

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

**Webster Gumindoga et al.**

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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

Received and published: 26 October 2017

Referee Comment

This manuscript, entitled "Performance of bias correction schemes for CMORPH rainfall estimates in the Zambezi River Basin", investigates the performance of bias cor-

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rected 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.

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However, in our efforts to revise the manuscript we tested and applied 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

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We have maintained frequency based metrics which we had used previously to evaluate the SRE rainfall detection performance: Mean, Min and Max.

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  $-\infty$  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 raingauge, 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,

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Paired t-tests – We aim to test whether there is a significant difference between rain-gauge 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 between the five bias correction schemes. After ANOVA is conducted, we determined which schemes differ significantly using post-hoc tests. 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 cross-validation. We aim to test the bias correction procedure leaving out few single stations 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 performed cross validation for 8 locations selected as follows: two stations in the < 250m elevation zone, three stations each at 250-950 and > 950 elevation zone. We selected the 8 stations at average elevation and at the centre for each zone. This left us with 52 stations for the main performance evaluation. See new section: 3.9. Validation of the bias correction procedures.

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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

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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

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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?

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#### 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 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 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

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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

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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 underestimate 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

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pattern, variability and magnitude of the variability..."

Specific comments.

#### 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 mostly prone to bias mainly because such estimates are indirectly derived from visible, infrared, and/or microwave based information of cloud properties...'

#### 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

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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

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Author's changes in the manuscript

We modified sentence to '...The recent cited publications on CMORPH in the African basins exist (Koutsouris et al., 2016; Jiang et al., 2016; Haile et al., 2015)...'

In line 146-149 we added the following statements: "...The above studies point to work on CMORPH in the African basins. However specific CMORPH data applicability following bias correction in the 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 be practical to add a 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

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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 292-304 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 351-353 now reads "...The grouping in this study is based on the hierarchical clustering technique as 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

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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.

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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 1998-2013) Figure 5 now shows the time-series-based metrics: 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 log-scale on the y-axis implemented as recommended by the reviewers

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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 1998-2013 period.

Author's changes in the manuscript

This has been clarified in the manuscript (section 4.3.6) and now Table 3 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.

We took note of the reviewer's comment.

Author's changes in the manuscript.

We corrected sentence in the conclusions section to: "The STB bias correction scheme effectively adjusted the daily mean of CMORPH estimates as shown by an increase of the correlation coefficient by 53 % and by reduction of the root mean square difference by 25 %". 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

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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.

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