Performance of bias correction schemes for CMORPH rainfall estimates in the Zambezi River Basin

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AUTHOR'S RESPONSE

Interactive comment on "Performance of bias correction schemes for CMORPH rainfall estimates in the Zambezi River Basin" by Webster Gumindoga et al.

Anonymous Referee #1
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Referee Comment
This manuscript, entitled "Performance of bias correction schemes for CMORPH rainfall estimates in the Zambezi River Basin", investigates the performance of bias corrected CMORPH rainfall estimates over the Zambezi River Basin. Although the topic is relevant and worthy to explore scientifically, I believe the manuscript should undergo major changes prior to publication.

Author's Response
We thank the referee for finding merit in our manuscript.

Author's changes in manuscript.

We have made substantial changes (from introduction to conclusions) to the manuscript to comply with the comments received from the reviewers.

Referee Comment

Questions posed to reviewers:
1. Does the paper address relevant scientific questions within the scope of HESS? The paper covers the relevant topic of bias correction of satellite-based rainfall estimates over the Zambezi River Basin and falls within the scope of HESS.

Author's Response
We thank the referee for the encouraging comment and for finding merit in our bias correction techniques.

Referee Comment
2. Does the paper present novel concepts, ideas, tools, or data? The novelty of the paper is limited as it follows the structure of similar efforts carried out for other river basins. This should not, however, invalidate its publication in light of the relevance of the case-study.

Author's Response
The authors took note of the comment. We agree to the comment for our techniques are similar to those applied by others.

Author's changes in manuscript.
However, in our efforts to revise the manuscript we tested and applied spatial and temporal cross-validation techniques that is not often seen in studies on Satellite Rainfall Estimates (SRE) bias correction studies.

Referee Comment

3. Are substantial conclusions reached? The results are not prone to a clear-cut conclusion, but the authors do a good job of comparing the different methodologies.

Author’s Response

The authors took note of the comment.

Author's changes in manuscript.

The authors have added additional performance metrics so that substantial conclusions are reached.

Referee Comment

4. Are the scientific methods and assumptions valid and clearly outlined? Generally yes, although clarifications on some of the methods and choices should be provided.

Author’s Response and changes in the manuscript

The authors added further clarifications on the methodologies (Section 3). Each of the methods, and selection of bias correction schemes are now justified.

Referee Comment

5. Are the results sufficient to support the interpretations and conclusions? I have mixed feelings about this. While the results are certainly sufficient to say something about the bias correction performance, I believe it should be further characterized by a more structured set of metrics that cover a broader range of features of the rainfall fields that are being corrected.

Author’s Response

We have maintained *frequency based metrics* which we had used previously to evaluate the SRE rainfall detection performance: Mean, Minimum, Max and ratio of satellite totals versus gauge totals.

We have also returned the bias and Taylor Diagram which covers (RMSD, Correlation Coefficient and standard deviation).

Author's changes in manuscript.

We have added the following *time-series-based metrics*, some which were also recommended by the reviewer:

Mean Absolute Error (MAE) - The Mean absolute Error (MAE) is the arithmetic average of the absolute values of the differences between the daily gauge and corrected or uncorrected CMORPH satellite rainfall estimates. We refer to Equation 10 of the revised manuscript.

Nash Sutcliffe (NSE): NS indicates how well the satellite rainfall matches the raingauge observation and it ranges between - ∞ and 1, with NSE = 1 meaning a perfect fit. We refer to Equation 11 of the revised manuscript.

In addition we have added the following graphical evaluation of the performance:

Quantile-quantile (Q-Q) plots - A graphical technique whose purpose is to check if two datasets (Gauge vs Uncorrected or Gauge vs Bias corrected Satellite rainfall) can be fit with the same distribution (Wilks, 2006;NIST/SEMATECH, 2001). A 45-degree reference line is plotted. If the satellite rainfall (corrected and uncorrected) has the same distribution as the rainguage, the points should fall approximately along this reference line. The greater the departure from this reference line, the greater the evidence for the conclusion that the bias correction scheme is less effective. This has been described in Section 3.8 of the revised manuscript.

We also added quantitative methods of describing, analysing, and drawing inferences (conclusions) from the continuous rainfall data. These are found in section 3.6 in the revised manuscript,

Paired t-tests – We aim to test whether there is a significant difference between raingauge vs uncorrected or vs bias corrected CMORPH SRE for the Zambezi basin. The paired t-test works well when dealing with continuous data and when we want to make comparison of measurements from the same place using 2 measurement techniques (e.g. gauge vs satellite). For detailed description of the t-test we refer to (Wilks, 2006;Field 2009).

Analysis of Variance (ANOVA) test

The one-way ANOVA aim to test whether there is a significant difference amongst the 5 bias correction techniques. The Null hypothesis is that there are no differences amongst the five bias correction schemes. After ANOVA is conducted, we determined which schemes differ significantly using post-hoc tests , namely: Tukey HSD, Schefe and the Bonferroni (Brown, 2005; Kucuk et al., 2018).. Results are summarized for the Upper, Lower and Middle Zambezi.

Referee Comment

Also, and perhaps more importantly, the paper fails to describe the performance assessment methodology in detail. I believe that such an assessment should be made based on a hold-out sample, and this does not seem to be the case.

Author's Response and changes in the manuscript

In response to recommendation by the reviewer we have carried out spatial and temporal cross-validation.

Spatial cross validation

The spatial cross-validation procedure (hold-out sample) applied in this study, involves the withdrawal of 8 in-situ stations for the sample of 60 when generating bias corrected SREs for all pixels across the study area.. Corrected SREs are then compared to the gauge estimates of the withdrawn stations to evaluate closeness of match. From the sample of 8 we selected 2 stations in the < 250 m elevation zone, and 3 stations in of at the 250-950 m and > 950 m elevation zones. Stations selected have elevation close to the average elevation zone value and are centred in an elevation zone. This left us with 52 stations for applying the bias correction methods and spatial interpolation. As performance indicators to evaluate results of cross-validation, we use the percentage bias, MAE, Correlation Coefficient and the estimated ratio which is obtained by dividing CMORPH rainfall totals and gauge based rainfall totals for the 1999-2013 period.

Temporal cross-validation

For evaluation of SREs in the the time domain we followed (Gutjahr and Heinemann, 2013) and omited rainfall estimates (both from gauge and satellite) for the 1998-1999 hydrological year to remain with 14 years for bias correction of SREs. Bias corrected estimates for 1998-1999 are then evaluated against estimates for the 14 years that served as reference.For evaluation we use the percentage bias, MAE, Correlation Coefficient and the estimated ratio, that all are averaged for the Upper, Middle and Lower Zambezi but also for the wet and dry seasons.

See new section: 3.9. Validation of the bias correction procedures.

Referee Comment

6. Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)?

Referee Comment

7. Do the authors give proper credit to related work and clearly indicate their own new/original contribution?

Referee Comment

8. Does the title clearly reflect the contents of the paper? Yes.

Author's Response

We thank the reviewer for the observation

Referee Comment

9. Does the abstract provide a concise and complete summary? Yes.

Author's Response

We thank the reviewer for the observation

Referee Comment

10. Is the overall presentation well-structured and clear? Yes.

Author's Response

We thank the reviewer for the observation

Referee Comment

11. Is the language fluent and precise? Yes.

Author's Response

We thank the reviewer for the observation

Referee Comment

12. Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Generally yes, perhaps with some exceptions. See the file attached to this review.

Author's Response

We thank the reviewer for the observation

Referee Comment

13. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? Yes. Please see comments and suggestions on the file attached to this review.

Author's Response

Specific comments have been attended to.

Referee Comment

14. Are the number and quality of references appropriate? I believe they are.

Author's response

We thank the reviewer for the observation

Referee Comment

15. Is the amount and quality of supplementary material appropriate? No supplementary material is provided.

Referee Comment

The paper focuses on relatively simple bias-correction methodologies and performance metrics. I believe it would be worth putting them into perspective by mentioning more elaborate techniques. In what concerns performance metrics the paper could also be improved. I recommend adding the root mean squared error, the mean absolute error, and quantile-quantile plots.

Author's Response and changes in the manuscript

In the revised manuscript, we argued/ added the selection of schemes we used. We also gave the overview over differences between outcomes but also similarities between outcomes such as mean values for instance.

The authors have now evaluated the performance of bias corrections schemes using additional metrics such as mean absolute error (MAE), Nash Sutcliffe Efficiency (NSE) and quantile-quantile plots. The RMSE is embedded in the Taylor Diagram formula and so cannot be used independently in this paper.

We also used quantitative methods (paired t-tests and Analysis of variance (ANOVA)) of describing, analysing, and drawing inferences (conclusions) from the gauge, corrected and uncorrected SREs.

Referee Comment

In what sample was the bias correction tested? The same which was used to calibrate the correction methods? I would like to see a comparison made on a hold-out sample (in space). Because the rain gauge data are already known, the value of using bias corrected CMORPH data is that they provide information on the regions between rain gauges. So being, it is important to know how the schemes perform in those regions.

One way to do it is to calibrate and apply the correction over N-1 gauging stations, use an interpolation model to infer the bias corrected CMORPH values over the Nth gauging station, and compute the error there. This could then be done holding out other gauging stations.
How can the uneven distribution of the relatively few rainfall stations that were used affect results and the interpretation of the results?

Author's Response and changes in the manuscript

In response to recommendation by the reviewer we have carried out cross-validation. We aim to test the bias correction procedure by leaving few single stations out that serve validation purposes. The test serve to assess if corrected SRE for locations where stations are left out agree to the actual gauge estimates. We aim to target only several locations. We selected 2 stations in the < 250m elevation zone, 3 stations each at 250-950 and > 950 elevation zone. Stations lie at average elevation of a zone and are sort of centred in the elevation zone, resulting in 8 stations that serve cross- validation. This left us with 52 stations for the main performance evaluation. Since the validation stations are not ones used in developing bias correction, we conclude that the bias correction results are not biased towards reducing the errors.

Referee Comment

Some of the rain gauge series are affected by missing data. I believe it is relevant to show exactly how much of the data is missing.

Author's Response and changes in the manuscript

We have added a table under supplementary data (Appendix 1) that shows percentage of missing observations for each station.

Appendix 1: Rain gauge stations in the Zambezi subbasins showing x and y location, subbasin they belong to, year of data availability, % of missing gaps, station elevation and distance from large scale open water bodies.

We initially removed it as it was suggested by a reviewer not to make the paper too long unnecessarily.

Referee Comment

How the corrections are interpolated between gauge locations needs explaining.
I would like the authors to clarify if and how the tested methodologies can be used in predictive mode (in other words, can they be used to correct CMORPH rainfall estimates even if no rain gauge data are available?).

Author's Response and changes in the manuscript

Following recommendation by the reviewer, we carried spatial interpolation of bias correction factors so that they are subsequently applied to respective SRE pixels. For interpolating daily bias correction factors to grid points, we employ the Universal Kriging technique (Yang et al., 2015). Thus to systematically correct all CMORPH estimates, station based bias factors are spatially interpolated to yield a bias factor map and to allow for comparison with other approaches, following Bhatti et al. (2016). The results indicate that, in principle that selected bias correction procedures adequate for the areas in the basin with no station coverage.

We however draw the reviewer to our cross-validation efforts as described where we assess the reliability and effectiveness of the bias correction techniques by leaving few single stations out.

Referee Comment

The disadvantages associated with each bias-correction method should also be clearly stated. If only (or mostly) advantages are highlighted the reader will be given incomplete information.

Author's Response and changes in the manuscript

The authors have included the disadvantages of each of the bias correction techniques in the methodology section in order to be more transparent to our readers of what each bias correction offers (changes done in section 3.3.1 – 3.3.5). As such we decided to apply a bias correction method, fully aware of these disadvantages, since the described advantages are essential to water resources applications.

We have also added that some techniques apply to individual stations whereas others apply to spatial zones. The introduction section also gives an overview of the merits and de-merits of each of the broader classes of the bias correction schemes such as linear, non-linear, regression based, multiplicative and power function etcetera.

Referee Comment

It is the first time I come across Taylor diagrams, so there is a high likelihood that I am wrong in my assertion (something I help the authors can help me with). The Pearson's correlation coefficient and the standard deviation are bias-insensitive (take a series, add a constant - a bias of the expected value - to it and it will display the same standard deviation; correlation between the original series and the biased one will be 1, regardless of the bias magnitude). As it is described (a function of R and STD), the root mean square difference appears to be also insensitive to what is perhaps the simplest form of bias. What is then the big advantage of the diagram, as employed in this paper, to assess the bias-correction methods?

Author Response

The premise of the Taylor diagram is that for different data sets, as generated by the different bias correction methods, best results are indicated for respective metrics. The main advantage of use of a Taylor diagram is that the diagram provides a statistical summary of how well patterns match each other in terms of the Pearson's product-moment correlation coefficient (R), root mean square difference (E), and the ratio of variances on a 2-D plot (Lo Conti et al., 2014;Taylor, 2001).

Author's changes in the manuscript

In Section '3.7. Assessment through Taylor diagram' we added the following sentences:
"….Some performance metrics indicate best range of variability, but does not capture the pattern whereas some do quite well with the pattern, but pronouncedly under-estimate the magnitude of variability. As such a Taylor diagram evaluates differences in data sets generated by respective bias correction schemes by providing a concise summary of how well bias correction results match gauge based estimates in terms of pattern, variability and magnitude of the variability. In addition, Taylor diagrams provide a quick, visual summary of the performance of each bias correction scheme…"

Specific comments.

Author Response

Referee Comment

line 32. Although SRE are certainly prone to bias, this fact alone does not explain why they are so. The same cloud properties leading to different precipitation "behaviors" in different regions would...

Author Response

We took note of the reviewer comments. Indeed, satellite products are mostly prone to errors as they are estimated from secondary sources (for instance, cloud top brightness temperature). The authors also note from literature e.g. Bhatti et al. (2016) and Rosenfeld and Mintz (1988) that Multiple passive microwave (PMW) precipitation products are subject to bias due to incorrect measured brightness temperature in semi-arid regions. CMORPH biases might be due to diurnal sampling bias, tuning of the instrument or the rainfall algorithm, or unusual surface or atmospheric properties that the instrument does not correctly interpret (Smith et al., 2006)

Author's changes in the manuscript

We revised line 32 to:

'..Satellite Rainfall Estimates (SRE) are prone to bias as they are indirect derivatives of the visible, infrared, and/or microwave cloud properties, hence SREs need correction….'

Referee Comment

line 71. What is the (relevant) difference between the rainfall depth and volume?

Author Response

Rainfall depth is the cumulative amount of rainfall received at a particular place during a given period and is expressed in depth units per unit time, usually as mm per hour (mm/h) or mm per day. Rainfall volume is the amount of rainfall for a given geographical area. Depending on application, we need to make sure we record rainfall at the appropriate spatial, as well as temporal, resolution.

Author's changes in the manuscript

We have however removed the word 'volume' in the manuscript and maintained 'rainfall depth' to avoid confusion to the readers.

Referee Comment

line 118. Please provide a reference for the estimated number of the people who depend on water from the Zambezi.

Author Response

Reference provided as (World Bank, 2010a):

World Bank: The Zambezi River Basin: A Multi-Sector Investment Opportunities Analysis, Volume 2 Basin Development Scenarios, 2010b.

Author's changes in the manuscript

We have since revised the figure to 30 million according to literature. Line 126

Referee Comment

line 138. Please clarify why each of the cited publications is relevant.

Author Response

Koutsouris et al., 2016 has recent applications comparing global precipitation data sets including CMORPH in eastern Africa

Jiang et al., 2016 contains evaluation of latest TMPA and CMORPH satellite precipitation products over Yellow River Basin

Haile et al., 2015 contains accuracy assessment of the CMORPH satellite-rainfall product over Lake Tana Basin in Eastern Africa

Author's changes in the manuscript

We modified sentence to 'Recent publications on CMORPH in African basins exist (Wehbe et al., 2017; Koutsouris et al., 2016; Jiang et al., 2016; Haile et al., 2015). However CMORPH data applicability following bias correction in the semi-arid Zambezi Basin has not been fully investigated. Therefore, evaluating and finding the appropriate bias correction method for the data is necessary for water resources management in the basin.

Referee Comment

line 162. The Zambezi contains, besides large lakes, very significant wetlands (e.g. the Barotse Plains and the Kafue Flats). Why were these not considered in the analysis?

Author Response

In this analysis we only focussed on large scale open water bodies since energy balance, heat storage and actual evapotranspiration for vegetation covered wetlands are not directly comparable to open water bodies.

Referee Comment

Figure 1, 2. The Zambezi River Basin does not correspond to the one displayed in the figures in the region of the outlet, near the Indian Ocean. What is represented as a small strip is in fact a very broad delta. Also, it would practical to add small map showing where the Zambezi is located in Africa.

Author Response

Our map of Zambezi basin (Figure 1, 2) remains the same as here we are only dealing with the actual hydrological boundary of the Lower Zambezi and not the delta.

Author's changes in the manuscript

We have added a map that shows where the Zambezi basin is in relation to Africa. Caption of Figure 1 now reads: Zambezi River Basin from Africa with sub basins, major lakes, rivers, elevation and locations of the 60 rain gauging stations used in this study. The Euclidian distance (km) from large open water bodies is also shown.

Referee Comment

line 225. What were the alternatives tested in the preliminary analysis?

Author's Response and changes in the manuscript

Windows of 5 days were tested in this study on 20 individual stations distributed over all three elevation zones. In addition these include different time windows of 5 days as also tested by Bhatti et al (2016) in the Nile basin. The authors came to a conclusion that the 7 day time window used in the present study is adequate. Changes are made in line 281-291 of the new manuscript.

Referee Comment

line 264. The authors mention that knowledge of the study area had a role in grouping. What was this role?

Author's Response

The authors refer to literature (e.g. World Bank, 2010b;Beilfuss, 2012) which guided the grouping of the raingauges into three elevation zones.

Author's changes in the manuscript

Line 327-329 now reads "….The grouping in this study is based on the hierarchical clustering technique, expert knowledge about the study area but also guided by relevant past studies in the basin (e.g. World Bank, 2010b; Beilfuss, 2012). …."

Referee Comment

line 322. I did not find any reference to "distribution transformation" in the work of Fang et al. (2015). There is an approach in that paper (variance scaling), whose expression resembles eq. 6 (although with differences). What is also puzzling is that the reference to correction of frequency-based indices appears in the abstract of that work, but applied to Quantile mapping and to the Power transformation methods. Can the authors clarify this?

Author's Response and changes in the manuscript

We have corrected the sentences following the comment that we much appreciate. We have cited Fang et al. (2015) for the Quantile mapping based on an empirical distribution (QME) method. We have since removed the reference of Fang et al. (2015) from the Distribution transformation (DT). This was a mix up on the part of the authors.

Referee Comment

line 367. Correlation does not imply interdependence.

Author's Response

This has been corrected

Referee Comment

line 384. Is it the ratio of variances being shown in the plots?

Author's Response

The metrics used to build the Taylor Diagram are Correlation, and the ratio of variances, Root Mean square Difference (RMSD) (Taylor, 2001;Lo Conti et al., 2014).

The final plot shows the Standard Deviation together with correlation coefficient and RMSD.

Referee Comment

Figure 2. Somewhat hard to read. I believe it should be improved.

Author's Response and changes in the manuscript

The figure has been improved on its resolution. Grey scale has been replaced with pseudo scale which is more visible.

Referee Comment

Figure 3. The quality of the plots differs. Please fix this.

Author's Response and changes in the manuscript

The quality and scale of the plots have been improved

Referee Comment

Figure 5. Is this information not already contained in Figure 4?

Author's Response

The two figures are different. Figure 4 which is now a bar graph provides frequency based statistics (mean, max, ratio of gauged sum vs CMORPH sum for 1999-2013)
Figure 5 now shows the time-series-based metrics: Nash Sutcliffe (NSE) Mean Absolute Error (MAE) and percentage bias of corrected and uncorrected CMORPH daily rainfall averaged for the Lower Zambezi, Middle Zambezi and Upper Zambezi.

Author's changes in the manuscript

We have also improved the annotations on these two figures to avoid confusion to the readers.

Referee Comment

Figure 7. The plots are difficult to interpret. Consider using a Log-scale on the y-axis.

Author's Response and changes in the manuscript

The visibility of the plots have been improved.

Referee Comment

Table 1. Please clarify what "estimated ratio" is.

Authors' Response

Estimated ratio is obtained by dividing CMORPH rainfall total and gauge based rainfall totals for the 1999-2013 period.

Author's changes in the manuscript

This has been clarified in the manuscript (section 4.3.6) and now Table 4 annotation.

Referee Comment

line 660. How does adjusting the daily mean directly affect correlation coefficients and root mean square differences (defined according to the paper)? Probably indirectly because daily means are time-variant. If so, the choice of window is very relevant and, unfortunately, only one window was explored.

Author's Response and changes in the manuscript.

We took note of the reviewer's comment.

Author's changes in the manuscript.

We corrected sentence in the conclusions section to: "Assessment through standard statistics, Taylor Diagrams, t-tests, ANOVA and q-q plots reveal that STB that accounts space and time variation of bias, is found more effective in reducing rainfall bias in the basin than the rest of the bias correction schemes that ignore spatial variability in rainfall. This indicates that the temporal aspect of CMORPH bias is more important than the spatial aspect in the Zambezi Basin".

On time windows, the authors used the analyses made by Bhatti et al. (2016) who explored sequential and moving windows. Tests for window lengths of 3, 5, 7, ..., 31 days indicated that a 7-day sequential time window is most appropriate for bias correction. Therefore a 7-day moving time window is adopted by preliminary analysis with accumulated rainfall of minimum 5 mm that occurred over at least 5 rainy days during the 7-day window. In addition, 5-day tests as preliminary were tested as well in this study. Preliminary analysis of wet season rainfall on all gauges in the Zambezi Basin indicates that the criterion in Bhatti et al. (2016) are commonly met so the above thresholds are adopted for this study.

References.

Beilfuss, R.: A Risky Climate for Southern African Hydro: Assessing hydrological risks and consequences for Zambezi River Basin dams, 2012.

Bhatti, H., Rientjes, T., Haile, A., Habib, E., and Verhoef, W.: Evaluation of Bias Correction Method for Satellite-Based Rainfall Data, Sensors, 16, 884, 2016.

Field , A.: Discovering statistics using SPSS 2nd ed. Sage Publications, 2009.

Lo Conti, F., Hsu, K.-L., Noto, L. V., and Sorooshian, S.: Evaluation and comparison of satellite precipitation estimates with reference to a local area in the Mediterranean Sea, Atmospheric Research, 138, 189-204, http://dx.doi.org/10.1016/j.atmosres.2013.11.011, 2014.

NIST/SEMATECH: e-handbook of statistical methods. Croarkin, C., Tobias, P., and Zey, C. (Eds.), NIST ;, [Gaithersburg, Md.] :, 2001.

Rosenfeld, D., and Mintz, Y.: Evaporation of Rain Falling from Convective Clouds as Derived from Radar Measurements, Journal of Applied Meteorology, 27, 209-215, 10.1175/1520-0450(1988)027<0209:eorffc>2.0.co;2, 1988.

Smith, T. M., Arkin, P. A., Bates, J. J., and Huffman, G. J.: Estimating Bias of Satellite-Based Precipitation Estimates, Journal of Hydrometeorology, 7, 841-856, 10.1175/JHM524.1, 2006.

Taylor, K. E.: Summarizing multiple aspects of model performance in a single diagram, Journal of Geophysical Research: Atmospheres, 106, 7183-7192, 10.1029/2000JD900719, 2001.

Wilks, D.: Statistical Methods in the Atmospheric Sciences, 2nd ed., Academic Press, Burlington, Mass, 2006.

World Bank: The Zambezi River Basin : A Multi-Sector Investment Opportunities Analysis - Summary Report. World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/2958 License: Creative Commons Attribution CC BY 3.0., 2010a.

World Bank: The Zambezi River Basin: A Multi-Sector Investment Opportunities Analysis, Volume 2 Basin Development Scenarios, 2010b.

Yang, X., Xie, X., Liu, D. L., Ji, F., and Wang, L.: Spatial Interpolation of Daily Rainfall Data for Local Climate Impact Assessment over Greater Sydney Region, Advances in Meteorology, 2015, 12, 10.1155/2015/563629, 2015.

Response to Interactive comment on "Performance of bias correction schemes for CMORPH rainfall estimates in the Zambezi River Basin" by Webster Gumindoga et al.

Anonymous Referee #2

Received and published: 05 December 2017

Referee Comment

This paper investigates the use of bias correction schemes to correct satellite rainfall estimates in the Zambezi basin, a region in the world where data gauged rainfall is limited. With 50 million people dependent on water from this basin, having an accurate spatial and temporal representation of rainfall can help with modelling the water balance accurately which in turn can be used in studies on for example drought mitigation and risk reduction. Lacking accurate data, understanding the uncertainty within the products that are available is essential. This work applies existing methodologies to a new location. I believe this work should be publish because it applies sounds scientific methods and theories in a region where despite the high risk of hydrological disasters there are little models and data available. I suggest minor changes to strengthen the paper hydrological aspects of this paper.

Author Response

The authors thank the reviewer for finding merit in our manuscript. We address all comments to strengthen the manuscript.

Referee Comment

Questions posed to reviewers:

(1) Does the paper address relevant scientific questions within the scope of HESS? I believe the hydrological application of this paper is currently limited and the paper could be strengthened in this aspect.

Author Response and changes in the manuscript

The authors have added in the results and discussion section that errors in rainfall estimates may have propagation effects in hydrological applications so bias should be assessed and corrected for to make satellite rainfall estimates (SREs) more reliable and accurate for use. We also note that the wrong detection of rainfall is a concern to hydrological application of CMORPH estimates such as shown for poor performance of CMORPH during the dry season, a finding also presented in other studies in Africa. Therefore, for monitoring the frequent droughts in the Zambezi Basin CMORPH estimates should be evaluated and corrected. Correction is also advocated for heavy rainfall events (> 20 mm /day) where CMORPH detection is found to be weak, which may cause deterioration of land surface hydrological process simulation and flood forecasting.

However the much detailed hydrological application are contained in the follow-up paper by the same authors entitled: 'Hydrologic evaluation of bias corrected CMORPH rainfall estimates at the headwater catchment of the Zambezi River'

Referee Comment

(2) Does the paper present novel concepts, ideas, tools, or data? This paper applies existing concepts to a new (very relevant) location.

Author Response

We thank the reviewers for the observation.

Referee Comment

(3) Are substantial conclusions reached? This is not possible with the results, but this does not affect the quality of the conclusion.

Author Response changes in the manuscript

The authors have revised the conclusions section so that the there is a clear match between the objectives, results and conclusions.

Referee Comment

(4) Are the scientific methods and assumptions valid and clearly outlined? Yes, although some clarification with regards to the gauged rainfall should be supplied.

Author's Response and changes in the manuscript

In section 3.1.2, the authors made clarifications on the 66 stations that were obtained from meteorological departments in Botswana, Malawi, Mozambique, Zambia and Zimbabwe that cover the study area. We have also added supplementary table that describes the location of the rain gauge stations in the Zambezi subbasins showing the subbasin they belong to, year of data availability, % of missing gaps, station elevation and distance from large scale water bodies.

Referee Comment

(5) Are the results sufficient to support the interpretations and conclusions? Generally yes, although conclusion should be caveated with regards to the limited gauged rainfall data and the expected misrepresentation spatially due to this.

Author Response

We have mentioned in the conclusions that the overall performance is affected among other things by the sparse and irregular distributed rain gauges (described in item (4) above) in the

Zambezi Basin. Rain gauge networks often have low density with stations that are not evenly distributed particularly in the North and North-Western part of the Basin.

Referee Comment

(6) Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? Yes, with exception of how the gauged rainfall was constructed.

Author Response

We revisited the description and made improvements in section 3.1.2 on gauge data.

Author's changes in the manuscript

Section 3.1.2 now reads:

'……All the stations are standard type raingauges with a measuring cylinder whose units of measurement is millimetres (mm). …..”

We also explained that stations are irregularly distributed across the vast basin and are located at elevations between 3 m to 1575 m. The minimum, maximum and average distance between the rain gauges is 3.5 km (Zumbo in Mozambique-Kanyemba in Zimbabwe), 1570 km (Mwinilunga in Zambia-Marromeu in Mozambique) and 565 km respectively. The rain gauged network has density of 1 station per 24.000 km^2. The network is most dense in the Shire River sub-basin in Malawi (1 station per 7.500 km2) and very sparse in Tete sub-basin in Mozambique (1 station per 16.000 km^2). The Quando/Chobo sub-basin has no rain gauges at all.

Referee Comment

(7) Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Yes

Author's Response

We thank the reviewers for the observation

Referee Comment

(8) Does the title clearly reflect the contents of the paper? Yes

Author's Response

We thank the reviewers for the observation

Referee Comment

Yes (9) Does the abstract provide a concise and complete summary? Yes

Author's Response

We thank the reviewers for the observation

Referee Comment

(10) Is the overall presentation well-structured and clear? Yes

Author's Response

We thank the reviewers for the observation

Referee Comment

(11) Is the language fluent and precise? Yes

Author's Response

We thank the reviewers for the observation

Referee Comment

(12) Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes

Author's Response

We thank the reviewers for the observation

Referee Comment

(13) Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? Yes, please see comments below.

Author's Response

Specific comments have been attended to.

Referee Comment

(14) Are the number and quality of references appropriate? Yes

Author's response

We thank the reviewers for the observation

Referee Comment

(15) Is the amount and quality of supplementary material appropriate? Not applicable.

GENERAL COMMENTS

Referee Comment

Topographical relationship and distance to lake relationship to bias not found. More details are required with regards to the used gauged data and in which category the gauges are locations e.g. are there an equal amount of gauges in all of the categories? Also the sensitivity of the method to the amount of gauged data should be discussed, perhaps if there were a few more gauges a relationship could be found.

Author Response and changes in the manuscript

Section 3.2 has been extended to explain the number of raingauges in each distance zone. The stations are not evenly distributed in the 4 distance zones. We note that the majority of the stations (47 %) lie in the > 100 km distance from large scale open water bodies whilst only less than 1 % are in the < 10 km zone.

The authors revisited the analysis made through Taylor diagrams on whether elevation or distance from large scale open water bodies affect the relationship between gauge and CMORPH. Analysis on gauge and CMORPH data show better performance for higher elevation in the Zambezi Basin. Such analysis was established for rain gauges within elevation classes of < 250 m, 250 - 950 m and > 950 m. The relationship between gauge and CMORPH data is improved for large distance to large-scale open water bodies. This was established for rain gauges located within specified distances of < 10 km, 10 -50 km, 50 -100 km and > 100 km to a large scale open water body.

Referee Comment

Discussion paper should be named as a caveat. Especially as the Elevation zone bias correction method performs well this conclusion requires more justification to be convincing or it needs to be changed/’mellowed’.

Author’s Response and changes in the manuscript

The authors have modified the conclusion to accommodate the good performance of the elevation zone bias. This is more so in the found improved relationship between distance from open water bodies and bias. However it should be noted that the linear baas correction scheme (STB) that considers space and time variation of SRE bias, is found more effective in reducing rainfall bias in the basin than the EZ which does not consider the spatial variability in rainfall. This indicates that the temporal aspect of SRE bias is more important than the spatial aspect of bias in the Zambezi Basin.

Referee Comment

Taylor diagrams, I have not come across these before and find them difficult to understand. I understand the benefit of showing 3 performance scores on one plot, perhaps when you introduce them you can try and clarify by using a simple diagram, showing where the perfect model would sit and what it means when the results are located up/down/sideways from this perfect point.

Author's Response

We have made more detailed clarification in the interpretation of the Taylor diagram.

Author's changes in the manuscript

In the methods section '3.6. Assessment through Taylor diagram' we have included a clearer explanation on how the Taylor Diagram is interpreted. In addition, in the results section where the Taylor diagram is appearing we are referring to a supplementary file (Appendix 2) that summarizes and gives the absolute values of the 3 performance scores (Pearson's product-moment correlation coefficient (R), root mean square difference (E), and the ratio of variances on a 2-D plot) used to develop the Taylor diagram.

Referee Comment

Strengthen link to hydrology by doing for example comparing cumulative rainfall volumes over the time period of a drought (or take the dry seasons) of the different methods. This quick analysis would give an indication of the uncertainty of the methods and the impact this would have for the volumes of water in any type of water balance analysis, which is essential for hydrological applications. A comparison to spatial rainfall derived from gauges isn't necessarily required to get an indication of the range of uncertainty of the methods.

Author Response and changes in the manuscript

The authors have strengthened the link to hydrology by expanding section 5.1.1 which provides seasonal influences on CMORPH bias correction. Tables 4 and 5 give 'estimated ratio' of cumulative rainfall volumes (1999-2013) for the five different bias correction schemes against the gauge estimates but grouped into dry (April-Sept) and wet (Oct-March) seasons. We believe this analysis is important for water balance assessment as also alluded to by the reviewer. Overall, the STB, PT and EZ methods are more effective in reducing the bias in the cumulative rainfall totals in the two seasons and can thus be used for water balance assessment in the basin.

Referee Comment

Discussion is missing. This is another opportunity to link to hydrology and perhaps list your next steps.

Author's Response and changes in the manuscript

The authors have strengthened the discussion section. Our next steps as mentioned in the manuscript are to evaluate application of CMORPH SREs for hydrologic modelling in the Zambezi basin by the REW model. This by selecting the two best bias correction schemes: STB and EZ. Through these results we aim to evaluate how the performance of REW model used for streamflow predictions is affected when bias corrected and uncorrected.

Referee Comment

Is there any gauged flow data? Especially in regions where gauge rainfall in scares, gauged flow can really help with verifying rainfall data.

Author's Response

We appreciate the reviewers for the comment and suggestion. However runoff modelling is not part of this paper but will be handles in the paper on 'Hydrologic evaluation of bias corrected CMORPH rainfall estimates at the headwater catchment of the Zambezi River' as already alluded to.

Referee Comment

Will you next test the performance of these methods using a hydrological model?

Author's Response

Yes, the authors are working on a manuscript on 'Hydrologic evaluation of bias corrected CMORPH rainfall estimates at the headwater catchment of the Zambezi River'

Referee Comment

Figure 1, use differences in colours and symbols for the gauges to indicate in which height and distance category they fall.

Author's Response

We thank the reviewer for the observation.

Author's changes in the manuscript

Figure 1 has been improved to include different colours of the raingauges according to the 3 elevation zones. However for the distance zones, we could not differentiate the colours as well since this wold make Figure 1 unreadable.

The contours on the map of Euclidian distance (km) from large open water bodies helps to illustrate the message that would have been shown by the different colours.

Referee Comment

Section 3.1.2, expand on which stations were omitted and add how many station per height and distance category were used. Include length of available time series. Consider using a table.

Author's Response and changes in the manuscript

Section 3.1.2 has been modified according to the reviewer suggestion and Table 1 shows Elevation and distance from large scale open water bodies.

We have included a table under supplementary data (Appendix 1) that shows the rain gauge stations in the Zambezi subbasins showing x and y location, subbasin they belong to, year of data availability, % of missing gaps, station elevation and distance from large open water bodies. After screening, 6 stations with suspicious time series were removed and these are not show in the supplementary table to reduce length of manuscript. Stations are affected by data gaps but the remaining 60 stations are of sufficiently long duration to serve the objectives of this study.

Referee Comment

Also, if spatial (gauged) rainfall was derived explain how, if it wasn't it might be helpful to state this too (if you have chosen not to, I'm assuming this is because generation spatial rainfall from point observations in ridden with uncertainties itself. You might want to add this is, because it gives insight in your understanding of the uncertainties related to your observations).

Author Response and changes in the manuscript

We have added a new section '3.1.3. comparison of satellite derived rainfall data with rain gauge observations'

In this study, we compare rain gauge observations at point scale to CMORPH satellite derived rainfall data at pixel scale. Comparison is at daily base but also are weekly time base covering the period 1999-2013. We follow (Cohen Liechti et al., 2012;Dinku et al., 2008;Haile et al., 2014;Hughes, 2006;Tsidu, 2012;Worqlul et al., 2014) who report on point-to-pixel comparisons in African basins. We resort to point- to- pixel comparison since a comparison of spatially interpolated rainfall at pixel scale to match CMORPH pixel scale would be rather doubtful. We note from past studies that interpolation using the data from sparse and uneven distributed rain gauges often bring unreliability and uncertainty to the results (Heidinger et al. 2012, Li and Heap 2011, Tobin and Bennett 2010, Yin et al. 2008). For pixel-to-pixel comparison, there is demand for a well distributed rain gauge network that would not hamper accurate interpolation (Worqlul et al., 2014).

We however also note that comparison on a point-to-pixel basis commonly has limitations of mismatch between the scales of observation and refer to studies by (Haile et al., 2013a;Haile et al., 2013b;Villarini et al., 2008).

Referee Comment

Figure 2, analysis would be more valuable if split into two figures of wet and dry season. The author indicates that the biases are different for these two so this paper would be insightful and helpful when assessing this rainfall product for application into a hydrological model.

Author Response and changes on manuscript

Seasonal influences on bias and bias removal are addressed is section 4.3.6. So the authors have maintained Figure 2 as it is. Changes have been made on the annotation of Figure 2 to now read: The spatial variation of bias (%) estimate for gauge vs CMORPH daily rainfall (1999-2013) for the Zambezi Basin. The gauge based isohyets for Mean Annual Precipitation (MAP) are also shown in blue.

Our next paper is on how uncorrected and bias corrected CMORPH satellite-based rainfall estimates are evaluated for application in the Representative Elementary Watershed (REW) modelling approach in the Zambezi Basin.

Referee Comment

Figure 4, I find this figure confusing. I don't understand where the gauged, uncorrected and bias corrected are. Also, what was used to construct the mean and the max is unclear to me. This means I don't understand how you come to the conclusion about effectiveness of the schemes in section 4.3.1. Maybe this can be solved simply be having a clearer legend and adding a sentence to section 4.3.1.

Author's Response and changes on manuscript

We have replaced the radar graph with a bar graph (Figure 4) which is easier to visualise and understand. The mean is simply the arithmetic mean of the daily rainfall time series (1999-2013) for the gauge, uncorrected and bias corrected satellite rainfall. This is same approach for the maximum and the ratio of cumulative gauged sum vs CMORPH sum for the Lower, Middle and Upper Zambezi subbasins.

Referee Comment

Figures 7, I find the greys difficult to distinguish. If a black and white figure is required please consider using fills/hatching. Otherwise the colours used in Figure 8 are excellent, so perhaps reuse these.

Author's Response and changes in the manuscript

Figure 7 has been improved following recommendation by the reviewer.

Thank you for your contribution to our understanding of rainfall products available for Africa. Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-385, 2017

References

Cohen Liechti, T., Matos, J. P., Boillat, J. L., and Schleiss, A. J.: Comparison and evaluation of satellite derived precipitation products for hydrological modeling of the Zambezi River Basin, Hydrol. Earth Syst. Sci., 16, 489-500, 2012.

Dinku, T., Chidzambwa, S., Ceccato, P., Connor, S. J., and Ropelewski, C. F.: Validation of high-resolution satellite rainfall products over complex terrain, International Journal of Remote Sensing, 29, 4097-4110, 10.1080/01431160701772526, 2008.

Habib, E., ElSaadani, M., and Haile, A. T.: Climatology-Focused Evaluation of CMORPH and TMPA Satellite Rainfall Products over the Nile Basin, Journal of Applied Meteorology and Climatology, 51, 2105-2121, 10.1175/jamc-d-11-0252.1, 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, http://dx.doi.org/10.1016/j.jag.2012.08.012, 2013a.

Haile, A. T., Habib, E., and Rientjes, T. H. M.: Evaluation of the climate prediction center CPC morphing technique CMORPH rainfall product on hourly time scales over the source of the Blue Nile river, Hydrological processes, 27, 1829-1839, 2013b.

Haile, A. T., Yan, F., and Habib, E.: Accuracy of the CMORPH satellite-rainfall product over Lake Tana Basin in Eastern Africa, Atmospheric Research. *In Press, Accepted manuscript*, http://dx.doi.org/10.1016/j.atmosres.2014.11.011, 2014.

Hughes, D. A.: Comparison of satellite rainfall data with observations from gauging station networks, Journal of Hydrology, 327, 399-410, http://dx.doi.org/10.1016/j.jhydrol.2005.11.041, 2006.

Tsidu, G. M.: High-Resolution Monthly Rainfall Database for Ethiopia: Homogenization, Reconstruction, and Gridding, Journal of Climate, 25, 8422-8443, 10.1175/JCLI-D-12-00027.1, 2012.

Villarini, G., Mandapaka, P. V., Krajewski, W. F., and Moore, R. J.: Rainfall and sampling uncertainties: A rain gauge perspective, Journal of Geophysical Research: Atmospheres, 113, n/a-n/a, 10.1029/2007jd009214, 2008.

Worqlul, A. W., Maathuis, B., Adem, A. A., Demissie, S. S., Langan, S., and Steenhuis, T. S.: Comparison of rainfall estimations by TRMM 3B42, MPEG and CFSR with ground-observed data for the Lake Tana basin in Ethiopia, Hydrol. Earth Syst. Sci., 18, 4871-4881, 10.5194/hess-18-4871-2014, 2014.

Abstract

Satellite Rainfall Estimates (SRE) are prone to bias as they are indirect derivatives of the visible, infrared, and/or microwave cloud properties, hence SREs need correction. We ~~test~~ evaluate the influence of elevation and distance from large scale open water bodies on bias for Climate Prediction Center-MORPHing (CMORPH) rainfall estimates in the Zambezi Basin. The effectiveness of five linear/non-linear and time-space variant/invariant bias correction schemes was evaluated for daily rainfall ~~rates~~ estimates and climatic seasonality. We used daily time series (1999-2013) from 52 gauge stations~~,~~ and for CMORPH SREs~~time series~~ for the Zambezi Basin. To evaluate effectiveness of the bias correction techniques, spatial cross-validation was applied~~,~~based on 8 stations whereas temporal cross-validation was based on the 1998-1999 CMORPH time series.~~ .~~ ~~Taylor diagrams show that station elevation and distance from large scale open water bodies have an influence on bias.~~ For correction, the Spatio-temporal Bias (STB) and Elevation Zone bias (EZ) schemes are more effective in removing bias~~ for the Lower, Middle and Upper Zambezi subbasins~~. STB improved the correlation coefficient and Nash Sutcliffe efficiency by 50 % and 53 % respectively and reduced the root mean squared difference and relative bias by 25 % and 33 % respectively. Paired t-tests showed that there is no significant difference ($p < 0.05$) in the daily means of CMORPH against gauge estimates after bias correction, whereas ANOVA post-hoc tests reveal that the STB and EZ bias correction schemes are preferable. Corrected CMORPH rainfall reveal an overestimation of very light rainfall (< 2.5 mm/day) and underestimation of very heavy rainfall (> 20.0 mm/day) for all five correction schemes. Bias is best reduced for rainfall rates of 0.0-2.5 and 5.0-10.0 mm/day, a result also ~~confirmed~~ shown through quantile-quantile (q-q) plots. Bias removal proved to be more effective in the wet season than in the dry. The spatial cross-validation approach revealed that the majority of the bias correction schemes removed bias by 28 %. The temporal cross-validation approach showed in some instances the effectiveness of the bias correction schemes. Taylor diagrams show that station elevation and distance from large scale open water bodies have an influence on CMORPH performance. ~~due to limited length of the time series. Therefore, the f~~ Findings of this study show ~~underscore~~ the importance of applying bias correction to satellite rainfall estimates before application in hydrological analyses.

Keywords: *distance zone, elevation zone, satellite rainfall estimates, spatio-temporal bias, Taylor diagram*

1. Introduction

Correction schemes for rainfall estimates are developed for climate models (Maraun, 2016;Grillakis et al., 2017;Switanek et al., 2017), for radar approaches (Cecinati et al., 2017;Yoo et al., 2014) and for satellite based, multi-sensor~~,~~ approaches (Najmaddin et al., 2017;Valdés-Pineda et al., 2016). In this study focus is on satellite rainfall estimates (SREs) to improve reliability in water resource applications.

Studies in satellite based rainfall estimation show that estimates are prone to systematic and random errors (Gebregiorgis et al., 2012;Habib et al., 2014;Shrestha, 2011;Tesfagiorgis et al., 2011;Vernimmen et al., 2012;Woody et al., 2014)~~.~~ Errors result primarily from the indirect estimation of rainfall from visible (VIS), infrared (IR), and/or microwave (MW) based satellite remote sensing of cloud properties (Pereira Filho et al., 2010;Romano et al., 2017). Systematic errors in SREs commonly are referred to as bias, which is a measure that indicates the accumulated difference between rain gauge observations and SREs. Bias in SREs is expressed for rainfall depth (Habib et al., 2012b), rain rate (Haile et al., 2013) and frequency at which rain rates occur (Khan et al., 2014). Bias may be negative or positive where negative bias indicates underestimation whereas positive bias indicates overestimation (Liu, 2015;Moazami et al., 2013).

Recent studies on CMORPH (Wehbe et al., 2017;Jiang et al., 2016;Liu et al., 2015;Haile et al., 2015) reveal that accuracy of CMORPH satellite rainfall varies across different regions, but causes are not directly indentifiable. As such correction schemes serve to reduce systematic errors and to improve aplicability of SREs. Correction schemes rely on assumptions that adjust errors in space and/or time (Habib et al., 2014). Some correction schemes consider correction only for spatial distributed patterns in bias, commonly known ~~in literature~~ as space variant/invariant. Approaches that correct for spatially averaged bias have roots in radar rainfall estimation (Seo et al., 1999) but are unsuitable for large scale basins (> 5,000 km^2) where rainfall may substantially vary in space (Habib et al., 2014). Studies by Tefsagiorgis et al. (2011) in Oklahoma (USA) and Müller and Thompson (2013) in Nepal concluded that space variant correction schemes are more effective in reducing CMORPH and TRMM bias than space invariant correction schemes. In a study conducted in the Upper Blue Nile basin in Ethiopia, Bhatti et al. (2016) show that CMORPH bias correction is most effective when correction is for a 7 day sequential window.

Bias correction schemes based on regression techniques have reported distortion of frequency of rainfall rates (Ines and Hansen, 2006;Marcos et al., 2018). Multiplicative shift procedures tend to adjust SRE rainfall rates, but Ines and Hansen (2006) reported that they do not correct systematic errors in rainfall frequency of climate models. Non-multiplicative bias correction schemes preserve the timing of rainfall within a season (Fang et al., 2015;Hempel et al., 2013). Studies that have applied non-linear bias correction schemes such as Power Function report correction of extreme values (depth, rate and frequency) thus mitigating the underestimation and overestimation of CMORPH rainfall (Vernimmen et al., 2012). The study by Tian (2010) in the United States noted that the Bayesian (likelihood) analysis techniques are found to over-adjust both light and heavy satellite rainfall towards moderate CMORPH rainfall.

Bias often exhibits a topographic and latitudinal dependency as, for instance, shown for the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center-MORPHing (CMORPH) product in the Nile Basin (Bitew et al., 2011;Habib et al., 2012a;Haile et al., 2013). For Southern Africa, Thorne et al. (2001), Dinku et al. (2008) and Meyer et al. (2017) show that bias in rainfall rate and frequency can be related to location, topography, local climate and season. First studies in the Zambezi Basin (Southern Africa) on SREs show evidence that necessitates correction of SREs. For example, Cohen Liechti (2012) show bias in CMORPH SREs for daily rainfall and for accumulated rainfall at monthly scale. Matos et al. (2013), Thiemig et al. (2012) and Toté et al. (2015) show that bias in rainfall depth at time intervals ranging from daily to monthly varies across geographical domains in the Zambezi Basin and may be as large as ±50 %. Besides topographic effects, rainfall is affected by presence of large scale open water bodies which influences surface or atmospheric properties (Haile et al., 2009;Rientjes et al., 2013a). As such, SREs may be affected as well as suggested in (Rientjes et al., 2013b).

For less developed areas such as in the Zambezi Basin that is selected for this study, applications of SREs are ~~very~~ limited. This is despite the strategic importance of the basin in providing water to over 30 million people (World Bank, 2010a). An exception is the study by Beyer et al. (2014) on correction of the TRMM-3B42 product for agricultural purposes in the Upper Zambezi Basin. Studies (Cohen Liechti et al., 2012;Meier et al., 2011) ~~(~~on use of SREs in the Zambezi River Basin mainly focused on accuracy assessment of the SREs using standard statistical indicators with little or no effort to perform bias correction despite the evidence of errors in these products. The use of uncorrected satellite rainfall is reported for hydrological modelling in the Nile Basin (Bitew and Gebremichael, 2011) and Zambezi Basin (Cohen Liechti et al., 2012), respectively, and for drought monitoring in Mozambique (Toté et al., 2015). The above studies highlight the ~~demand~~ need ~~for the use of~~ to correct~~ed~~ SREs. ~~Our~~ The selection of CMORPH satellite rainfall for this study is based on successful applications of bias corrected CMORPH estimates in African basins for hydrological modelling (Habib et al., 2014) and flood predictions in West Africa (Thiemig et al., 2013). In first publications on CMORPH, Joyce et al. (2004) describe CMORPH as a gridded precipitation product that estimates rainfall with information derived from IR data and MW data. CMORPH combines the retrieval accuracy of passive MW estimates with IR measurements which are available at high temporal resolution but with low accuracy. The important distinction between CMORPH and other merging methods is that the IR data are not used for rainfall estimation but used only to propagate rainfall features that have been derived from microwave data. The flexible ‘morphing’ technique is applied to modify the shape and rate of rainfall patterns. CMORPH is operational since 2002 for which data is available at the CPC of the National Centers for Environmental Prediction (NCEP) (after http://www.ncep.noaa.gov/). Recent publications on CMORPH in African basins exist (Wehbe et al., 2017;Koutsouris et al., 2016;Jiang et al., 2016;Haile et al., 2015). However CMORPH data applicability ~~following~~after bias correction in the semi-arid Zambezi Basin has not been fully investigated. Therefore, evaluating and finding the appropriate bias correction method for the data is necessary for water resources management in the basin.

In this study we use daily CMORPH and rain gauge data for Upper, Middle, and Lower Zambezi basins to (1) evaluate if performance of CMORPH rainfall is affected by elevation and distance from large scale open water bodies (2) evaluate the effectiveness of linear/non-linear and time-space variant/invariant bias correction schemes and (3) assess the performance of bias correction schemes to represent different rainfall rates and climate seasonality. Analysis serve to improve reliability of SREs applications in water resource applications in the Zambezi basin such as in drought analysis, flood prediction, weather forecasting and rainfall runoff modeling~~.~~

2. Study area

The Zambezi River is the fourth-longest river (~2,574 km) in Africa with basin area of ~1,390,000 km^2 (~4 % of the African continent). The river drains into the Indian Ocean and has mean annual discharge of 4,134 m^3/s (World Bank, 2010a). The river has its source in Zambia with~~,~~ basin boundaries ~~form country boundaries of~~ in Angola, Namibia Botswana, Zambia, Zimbabwe and Mozambique (Fig. 1). The basin is characteriszed by ~~has~~ considerable differences in elevation and topography, ~~and~~ distinct climatic seasons and presence of large scale open water bodies and, as such, makes the basin well suited for this study. The basin is divided into three subbasins i.e., the Lower Zambezi comprising the Tete, Lake Malawi/Shire, and Zambezi Delta basins, the Middle Zambezi ~~made~~ comprising ~~up of~~ the Kariba, Mupata, Kafue, and Luangwa basins, and the Upper Zambezi comprising~~nstituted by~~ the Kabompo, Lungwebungo, Luanginga, Barotse, and Cuando/Chobe basins (Beilfuss, 2012).

The elevation of the Zambezi basin ranges from < 200 m (for some parts of Mozambique) to >1500 m above sea level (for some parts of Zambia). Large scale open water bodies in and around the basin are Kariba, Cabora Bassa, Bangweulu, Chilwa and Nyasa. The Indian Ocean is to the east of Mozambique. Typical landcover types are woodland, grassland, water surfaces and cropland (Beilfuss et al., 2000). The basin is characterized by high annual rainfall (>1,400 mm/yr) in the northern and north-eastern areas but low annual rainfall (<500 mm/yr) in the southern and western parts (World Bank, 2010b). Due to this rainfall distribution, northern tributaries in the Upper Zambezi subbasin contribute 60 % of the mean annual discharge (Tumbare, 2000). The river and its tributaries are subject to seasonal floods and droughts that have devastating effects on the people and economies of the region, especially the poorest members of the population (Tumbare, 2005). It is not uncommon to experience both floods and droughts within the same hydrological year.

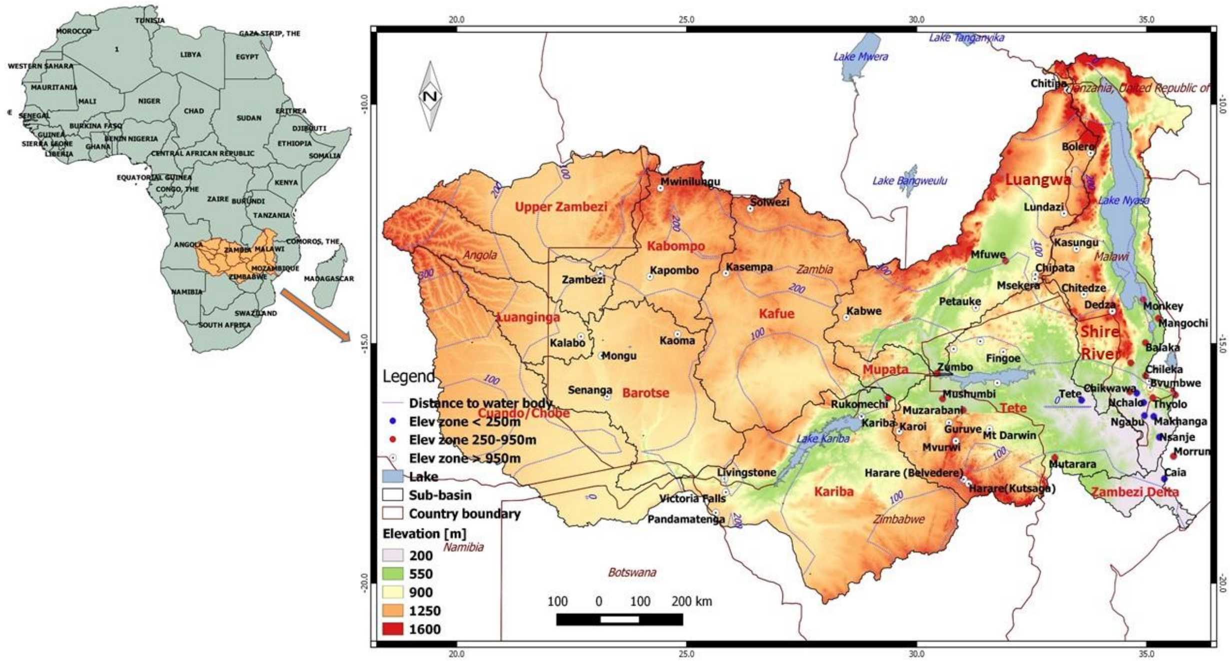


Figure 1: Zambezi River Basin from Africa with sub basins, major lakes, rivers, elevation, and locations and names of the 60 rain gauging stations used in this study. The Euclidian distance (km) from large scale open water bodies is also shown.

3. Materials and Methodology

3.1. Rainfall data

3.1.1. CMORPH

For this study, time series of CMORPH rainfall ~~product~~ images (1998-2013) at 8 km × 8 km, 30-minute resolution ~~are~~ were selected. Images are downloaded by means of the GeoNETCAST ISOD toolbox of ILWIS GIS software (http://52north.org/downloads/). Half hourly estimates ~~data was~~were aggregated to daily totals to match the observation interval of gauge based daily rainfall .

3.1.2. Rain gauge network

Time series of daily rainfall from 66 stations were obtained from meteorological departments in Botswana, Malawi, Mozambique, Zambia and Zimbabwe for stations that cover the study area. All the stations are standard type raingauges with a measuring cylinder whose units of measurement is millimetres (mm).

After screening, 6 stations with suspicious time series ~~are~~ were removed to remain with 60 stations. Some stations are affected by data gaps but the available time series are of sufficiently long duration to serve the objectives of this study. Stations are irregularly distributed across the vast basin and are located at elevation~~s~~ between 3 m to 1575 m (Figure 1). The minimum, maximum and average distance between the rain gauges is 3.5 km (Zumbo in Mozambique-Kanyemba in Zimbabwe), 1570 km (Mwinilunga in Zambia-Marromeu in Mozambique) and 565 km respectively. This variation of distances provides a good spatial base for~~-~~analysis in ths study. ~~of comparison of the performance of the SRE~~. ~~The Quando/Chobo sub-basin has no rain gauges at all.~~ Stations are located between an elevation range of 3 m to 1600 masl. Distances to ~~a~~ large scale open water bodies range between 5 km and 615 km. This allows us to evaluate if ~~assess the effect of~~ elevation and distance to large scale open water bodies affects CMORPH performance.

3.1.3. *Comparison of CMORPH and rain gauge estimates~~observations~~*

In this study, we compare rain gauge estimates at point scale to CMORPH satellite derived rainfall estimates~~data~~ at pixel scale (point-to-pixel). Comparison is at a daily time interval covering the period 1998-2013, following (Cohen Liechti et al., 2012;Dinku et al., 2008;Haile et al., 2014;Hughes, 2006;Tsidu, 2012;Worqlul et al., 2014) who report on point-to-pixel comparisons in African basins. We apply point-to-pixel comparison~~s~~ to rule out any aspect of interpolation error as a consequence of the low density network with unevenly distributed stations. ~~since a comparison of spatially interpolated rainfall at pixel scale to match CMORPH pixel scale~~, ~~From studies that rely on interpolation using data from sparse and uneven distributed rain gauges it is known that effects inherent to interpolation introduces unreliability and uncertainty to the results~~ We refer to (Heidinger et al., 2012;Li and Heap, 2011;Tobin and Bennett, 2010;Yin et al., 2008) who report that interpolation introduces unreliability and uncertainty to pixel basd rainfall estimates. Also, Worqlul et al. (2014)~~)~~ describe that for pixel-to-pixel comparison, there is demand for a well distributed rain gauge network that would not hamper accurate interpolation..

3.2. Elevation and distance from large scale open water bodies

Studies by (Habib et al., 2012a;Haile et al., 2009;Rientjes et al., 2013a)~~.~~ in the Nile Basin reveal that elevation and distance to large-scale open water bodies affect ~~rainfall distributions but and also affect the~~ performance of SREs. To assess such influences, ~~As such,~~ we classified the Zambezi Basin into 3 elevation zones for which the hierarchical cluster ‘within-groups linkage’ method in the Statistical Product and Service Solutions (SPSS) software was used. (Table 1).

Based on ~~rain gauge~~ Euclidian distance to large-scale open water bodies, 4 arbitrary distance zones are defined to group stations (Table 1). A detailed description on~~f~~ the individual stations, their elevation and distance to large-scale open water bodies is~~are~~ provided in Appendix 1. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) based DEM of 30 m resolution obtained from http://gdem.ersdac.jspacesystems.or.jp/, is used to represent elevation across the Zambezi Basin. The Euclidian distance of each rain gauge location to large-scale open water bodies is ~~computed~~ defined in a GIS environment through the distance calculation algorithm. Large-scale open water bodies are defined as perennial open water bodies with surface area > 700 km^2.

Table 1: Elevation and distance from large scale open water bodies

Zone ID	Elevation (m)	No. of stations	Mean elevation of stations (m)
Zone 1	< 250	8	90
Zone 2	250-950	21	510
Zone 3	> 950	31	1140

Zone ID	Distance (km)	No. of stations	Mean distance to large-scale open water bodies (km)
Zone 1	< 10 km	4	5
Zone 2	10 - 50	10	35
Zone 3	50 - 100	18	80
Zone 4	> 100	28	275

3.3. Bias correction schemes

Bias correction schemes evaluated in this study are the Spatio-temporal bias (STB), Elevation zone bias (EZ), Power transform (PT), Distribution transformation (DT), and the Quantile mapping based on an empirical distribution (QME). The five schemes are chosen based on merits documented in literature (Bhatti et al., 2016; Habib et al., 2014; Teutschbein and Seibert, 2013; Themeßl et al., 2012; Vernimmen et al., 2012), since we aim to correctwhile daily rainfall variability is preserved. We note that findings on the performance of selected bias correction schemes in literature do not allow for generalization but findings only apply to the respective study domains (Wehbe et al., 2017;Jiang et al., 2016;Liu et al., 2015;Haile et al., 2015).

In the procedure to define a time window for bias correction we follow (Habib et al., 2014) and (Bhatti et al.; 2016) who in the Lake Tana ~~basin~~ Basin (Ethiopia) carried out a sensitivity analysis on moving time windows and on sequential time windows. Window lengths of ~~between~~ 3~~, 5, 7, ...,~~and 31 days~~,~~ ~~respectively~~ are tested. Findings ~~from the aforementioned above mentioned studies~~ indicated that a 7-day sequential time window is most appropriate but only when a minimum of five rainy days were recorded within the 7-day window with a minimum rainfall accumulation depth of 5 mm, otherwise no bias is estimated (i.e. a value of 1 applies as bias correction factor). Preliminary tests in this study on 5 and 7-day moving and sequential windows on 20 individual stations distributed over the three elevation zones indicates that the 7-day sequential approach is well applicable in the Zambezi ~~basin~~Basin. As such the approach ~~is~~was selected.

The bias correction factors are calculated using only rain days (rainfall ≥ 1 mm). Otherwise in cases where both the gauge and satellite have zero values (RG=0 and CMORPH =0), correction is not applied and the ~~new~~ SRE value remains 0 mm/day.

Following Bhatti et al. (2016), we spatially ~~-~~interpolated ~~ion of~~ the bias correction factors so that factors are subsequently applied to all SRE pixels. For interpolation Universal Kriging was applied. Thus to systematically correct all CMORPH estimates, station based bias factors for each time window are spatially interpolated to arrive at spatial coverage across the study area and to allow for comparison with other approaches.

3.3.1. Spatio-temporal bias correction (STB)

This linear bias scheme has its origin in the correction of radar based precipitation estimates (Tesfagiorgis et al., 2011) and downscaled precipitation products from climate models. The CMOPRH daily rainfall estimates (S) are multiplied by the bias correction factor for the respective sequential time window for individual stations resulting in corrected CMORPH estimates (STB) in a temporally and spatially coherent manner (Equation [1]).

$$STB = S\frac{\sum_{t=d}^{t=d-l} S(i,t)}{\sum_{t=d}^{t=d-l} G(i,t)} \qquad \textbf{[1]}$$

Where:

G = ~~daily~~ gauged rainfall estimate (mm/day)
i = gauge number
d = day number
t = julian day number
l = length of a time window for bias correction

The advantages of this bias correction scheme is that it is straightforward and easy to implement due to its simplicity and modest data requirements. However, just like any multiplicative shift procedures of bias correction, STB does not correct intensities and systematic errors in rainfall frequency particularly the wet-day frequencies (Lenderink et al., 2007; Teutschbein and Seibert, 2013).

3.3.2. Elevation zone bias correction (EZ)

This bias scheme is proposed in this study and aims at correcting satellite rainfall for elevation influences. This method groups rain gauge stations into 3 elevation zones based on station elevation. The grouping in this study is based on the hierarchical clustering technique, expert knowledge about the study area but also guided by relevant past studies in the basin (e.g. World Bank, 2010b;Beilfuss, 2012). Each zone has the same bias correction factor but differs across the three zones. In the time domain bias factors vary following the 7-day sequential window approach. The corrected CMORPH estimates (EZ) at daily time interval are obtained by multiplying the uncorrected CMOPRH daily rainfall estimates (S) by the daily bias correction factor of each elevation zone.

$$EZ = S\,\frac{\sum_{t=d}^{t=d-l}\sum_{i=1}^{i=n} S(i,t)}{\sum_{t=d}^{t=d-l}\sum_{i=1}^{i=n} G(i,t)} \qquad \textbf{[2]}$$

The merits of this bias correction scheme is that the effects of elevation on rainfall depth are accounted for. SREs often have difficulties in capturing rainfall events due to orographic effects and thus require elevation based correction.

3.3.3. Power transform (PT)

The non-linear PT bias correction scheme has its origin in studies of climate change impact {Lafon, 2013 #926}. (Vernimmen et al., 2012) show that the scheme could be applied to correct satellite rainfall estimates for use in hydrological modelling and drought monitoring. The PT method uses an exponential form to adjust the standard deviation of rainfall series. The daily bias corrected CMORPH rainfall (PT) for a pixel that overlays a station is obtained using equation:

$$PT = aG(i,t)^{b} \qquad \textbf{[3]}$$

Where:
G = rain gauge estimate (mm/day)
a = prefactor such that the mean of the transformed CMORPH values is equal to the mean of gauge estimates
b = factor calculated such that for each rain gauge the coefficient of variation (CV) of CMORPH matches the gauge based counter parts
i = gauge number
t = day number

Optimized values for a and b are obtained through the generalized reduced gradient algorithm (Fylstra et al., 1998). Values for a and b vary for the 7-day time sequential window since correction is at daily time base. In the case of utilizing the PT method in a certain area (or for a certain period), the bias correction factor is spatially interpolated to result in comparable estimates with other bias correction schemes. The advantage of the bias scheme is that it adjusts extreme precipitation values in CMORPH estimates (Vernimmen et al., 2012). PT has reported limitations in correcting wet-day frequencies and intensities (Leander et al., 2008; Teutschbein and Seibert, 2013).

3.3.4. Distribution transformation (DT)

DT is an additive bias correction approach which has its origin in statistical downscaling of climate model data (Bouwer et al., 2004). The method transforms a statistical distribution function of daily CMORPH rainfall ~~rates~~estimates to match the distibution by gauged rainfall estimates. The procedure to match the CMORPH distribution function to gauge rainfall based counter parts is described in equations [4-8]. The principle to matching is that the difference in the mean value and differences in the variance are corrected for, in the 7-day sequential window. First, the bias correction factor for the mean (DTu) is determined by equation [4]:

$$DT_u = \frac{G_u}{S_u} \qquad \textbf{[4]}$$

G_u and S_u are mean values of 7-day gauge and CMORPH rainfall estimates.

Secondly, the correction factor for the variance $(DT\tau)$ is determined by the quotient of the 7-day standard deviations, $G\tau$ and $S\tau$, for gauge and CMORPH respectively.

$$DT\tau = \frac{G\tau}{S\tau} \qquad \textbf{[5]}$$

Once the correction factors which vary within a 7-day time sequential window are established, they are then applied to correct all daily CMORPH estimates (S) through equation [6] to obtain corrected CMORPH rainfall estimate (DT). The parameters DTu and $DT\tau$ are developed within a 7-day sequential window but correction is then at daily time intervals.

$$DT = (S(i,t) - Su)DT\tau + DTu * S\tau \qquad \textbf{[6]}$$

Uncorrected CMORPH daily values are returned if [6] results in negative values. The merit of this bias correction scheme is that it corrects wet-day frequencies and intensities. The disadvantage of this bias correction scheme is that adding the gauge based mean deviation to the satellite data destroys the physical consistency of the data. In addition, the method might result in the generation of too few rain days in the wet season, and sometimes the mean of daily intensities might be unrealistically corrected (Johnson and Sharma, 2011; Teutschbein and Seibert, 2013).

3.3.5. Quantile mapping based on an empirical distribution (QME)

This is a quantile based empirical-statistical error correction method with its origin in empirical transformation and bias correction of regional climate model-simulated precipitation (Themeßl et al., 2012). The method corrects CMORPH precipitation based on empirical cumulative distribution functions (*ecdfs*) which are established for each 7-day time window and for each station. The bias corrected rainfall (*QME*) using quantile mapping are expressed in terms of the empirical cumulative distribution function (*ecdf*) and its inverse (ecdf^{-1}). Parameters apply to a 7-day sequential window but correction is then at daily time interval with bias spatially averaged for the entire domain to allow for comparison with other approaches

$$QME = ecdf_{obs}^{-1}(ecdf_{raw}(S(i,t))) \quad \textbf{[7]}$$

Where:

$ecdf_{obs}$ = empirical cumulative distribution function for the gauge based observation
$ecdf_{raw}$ = empirical cumulative distribution function for the uncorrected CMORPH

The advantage of this bias scheme is that it corrects quantiles and preserves the extreme precipitation values (Themeßl et al., 2012). However, it also has its limitation due to the assumption that both the observed and satellite rainfall follow the same proposed distribution, which may introduce potential new biases.

3.4. Rainfall rates and seasons

To assess the performance of SREs for different classes of daily rainfall rates five classes are defined which indicate: very light (< 2.5 mm/day), light (2.5-5.0), moderate (5.0-10.0 mm/day), heavy (10.0-20.0 mm/day) and very heavy rainfall (> 20 mm/day).

Furthermore, gauge based estimates were divided into wet and dry seasonal periods to assess the influence of seasonality on performance of bias correction schemes. The wet season in the Zambezi Basin spans from October-March whereas the dry season spans from April-September.

3.5. Evaluation of CMORPH estimates

~~An evaluation of c~~Corrected and uncorrected CMORPH satellite rainfall estimates are evaluated with reference to ~~with~~ rain gauge estimates ~~data was performed~~ using statistics that measure systematic differences (i.e. percentage bias and Mean Absolute Error (MAE)), measures of association (e.g. correlation coefficient and Nash Sutcliffe Efficency (NSE)) and random differences (e.g. standard deviation of differences and coefficient of variation) (Haile et al., 2013). Bias is a measure of how the satellite rainfall estimate deviates from the raingauge estimate, and the result is normalised by the summation of the gauge values. A positive value indicates overestimation whereas a negative value indicates underestimation. The correlation coefficient (ranging between +1 and −1) represents the linear dependence of gauge and CMORPH data. MAE is the arithmetic average of the absolute values of the differences between the daily gauge and CMORPH satellite rainfall estimates. The MAE is zero if the rainfall estimates are perfect and increases as discrepancies between the gauge and satellite become larger. NSE indicates how well the satellite rainfall matches the raingauge observation and it ranges between - ∞ and 1, with NSE = 1 meaning a perfect fit (Nash and Sutcliffe, 1970).

Equations [8-11] apply.

$$bias\ (\%) = \frac{\sum(S-G)}{\sum G} * 100 \qquad \textbf{[8]}$$

$$R = \frac{\sum(G-\bar{G})(S-\bar{S})}{\sqrt{\sum(G-\bar{G})^2}\sqrt{\sum(S-\bar{S})^2}} \qquad \textbf{[9]}$$

$$MAE = \frac{1}{n}\sum|S-G| \qquad \textbf{[10]}$$

$$NSE = \frac{\sum(G-S)^2}{\sum(G-\bar{G})^2} \qquad \textbf{[11]}$$

Where:

S = satellite rainfall estimates (mm/day)
$\bar{S}$ = mean of the satellite rainfall estimates (mm/day)
G = rainfall estimates by a rain gauge (mm/day)
$\bar{G}$ = mean values of rainfall recorded by a rain gauge (mm/day)
n = number of observations

3.6. Test for differences of mean

To detect significant differences between gauge and satellite rainfall (corrected and uncorrected) and differences amongst the five bias correction methods described in Section 3.3, we apply paired t-test and analysis of variance (ANOVA) tests.

3.6.1. Paired t-tests

A paired t-test was used to test whether there is a significant difference between raingauge, uncorrected and bias corrected CMORPH satellite rainfall for the 52 raingauges. Results are summarized for the Upper, Lower and Middle Zambezi. The paired t-test compares the mean difference of the values to zero. It depends on the mean difference, the variability of the differences and the number of data. The null hypothesis (H_0) is that there is no difference in mean gauge and satellite daily rainfall (uncorrected and bias corrected). If the p-value is less than or equal 0.05 (5%), the result is deemed statistically significant, i.e., there is a significant relationship between the gauge and satellite rainfall (Wilks, 2006;Field 2009).

3.6.2. Analysis of Variance (ANOVA) test

The ANOVA-test aims to test whether there is a significant difference amongst the 5 bias correction techniques. The Null hypothesis (H_0) is that there are no differences amongst the five bias correction schemes. We further determined which schemes differ significantly using

3 post-hoc tests, namely: Tukey HSD, Schefe and the Bonferroni (Brown, 2005; Kucuk et al., 2018). Results are summarized for the Upper, Lower and Middle Zambezi~~.~~

~~3.6.~~3.7. ~~Assessment through~~ Taylor diagram

We apply a Taylor diagram to evaluate~~s~~ differences in data sets generated by respective bias correction schemes by providing a ~~concise~~ summary of how well bias correction results match gauge based estimates in terms of pattern, variability and magnitude of the variability. Visual comparison of SRE performance is done by analysing how well patterns match each other in terms of the Pearson's product-moment correlation coefficient (*R*), root mean square difference (*E*), and the ratio of variances on a 2-D plot (Lo Conti et al., 2014;Taylor, 2001). The reason that each point in the two-dimensional space of the Taylor diagram can represent the above three different statistics simultaneously is that the centered pattern of root mean square difference (E^i), and the ratio of variances are related by the following:

$$E^i = \sqrt{\sigma_f^2 + \sigma_r^2 - 2\sigma_f\sigma_r R} \qquad \textbf{[12]}$$

Where:

σ_f and σ_r = standard deviation of CMORPH and rain gauge rainfall, respectively.

Development and applications of Taylor diagrams have roots in climate change studies (Smiatek et al., 2016;Taylor, 2001) but also has frequent applications in environmental model evaluation studies (Cuvelier et al., 2007;Dennis et al., 2010;Srivastava et al., 2015). Bhatti et al., (2016) propose the use of Taylor Diagrams for assessing effectiveness of SREs bias correction schemes. The most effective bias correction schemes will have data that lie near a point marked 'reference' on the x-axis, relatively high correlation coefficient and low root mean square difference. Bias correction schemes matching gauged based standard deviation have patterns that have the right amplitude.

3.8. Quantile-quantile (q-q) plots

A q-q plot is used to check if two datasets (in this case gauge vs CMORPH rainfall) can fit the same distribution (Wilks, 2006). A q-q plot is a plot of the quantiles of the first data set against the quantiles of the second data set. A 45-degree reference line is also plotted. If the satellite rainfall (corrected and uncorrected) has the same distribution as the rainguage, the points should fall approximately along this reference line. The greater the departure from this reference line, the greater the evidence for the conclusion that the bias correction scheme is less effective (NIST/SEMATECH, 2001).

The main advantage of the q-q plot is that many distributional aspects can be simultaneously tested. For example, changes in symmetry, and the presence of outliers can all be detected from this plot.

3.9. Cross validation of bias correction

3.9.1. Spatial cross-validation

The spatial cross-validation procedure (hold-out sample) applied in this study, involves the withdrawal of 8 in-situ stations from the sample of 60 when generating bias corrected SREs for all pixels across the study area.. Corrected SREs are then compared to the gauge estimates of the withdrawn stations to evaluate closeness of match. From the sample of 8 we selected 2 stations in the < 250 m elevation zone, 3 stations in the 250-950 m zone and 3 stations in > 950 m elevation zone. Stations selected have elevation close to the average elevation zone value and are centred in an elevation zone. This left us with 52 stations for applying the bias correction methods and spatial interpolation. As performance indicators to evaluate results of cross-validation, we use the percentage bias, MAE, Correlation Coefficient and the estimated ratio which is obtained by dividing CMORPH rainfall totals and gauge based rainfall totals for the 1999-2013 period.

3.9.2. Temporal cross-validation

For evalutation of SREs in the time domain we followed (Gutjahr and Heinemann, 2013) and omited rainfall estimates (both from gauge and satellite) for the 1998-1999 hydrological year to remain with 14 years for bias correction of SREs. Bias corrected estimates for 1998-1999 are then evaluated against estimates for the 14 years that served as reference. For evaluation we use the percentage bias, MAE, Correlation Coefficient and the estimated ratio, that all are averaged for the Upper, Middle and Lower Zambezi but also for the wet and dry seasons.

4. Results and Discussion

4.1. Performance of uncorrected CMORPH rainfall

The spatially interpolated values of bias (%) covering the Zambezi Basin are shown in Figure 2. Areas in the central and western part of the basin have bias relatively close to zero suggesting good performance of the uncorrected CMORPH product. However large negative bias values (-20 %) are shown in the Upper Zambezi‘s high elevated areas such as Kabompo and northern Barotse Basin, in the south-eastern part of the basin such as Shire River Basin and in in the Lower Zambezi’s downstream areas where the Zambezi River enters the Indian Ocean. ~~Generally,~~ CMORPH overestimates rainfall locally in Kariba, Luanginga, and Luangwa basins by positive bias values. As such CMORPH estimates do not consistently provide results that match gauge observations. Since CMORPH estimates have pronounced error (-10 >bias (%) >10), we first need to remove the bias before the product may be applied in hydrological and water resources applications. Figure 2 also show contours for rain gauge mean annual precipitation (MAP) in the Zambezi Basin with higher values in the northern parts of the basin (Kabompo and Luangwa) compared to the of lower localised estimates of MAP such as in Shire River and Kariba subbasins.

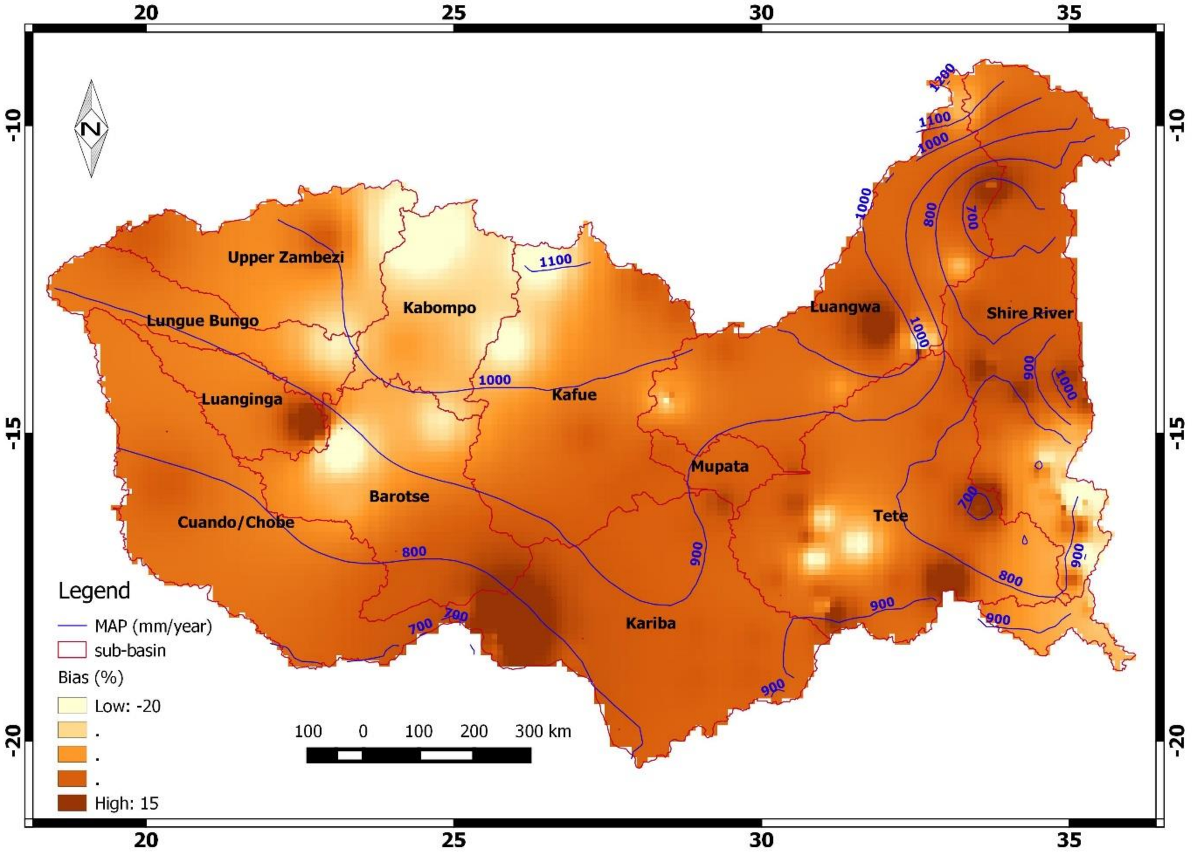
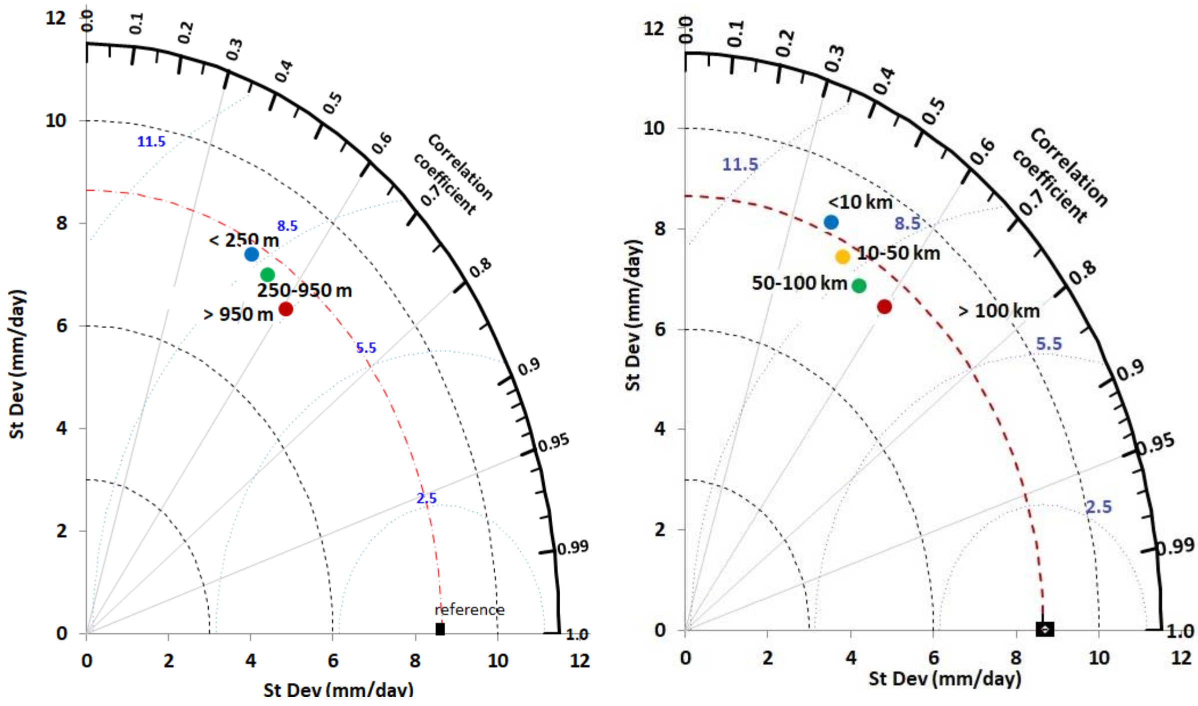


Figure 2: The spatial variation of bias (%) estimate for gauge vs CMORPH daily rainfall (1998-2013) for the Zambezi Basin. The gauge based isohyets for Mean Annual Precipitation (MAP) are shown in blue.

4.2. Effects of elevation and distance from large-scale open water bodies on CMORPH bias

Figure 3 shows Taylor diagrams with a comparison of basin lumped estimates of daily uncorrected time series (1999–2013) of CMORPH and raingauge estimates for the 3 elevation zones (left panes) and 4 distance zones from large-scale -open water bodies (right panes). The purpose of the diagrams is to show if elevation or distance from large-scale open water bodies affect ~~of~~ the perfromance in the CMORPH estimates. Here the perfromance in CMORPH is defined for the root mean square difference (*E*), correlation coefficient (*R*) and standard deviation. Figure 3 reveals that the standard deviations in the elevation zones and the distance zones (except for the < 10 km distance zone) are lower than the reference/rain gauge standard deviation which is indicated by the dashed brown arc (value of 8.45 mm/day). The stations in the high elevation zone (> 950 m) and long distance zone (> 100 km) reveal lower variability than stations at lower elevation and shorter distance zones. With respect to the reference line, CMORPH estimates that are lumped for respective elevation zones and distance to a large water body do not match standard deviation of raingauge based counterparts. ~~Also, a~~ Figure 3 also reveals that CMORPH standard deviations that are close to gauge estimates belong to lower elevation and shorter distance zones. Based on the Taylor diagrams, the statistics (*R* and *E*) for uncorrected CMORPH show increasing performance for increasing elevation and distance from large-scale -water bodies. Specifically, stations in the lower elevation zones (< 250m) have lower ~~poor~~ *R* and higher *E* than the higher elevation zones (> 950 m). The shorter distance zones also have lower~~poor~~ *R* and and higher *E* than for ~~the~~ longer distance zones (> 100 km).



a) Elevation zones b) distance zones

Figure 3. Time series of rain gauge (reference) vs CMORPH estimations, period 1999-2013, for elevation zones (left panes) and distance zones (right panes) in the Zambezi Basin. The correlation coefficients for the radial line denote the relationship between CMORPH and gauge based observations. Standard deviations on both the x and y axes show the amount of variance between the two-time series. The standard deviation of the CMORPH pattern is proportional to the radial distance from the origin. The angle between symbol and abscissa measures the correlation between CMORPH and rain gauge observations. The root mean square difference (blue contours) between the CMORPH and rain gauge patterns is proportional to the distance to the point on the x-axis identified as "reference”. For details, see Taylor (2001)

Our results show that aspects of elevation and distance from large scale open water bodies are distinctively represented (clear signature) in the relationship between CMORPH and gauge rainfall in the Zambezi Basin. For elevation, Romilly and Gebremichael (2011) showed that the accuracy of CMORPH at monthly time base is related to elevation for six river basins in Ethiopia. A similar finding was reported by (e.g. Haile et al., 2009;Katiraie-Boroujerdy et al., 2013;Rientjes et al., 2013a;Wu and Zhai, 2012) who found that ~~bias~~ perfromance of CMORPH is affected by elevation. ~~range~~s. Contrary to these findings, Vernimmen et al. (2012) concluded that ~~relationship between~~ TRMM Multi-satellite Precipitation Analysis (TMPA) 3B42RT performance ~~were~~was not affected by ~~against~~ elevation ~~could not be identified~~ ($R^2 = 0.0001$) for Jakarta, Bogor, Bandung, Java, Kalimantan and Sumatra regions (Indonesia)~~a~~. The study by Gao and Liu (2013) showed that the bias in CMORPH rainfall over the Tibetan Plateau is affected by elevation. Whilst distance from large scale open water bodies and elevation have been assessed separately for this study, Habib et al. (2012a) revealed that the two (distance from large scale open water bodies and elevation) interact in the Nile Basin to produce unique circulation patterns to affect the performance of SRE.

We note that the overall performance could also be affected among other things by the sparse and irregular distributed rain gauges in the Zambezi Basin.

4.3. Evaluation of bias correction

4.3.1. Standard statistics

Figure 4 shows frequency based statistics (mean and maximum) on accuracy of CMORPH rainfall estimates for each bias correction method. The ratio of cumulated estimates (1999-2013) from gauged and CMORPH estimates for the Lower, Middle and Upper Zambezi subbasins are shown. Results show that the bias of CMORPH ~~estimates has~~ moderately reduced for each of the five bias correction schemes. However, the effectiveness of the schemes vary spatially with best performance in Lower and Upper Zambezi subbasin and relatively poor performance in the Middle Zambezi subbasin (see Figure 4).

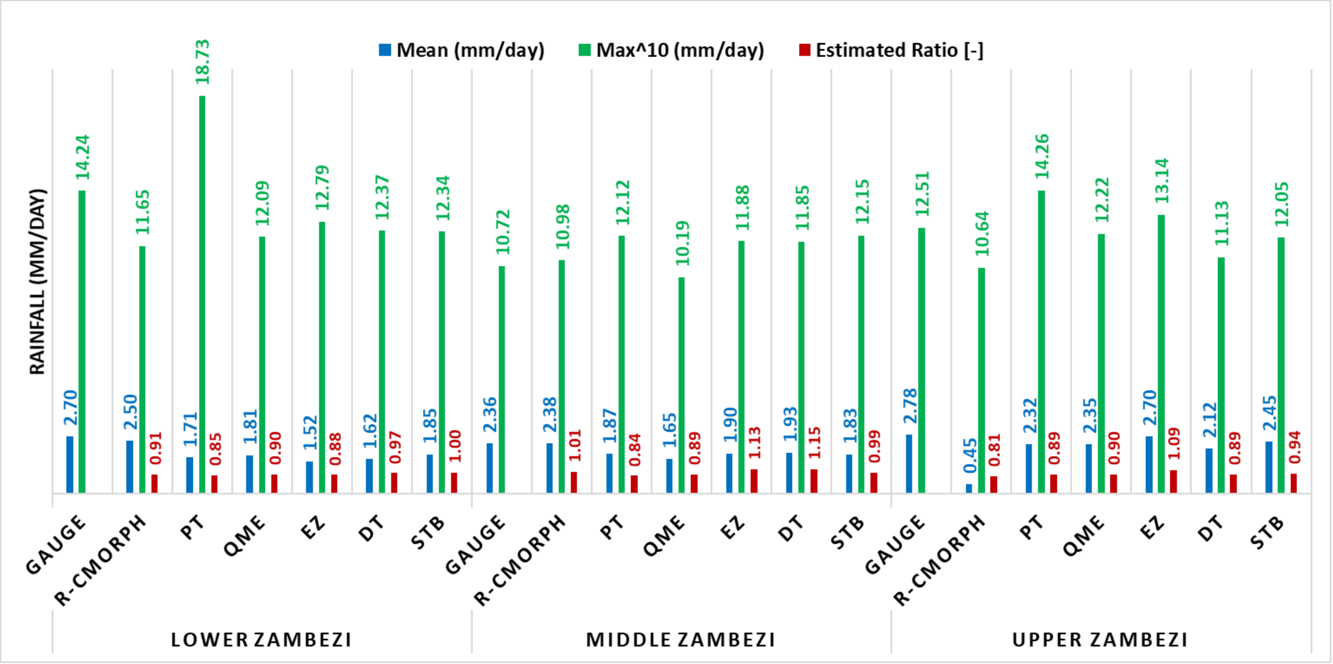


Figure 4: Frequency based statistics (mean, max~~,~~ and estimated ratio of gauged sum vs CMORPH sum for 1999-2013) for the Zambezi Basin.

Judging by the three performance indicators (mean, max and estimated ratio), results indicate that STB bias correction scheme is consistently effective in removing CMORPH rainfall bias in the Zambezi Basin. STB and PT effectively adjust for the mean of CMORPH rainfall estimates. Statistics in Figure 5 confirm these findings especially for the Upper Zambezi subbasin where the mean of corrected estimates improved by > 60% from the mean of uncorrected estimates. In addition, PT in the Lower Zambezi, QME in both Middle and Upper Zambezi and STB in the Upper Zambezi were also effective (improvement by 16 %) in correcting for the highest values in the rainfall estimates. ~~The~~ STB performs better than other bias schemes in reproducing rainfall for the Lower and Upper Zambezi subbasin, where the ratio of gauge total to corrected CMORPH total is close to 1.0.

Figure 5 shows the mean absolute error (MAE) and percentage bias (% bias) on the left axis and Nash Sutcliffe Efficency (NSE) on the right axis. The three performance indicators were used as ~~as~~ a ~~verification~~ measure to evaluate performance of ~~for~~ bias correction schemes in the Zambezi Basin. The effectiveness of the bias correction by all schemes varies over the different parts of the basin but is higher in Lower and Upper than in Middle Zambezi. The STB, PT and EZ shows improved performance by exhibiting smaller MAEs compared to the uncorrected CMOPRH (R-CMORPH). A greater improvement is shown for the Middle Zambezi where the uncorrected MAE of 1.89 mm/day is reduced to 0.86 mm/day after bias correction by the elevation zone bias correction scheme (EZ). The ~~–~~signal on improved performance for the Lower and Middle Zambezi as compared to the Upper Zambezi is also evident for the majority of the bias correction techniques. However, relatively large error remains in the MAE.

The NSE for STB is above 0.8 for all three Zambezi subbasins. This is followed by EZ which for all three subbasins s is above 0.7 for the three subbasins. The lowest NSE is for QME which is close to 0.65 for all three subbasins. With regard to reducing bias (% bias), best results are obtained by EZ in the Lower Zambezi (percentage bias of 0.7 % ~ absolute bias of 0.10 mm/day) and Upper Zambezi (0.22 % ~0.23 mm/day), PT in the Lower and Middle Zambezi (-0.84 % ~0.18 mm/day) and STB in all the basins (< 3.70 % ~0.24 mm/day). Gao and Liu (2013) asserts that EZ (a correction process based on elevation) is valuable in correcting systematic biases to provide a more accurate precipitation input for rainfall-runoff modelling. Significant underestimation for the uncorrected (-21.16 % ~0.44 mm/day) and for bias corrected CMORPH are shown for the Upper Zambezi subbasin..

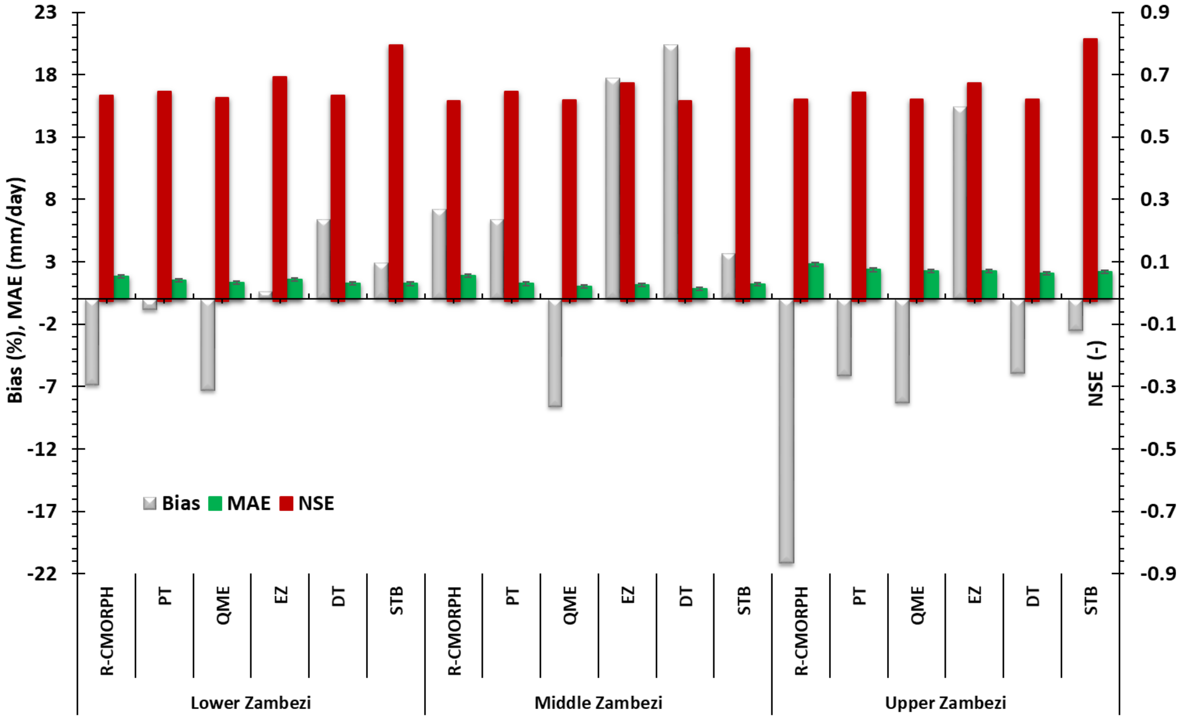


Figure 5: Percentage bias, Mean Absolute Error (left axis) and Nash Sutcliffe (NSE) (right axis) of corrected and uncorrected CMORPH (R-CMORPH) daily rainfall averaged for the Lower Zambezi, Middle Zambezi and Upper Zambezi.

4.3.2. Significance testing

Table 2 shows results of statistical tests to assess whether there is a significant difference (p< 0.05) between raingauge vs uncorrected and bias corrected CMORPH satellite rainfall for each of the 52 raingauge stations. Results are summarised for the Upper, Middle and Lower Zambezi and in the Zambezi basin. The null hypothesis is rejected for PT (Lower Zambezi), DT (Upper Zambezi) and QME (all the 3 sub-basins) since p < 0.05. This means that statitsically the above mentioned bias correction schemes results deviate from the gauge. The null hypothesis is accepted for STB and EZ (all t three sub-basins), DT (Lower and Upper Zambezi) and PT (Middle and Upper Zambezi), since p >0.05 showing the effectiveness of these bias correction schemes. Compared to uncorrected satellite rainfall (R-MORPH), results also reveal that the bias corrected satellite rainfall is closer to the gauge based estimates.

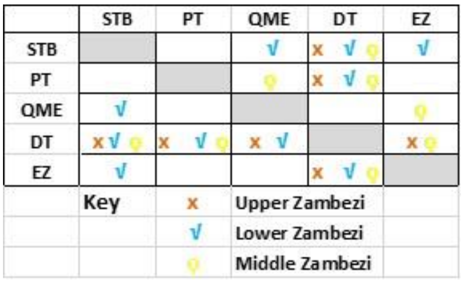
Table 2: Paired t-tests for the Upper, Middle and Lower Zambezi. The mean difference is significant at the 0.05 level. Bold shows significant values..

Basin	Rainfall Estimate	t-value	Mean Std. Error	p-value (0.05)
Lower Zambezi	R-CMORPH	8.95	0.04	**0.04**
	DT	39.86	0.09	0.35
	PT	21.08	0.04	**0.03**
	QME	23.99	0.04	**0.04**
	EZ	36.43	0.03	0.27
	STB	14.7	0.04	0.46
Middle Zambezi	R-CMORPH	3.27	0.03	**0.001**
	DT	41.9	0.07	0.24
	PT	26.02	0.03	0.14
	QME	18.38	0.03	**0.00**
	EZ	26.60	0.02	0.07
	STB	23.6	0.03	0.09
Upper Zambezi	R-CMORPH	4.28	0.08	**0.00**
	DT	22.63	0.14	**0.01**
	PT	12.98	0.07	**0.05**
	QME	13.27	0.07	**0.00**
	EZ	13.73	0.07	0.14
	STB	13.62	**0.07**	**0.08**

4.3.3. Analysis of variance (ANOVA test)

The ANOVA test is similar to a t-test except that the test can be used to compare the means from three or more data samples. Results of ANOVA shows that there is a significant ($p < 0.05$) difference in the means of the 5 bias correction results across the three subbasins. This warranted the running of a post-hoc test to determine which schemes differ significantly. The contigency matrix in Table 2 shows results of the post-hoc tests results summarized for the Tukey HSD, Schefe and the Bonferroni methods but also for the Upper, Lower and Middle Zambezi. Table 3 also show that STB, PT and EZ are significantly different from the distribution transformation technique (DT) for the three sub-basins. STB, the best perfoming bias correction scheme identified using majority of the indicators is also significantly different from QME and EZ. QME which has poorly perfomed is significantly different from EZ. Results are important for further application of the bias correction schemes for studies such as flood, drought and water resources modelling.

Table 3: ANOVA post-hoc tests for the results of the five bias correction schemes (p<0.05). The checklist table gives a indication (symbol) where two bias correction scheme's results are significantly different from each other. Where there is no symbol, it means that the schemes' results are not significantly different. The different symbols represent the Upper, Middle and Lower Zambezi basins.



	STB	PT	QME	DT	EZ
STB			√	x √ ǫ	√
PT			ǫ	x √ ǫ	
QME	√				ǫ
DT	x √ ǫ	x √ ǫ	x √		x ǫ
EZ	√			x √ ǫ	
	Key	x	Upper Zambezi		
		√	Lower Zambezi		
		ǫ	Middle Zambezi		

~~4.3.2.~~4.3.4. Taylor Diagrams

Figure 6 shows the Taylor diagram for time series of rain gauge (reference) observations vs CMORPH bias correction schemes averaged for the Lower Zambezi (UZ), Middle Zambezi (MZ) and Upper Zambezi (UZ). Absolute values used to develop the Taylor diagram are shown in Appendix 2. The position of each bias correction scheme and uncorrected satellite rainfall (R-MORPH) on Figure 6 shows how closely the rainfall by R-MORPH matches rain gauge observations as well as effectiveness of each of the bias schemes. Overall, all bias correction schemes show intermediate performance in terms of bias removal. Only the PT and STB for the Lower Zambezi subbasin lie on the line of standard deviation (brown dashed arc) and means the standard deviation of the data for the two bias correction schemes matches the gauge observations. This also indicates that rainfall variations after PT and STB bias correction for the Lower Zambezi resembles gauge based standard deviation. Note however that STB performs better than EZ as shown by the superior correlation coefficient. Compared against the reference line of mean standard deviation (8.5 mm/day), the rainfall standard deviation for most bias correction schemes is below this line and as such exhibit low variability across the Zambezi Basin.

Figure 6 also shows that most of the bias correction schemes have standard deviation range of 6.0 to 8.0 mm/day. There is a consistent pattern between the bias correction schemes that have low R and high ~~root mean square error~~ RMSE difference indicating that these schemes are not effective in bias removal. Overall, the best performing bias correction schemes (STB and EZ) have R > 0.6, standard deviation relatively close to the reference point and ~~a~~ RMSE < 7 mm/day. The uncorrected CMORPH (R-MORPH) lies far away from the marked reference (gauge) point on the x-axis suggesting an intermediate overall effectiveness of the bias correction schemes such as STB, EZ, DT and PT in removing error as they are relatively closer to the marked reference point.

The least performing bias correction scheme is QME relatively large RSMD (> 8 mm/day) and ~~,~~ with ~~a considered~~ low R (< 0.49) and standard deviation (< 6.5 mm/day). ~~that is lower than~~

~~the reference, but with relatively large RSMD (> 8 mm/day)~~. Inherent to the methodology of most of bias correction schemes (e.g. QME) is that the spatial pattern of the SRE does not change and therefore the R for a specific station for daily precipitation does not necessarily improve. The bias correction results by the Taylor Diagram in Figure 6 corroborates with findings shown in Figure 4 and Figure 5 for mean, max, ratio of rainfall totals and bias as performance indicators.

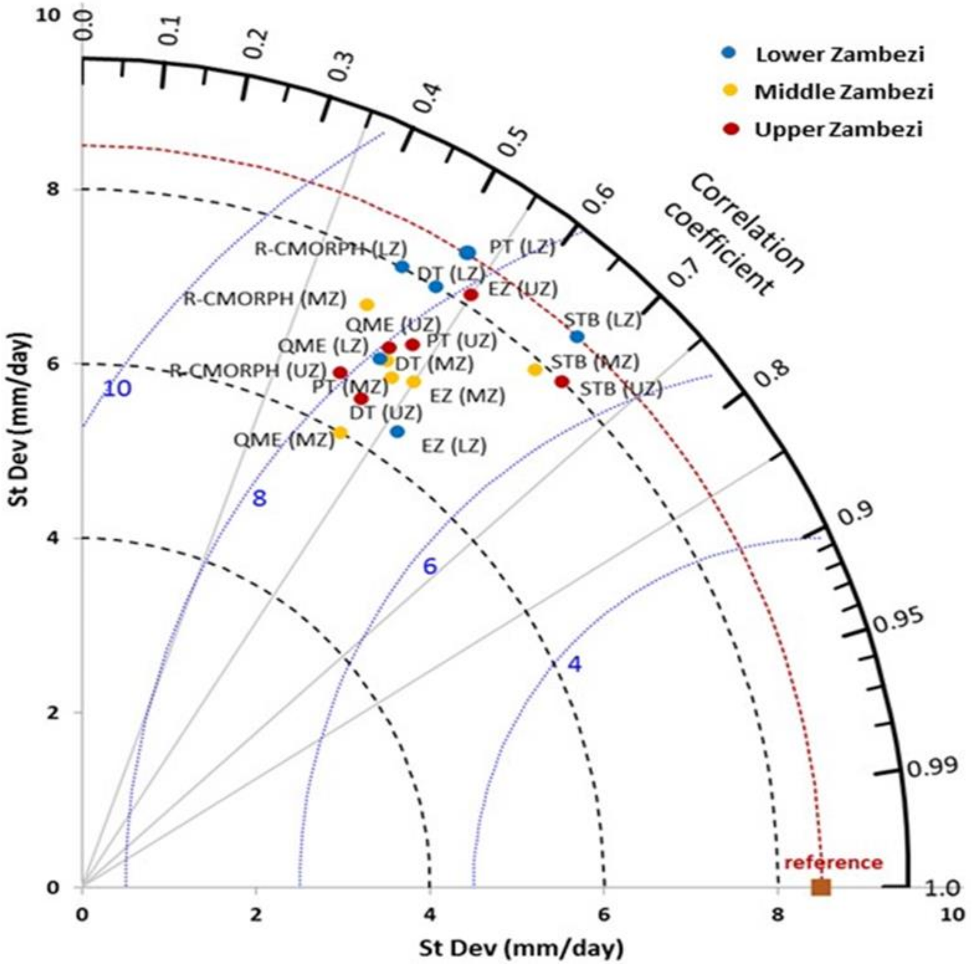


Figure 6: Taylor's diagram on Rain gauge (reference) observations and CMORPH bias corrected estimates (all 5 schemes) as averaged for the Lower Zambezi (LZ), Middle Zambezi (MZ), and Upper Zambezi (UZ) for the period 1999-2013. The distance of the symbol from point (1, 0) is also a relative measure of the bias correction scheme perfromance. The position of each symbol appearing on the plot quantifies how closely precipitation estimates by respective bias correction scheme's matches counterparts by rain gauge. The dashed blue lines indicate the root mean square difference (mm/day).

4.3.5. q-q plots

Figure 7 shows q-q plots for the Upper, Middle and Lower Zambezi for gauge estimates against uncorrected and bias corrected CMORPH rainfall. Results show that the STB q-q plots for bias corrected CMORPH across the 3 basins has majority of points that fall approximately along the 45-degree reference line. This means that the STB bias corrected satellite rainfall has closer distribution to the raingauge as compared to the uncorrected CMORPH counterparts suggesting effectiveness of the bias correction scheme. Other bias correction schemes such as QME, EZ and PT have data points showing a greater departure from the 45-degree reference line so performance is less effective.

In some instances in both the Upper, Middle and Lower Zambezi, bias corrected values are significantly higher than the corresponding gauge values whereas in some instances there is serious underestimation. All tq-q plots also show that for all bias correction schemes, the differences between gauge and satellite rainfall are minimal for low rainfall rates (< 2.5 mm/day) and increasing for heavy rainfall (> 20.0 mm/day). In more detail, all the bias correction schemes show a larger difference for the transition area from low to heavy rainfall. QME and PT are not in good agreement with the rest of the bias correction schemes for higher rainfall estimates (40 and 60 mm/day).

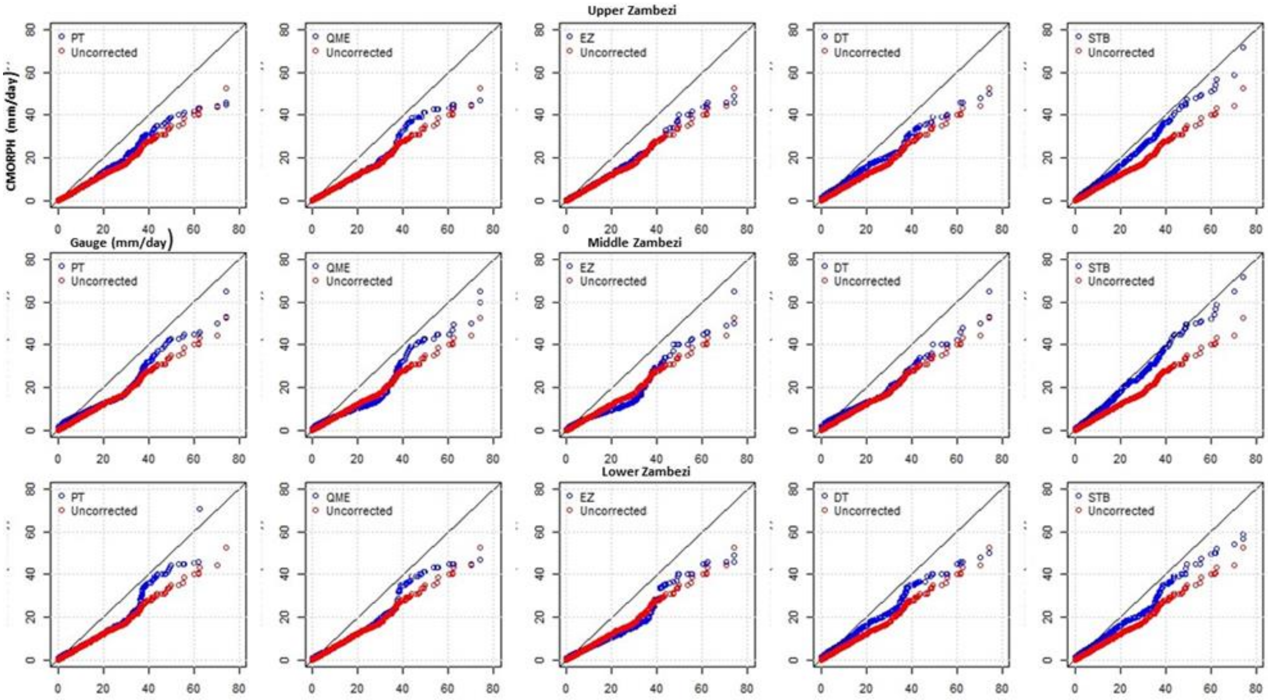


Figure 7: q-q plot for gauge vs satellite rainfall (corrected and bias corrected) for the Upper (top panes), Middle (middle panes) and Lower (bottom panes) Zambezi.

~~4.3.3.~~4.3.6. CMORPH rainy days

Occurance (%) of rainfall rates in the Zambezi Basin for each bias correction scheme is shown in Figure 8. The highest percentage (80-90 %) is shown for very light rainfall (0.0-2.5 mm/day). A smaller percentage is shown for 2.5-5.0 mm/day which is the light rainfall class. Smallest percentage (< 5%) is shown for heavy rainfall (> 20.0 mm/day). The CMORPH rainfall corrected with STB, PT and DT matches the gauge based rainfall (%) in the Lower, Middle and Upper Zambezi suggesting good performance. All five bias correction schemes in the Zambezi Basin generally tend to overestimate low rainfall (< 2.5 mm/day). There is a small difference for moderate rainy days classification of 10.0-20.0 mm/day. For QME in the Middle and Upper Zambezi, there is overestimation by > 80 %. There is underestimation of rainfall greater than 20 mm/day. Results are consistent with findings by Gao and Liu (2013) in the Tibetan Plateau who also found consistent under and overestimation of occurence by CMORPH for rainfall rates ->10.0 mm/day. ~~The ~~A study by Zulkafli et al. (2014) in French Guiana and North Brazil noted that the low sampling frequency and consequently missed short-duration precipitation events between satellite measurements results in underestimation, particularly for heavy rainfall.

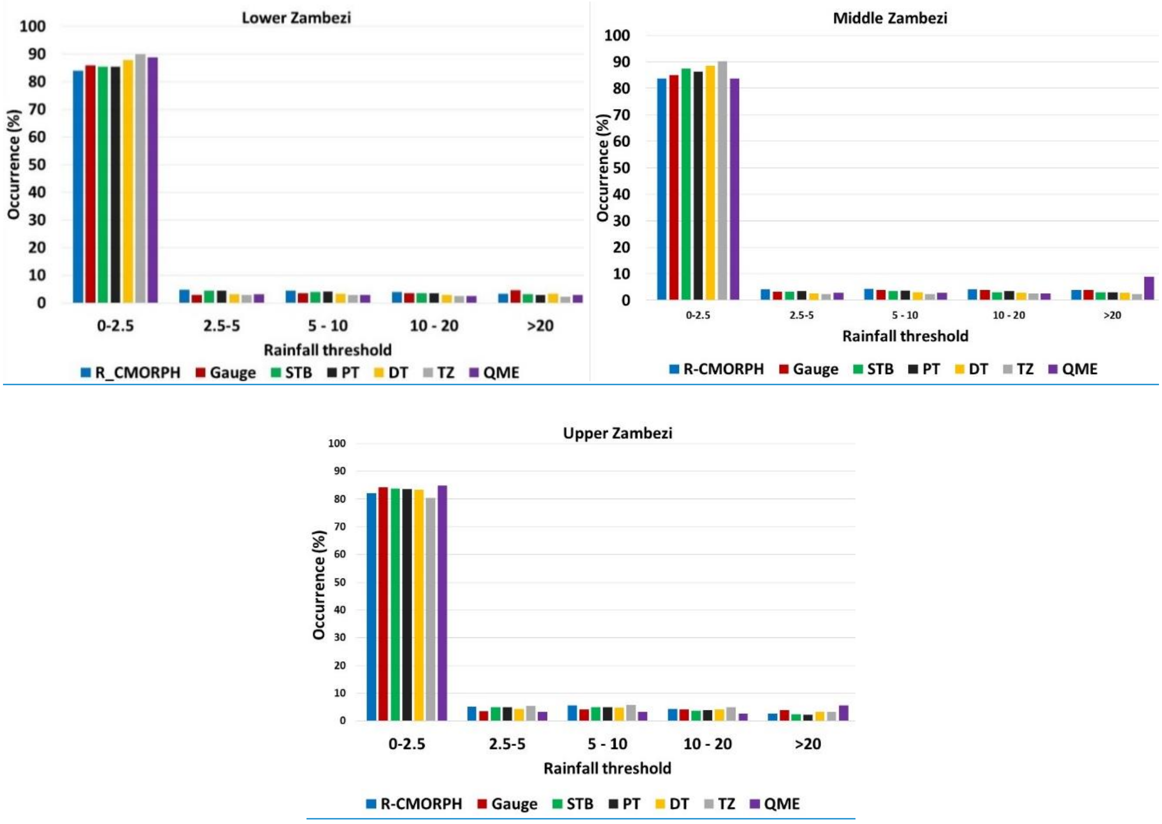


Figure 8: Percentage of days for rainfall rate classes

Figure 9 gives the bias correction performance for the different rainy day classes. Results of bias removal varies for the Lower, Middle and Upper Zambezi. Comparatively, the STB and EZ show effectiveness in bias removal with an average bias correction of 0.97 % and 3.6 % in the whole basin respectively. Results show more effectiveness in reducing the percentage bias for light rainfall and moderate rainfall (0-2.5 and 5.0-10.0 ~~m~~mm/day) than the high to very high rainfall (10.0-20.0 mm/day and >20.0 mm/day) across the whole basin. The poor performance of correction for the heavy rainfall class is caused by, sometimes, large mismatch of high rain gauge values versus low CMORPH values. This leads to unrealistically high CMORPH values which remain poorly corrected by bias schemes.

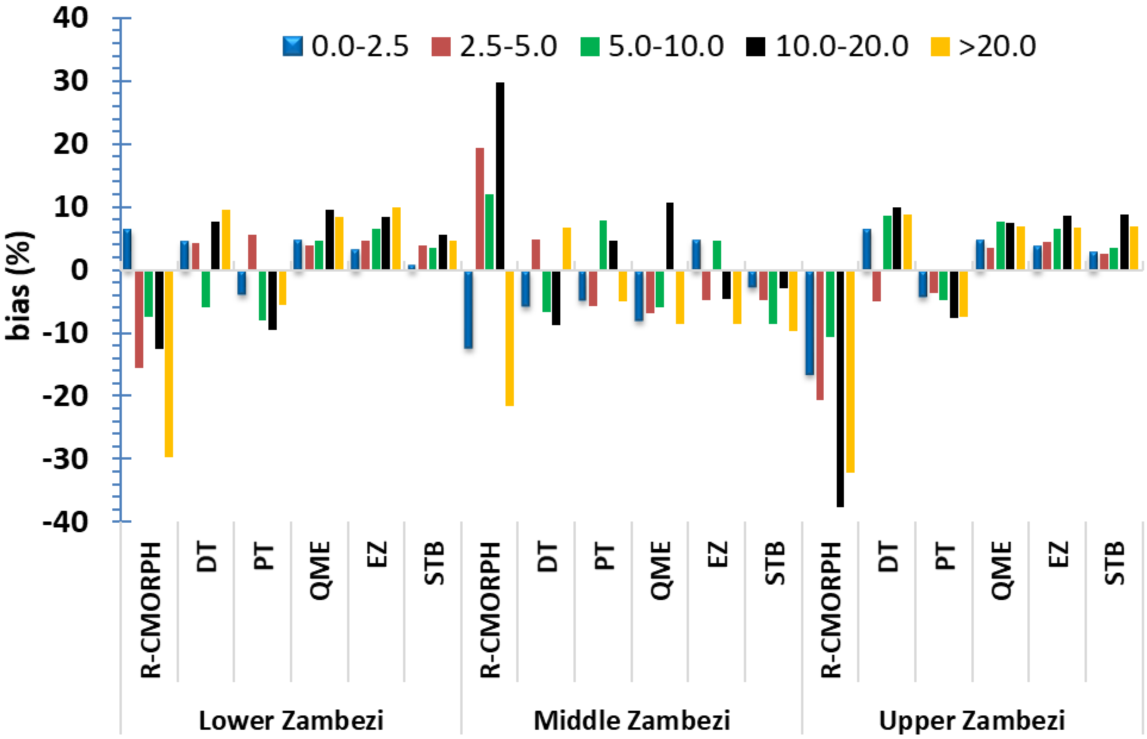


Figure 9: Bias correction (%) for respective rainfall rate classes

4.4. Spatial cross-validation

Table 4 shows the cross-validation results on bias correction for 8 stations for wet and dry seasons. It is evident that CMORPH has a considerable bias, although this bias is not always consistentfor all 8 validation stations.. Overall, Mutarara station has the highest positive bias (overestimation) whereas Makhanga has the highest negative bias (underestimation) for uncorrected CMORPH. Bias is effectively being removed by the STB followed by the EZ bias correction schemes. Bias is more effectively removed for the wet season than for the dry season. For the dry season, the STB shows good performance for Mkhanga and Nchalo stations, whereas good performance is shown for Kabompo and Chichiri stations. However, the MAE is higher for the wet season than for the dry season. Correlation coefficient for bias corrected satellite rainfall is higher for the wet season than for the dry season. The study by Ines and Hansen (2006) for semi-arid eastern Kenya showed that multiplicative bias correction schemes such as STB were effective in correcting the total of the daily rainfall grouped into seasons. Our results show that effectiveness in bias removal in the wet season is higher than in the dry season This is contrary to Vernimmen et al. (2012) who showed that for the dry season, bias for PT decreased in Jakarta, Bogor, Bandung, East Java and Lampung regions after bias correction of monthly TMPA 3B42RT precipitation estimates over the period 2003–2008. Habib (2014) evaluated sensitivity of STB for the dry and wet season and concluded that the bias correction factor for CMOPRH shows lower sensitivity for the wet season as compared to the dry season. Our findings also reveal that bias factors for all the schemes are more variable in the dry season than in the wet season and lead to poor performance of the bias correction schemes in the dry season.

Validation results for all 8 stations for the period 1999-2013 show that the bias on CMORPH reduces the MAE by 23 %. This represents 22 % of the average MAE estimated using 52 raingauges. Since the stations used for validation are different from the stations used to develop the bias correction procedures, we conclude that the results are independent of deliberate efforts to reducing the errors. Similar cross-validation techniques where measures of performance are evaluated using a sample that was not included in the calibration of the correction procedure gave good performance in the the state of Rhineland-Palatinate in Europe (Gutjahr and Heinemann, 2013).

Table 4: Cross validation results for the bias correction procedure with 8 gauging stations for the dry and wet season. Stations lie at average elevation zone and sort of centred in an elevation zone. R-Morph is the uncorrected R-CMOPRPH estimate. DT, PT, QME, EZ and STB are the bias corrected rainfall estimate. Bold values indicate best performance. * = zone 1: elevation of < 250 m , ** = zone 2: elevation range of 250 - 950 m and *** = zone 3: elevation > 950 m

		Dry Season (April-Sept)				Wet Season (Oct-March)			
Station	Rainfall Estimate	Bias (%)	MAE	Correlation	Estimated Ratio	Bias (%)	MAE	Correlation	Estimated Ratio
Makhanga*	R-CMORPH	-28.69	1.23	0.42	0.87	-21.17	8.63	0.43	0.91
	DT	-1.37	0.53	0.56	0.99	-1.66	3.96	0.65	0.94
	PT	-5.62	0.52	0.54	0.95	-3.5	4.67	0.64	1.02
	QME	1.98	0.54	0.54	0.95	-0.64	4.86	0.65	0.97
	EZ	2.10	0.47	0.55	1.03	-0.11	4.08	0.58	0.96
	STB	0.77	0.61	0.56	1.04	0.5	5.06	0.62	1.02
Nchalo*	R-CMORPH	-33.05	1.13	0.42	0.84	-25.18	8.05	0.38	0.83
	DT	-0.23	0.73	0.56	0.96	-2.61	3.65	0.50	0.87
	PT	-4.28	0.68	0.54	0.93	-6.48	5.05	0.59	0.92
	QME	1.90	0.72	0.53	0.81	-0.56	5.29	0.53	0.91
	EZ	0.35	0.63	0.54	0.99	**0.22**	4.4	0.60	1.06
	STB	-0.43	0.73	0.58	0.96	-1.23	5.54	0.61	1.02
Rukomichi**	R-CMORPH	-23.05	0.93	0.42	0.86	-21.18	6.69	0.31	0.73
	DT	-0.23	0.90	0.56	0.94	-6.2	3.51	0.60	0.87
	PT	-4.28	0.73	0.54	0.93	-2.48	3.62	0.59	0.92
	QME	1.90	0.75	0.53	1.03	-0.56	3.88	0.54	0.83
	EZ	0.35	0.71	0.54	0.99	**0.22**	3.5	0.60	1.06
	STB	-0.43	0.76	0.58	0.94	-1.26	3.33	0.61	1.02
Mutarara**	R-CMORPH	20.15	0.24	0.49	1.10	20.1	2.34	0.50	1.05
	DT	11.4	0.18	0.60	1.03	8.7	1.23	0.63	1.04
	PT	8.4	0.12	0.55	0.91	4.3	1.28	0.68	1.03
	QME	5.7	0.14	0.63	1.1	8.1	1.4	0.65	0.98
	EZ	-12.8	**0.09**	0.54	0.95	1.9	1.23	0.69	1.03
	STB	4.5	0.14	0.53	1.1	2.1	1.33	**0.73**	**1.01**
Mfuwe**	R-CMORPH	40.2	0.28	0.45	0.85	35.4	6.4	0.48	1.08
	DT	2.9	0.62	0.53	0.96	4.6	3.9	0.62	0.98
	PT	3.7	0.22	0.55	0.92	7.9	5.25	0.65	0.96
	QME	3.9	0.30	0.55	0.93	5.4	5.68	0.64	0.97
	EZ	6.1	0.24	0.54	0.92	3.8	5.18	0.56	0.98
	STB	5.4	0.26	0.65	0.93	1.2	4.66	0.65	0.96
Kabombo***	R-CMORPH	25.3	0.70	0.44	0.95	24.3	3.8	0.48	0.85

	DT	7.7	0.32	0.51	0.96	5.7	3.5	0.62	0.94
	PT	9.2	0.13	0.54	1.10	8.7	3.0	0.64	0.96
	QME	2.7	0.32	0.62	1.10	2.8	3.2	0.63	0.95
	EZ	5.6	0.22	0.53	0.91	3.3	2.7	0.54	0.96
	STB	19	0.13	0.62	1.01	9.3	2.7	0.64	0.93
Chichiri***	R-CMORPH	34.5	1.56	0.47	0.8	-37.3	4.7	0.45	0.84
	DT	12.2	0.60	0.51	0.85	5.5	3.2	0.51	0.93
	PT	9.4	0.42	0.52	1.04	-7.8	4.1	0.54	0.95
	QME	8.4	0.92	0.56	1.05	-13.0	4.1	0.64	1.04
	EZ	-13	0.61	0.60	0.94	-9.9	4.2	0.60	0.96
	STB	3.2	0.45	0.63	0.98	-14.3	2.1	0.65	**0.99**
Chitedze***	R-CMORPH	41.5	0.90	0.47	1.06	42.3	5.4	0.48	0.89
	DT	16.7	0.53	0.54	0.98	-13.2	3.3	0.62	0.86
	PT	-16.5	0.44	0.55	0.99	22.2	4.5	0.65	1.05
	QME	18.2	0.41	0.57	1.04	18.5	4.3	0.64	1.04
	EZ	11.7	0.32	0.57	1.02	8.4	4.6	0.55	1.03
	STB	3.9	0.23	0.60	0.03	-8.2	3.7	0.65	0.97

4.5. Temporal cross-validation

The same performance indicators in spatial cross-validation are calculated for the temporal cross-validation. Results are prsented in Table 5. The structure of the error is the same as in Table 4, where the MAE is higher for the wet season than for the dry season. However, compared to the spatial cross-validation the difference in effectiveness in the error removal between the dry and wet season is much larger due to the limited length of the time series (1998-1999). STB outperforms both bias correction methods but does also have problems correcting the estimated ratios. After the correction, the correlation coefficient is much improved. The fact that MAE remains relatively large indicates z that errors remain locallylarge. . These values are almost in same range to performance indicators obtained from the main performance assessment period (1999-2013). However using one year (1998-1999) to correct bias in CMORPH increased the MAE by 10 % compared to the main performance assessment period (1999-2013) The estimated ratio adjustment in the temporal cross-validation reduced by 7 % from the 1999-2013 period.

Table 5: Temporal-cross validation results for the period 1998-1999 for the wet and dry season

		Dry Season (April-Sept)				Wet Season (Oct-March)			
Station	Rainfall Estimate	Bias (%)	MAE	Correlation	Estimated Ratio	Bias (%)	MAE	Correlation	Estimated Ratio
Lower Zambezi	R-CMORPH	-28.26	1.10	0.42	0.86	-22.51	7.79	0.37	0.82
	DT	-0.61	0.72	0.56	0.96	-3.49	3.71	0.58	0.89
	PT	-4.73	0.64	0.54	0.94	-4.15	4.45	0.61	0.95
	QME	1.93	0.67	0.53	0.93	-0.59	4.68	0.57	0.90
	EZ	0.93	0.60	0.54	1.00	0.11	3.99	0.59	1.03
	STB	-0.03	0.70	0.57	0.98	-0.66	4.64	0.61	1.02
Middle Zambezi	R-CMORPH	28.55	0.41	0.46	0.97	26.60	4.18	0.49	0.99
	DT	7.33	0.37	0.55	0.98	6.33	2.88	0.62	0.99

	PT	7.10	0.16	0.55	0.98	6.97	3.18	0.66	0.98
	QME	4.10	0.25	0.60	1.04	5.43	3.43	0.64	0.97
	EZ	-0.37	0.18	0.54	0.93	3.00	3.04	0.60	0.99
	STB	9.63	0.18	0.60	1.01	4.20	2.90	0.67	0.97
Upper Zambezi	R-CMORPH	38	1.23	0.47	0.93	2.5	5.05	0.465	0.865
	DT	14.45	0.565	0.525	0.915	-3.85	3.25	0.565	0.895
	PT	-3.55	0.43	0.535	1.015	7.2	4.3	0.595	1
	QME	13.3	0.665	0.565	1.045	2.75	4.2	0.64	1.04
	EZ	-0.65	0.465	0.585	0.98	-0.75	4.4	0.575	0.995
	STB	3.55	0.34	0.615	0.505	-11.25	2.9	0.65	0.98

5. Conclusions

We present methods to assess the performance of bias correction schemes for CMORPH rainfall estimates in the Zambezi River Basin. Conclusions of this study are:

1. Analysis on gauge and CMORPH rainfall estimates shows that performance increases for higher elevation (>950 m) in the Zambezi Basin and that CMORPH has largest mismatch at low elevation. Such analysis was established for rain gauges within elevation classes of < 250 m, 250 - 950 m and > 950 m. The match between gauge and CMORPH estimates improved at increasing distance to large-scale open water bodies (poorest for short distances). This was established for rain gauges located within specified distances of < 10 km, 10 -50 km, 50 -100 km and > 100 km to a large scale open water body.

2. For each of the five bias correction methods applied, accuracy of the CMORPH satellite rainfall estimates improved. Assessment through standard statistics, Taylor Diagrams, t-tests, ANOVA and q-q plots reveal that STB that accounts space and time variation of bias, is found more effective in reducing rainfall bias in the basin than the rest of the bias correction schemes. This indicates that the temporal aspect of CMORPH bias is more important than the spatial aspect in the Zambezi Basin. Quantile-quantile (q-q) plots for all the bias correction schemes show, in general, that bias corrected rainfall is in good agreement with gauge based estimates for low rainfall rates but that high rainfall rates are largely overestimated.

3. Evaluation of results by the five bias correction schemes was successfully performed using spatial and temporal cross-validation. The hold-out sample of 8 stations in this work showed the applicability of different bias correction methods under different geographical space (spatial). It is noted that the relatively short time series used for temporal validation may have affected results.

4. Differences in the mechanisms that drive precipitation throughout the year could result in different biases for each of the seasons, which motivated us to calculate the bias correction

factors for each of the seasons separately. CMORPH rainfall time series were divided into wet and dry seasonal periods to assess the influence of seasonality on performance of bias correction schemes. Overal, the bias correction schemes reveal that bias removal is more effective in the wet season than in the dry season.

5. We assessed whether bias correction varies for different rainfall rates of daily rainfall in the Zambezi Basin. There is overestimation of very light rainfall (< 2.5 mm/day) and underestimation of very heavy rainfall (>20 mm/day) after application of the bias correction schemes. Bias was more effectively reduced for very low to moderate rainfall (< 2.5 and 5.0-10.0 mmm/day) than for high to very high rainfall (10.0-20.0 mm/day and >20.0 mm/day). Overall, the STB and EZ more consistently removed bias in all the rainy days classification compared to the three other bias correction schemes.

Analysis serve to improve reliability of SREs applications in water resource applications in the Zambezi basin such as in drought analysis, flood prediction, weather forecasting and rainfall runoff modelling. In follow-up studies, we ~~want~~ aim at ~~to investigate the~~ hydrologic evaluation of bias corrected CMORPH rainfall estimates at the headwater catchment of the Zambezi River.

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Author Contributions

Webster Gumindoga was responsible for the development of bias correction schemes in the Zambezi basin and research approach~~-~~. Tom Rientjes and Alemseged Haile were responsible for synthesising the methodology and made large contributions to the manuscript write-up. Hodson Makurira provided some of the rain gauge data and related findings of this study to previous work in the Zambezi Basin. Reggiani Paulo assisted in interpretation of bias correction results.

Conflict of Interests

The authors declare no conflict of interests.

References

Beilfuss, R., Dutton, P., and Moore, D.: Landcover and Landuse change in the Zambezi Delta, in: Zambezi Basin Wetlands Volume III Landuse Change and Human impacts, Chapter 2, Biodiversity Foundation for Africa, Harare, 31-105, 2000.

Beilfuss, R.: A Risky Climate for Southern African Hydro: Assessing hydrological risks and consequences for Zambezi River Basin dams, 2012.

Beyer, M., Wallner, M., Bahlmann, L., Thiemig, V., Dietrich, J., and Billib, M.: Rainfall characteristics and their implications for rain-fed agriculture: a case study in the Upper Zambezi River Basin, Hydrological Sciences Journal, null-null, 10.1080/02626667.2014.983519, 2014.

Bitew, M. M., and Gebremichael, M.: Evaluation of satellite rainfall products through hydrologic simulation in a fully distributed hydrologic model, Water Resources Research, 47, 2011.

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, 10.1175/2011jhm1292.1, 2011.

Bouwer, L. M., Aerts, J. C. J. H., Van de Coterlet, G. M., Van de Giessen, N., Gieske, A., and Manaerts, C.: Evaluating downscaling methods for preparing Global Circulation Model (GCM) data for hydrological impact modelling. Chapter 2, in Aerts, J.C.J.H. & Droogers, P.

Brown, A. M.: A new software for carrying out one-way ANOVA post hoc tests, Comput. Methods Programs Biomed., 79(1), 89–95, doi:https://doi.org/10.1016/j.cmpb.2005.02.007, 2005.

(Eds.), Climate Change in Contrasting River Basins: Adaptation Strategies for Water, Food and Environment. (pp. 25-47). Wallingford, UK: Cabi Press., 2004.

Cecinati, F., Rico-Ramirez, M. A., Heuvelink, G. B. M., and Han, D.: Representing radar rainfall uncertainty with ensembles based on a time-variant geostatistical error modelling approach, Journal of Hydrology, 548, 391-405, http://dx.doi.org/10.1016/j.jhydrol.2017.02.053, 2017.

Cohen Liechti, T., Matos, J. P., Boillat, J. L., and Schleiss, A. J.: Comparison and evaluation of satellite derived precipitation products for hydrological modeling of the Zambezi River Basin, Hydrol. Earth Syst. Sci., 16, 489-500, 2012.

Cuvelier, C., Thunis, P., Vautard, R., Amann, M., Bessagnet, B., Bedogni, M., Berkowicz, R., Brandt, J., Brocheton, F., Builtjes, P., Carnavale, C., Coppalle, A., Denby, B., Douros, J., Graf, A., Hellmuth, O., Hodzic, A., Honoré, C., Jonson, J., Kerschbaumer, A., de Leeuw, F., Minguzzi, E., Moussiopoulos, N., Pertot, C., Peuch, V. H., Pirovano, G., Rouil, L., Sauter, F., Schaap, M., Stern, R., Tarrason, L., Vignati, E., Volta, M., White, L., Wind, P., and Zuber, A.: CityDelta: A model intercomparison study to explore the impact of emission reductions in European cities in 2010, Atmospheric Environment, 41, 189-207, http://dx.doi.org/10.1016/j.atmosenv.2006.07.036, 2007.

Dennis, R., Fox, T., Fuentes, M., Gilliland, A., Hanna, S., Hogrefe, C., Irwin, J., Rao, S. T., Scheffe, R., Schere, K., Steyn, D., and Venkatram, A.: A framework for evaluating regional-scale numerical photochemical modeling systems, Environmental Fluid Mechanics, 10, 471-489, 10.1007/s10652-009-9163-2, 2010.

Dinku, T., Chidzambwa, S., Ceccato, P., Connor, S. J., and Ropelewski, C. F.: Validation of high-resolution satellite rainfall products over complex terrain, International Journal of Remote Sensing, 29, 4097-4110, 10.1080/01431160701772526, 2008.

Fang, G. H., Yang, J., Chen, Y. N., and Zammit, C.: Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China, Hydrol. Earth Syst. Sci., 19, 2547-2559, 10.5194/hess-19-2547-2015, 2015.

Field , A.: Discovering statistics using SPSS 2nd ed. Sage Publications, 2009.

Fylstra, D., Lasdon, L., Watson, J., and Waren, A.: Design and Use of the Microsoft Excel Solver, Interfaces, 28, 29-55, doi:10.1287/inte.28.5.29, 1998.

Gao, Y. C., and Liu, M. F.: Evaluation of high-resolution satellite precipitation products using rain gauge observations over the Tibetan Plateau, Hydrol. Earth Syst. Sci., 17, 837-849, 10.5194/hess-17-837-2013, 2013.

Gebregiorgis, A. S., Tian, Y., Peters-Lidard, C. D., and Hossain, F.: Tracing hydrologic model simulation error as a function of satellite rainfall estimation bias components and land use and land cover conditions, Water Resources Research, 48, n/a-n/a, 10.1029/2011wr011643, 2012.

Grillakis, M. G., Koutroulis, A. G., Daliakopoulos, I. N., and Tsanis, I. K.: A method to preserve trends in quantile mapping bias correction of climate modeled temperature, Earth Syst. Dynam. Discuss., 2017, 1-26, 10.5194/esd-2017-53, 2017.

Gutjahr, O. and Heinemann, G.: Comparing precipitation bias correction methods for high-resolution regional climate simulations using COSMO-CLM, Theor. Appl. Climatol., 114(3–4), 511–529, doi:10.1007/s00704-013-0834-z, 2013.

Habib, E., ElSaadani, M., and Haile, A. T.: Climatology-Focused Evaluation of CMORPH and TMPA Satellite Rainfall Products over the Nile Basin, Journal of Applied Meteorology and Climatology, 51, 2105-2121, 10.1175/jamc-d-11-0252.1, 2012a.

Habib, E., Haile, A. T., Tian, Y., and Joyce, R. J.: Evaluation of the High-Resolution CMORPH Satellite Rainfall Product Using Dense Rain Gauge Observations and Radar-Based Estimates, Journal of Hydrometeorology, 13, 1784-1798, 10.1175/jhm-d-12-017.1, 2012b.

Habib, E., Haile, A., Sazib, N., Zhang, Y., and Rientjes, T.: Effect of Bias Correction of Satellite-Rainfall Estimates on Runoff Simulations at the Source of the Upper Blue Nile, Remote Sensing, 6, 6688-6708, 2014.

Haile, A. T., Rientjes, T., Gieske, A., and Gebremichael, M.: Rainfall Variability over Mountainous and Adjacent Lake Areas: The Case of Lake Tana Basin at the Source of the Blue Nile River, Journal of Applied Meteorology and Climatology, 48, 1696-1717, 10.1175/2009JAMC2092.1, 2009.

Haile, A. T., Habib, E., and Rientjes, T. H. M.: Evaluation of the climate prediction center CPC morphing technique CMORPH rainfall product on hourly time scales over the source of the Blue Nile river, Hydrological processes, 27, 1829-1839, 2013.

Haile, A. T., Yan, F., and Habib, E.: Accuracy of the CMORPH satellite-rainfall product over Lake Tana Basin in Eastern Africa, Atmospheric Research. *In Press, Accepted manuscript*, http://dx.doi.org/10.1016/j.atmosres.2014.11.011, 2014.

Haile, A. T., Yan, F., and Habib, E.: Accuracy of the CMORPH satellite-rainfall product over Lake Tana Basin in Eastern Africa, Atmospheric Research, 163, 177-187, http://dx.doi.org/10.1016/j.atmosres.2014.11.011, 2015.

Heidinger, H., Yarlequé, C., Posadas, A., and Quiroz, R.: TRMM rainfall correction over the Andean Plateau using wavelet multi-resolution analysis, International Journal of Remote Sensing, 33, 4583-4602, 10.1080/01431161.2011.652315, 2012.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., and Piontek, F.: A trend-preserving bias correction - the ISI-MIP approach, Earth Syst. Dynam., 4, 219-236, 10.5194/esd-4-219-2013, 2013.

Hughes, D. A.: Comparison of satellite rainfall data with observations from gauging station networks, Journal of Hydrology, 327, 399-410, http://dx.doi.org/10.1016/j.jhydrol.2005.11.041, 2006.

Ines, A. V. M., and Hansen, J. W.: Bias correction of daily GCM rainfall for crop simulation studies, Agricultural and Forest Meteorology, 138, 44-53, http://dx.doi.org/10.1016/j.agrformet.2006.03.009, 2006.

Jiang, S.-h., Zhou, M., Ren, L.-l., Cheng, X.-r., and Zhang, P.-j.: Evaluation of latest TMPA and CMORPH satellite precipitation products over Yellow River Basin, Water Science and Engineering, 9, 87-96, http://dx.doi.org/10.1016/j.wse.2016.06.002, 2016.

Johnson, F. and Sharma, A.: Accounting for interannual variability: A comparison of options for water resources climate change impact assessments, Water Resour. Res., 47(4), doi:10.1029/2010WR009272, 2011.

Katiraie-Boroujerdy, P., Nasrollahi, N., Hsu, K., and Sorooshian, S.: Evaluation of satellite-based precipitation estimation over Iran, Elsevier, Kidlington, ROYAUME-UNI, 15 pp., 2013.

Khan, S. I., Hong, Y., Gourley, J. J., Khattak, M. U. K., Yong, B., and Vergara, H. J.: Evaluation of three high-resolution satellite precipitation estimates: Potential for monsoon monitoring over Pakistan, Advances in Space Research, 54, 670-684, http://dx.doi.org/10.1016/j.asr.2014.04.017, 2014.

Koutsouris, A. J., Chen, D., and Lyon, S. W.: Comparing global precipitation data sets in eastern Africa: a case study of Kilombero Valley, Tanzania, Int. J. Climatol., 36, 2000-2014, 10.1002/joc.4476, 2016.

Kucuk, U., Eyuboglu, M., Kucuk, H. O. and Degirmencioglu, G.: Importance of using proper post hoc test with ANOVA, Int. J. Cardiol., 209, 346, doi:10.1016/j.ijcard.2015.11.061, 2018.

Leander, R., Buishand, T. A., van den Hurk, B. J. J. M. and de Wit, M. J. M.: Estimated changes in flood quantiles of the river Meuse from resampling of regional climate model output, J. Hydrol., 351(3–4), 331–343, doi:10.1016/j.jhydrol.2007.12.020, 2008.

Lenderink, G., Buishand, A. and van Deursen, W.: Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach, Hydrol. Earth Syst. Sci., 11(3), 1145–1159, doi:10.5194/hess-11-1145-2007, 2007.

Li, J., and Heap, A. D.: A review of comparative studies of spatial interpolation methods in environmental sciences: Performance and impact factors, Ecological Informatics, 6, 228-241, http://dx.doi.org/10.1016/j.ecoinf.2010.12.003, 2011.

Liu, J., Duan, Z., Jiang, J., and Zhu, A.-X.: Evaluation of Three Satellite Precipitation Products TRMM 3B42, CMORPH, and PERSIANN over a Subtropical Watershed in China, Advances in Meteorology, 2015, 13, 10.1155/2015/151239, 2015.

Liu, Z.: Comparison of precipitation estimates between Version 7 3-hourly TRMM Multi-Satellite Precipitation Analysis (TMPA) near-real-time and research products, Atmospheric Research, 153, 119-133, http://dx.doi.org/10.1016/j.atmosres.2014.07.032, 2015.

Lo Conti, F., Hsu, K.-L., Noto, L. V., and Sorooshian, S.: Evaluation and comparison of satellite precipitation estimates with reference to a local area in the Mediterranean Sea, Atmospheric Research, 138, 189-204, http://dx.doi.org/10.1016/j.atmosres.2013.11.011, 2014.

Maraun, D.: Bias Correcting Climate Change Simulations - a Critical Review, Current Climate Change Reports, 2, 211-220, 10.1007/s40641-016-0050-x, 2016.

Marcos, R., Llasat, M. C., Quintana-Seguí, P., and Turco, M.: Use of bias correction techniques to improve seasonal forecasts for reservoirs — A case-study in northwestern

Mediterranean, Science of The Total Environment, 610–611, 64-74, https://doi.org/10.1016/j.scitotenv.2017.08.010, 2018.

Matos, J. P., Cohen Liechti, T., Juízo, D., Portela, M. M., and Schleiss, A. J.: Can satellite based pattern-oriented memory improve the interpolation of sparse historical rainfall records?, Journal of Hydrology, 492, 102-116, http://dx.doi.org/10.1016/j.jhydrol.2013.04.014, 2013.

Meier, P., Frömelt, A., and Kinzelbach, W.: Hydrological real-time modelling in the Zambezi river basin using satellite-based soil moisture and rainfall data., Hydrol. Earth Syst. Sci., 15, 999-1008, 2011.

Meyer, H., Drönner, J., and Nauss, T.: Satellite-based high-resolution mapping of rainfall over southern Africa, Atmos. Meas. Tech., 10, 2009-2019, 10.5194/amt-10-2009-2017, 2017.

Moazami, S., Golian, S., Kavianpour, M. R., and Hong, Y.: Comparison of PERSIANN and V7 TRMM Multi-satellite Precipitation Analysis (TMPA) products with rain gauge data over Iran, International Journal of Remote Sensing, 34, 8156-8171, 10.1080/01431161.2013.833360, 2013.

Müller, M. F., and Thompson, S. E.: Bias adjustment of satellite rainfall data through stochastic modeling: Methods development and application to Nepal, Advances in Water Resources, 60, 121-134, http://dx.doi.org/10.1016/j.advwatres.2013.08.004, 2013.

Najmaddin, P. M., Whelan, M. J., and Balzter, H.: Application of Satellite-Based Precipitation Estimates to Rainfall-Runoff Modelling in a Data-Scarce Semi-Arid Catchment, Climate, 5, 32, 2017.

NIST/SEMATECH: e-handbook of statistical methods. Croarkin, C., Tobias, P., and Zey, C. (Eds.), NIST ;, [Gaithersburg, Md.] :, 2001.

Pereira Filho, A. J., Carbone, R. E., Janowiak, J. E., Arkin, P., Joyce, R., Hallak, R., and Ramos, C. G. M.: Satellite Rainfall Estimates Over South America – Possible Applicability to the Water Management of Large Watersheds1, JAWRA Journal of the American Water Resources Association, 46, 344-360, 10.1111/j.1752-1688.2009.00406.x, 2010.

Rientjes, T., Haile, A. T., and Fenta, A. A.: Diurnal rainfall variability over the Upper Blue Nile Basin: A remote sensing based approach, International Journal of Applied Earth Observation and Geoinformation, 21, 311-325, http://dx.doi.org/10.1016/j.jag.2012.07.009, 2013a.

Rientjes, T. H. M., Muthuwatta, L. P., Bos, M. G., Booij, M. J., and Bhatti, H. A.: Multi-variable calibration of a semi-distributed hydrological model using streamflow data and satellite-based evapotranspiration, Journal of Hydrology, 505, 276-290, http://dx.doi.org/10.1016/j.jhydrol.2013.10.006, 2013b.

Romano, F., Cimini, D., Nilo, S., Di Paola, F., Ricciardelli, E., Ripepi, E., and Viggiano, M.: The Role of Emissivity in the Detection of Arctic Night Clouds, Remote Sensing, 9, 406, 2017.

Romilly, T. G., and Gebremichael, M.: Evaluation of satellite rainfall estimates over Ethiopian river basins, Hydrol. Earth Syst. Sci., 15, 1505-1514, 10.5194/hess-15-1505-2011, 2011.

Seo, D. J., Breidenbach, J. P., and Johnson, E. R.: Real-time estimation of mean field bias in radar rainfall data, Journal of Hydrology, 223, 131-147, http://dx.doi.org/10.1016/S0022-1694(99)00106-7, 1999.

Shrestha, M. S.: Bias-adjustment of satellite-based rainfall estimates over the central Himalayas of Nepal for flood prediction. PhD thesis, Kyoto University, 2011.

Smiatek, G., Kunstmann, H., and Senatore, A.: EURO-CORDEX regional climate model analysis for the Greater Alpine Region: Performance and expected future change, Journal of Geophysical Research: Atmospheres, 121, 7710-7728, 10.1002/2015JD024727, 2016.

Srivastava, P. K., Islam, T., Gupta, M., Petropoulos, G., and Dai, Q.: WRF Dynamical Downscaling and Bias Correction Schemes for NCEP Estimated Hydro-Meteorological Variables, Water Resources Management, 29, 2267-2284, 10.1007/s11269-015-0940-z, 2015.

Switanek, M. B., Troch, P. A., Castro, C. L., Leuprecht, A., Chang, H. I., Mukherjee, R., and Demaria, E. M. C.: Scaled distribution mapping: a bias correction method that preserves raw climate model projected changes, Hydrol. Earth Syst. Sci., 21, 2649-2666, 10.5194/hess-21-2649-2017, 2017.

Taylor, K. E.: Summarizing multiple aspects of model performance in a single diagram, Journal of Geophysical Research: Atmospheres, 106, 7183-7192, 10.1029/2000JD900719, 2001.

Tesfagiorgis, K., Mahani, S. E., Krakauer, N. Y., and Khanbilvardi, R.: Bias correction of satellite rainfall estimates using a radar-gauge product – a case study in Oklahoma (USA), Hydrol. Earth Syst. Sci., 15, 2631-2647, 10.5194/hess-15-2631-2011, 2011.

Themeßl, M. J., Gobiet, A., and Heinrich, G.: Empirical-statistical downscaling and error correction of regional climate models and its impact on the climate change signal, Clim. Change, 112, 449–468 2012.

Thiemig, V., Rojas, R., Zambrano-Bigiarini, M., Levizzani, V., and De Roo, A.: Validation of Satellite-Based Precipitation Products over Sparsely Gauged African River Basins, Journal of Hydrometeorology, 13, 1760-1783, 10.1175/jhm-d-12-032.1, 2012.

Thiemig, V., Rojas, R., Zambrano-Bigiarini, M., and De Roo, A.: Hydrological evaluation of satellite-based rainfall estimates over the Volta and Baro-Akobo Basin, Journal of Hydrology, 499, 324-338, 10.1016/j.jhydrol.2013.07.012, 2013.

Thorne, V., Coakeley, P., Grimes, D., and Dugdale, G.: Comparison of TAMSAT and CPC rainfall estimates with raingauges, for southern Africa, International Journal of Remote Sensing, 22, 1951-1974, 10.1080/01431160118816, 2001.

Tian, Y., Peters-Lidard, C. D., and Eylander, J. B.: Real-Time Bias Reduction for Satellite-Based Precipitation Estimates, Journal of Hydrometeorology, 11, 1275-1285, 10.1175/2010JHM1246.1, 2010.

Tobin, K. J., and Bennett, M. E.: Adjusting Satellite Precipitation Data to Facilitate Hydrologic Modeling, Journal of Hydrometeorology, 11, 966-978, doi:10.1175/2010JHM1206.1, 2010.

Toté, C., Patricio, D., Boogaard, H., van der Wijngaart, R., Tarnavsky, E., and Funk, C.: Evaluation of Satellite Rainfall Estimates for Drought and Flood Monitoring in Mozambique, Remote Sensing, 7, 1758, 2015.

Tsidu, G. M.: High-Resolution Monthly Rainfall Database for Ethiopia: Homogenization, Reconstruction, and Gridding, Journal of Climate, 25, 8422-8443, 10.1175/JCLI-D-12-00027.1, 2012.

Tumbare, M. J.: Management of River Basins and Dams: The Zambezi River Basin, edited by: Tumbare, M. J., Taylor & Francis, 318 pp., 2000.

Tumbare, M. J.: The Management of the Zambezi River Basin and Kariba Dam, Bookworld Publishers, Lusaka, 2005.

Valdés-Pineda, R., Demaría, E. M. C., Valdés, J. B., Wi, S., and Serrat-Capdevilla, A.: Bias correction of daily satellite-based rainfall estimates for hydrologic forecasting in the Upper Zambezi, Africa, Hydrol. Earth Syst. Sci. Discuss., 2016, 1-28, 10.5194/hess-2016-473, 2016.

Vernimmen, R. R. E., Hooijer, A., Mamenun, Aldrian, E., and van Dijk, A. I. J. M.: Evaluation and bias correction of satellite rainfall data for drought monitoring in Indonesia, Hydrol. Earth Syst. Sci., 16, 133-146, 10.5194/hess-16-133-2012, 2012.

Wehbe, Y., Ghebreyesus, D., Temimi, M., Milewski, A., and Al Mandous, A.: Assessment of the consistency among global precipitation products over the United Arab Emirates, Journal of Hydrology: Regional Studies, 12, 122-135, http://dx.doi.org/10.1016/j.ejrh.2017.05.002, 2017.

Wilks, D.: Statistical Methods in the Atmospheric Sciences, 2nd ed., Academic Press, Burlington, Mass, 2006.

Woody, J., Lund, R., and Gebremichael, M.: Tuning Extreme NEXRAD and CMORPH Precipitation Estimates, Journal of Hydrometeorology, 15, 1070-1077, 10.1175/jhm-d-13-0146.1, 2014.

World Bank: The Zambezi River Basin : A Multi-Sector Investment Opportunities Analysis - Summary Report. World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/2958 License: Creative Commons Attribution CC BY 3.0., 2010a.

World Bank: The Zambezi River Basin: A Multi-Sector Investment Opportunities Analysis, Volume 2 Basin Development Scenarios, 2010b.

Worqlul, A. W., Maathuis, B., Adem, A. A., Demissie, S. S., Langan, S., and Steenhuis, T. S.: Comparison of rainfall estimations by TRMM 3B42, MPEG and CFSR with ground-observed data for the Lake Tana basin in Ethiopia, Hydrol. Earth Syst. Sci., 18, 4871-4881, 10.5194/hess-18-4871-2014, 2014.

Wu, L., and Zhai, P.: Validation of daily precipitation from two high-resolution satellite precipitation datasets over the Tibetan Plateau and the regions to its east, Acta Meteorol Sin, 26, 735-745, 10.1007/s13351-012-0605-2, 2012.

Yang, X., Xie, X., Liu, D. L., Ji, F., and Wang, L.: Spatial Interpolation of Daily Rainfall Data for Local Climate Impact Assessment over Greater Sydney Region, Advances in Meteorology, 2015, 12, 10.1155/2015/563629, 2015.

Yin, Z. Y., Zhang, X., Liu, X., Colella, M., and Chen, X.: An assessment of the biases of satellite rainfall estimates over the tibetan plateau and correction methods based on topographic analysis, Journal of Hydrometeorology, 9, 301, 2008.

Yoo, C., Park, C., Yoon, J., and Kim, J.: Interpretation of mean-field bias correction of radar rain rate using the concept of linear regression, Hydrological Processes, 28, 5081-5092, 10.1002/hyp.9972, 2014.

Zulkafli, Z., Buytaert, W., Onof, C., Manz, B., Tarnavsky, E., Lavado, W., and Guyot, J.-L.: A Comparative Performance Analysis of TRMM 3B42 (TMPA) Versions 6 and 7 for Hydrological Applications over Andean–Amazon River Basins, Journal of Hydrometeorology, 15, 581-592, doi:10.1175/JHM-D-13-094.1, 2014.

Appendix 1: Rain gauge stations in the Zambezi subbasins showing x and y location, subbasin they belong to, year of data availability, % of missing gaps, station elevation and distance from large-scale water bodies.

Station	**Subbasin**	**Zambezi classification**	**X Coord**	**Y Coord**	**Start date**	**End Date**	**% gaps (missing records)**	**Elevation (m)**	**Distance from lake (km)**
Marromeu	Zambezi Delta	Lower Zambezi	36.95	-18.28	29/05/2007	31/12/2013	0.37	3	90
Caia	Zambezi Delta	Lower Zambezi	35.38	-17.82	29/05/2007	31/12/2013	0.13	28	265
Nsanje	Shire	Lower Zambezi	35.27	-16.95	01/01/1998	31/12/2013	3.49	39	157
Makhanga	Shire	Lower Zambezi	35.15	-16.52	01/01/1998	31/12/2013	9.43	48	113

Nchalo	Shire	Lower Zambezi	34.93	-16.23	01/01/1998	31/12/2013	0.60	64	96
Ngabu	Shire	Lower Zambezi	34.95	-16.50	01/01/1998	3112/2010	0.74	89	123
Chikwawa	Shire	Lower Zambezi	34.78	-16.03	01/01/1998	31/12/2010	0.93	107	77
Tete (Chingodzi)	Tete	Lower Zambezi	33.58	-16.18	29/05/2007	31/12/2013	0.17	151	135
Chingodzi	Shire	Lower Zambezi	34.63	-16.00	29/05/2007	10/01/2013	11.8	280	101
Zumbo	Shire	Lower Zambezi	30.45	-15.62	29/05/2007	12/09/2012	0.16	345	<5
Mushumbi	Kariba	Middle Zambezi	30.56	-16.15	11/06/2008	11/12/2013	7.47	369	43
Kanyemba	Tete	Middle Zambezi	30.42	-15.63	01/01/1998	30/03/2013	5.86	372	<5
Morrumbala	Zambezi Delta	Lower Zambezi	35.58	-17.35	29/05/2007	10/01/2013	13.3	378	206
Mágoè	Tete	Middle Zambezi	31.75	-15.82	01/01/2009	31/12/2013	9.6	427	10
Muzarabani	Tete	Middle Zambezi	31.01	-16.39	01/01/1998	31/12/2013	1.14	430	49
Monkey	Shire	Lower Zambezi	34.92	-14.08	01/01/1998	30/11/2010	0.00	478	<5
Mangochi	Shire	Lower Zambezi	35.25	-14.47	01/01/1998	31/12/2010	0.02	481	<5
Rukomechi	Kariba	Middle Zambezi	29.38	-16.13	01/01/1998	31/12/2013	6.40	530	68
Mutarara	Shire	Lower Zambezi	33.00	-17.38	29/05/2007	10/01/2013	11.7	548	201
Mfuwe	Luangwa	Middle Zambezi	31.93	-13.27	01/01/1998	31/12/2010	2.70	567	246
Mimosa	Shire	Lower Zambezi	35.62	-16.07	01/01/1998	31/12/2010	3.96	616	72
Kariba	Kariba	Middle Zambezi	28.80	-16.52	01/01/1998	31/12/2013	0.01	618	21
Balaka	Shire	Lower Zambezi	34.97	-14.98	01/01/1998	30/04/2010	0.78	618	24
Thyolo	Shire	Lower Zambezi	35.13	-16.13	01/01/1998	31/12/2010	0.11	624	86
Chileka	Shire	Lower Zambezi	34.97	-15.67	01/01/1998	31/12/2013	0.60	744	64
Fingoe	Tete	Middle Zambezi	31.88	-15.17	01/01/2009	31/12/2013	5.9	881	44
Muze	Tete	Zambezi	31.38	-14.95	01/01/2009	31/12/2013	8.8	888	75
Neno	Shire	Lower Zambezi	34.65	-15.40	01/01/1998	01/01/2010	9.14	903	64
Zámbue	Tete	Middle Zambezi	30.80	-15.11	01/01/2009	31/12/2013	9.8	950	56
Mt Darwin	Tete	Middle Zambezi	31.58	-16.78	01/01/1998	02/03/2008	5.00	962	94
Chipata	Shire	Lower Zambezi	32.58	-13.55	01/01/1998	13/08/2003	1.11	995	179
Makoka	Shire	Lower Zambezi	35.18	-15.53	01/01/1998	31/12/2010	0.00	996	27
Livingstone	Kariba	Middle Zambezi	25.82	-17.82	01/01/1998	31/12/2013	0.00	996	107
Senanga	Barotse	Upper Zambezi	23.27	-16.10	01/01/1998	31/12/2013	8.90	1001	444
Petauke	Luangwa	Middle Zambezi	31.28	-14.25	01/02/1998	31/12/2013	0.40	1006	155
Msekera	Luangwa	Middle Zambezi	32.57	-13.65	01/03/1998	31/12/2015	19.7	1028	179
Kalabo	Lungue Bungo	Upper Zambezi	22.70	-14.85	01/01/1998	31/12/2011	5.20	1033	582
Mongu	Barotse	Upper Zambezi	23.15	-15.25	01/01/1998	31/12/2013	0.51	1052	518

Kasungu	Shire	Lower Zambezi	33.47	-13.02	01/01/2003	31/07/2013	0.00	1063	89
Victoria Falls	Kariba	Middle Zambezi	25.85	-18.10	01/01/1998	31/12/2013	2.26	1065	107
Bolero	Luangwa	Middle Zambezi	33.78	-11.02	01/01/2003	31/05/2013	0.00	1070	38
Pandamatenga	Kariba	Middle Zambezi	25.63	-18.53	01/01/1998	31/12/2013	0.01	1071	151
Zambezi	Lungue Bungo	Upper Zambezi	23.12	-13.53	01/01/1998	31/12/2013	1.60	1075	611
Kabompo	Kabombo	Upper Zambezi	24.20	-13.60	01/01/1998	30/04/2005	0.08	1086	505
Chichiri	Shire	Lower Zambezi	35.05	-15.78	01/01/1998	31/12/2010	0.00	1136	40
Chitedze	Shire	Lower Zambezi	33.63	-13.97	01/01/2003	30/04/2013	0.00	1150	84
Lundazi	Luangwa	Middle Zambezi	33.20	-12.28	01/01/2003	30/04/2013	1.40	1151	91
Guruve	Tete	Middle Zambezi	30.70	-16.65	01/01/1998	30/03/2013	0.02	1159	86
Kaoma	Barotse	Upper Zambezi	24.80	-14.80	01/01/1998	31/11/2013	9.89	1162	358
Bvumbwe	Shire	Lower Zambezi	35.07	-15.92	01/01/1998	01/01/2011	0.00	1172	59
Kasempa	Kafue	Middle Zambezi	25.85	-13.53	01/01/1998	31/12/2013	9.10	1185	431
Kabwe	Luangwa	Middle Zambezi	28.47	-14.45	01/01/1998	13/10/2012	1.54	1209	230
Chitipa	Shire	Lower Zambezi	33.27	-9.70	01/01/2003	06/01/2013	0.05	1288	62
Mwinilunga	Kabompo	Upper Zambezi	24.43	-11.75	01/01/1998	31/12/2013	4.81	1319	520
Karoi	Tete	Middle Zambezi	29.62	-16.83	01/01/1998	31/12/2004	15.08	1345	88
Solwezi	Kafue	Middle Zambezi	26.38	-12.18	01/01/1998	31/12/2013	0.02	1372	356
Harare (Belvedere)	Tete	Middle Zambezi	31.02	-17.83	01/01/1998	31/03/2013	7.80	1472	209
Harare(Kutsaga)	Tete	Middle Zambezi	31.13	-17.92	01/01/2004	30/09/2010	0.55	1488	209
Mvurwi	Tete	Middle Zambezi	30.85	-17.03	01/01/1998	11/12/2000	0.00	1494	102
Dedza	Shire	Lower Zambezi	34.25	-14.32	01/01/2003	31/10/2012	0.00	1575	44

Appendix 2: Bias correction scheme based Taylor Diagram performance indicators (correlation coefficients, standard deviations and RMSE) of rain gauge (reference) vs CMORPH estimations (corrected and uncorrected), period 1998-2013, for Lower, Middle and Upper Zambezi Basin.

Subbasin	Rainfall estimate	RMSE (mm/day)	Correlation Coefficient	Standard Deviation (mm/day)
Lower Zambezi	Gauge	-	-	9.38
	R-CMORPH	9.98	0.46	8.00
	PT	10.41	0.57	8.52
	QME	9.15	0.55	6.98
	EZ	10.48	0.62	6.35
	DT	9.30	0.56	6.55
	STB	8.59	0.72	7.17
Middle Zambezi	Gauge	-	-	7.94
	R-CMORPH	8.12	0.49	7.44
	PT	7.87	0.62	6.84
	QME	7.51	0.60	6.00

	EZ	10.69	0.65	6.93
	DT	8.04	0.59	6.96
	STB	7.49	0.76	6.81
Upper Zambezi	Gauge	-	-	8.29
	R-CMORPH	7.23	0.45	6.60
	PT	7.97	0.62	7.29
	QME	8.05	0.55	7.12
	EZ	11.50	0.60	8.13
	DT	7.85	0.55	6.45
	STB	0.54	0.74	7.29