Application of hourly radar-gauge merging method for quantitative precipitation estimates

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Abstract. Gridded quantitative precipitation estimation (QPE) of high spatial and temporal resolution is now being increasingly used for instance for hydrological modelling. The combination between observations from radar data and in-situ rain-gauge measurement is a popular mean to produce QPEs. Since the QPE generated from radar data only is considered to be not satisfactory, some corrections should be introduced in order to achieve better accuracy of the instant precipitation estimation. The correction method that were used were Mean Field Bias Correction (MFB) and static adjustment. MFB was applied by the assumption that the radar estimation was affected by uniform multiplicative error. The static adjustment was applied to correct radar rainfall data through plotting between radar rainfall and rain gauge so that the regression line between radar and rain gauge was approaching one. The purpose of radar QPE corrections was for hydrological modelling applications.

Keywords: QPE; weather radar; Mean Field Bias (MFB) correction; static adjustment; rain gauge measurement; hydrological modelling.

1. Introduction
Rainfall is one important variable in the success of applications such as hydrological modeling and flood forecasting for short-term studies. Resolution requirement of space-time rainfall estimation varies greatly depending on the application, the catchment area, types of rain events and the type of model used. Rainfall-runoff “lumped” models generally requiring area precipitation estimation while distributed model needs rainfall estimation based on grid. The shape of the catchment area and characteristics of rain influence temporal resolution of rainfall that will be used and might be varied starting from interval of 5 minutes to daily interval or even more [1].

It is not easy to estimate the value of precipitation if our calculation is only rely on one instrument. A rain gauge measurement although has a high accuracy in absolute values, the recorded data were often not distributed equally so that the representation level was still limited [2, 3]. One of the complementary instruments to estimate the spatial distribution of precipitation accurately is utilization of weather radar. Rainfall intensity can be estimated by weather radar through equation of reflectivity and rain intensity (rain rate).

There is increasing demand for accurate gridded quantitative precipitation estimation (QPE) with high spatial and temporal resolution for many applications. The scales of interest often very challenging because sometimes at scale of a single kilometer and only for some hours. Gridded QPE
usually used in meteorology and climatology. On the other side, spatial precipitation analyses are increasingly used by other user groups as input data for models of natural system for instance for hydrological modelling that requires high-resolution QPE grids [2].

Evaluation and correction of the radar data is generally performed using a rain gauge measurement. Several methods have been proposed for correcting and validating radar precipitation products, from simple methods such as simple static adjustment, a multiplicative calibration, multi quadratic surface fitting to the more complex method e.g. geo statistics, co-Kriging or dynamic adjustment [1, 2, 4, 5].

The aim of this article was to perform a long-term verification with Mean Field Bias (MFB) correction method and static bias adjustment. Verification of these methods faced the problem that the real precipitation field was unknown. A traditional approach is to compare precipitation estimated with rain gauges measurement. Merging method was carried out on hourly basis accumulations. Several statistical analysis were performed followed by computational evaluation and comparing these two methods.

2. Radar and gauge observation

The output of the weather radar was reflectivity, Z, which depended on sum of sixth power of drop diameter. The real drop size distribution was highly variable depending on the type of precipitation, but because it is usually unknown, a default drop size distributions was used [6]. Various studies has been done to connect reflectivity radar data with rainfall intensity with the general equation:

\[ Z = N(D) D^6 = aRb \]  

(1)

where \( Z \) is the radar reflectivity (mm\(^6\) m\(^{-3}\)); \( D \) is the diameter of raindrops (mm); \( N(D) \) is the number of droplets in a diameter per cubic meter; \( R \) is the rainfall at the surface (mm h\(^{-1}\)); and \( a, b \) are coefficients, depending on the latitude, longitude, and kind of rainy season (convective, stratiform). Coefficient values (\( a, b \)) calculated using the distribution \( N(D) \) or taken from the literature. Some \( Z-R \) relationship equation: \( Z = 200R^{1.6} \) is a Marshall and Palmer equation for stratiform rain; \( Z = 31R^{1.71} \) is Blanchard equation for orographic rain; \( Z = 500R^{1.5} \) for the thunderstorm; and \( Z = 350R^{1.4} \) for the convective rain.

Indonesia Meteorological, Geophysical and Climatological Agency or BMKG operates the C-Band weather radar at Tangerang District. The radar observation routinely used for operational short-term precipitation forecasting and for detecting the severe thunderstorm. BMKG also operates five rain gauges with hourly basis data accumulation surrounding Tangerang weather radar site (figure1).

Figure 1. Location of radar site (yellow pin) and five rain gauges (red balloon).
3. Description of the methods

Comparing between radar rainfall data and rain gauges measurement become a challenge due to the different sampling size of the instruments. Radar measurement volume can be several kilometers wide and thick, while the measurement area of a gauge is 400 cm$^2$ (weighting gauges) or 100 cm$^3$ (optical instruments). During the case study periods (June 2013 – June 2016), radar data were available at 10 minutes time interval and total of five rain gauges that provide detailed point information, which was used to correct the radar rainfall field. The spatial sampling issue is a crucial importance when the radar areal estimation is compared with rain gauge point measurement. A systematic difference or “bias” between radar rainfall and rain gauge measurement can be progressively removed using information provided by rain gauges. This is performed through an adjustment factor that is estimated as the ratio of the accumulated rain gauge rainfall, $G$, and the accumulated radar rainfall, $R$. The simplest method of bias correction is to multiply the $R$ values by $G/R$. Note that the expected value of $G/R$ is 1.0 [7].

3.1. Mean field bias correction (MFB)

A mean field bias correction algorithm aims to reduce the gross error in the truncated 1-h precipitation accumulation as observed against the automatic rain gauge observation. The assumption here is that the radar estimation affected by uniform multiplicative error. The bias-adjusted precipitation estimation calculated on hourly basis from the uncorrected radar data:

$$C_{MFB} = \frac{\sum_{i=1}^{n} G_i}{\sum_{i=1}^{n} R_i}$$

$$R_{i,adj} = C_{MFB} \cdot R_i$$

where $C_{MFB}$ is the correction factor, $n$ is the number of valid radar-gauge pairs, $G_i$ is the measured rainfall at gauge $i$ and $R_i$ is radar measured rainfall values coincident with $i$ gauge location. $R_{i,adj}$ is radar bias adjusted at $i$ gauge location and $R_i$ is uncorrected (raw) radar data before correction. The radar rainfall measured at the gauge taken as the spatial integration of rainfall for the radar grid above the rain gauge location. The correction factors are obtained at a set time step (e.g., hourly, daily, etc.). The correction factor then applied to the entire spatial domain of the radar, as it is multiplied with the radar value at each grid location in order to develop the adjusted radar image. Only the pairs for which both $G$ and $R$ exceed 1 mm h$^{-1}$ are considered as valid. This minimizes discretization errors and the influence of anomalous propagation. MFB correction has become a widely recognized and applied technique for adjusting radar rainfall grids due to its simplicity and ease in implementation in near-real time.

3.2. Static gauge-adjustment

This method attempts to improve the radar data by identifying the long-term bias of a radar dataset then correcting for it. For the $i$’th rain gauge, the ratio bias, $B_i$, defined as the long-term arithmetic mean ratio of rain gauge and radar rainfall estimates over n 60 minutes time interval:

$$B_i = \frac{1}{n} \sum \frac{R_{g}^i}{R_{r}^i}$$

where $R_{g}^i$ is the raw radar estimation for the grid square coincident with the $i$’th rain gauge. The ratio is only calculated if both $R_{g}^i$ and $R_{r}^i$ exceed 1 mm h$^{-1}$. Averaging this over the $N$ rain gauges gives the ratio bias, $B$, of the radar as:

$$B = \frac{1}{N} \sum B_i$$
Applying this factor to the entire radar dataset gives the static gauge adjusted radar rainfall estimates. Figure 2 showing the whole procedure sequence.

![Work flowchart of the radar bias adjustment](image)

**Figure 2.** Work flowchart of the radar bias adjustment.

4. **Result and Discussion**

4.1. **Mean field bias correction (MFLong-term verification methodology)**

The performance of the different methods verified against to surface rain gauge observation of rainfall accumulation data. The testing period extends from June 2013 – May 2016. The statistical quantification commonly based on the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE), calculated with these data sets:

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n}(R_i - G_i)^2}{N}} \tag{6}
\]

\[
MAE = \frac{\sum_{i=1}^{n}|R_i - G_i|}{N} \tag{7}
\]

4.2. **Results**

The correction methodology with MFB was applied for three years data from five locations. As shown in table 1, the bias, RMSE and MAE of the original radar data decreased significantly after MFB correction. RMSE reduced about 20 – 25% for three locations (Serang, Darmaga and Pondok Betung) and about 45% for Kemayoran. In the contrary, for Citeko the RMSE increased about 25%. For MAE, all of five locations showed that MAE decreased about 28 % - 50%. As shown in figure 3, the MFB correction method provided the greatest reduction in error as compared to the raw radar data before MFB correction. Kemayoran had a significant increasing with $R^2$ (from 0.12 to became 0.60) while Citeko had a smallest $R^2$ (from 0.0 to became 0.17). A visualization for MFB correction method can be seen at figure 3.
Figure 3. Plots of QPE radar data (x-axis) against observed rain-gauge values (y-axis) for 5 locations.

The continuous black line is a linear fit to the data set and the dashed red line represents the perfect 1:1 fit in the plots. Left graph (a, c, e, g and i) showing data before MFB corrections while right graph (b, d, f, h and j) after MFB correction.
Table 1. Error statistics for non-MFB and MFB correction between five rain gauges and radar data.

| Rain Gauge | Non MFB Bias | With MFB Bias | Non MFB RMSE | With MFB RMSE | Non MFB MAE | With MFB MAE |
|------------|--------------|---------------|--------------|---------------|-------------|--------------|
| Serang     | 3.4          | 1.8           | 10.4         | 8.3           | 6.5         | 4.1          |
| Kemayoran  | 3.6          | 1.8           | 12.4         | 6.6           | 7.9         | 3.9          |
| Darmaga    | 4.5          | 2.4           | 15.7         | 11.8          | 9.2         | 6.6          |
| Pondok Betung | 4.0  | 2.6           | 11.7         | 8.6           | 7.3         | 5.2          |
| Citeko     | 4.5          | 2.4           | 15.7         | 11.8          | 9.2         | 6.6          |

Figure 4. One hour raw radar rainfall accumulations data (a), rainfall accumulations derived using MFB correction (b) and rainfall accumulation derived using static gauge adjustment at 21 UTC January 1st, 2014 (c).

Over the 3 years case study, the ratio bias of the QPE radar data was calculated to be approximately 3.4. The monthly ratio biases calculated using individual rain-gauges, and as a mean over all rain-gauges are presented in figure 5 along with the ratio biases for the whole period (also listed in table 2). There does not appear to be a seasonal variation but there is some positive association with range and elevation with the higher rain-gauges having larger ratio biases.

Figure 5. Monthly ratio bias for QPE radar data coincident with each rain-gauge locations over the period June 2013 to June 2016. The ratio bias averaged over all rain-gauge is denoted by black solid dots.
Table 2. Rain-gauges used for the case study and ratio bias of radar data at rain-gauge location.

| Location | Elevation (meter above sea level) | Time Period |
|----------|----------------------------------|-------------|
|          |                                  | Jan | Feb | Mar | Apr | Mei | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Mean Bias |
| Serang   | 37                               | 3.4 | 1.9 | 2.4 | 4.0 | 1.1 | 3.7 | 3.9 | 5.3 | 0.9 | 3.7 | 5.6 | 0.7 | 3.1       |
| Kemayoran| 5                                | 3.8 | 4.4 | 3.4 | 4.1 | 2.7 | 3.2 | 2.9 | 2.2 | 1.1 | 2.2 | 3.0 | 4.6 | 3.1       |
| Darmaga  | 29                               | 9.0 | 7.0 | 4.9 | 3.4 | 1.6 | 0.1 | 1.6 | 3.7 | 0.4 | 4.0 | 4.3 | 2.8 | 3.6       |
| Pondok   | 169                              | 1.8 | 4.5 | 2.5 | 5.1 | 6.1 | 2.4 | 4.1 | 5.4 | 1.6 | 1.5 | 5.8 | 3.4 | 3.7       |
| Betung   | Citeko                           | 973 | 7.1 | 3.5 | 3.4 | 4.5 | 5.0 | 1.3 | 1.1 | 3.3 | 3.1 | 3.4 | 3.6 | 4.3       |
|          | Mean Bias                        | 5.0 | 4.2 | 3.3 | 4.2 | 3.3 | 2.1 | 2.7 | 4.0 | 1.4 | 3.0 | 4.5 | 3.2 | 3.4       |

The RMSE results for the static bias adjustment method show that there are high fluctuation for the five locations with the highest in Darmaga at August and the smallest is in Kemayoran at September.

Table 3. Root mean square error (RMSE) with Static gauge-adjustment method for five locations.

| Location | Time Period |
|----------|-------------|
|          | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Serang   | 5.9  | 3.8  | 15.9 | 12.7 | 1.8  | 5.8  | 9.3  | 15.6 | 4.5  | 8.0  | 17.1 | 0.4  |
| Kemayoran| 12.2 | 11.9 | 13.1 | 20.7 | 11.8 | 10.0 | 8.8  | 8.6  | 0.5  | 7.5  | 9.2  | 13.1  |
| Darmaga  | 19.2 | 20.3 | 8.0  | 5.8  | 0.9  | 8.0  | 11.6 | 24.5 | 8.4  | 5.7  | 16.4 | 5.2   |
| Pondok   | Betung| 4.3  | 7.0  | 15.4 | 18.3 | 13.6 | 10.2 | 9.4  | 12.2 | 3.2  | 2.8  | 15.7 | 3.5   |
| Citeko   |      | 10.6 | 4.6  | 5.1  | 9.2  | 8.1  | 1.7  | 1.4  | 7.5  | 2.7  | 6.9  | 9.3   | 10.6  |

The RMSE results for the static bias adjustment method show that there are high fluctuation for the five locations with the highest in Darmaga at August and the smallest is in Kemayoran at September.

5. Conclusion

Two methods combining rainfall estimation from a QPE radar product and an automatic rain gauge network have been implemented. A 3 (three) years QPE radar was carried out against 5 rain gauges location of hourly measurement. Several statistics have been computed to evaluate the performance of the radar-gauge merging methods. The result pointed out that mean field bias correction can significantly reduce the error of the radar estimation. Nevertheless, there is a clear benefit of using a spatial correction factor. Based upon this study the best method is the mean field bias correction which makes use of the radar as secondary information to improve the spatial interpolation of gauge values.

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