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 #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 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.*

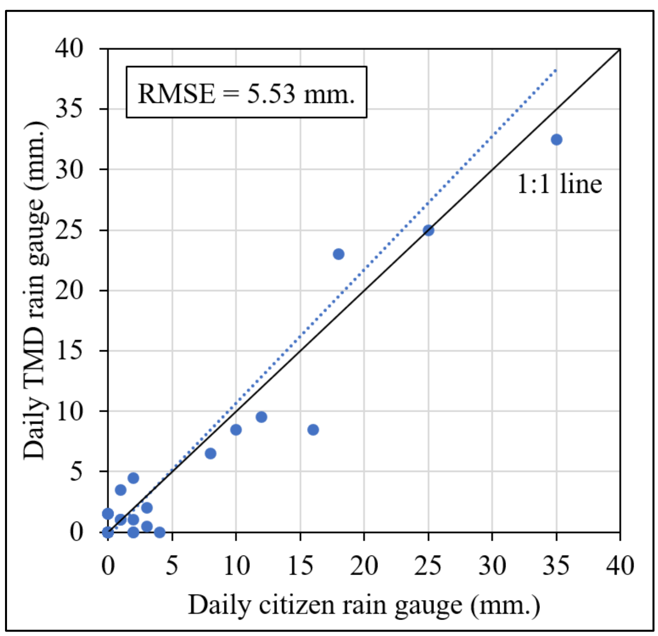

Figure S2: (in supplementary information to the revised manuscript) Daily rainfall depth comparison between the TMD and citizen rain gauge at location R.3 during August – October 2019.

RC (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 will be provided in the introduction section 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 will insert a brief review of the citizen rain observations and the downscaling methods in the introduction between lines 64 to 66 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".

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 modified to show all used gauges including the 14 rain gauges in Chonburi and Rayong provinces as shown by the following.

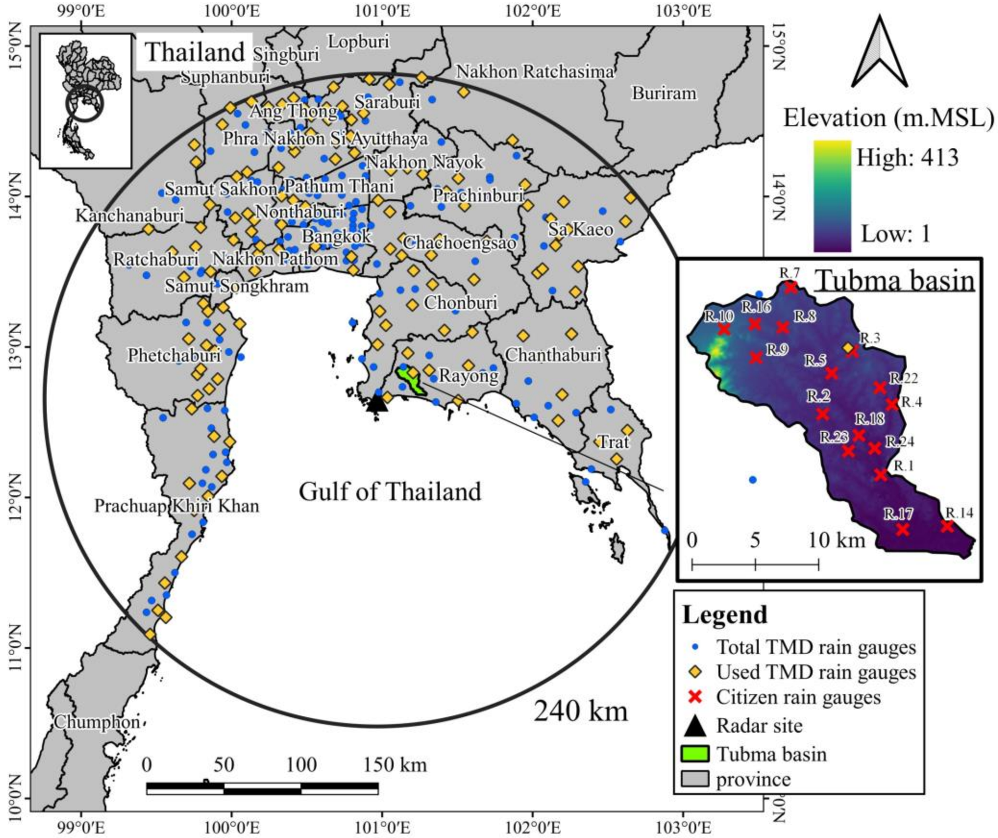

Figure 1 (in the revised manuscript): Location of study domain, showing Thai Meteorological Department (TMD) automatic rain gauges, citizen rain gauges, Sattahip radar, and Tubma basin.

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 will be 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.1 will show 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 will revise 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 will be rephrased for clearer understanding 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. Sections 3.4 and 4.2.2 will be 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, …" will be modified between Lines 327 to 328 of section 3.4. Furthermore, "Results associated with validating the bias correction performance within the Tubma basin were presented in Fig. 6 (b). This shows …" will be added to line 411 at the beginning of the paragraph.

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 will be adjusted as 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 will carefully be 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: For clearer understanding, we will start section 4.3.4 with: "Results for this section are presented in Figs. 7, 8, and 9.". Additionally, *the following sentences, "Analysis of hourly rainfall hyetographs obtained from TMD rain gauge network compared with the validated rain gauge occurring in 3 different days were illustrated in Figure 8. It appears … ." will be inserted to line 444 in the revised manuscript.*

By the way, because Fig. 7 was the main results for section 4.3.4, while Fig.8 and 9 are supporting figures. Therefore, it is not easy to end all discussions related to Fig.7, followed by

Fig.8 and 9, respectively. Therefore, please allow separation in the description of Fig. 7 as mentioned above.

Edits to text:

-line 444: replace "Figure 8 appears that the considerable RMSE occurs from…" by "Figure 8 shows considerable RMSE from…"

-line 446: 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.

Reference

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