

# ***Interactive comment on “Performance of GPM-IMERG precipitation products under diverse topographical features and multiple-intensity rainfall in an arid region” by Safa A. Mohammed et al.***

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The authors would like to thank Dr. Husain Najafi for his valuable comments. We really appreciate the time invested in reviewing the manuscript, which indeed help to improve the quality of our paper. We have followed the comments carefully and responded to each comment or suggestion.

The reviewer has touched upon important points that need to be addressed in our revision of the manuscript. The authors' strived to make sure that the applied methods in

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this research are robust and valid. The reviewer noted that the authors' have attempted to evaluate GPM-IMERG products in different parts of the Arabian Peninsula, however the analysis presented in this study is a major departure than that made in the previous study on Saudi Arabia because of the following:

1. The data used in this study covers a longer period of analysis (4 years); which allowed to perform the evaluation on multiple seasons. While a shorter duration (one rainy season) used in the previous studies (this was already mentioned in the text Lines 127-130);
2. The analysis in this study focuses on evaluating IMERG products with respect to natural geographical factors such as rainfall intensity, topography, and hydrological zones whereas previous studies have focused on station-based and geopolitical (provincial-based) evaluation (this also was already mentioned in the text Lines 131-139); and
3. Since newer versions of algorithms for IMERG products are being rolled out every few months, the scientific community can benefit from some form of repetition of analysis to track the effectiveness of these changes.

Specific comments:

1. Comment: Research questions are not clearly mentioned in the introduction.

Reply: The authors did mention the objectives of this study in the last paragraph of the introduction section (Lines 133-139). However, we will add the specific research questions of this study to the last paragraph of the introduction section to read as follows:

"Upon investigating the previous studies, several research gaps were found such as the impact of complex topography, where precipitation has high spatial and temporal variations, on the estimates of the GPM satellite precipitation retrievals. In addition to complex topography, there is a need to test the claim that GPM satellite instruments are capable of detecting low rainfall intensity events, which was not addressed in arid

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and semi-arid regions to date."

2. Comment: In the first section of the paper, some aspects of advances and challenges of evaluating satellite precipitation products is discussed. Extensive introduction is provided on precipitation measurements with specific focus on remote sensing of precipitation. However, literature on the result of other studies which evaluate satellite-based products in arid regions is not sufficiently elaborated. Findings from other research studies, which assessed the performance of GPM-IMERG products in regional scale in general, and the area under study in specific, is not provided.

Reply: The authors did touch upon the results of other studies evaluating satellite-based products in arid regions in the introduction section (Lines 91-95 and 127-130). However, the reviewer has a point in requesting more elaboration since the main focus of the manuscript is on 'arid regions'. The authors will add a few sentences regarding studies on arid regions.

"Several studies were conducted to evaluate the detection accuracy of satellite rainfall products in arid and semiarid regions. One study carried out by (Dinku et al., 2010) evaluated seven satellite rainfall products over an arid and semiarid region that spans from Northwestern Africa to Northwestern India. These satellite precipitation products included CMORPH, GSMaP-MVK, GSMaP-MVK1, TRMM (3B42), TRMM (3B42RT), African rainfall climatology, and African rainfall estimation algorithm. Their findings showed that the satellite precipitation measurements had an overall positive detection performance, particularly in the wet season. Few studies specifically focused on evaluating the performance of GPM IMERG products over arid regions. The latest studies (Mahmoud et al., 2019, and Nashwan et al., 2019) assessed the performance of GPM IMERG rainfall products over the United Arab Emirates and Egypt, respectively. Both are considered arid countries with high rainfall scarcity. Mahmoud et al. (2019) found that the calibrated IMERG product outperformed the near real-time products giving the highest detection accuracy and the lowest errors. Moreover, Nashwan et al. (2019) evaluated two products other than IMERG, namely: GSMaP and CHIRPS. The results

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showed the superiority of IMERG products in rainfall occurrence detection and the capability to represent the rainfall spatial variability during extreme events."

3. Comment: Seasonal and annual rainfall based on Ministry of Environment, Water, and Agriculture (MEWA) rain gauges are not provided in section 2. This information can provide a basis for comparison between reference data and GPM-IMERG.

Reply: The total annual rainfall over the study area was mentioned on line 155 of section 2. However, the authors will add the following table R-1 (attached) with statistical description of rainfall based on rain gauge data.

4. Comment: Since the research is based on local rainfall data, access protocol to the data is not provided. It is mentioned in line 194 that the data was downloaded from MEWA website; however, the corresponding link is not provided. Relevant aspects of reproducibility of scientific result is not addressed.

Reply: The access protocol to rain gauge data acquired from MEWA website is by request. The authors invite any researcher with interest in investigating rainfall on KSA to communicate with MEWA directly to acquire the data through the following link (<https://www.mewa.gov.sa/en/InformationCenter/OpenData/RequestOpenData/Pages/RequestOpenData.aspx>).

5. Comment: The overall quality of selected reference data (MEWA stations) is not mentioned in section 3.1. Quality control procedure applied to MEWA data is not explained. Previous studies which have used this dataset are not cited. Convincible reasons is required on why MEWA is selected as the reference data of the research besides the reason mentioned in lines 172-174. It was helpful if mentioned which authorities are responsible for recording rainfall within the study area, and to provide some arguments on reliability of MEWA compared to other rainfall sources. The type of MEWA rain gauges is not mentioned.

Reply: The authors will add a statement to line 172 to make it clear that MEWA is the authority that owns, operates, and maintains the rain gauges used in this study. Also,

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a citation of other studies, Mahmoud et. al. 2018, will be added to the text. In the past, KSA had two sources of precipitation data namely: MEWA and The General Authority of Meteorology and Environmental Protection. Currently, both datasets were merged under MEWA; however, in this study we excluded the data of The General Authority of Meteorology and Environmental Protection because, this data is used to build up the GPCP product, which is used to calibrate the GPM IMERG-F. Thus to make this study independent, we excluded these stations (this was clearly stated in the v1 of the manuscript L173). Even though it would be interesting to know the type of rainguages used by MEWA and the quality measures undertaken by the authority, such information is not available and falls outside the scope of this analysis.

6. Comment: Domain selection requires careful attentions for evaluating a satellite precipitation product in the absence of a dense rain gauge network. Although two important aspects (topographical effect and evaluating satellite products in hydrological regions) have been studied to investigate the performance of GPM-IMERG, the results are likely to be sensitive and dependent to some unknown extent on the spatial evaluation de-scribed in section 4.3.3. The low density and spatially non-uniform rainfall network selected as reference in this research will influence spatial evaluation of GPM-IMERG in at least some regions reported in section 5.3. There is not any rain gauge station located between 16 -24 N and 48 -55 E. Given the low density of MEWA stations in regions I, II, III, IV, VII, VIII, and their corresponding topographical classes, robustness of the results provided in section 5.3.1 and 5.3.2 is under question and not straight forward. It is explicitly declared in the conclusion section of the manuscript (lines 466-469) that the issue (low density of rain gauge stations) prevents a proper evaluation of the rainfall satellite product. Results provided in table 6 for hydrologic regions number II, III and VII also provide evidence that the highest percentage of relative bias (RBIAS) are calculated in those areas incorporating small number of gauge stations (see Figure 4). This argument is critical and requires careful considerations as it could highly effect the result.

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Reply: The authors concur to the importance of rain-gauge density in evaluating satellite measurements. However, we carefully included such an impact in our interpretation of the results in the section that the reviewer noted. As researchers we can only note this impact in the results. It would be interesting to evaluate GPM satellite products on a larger scale, limiting the areas investigated to those having high density rain-gauges.

7. Comment: In lines 136-138, it is stated that a comprehensive evaluation is presented in the current study. However, often-used metrics namely statistical distribution and metrics on extended contingency table have not been considered.

Reply: The authors used typical statistical matrices used by almost all of the researchers in the field. Specifically the ones who conducted their research on GPM products' assessment. The purpose of using the same matrices is to facilitate the comparison between the results obtained in this research and the previous studies (Anjum et al., 2018; Gadelha et al., 2019; Tang et al., 2016).

8. Comment: It is not apparent how the methodology described in line 206 as "point to point analysis" is used for spatial evaluation (explained in section 4.3.3). The research method used in generating figures 5 and 6 is not clear. How metrics provided in Table 1 are calculated for spatial evaluation? How Probability of Detection (POD) is calculated over the five topographical classes, and ten hydrological regions? Relevant formulation on pointwise analysis and areal-average evaluation is not provided for metrics in Table 1.

Reply: Point-to-point analysis was explained in the text L206-209. However, the reviewer is correct in requesting further explanation of the spatial analysis. The authors will add the following text to section 4.3.3 in the revised manuscript:

"For each analyzed region, whether topographical or hydrological, the statistical measures were calculated for two aggregated datasets formulated by point to point matching. For example, if a set of rain-gauges fall within one region the observations from these rain-gauges will form one dataset to be compared to the dataset formed from the

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matching (nearest) satellite point precipitation estimates."

9. Comment: Figure 3 and Figure 4 provide the spatial coverage of MEWA rain gauges within correspondent topographical and hydrological regions. However, the percentage of areas correspond to each class and corresponding percentage of MEWA stations is not provided. The number of rainfall events for each intensity class is not provided.

Reply: The percentage of rain gauge stations present in each topographical zona and each hydrologic zone was calculated and will be added as new tables R-2 and R-3 in the attachment.

10. Comment: Evaluation methods for comparing satellite rainfall to gauge-based products have limitations which are not addressed.

Reply: If the reviewer is referring to statistical evaluation methods, these are quite robust and have been consistently used in all hydrological research studies. However, if the reviewer is referring to limitations due to errors in ground and satellite observations, then this falls outside the scope of this evaluation. If the authors missed what was intended from the reviewer's comment, then an elaboration from the reviewer's side would be appreciated.

11. Comment: In section 4.1, it is mentioned that rainfall events are determined during March 2014 to June 2018 based on ground observations. However, missing rate is not provided. The way missing data is treated to detect rainfall events is not mentioned in the research methodology.

Reply: The methodology we followed in this research was based on rainfall events, because in arid regions, we have a few number of rainy days. Therefore, a time series of data was not provided by MEWA, rather only events of detected rainfall on separate days was provided. Only the detected events reported by MEWA were used in the analysis to avoid arguments on whether to consider missing data as zero events.

12. Comment: The sentence "The main superiority of satellite data over rain gauge

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data is that it provides uniform spatial coverage at high temporal resolution” stated in lines 53 and 54 is subject to argument

Reply: While the generalization that the authors made on lines 53 and 54 is generally accepted by researchers using satellite-based data, the authors have decided to modify the statement and make it specific to the study area where the density and coverage of rain gauges is low. The new sentence will read:

"The main superiority of satellite data over rain gauge data over poorly-gauged regions such as KSA is that it provides uniform spatial coverage at high temporal resolution."

13. Comment: Lines 97-102: It is argued that availability of rain gauges in mountains areas is not common. The statement is general, and might not hold valid for some regions.

Reply: The authors agree that generalization hurts the intended message. The sentence will be modified to read:

"It is not common to find rain gauges in mountainous regions in our study area due to accessibility issues."

14. Comment: Same as above, Lines 167-168: The sentence “Many researchers used the (<http://www.dwd.de/>) gauge data for evaluation purposes; this data is not of sufficient density nor distribution for obtaining ground observation data at fine spatial resolution (Wang et al., 2017)” is a general statement and is subjected to arguments.

Reply: The statement is true for the study area and the authors modified it to be only specific to the study area. The modified statement will read:

"Using GPCC (<http://www.dwd.de/>) gauge data for evaluation purposes is not sufficient in certain countries (Wang et al., 2017) since the data included is not of sufficient density nor distribution for obtaining ground observation data at fine spatial resolution, this is true for KSA."

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15. Comment: Lines 243-247: How seasonal evaluation of GPM-IMERG products during March 2014-June 2018 could help to bring a better understanding of the climate of Saudi Arabia and monitoring climate change in the region?

Reply: As mentioned in line 245, the use of GPM-data in monitoring climate change is mainly to enhance the ability to forecast extreme hazardous events (e.g. floods). This has been extensively discussed in previous research (Hollmann et al., 2013a; Mazzoglio et al., 2019)

Technical comments

16. Comment: Sentence in line 128 requires revision.

Reply: The sentence will be revised to read:

"A recent study validated the IMERG products over Saudi Arabia, the findings showed that the final-run product had a better performance than other products in detecting and estimating precipitation in the study area (Mahmoud et al., 2018)."

17. Comment: Geographical coordination of area under study provided in lines 142 and 143 re-quires revision.

Reply: The geographical coordinates were revised. The sentence in line 142 and 143 will be modified to read:

"The country covers a complex topographical surface, which falls between 34°– 55°E and 16° – 32° N, as represented in Figure 1."

18. Comment: Figure 1 does not have a legend. Both MEWA stations and major cities within the study area are represented in black dots.

Reply: The authors would like to draw the reviewer attention that we have used red dots to represent MEWA stations, while major administrative regions were shown in labels not dots. However, to clearly represent the location of the study area and MEWA stations the authors reproduced the figure and it will be included in the modified version

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of the manuscript. The figure is attached with this response.

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## HESSD

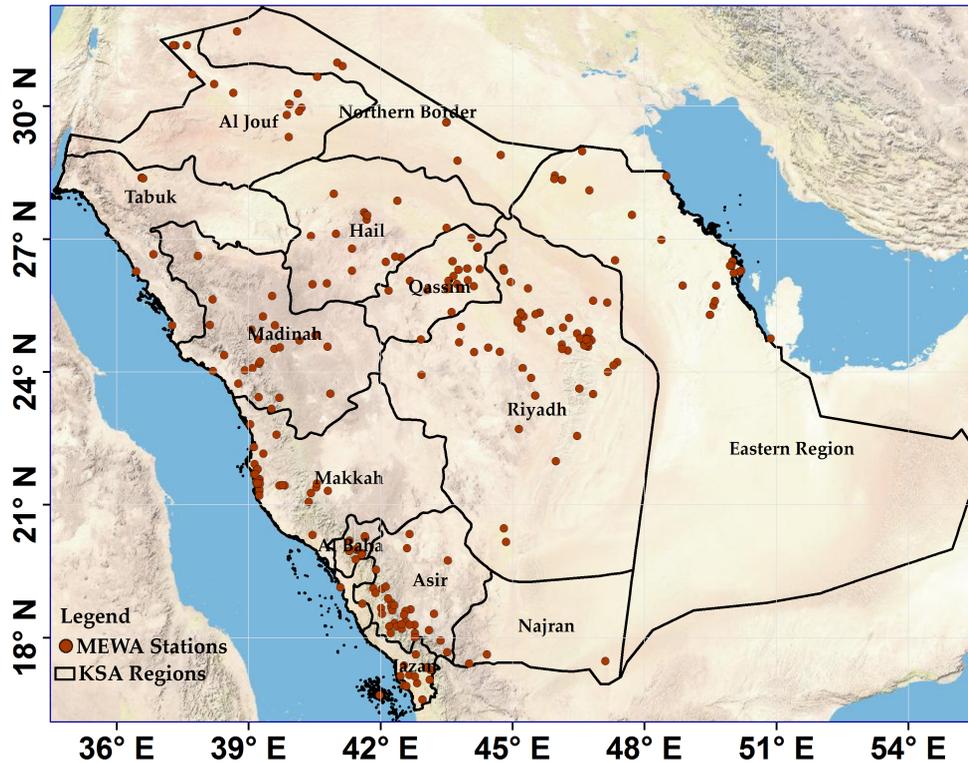
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**Fig. 1.** Distribution of rain gauge network operated by Ministry of Environment, Water, and Agriculture (MEWA), KSA.

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Table R-1. Statistical analysis of the regional annual rainfall measured by MEWA stations

Year	No. of Observations	Mean	Standard Error	Standard Deviation	Variance	Kurtosis	Skewness	Range	Max.	Total *
2014	790	9.94	0.36	10.12	102.39	5.84	2.06	79.9	80	7855
2015	1492	10.82	0.29	11.34	128.70	7.35	2.29	93.9	94	16138
2016	1572	12.69	0.37	14.76	217.89	16.28	3.02	175	175	19945
2017	1055	11.78	0.43	14.02	196.63	28.53	3.92	165	165	12428
2018	529	9.02	0.42	9.61	92.38	4.97	2.11	55.8	56	4771

\* Total Rainfall: Accumulative rainfall for the whole stations observations during the year.

Note: All measurements are in mm.

**Fig. 2.** Table R-1 Statistical analysis of the regional annual rainfall measured by MEWA stations

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Table R-2 Rain gauge stations distribution in each hydrological zone

Hydrological Zones	No. of Observations	No. of Stations	Station density #/1000km <sup>2</sup>
Region I	937	51	0.14
Region II	3	3	0.03
Region III	183	13	0.10
Region IV	508	27	0.06
Region V	885	45	0.45
Region VI-N	204	21	0.19
Region VI-S	2100	52	0.77
Region VII	4	1	0.01
Region VIII	248	14	0.05
Region IX	71	21	1.35
Total	5143	248	

**Fig. 3.** Table R-2 Rain gauge stations distribution in each hydrological zone

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Table R-3 Rain gauge distribution in each Topographical region.

Topographical Regions	No. of Observations	No. of Stations	Station density #/1000km <sup>2</sup>
Coastal region	1140	63	0.14
Areas adjacent to the coasts	1657	58	0.15
Inland region	1918	96	0.46
Foothills region	215	19	0.52
High mountains region	213	12	0.01
Total	5143	248	

**Fig. 4.** Table R-3 Rain gauge distribution in each Topographical region

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