Bias Adjustments of Radar Rainfall during Seasonal March of the Summer Monsoon in the Middle of Thailand

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Abstract

Accurate rainfall estimates are crucial data in the tropics to understand the global circulation of water cycles. This study focuses on evaluation of bias adjustment methods applied to correct a constructed radar rainfall estimate of Phetchabun radar in Thailand. The radar rainfall during the summer monsoon season from July to September 2010 has been investigated with the use of weather radar open source library, wradlib, written in python. The CAPPI of instantaneous scanning at a height of 3 km has been constructed to produce hourly rainfall estimates after transformation using the Z-R relation of Marshall et al. (1955). The calibration and validation processes of the applied bias adjustment method have been done with 50 and 20 gauge stations, respectively. The results show that the mean field bias adjustment method can reduce the difference between both rainfall sources with a reduction of the mean absolute error by 70%. In addition, the mean field bias method is less sensitive to rainfall systems in both monthly and event-based variations. Moreover, spatial bias adjustment using spatial interpolation of ordinary kriging produces a good result in the reduction of mean absolute error compared to spatial interpolation of IDW used in SRD-IDW and SBA. The result in the investigation of rainfall events indicate that using the appropriate Z-R relation according to rain types is crucial to the step of the transformation of radar reflectivity factor to the rain rate.

Keywords: Radar rainfall, Bias adjustments, Quantitative precipitation estimates, Radar-gauge merging methods, the middle of Thailand
INTRODUCTION

Accurate rainfall estimates are a crucial factor to understanding atmospheric global circulation and water cycles. Furthermore, it is a main input of physical models to the forecast process of disaster-related events of both meteorological and hydrological fields for effective disaster management. At the present time, there are various sources of rainfall estimates available for public use, especially in developed countries, such as rainfall observation at gauge stations, rainfall product estimation by assimilation of multi-sensor satellite data sources, and rainfall estimation derived from reflectivity factors of weather radar. There are advantages and disadvantages on the use of these mentioned procedures, but it is generally accepted that rainfall observation at gauge stations is highly accurate as the point observation provides a truth of ground rainfall. However, rainfall estimates from weather radar produces a higher spatio-temporal resolution than the others. Therefore, many attempts have been made in the past few decades to utilize the advantage of rain observation at gauge stations and via weather radar.

Weather radar measures indirect precipitation at a certain altitude, while a rain gauge is a direct measurement of rain quantity observed at a point near the ground surface. Thus, inequality of rain quantity always exists between the two data sets. Furthermore, various inherent errors are associated with the observation by weather radar such as mis-calibration errors in the radar electronic devices, partial beam filling caused by an increasing volume of beams in the far range, contamination of non-metereological echoes, and attenuation due to a wet radome (Collier, 1986; Wilson and Brandes, 1979; Germann 1999). There are attempts to utilize rain observed at gauge stations (hereafter referred to as gauge rainfall) derived from a dense gauge network in the calibration process of rainfall estimated from radar reflectivity (hereafter referred to as radar rainfall estimates) to compensate for those errors during quantitative precipitation estimate (QPE).

There are many methods used in radar rainfall bias adjustment that employ a dense gauge network. This ranges from simple to complicated processes. Michelson and Koistinen (2000) categorized the methods into two groups. The first group is to find a different ratio between gauge rainfall and radar rainfall estimates, or mean field bias (MFB). Although MFB is the most efficient method to remove systematic biases in radar QPE, it does not account for local variation of the bias that spatial interpolation techniques do (Fulton et al., 1998; Tabary, 2007; Zhang et al. 2014). The other way is to employ statistics and geostatistics methods to find a relation of the two sources such as spatial interpolation techniques, a kalman filter or probability matching (e.g. Krajewski and Smith, 2002; Chumchean 2006; Thorndahl et al. 2014).

Radar rainfall estimates are already used in operational work in developed countries (e.g. Tabary, 2007; Fulton et al., 1998; Zhang et al. 2011; Zhang et al. 2014). However, developing countries such as Thailand use radar products only in organizations that are operating the radar instruments. That may cause a public side to lose the benefit of access to the radar rainfall products. To implement a framework for radar rainfall bias adjustment toward radar rainfall products in Thailand, this study attempts to evaluate...
the selected bias adjustment methods after application of radar rainfall estimates during seasonal march of the summer monsoon in 2010 with the use of weather radar open source library to construct radar rainfall estimate mapping of instantaneous times.

**Figure 1**: Map of the study area within range of the Phetchabun radar (represented as square) at a radius of 60 and 120 km represented as dash lines. Rain gauges distributed over the radar coverage area are represented as dots. Validation gauges are represented as black dots. The boundary of river basins under the radar observation area is represented as black lines.

**STUDY AREA AND DATA**
This study uses reflectivity from the weather radar of Phetchabun located in the middle of Thailand and operated by the Thai Meteorological Department (TMD). The radar site is located at the geographic coordinates at latitude of 15° 39′ 24″ and longitude of 101° 6′ 29″ over the height of the terrain at 74 m above mean sea level. The observation radius of the radar is at 240 km with C-band frequency in the single polarization mode.
Various important river basins in the central part of Thailand are located under the radar coverage such as Pasak, Nan, Yom, Chao Phraya, Mun and Chi as shown in Figure 1. Mountainous ranges that are west, east of the Phetchabun and Dong Phraya mountain ranges, align in the west, east and southeast of the radar site, respectively.

The range resolution of the radar is at 500 meters with a beam width of 1 degree. The observation frequency of the radar are three times per hour with volume scanning of 10 elevation angles (0.0°, 1.3°, 2.9°, 4.9°, 7.3°, 10.2°, 13.8°, 18.2°, 23.5°, 30.0°). The radar reflectivity of the 3 months during the summer monsoon season from July to September of 2010 was analyzed. First, the reflectivity of the radar volumes in the range of 7-55 dBZ, in order to avoid noise and hails (Holleman, 2007), were used for all sweep angles in the construction of the constant altitude plan position indicator (CAPPI) at an altitude of 3 km to avoid ground clutter. The observation radius of CAPPI has been limited at 120 km, which covers 4,523 sq.km. The spatial resolution of the produced CAPPI was at 1 km of the horizontal grid in the dBZ unit of instantaneous observation time. Since Drop Size Distribution (DSD) information does not exist in the study area, the radar reflectivity and rainfall rate are related with a fixed Z-R relationship, regardless of a varying DSD in temporal changes (e.g. Collier 1986; Fulton et al. 1998; Smith and Krajewski, 1991). Subsequently, each instantaneous observation CAPPI was transformed to the rain rate with the use of Z-R relation:

\[ Z = AR^B \]

Where Z is reflectivity (mm^6m^-3), R is rainrate (mmh^-1). A and B are based on the standards of Marshall et al.’s (1955) parameters which are 200 and 1.6, respectively. This currently used Z-R relationship represents stratiform rain. TMD also uses the same Z-R relation in their operational works. Then the radar rainfall fields were aggregated into hourly accumulations which have been constructed in the cartesian grid form for the further analysis.

The gauge rainfall delivered from TMD was spatially distributed over the radar coverage at 70 stations as shown in Figure 1. This dense gauge network automatically collected and sent the information to the server in the main office of TMD. The density of the gauge network is about 646 sq.km per one gauge. These gauges have been inspected by examining the outlier existing in the data and comparing them with neighboring stations before being selected in the analysis process which would be used as the ground truth of rainfall near the surface. The gauge stations have been separated into two groups of the process. The first group had 50 gauge stations that would be used in the calibration process, while the other group of 20 gauge stations was to be used in the validation process to evaluate the performance before and after application of all methods used in the bias adjustment.
High-level computer programming language, i.e. python, was used in the analysis of the current study. It has an effective capacity to manipulate space-time data. In addition, an open source library of weather radar written in python, i.e. wradlib (Heistermann et al., 2013), was used in the main analysis processes of radar mapping. The results of produced CAPPI can be easily converted to external systems like GIS for further analysis.

A comparison of the daily area average rainfall observed from three sources which were the original converted radar rainfall estimate (ORI), gauge rainfall, and daily rainfall estimates from TRMM3B42 (V.7) rain products (Huffman et al. 2007) are shown in Figure 2. All three data sources showed similarity in the pattern of rainfall, while amplitude is barely equal. Noticeably, the rainfall peak of ORI has shown an underestimation of the rainfall amount observed over the gauges. Therefore, the calibration processes must be applied to ORI to reduce the bias from the ground truth rainfall and evaluation of the selected calibration methods and it must be analyzed.

**Figure 2**: Spatial average of accumulated daily rainfall over the position of rain gauges from 1 July to 30 September 2010. ORI, TRMM3B42 and gauge rainfall are represented in black-solid, dot and dashed-solid lines, respectively. Highlighted areas are the selected 4 rain events. The numbers indicate rain events (see text for details).
Bias adjustment methods have been evaluated in this study based on practical simplicity toward the implementation in the operational work. The difference between radar rainfall estimates and gauge rainfall is evaluated among the selected methods. Firstly, hourly rainfall of both radar and gauge rainfall are compared in local time to match a pair of rainfall data with intensity greater than 0.5 mm. Then, accumulation of the both data sources at the position of gauge has been done thoroughly throughout the whole period of each gauge position to compare the bias of before and after application of the methods as shown in Figure 3a and 3b in case of Mean Field Bias (MFB) adjustment. Although ORI has high correlation with gauge rainfall by 0.595, it shows overestimation of gauge rainfall around 44%, as shown in Figure 3a, indicates the ORI. However, the difference between rainfall amounts between these two data decreased by 10% after application of MFB associated with the improvement of correlation up to 0.658. The details of selected bias adjustment methods are as follows:

1. Mean field Bias (MFB) is the method to compute the difference between gauge (G) and radar rainfall estimates (R) that will be used in multiplicative adjustments to the ORI. The assumption of MFB is built on the spatial uniform of intrinsic errors caused by either calibration of electronic devices or inappropriate selection of Z-R relation to DSD of rain systems with the equation as follows:

\[
C_{MFB} = \frac{\sum_{i=1}^{N} G_i}{\sum_{i=1}^{N} R_i}
\]

Where N is number of matched pairs of G and R associated with gauge \( i \).
2. Range Dependent Adjustment (RDA) is one of the gauge adjustment techniques that find the gauge-radar ratio to derive a distance-dependent adjustment factor (Michelson et al. 2000; Michelson and Koistinen, 2000). The increasing of radar volume as a function of radar observation range is realized to occur with the increasing effect of partial beam filling. Thus, the nature of the returned radar reflectivity factor in the far range is always attained with an estimation of underestimated rainfall. In addition, attenuation occurs and is associated with the power returned reflectivity factor to the radar receiver. RDA is calculated as a function of distance between the relation of G and R in the logarithm scale as follows:

\[ \log C_{RDA} = ar^2 + br + c \]

Where \( r \) is the distance from the radar to each gauge station, and \( a, b \) and \( c \) are coefficients computed from a polynomial fitted line with the use of the least square.

3. Spatial Bias Adjustment (SBA) (Goudenhooft and Delobe, 2009) is computed with the assumption of spatially distributed local bias over the study area. Firstly, the bias between G and R has been individually computed above gauge locations. Next, the deterministic spatial interpolation and inverse distance weighting have been applied to construct the bias field before the application to correct the hourly radar rainfall in the Cartesian grid form.

4. Static local bias adjustment and Range Dependent Adjustment (SRD) is a spatial bias adjustment that attempts to reduce a local bias. First, MFB was applied to correct the hourly radar rainfall estimates before the computation of the ratio between G and R of each gauge location that are used in the interpolation of bias field using experiments of two spatial interpolation which are IDW (SRD-IDW) and the ordinary kriging (SRD-OK) (e.g. Goovaerts, 1997). During the interpolation of IDW, the neighboring gauge at 20 points was included in the weighting stage, while linear variogram model was used in OK with a lag distance set at 10 km in accordance with Haberlandt (2007). Finally, application of the two spatial fields to hourly radar rainfall estimates was done.

Statistics of evaluation

When the products of all bias adjustment methods were produced, the validation of the adjustments was done with randomly distributed validation gauges of 20 stations that were independent from the calibration process. The details of evaluation statistics are as follows:

1. Mean Absolute Error (MAE) is widely used in the evaluation performance of the radar rainfall estimates against validation gauges because it is less sensitive to large errors. MAE is used as the main evaluator in this present study. A perfect match between G and R corresponding to MAE is equivalent to 0 mm.
\[ MAE = \frac{1}{N} \sum_{i=1}^{N} |R_i - G_i| \]

2. Root Mean Square Error (RMSE) is the most commonly used in validation works.
\[ RMSE = \sqrt{\frac{\sum_{i=1}^{N} (R_i - G_i)^2}{N}} \]

3. Mean Bias (MB) is the ratio between radar rainfall estimates and gauge rainfall represented in decibel units.

4. Correlation coefficient (COR) is the measurement of the strength and direction of both radar rainfall estimates and gauge rainfall relation.

5. The Nash-Sutcliffe-Efficiency (NSE, Nash and Sutcliffe, 1970)
\[ NSE = 1 - \frac{\sum_{i=1}^{N} (R_i - G_i)^2}{\sum_{i=1}^{N} (G_i - \bar{G})^2} \]

Where \( R_i \) is the radar rainfall estimates of each different bias adjustment method. NSE equivalent to 0 mm means that the radar rainfall estimates are equivalent to the mean of the gauge rainfall.

**RESULTS**

![Figure 4](image-url)

**Figure 4**: Mean absolute error of all methods used in the adjustment of radar rainfall estimates from July-September 2010.
Accuracy of bias adjustment methods

In this section, we evaluate the accuracy of the bias adjustment methods with the use of the whole period data in 2010 using validation gauges to find the best methods that produce effective performance reduction of bias in terms of statistical evaluation. Figure 4 shows that ORI which are not yet applied. The bias adjustment produces the highest MAE at 2.55 mm. The best bias adjustment method is MFB which can reduce MAE up to 70%. Furthermore, spatial bias adjustment by using SRD-OK can reduce MAE by 53% of ORI. SRD-IDW and SBA have also been shown to reduce MAE by about 40%.

Table 1: Verification statistics of radar-gauge merging methods as described in this section.

<table>
<thead>
<tr>
<th>Methods</th>
<th>MAE(mm)</th>
<th>RMSE(mm)</th>
<th>Correlation</th>
<th>NSE</th>
<th>MB(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORI</td>
<td>2.515</td>
<td>2.929</td>
<td>0.595</td>
<td>-7.987</td>
<td>2.450</td>
</tr>
<tr>
<td>MFB</td>
<td>0.758</td>
<td>0.964</td>
<td>0.658</td>
<td>0.057</td>
<td>0.450</td>
</tr>
<tr>
<td>RDA</td>
<td>0.839</td>
<td>0.987</td>
<td>0.735</td>
<td>-0.183</td>
<td>-1.508</td>
</tr>
<tr>
<td>SBA</td>
<td>1.512</td>
<td>2.030</td>
<td>0.730</td>
<td>-2.224</td>
<td>1.144</td>
</tr>
<tr>
<td>SRD-IDW</td>
<td>1.457</td>
<td>2.089</td>
<td>0.625</td>
<td>-3.202</td>
<td>1.317</td>
</tr>
<tr>
<td>SRD-OK</td>
<td>1.193</td>
<td>1.492</td>
<td>0.716</td>
<td>-1.326</td>
<td>0.726</td>
</tr>
</tbody>
</table>

As illustrated in Table 1, we found that MFB is the best bias adjustment based on evaluation statistics. ORI usually indicates an overestimation at 50% compared to gauge rainfall. However, the MFB method can significantly reduce MAE with a remaining 10% in total. Although RDA produces radar rainfall estimates lower than the gauge rainfall, MFB has shown more improvement than that of ORI. The correlation of each bias adjustment method is improved when compared to ORI. RDA produces the highest correlation between radar rainfall estimates and gauge rainfall by 23% compared to ORI. The MFB method produces the best results of the evaluation statistics compared to other methods such as RMSE, NSE and MB, which are 0.964 mm, 0.057 and 0.450 dB, respectively.
Sensitivity of the methods in each month

Figure 5: Mean absolute error of all radar-gauge methods during the summer monsoon months of 2010.

Variation of rainfall characteristics occurs as a function of the background of physical factors changes which are associated with temporal changes ranging from diurnal, intra-seasonal, and inter-annual variation. The study area is located among the southwest monsoon season associated with disturbances from the northwest Pacific in terms of depression dissipating from tropical storms. The variation of rain systems exists during the seasonal March change that increases a variation of bias caused by an unrepresentative Z-R relationship (e.g. Wilson and Brandes 1979; Austin 1987; Andrieu et al. 1997) that exists in the adjustment methods. Therefore, a sensitivity test of bias adjustment methods during seasonal march has been conducted. Figure 5 shows a comparison of MAE normalized with MAE of ORI for all methods. It was found that every method can reduce MAE by 50% in all months. Noticeably, RDA can reduce MAE better than MFB in both July and August, while MFB does better in September. In case of spatial interpolation, SRD-OK does better in every month with a greater reduction of MAE than SBA and SRD-IDW.
Verification with range dependent effects

![Figure 6](image.png)

Figure 6: Effect of the distance from the radar on mean absolute error of all methods normalized by the mean absolute error of the original radar rainfall estimates.

Although the CAPPI distance is already limited to 120 km distance from the radar site, a range dependent effect still exists in weather radar observation. Therefore, the sensitivity analysis of the effects has been investigated in the separation of distance at four ranges, which are 0-60, 60-80, 80-100 and 100-120 km. The first range is wider than the others because there is a fewer number of gauge stations in this range. Figure 6 shows that most methods of the bias adjustment in all ranges have a lower MAE compared to ORI except for SRD-IDW and SBA, which are based on IDW interpolation. SRD-IDW produces the highest MAE in this analysis at a range of 0-60 km which might be caused by a low density of the gauge network. Although it is a simple method in the nature, MFB produces good results of MAE significantly reduced after the application.
Verification of the methods during different rain systems

Table 2: Rainfall events selected for investigation of sensitivity of all bias adjustment methods in radar rainfall estimates.

<table>
<thead>
<tr>
<th>Event</th>
<th>Characteristics of rain</th>
<th>Periods</th>
<th>Area average of total rain (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rainfall systems associated with convective cells mostly moving from west to east</td>
<td>Jul 14, 00Z–Jul 18, 23Z</td>
<td>17.257</td>
</tr>
<tr>
<td>2</td>
<td>Rain systems producing light rainfall amount moving from north to south and small convective rain cell moving from southwest to northeast</td>
<td>Aug 23, 00Z–Aug 25, 23Z</td>
<td>5.457</td>
</tr>
<tr>
<td>3</td>
<td>Rain systems moving from south to north and west to east associated with scattered convective cells</td>
<td>Aug 28, 00Z–Aug 29, 23Z</td>
<td>25.169</td>
</tr>
<tr>
<td>4</td>
<td>Rain systems of mixed types associated with convective cells moving from west to east, from southwest to northeast and found scattered convective cells</td>
<td>Sep 01, 00Z–Sep 03, 23Z</td>
<td>33.346</td>
</tr>
</tbody>
</table>

The sensitivity of bias adjustment methods to rain systems has been verified with the comparison of normalized MAE by MAE of the ORI. Four rain events have been chosen with the details as shown in Table 2. The first two events are based on moving tropical storms named Conson and Mindulle toward the Indochina peninsula in the northern and middle regions of Vietnam, respectively. These two storms weakened as it was the Vietnam land inducing moisture toward the center of the low pressure areas. In addition to the two storms, we selected rain events numbered 3 and 4 based on the highest daily accumulated rainfall amount as shown in Figure 2. The results show that MAE of each method varied by rain systems associated with the rain events as shown in Figure 7.
However, MFB is the only method that is less sensitive to the rain events because the MAE of the MFB is lower than the MAE of the ORI for all rain events. Furthermore, MAE produced by all methods in rain event #2 showed the best improvement as the event produced a light rain intensity associated with stratiform clouds over the observation area producing a total rainfall area average of 5.457 mm as shown in Figure 8. The instantaneous reflectivity factor of the radar was drawn as CAPPI at a height of 3 km of rain event #2 that occurred on 25 August 2010 at 07:00 local time. It was found that the light rainfall rate produced from the stratiform rain covered the whole radar observation area associated with the weak reflectivity of echo shown in all altitudes of radar volume.
In contrast, MAE of rain events #1 and #3 had lower MAE than MAE of ORI except for SRD-IDW which showed a higher rate than others. The higher MAE of SRD-IDW might have been effected by the occurrence of either mixed or convective rain types which may cause the failure of IDW interpolation to estimate the adjustment field as well as the SBA method. In addition, the rain system of event #4 is a mixed type which includes convective and stratiform rain that may possibly affect the bias adjustment methods to fail to produce appropriate bias field causing in the higher MAE than the MAE of ORI except for MFB.

Figure 9a shows the stratiform rain distributed over the radar coverage on 23 September 2010 at 06:00 local time. However, the convective rain appears in the northeast of the radar area associated with a strong echo of reflectivity greater than 50 dBZ in all altitudes. In addition, Figure 9b illustrates the reflectivity of scattered convective rain on 21 September 2010 at 18:00 local time and has convective cores associated with the reflectivity greater than 50 dBZ which may lead to inappropriate usage of the Z-R
relation of the stratiform rain to relate the reflectivity factor with the rain rate. As pointed out by Battan (1973), the power law functions to relate the radar reflectivity and the rainfall rate depending on the changing DSD of specific rainfall. Therefore, separation of cloud types (e.g. Steiner et al., 1995; Caine et al., 2009, Zhang et al. 2011) is necessary to distinguish between convective and stratiform rain types for appropriate application of the Z-R relation of the rain events.

Figure 9: Sample of instantaneous CAPPI of rain event #4: (a) mixed rain types on 23 September 2010 at 06:00 local time; and (b) scattered convective rain systems on 21 September 2010 at 18:00 local time
CONCLUSION

In this paper, we have focused on the evaluation of radar rainfall estimates based on various selected bias adjustment methods which are suitable for operational works in developing countries such as Thailand toward the implementation of radar rainfall products. The volume of radar reflectivity during the summer monsoon season of 2010 was observed by the Phetchabun radar in Thailand and this was used in the construction of CAPPI at a height of 3 km for instantaneous time to create an hourly rainfall rate with the use of Z-R relation of stratiform rain based on Marshall et al. (1955). The main conclusions are as follows:

All methods are able to reduce the mean absolute error and other evaluation-related statistics used also mostly indicate an improvement of ORI rain estimates after application of the bias adjustment. Furthermore, this simple method, the mean field bias adjustment, can reduce the mean absolute error by 70% when all data are used against the independent validation gauges. When considering the results of after-application bias adjustment methods in each month, the mean field bias method shows the best result which is less sensitive to variation of rain systems. In addition, interpolation of ordinary kriging used in SRD-OK can reduce the mean absolute error better than spatial interpolation of IDW that are employed in SRD-IDW and SBA. We investigated the sensitivity of all methods on the effect of the range dependent. It was found that the mean field bias adjustment produce the best results in all ranges, while SRD-OK produces a strong performance on the reduction of the mean absolute error among spatial interpolation which is consistent with previous studies (e.g. Haberlandt 2007; Goudenhoofdt and Delobe 2009; Berndt et al. 2014). Finally, the sensitivity of applied methods on the rain events has been investigated. The results indicate that the mean field bias is less sensitive to rainfall types with an ability to reduce the mean absolute error during mixed rain types of both convective and stratiform rain systems, while other methods are sensitive to mixed rain types. The results suggest that separation of cloud types is necessary to improve QPE regarding application of an appropriate Z-R relation. The bias adjustment of shorter temporal observation needs to be further investigated, especially for events of severe storms.

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