fit the hydrograph in practice. The author, in my opinion, should redesign the experiments: calibrate the hydrology model with gauge observations to obtain a suit of best parameters, and then use the parameters to simulate stream flow for comparison. The authors can interpolate the gauge into gridded analysis with TRMM or CFSR based on Kriging/inverse distance weight/Optimal *interpolation technique, or you can use the gauge gridded analysis product Uniïnˇ A̡ed Gauge daily precipitation Analysis [Chen et al., 2008b] provided by National Oceanic and Atmospheric.*

Response 5

The reviewer misinterpreted our text. The performance of calibrated model for gauged and satellite rainfall data is validated by using the same set of parameters used for calibration using a different time period of rainfall data. As on page 2087 line 10 to 11 we indicated the calibration model parameters are validated using a rainfall data from 2004 to 2006. In addition the performance of TRMM and CFSR data on capturing the stream flow is tested by using the calibrated and validated model parameter sets of gauged rainfall data.

Consequently in our modified manuscript we have done exactly what the reviewer suggest us to do "…calibrate the hydrology model with gauge observations to obtain a suit of best parameters, and then use the parameters to simulate stream flow for comparison." We have included a text under section **3.2.3. Validation of CFSR rainfall estimate by gauged rainfall calibrated and validated parameters as follows.**

Moreover the statement that: "Results with such experiment would be unbelievable and don't make senses, because even the poor precipitation input can lead to good simulated flow if some important parameters are manfully tuned to fit the hydrograph in practice" is not in accordance what has been reported in the literature.

In the following we cite verbatim the following from Photiadou et al (2011):

> "Daily observations between 1961 and 1995 of the International Commission for the Hydrology of the Rhine basin (CHR) are often used to evaluate and correct biases in climate model projections. …….Hurkmans et al. (2010) studied the impact of climate change for the Rhine taking into account climate scenarios …. using a Land Surface Model (LSM). Shabalova et al. (2003) studied changes in the discharge of the Rhine by

the end of the 21st century using integrations of the Hadley Centre regional climate model HadRM2 and the RhineFlow model. Both studies used the CHR data (set as observational reference to correct the climate model bias on a daily basis for each of the 134 sub-catchments of the Rhine. Implementing a bias correction method proposed by Leander (2009), Terink et al. (2010) used the CHR precipitation and temperature to correct European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis data, ERA15".

Bitew and Gebremichael (2011) have used the same approach to assess the suitability of satellite rainfall products of CMORPH, TMPA 3B42RT, TMPA 3B42 and PERSIANN. They have used those satellite rainfall products as input to the semi-distributed hydrological model SWAT for daily stream flow simulation in Gilgel Abay and Koga watersheds. Here we cite verbatim (Bitew and Gebremichael, 2011):

"We calibrated the model parameters for each watershed and rainfall input source, separately, over a two-year period (2003–2004) by comparing the simulated and observed daily streamflow hydrographs. The resulting model parameter estimates are shown in Table 1."

Table 1 of Bitew and Gebremichael (2011) paper indicates calibrated model parameter sets for the gauged rainfall, CMORPH, TRMM 3B42RT, TRMM 3B42 and PERSIANN.

Moreover, numerous other studies have used streamflow measurements to evaluate rainfall products. However in citing these studies it might be more useful to point out conceptually why we can use watersheds as rain gages…

Finally, conceptually using watersheds as large rainfall gauges can be justified as follows: The outflow of a watershed over a long enough time period has to be equal to the rainfall minus the evaporation according to a mass balance since the change in storage is negligible compared to the input and output of the watersheds. For watershed with large ground water reservoirs this period can be decades but for the watershed chosen by us where the ground water storage is extremely small and the water balance will close for each year. The models chosen for this study to evaluate rainfall products are water balance models and the adjustable parameters in the model affect the amount of baseflow (arriving slowly at the gage), interflow (arriving within a month at the gage in the Gilgel Abay) and direct runoff (arriving on the same day as the rainfall at the gage).

Thus indeed a watershed can be considered therefore as a large gage that collects all the rainfall and route it to one point where it is measured. By subtracting the evaporation that can be calculated well with any model that uses the moisture content in the soil to scale the evaporation such as the Thornthwaite Mather method the amount of rainfall in the watershed can be derived (see Steenhuis and van der Molen (1989) for a description of the method). For Ethiopia this is well demonstrated since any model validated on a daily basis gives a good Nash-Sutcliffe efficiency.

Finally unlike point measurements with gages, there is no problem with the efficiency of the rain gage in catching the rainfall. Especially in the case of the Gilgil Abay, the watershed methods should work well, because of the steep terrain and the degraded soils, the interflow time to reach the gage is in the same order as the time period over which the rainfall is summed.

Comment 6:

The sentence "The study is comprised of two parts, in the first part, after estimating the areal long-term monthly rainfall estimates of gauged rainfall, CFSR and TRMM data from 1994–2006 for Gilgel Abay and Main Beles basins a comparison is done by using simple standard statistics (i.e., coefficient of determination)." Is very long, and the subject part should be moved in the front.

Response 6

We have accepted your comment and modified the sentence under page 2087 line 2 to 6 to the following:

> The study comprises of two parts, in the first part, the satellite rainfall estimates (TRMM and CFSR) are compared with gauged rainfall data within the satellite grid box. Then a monthly comparison is done using a standard statistics (i.e., coefficient of determination and bias). The areal rainfall of the gauged data and satellite grids is estimate by using inverse distance interpolation.

Comment 6 continued

For ". . .variation and CFSR data could capture 73% of the rainfall variation (Table 2)" on line 5 in page 2092, I see the regression coefficient for CFSR in Gilgel Abay basin is 0.77, not 0.73, in Table 2. Is it right?

Response **^**

Thank you for pointing that out. In HBV, the calibrated CFSR data captured 73% of the observed flow variation and in PED the calibrated CFSR data has captured 77% of the observed flow variation. But after reviewer two comment, we have interpolated the gauged and CFSR data by inverse distance and the calibration is done. The following tables and figures are changed after inverse distance interpolation of the gauged and satellite rainfall.

Table 1: Coefficient of Determination (R^2) areal gauged and satellite rainfall estimates for Gilgel Abay and Main Beles basins.

Basins		Main Beles			Gilgel Abay		
		TRMM	CFSR	Gauged	TRMM	CFSR	Gauged
Main Beles	TRMM	1.00					
	CFSR	0.10	1.00				
	Gauged	0.15	0.93	1.00			
Gilgel Abay	TRMM	0.87	0.26	0.37	1.00		
	CFSR	0.11	0.99	0.90	0.26	1.00	
	Gauged	0.16	0.94	0.99	0.38	0.93	1.00

Table 2: Optimized model parameter set of PED and model performance for gauged rainfall and CFSR data for Gilgel Abay and Main Beles.

Description		Gilgel Abay		Main Beles	
		Gauged rainfall	CFSR	Gauged rainfall	CFSR
Fraction of saturated area (%)		0.07	0.06	0.02	0.02
Fraction of degraded area (%)		0.05	0.05	0.05	0.02
Fraction of hillside area (%)		0.86	0.57	0.73	0.35
$t_{1/2}$ (days)		45	45	18	20
τ^* (days)		40	40	46	66
Calibration Period (1994 to 2003)	PBIAS (%)	10	7.6	-8.0	4.9
	NSE	0.74	0.73	0.61	0.63
	R^2	0.75	0.74	0.63	0.65
Validation period (2004 to 2006)	PBIAS (%)	-9.2	-5.9	-9.0	6.2
	NSE	0.65	0.63	0.68	0.66
	R^2	0.76	0.68	0.69	0.72

Table 3: Optimized model parameter set of HBV model and its performance for gauged rainfall and CFSR data.

Description		Gilgel Abay		Main Beles	
		Gauged rainfall	CFSR	Gauged rainfall	CFSR
Alpha		0.50	0.50	0.80	0.50
Beta		1.00	1.00	1.30	1.00
FC		245	1200	650	1400
LP		0.99	0.99	0.70	0.40
PERC		1.30	0.08	0.70	0.60
K4		0.04	0.04	0.002	0.002
Khq		0.10	0.08	0.13	0.08
Calibration Period (1994 to 2003)	PBIAS (%)	3.02	6.81	-3.12	2.82
	NSE	0.78	0.72	0.63	0.62
	R^2	0.79	0.73	0.65	0.63
Validation period (2004 to 2006)	PBIAS (%)	10.0	0.19	9.2	9.6
	NSE	0.71	0.62	0.61	0.60
	R^2	0.81	0.68	0.63	0.61

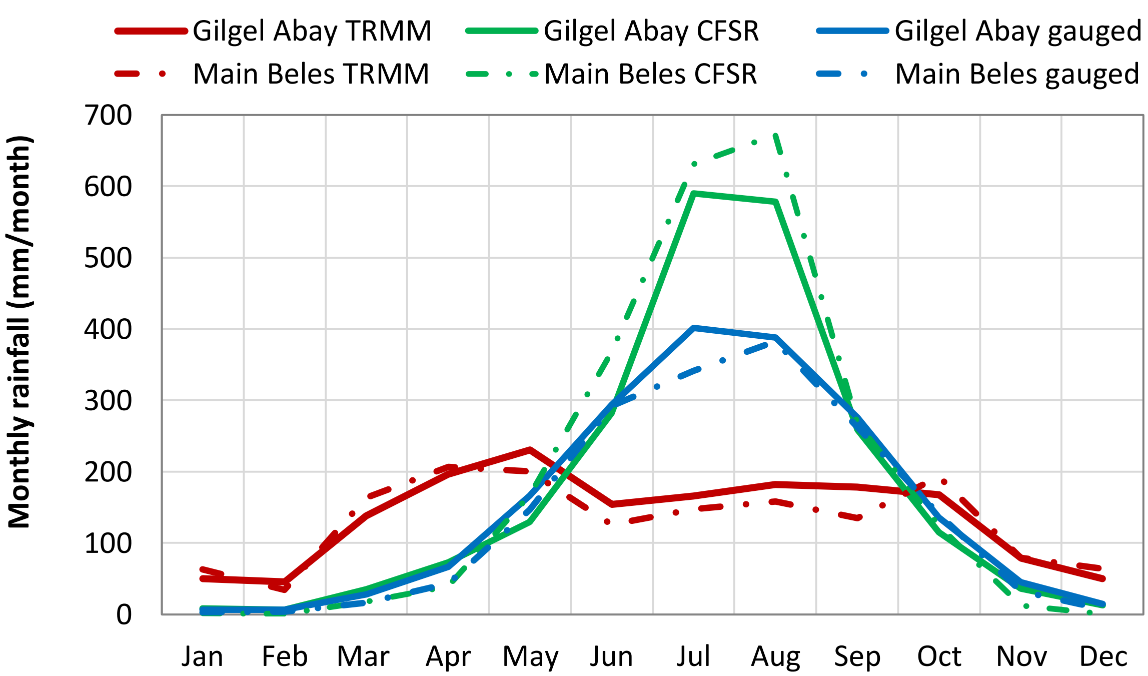


Figure 1: Long-term monthly average areal rainfall of gauged rainfall, CFSR data (from 1994 to 2003) and TRMM (from 1998 to 2003) for Gilgel Abay and Main Beles basins.

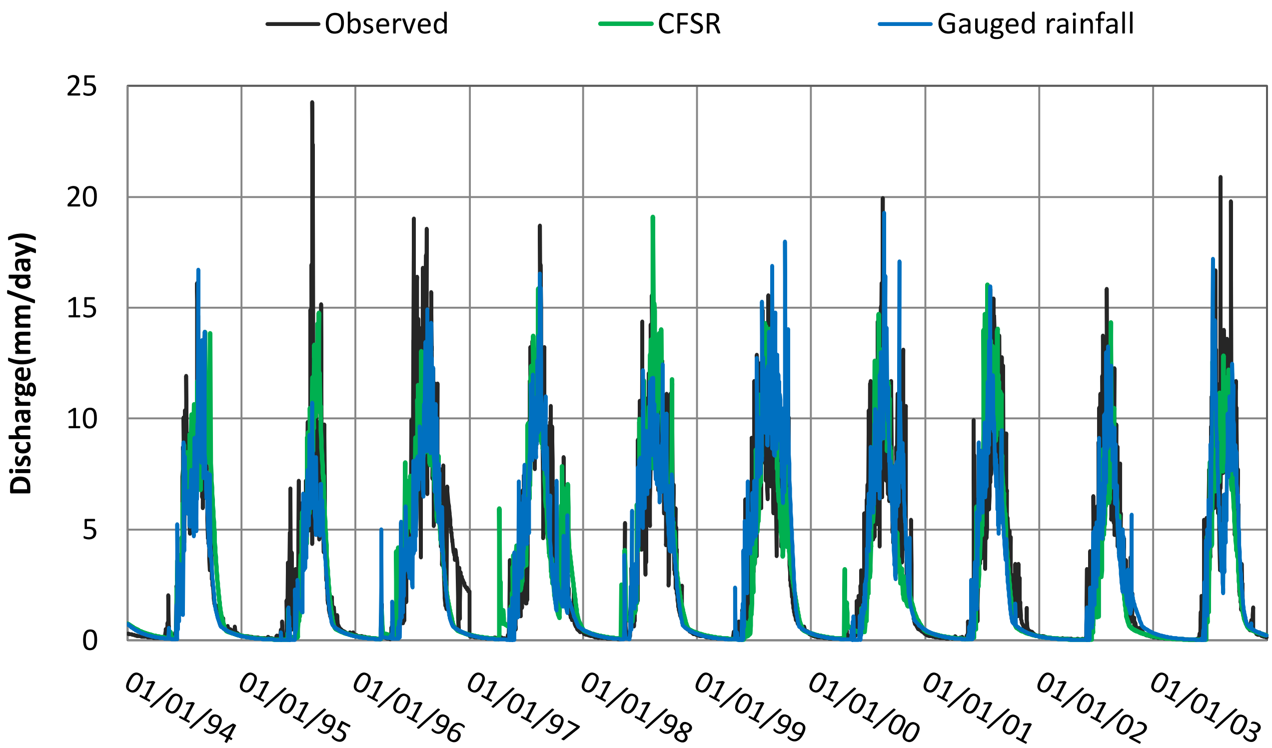


Figure 5: Simulated flow of PED model by gauged rainfall and CFSR data plotted with observed flow for Gilgel Abay basin.

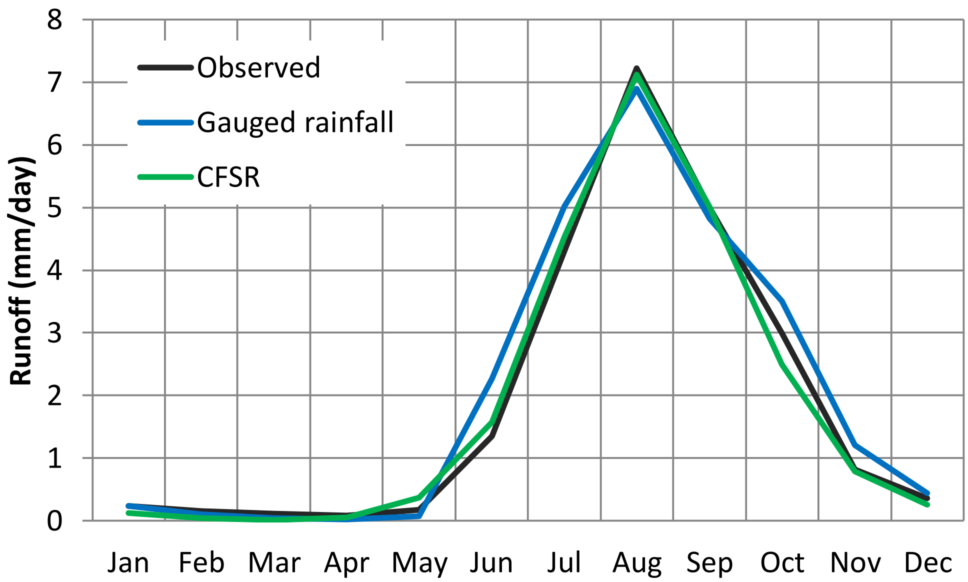
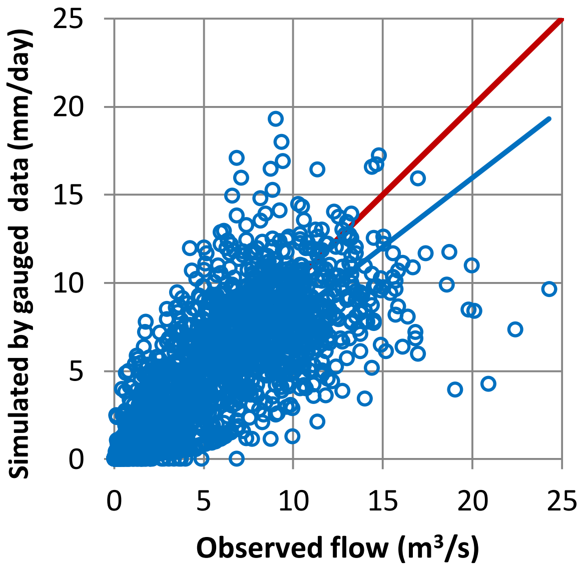
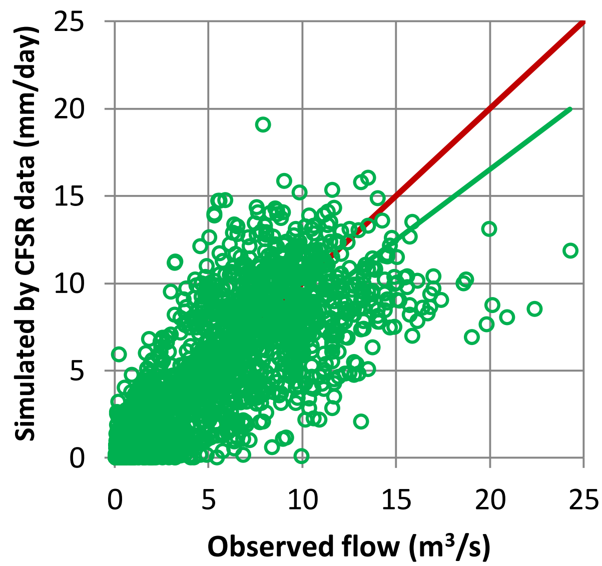


Figure 6: Comparison of long-term average monthly Gilgel Abay observed flow and PED simulation for gauged rainfall, CFSR (from 1994 to 2003) and TRMM rainfall estimate (from 1998 to 2003).



(a) Observed flow vs. flow simulated by gauged rainfall



(b) Observed flow vs. flow simulated by CFSR data

Figure 7: Correlation between observed flow and simulated flow for the calibration period using (a) gauged rainfall and (b) CFSR data for the Gilgel Abay Basin using PED model.

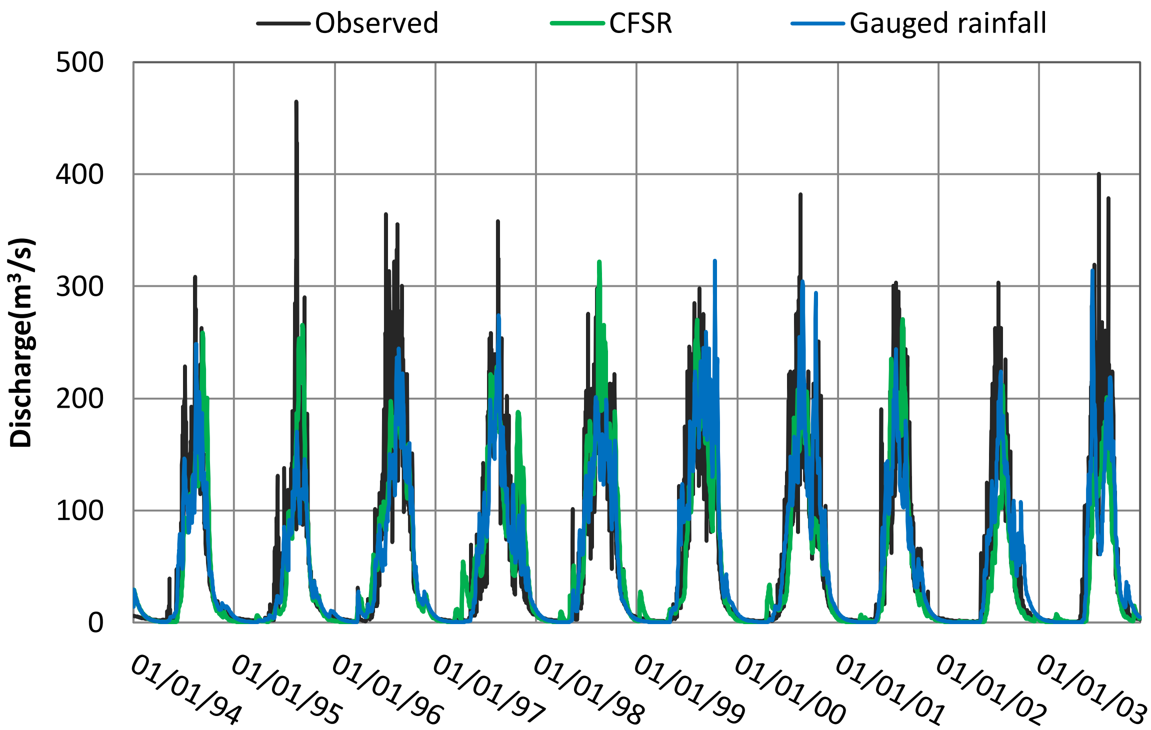


Figure 8: Simulated flow of HBV model by gauged rainfall and CFSR data plotted with observed flow for Gilgel Abay basin (1994-2003).

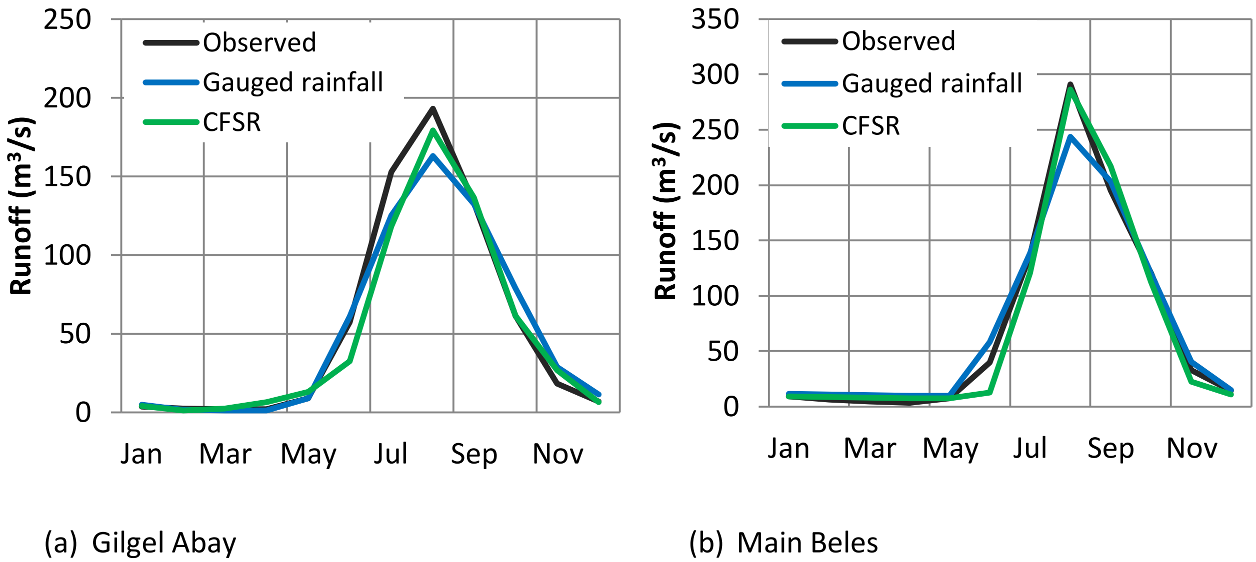
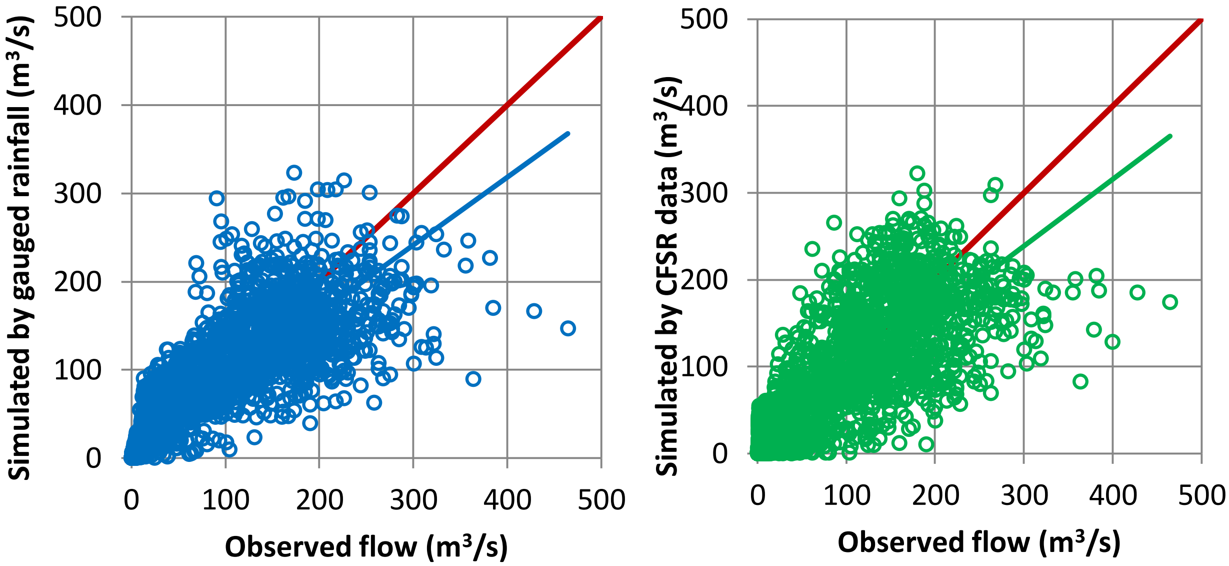


Figure 9: Comparison of long-term average monthly observed flow and HBV simulation for gauged rainfall, TRMM and CFSR rainfall estimate of (a) Gilgel Abay and (b) Main Beles basins.



(a) Observed flow vs. flow simulated by gauged rainfall

(b) Observed flow vs. flow simulated by CFSR data

Figure 10: Correlation between observed flow and simulated flow for the calibration period using (a) gauged rainfall and (b) CFSR data for the Gilgel Abay Basin using HBV model.

References

Bitew, M., and Gebremichael, M.: Assessment of satellite rainfall products for streamflow simulation in medium watersheds of the Ethiopian highlands, Hydrology and Earth System Sciences, 15, 1147-1155, 2011.

Bitew, M. M. and Gebremichael, M.: Evaluation through independent measurements: Complex terrain and humid tropical region in Ethiopia. In: Satellite Rainfall Applications for Surface Hydrology, Springer, 2010.

Bitew, M. M., Gebremichael, M., Ghebremichael, L. T., and Bayissa, Y. A.: Evaluation of hig h-resolution satellite rainfall products through streamflow simulation in a hydrological modeling of a small mountainous watershed in Ethiopia, Journal of Hydrometeorology, 13, 338 -350, 2012.

Chen, S., Hong, Y., Cao, Q., Gourley, J. J., Kirstetter, P. E., Yong, B., Tian, Y., Zhang, Z., Shen, Y., and Hu, J.: Similarity and difference of the two successive V6 and V7 TRMM multisatellite precipitation analysis performance over China, Journal of Geophysical Research: Atmospheres, 118, 13,060-013,074, 2013.

Dinku, T., Ceccato, P., Grover-Kopec, E., Lemma, M., Connor, S., and Ropelewski, C.: Validation of satellite rainfall products over East Africa's complex topography, International Journal of Remote Sensing, 28, 1503-1526, 2007.

Dinku, T., Chidzambwa, S., Ceccato, P., Connor, S., and Ropelewski, C.: Validation of high-resolution satellite rainfall products over complex terrain, International Journal of Remote Sensing, 29, 4097-4110, 2008.

Dinku, T., Connor, S. J., and Ceccato, P.: Comparison of CMORPH and TRMM-3B42 over mountainous regions of Africa and South America, in: Satellite Rainfall Applications for Surface Hydrology, Springer Netherlands, 193-204, 2010.

Gebregiorgis, A. S., Moges, S. A., and Awulachew, S. B.: Basin Regionalization for the Purpose of Water Resource Development in a Limited Data Situation: Case of Blue Nile River Basin, Ethiopia, Journal of Hydrologic Engineering, 18, 1349-1359, 2012.

Haile, A. T., Habib, E., Elsaadani, M., and Rientjes, T.: Inter-comparison of satellite rainfall products for representing rainfall diurnal cycle over the Nile basin, International journal of applied earth observation and geoinformation, 21, 230-240, 2013.

Huffman, G. J. and Bolvin, D. T.: TRMM and other data precipitation data set documentation, NASA, Greenbelt, USA, 2013. 1-40, 2013.

Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., Hong, Y., Bowman, K. P., and Stocker, E. F.: The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. , Journal of Hydrometeorology, 8, 38-55, 2007.

Huffman, G. J., and Bolvin, D. T.: TRMM and other data precipitation data set documentation, NASA, Greenbelt, USA, 1-40, 2013.

Hurkmans, R., Terink, W., Uijlenhoet, R., Torfs, P., Jacob, D., Troch, P. A.. 2010. Changes in Streamflow Dynamics in the Rhine Basin under Three High -Resolution Regional Climate Scenarios. J. Climate, 23: 679–699,

Javanmard, S., Yatagai, A., Nodzu, M., BodaghJamali, J., and Kawamoto, H.: Comparing high - resolution gridded precipitation data with satellite rainfall estimates of TRMM_3B42 over Iran, Advances in Geosciences, 25, 119-125, 2010.

Moazami, S., Golian, S., Hong, Y., Sheng, C., and Kavianpour, M. R.: Comprehensive evaluation of four high-resolution satellite precipitation products over diverse climate conditions in Iran, Hydrological Sciences Journal, 2014.

Ochoa, A., Pineda, L., Crespo, P., and Willems, P.: Evaluation of TRMM 3B42 precipitation estimates and WRF retrospective precipitation simulation over the Pacific–Andean region of Ecuador and Peru, Hydrology and Earth System Sciences, 18, 3179-3193, 2014.

Ouma, Y. O., Owiti, T., Kipkorir, E., Kibiiy, J., and Tateishi, R.: Multitemporal comparative analysis of TRMM-3B42 satellite-estimated rainfall with surface gauge data at basin scales: daily, decadal and monthly evaluations, International Journal of Remote Sensing, 33, 7662-7684, 2012.

Photiadou, C. S.; Weerts, A. H.; van den Hurk, B. J. J. M. 2011. Evaluation of two precipitation data sets for the Rhine River using streamflow simulations 15:3355-3366

Romilly, T., and Gebremichael, M.: Evaluation of satellite rainfall estimates over Ethiopian river basins, Hydrology and Earth System Sciences, 15, 1505-1514, 2011.

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., and Behringer, D.: The NCEP climate forecast system reanalysis, Bulletin of the American Meteorological Society, 91, 1015-1057, 2010.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., Chuang, H.-y., and Iredell, M.: The NCEP climate forecast system version 2, Journal of Climate, 27, 2185-2208, 2014.

Shabalova, M. V., Van Deursen, W. P. A., and Buishand, T. A. 2003Assessing future discharge of the river Rhine using regional climate model integrations and a hydrological model, Clim. Res., 23, 233–246

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., Chuang, H.- y., and Iredell, M.: The NCEP climate forecast system version 2, Journal of Climate, 27, 2185-2208, 2014.

Szczypta, C., Decharme, B., Carrer, D., Calvet, J.C., Lafont, S., Somot, S., Faroux, S., Martin, E. 2012. Impact of precipitation and land biophysical variables on the simulated discharge of European and Mediterranean rivers. Hydrol. Earth Syst. Sci.16: 3351-3370.

Tian, Y., Peters-Lidard, C. D., Choudhury, B. J., and Garcia, M.: Multitemporal analysis of TRMM-based satellite precipitation products for land data assimilation applications, Journal of Hydrometeorology, 8, 1165-1183, 2007.

Linde, A. H., Aerts, J. C. J. H., Hurkmans, R. T. W. L., and Eberle, M., 2010. Comparing model performance of two rainfall-runoff models in the Rhine basin using different atmospheric forcing data sets, Hydrol. Earth Syst. Sci., 12: 943–957

Terink, W., Hurkmans, R. T. W. L., Torfs, P. J. J. F., and Uijlenhoet, R; 2010: Evaluation of a bias correction method applied to downscaled precipitation and temperature reanalysis data for the Rhine basin, Hydrol. Earth Syst. Sci., 14, 687–703.

Tian, Y., Peters-Lidard, C. D., Choudhury, B. J., and Garcia, M.: Multitemporal analysis of TRMM-based satellite precipitation products for land data assimilation applications, Journal of Hydrometeorology, 8, 1165-1183, 2007.

Wang, W., Xie, P., Yoo, S.-H., Xue, Y., Kumar, A., and Wu, X.: An assessment of the surface climate in the NCEP climate forecast system reanalysis, Climate dynamics, 37, 1601-1620, 2011.

Xue, X., Hong, Y., Limaye, A. S., Gourley, J. J., Huffman, G. J., Khan, S. I., Dorji, C., and Chen, S.: Statistical and hydrological evaluation of TRMM-based Multi-satellite Precipitation Analysis over the Wangchu Basin of Bhutan: Are the latest satellite precipitation products 3B42V7 ready for use in ungauged basins?, Journal of Hydrology, 499, 91-99, 2013.

Bitew, M. and Gebremichael, M.: Assessment of satellite rainfall products for streamflow simulation in medium watersheds of the Ethiopian highlands, Hydrology and Earth System Sciences, 15, 1147-1155, 2011.

Bitew, M. M. and Gebremichael, M.: Evaluation through independent measurements: Complex terrain and humid tropical region in Ethiopia. In: Satellite Rainfall Applications for Surface Hydrology, Springer, 2010.

Bitew, M. M., Gebremichael, M., Ghebremichael, L. T., and Bayissa, Y. A.: Evaluation of high-resolution satellite rainfall products through streamflow simulation in a hydrological modeling of a small mountainous watershed in Ethiopia, Journal of Hydrometeorology, 13, 338-350, 2012.

Chen, S., Hong, Y., Cao, Q., Gourley, J. J., Kirstetter, P. E., Yong, B., Tian, Y., Zhang, Z., Shen, Y., and Hu, J.: Similarity and difference of the two successive V6 and V7 TRMM multisatellite precipitation analysis performance over China, Journal of Geophysical Research: Atmospheres, 118, 13,060-013,074, 2013.

Dinku, T., Ceccato, P., Grover-Kopec, E., Lemma, M., Connor, S., and Ropelewski, C.: Validation of satellite rainfall products over East Africa's complex topography, International Journal of Remote Sensing, 28, 1503-1526, 2007.

Dinku, T., Chidzambwa, S., Ceccato, P., Connor, S., and Ropelewski, C.: Validation of high-resolution satellite rainfall products over complex terrain, International Journal of Remote Sensing, 29, 4097-4110, 2008.

Dinku, T., Connor, S. J., and Ceccato, P.: Comparison of CMORPH and TRMM-3B42 over mountainous regions of Africa and South America. In: Satellite Rainfall Applications for Surface Hydrology, Springer Netherlands, 2010.

Gebregiorgis, A. S., Moges, S. A., and Awulachew, S. B.: Basin Regionalization for the Purpose of Water Resource Development in a Limited Data Situation: Case of Blue Nile River Basin, Ethiopia, Journal of Hydrologic Engineering, 18, 1349-1359, 2012.

Haile, A. T., Habib, E., Elsaadani, M., and Rientjes, T.: Inter-comparison of satellite rainfall products for representing rainfall diurnal cycle over the Nile basin, International journal of applied earth observation and geoinformation, 21, 230-240, 2013.

Huffman, G. J. and Bolvin, D. T.: TRMM and other data precipitation data set documentation, NASA, Greenbelt, USA, 2013. 1-40, 2013.

Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., Hong, Y., Bowman, K. P., and Stocker, E. F.: The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. , Journal of Hydrometeorology, 8, 38-55, 2007.

Javanmard, S., Yatagai, A., Nodzu, M., BodaghJamali, J., and Kawamoto, H.: Comparing high-resolution gridded precipitation data with satellite rainfall estimates of TRMM_3B42 over Iran, Advances in Geosciences, 25, 119-125, 2010.

Moazami, S., Golian, S., Hong, Y., Sheng, C., and Kavianpour, M. R.: Comprehensive evaluation of four high-resolution satellite precipitation products over diverse climate conditions in Iran, Hydrological Sciences Journal, 2014. 2014.

Ouma, Y. O., Owiti, T., Kipkorir, E., Kibiiy, J., and Tateishi, R.: Multitemporal comparative analysis of TRMM-3B42 satellite-estimated rainfall with surface gauge data at basin scales: daily, decadal and monthly evaluations, International Journal of Remote Sensing, 33, 7662-7684, 2012.

Romilly, T. and Gebremichael, M.: Evaluation of satellite rainfall estimates over Ethiopian river basins, Hydrology and Earth System Sciences, 15, 1505-1514, 2011.

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., and Behringer, D.: The NCEP climate forecast system reanalysis, Bulletin of the American Meteorological Society, 91, 1015-1057, 2010.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., Chuang, H.-y., and Iredell, M.: The NCEP climate forecast system version 2, Journal of Climate, 27, 2185-2208, 2014.

Tian, Y., Peters-Lidard, C. D., Choudhury, B. J., and Garcia, M.: Multitemporal analysis of TRMM-based satellite precipitation products for land data assimilation applications, Journal of Hydrometeorology, 8, 1165-1183, 2007.

Wang, W., Xie, P., Yoo, S.-H., Xue, Y., Kumar, A., and Wu, X.: An assessment of the surface climate in the NCEP climate forecast system reanalysis, Climate dynamics, 37, 1601-1620, 2011.

Xue, X., Hong, Y., Limaye, A. S., Gourley, J. J., Huffman, G. J., Khan, S. I., Dorji, C., and Chen, S.: Statistical and hydrological evaluation of TRMM-based Multi-satellite Precipitation Analysis over the Wangchu Basin of Bhutan: Are the latest satellite precipitation products 3B42V7 ready for use in ungauged basins?, Journal of Hydrology, 499, 91-99, 2013.