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

by Punpim Puttaraksa Mapiam [1], Monton Methaprayun [1], Thom Adrianus Bogaard [2], Gerrit Schoups[2], Marie-Claire Ten Veldhuis[2]*

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Responses to referee #1

RC: Referee comment

AR: Author response

General comments

My research interest is focused on citizen science weather observations (in particular rainfall monitoring), so whilst I am confident in reviewing that element of the paper, I am not well placed to comment on the technical aspects of radar rainfall bias correction.

The paper presents a novel approach to undertaking radar rainfall bias correction in an area with sparse official ground based rain gauges. The focus of the paper is on the methodology for bias correction, however there perhaps should be equal prominence for the selection of a method for the disaggregation of daily data to hourly, which seems as significant. Many researchers are sceptical about the accuracy of citizen science weather observations, and it would be beneficial to allay such concerns by providing more detail on how to undertake citizen science that generates data good enough to draw the conclusion made herein. Given the intrinsic difficulties in establishing the "true" rainfall amount due to spatial and temporal variation, the conclusions could have been more robustly supported by applying the methodology to an area where validation using official gauges could have been more effectively applied.

AR: Thanks for your comment, we agree that acquiring good quality citizen observations is a challenge and we put considerable effort into citizen engagement during the measurement campaign and in data quality control afterwards. Since the focus of this paper is on bias correction, we chose not to include details on the citizen science campaign in the paper. We agree that conducting a similar campaign in an area well supported by official gauges, could have led to more robust results, however we believe that the added value of citizen science lies precisely in the type of region where we conducted our study. Regions supported by dense, high-quality rain gauge networks (like EU, US) represent different conditions for implementation of citizen science and generally different rainfall climatologies.

Specific comments

RC (1): A detailed methodology relating to the Kalman Filter is provided, but it overshadows some of the more basic and fundamental details on which the paper is based. There is no justification provided on the selection of the Tubma basin as the research area. More information would be appreciated in "Section 2.1 Study Area" describing the nature of the basin and the climatic characteristics. Lines 456 – 459 highlight some of the limitations of the study area, which I feel deserve more prominence. The location seems like a difficult place to study and have confidence in the results due to the limited opportunity for external validation via TMD gauging.

AR: More information describing the reason why the Tubma basin was selected as a research area was added in section 2.1 between lines 91 and 98 of the revised manuscript as described below.

"In Figure 1, we show the climatological variation across the study area and its surroundings, based on 30-year (1987-2017) annual mean rainfall from the network of 311 daily rain gauges owned by the TMD and situated within 200 km range from the Tubma basin. Spatial rainfall patterns were generated by inverse distance squared (IDS) between the gauge locations. The map shows that while there is small gradient in mean annual rainfall (1,100 to 1,700 mm mean annual rainfall) across the area of Rayong and Chonburi provinces (within 90 km from the study area), changes are more pronounced when the distance exceeds the beyond the 90 km boundary, especially to the east of the study area. This is because these areas are affected differently by the southwest monsoon. Consequently, evaluating the effectiveness of bias correction techniques were carried out within 90 km range from the study area with similar climatology."

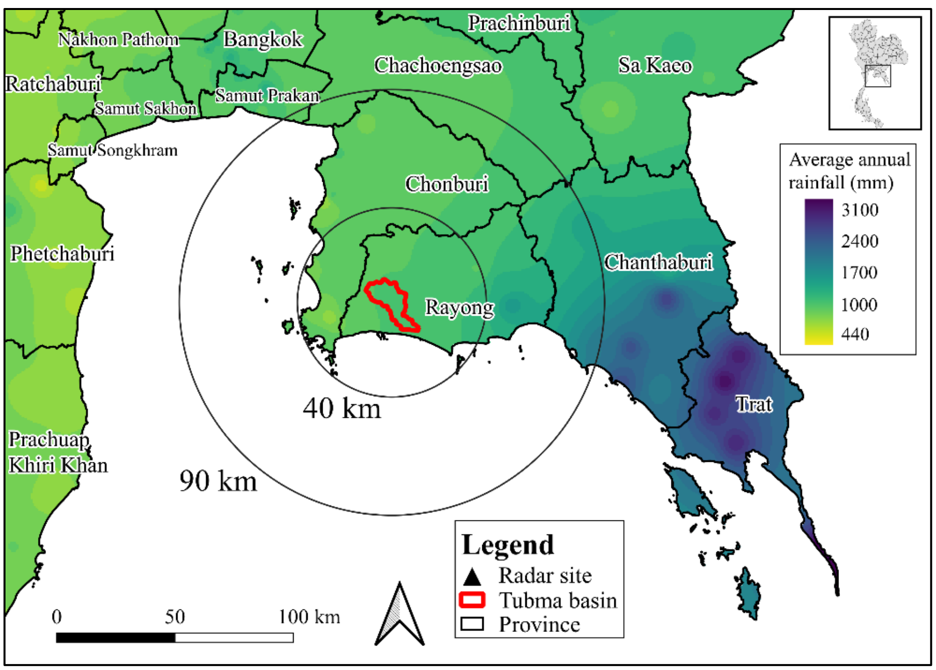


Figure 1: Climatological spatial rainfall distribution within 200 km ranges from the centroid of the Tubma basin calculated from 30-year average annual rainfall data of 311 daily rain gauge network by using IDS method.

RC (2): Given the climatic variation across the study area noted in Section 4.3.4, justification on the use of a 100Km radius for evaluation would be welcome.

AR: The 100 km radius refers to the coverage area of the Sattahip radar. The correct radar range is actually 90 km, as indicated in section 4.3.4, we carefully made sure to correct all references to 100 km by 90 km in the revised manuscript.

RC (3): There is no explanation of how citizen science observations were made, how participants were recruited and trained, or discussion of citizen science limitations either in general or encountered in this research.

AR: For more precise understanding about the citizen rain observation, lines between 130 to 138 in the old manuscript were 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. 2) 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.*

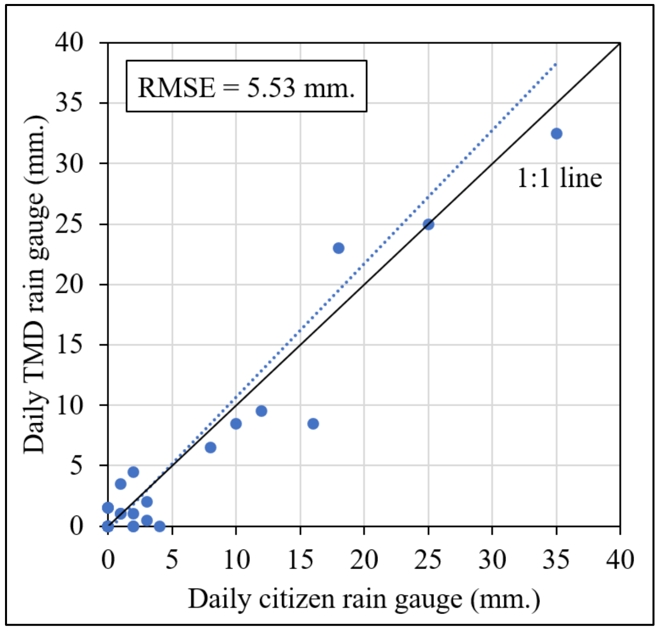


Figure S2: (in supplementary information to the revised manuscript) Daily rainfall depth comparison between the TMD and citizen rain gauge at location R.3 during August – October 2019.

RC (4): There do appear to be interesting results from the citizen science gauges that warrant further discussion. E.g, Fig.9 (a) indicates a range in the monthly cumulative rainfall from citizen science gauges of ~170 – 400mm and multiple reporting gaps, whereas (b) the TMD gauge range is ~150 – 260mm. A map with the gauges identified and some detail on elevation or climatic region could be included.

AR: Note that Fig. 9 in the old manuscript was changed to Fig. 10 in the updated paper. Indeed, *Fig.10 (a) and (b) show that one of the citizen gauges (R.18) collected cumulative monthly rainfall higher than the range of the other citizen and TMD rain gauges. This is associated with a storm event that occurred in September 2019, with the storm center over R.18, while the surroundings received appreciably less rainfall. Figure S4 (this figure was added in the supplementary of the revised manuscript) shows the radar reflectivity field at 13.00 h on 22 September 2019, during the peak of the storm, confirming the heavy rainfall affecting gauge location R.18. This shows the citizen gauge network is able to capture local storm features thanks to the high density of the network.* The multiple reporting gaps visible in Fig. 10 (a) are caused by time errors in the observations submitted by local residents were removed from the analysis (as explained in new section 2.3.2 of the revised manuscript). This information and the associated figure were provided in Supplementary Information of the revised *manuscript.*

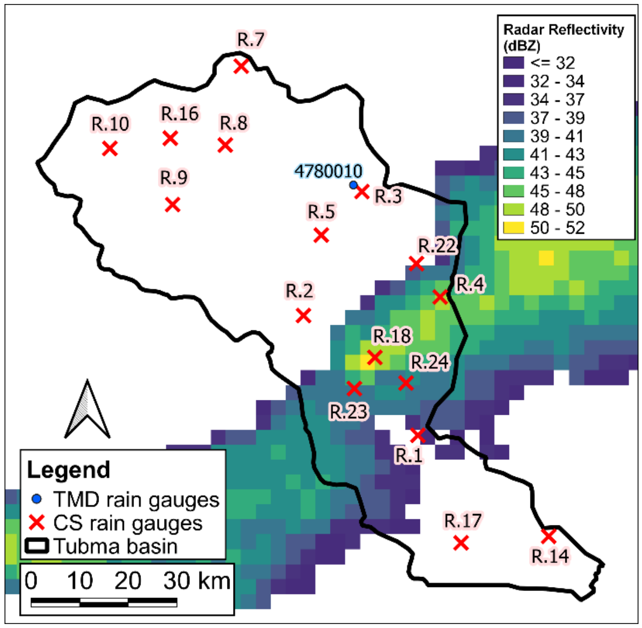


Figure S4: Overlapping between citizen rain gauges network and spatial radar reflectivity data on 22 September 2019 at 13.00 hour

RC (5) If some detail on the application of existing methods could be moved to "Supplementary Information", it would allow more space for consideration of the citizen science element.
AR: Since the focus of our study is on radar bias adjustment, we have not elaborated in detail on the citizen observations network separately. We believe it would distract from the focus of the study, which is on the 2-step Kalman-filter bias adjustment methodology. This is the most novel element of the work.

Technical comments

RC (5): General point – Although common practice I found the use of acronyms made the paper hard to follow at times e.g. Section 4.2
AR: Because we have many approaches for comparison and would like to make the paper short, we then use the acronyms to drive the story.

RC (6): Figure 1 – Identification of citizen science gauges
AR: Figure. 1 was modified to Figure 2 in the revised manuscript to show all used gauges including the 14 rain gauges in Chonburi and Rayong provinces as shown by the following. The identification of citizen rain gauges was also added in the figure.

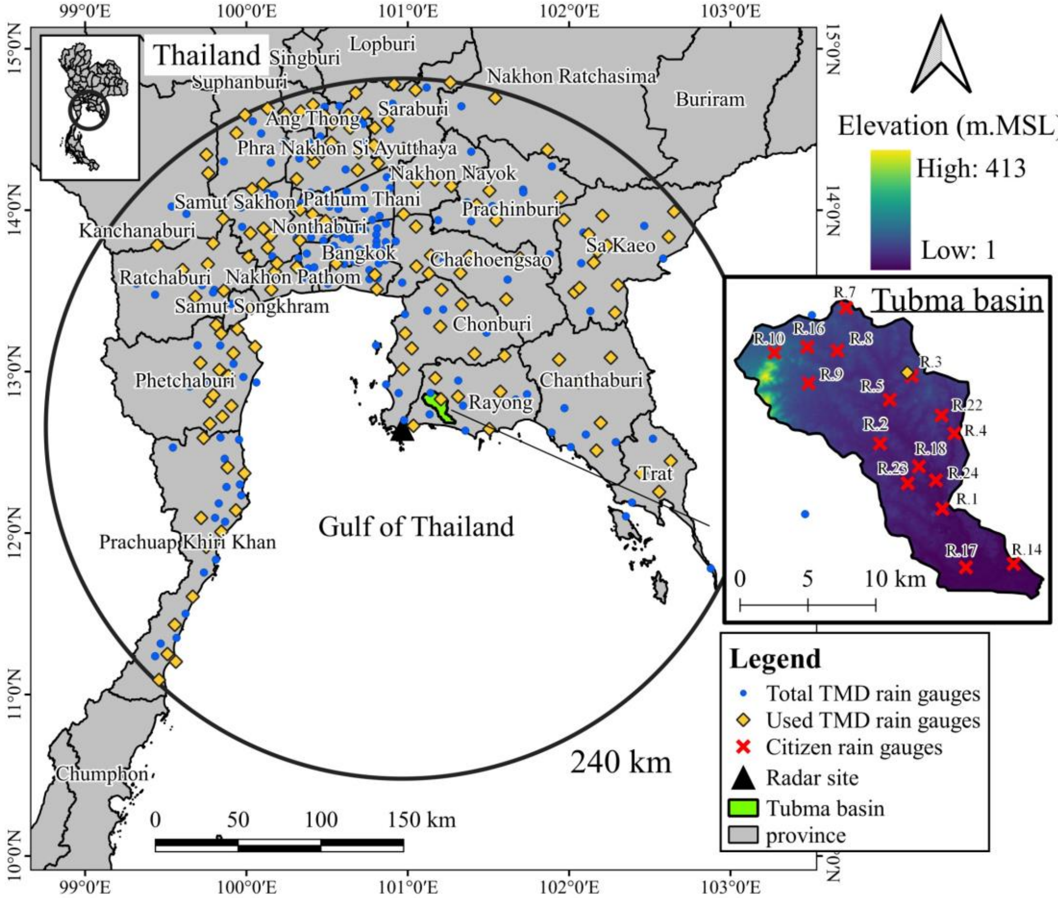


Figure 2 (in the revised manuscript): Location of study domain, showing Thai Meteorological Department (TMD) automatic rain gauges, citizen rain gauges, Sattahip radar, and Tubma basin.

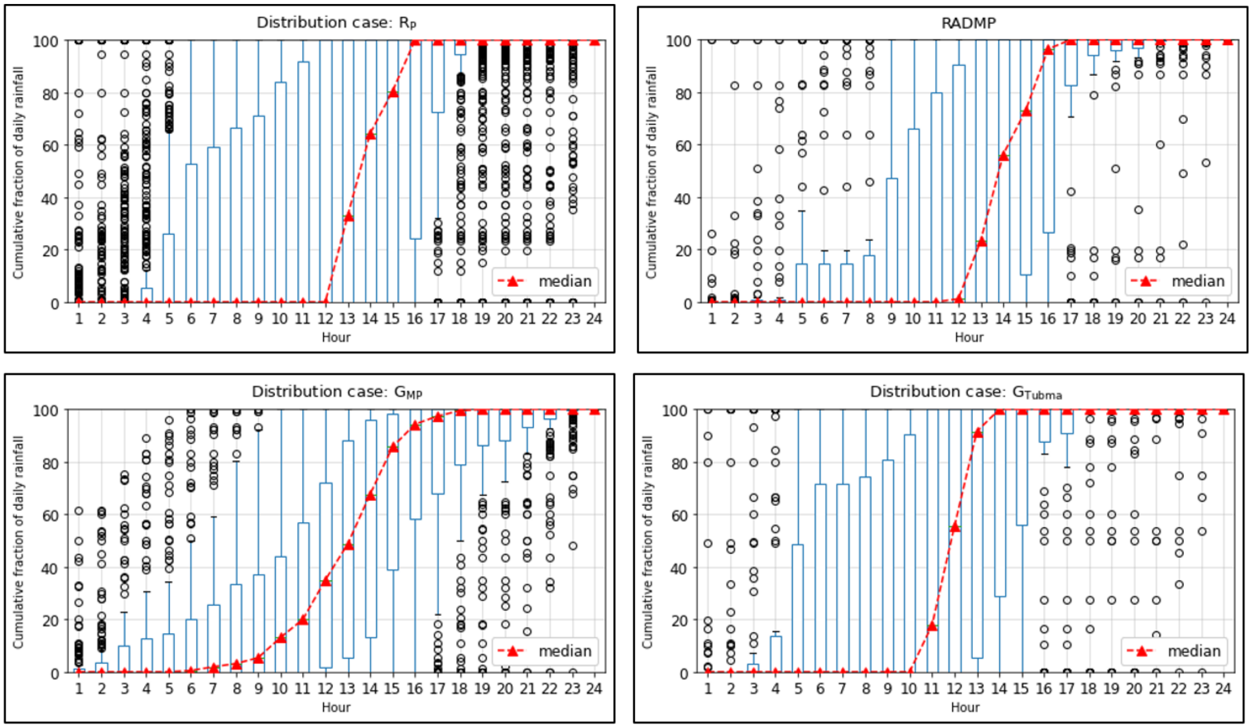
RC (7): Line 164 – replace full stop with comma
AR: We checked the format and replaced them correctly in the revised manuscript.

RC (8): Line 254 – Point 1 is not clear about the timing of data, could this be rephrased?
AR: The point 1 of P10L254 was rephrased according to the comment between lines 295 and 297 in the revised manuscript as appeared below.

"1) Since the citizen rain gauge data were received at the last hour of day *i*, before receiving the downscaled hourly citizen rain gauge data of day *i*, the ordinary KF and observed hourly data of TMD were used to predict and correct the hourly bias adjustment factor of the day *i*"

RC (9): Line 270 – replace "In case" with "Where"
AR: This correction was implemented in the revised manuscript.

RC (10): Figure 4 – a grid may make reading easier, or may be too cluttered?
AR: Figure 4 was modified as shown below and was placed in the revised manuscript.



RC (11): Figure 9 – The colours are indistinct for the different gauges, the x ticks could be 'day' and the figures in general are very small making them hard to read on the page

AR: Thank for the suggestion, the figure was adjusted as the following.

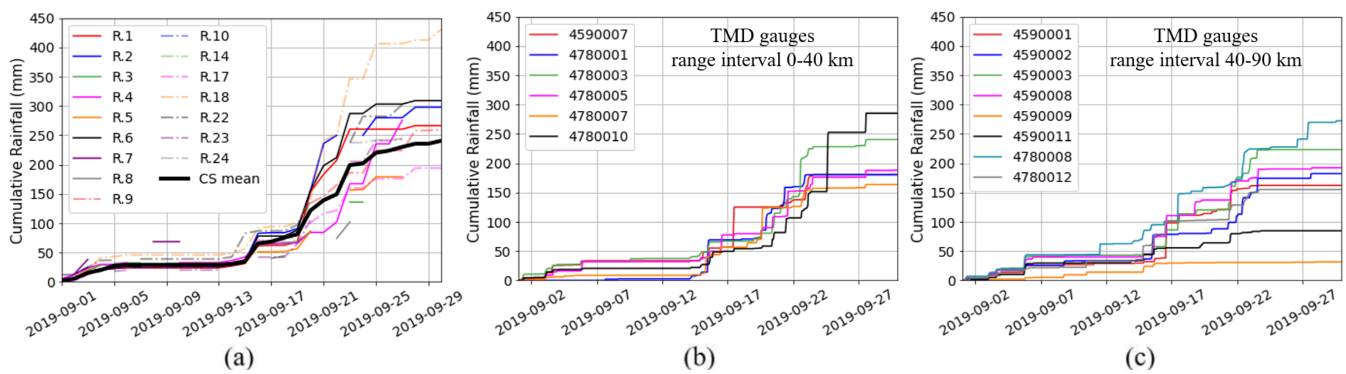


Figure 9 (in the revised manuscript): Comparison of mass curve of hourly rainfall among various rain-gauge locations (a) the citizen rain gauges located in the Tubma basin (b)TMD rain gauges within 0-40 km radius from the Tubma basin (c) TMD rain gauges within 40-90 km radius from the Tubma basin.

Reference

Mobile Water Management: https://mobilewatermanagement.nl/, last access: 25 October 2020.

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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 recorded rainfall amounts 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 also modified Figure 1 (changed to be Figure 2 in the revised manuscript), to distinguish the selected rain gauges:

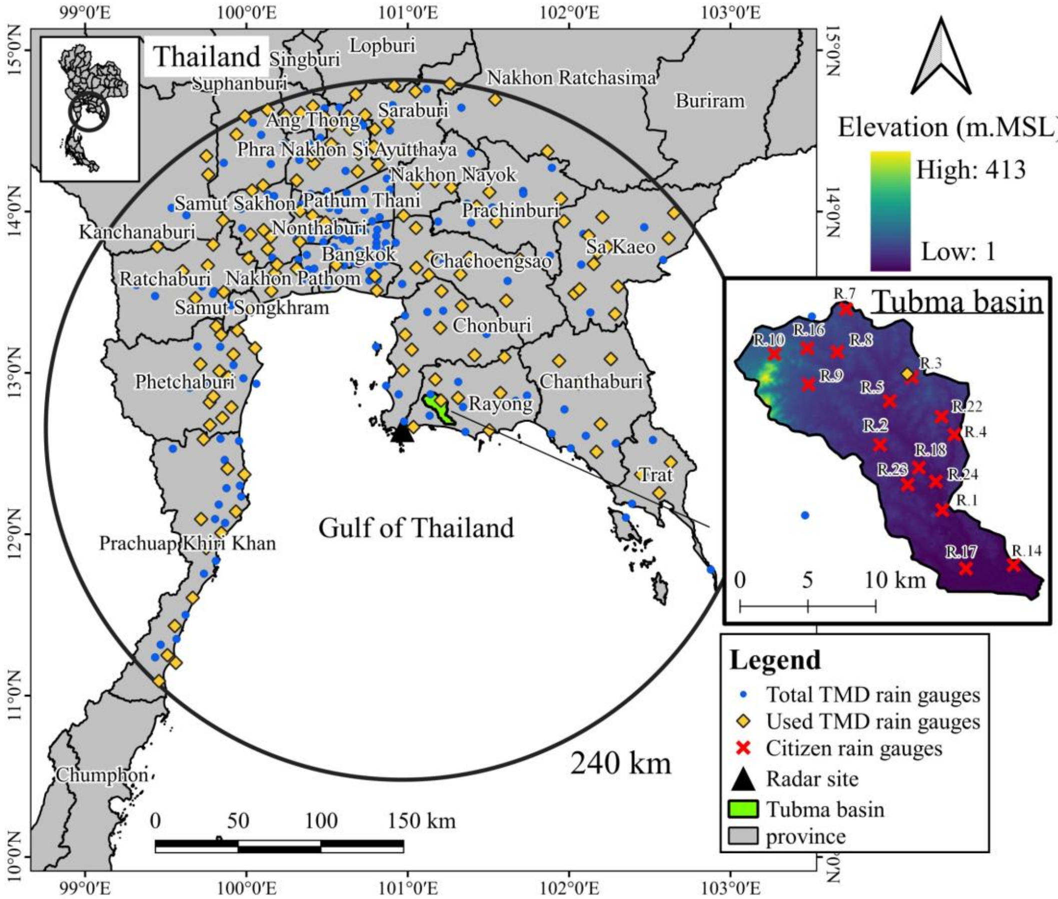

Figure 2 (modified for revised manuscript): Location of study domain, showing Thai Meteorological Department (TMD) automatic rain gauges, citizen rain gauges, Sattahip radar, and Tubma basin.

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: To clarify this point, we added the following information and the Fig. S3 in section S2 of the supplementary Information.

"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 (Fig. S3). Figure S3 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."

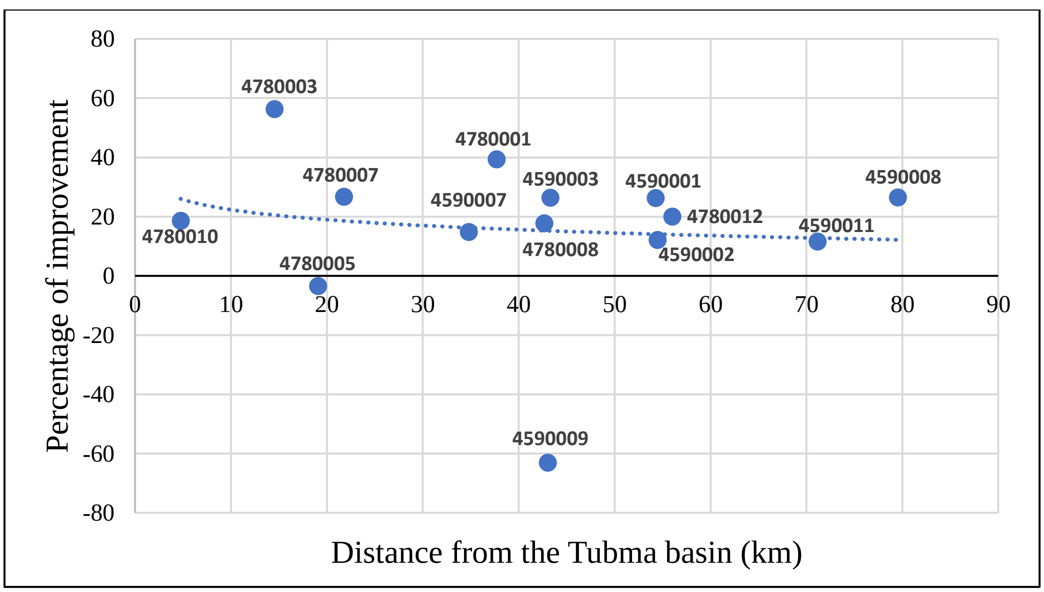

Figure S3: Alteration of the percentage improvement in radar rainfall estimates of using CKF-R_P compared to No-Bias at each rain gauge with different distance from the Tubma basin.

Minor comments

RC (1) Title: “Citizen rain gauge improves …” → “Citizen rain gauges improve …”

AR: Thanks for correcting this, we revised 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 was 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) were 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 were 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 100 mm/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.*

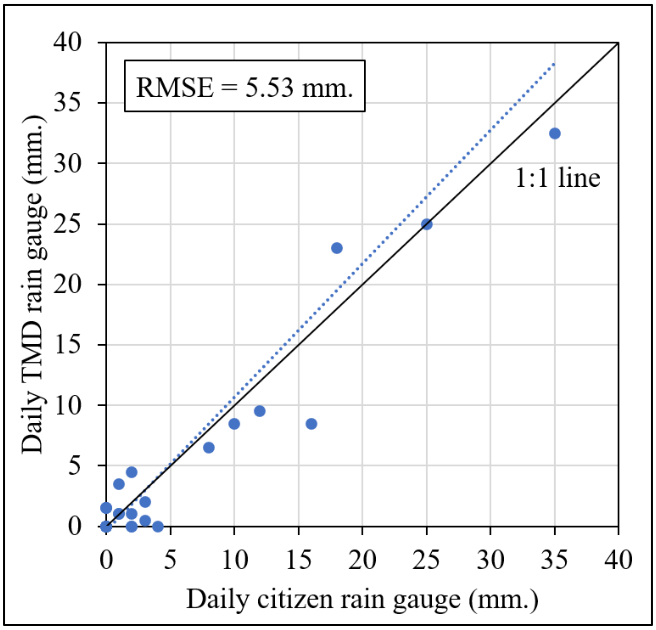

Figure S2: (in supplementary information to the revised manuscript) Daily rainfall depth comparison between the TMD and citizen rain gauge at location R.3 during August – October 2019.

RC (7) P3L75: 101°17’51” → : 101°17’51”E

RC (8) P3L75: “of approximately 197km^2” → “of 197km^2” or “of approximately 200km^2”

AR: Comments number (7) to (8) were adjusted in the revised the manuscript.

RC (9) P3L83, P3L84: “240 km x 240 km (...) 0.6x0.6km” → Please stay with one style

AR: We edited 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) were 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. 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. Line 10 and 158 in the revised manuscript was corrected 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) were 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 in the revised manuscript.

"

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

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 replaced "have tipping-bucket sizes of 0.5mm" with "have a resolution of 0.5mm"

RC (21) P4L130: "in the 197km^2 Tubma basin" → "in the Tubma basin"

AR: The manuscript was adjusted according to the comment.

RC (22) P4L133: 1 gauge/15km^2: How did you calculate that? One TMD station + 16 citizen rain gauges = 17 stations. 197km^2 / 17 stations → 1 gauge/~12km^2

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 changed to be 197 km^2 / 16 stations → 1 gauge/~12km^2 on line 166 in the revised manuscript.

RC (23) P6Table1: "Code description" → "Code Description"
AR: This was 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 were carefully 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) were carefully 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, the abbreviations were gently checked.

RC (33) P13L303: "1 TMD" → "one TMD"
AR: This suggestion was 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 was rewritten between lines 347 and 349 in the revised manuscript as described below.

"For each round of cross-validation, one rain gauge was left out for validation and the remaining rain gauges were used as the calibration rain gauges to calculate the bias adjustment factor using the three 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) were 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) were corrected in the revised manuscript.

RC (51) Figure 9: Please increase the font size and add a grid.

AR: Figure 9 was adjusted in the revised manuscript as follows.

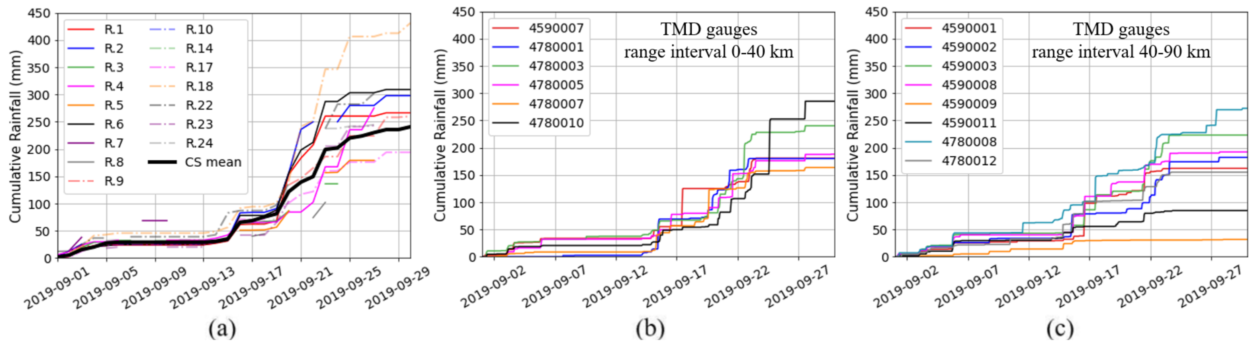

Figure 9 (in the manuscript): Comparison of mass curve of hourly rainfall among various rain-gauge locations (a) the citizen rain gauges located in the Tubma basin (b)TMD rain gauges within 0-40 km radius from the Tubma basin (c) TMD rain gauges within 40-90 km radius from the Tubma basin.

RC (52) P22L490: "(August-October, 2019)" → "(August-October 2019)"

AR: This suggestion was implemented in the revised manuscript.

RC (53) P22L495 and L497: "Kalman filter" → "KF" or "Kalman Filter"

AR: Let us use "Kalman filter" in the conclusion section.

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

by Punpim Puttaraksa Mapiam [1], Monton Methaprayun [1], Thom Adrianus Bogaard [2], Gerrit Schoups[2], Marie-Claire Ten Veldhuis[2]*

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Responses to referee #3

RC: Referee comment

AR: Author response

General comments

The sparsity of the conventional rain gauge network is a limiting factor for radar rainfall bias correction. Citizen rain gauges offer an opportunity to provide additional information at higher spatial resolution. This paper performs radar rainfall bias adjustment using two sources of rainfall information: observations measured by TMD (Thailand Meteorological Department) and daily citizen rainfall observations. The radar rainfall bias correction factor was sequentially updated based on the TMD data and downscaled hourly citizen data via a two-step Kalman filter. The results showed that citizen rain gauges improved the performance of radar rainfall bias adjustment especially for small ranges from the center of these gauges.

My reading through this manuscript suggests that the following three issues should be dealt with or stressed more clearly in the paper:

RC (1): The citizen rain gauges are very important in the context of this paper. However, the relevant introduction is too simple. What kind of equipment are they? How uncertain are the measurements compared to the official TMD data? Please add more information on them.

AR: For more in-depth description of the citizen rain observation, lines 130 to 138 in the old manuscript were 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 100 mm/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.*

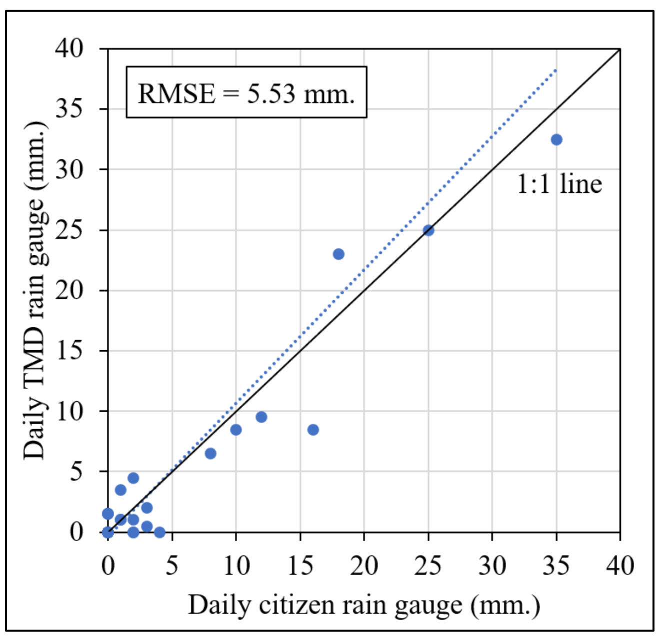

Figure S2: (in supplementary information to the revised manuscript) Daily rainfall depth comparison between the TMD and citizen rain gauge at location R.3 during August – October 2019.

RC (2): The strategy used to downscale the daily measured citizen rainfall observations into hourly temporal resolution is essential in this context. However, there were no references on this topic. Four relatively simple downscaling strategies were tested, and the results showed that the one that utilized gauge-respective radar rainfall patterns performed the best. Yet I do think there is room for improvement.

AR: The focus of the paper is on developing a new algorithm called two-step Kalman filter using two sources of observed rain gauge data. The strategy for combing TMD and citizen rain gauge datasets in the second measurement updating of the Kalman filter was a core of the development. Simulating different hourly citizen dataset with 4 downscaled strategies was carried out to investigate the sensitivity of the modified KF approach. As a result, in this study, we decided to use a simple fraction method for disaggregating daily rainfall to hourly values. A similar strategy has been applied in several previous applications (Paulat et al., 2008; Wüest et al., 2010; Vormoor and Skaugen, 2013; Sideris et al., 2014; Barton et al., 2019). Additional literature review on downscaling techniques was provided in the introduction section between the lines 72 and 79 of the revised manuscript as described below.

"There has been a variety of temporal rainfall downscaling methods developed since the 1970s. The simplest approach is to distribute daily rainfall data to sub-daily resolutions by assuming uniform distributions. Stochastically generating sub-period data or spatially transferring finer resolution rainfall from a nearby rain gauge station to the study area based on spatial correlations are alternative approaches (Koutsoyiannis, 2003; Debele et al., 2007). However, these methods are not usually designed for real-time data disaggregation over large areas. Instead, a common approach for such scenarios is to downscale daily rainfall based on a simple fraction technique by considering the distribution patterns of high-resolution gridded rainfall products from radar or satellite sensors (Paulat et al., 2008; Wüest et al., 2010; Vormoor and Skaugen, 2013; Sideris et al., 2014; Barton et al., 2019)."

RC (3): I am concerned about the strategy used for applying the proposed approach. There is a spatial separation of the gauges used for performing the 1st step of the Kalman filter (KF) and the gauges used for performing the 2nd step of the KF. The 1st step used 14 TMD gauges that are within 100 km radius of the center of Tubma basin, from which only 1 is inside the basin, whereas the 2nd step used 16 citizen rain gauges that are within the basin. The 1st step was applied under the assumption that the radar rainfall bias correction factor is relatively stable in space. However, there were signs of spatial instability, e.g., the downscaling strategy G_{MP (where the hourly rainfall patterns of the 14 TMD gauges were averaged and used for downscaling) had the worst performance, as shown in Fig. 6(c). More obvious signs were shown in Figs. 8 and 9. Hence, I strongly recommend the authors improve the strategy for applying the approach.

AR: Thank you very much for your comments. To possibly reduce both temporal and spatial uncertainty in radar rainfall estimates, this would require a spatiotemporal varying bias model in the analysis, which may be more challenging given the limited number of gauges. Instead, in our model, any spatial variations are captured as random noise and quantified by a standard deviation (or variance), which is then used in the Kalman filter to properly weight and incorporate each observation. Kalman Filter has the benefit of accounting for uncertainties in the observations by weighting the contribution of measurements by their respective variances. The 1st step represents a real situation that there are only 14 TMD gauges available. The observation error variance reflecting spatial instability of the observed data at time t was thereafter calculated as the weight for correcting the predicted mean bias instead of using only the calculated mean field bias. Measurement updating is a key step to correct the spatially uniform mean field bias. To improve the accuracy of the KF, enhancing the density of rainfall data with lower observation error variance can play an important role for the 2nd step. The downscaling strategy G_{MP} showed the highest median value of the estimated observation error variances of CKF-G_{MP} (see Fig. 5(c) in the manuscript) leading to the worst performance of radar rainfall estimates.

Specific comments/ technical corrections

1. Introduction

RC (1.1) The description related to Citizen rain gauges/rainfall observations is too simple. Whereas, as indicated by the title "Citizen rain gauge improves hourly radar rainfall bias correction using a two-step Kalman filter", the readership might expect more information on the citizen rain gauges/rainfall observations from the introduction. Besides, it seems that the downscaling strategy is very important in this context. It might be necessary to give a brief review of the downscaling methods in scientific literature.

AR: We inserted a brief review of the citizen rain observations and the downscaling methods in the introduction section between the lines 65 and 79 in the revised manuscript as explained below.

"In basins where a dense rainfall network is not available, Citizen Science (CS) offers a promising opportunity for enhancing the density of rainfall observations (Davids et al., 2019). With the popularization of smartphones and the availability of (relatively) simple and cheap equipment, abundant mobile applications and projects have been initiated in Water Resources Management to measure hydrometeorological variables like rainfall, water level height or water quality, as well as to ground-truth remotely sensed information on e.g. land use (Srivastra et al., 2018; Davids et al., 2019; See, 2019; Seibert et al., 2019). In the current study, we focus on rainfall measured by local citizens using a network of cheap rain gauges and a specially designed mobile application.

Since citizen rainfall observations are typically provided at daily scale, a temporal downscaling technique is needed for sub-daily applications. There has been a variety of temporal rainfall downscaling methods developed since the 1970s. The simplest approach is to distribute daily rainfall data to sub-daily resolutions by assuming uniform distributions. Stochastically generating sub-period data or spatially transferring finer resolution rainfall from a nearby rain gauge station to the study area based on spatial correlations are alternative approaches (Koutsoyiannis, 2003; Debele et al., 2007). However, these methods are not usually designed for real-time data disaggregation over large areas. Instead, a common approach for such scenarios is to downscale daily rainfall based on a simple fraction technique by considering the distribution patterns of high-resolution gridded rainfall products from radar or satellite sensors (Paulat et al., 2008; Wüest et al., 2010; Vormoor and Skaugen, 2013; Sideris et al., 2014; Barton et al., 2019)."

2. Study Area and Data

RC (2.1): (Pg 5, L.125-126) I'm not clear with the sentence "A rain gauge with more than 80% of the dataset below the threshold was excluded from the analysis." Please explain.

AR: The meaning of the sentence "A rain gauge with more than 80% of the dataset below the threshold was excluded from the analysis." is that any rain gauge with more than 80% of the dataset being daily rainfall values of less than 0.5 mm was excluded from the analysis. To clarify, we replaced "80% of the dataset" by "80% of recorded rainfall amounts" on line 150 in the revised manuscript.

RC (2.2): (Pg 5, L.128-129) It is necessary to show the 14 rain gauges in Fig. 1 as well because the 14 rain gauges were intensively utilized in the following sections.

AR: Figure. 1 was changed to Figure 2 in the adjusted manuscript and was modified to show all used gauges including the 14 rain gauges in Chonburi and Rayong provinces as shown by the following.

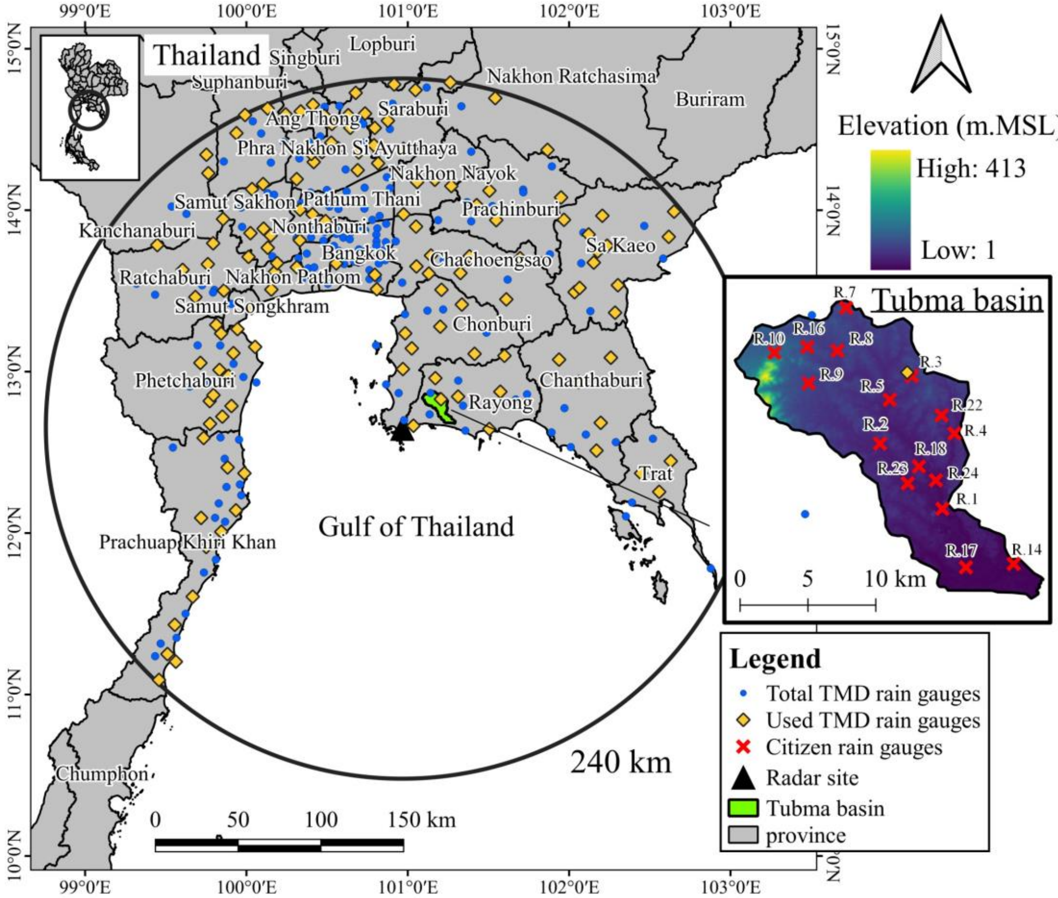

Figure 2 (in the revised manuscript): Location of study domain, showing Thai Meteorological Department (TMD) automatic rain gauges, citizen rain gauges, Sattahip radar, and Tubma basin.

RC (2.3): (Pg.5, L. 131-136) Concerning the low-cost citizen rain gauges, are they tipping buckets? What kind of equipment are they? Were the measurements compared with the TMD rain gauges (As shown in Fig. 1, there are 2 TMD gauges very close to them)? If so, how uncertain were the data? Or, in the other case, were the quality checks performed in an intra-group manner. It is hard to tell from the current description. Please make it clear.

AR: More information on the citizen rain gauge observation was added in a new section "2.3.2 Citizen Rain Observation" in the revised manuscript as described in the first general comment. It is noted that in the revised manuscript Fig.2 shows total rain gauges and used rain gauge networks that passed the quality control. Consequently, there is only TMD rain gauge located in the Tubma basin and can be used for the measurement comparison between the citizen and TMD rain gauges.

3. Methods

RC (3.1): (Pg. 7, Table 1) Concerning the downscaling method "G_{Tubma}", instead of using only one TMD station within the basin (I noticed there is another one very close to the basin as shown in the small figure in Fig. 1), why not use this one as well. Besides, how variable are the hourly rainfall patterns across the basin. A comparison of the patterns from these two stations might provide useful information.

AR: Note that we have only one TMD rain gauge that passed quality control. This limitation then forced us to use only one TMD station for constructing the G_{Tubma}.

RC (3.2): (Pg. 14, L. 324): Please keep the term "KF-TMD" consistent with that shown in Table 2.

AR: We revised the manuscript accordingly.

4. Results and discussion

RC (4.1): (Pg. 15, L. 360): "..., while R_P and G_{MP} showed larger variability over the day, ...". There might be a mistake. The R_P-based result has a sharp mean cumulative fraction curve and large variance in the downscaled hourly data if one observes the box plots, whereas the other has a flat mean cumulative fraction curve and small variance in the downscaled hourly data. In other words, these two are different in both respects. The problem comes down to how the variability is defined. Please explain.

AR: The variability in that context defines the variability in the downscaled hourly data, which both R_P and G_{MP} exhibited a lot of outliers from the boxplot in each hour. P15L360 was rephrased for clearer understanding on the line 404 and 405 in the revised manuscript as explained below.

"…, while R_P and G_{MP} showed larger variability in the downscaled hourly data with substantial outliers in the box plots, … "

RC (4.2): (Pg. 18, Sect. 4.2.2) I am concerned about the validation scheme referred to as "KF - TMDD", especially about the separation of the gauges for performing KF/MFB and gauges for validation purposes. The bias correction was made for a large area with a radius of 100 km, whereas the validation was performed on a much smaller basin. I am afraid the separation makes the validation results less representative. Perhaps LOOCV for the 14 TMD gauge (as used in the "KF -TMD-H" strategy) is more persuading. If the purpose of using "KF -TMD-D" is to validate the bias correction performance within the basin, the authors should specify it explicitly (perhaps, also in Sect. 3.4). Anyhow, the separation mentioned above could be a bit problematic.

AR: For the KF -TMD-D case, we tried to imitate the actual situation if we have only 14 TMD rain gauges available for radar rainfall estimation in the Tubma basin, which bias adjustment method (MFB or KF) can produce more accurate radar rainfall in the basin. In Section 4.2.2, we, therefore, aimed to validate the bias correction performance within the basin by testing at all the citizen rain gauge locations. Any problems arising from the gauge's separation could be solved by the CKF-D. To clarify, sections 3.4 and 4.2.2 were modified in the revised manuscript as described below.

The Sentence "To identify which approach between MFB and KF is more accurate for daily rainfall simulation in the Tubma basin if there are only 14 TMD rain gauges available, …" of section 3.4 in the revised manuscript were modified between Lines 370 to 371. Furthermore, "Results associated with validating the bias correction performance within the Tubma basin were presented in Fig. 6 (b). This shows …" was added to line 456 at the beginning of the paragraph of section 4.2.2 in the revised manuscript.

Edit to text: on line 415, remove "be"

RC (4.3): (Pg. 19, L. 437-438) "While there is a modest improvement in mean RMSE, the upper 75%-ile RMSE is reduced from about 6 mm/h to 3.5 mm/h. Mean MBE is changed from 0.1 to -0.15 mm/h." I found it hard to follow here. Please use the terms presented in Fig. 7(b) to refer to the results.

AR: These sentences were adjusted between lines 482 and 485 in the revised manuscript as described follows.

"While there is a modest improvement in mean RMSE (see the black line connecting the mean values of the box plots from MFB-TMD to CKF-R_P), the upper 75%-ile RMSE is reduced from about 6 mm/h to 3.5 mm/h. Mean MBE is changed from 0.1 to -0.15 mm/h (see the red-dotted line connecting the mean values from MFB-TMD to CKF-R_P).

RC (4.4): (Pg. 19, L. 439) Please correct "MFB-TMB" and "KF-TMB" to "MFB-TMD" and "KF-TMD",respectively.

AR: The mistake was carefully corrected in the revised manuscript.

RC (4.5): (Pg 19-20, Sect. 4.3.4) I think the description of the results/figures could be organized in a more readable way. For example, there is a direct shift from the description of Fig. 7 to that of Fig. 8 (Pg.19, L. 440-444) without telling the readers that the content is related to Fig. 8, and there is a separation in the description of Fig. 7 (Pg. 19, L. 433- and Pg. 20, L. 451-).

AR: Note that Figs. 7 to 9 in the old manuscript was reordered to be Figs. 8 to 10 in the revised manuscript. For clearer understanding, we started section 4.3.4 of the revised manuscript with:

"Results for this section are presented in Figs. 8, 9, and 10." Additionally, *the following sentences, "Analysis of hourly rainfall hyetographs obtained from TMD rain gauge network compared with the validated rain gauge occurring in three different days are illustrated in Fig. 9. It appears … ." were inserted between lines 490 and 492 in the revised manuscript.* By the way, because Fig. 8 (in the revised manuscript) was the main results for section 4.3.4, while Fig.9 and 10 are supporting figures. Therefore, it is not easy to end all discussions related to Fig.8, followed by Fig.9 and 10, respectively. Therefore, please allow separation in the description of Fig. 8 as mentioned above.

Edits to text:

-*line 492 in the updated manuscript: replace "Figure 8 appears that the considerable RMSE occurs from…" by "It shows considerable RMSE from…"*

-*line 494 in the updated manuscript: replace "However, these RMSE can considerably reduce if…" by "However, these RMSE values decrease considerably if…"*

RC (4.6): (Pg. 19 at the end) I am not clear with the sentence " Figure 9 illustrates that hourly rainfall distribution patterns of TMD rain gauges in the 40-90 km range, influenced mainly by the southwest monsoon, appear to be more similar to the mean citizen rain gauge data than the range beyond 40 km." Please explain.

AR: In the mentioned sentence, we realize to change the words "40-90 km" to be "0-40 km" in the revised manuscript.

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