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 #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 will be added in section 2.1 of the revised manuscript as described below.

"In Figure 1 (will be inserted in the revised manuscript) 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."

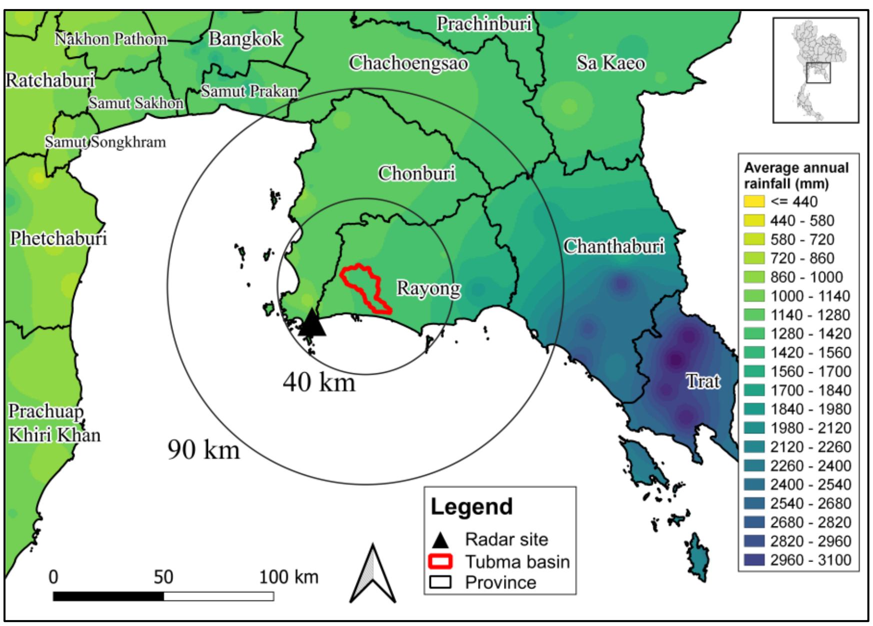


Figure 1: Climatological spatial rainfall distribution within 200 km range from the centroid of the Tubma basin calculated from 30-year average annual rainfall data of 311 daily rain gauge network by using IDS method.

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 will make 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, 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. 2: Note that Fig . 2 in the revised manuscript will be adjusted from the Fig. 1 of the old manuscript) 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.*

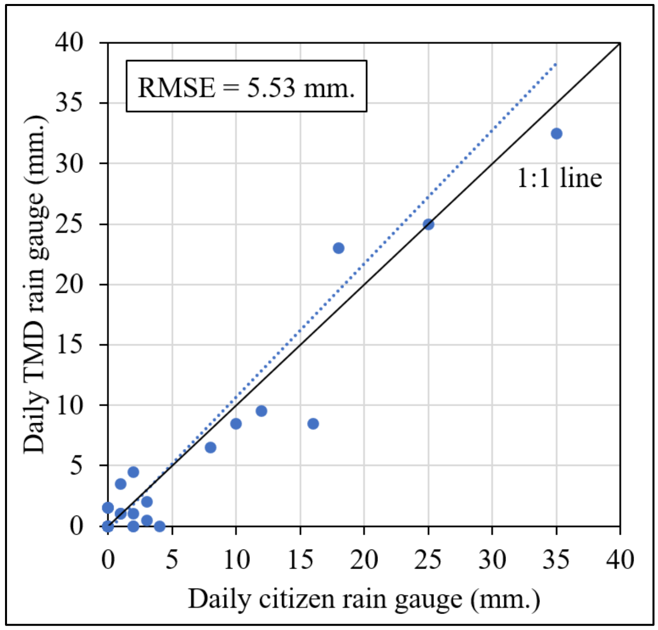


Figure S2: (in supplementary information to the revised manuscript) Daily rainfall depth comparison between the TMD and citizen rain gauge at location R.3 during August – October 2019.

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: Indeed, Fig.9 (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 S2 (this figure will be added in the supplementary of the revised manuscript) shows the radar reflectivity field at 13.00h 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. 9 (a) are caused by time errors in the observations submitted by local residents were removed from the analysis (as will be explained in new section 2.3.2). The map shown in Figure S3 will be provided in the revised manuscript.

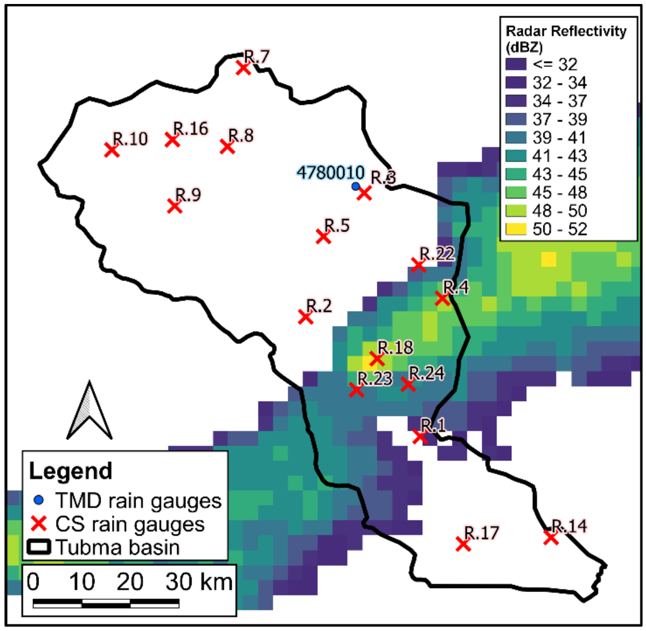


Figure S2: Overlapping between citizen rain gauges network and spatial radar reflectivity data on 22 September 2019 at 13.00 hour

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 a lot of approaches for comparison and would like to make the paper short, we then use the acronyms to tell the story. However, we will try to use as less acronyms as possible.

RC (6): Figure 1 – Identification of citizen science gauges
AR: Figure. 1 was modified to be 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.

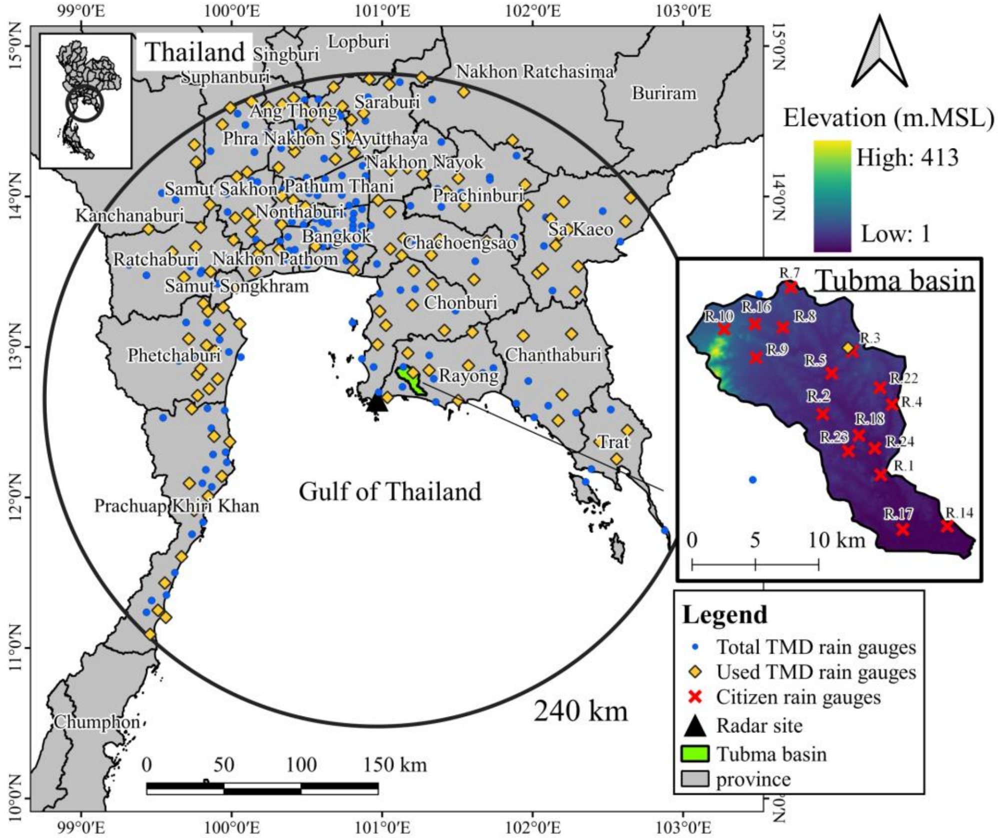


Figure 2 (in the revised manuscript): Location of study domain, showing Thai Meteorological Department (TMD) automatic rain gauges, citizen rain gauges, Sattahip radar, and Tubma basin.

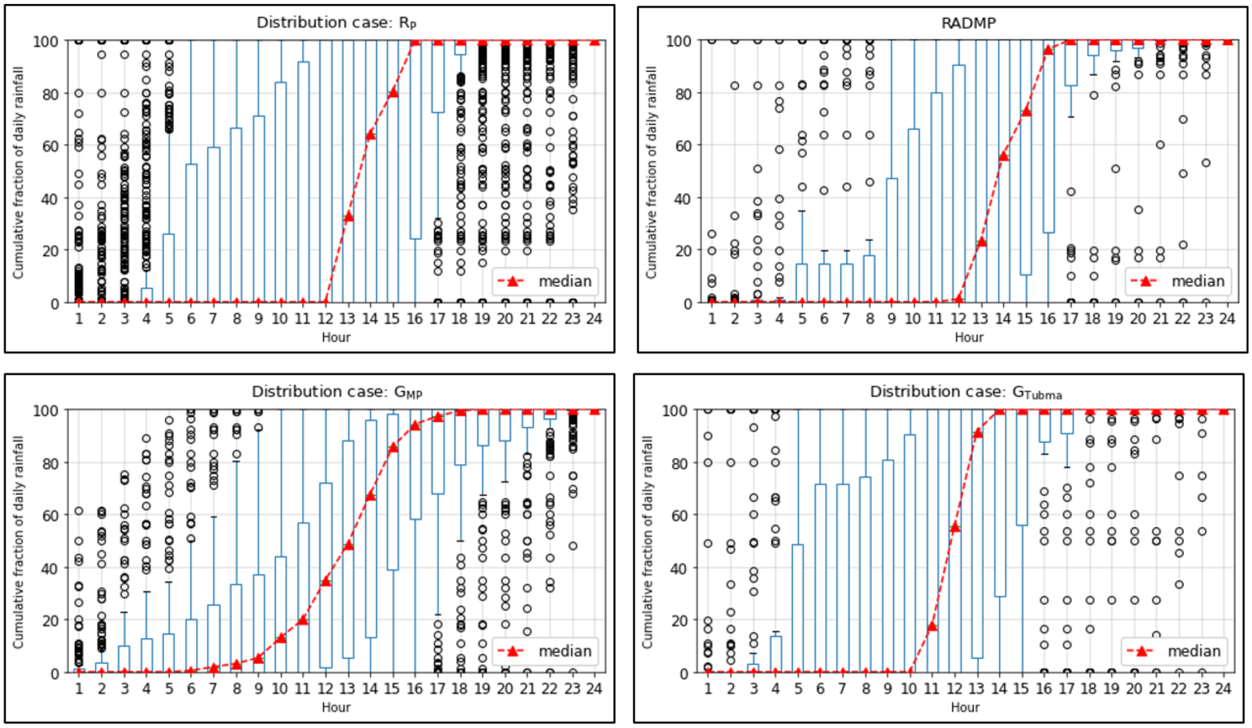
RC (7): Line 164 – replace full stop with comma
AR: We will check the format and replace them correctly in the revised manuscript.

RC (8): Line 254 – Point 1 is not clear about the timing of data, could this be rephrased?
AR: The point 1 of P10L254 will be rephrased according to the comment by follows.

"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 "

RC (9): Line 270 – replace "In case" with "Where"
AR: This correction will be 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 will be 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 will be adjusted as the following.

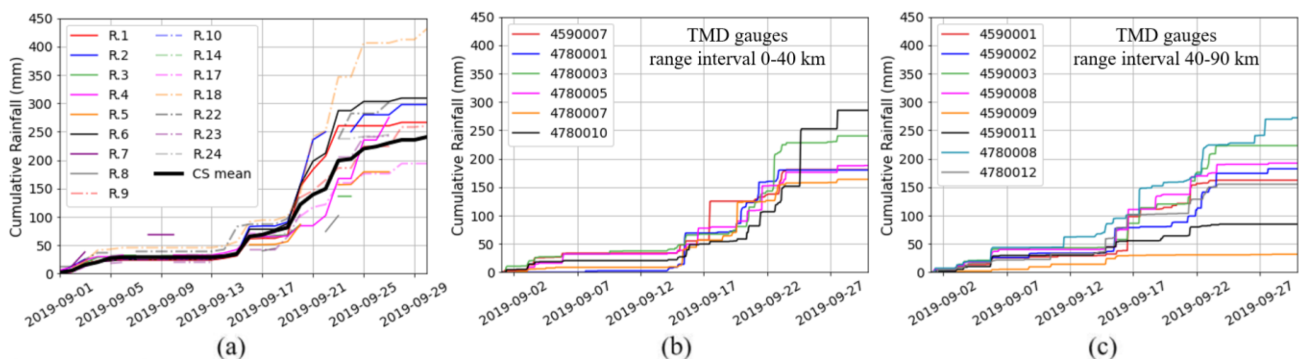


Figure 9 (in the revised manuscript): Comparison of mass curve of hourly rainfall among various rain-gauge locations (a) the citizen rain gauges located in the Tubma basin (b)TMD rain gauges within 0-40 km radius from the Tubma basin (c) TMD rain gauges within 40-90 km radius from the Tubma basin.

Reference

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