Author Response to the referee comments on "Citizen rain gauge improves hourly radar rainfall bias correction using a two-step Kalman filter"

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Responses to referee #2

RC: Referee comment

AR: Author response

Major comments

RC (1) In Chapter 2.3.1 you describe that all TMD rain gauges "with more than 80% of the dataset below the threshold was excluded" (P5L125). Since the threshold of 0.5 is equal to the tipping bucket resolution, you excluded all station with an hourly p0 (probability of value zero in the dataset) above 0.8. On P16L363 you mention that "the others having a period of heavy rainfall around 4-5 hours a day" which leads to a p0 of around 0.8. This applied filter excluded approximately 55% of the stations which is a lot due to the fact that the data is provided by the Thai Meteorological Department. Can you please provide a figure showing all TMD gauges on the one side and the used gauges on the other side?

AR: thanks for pointing this out, we realize the phrasing may have created confusion.
The rain gauge selection was based on a threshold p0 of 0.8 at the daily scale. Only 134 out of 297 stations passed this test. Actually, many of the rejected stations recorded zero values throughout most of the study period. Of the remaining stations, many reported heavy rainfall during 4-5 hours of the day (which indeed leads to a p0 of 0.8 at the hourly scale), as stated in P16L363.

We propose to rephrase the sentence (P5L125) as follows, to avoid confusion:
"Rain gauges with more than 80% of the recordings below the 0.5 mm threshold at daily scale were excluded from the analysis. It turns out that many of these faulty gauges recorded zero rainfall throughout most of the study period."

We will also modify figure 1, to distinguish the selected rain gauges:

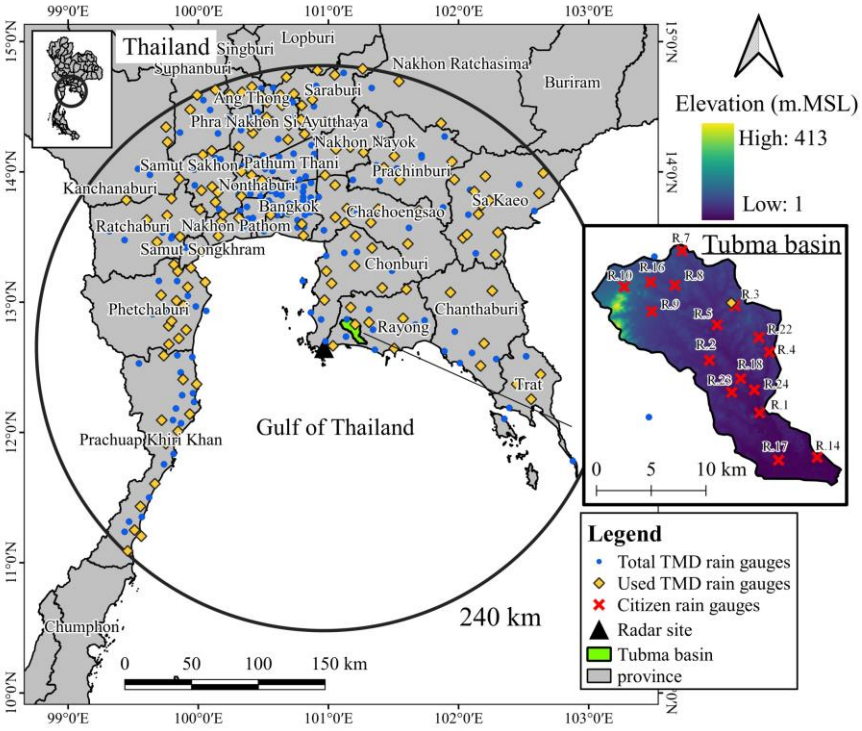

Figure 1 (modified for revised manuscript): Location of study domain, showing Thai Meteorological Department (TMD) automatic rain gauges, citizen rain gauges, Sattahip radar, and Tubma basin.

RC (2) Was there a specific reason why the validation was done with two different data sets? This means that a comparison between the daily and the hourly data set is not meaningful.

AR: The question we aimed to answer in this manuscript is to what extent citizen rainfall observations improve the accuracy of hourly radar rainfall estimates (by using a 2-step Kalman filter approach). Since the citizen rainfall observations are made at daily scale, we need a downscaling procedure to match the radar data scale. The downscaling step introduces additional uncertainty, that's why we chose to validate the bias correction results not only at hourly but also at daily time-scale. The validation procedures are explained in detail in Section 3.4 and summarized in Table 2.

RC (3) Was there a specific reason why the boundary between "near" stations and the "far" stations was chosen at 40km in Case 4? I think that the boundary could have been anywhere outside the Tubma basin and there would have been a significant change in the results.

AR: We chose the 40 km separation boundary to achieve an equal number of gauges in the "near" and "far" groups. Following the referee's comment, we investigated RMSE between gauge rainfall and radar rainfall without bias adjustment ($RMSE_{No\text{-}Bias}$) and with the CKF-R_P ($RMSE_{CKF\text{-}RP}$) for individual stations (located at distances 5 – 80 km from the Tubma basin). We computed the percentage improvement in radar rainfall estimates using CKF-R_P compared to No-Bias at each rain gauge, indicating the relative errors changing with distance from the Tubma basin (Figure 2).

Figure 2 shows that the improvement percentage of using CKF-R_P tends to reduce with increasing distance from the Tubma basin, where the citizen gauges are located. The percentage reduction gradually decreases beyond a distance of about 40 km.

Note that the gauge 4780010 situated at the nearest range is expected to provide the best improvement, however, the Sattahip radar temporarily stopped measuring for 3 hours (during 16:00 h - 19:00 h of 24 September 2019) which is associated with a heavy storm's center was only at the gauge 4780010. This leads to significant degradation of the radar rainfall performance. Furthermore, the lower percentage improved for station 4780005 is associated with a localized heavy rainfall event that was recorded only at this location, negatively affecting its performance as a representative station for bias correction.

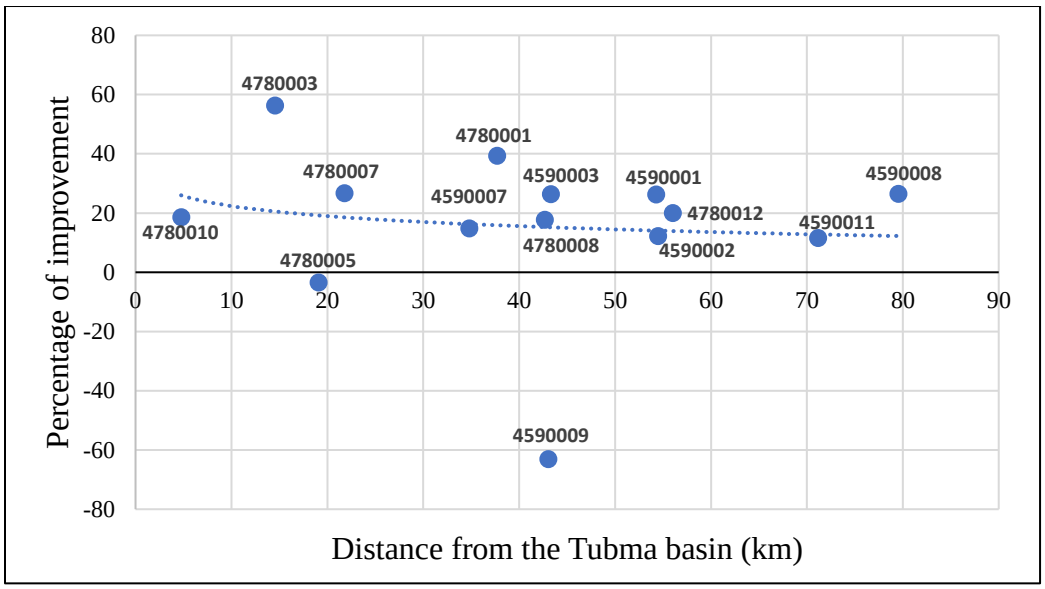

Figure 2: Alteration of the percentage improvement in radar rainfall estimates of using CKF-R_P compared to No-Bias at each rain gauge with different distance from the Tubma basin.

We propose to add this information and the associated figure in Supplementary Information.

Minor comments

RC (1) Title: "Citizen rain gauge improves …" → "Citizen rain gauges improve …"
AR: Thanks for correcting this, we will revise the manuscript accordingly.

RC (2) Title, P1L11, P1L15, P1L20, P2L55, …: Kalman filter, Kalman Filter, … please be consistent in using capital letters or not.
AR: This mistake will be corrected in the revised manuscript by using only the Kalman filter.

RC (3) P2L32: “the A and b parameters” → “the parameters A and b”
RC (4) P2L43, P2L44: “… the reference A parameters (…) to the A parameters for sub-daily resolutions.” → please reformulate
RC (5) P2L61 and P2L62: “They found …” → please reformulate
AR: Comments number (3) to (5) will be reformulated in the revised the manuscript.

RC (6) P3L66: “…typically provided at daily scale” → Please define citizen rain observation more precisely so that it is clear that this refers to soda bottles, for example.
AR: For more precise understanding about the citizen rain observation, line between 130 to 138 in the old manuscript will be rewritten as a new section “2.3.2 Citizen Rain Observation” as described below.

“2.3.2 Citizen Rain Observation

Out of the total TMD rain gauge network, only one rain gauge is located in the Tubma basin. To increase the density of the rain gauge network in the basin, low-cost citizen rain gauges were implemented in this study to better capture spatial heterogeneity of rainfall in the basin. Sixteen citizen rain gauges were installed (Fig. 1) with local residents taking daily measurements. The additional 16 citizen rain gauges with one station located at the same place of the existing TMD gauge increased the density of rain gauges in the Tubma basin to 1 gauge/12 km^2. The citizen observations were made by installing a cone-shape transparent plastic rain gauge which is standardly used in South Africa (see Fig. S1) with a diameter of 5 inches and capacity of 100 mm in open space area around a school, Monasteries, bridge or other building. Mobile application developed by Mobile Water Management (MWM) (Mobile Water Management, 2020), the Netherlands, was used to record rainfall data for each rain gauge on a daily basis. The application has a an easily accessible and user-friendly interface where participants simply fill in the observed rainfall amount, take a photo of the rain gauge and upload this to the application. The photo and the rainfall data, together with the measuring location and time, are automatically stored in the database. Photos are used for visual validation of the recorded rainfall depth to eliminate errors.

In this study, participants were recruited amongst government officers, teachers, and local residents living close to the stations and were trained to take measurements at around 7 a.m. daily according to the TMD standards. Quality of the collected data was assured by the high photo resolution for double-checking the observations and strict requirements on measurement times to be consistent with the same standard of TMD for daily rainfall recording. Note that the maximum rainfall for the citizen gauges is 100mm/day.

Validation of the cone-shaped citizen gauges was conducted based on a citizen gauge co-located with an automatic TMD gauge located in the Tubma basin, during August – October 2019. The citizen gauge installed at the same location R3 (Fig. S2) as a TMD gauge showed good similarity with a random RMSE of 5.5 mm.

Quality control consisted of screening all citizen rain gauge data for errors and inconsistencies using double mass curves. If citizen rain gauges reported >100mm/day rainfall (maximum capacity of the citizen rain gauge) this data was excluded from the analysis. If days with no-rainfall data were found from all citizen rain gauges, the bias correction of that day was discarded from the dataset. By considering the data selection criteria, rainfall data recorded during August–October 2019 with rainy days, more than 80% of the whole period for the bias adjustment process was then used for further analysis."

Figure S1: (in supplementary information to the revised manuscript) An example of installing a cone-shape transparent plastic citizen rain gauge *at location R.22, Map Tong school.*

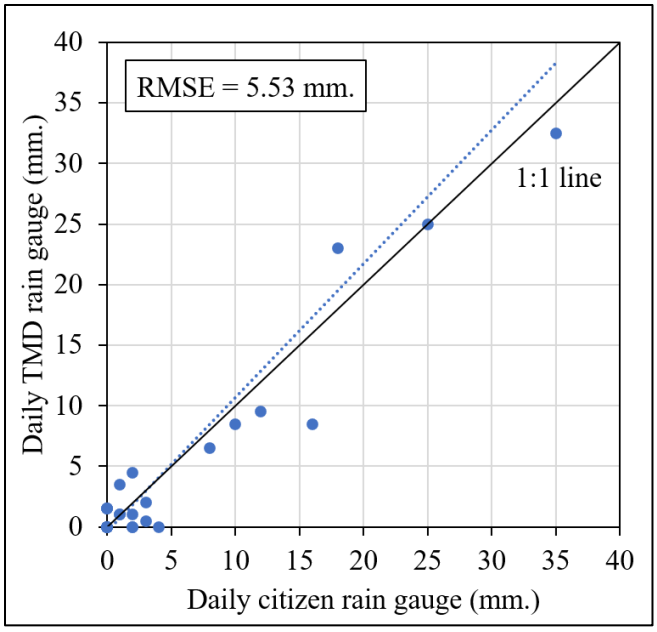

Figure S2: (in supplementary information to the revised manuscript) Daily rainfall depth comparison between the TMD and citizen rain gauge at location R.3 during August – October 2019.

RC (7) P3L75: 101°17'51" → : 101°17'51"E
RC (8) P3L75: "of approximately 197km²" → "of 197km²" or "of approximately 200km²"
AR: Comments number (7) to (8) will be changed in the revised the manuscript.

RC (9) P3L83, P3L84: "240 km x 240 km (…) 0.6x0.6km" → Please stay with one style
AR: We will edit 240 km x 240 km to 240x240 km.

RC (10) P3L84: "… spatial resolution and 6-min temporal resolution" → "spatial and 6-min temporal resolution"
RC (11) P3L90: "3 datasets"→ "three datasets"
AR: Comments number (10) to (11) will be rewritten in the revised the manuscript.

RC (12) P3L90-92: What happened between 2014 and 2019?
AR: Since, the citizen rain gauges were installed in the Tubma basin in rainy season of 2019. This is quite a short period for the Z-R calibration and verification. We then collected more data in 2013 and 2014 for the analysis of Z-R calibration and validation, while keep the data in 2019 for the bias correction development and evaluation.

RC (13) P3L121: Is it "Thai Meteorological Department" or "Thailand Meteorological Department"?

AR: It is Thai Meteorological Department officially. We will correct the caption of Figure 1 in the manuscript accordingly.

RC (14) P4L102 and L103: "1-hour" → "hourly"
RC (15) P4L103: "A parameters" → "parameters A"
RC (16) P4L104: "b exponent" → "exponent b"
RC (17) P4L106: "b parameter" → "parameter b"
RC (18) P4L108: "mean absolute error" → "MAE" (defined on P4L104)

AR: Comments number (14) to (18) will be corrected in the revised the manuscript.

RC (19) P4L110: Since NG,t seems not be equal to N over the entire period T, the Equation is incorrect. Which equation was used in your calculations?

AR: Thanks for pointing this out. $N_{G,t}$ was changed to N_G to represent the number of rain gauges and N was replaced with multiplying between T and N_G to represent total number of data pairs used in the calculation. The equation was revised including related description of each variable as described below.

$$MAE = \frac{1}{TN_G}\sum_{t=1}^{T}\sum_{i=1}^{N_G}|G_{i,t} - R_{i,t}|$$

where $G_{i,t}$ is the gauge rainfall (mm/h) at gauge i for hour t, $R_{i,t}$ is the radar rainfall accumulation (mm/h) at the pixel corresponding to the i^{th} rain gauge for hour t, N_G is the number of rain gauges, and T is the number of time period used in the calculation.

RC (20) P4L122: "have tipping-bucket sizes of 0.5mm" → something like "have a resolution of 0.5mm"

AR: We will replace "have tipping-bucket sizes of 0.5mm" with "have a resolution of 0.5mm"

RC (21) P4L130: "in the 197km² Tubma basin" → "in the Tubma basin"

AR: This will be corrected in the revised the manuscript.

RC (22) P4L133: 1 gauge/15km²: How did you calculate that? One TMD station + 16 citizen rain gauges = 17 stations. 197km² / 17 stations → 1 gauge/~12km²

AR: There was a mistake because of using a wrong number of citizen rain gauges in the calculation. The correct total number of rain gauges is 16 stations since 1 station of citizen rain gauge was located at the same place of the existing TMD. The density was change to be 197 km² / 16 stations → 1 gauge/~12km² in the revised manuscript.

RC (23) P6Table1: "Code description" → "Code Description"

AR: This will be corrected in the revised the manuscript.

RC (24) P7L158: Is MFB the abbreviation for "Mean field bias" or "Mean field bias adjustment"? If the latter, I would suggest MFBA, since MFB is a common abbreviation for mean field bias. If the former, use this abbreviation (P7L162, P7L168).
AR: MFB is the abbreviation for Mean field bias, so P7L162 and P7L168 we will carefully be corrected.

RC (25) P7L163f: "…Smith and Krajewski (1991), Anagnostou et al. (1998), and Seo et al. (1999), Chumchean et al. (2006), Kim and Yoo, (2014), Shi et al. (2018)." → "…Smith and Krajewski (1991), Anagnostou et al. (1998), Seo et al. (1999), Chumchean et al. (2006), Kim and Yoo, (2014), and Shi et al. (2018)."
RC (26) P7L177: "The radar bias at time t …" → "The radar bias at time *t* …")
RC (27) P10L254: "… day i …" → "… day *i* …"
RC (28) P11Figure3: "Is hourly TMD data at hour t available?" → "Is hourly TMD data *y* at hour *t* available?"
RC (29) P11Figure3: "Is hourly citizen rain gauge data at hour t available?" → "Is hourly citizen rain gauge data *z* at hour *t* available?"
RC (30) P12L287: "… hour t …" → "… hour *t* …"
RC (31) P12L290: "… time t …" → "… time *t* …"
AR: All the mistakes mentioned in the comment numbers (25)-(31) will carefully be corrected in the revised manuscript.

RC (32) P12L295: "Kalman Filter" → "KF" From here on, no more explicit mention for missing abbreviations. Please check independently in the following.
AR: We thank for pointing this out, we will carefully check the abbreviations.

RC (33) P13L303: "1 TMD" → "one TMD"
AR: This suggestion will be implemented in the revised manuscript.

RC (34) P13L306: "randomly": Was the LOOCV done for all 16 citizen rain gauges or did you randomly sample 16 times? If the former, it is not really randomly.
AR: The LOOCV was done for all the 16 citizen rain gauges. Therefore, P13L306 will rewritten as follows.

"Leave-one-out cross-validation (LOOCV) algorithm was implemented to avoid bias occurring from selecting the validation rain gauges. For each round of cross-validation, one rain gauge was left out for validation and the remaining rain gauges was used as the calibration rain gauges to calculate the bias adjustment factor using the 3 different techniques."

RC (35) P13L306: "3 different techniques, and 1 rain gauge" → "three different techniques, and one rain gauge"
RC (36) P13L310: "… gauge i …" → "… gauge *i* …"

RC (37) P14L324: see P13L306
RC (38) P14L325: “1 TMD” → “one TMD”
RC (39) P14L327f: “fourteen TMD” → “14 TMD”
RC (40) P14L338: “(leave 1 TMD out)” → “(leave one TMD out)”
RC (41) P14L345 and L347: “Kalman Filter” → “KF”
RC (42) P15L347: “r1 parameter” → “parameter r1”
RC (43) P15L350: “over the same time-series period” → “over the same period”
RC (44) P16L372: “figure 5” → “Fig.5”
RC (45) P17L391: “observationss” → “observations”
RC (46) P17L393: “are based on 4” → “are based on four”
AR: All the mistakes mentioned in the comment numbers (35)-(46) will carefully be corrected in the revised manuscript.

RC (47) Figure 6 and 7: Since RMSE and MBE have different limits (0 to infinity vs. -infinity to infinity), it does not make sense to put both assessment measures on one graph.
AR: Regarding these figures, we intended to compare RMSE and MBE across different techniques corresponding to each scenario of the study. We then designed the graph to be readable from two independent y-axes. The primary y-axis on the left indicates the RMSE and the secondary y-axis on the right indicates the MBE.

RC (48) P18L414: “respectively)” → “respectively).”
RC (49) P18L432: “Figure 7 (b) and Fig. 7 (c)” → “Figure 7 (b) and (c)”
RC (50) P18L435: see P18L432
AR: All the mistakes mentioned in the comment numbers (48)-(50) will carefully be corrected in the revised manuscript.

RC (51) Figure 9: Please increase the font size and add a grid.
AR: Figure 9 will be adjusted in the revised manuscript as follows.

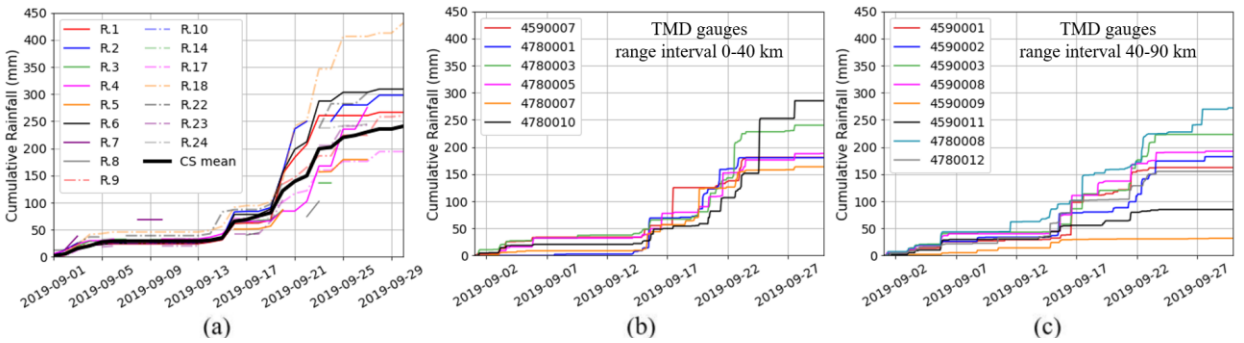

Figure 9 (in the manuscript): Comparison of mass curve of hourly rainfall among various rain-gauge locations (a) the citizen rain gauges located in the Tubma basin (b)TMD rain gauges within 0-40 km radius from the Tubma basin (c) TMD rain gauges within 40-90 km radius from the Tubma basin.

RC (52) P22L490: “(August-October, 2019)” → “(August-October 2019)”
AR: This suggestion will be implemented in the revised manuscript.

RC (53) P22L495 and L497: “Kalman filter” → “KF” or “Kalman Filter”
AR: Kalman filter will only be used in the revised manuscript.