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# Bias correction of satellite rainfall estimation using a radar-gauge product

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Satellite rainfall estimates can be used in operational hydrologic prediction, but are prone to systematic errors. The goal of this study is to seamlessly blend a radar-gauge product with a corrected satellite product that fills gaps in radar coverage. To blend different rainfall products, they should have similar bias features. The paper presents a pixel by pixel method, which aims to correct biases in hourly satellite rainfall products using a radar-gauge rainfall product. Bias factors are calculated for corresponding rainy pixels, and a desired number of them are randomly selected for the analysis. Bias fields are generated using the selected bias factors. The method takes into account spatial variation and random errors in biases. Bias field parameters were determined on a daily basis using the Shuffled Complex Evolution optimization algorithm. To include more sources of errors, ensembles of bias factors were generated and applied before bias field generation. The procedure of the method was demonstrated using a satellite and a radar-gauge rainfall data for several rainy events in 2006 for the Oklahoma region. The method was compared with bias corrections using interpolation without ensembles, the ratio of mean and maximum ratio. Results show the method outperformed the other techniques such as mean ratio, maximum ratio and bias field generation by interpolation.

#### 1 Introduction

Infrared (IR) imageries from GEOstationary (GOES-East and -West) Satellite provide information about cloud at a resolution of 15 min over the contagious US. This gives a greater opportunity to meteorologists, hydrologists and climatologists to develop satellite based rainfall estimates at a higher spatial and time scale. However, the relationship between rainy/non-rainy cloud pixels and identification of the actual precipitation reaching over a particular area has been complicated. Several studies proposed different approaches of discriminating the rainy/non-rainy cloud pixels, leading to the

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development of various satellite precipitation estimation algorithms. For instance, at National Oceanic and Atmospheric Administration (NOAA) – National Weather Service (NWS), several GOES IR based rainfall products are available; namely: Hydro-Estimator (Scofield and Kuligowski, 2003), GOES Mult-Spectral Rainfall Algorithm (GMSRA) (Ba and Gruber, 2001), Self Calibrating Multi-variate Precipitation Retrieval (SCaMPR) (Kuligowski, 2002) and Auto-Estimator (AE) (Vicente et al., 1998). The performance of these various algorithms can differ appreciably (Ebert et al., 2007).

Since satellite based rainfall estimates are approximate and observations are indirect, they are prone to errors. However, if errors are corrected, GOES IR rainfall products can still be used in developing operational real-time flood forecasting and hydrological prediction models for the following reasons. First, satellite IR data are available at high spatial (4 km) and temporal resolutions (every 15 min) that are required for severe storm and flood nowcasting. Second, satellite IR products are the only sources of rainfall observation in mountainous regions where orographic effects cause heavier precipitation consequently results in severe flash floods.

Different authors proposed and exploited different bias quantification and correction techniques to improve precipitation products from radar and satellite. Several investigators (e.g. Anagnostou et al., 1998; Smith and Krajewski, 1990; Ahernet et al., 1986 and Seo et al., 1999) used mean field bias estimation and correction approaches to solve the problem of biases in radar precipitation products; (Seo and Breidenbach, 2002) used a spatially varying local bias correction approach to reduce biases in radars. In their approaches, their hypothesis was that radar-gauge biases are spatially and temporally coherent. Recent efforts have also been made to quantify and correct biases in satellite rainfall estimates using rain-gauges (e.g. Boushaki et al., 2009; Smith et al., 2006). McCollum et al. (2002) evaluated biases of satellite rainfall products using a gauge corrected radar product.

Most of the above mentioned works assumed rain-gauges which are point observations of rainfall as "true" measurements to evaluate and correct the errors in satellite and radar rainfall products. However, the rain-gauge network does not always

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accurately represent a region's rainfall, and errors can arise in using point rain-gauges to represent rainfall of radar or a satellite pixel (Chumchean et al., 2003). In mountainous regions, such as the north-western part of the US where rain-gauges are sparse, many of rain-gauge based bias correction approaches have limited utility. In contrast, radars provide rainfall measurements with better spatial coverage and sampling advantage than rain-gauges. However, radar coverage itself is often limited by terrain blockages and beam overshooting, even within fairly dense networks. Such limitations are most apparent in mountainous regions, which also feature hydrologically sensitive areas. A radar-gauge mosaiked product provides a reasonable aerial and time representation for the study area when it is compared with rain-gauges and radar-only products. US has more radar coverage than point rain-gauges. Thus, there are smaller sampling and random errors (Xie and Arkin, 1997) in using radar-gauge products than a relatively sparse and point rain-gauges. Therefore, radar-gauge rainfall product provides a more realistic advantage than rain-gauges to correct biases in satellite products.

The objective of the present study is to improve satellite rainfall products using a radar-gauge mosaiked rainfall product, thereby making them more suitable for blending with radar estimates. We also aimed at producing a satellite product with similar bias features as radar, so that it can be used in the absence of radar products. In our approach, the underlying assumption is that satellite rainfall biases are spatially variable. A spatially varying local bias correction has previously been implemented by Seo and Breidenbach (2002). In their approach, they used rain-gauges to correct radar rainfall estimates using the method of exponential smoothing. Their approach can also be usable to correct satellite products too. However, rain-gauges are point measurements and they are not always available in an extended spatial coverage. The accuracy of rain-gauge based methods can also depend on the number of rain-gauges reporting positive rainfall. Besides, rainfall differs from pixel to pixel, so does bias. Considering these problems and our goals, in this work, a pixel by pixel varying bias correction of satellite rainfall products using a radar-gauge product is implemented.

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In the process of bias correction, each hourly satellite product pixel will have a corresponding multiplication bias factor in the bias field. The bias fields are generated using randomly selected bias factors calculated from corresponding satellite and radar-gauge rainy pixels. To reduce sampling errors, bias factors selected for bias field generation should spread over the study area (Smith et al., 2006). A Monte-Carlo approach is applied to select bias factors spread over the study area. An exponential correlation function is applied to estimate the spatial covariance of bias factors. In the previous spatially varying local bias correction technique (Seo and Breindenbach, 2002), random errors have not been fully considered. In this paper, the effect of random errors in the bias factors is considered by imposing ensembles. For comparison, in addition to a spatially varying bias correction without ensembles, mean and maximum ratios as bias correctors are used. Operation products, namely hourly 4 km gridded satellite precipitation product, Hydro-Estimator (HE) and Stage-IV (ST-IV) radar-gauge data were used for the Oklahoma region for simulation and testing. Several cases of rainfall events for 2006 are simulated.

This paper is organized as follows. In Sect. 2, the satellite and radar-gauge data are described, including the study area. In Sect. 3, the overall approach of the model is described. This includes parameter estimation and generation of ensembles. Section 4 presents the results and provides interpretations and their implication. The last section offers the conclusion and recommendation for future work.

#### 2 Study area and data sets

Part of the Oklahoma state, south of the US, geographically bounded by 34°–37° latitude North and 94.5°–100° longitude West was selected for this study. The study location encompasses an area of about 136 000 km². The topographic elevation of the area ranges from 87 m (287 ft) near Little river to 1518 m (4973 ft) on Black-Mesa and its mean annual precipitation ranges 432 mm (17 inches) in Western high plain to 1296 mm (51 inches) in Ozark forest (Arndt).

Because of its rich meteorological rain-gauge network, the region and the watersheds inside the area have been served as a test bed for many climatological and hydrological studies. Besides, reliable radar rainfall estimates over the area can be obtained as a good network of ground based radars eliminates contamination of signals because of topographic features. This makes the area more important for our study to use the radar precipitation estimates to correct the satellite based estimates.

#### 2.1 Hydro-Estimator (HE)

There are several approaches to correlate cloud top brightness temperature provided by satellites with surface rainfall. One of the approaches, HE (Scofield and Kuligowski, 2003) uses GOES Infrared window channel-4 (10.7  $\mu$ m wavelength) as the main input data to estimate the rate of surface rainfall. Since satellite rainfall estimations are not direct, they are usually liable to systematic errors. HE is one of the data sets chosen to be corrected for systematic error in this study. At the (NOAA)/National Environmental, Data, and Information Service (NESDIS), HE has been operational and available for use at a spatial scale of 4 km by 4 km and time scale of as high as 1 h for the Continental US (CONUS) since 2002. For our study, hourly products at a spatial scale of 4 km by 4 km for the year 2006 have been used.

#### 2.2 Radar-gauge Stage-IV (ST-IV)

Radars have assisted rainfall estimations for more than four decades. The NEXt generation RADar (NEXRAD) system, the present network of 159 WSR-88 in the USA operated by the National Weather Service (NWS) under NOAA has been serving in weather prediction and precipitation estimations. The principles of Doppler radars for rainfall estimations are by converting the reflectivity (Z) of the radar signal backscattered by rain drops into rainfall estimates (R) by using non-linear power function. A comprehensive reference is available in (Doviak and Zrinc, 1984).

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In this study, it is assumed that quality controlled radar-gauge products can be used as reference precipitation estimation sources to correct systematic errors in satellite rainfall estimations. Hourly ST-IV, a radar-gauge mosaicked product over the CONUS with a spatial resolution of  $4 \times 4 \,\mathrm{km}$  for the year 2006 has been used in this study. It is produced by merging more than 3000 automated hourly rain-gauge observations and WSR-88D radar based digital precipitation arrays (DPA) (Fulton et al., 1998) product since 2001. ST-IV differs from its predecessor stage II; because of that ST-IV is manually quality controlled on one and six hourly basis by the NWS's 12 River Forecast Centers.

### 3 Methodology

Systematic errors, commonly known as biases are the deviation from the true value. Biases in precipitation prevail themselves in various forms. To mention two of them, there are spatial deviations and intensity deviations. In this study, only intensity deviations are considered. Sources of biases in radar can be improper *Z-R* relationship; evaporation of rain drops after they are intercepted by the radar signal, overshooting the cloud system, and mis-calibrated radar (Doviak and Zrinc, 1984).

HE and ST-IV data are polar-stereographic projection. They are converted to a regular grid of 4 km  $\times$  4 km resolution using the nearest neighborhood method. In our choice of the nearest neighborhood method, a pixel value is calculated by the mean of the values with in a search radius. In a 4 km grid, the search radius is  $\sqrt{2^2 + 2^2}$ , which is the radius of a circle that circumscribes a 4 km  $\times$  4 km grid.

According to (Anagnostou et al., 1998), mean bias field is defined as the ratio of the true mean area rainfall to the "biased" radar estimated mean-area rainfall and is given as: HESSD

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 $B_{h} = \frac{\sum_{i=1}^{n} G_{h}(x_{i})}{\sum_{i=1}^{n} R_{h}(x_{i})}$ (1)

where  $G_h(x_i)$  and  $R_h(x_i)$  are the gauge and radar measurements at location  $x_i$  and hour h. Following the same definition, a bias factor or ratio between radar-gauge and satellite products at a pixel level can be written as:

$$_{5} B(x_{k,h}) = \frac{R_{h}(x_{k})}{S_{h}(x_{k})}$$
 (2)

where  $R_h(x_k)$  and  $S_h(x_k)$  are the radar-gauge (the "true" measurement in this study) and satellite measurements, respectively, at location  $x_k$  and hour h.

The procedure of this bias correction starts with picking up corresponding rainy pixels for satellite and radar rainfall estimates, and calculate bias factors using Eq. (2). For better analysis and comparison, a pixel is considered as rainy if it registers a rainfall value of greater than 0.1 mm/hr. It is necessary to avoid selecting two closely located pixels as this creates unnecessary computational inefficiency, and it may also cause instability in the analysis algorithm when the closely located pixels have a significant difference in rainfall values.

A Monte-Carlo approach was used for randomly selecting the bias ratios spread over the study area. In a Monte-Carlo framework, independent and identically distributed (i.i.d) pixels in the study area are randomly chosen (Lemieux and L'Ecuyer, 2001). The process continues until we get the required number of pixels with positive bias factor values.

Satellite rainfalls have several hidden sources of errors. These uncertainties can be systematic that have not been considered in algorithm development. They can also be random errors that have stem from spatial variation of biases and/or detection of rainy/non-rainy pixels. Imposing ensembles of bias fields can be useful to account for

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various random error sources. We implemented ensembles in the generation of bias fields. Instead of having one bias field generated at a time, we will have a number of randomly generated bias field realizations known as ensembles (Mandel et al., 2009).

Following the acquisition of the required number of bias factors, the ensembles of bias factors were created by following a similar procedure as in (Mandel et al., 2009). This approach used Cholesky decomposition of the state covariance matrix to generate posterior ensembles in ensemble Kalman filter. Similarly, (Germann et al., 2006b) used Cholesky decomposition of the error covariance to generate ensembles of radar precipitation fields. The method was found to be flexible to the space-time dependence of mean, variance and auto-covariance of error in radar rainfall estimates (Germann et al., 2006b). Here, we adopted a similar approach to perturb the bias factors at known locations before we carry out the spatial interpolation for each ensemble members.

In our ensemble generation, let b be an n by 1 vector of the randomly chosen known bias factors. M is the initial perturbation matrix of size n by N, where N is the required ensemble size; and M is assumed to have the form:

$$M = O + G \tag{3}$$

**O** is a matrix of size n by N. The columns of **O** are replicates of  $\boldsymbol{b}$ . **G** is a random matrix variable assumed to be from  $N(0, \sigma^2)$ , a normal distribution with mean zero and unknown variance  $\sigma^2$ .

The initial perturbation matrix  ${\bf M}$  is multiplied by the decomposition of the spatial covariance matrix  ${\bf C}$  to produce new ensembles.

$$\hat{\mathbf{M}} = \mathbf{M} \cdot \mathbf{Q}; \ \mathbf{C} = \mathbf{Q} \cdot \mathbf{Q}^{T} \tag{4}$$

$$\mathbf{C} = \sigma^2 f(d_i - d_i) \tag{5}$$

where  $\hat{\mathbf{M}}$  is the new ensemble of bias factors,  $\mathbf{C}$  is a positive definite matrix of dimension n by n for  $f(d_i-d_j)$  representing a positive spatial correlation function.  $\hat{\mathbf{M}}$  is updated continuously for a new  $\sigma^2$ .

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$$f(d_i - d_j) = \exp\left(-\frac{|d_i - d_j|}{\eta}\right) \tag{6}$$

where  $(d_i - d_j)$  is the Euclidean separation distance in km between two bias factors indexed at i and j pixels, and  $\eta$  (km) is the range parameter.

The next step is to generate bias fields using each column of  $\hat{\mathbf{M}}$ . There are several spatial statistics approaches to generate spatial fields from the ensemble bias factors, including Linear, kriging, spline and inverse distance weight (Cressie, 1993). In this work, a multiplicative bias factor for the satellite rainfall product has been generated for each unknown pixel on an hourly basis using an Inverse Distance Weight (IDW) interpolation method given by (Shepard, 1968):

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$$b(x_{i,h}) = \sum_{k=0}^{n} \frac{W_{k,h}(x)}{\sum_{k=0}^{n} W_{k,h}(x)} b(x_{k,h})$$
 (7)

$$W_{k,h}(x) = \frac{1}{D(x_{i,h}, x_{k,h})^{\rho}}$$
 (8)

where  $D(x_{i,h}, x_{k,h})$  is the distance from the unknown bias factor pixel  $x_{i,h}$  to all known bias factor calculated pixels  $x_{k,h}$ . Values farther from a known value will tend toward the average of all the values (Shepard, 1968). p is the power parameter, n is the number of known bias factors at hour h. Finally the bias corrected satellite rainfall

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$$S_{\text{cor},i,h} = \sum_{j=1}^{N} \frac{S_{i,h} \cdot b_{i,h,j}}{N}$$
(9)

where  $S_{cor,i,h}$  is the bias corrected HE at hour h,  $S_{i,h}$  is the HE at hour h and  $b_{i,h,j}$  is the j-th member bias field at hour h. i is the pixel index in the rainfall field.

#### 3.1 Parameter estimation

Important parameters,  $\eta$ ,  $\sigma^2$  and p have to be optimized to produce unbiased results. Parameter estimation has been carried out routinely on a daily basis. Hourly radar and satellite estimates were aggregated for a 24 h before we take ratios of corresponding rainy pixels for parameter estimation. This is under the assumption that meteorological variables like wind speed, dew point temperature, cloud height and others that have significant influences on radar and satellite rainfall estimation have less variation in a single day. In an operational set-up, the parameters can be estimated using the duration of the previous rainy hours. Parameters can also be estimated on hourly basis.

Because of computational cost of the analysis of ensembles and their mean values, it was difficult to optimize the three parameters at the same time. Therefore, optimization was achieved by optimizing a single parameter at a time, whilst the others were kept constant. For parameter determination, an optimization algorithm, shuffled complex evolution optimization (Duan et al., 1993), originally developed for hydrologic modeling was used. Optimum values for parameters were achieved based on minimizing the objective function, the Root Mean Squared Error (RMSE) between the radar-gauge and mean ensemble bias corrected satellite rainfall estimates for a 24 h rainy period (see Eq. 10).

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where n is the number of corresponding rainy pixels, and R is ST-IV radar product. Ideally, this value should be as small as zero. But for analysis that involves higher order mathematics, like this one, for practical reasons, it is not possible to attain.

The few number of undetermined parameters makes this approach efficient. In addition, it takes into account the spatial variation of biases, for each pixel. For comparison, ratios of mean and maximum were used as bias factors to correct HE. It is expected that this approach is more robust than the traditional mean and maximum ratio bias factor estimators.

#### 4 Results and discussion

In the literature, most of the bias corrections of satellite and radar rainfall estimates were carried out using rain-gauges as "true" observations, and again, these methods are mean field and local mean field bias techniques. Mean field biases consider a constant bias factor in a study area and do not consider spatial variation of biases. It is known that rain-gauges are limited in spatial coverage and sampling, and biases are spatially varying. Since, radar-gauge provides a better spatial coverage and statistical sampling; here we attempted bias correction of satellite rainfall estimates using radar-gauge rainfall products as "true" estimates. The method of using radar-gauge estimate to correct satellite rainfall products is explained in the previous section. The detailed assessment of the performance of the method (the method of ensembles here after), to correct biases in satellite rainfall estimates is provided in this part. Also, the performance of the method of ensembles is compared with bias corrections by interpolation, the method of mean and maximum ratios as bias factors.

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Here, the process of the bias correction using the method of ensembles involves obtaining the optimized model parameters: namely, the range  $(\eta)$ , the power (p) and the variance  $(\sigma^2)$  based on 24 h aggregates of satellite and radar-gauge rainfalls. The objective function in Eq. (10) was minimized using the SCE (Duan et al., 1993) for 5 each rainy event to obtain the parameters. Four representative 24 h rainy events of year 2006, one from each of the four seasons were chosen for model evaluation. To assess wintertime performance, which for satellite precipitation estimation is generally poor, an additional winter case was chosen for overall evaluation of the model. The second and the last rainy events of the five events listed in Table 1 represent winter cases; event 1 is spring case; event 3 is summer; and event 4 is fall case.

For each rainy event, Table 1 lists the optimal values of the three parameters, range  $(\eta)$ , variance  $(\sigma^2)$  and power (p). As can be seen in Table 1, these parameters vary from one rainy event to another. The range parameter shows a significant variation from storm to storm; where as the variance shows moderate variation. The variance range was from 0.5 for event 5 to 1.19 for event 4. The lowest power parameter of 2.7 was observed for event 5 while a maximum value of 4.44 was observed for event 1. Similarly, the range parameter varies from 4.43 for event 2 to 8.55 for event 5.

After obtaining model parameters, the sensitivity of these parameters had to be checked. To investigate the influence of the parameters in the bias correction model, we plotted the RMSE versus the respective parameter for rainy hour 06071022 (YYM-MDDHH). Figure 1 shows the response of the bias model in RMSE for variation of each parameter around their optimal values. The sensitivity of parameters was checked by varying each parameter about their optimal values by 10%, while keeping the rest of them fixed. The model was insensitive to the power parameter up to a power of 4.5. For p values greater than 5, the model is acutely sensitive and RMSE value decreased steadily. High value of power parameter in IDW is associated with sharp variation among the interpolated pixels (Shepard, 1968). This suggests the complex nature of spatial distribution of rainfall biases that cannot be represented by a lower power function, which is a smooth interpolation. The range parameter that influences the spatial

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correlation function shows a remarkably steep decline in RMSE for values less than 4 km. However, it is not practical to use a range value less than 4 km because the study area is a 4 km spatial grid. The model is relatively insensitive for a range value of 4 to 7 km. However, there is a steep gradient change in RMSE for a range value 5 of greater than 7 km. This shows that the exponential correlation function Eq. (6) diminishes quickly for a range value of more than 7 km, which implies the relationship between two rainy pixels located at a distance of more than 7 km is insignificant.

Following optimization and sensitivity analysis of model parameters for each rainy event, the method of ensemble bias correction was employed as follows. (a) Ratios of hourly corresponding rainy pixels between the radar-gauge and the satellite rainfall estimates were calculated. (b) A maximum of 150 bias ratios depending on the areal coverage of storms were randomly picked up (see Fig. 2) for analysis. (c) Based on the bias correction method using ensembles explained in the Sect. 3, hundred realizations of bias fields were generated for each rainy hour using the selected bias ratios and the optimized parameters for each 24 h event period (Fig. 3b). (d) Hundred simulated bias corrected HE for each hour were obtained by multiplying the original satellite product with each generated bias field realizations, or bias field ensemble member. (d) The mean of the hundred realizations that represents the final bias corrected HE using the method of ensembles (Fig. 3c) is calculated using Eq. (9).

The corrected satellite rainfall estimate using the method of ensembles was checked for its performance by comparing it with other bias correction techniques. The method of interpolation, the mean ratio and maximum ratio were taken as the bias correction factors for comparison. The method of mean ratio works by multiplying the original HE by the ratio of hourly mean of radar-gauge estimation to hourly mean of the satellite estimation. Similarly, the method of the ratio of maximums works by multiplying HE by the ratio of hourly maximum rainy pixels between the radar-gauge and the satellite estimation irrespective of their location. The bias fields in the method of interpolation are generated using Eq. (7) without ensembles. Note that the only parameter that involves in the interpolation method is p.

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A rainy hour that shows the method of maximum and mean ratio bias correction is displayed in Fig. 3a and b, respectively. As shown in Fig. 3a, the satellite estimate corrected using the maximum ratio method gave a better estimate in correcting high rainfall pixel values when it is compared with ST-IV. The output from the ratio of means method (see Fig. 3b) shows slight improvement from the original satellite rainfall output (Fig. 3d). Figure 3c displays the bias corrected HE using the method of ensembles. As shown in the figure, the distribution of rainfall in Fig. 3c is more alike in Fig. 3d.

Further statistical quantification was done to evaluate the performance of the individual bias correction techniques. Table 2 compares the performance of bias correction using the ratio of means, ratio of maximums, interpolation method and the method of ensembles. The table summarizes the statistical measurements RMSE, Correlation Coefficient (CC) and absolute bias for five rainy hours each from the rainy events in Table 1. The statistical measurements are defined as:

Hourly absolute bias,

$$\sum_{j=1}^{M} |S_{cor} - R|_{j}$$
Absolute BIAS = 
$$\frac{\sum_{j=1}^{M} |S_{cor} - R|_{j}}{M}$$
(11)

where j is the grid index, M is the number of all corresponding rainy pixels. The hourly Root Mean Squared Error (RMSE),

$$RMSE = \sqrt{\frac{\sum_{j=i}^{M} (S_{cor} - R)_j}{M - 1}}$$
(12)

The hourly Correlation Coefficient (CC) between the bias corrected satellite and radar-gauge rainfall estimates for corresponding rainy pixels,

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where COV(.) is the covariance of the radar-gauge rainfall estimates and the bias corrected satellite estimates. VAR(.) is the variance of the rainfall estimate.

Table 2 shows that RMSE, CC and the absolute bias, vary from one case to another. For comparison, Table 2 also includes the mean and standard deviation (STDEV) of ST-IV. In terms of RMSE, the performance of the method of mean ratio and maximum ratio correction techniques are comparable. RMSE before and after bias correction using the method of mean and maximum ratios are the same. On the other hand, the method of ensembles has improved the RMSE between the original satellite rainfall estimation and ST-IV by 8, 25, 17, 54 and 37.2 percent in cases I, II, III, IV and V, respectively. The absolute bias measures the mean absolute bias improvement in the different techniques at a pixel level better than the non-absolute bias parameter. The mean ratio bias correction method improved the absolute bias in the original estimation better than the other bias correction methods in cases II and III. For cases, I, IV and V the method of ensembles improved the absolute bias in the original estimation better than the rest of the methods. The methods of mean ratio and maximum ratio have helped to improve biases in intensities. However, they fail to address the correlation coefficient correction.

Figure 4a, b, c, d and e illustrates scatter plots of rainy hours 06071022, 06020704, 06091017, 06122917 and 06031906, respectively. They are scatter plots for randomly chosen hours in each rainy event shown in Table 1. The right side of Fig. 4 represents the scatter plot after bias correction and the left side represents scatter plots before bias correction. For each hour, the correlation coefficient was calculated to evaluate the performance of the bias correction approach and is shown at the left top of the figure. The correlation coefficient between the HE and ST-IV before bias correction ranged from –0.13 to 0.65. The percentage in improvement of the correlation coefficient varies from case to case. HE has shown significant improvements after bias correction was made

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using the method of ensembles. For instance, for hour 06071022, the bias correction improved the CC between HE and ST-IV by 20%. For cases with already higher correlation coefficient between the radar-gauge and original satellite estimates, a lower percentage of improvement was observed than the ones with low correlation between the original HE and ST-IV. The scatter plots indicate that the model has effectively improved the satellite estimation in randomly picked hours in every season. At times because of the weak performance of satellite rainfall estimations in the cold season a much weaker relationship was observed between the satellite and radar-gauge rainfall estimations with a correlation coefficient -0.1 (see Fig. 4). Yet the performance of the ensemble bias correction is accomplished in such poor condition of rainfall detection in satellites.

In addition to the statistics explained in the above paragraphs, it was worthwhile to examine the performance of the bias correction techniques in a time series framework. Four pixels were randomly selected from each season, and their 24 h rainfall time-series were depicted from Figs. 5 to 8. The pixels were selected in such a way that they were raining for a representative duration for the rainy events listed in Table 1. Figures 5, 6, 7 and 8 are time series for the selected pixels for events 1, 2, 3 and 5, respectively. We could not identify a rainy pixel for long enough duration to show the significance of the time series for event 4. Each figure shows the time series of accumulated hourly rainfall of ST-IV, HE, 100 ensemble members of the model, the mean bias corrected HE using the method of ensembles and bias corrected HE using interpolation for the chosen pixel. The gray crosses represent the hundred ensemble members simulated using the ensemble bias correction method for the respective pixels in rainv events, whereas the red circles and the cyan triangles represent the original HE and ST-IV estimations, respectively, the blue square represents a bias corrected HE using interpolation without ensembles. The green circles are the mean of the hundred gray crosses (ensemble members). As shown in the figures, the green circles (mean of the ensemble members) are closer to the cyan triangles (ST-IV estimates or "true" estimates). Figure 5 shows that the mean of the ensembles reduced the over-estimation

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made by the original HE at hours 8, 9 and 10, and improved the underestimation at hours 13 and 14. Similar outputs were observed for cases in Figs. 7 and 8. In Figs. 7 and 8, the ensemble bias correction technique improved the satellite rainfall estimation in such a way that the discrepancies between the radar-gauge and satellite rainfall estimates are reduced. In Fig. 7, the method of ensembles over-estimated the rainfall at hour 24 and 25.

The results discussed in this part of the paper showed with parameters as few as 3, the method of ensembles as a bias correction method is flexible, time independent and has a potential use in rain-gauge sparse area.

#### **Summary and conclusion**

The results of this work showed a pixel by pixel bias correction approach under spatially varying bias factors, as opposed to the mean field and maximum ratio approaches. For improved spatial coverage and sampling, instead of rain-gauge measurements, a radar-gauge mosaicked rainfall product is used to correct satellite rainfall estimation. This approach is highlighted and tested using five rainy events in 2006 for the Oklahoma region. Simulation and verification of the method is performed based on these events. We note that the rainy events are selected to represent all seasons during a year. Prior to generating bias fields, bias factors were calculated for hourly corresponding rainy pixels. Based on the storm size, bias factors were randomly selected over the study area using the Monte-Carlo approach. The Monte-Carlo framework helped a uniform distribution of bias factors throughout the rainy event.

For parameter estimation, 24 hourly accumulated HE and ST-IV were used. Parameter estimation was carried out using the Shuffled Complex Evolution Optimization Algorithm (Duan et al., 1993) to satisfy the objective function (see Eq. 10). Results of this work suggested that the power parameter affected the Inverse Distance Weight (IDW) interpolation; variance affected the distribution of the ensembles and the covariance correlation function; and the range affected the correlation distance among the

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rainy pixels in radar-gauge and satellite products. The sensitivity of parameters was checked by varying one parameter by 10% around its optimal value whilst keeping the others constant. Results show that all the parameters seem to affect the model equally. As one of the efficiencies of the method, it was shown that every 24 h update of parameters was sufficient to adjust biases in hourly satellite products. Once the parameters were obtained, ensembles of bias factors were imposed to accommodate random errors in bias factors.

The performance of the proposed bias correction method was evaluated using RMSE, Absolute bias and correlation analysis. These statistical parameters were calculated between the radar-gauge and the satellite products before and after bias correction using the different bias correction techniques mentioned in this paper. When it is compared with the methods of the ratio of mean, interpolation and maximum ratio, the proposed method in this paper (method of ensembles) outperform the rest. The method produced a correlation coefficient of 90% in one case while the other techniques did not show much improvement in the satellite product. Finally, a time series for four randomly picked pixels were checked before and after bias correction. Results show the proposed method significantly reduced the discrepancies in the time series. Even if the rainy hours were treated separately, the method produced results that emulate as if they were from the same time-series analysis. This implies that our method is robust and can be applied for independent rainy hours by calculating the required parameters at hourly levels.

By adjusting biases in satellite products, we produced radar-gauge like satellite rainfall products. This has a considerable advantage in producing radar like products in radar gaps and radar outages. During radar outages, this approach can provide radar like products using radar data from the previous hour and satellite product from the present hour. Most importantly, this work is applicable to correct biases where raingauges are sparse and unavailable. Furthermore, the method can complement the existing operational bias corrections, which are rain-gauge based.

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The major results of this work suggest that satellite intensity biases can be corrected using radar products so that satellite estimates can be used in operational set-up. However, a companion study will look at spatial discrepancies (spatial biases) between the satellite and radar rainfall, which was not addressed in this work.

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**Table 1.** Optimized parameters for the five rainy events in 2006.

		Parameter		
Rainy Event	Rainy Period (YYMMDDHH)	Range (η)	Variance $(\sigma^2)$	Power (p)
1	06031818-06031918	6.87	0.75	4.44
2	06020605-06020705	4.43	0.75	4.07
3	06071021-06071121	6.58	0.85	3.23
4	06091008-06071121	6.59	1.19	4.09
5	06122902-06123002	8.55	0.50	2.70

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**Table 2.** Statistical outputs for five rainy hours each from the five rainy events.

Statistics	Methods	Case I 06071022	Case II 06020704	Case III 06091017	Case IV 06122917	Case V 06031906
Mean (mm)	ST-IV	4.33	2.1	2.41	1.18	1.53
STDEV(mm)	ST-IV	6.60	3.90	3.59	1.44	1.59
RMSE(mm)	Original	5.780	3.744	4.936	3.750	2.552
	Mean ratio	5.780	3.744	4.936	3.750	2.552
	Max ratio	5.780	3.744	4.636	3.750	2.552
	Interpolation	4.301	3.900	4.720	1.330	1.652
	Ensemble fields	5.338	2.802	4.098	1.708	1.596
Absolute	Original	3.918	2.760	2.810	2.706	1.744
Bias(mm)	Mean ratio	3.920	1.845	3.192	1.312	0.610
	Max ratio	4.667	3.634	8.990	3.912	1.037
	Interpolation	2.720	1.400	3.601	1.750	0.760
	Ensemble fields	3.733	4.612	5.761	1.212	1.034
CC	Original	0.650	0.668	-0.01	0.360	0.06
	Mean ratio	0.650	0.668	-0.01	0.360	0.060
	Max ratio	0.650	0.668	-0.01	0.360	0.060
	Interpolation	0.800	0.840	0.420	0.540	0.450
	Ensemble fields	0.840	0.890	0.430	0.610	0.570

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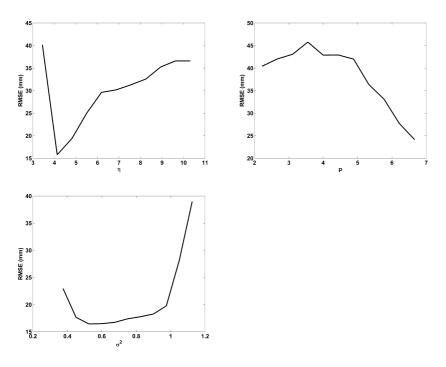
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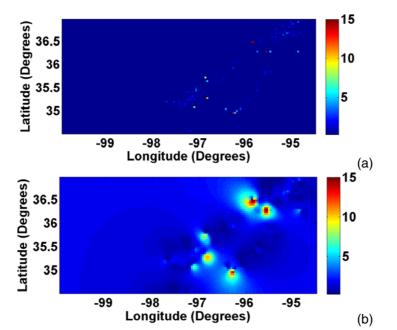
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**Fig. 1.** Parameter sensitivity check for the range  $(\eta)$ , the power (p) and the variance  $(\sigma^2)$ .



**Fig. 2. (a)** 150 randomly chosen bias factors between the radar and satellite for hour 06071022. **(b)** A randomly generated ensemble bias field using the 150 bias ratios.

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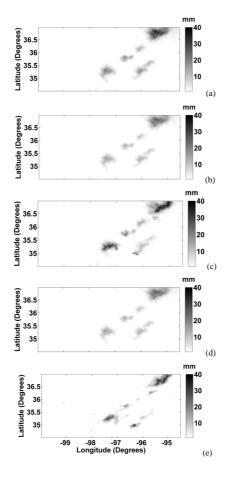


Fig. 3. A bias corrected satellite estimate at hour 06071022 using (a) Maximum ratio, (b) Mean ratio (c) Ensemble bias field (d) the original HE, (e) ST-IV.

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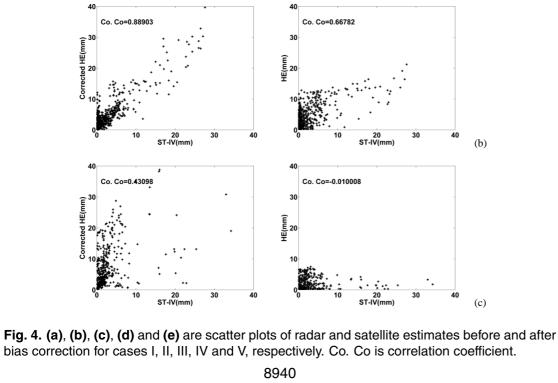
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Co. Co=0.64887

20 ST-IV(mm)

(a)

(m m) 20

30

ST-IV(mm)

Co. Co=0.8432

Corrected HE(mm)

bias correction for cases I, II, III, IV and V, respectively. Co. Co is correlation coefficient.

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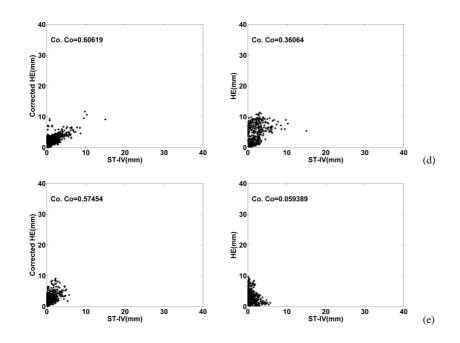
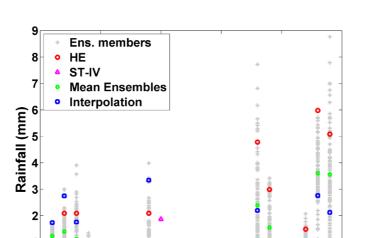


Fig. 4. Continued.



**Fig. 5.** Time series of HE, ST-IV, bias corrected HE using Ensembles (Mean members), 100 realizations of ensemble members (Ens. members) for event 1.

Time (hr)

15

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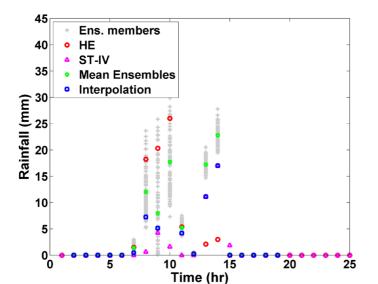
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**Fig. 6.** Time series of HE, ST-IV, bias corrected HE using Ensembles (Mean members), 100 realizations of ensemble members (Ens. members) for event 2.

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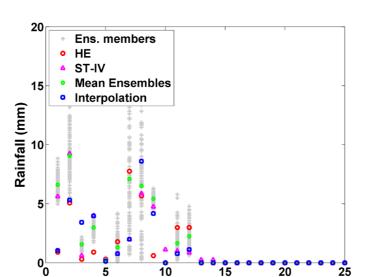
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**Fig. 7.** Time series of HE, ST-IV, bias corrected HE using Ensembles (Mean members), 100 realizations of ensemble members (Ens. members) for event 3.

Time (hr)

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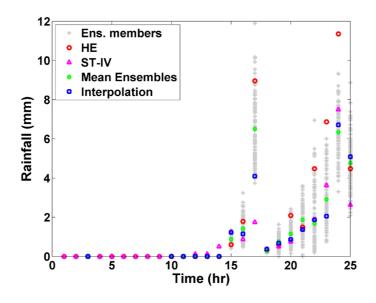


Fig. 8. Time series of HE, ST-IV, bias corrected HE using Ensembles (Mean members), 100 realizations of ensemble members (Ens. members) for event 5.