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Towards a nonlinear radar-gauge adjustment of radar *via* a piece-wise method

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ABSTRACT: The use of radar to provide rainfall estimates is becoming more attractive, especially with the number of rain-gauges in operation reducing year on year in many countries. However, while radars give very good spatial representations of rainfall, they tend to underestimate rainfall when compared to rain-gauges, for the selected area. To improve the accuracy of radar estimates, they are usually adjusted by comparing the radar and rain-gauge estimates. Most of the adjustment methods consist of either using a value that may or may not vary with distance from the radar, or by varying the Z–R relationship. With the exception to the methods that involve varying the Z–R relationship, the effects of rainfall intensity on the adjustment factor are ignored. Two new methods that take into account the variability in the intensity of rainfall are proposed: one that varies the adjustment value based on discrete intensity bins and the other varies continuously. The proposed method is shown to be better than uniform adjustment in both calibration and validation in split-sample tests.

KEY WORDS radar rainfall; gauge adjustment; QPE

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1. Introduction

For catchment modelling and flood forecasting, weather radar precipitation estimates can have a number of advantages over estimates derived from rain-gauges. Weather radar has the ability to observe precipitation with both high spatial and temporal resolutions (Dalezios, 1988; Steiner *et al.*, 1999; Borga, 2002) even in difficult terrain (Joss and Waldvogel, 1990; Pellarin *et al.*, 2002; Morin and Gabella, 2007), which is unmatched by most conventional rain-gauge networks (Overeem *et al.*, 2009). However, radar rainfall estimates are subject to a large number of sources of error, including ground clutter, sampling and smoothing, calibration of the radar, anomalous propagation, attenuation, vertical structure of the precipitation, updraft and downdraft and incorrect Z–R relationships (Wilson and Brandes, 1979; Zawadzki, 1984; Collier, 1989; Joss and Waldvogel, 1990). Thus, it is generally accepted that radar estimates of precipitation require some numerical adjustment and that this is best done with rain-gauge estimates that are regarded as closer to 'ground truth', i.e. giving estimates close to the actual rainfall amount. Although Barnston (1991) suggests that when radar measurements are available rain-gauge measurements should not be regarded as ground truth unless an 'exceptionally dense' rain-gauge network is available, nevertheless the adjustment of radar rainfall estimates using rain-gauge data generally improves the accuracy of the radar rainfall estimates compared to the raw unadjusted radar (Borga *et al.*, 2002; Einfalt *et al.*, 2005; Zhang and Srinivasan, 2010). There is a large number of existing gauge adjustment methods, for example, a single adjustment (Wilson, 1970; Steiner *et al.*, 1999; Holleman, 2007), spatial adjustments (Brandes, 1975; Collier, 1989; Michelson and Koistinen, 2000) or a probability-matching method (Rosenfeld *et al.*, 1993; Rosenfeld and Amitai, 1998). Other research suggests varying the underlying Z–R relationship with time (Alfieri *et al.*, 2010) and that greater flexibility is required in applying the Z–R relationship both temporally and spatially (Fox and Collier, 2000). Other approaches are possible, for instance (1) Michelson *et al.* (2005) describe a method called 'Down to Earth' that combines radar data with data from numerical weather predication models, and (2) Cummings *et al.* (2009) described a procedure to adjust radar data using information on the performance of microwave links.

In this study the established practice of using a number of point rain gauge measurements to adjust the spatial radar estimates of precipitation is re-visited and a new adjustment method is proposed that retains the simplicity of existing methods and has shown promising performance in Irish catchments. This is a single adjustment factor applied to the entire radar field. Its novelty is that the adjustment factor is non-linearly related to the measured radar rainfall intensity. The paper describes two different ways of implementing the relationship: (1) as a piece-wise linear framework, and (2) as a direct nonlinear equation. While the use of nonlinear methods is not new, for instance Rosenfeld *et al.* (1993) developed nonlinear Z–R relationships from high quality disdrometer data, the present nonlinear method can be easily applied to the type of radar rainfall products typically available to end-users. This is important for hydrologists as they usually have access to two dimensional radar rainfall intensities and not the three dimensional reflectivities that are typically available to the meteorologist. In this paper, this new procedure is described and its performance is compared to three existing adjustment methods based on fixed adjustment factors.

2. Data and method

2.1. Data

The radar rainfall data used for this study were provided by Met Éireann from a C-band radar located at Dublin Airport. The characteristics of the Dublin Airport radar are listed in

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Table 1. Technical characteristics of the Dublin Airport radar.

Characteristic	Value
Position	6° 14 ′ W, 53° 26 ′ N
Frequency	5640 MHz (Wavelength = 5.3 cm; C-Band)
Transmitter power	250 kW
Pulse repetition frequency	250 p.p.s.
Scan rate	2 or 3 r.p.m.
Antenna size	4.2 m diameter
Beam width	1°
Maximum range	600 km
Useful range	250 km
Max. detectable wind speed	48 m s^{-1} (= 100 knots)
Max. range for wind	120 km
No. of elevation scanned	10 (0.5–15°)
Scan schedule	10 elev. reflectivity measurement every 15 min at 240 km 10 elev. Doppler rain/wind every 15 min at 120 km 1 elev. rain intensity every 15 min at 480 km

Table 1. From this radar, Met Éireann produce a number of radar visualization products and the precipitation accumulation (PAC) product is used in this study. It is a variation of the Constant Altitude Plan Position Indicator (CAPPI) product. The PAC product precipitation estimates for a 1 km square mesh at an altitude 1 km above the topographical surface and, for the Dublin radar, has a maximum effective range of 70 km. The PAC product has built-in algorithms to correct for signal attenuation, due to atmospheric gases, with distance (Gematronik, 2003). The output of the PAC model is rainfall intensities measured in mm h^{-1} and is obtained by using a constant Z–R relationship of $Z = 200\mathrm{R}^{1.6}$.

Rain-gauge data for gauges within the radar coverage were also obtained from Met Éireann. Initially 44 daily rain-gauge locations were identified for use in this study; however, this number was reduced to 20 based on: (1) distance from the radar; (2) the amount of missing values, and (3) similarity of patterns of wet and dry days to the radar. Figure 1 shows the selected rain-gauge locations with respect to the Dublin Airport radar and the 70 km range of the radar. All rain-gauges used in this study are located to the north and west of the radar, this is a relatively flat area of Ireland (see Figure 1) where shielding and beam blockages are not an issue. To illustrate that shielding and beam blockages are not an issue in this area, the accumulation of the radar precipitation estimates over the calibration period is shown in Figure 2.

2.2. Existing method – uniform adjustment factors

Most currently used gauge adjustment methods use a uniform adjustment factor determined from a comparison of past radar estimates with corresponding rain-gauge data. Here tests of a number of them provide a baseline with which to compare the new proposed nonlinear method. It should be noted as only daily rain-gauge data are available with the range of the radar product all analysis is performed using a daily time-step. The three different, existing, methods that are compared with the proposed new method are:

1. Method 1 (A_{U1}, Equation (1)) which adjusts each observation with a factor which is the time-series averaged ratio of the total radar rain-gauge observed depths summed over the entire domain to the corresponding summation of the radar precipitation estimated at collocated radar bins.
2. Method 2 (A_{U2}, Equation (2)) which calculates an adjustment factor for each observation and uses the average of these to adjust the radar, and,
3. Method 3 (A_{U3}, Equation (3)) which uses a weight which is the ratio of the totals of the radar and rain-gauge data.

$$A_{U1} = \frac{1}{n}\sum_{1}^{t=n}\left[\frac{\sum_{1}^{i=N} G_{i,t}}{\sum_{1}^{i=N} R_{i,t}}\right] \tag{1}$$

$$A_{U2} = \frac{1}{n}\sum_{1}^{t=n}\left[\frac{1}{N}\sum_{1}^{i=N}\frac{G_{i,t}}{R_{i,t}}\right] \tag{2}$$

$$A_{U3} = \frac{\sum_{1}^{t=n}\sum_{1}^{i=N} G_{i,t}}{\sum_{1}^{t=n}\sum_{1}^{i=N} R_{i,t}} \tag{3}$$

Where $G_{i,t}$ denotes the precipitation accumulation during one time period (t) at rain-gauge i and $R_{i,t}$ denotes the precipitation accumulation during the corresponding time period in the 1 km square radar pixel corresponding to the location of rain-gauge i, estimated from the raw radar rainfall intensity data. The variable n denotes the total number of time-steps used and N denotes the total number of rain-gauges.

Although straightforward in principle, implementation must take account of rain-free days which can degrade the calculation of the adjustment factor because the radar may still estimate a small amount of precipitation for these days. For this reason, the summations in calculating the adjustment factor are taken only for the time-steps where $G_{i,t}$ and $R_{i,t}$ are greater than a predefined minimum threshold, thus ignoring rain-free days. However, this means the value of the adjustment factor also depends on the choice of this threshold. To show this dependency, each adjustment factor is calculated with a range of different thresholds from 0.0 to 5.0 mm day^{-1}, Table 2, and all are compared with the proposed method. While this increases the number of 'baseline' cases in the comparisons and in Table 2, it does allow the best possible baseline performance to be compared with the new proposed nonlinear method.

2.3. Proposed piece-wise adjustment factor (PWAF) method

The proposed new piece-wise adjustment factor is not a constant but is determined at each time step as a function of the magnitude of the radar rainfall estimate for that time step. This new procedure was first developed as a piece-wise adjustment factor (PWAF), in which the range of radar time-step accumulations is divided into a pre-determined number of intervals, based on

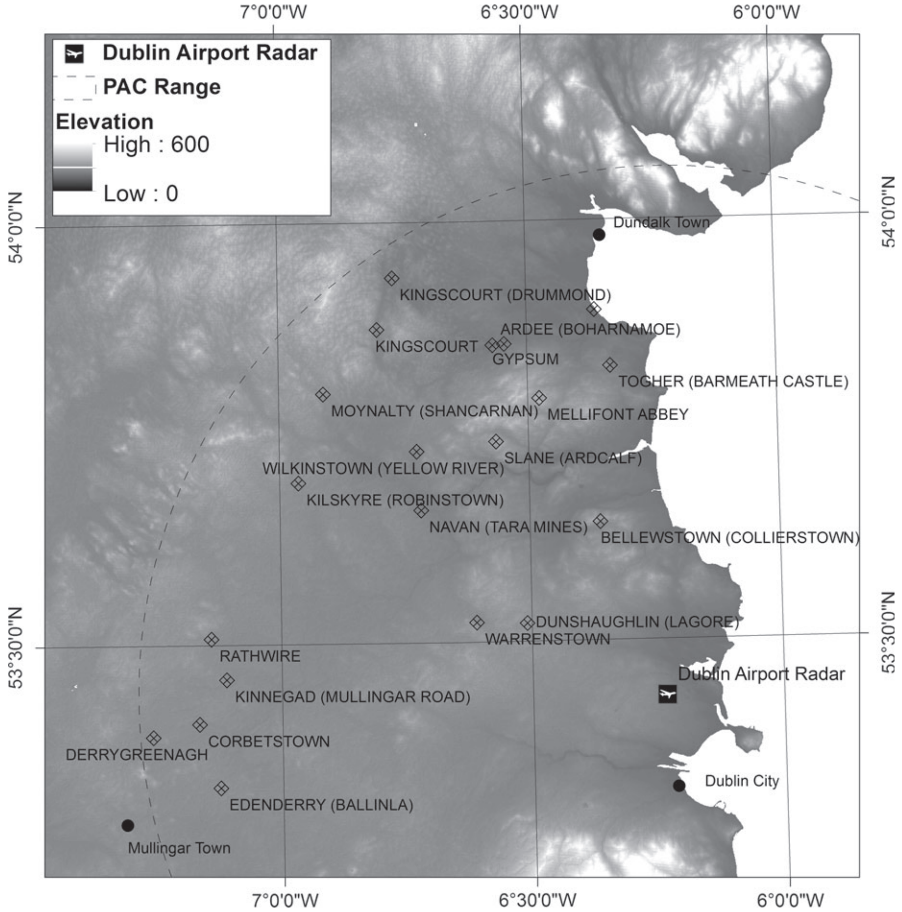

Figure 1. Rain-gauge locations with respect to the Dublin Airport radar, Dublin city, Mullingar and Dundalk Towns (the dashed line shows the 70 km range of the radar precipitation product).

the amount of precipitation and, for each interval, a separate, constant, adjustment factor is determined from the data falling within the range of that interval. For each time-step, the radar rainfall accumulations are assigned to one of these intervals and are compared with the corresponding measured rain-gauge accumulation for that time-step. An adjustment factor is calculated for each of the intervals using one of the equations (Equations (1)–(3)) used above for the uniform adjustment factors. Not surprisingly, the performance of the method is influenced by the number and magnitude of the intervals used. To thoroughly test the proposed method, three different arrangements of interval bins (A, B and C) are tested in this study, two contain five intervals with different limits and the other with four intervals. Table 3 shows the intervals, together with the percentage of the total number of radar observations assigned to each interval. Essentially, a different adjustment factor is estimated for each range of precipitation magnitude (as determined by the radar). Using each of these with one of the three equations (Equations (1)–(3)) gives nine different variations of the method (Table 4). PW1–PW3 use the first set of intervals, PW4–PW6 use the second set of intervals and PW7–PW9 use the final set of intervals. The thresholds indicated in Table 3 are only applied to the radar rainfall estimate.

2.4. Comparison metrics

Comparisons between the proposed piece-wise rain-gauge rainfall estimate and the gauge rainfall estimates were done using three different metrics, the mean residual error (MRs, Equation (4)) i.e. the bias, the mean absolute error (MAE, Equation (5)) and the root mean square error (RMSE, Equation (6)).

$$MRs = \frac{1}{n}\sum_{t=1}^{n}\frac{1}{N}\sum_{i=1}^{N}\left(R_{i,t} - G_{i,t}\right) \tag{4}$$

$$MAE = \frac{1}{n}\sum_{t=1}^{n}\frac{1}{N}\sum_{i=1}^{N}\left|R_{i,t} - G_{i,t}\right| \tag{5}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\frac{1}{N}\sum_{i=1}^{N}\left(R_{i,t} - G_{i,t}\right)^2} \tag{6}$$

2.5. Split sample tests

The data used in the study were divided into two independent data sets, one for calibration and the other for validation. The calibration of the adjustment estimate was performed for the period 1 October 2006 to 30 September 2007 (365 days) and the validation of the resulting adjustment estimates was undertaken for the period between 1 October 2007 and 17 May 2009 (595 days). The use of two independent data sets allowed the robustness of the adjustment estimates to be studied as the best adjustment method would have to perform well for both the calibration and validation period.

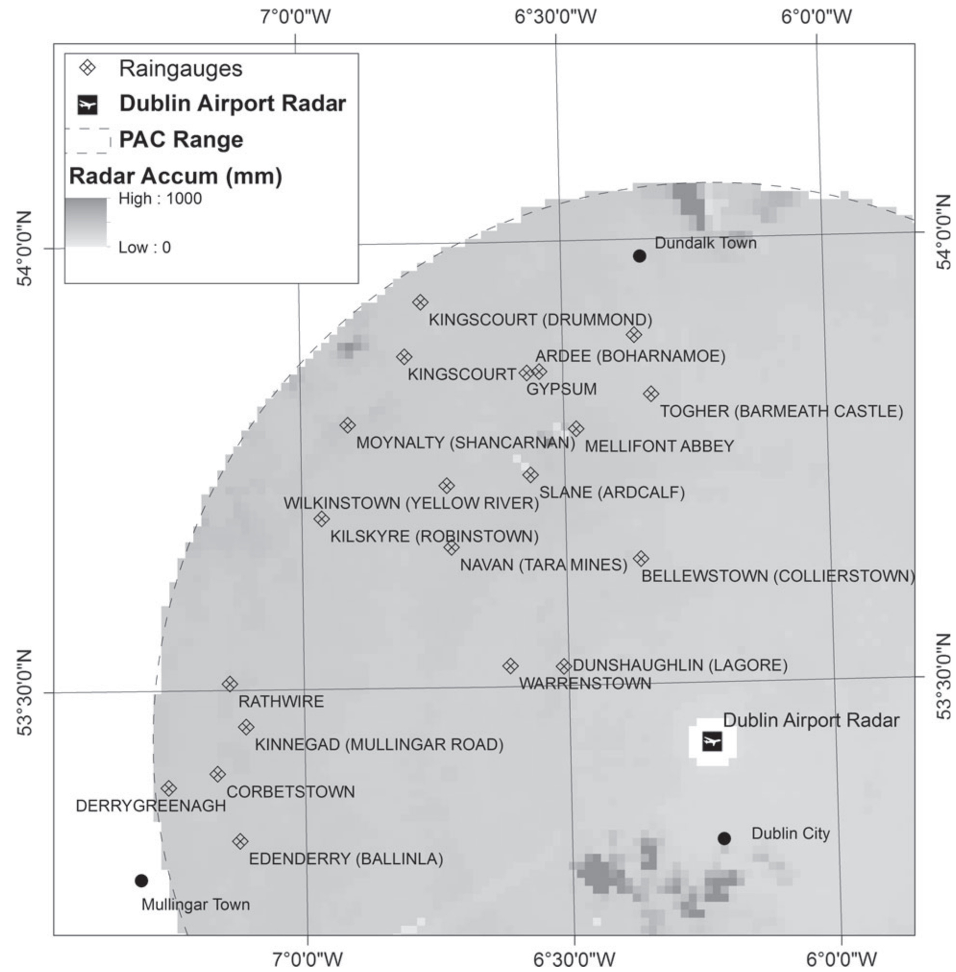

Figure 2. Radar precipitation estimate accumulation of the calibration period (1 October 2006 to 30 September 2007).

3. Comparison of PWAF and uniform methods

3.1. Comparison with respect to adjustment factor values

Tables 5–8 show the calculated adjustment factors with respect to: (1) the method used, and (2) the minimum threshold values used in calculation of the adjustment factor.

The effect of using different magnitude ranges when calculating adjustment factors is clearly visible. For both the uniform adjustment factors and the adjustment factors produced by the PWAF method, there is a clear relationship between the magnitude of the adjustment factor and the radar rainfall intensity. The value of the adjustment factor decreases monotonically with an increase in the radar precipitation values (Figure 3). This implies that the relative deviation of the radar from actual rainfall amounts is greater for the lower intensity rainfalls and less for the higher intensities. The factor is much greater than 1.0 for the lower intensities, indicating an underestimate by the radar, and can be 1 or less for the higher intensities (generally > 5 mm day^{-1}), indicating a slight overestimate by the radar.

For the PWAF method, the size of the intervals also has an impact on the adjustment factor. For example, using the adjustment factors calculated using method 1 (i.e. PW1, PW4 and PW7) for radar rainfall estimates less than or equal to 5 mm day^{-1}, if a single interval is used (PW7), then all values less than or equal to 5 mm day^{-1} would be multiplied by a factor 9.867, Table 8; however, if the same range is split into two intervals (PW4), the radar rainfall less than or equal to 1.0 mm day^{-1} is multiplied by 13.959 and the remaining radar rainfall estimates less than or equal to 5.0 mm day^{-1} would be multiplied by 2.750 (Table 7). The same pattern is observed for PW1, where three intervals are employed, the lower the rainfall estimate, the higher is the corresponding adjustment factor for that interval range.

The influence of the different equations for calculating the adjustment factors is also clearly seen in Tables 5–8. For uniform adjustments, Equation (3) (AU3) produces the smallest adjustment factors for all the minimum threshold values used and also results in the smallest variation between the threshold values with a value of 67% of the smallest value. Equation (2) (AU2) produces the largest adjustment factors for the majority of the thresholds and also has the largest variation with 840%. Note Equation (1) (AU1), gives slightly smaller adjustment factors than method 2, with the exception when the minimum threshold is 5.0 mm day^{-1} which produces the largest adjustment factor. The variation between maximum and minimum values for Equation (1) is 441%.

For the PWAF method, the results follow a pattern similar to the uniform methods up to the threshold of 5.0 mm day^{-1}, with Equation (3) giving the smallest adjustment factors and Equation (2) giving the largest adjustments. However, for radar rainfall estimates above the 5.0 mm day^{-1} threshold, the pattern is reversed with Equation (3) giving higher adjustment factors and Equation (1) producing the smallest adjustment factors.

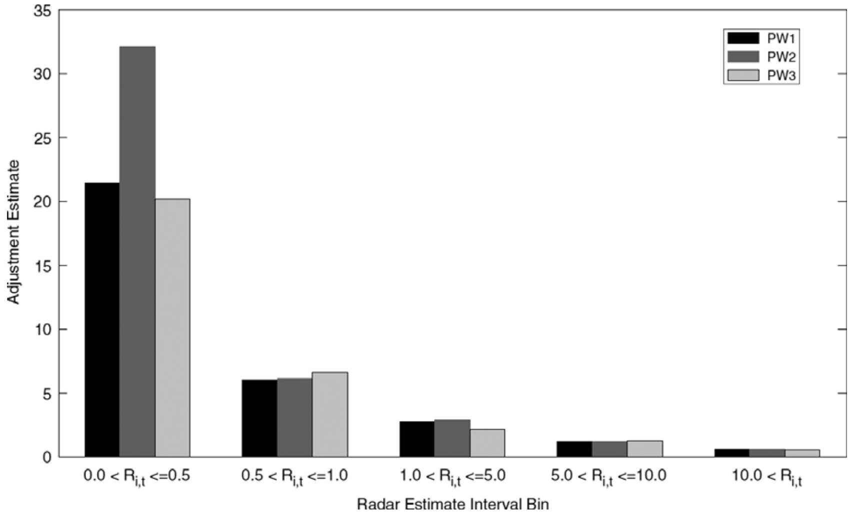

Figure 3. PWAF estimates for interval range category A (see Table 6) (The vertical axis shows the adjustment estimate and the horizontal axis shows the interval ranges where $R_{i,t}$ is the radar estimate at time, t, and location, i).

Table 2. Uniform adjustment estimate methods (in column 1, AU indicates uniform adjustment, the first digit indicates the equation used and the second number indicates the threshold value).

Adjustment factor method	Equation used	Threshold (mm day^{-1})
AU1_0	Equation (1)	0.0
AU1_0.1	Equation (1)	0.1
AU1_0.2	Equation (1)	0.2
AU1_0.5	Equation (1)	0.5
AU1_1	Equation (1)	1.0
AU1_2	Equation (1)	2.0
AU1_5	Equation (1)	5.0
AU2_0	Equation (2)	0.0
AU2_0.1	Equation (2)	0.1
AU2_0.2	Equation (2)	0.2
AU2_0.5	Equation (2)	0.5
AU2_1	Equation (2)	1.0
AU2_2	Equation (2)	2.0
AU2_5	Equation (2)	5.0
AU3_0	Equation (3)	0.0
AU3_0.1	Equation (3)	0.1
AU3_0.2	Equation (3)	0.2
AU3_0.5	Equation (3)	0.5
AU3_1	Equation (3)	1.0
AU3_2	Equation (3)	2.0
AU3_5	Equation (3)	5.0

These results might have been expected. For instance, the variation in values for Equation (3) can be expected to be the smallest, as it calculates the adjustment factor so that water is conserved over the entire data period and is not affected by variations between individual radar rainfall estimates and rain-gauge estimates as much as the other equations. Equation (2), as expected, gave the largest variations; it calculates the adjustment factors based on the sum of the ratio of rain-gauge estimates and radar rainfall estimates for each observation and is the most susceptible to individual variations between radar rainfall estimates and rain-gauge estimates.

While these values are large when compared to adjustment calculated in other countries, it should be noted that no calibration with rain-gauges is performed on the radar station at Dublin Airport, which explains the large differences between radar and rain-gauge estimates. These large values are also supported by Figure 4, which shows a scatterplot of weekly accumulations for the rain-gauge at Edenderry the corresponding non-adjusted accumulation for the corresponding radar cell. This figure shows that there is a large difference between the weekly accumulations for both rain-gauge and radar.

3.2. Comparison with respect to rain-gauges

Tables 9 and 10 show the top performing adjusted radar rainfall estimates when compared to the rain-gauge estimates in calibration and validation respectably. The top 10 performing estimates are listed for each of the three comparison metrics.

It is clear that the piece-wise adjustment factor methods (PWAF) perform substantially better than the uniform adjustment methods in term of mean residual and mean square error. For the mean residual error analysis, there is a distinct jump in performance between the best of the top 10 (MRs less than ± 0.1) and the other methods (MRs of ± 0.1 and greater). The former are essentially unbiased while the latter have greater bias. For the calibration period, only the PWAF methods come before this jump in performance, and these were based on Equation (3) (PW3, PW6 and PW9). However, in validation, PW9 is the only estimate that appears before the jump in performance. PW3 and PW6 still out-performed all but one of the uniform methods (AU3_0). There is also a jump in performance between the best performing estimate in both calibration and validation with respect to root mean square error. This jump is not as significant as for MRs, with PW3 the only estimate that is before the jump in performance in both calibration (RMSE = 4.920 mm day^{-1}) and validation (RMSE = 4.948 mm day^{-1}). The next best performing estimate was PW6 in both calibration (RMSE = 5.069 mm day^{-1}) and validation (RMSE = 5.035 mm day^{-1}). There is no clear jump in performance for the mean absolute error criterion. However, unlike for the other two criteria, the constant adjustment factor methods out-performed all the PWAF methods, with the best PWAF coming in 10th place in calibration.

Ignoring the rainfall estimates produced by the PWAF methods, the next best estimates were produced by the uniform method A_{U3}. The adjustment factor for this method is produced

Table 3. PWAF intervals and percentages of observations in each interval.

Interval range category	A	B	C
No. of intervals	5	5	4
	0.0–0.5 (34.2%)	0.0–1.0 (49.9%)	0.0–5.0 (92.0%)
	0.5–1.0 (15.7%)	1.0–5.0 (42.1%)	5.0–10.0 (6.5%)
Interval ranges rain value (mm) is within the indicated limits	1.0–5.0 (42.1%)	5.0–10.0 (6.5%)	10.0–20.0 (1.4%)
	5.0–10.0 (6.5%)	10.0–20.0 (1.4%)	20.0 < (0.1%)
	10.0 < (1.5%)	20.0 < (0.1%)	—

Percentages indicate the percentage of the total sample inside each interval range.

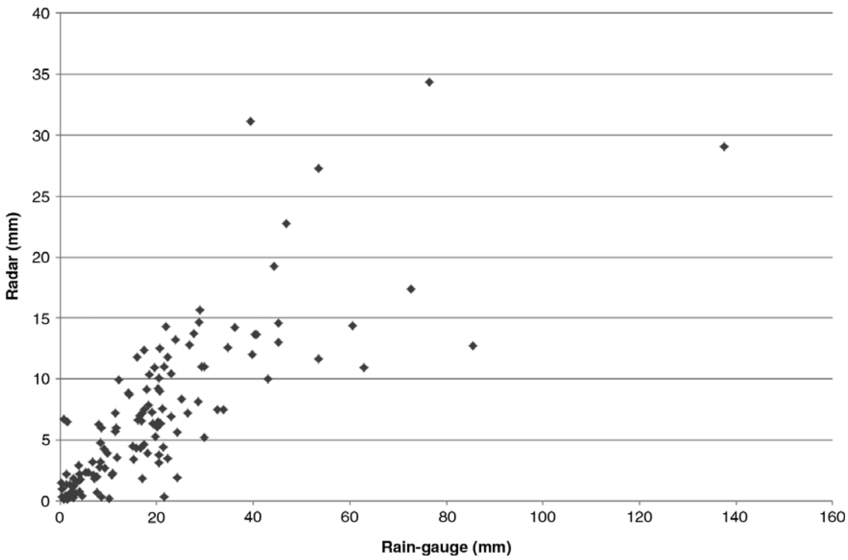

Figure 4. Scatterplot of weekly accumulations for the rain-gauge at Edenderry and the corresponding radar cell over the entire study period.

Table 4. Piece-wise adjustment estimation methods showing range category shown in Table 3 and equations used in calculating each method.

Method	Range category (see Table 3)	Adjustment equation used
PW1	A	Equation (1)
PW2	A	Equation (2)
PW3	A	Equation (3)
PW4	B	Equation (1)
PW5	B	Equation (2)
PW6	B	Equation (3)
PW7	C	Equation (1)
PW8	C	Equation (2)
PW9	C	Equation (3)

Table 5. Uniform adjustment factor values showing effect of equation and threshold value used.

Adjustment method	Adjustment factor
AU1_0	9.655
AU1_0.1	6.360
AU1_0.2	5.084
AU1_0.5	3.962
AU1_1	3.115
AU1_2	2.115
AU1_5	1.784
AU2_0	16.927
AU2_0.1	8.096
AU2_0.2	6.110
AU2_0.5	4.337
AU2_1	3.279
AU2_2	2.170
AU2_5	1.800
AU3_0	2.746
AU3_0.1	2.617
AU3_0.2	2.510
AU3_0.5	2.310
AU3_1	2.087
AU3_2	1.822
AU3_5	1.637

using Equation (3), as with PW3, PW6 and PW9. A_{U3} had a third of the top 10 results in calibration period and just over a third of the top 10 results in the validation period. Overall, the estimates produced by method 3, either by the uniform method A_{U3} or by the PWAF methods (PW3, PW6 and PW9) account for just over 50% of the top 10 results, with method 1 accounting for just over 25% and method 2 accounting for the remainder.

The impact of using different thresholds is also apparent. For the uniform methods, with the exception of method 3, the use of low threshold values results in larger errors. The best estimates produced by either method 1 or 2 used a minimum threshold greater than 1.0 mm day^{-1} when calculating the corresponding adjustment factor. The influence of the number of threshold interval bins was also observed. The use of five interval bins to calculate the adjustment factors produced better estimates than

Table 6. PWAF values for interval category A (see second column of Table 3).

Threshold interval (mm day^{-1})	PW1	PW2	PW3
0.0–0.5	21.439	32.077	20.134
0.5–1.0	5.996	6.105	6.594
1.0–5.0	2.750	2.876	2.161
5.0–10.0	1.156	1.161	1.216
10.0 <	0.549	0.560	0.528

Table 7. PWAF values for interval category B (see third column of Table 3).

Threshold interval (mm day^{-1})	PW4	PW5	PW6
0.0–1.0	13.959	22.850	11.629
1.0–5.0	2.750	2.876	2.161
5.0–10.0	1.156	1.161	1.216
10.0–20.0	0.557	0.566	0.532
20.0 <	0.495	0.495	0.479

Table 8. PWAF values for interval category C (see fourth column of Table 3).

Threshold interval (mm day^{-1})	PW7	PW8	PW9
0.0–5.0	9.867	17.252	3.663
5.0–10.0	1.156	1.161	1.216
10.0–20.0	0.557	0.566	0.532
20.0 <	0.495	0.495	0.479

Table 9. Top 10 PWAF and uniform estimate comparisons with rain-gauges for calibration with respect to mean residual error(MRs), root mean square error (RMSE) and mean absolute error(MAE).

	MRs		RMSE		MAE
PW9	−0.008	PW3	4.920	AU3_1	2.619
PW3	−0.024	PW6	5.069	AU3_5	2.619
PW6	−0.036	PW1	5.080	AU1_1	2.664
AU3_0	0.103	AU3_1	5.174	AU1_5	2.664
AU3_01	0.227	AU3_5	5.174	AU2_1	2.669
AU3_02	0.329	AU1_1	5.237	AU2_5	2.669
PW1	−0.347	AU1_5	5.237	AU3_2	2.677
AU3_05	0.520	AU2_1	5.244	AU1_2	2.785
PW4	−0.601	AU2_5	5.244	AU2_2	2.807
AU2_2	0.654	AU3_2	5.255	PW3	2.863

First, third and fifth columns indicate the radar adjustment method.

Table 10. Top 10 PWAF and uniform estimate comparison with rain-gauges for validation with respect to mean residual error(MRs), root mean square error(RMSE) and mean absolute error(MAE).

	MRs		RMSE		MAE
PW9	0.014	PW3	4.948	AU3_1	2.445
AU3_0	0.142	PW6	5.035	AU3_5	2.445
PW6	−0.173	AU3_1	5.068	AU1_1	2.485
PW3	−0.197	AU3_5	5.068	AU1_5	2.485
AU3_01	0.253	PW1	5.104	AU2_1	2.490
AU3_02	0.345	AU1_1	5.128	AU2_5	2.490
PW1	−0.486	AU1_5	5.128	AU3_2	2.497
AU3_05	0.517	AU2_1	5.135	AU1_2	2.593
AU2_2	0.637	AU2_5	5.135	AU2_2	2.613
AU1_2	0.685	AU3_2	5.146	AU3_05	2.668

First, third and fifth columns indicate the radar adjustment method.

using four bins, in fact two of the worst estimates were from PW7 and PW8 both of which were calculated using only four interval bins. The first set of intervals, which were concentrated around the lower radar rainfall thresholds performed better than the other.

4. Continuous nonlinear adjustment curve (NAC)

4.1. Method and curves

From the comparison of the uniform and PWAF methods, it is clear that there is an argument for the use of a nonlinear adjustment factor. The results of the PWAF method and Figure 3 suggested that a continuous nonlinear adjustment curve might perform as well as the other two methods. To test this, the PWAF approach is generalized. Instead of dividing the radar intensities into bins, a continuous nonlinear adjustment curve (NAC) is fitted to the data. . To determine an appropriate form for the NAC equation, four different types of curve were tested;

1 a single exponential function for all rain intensities (Equation (7));
2 a single power law function for all rain intensities (Equation (8));
3 two different exponential functions, one for low rain intensities and the other for high intensities, and
4 two different power law functions, one for low rain intensities and the other for high intensities.

For methods (3) and (4) radar rainfall intensities less than 2 mm day^{-1} are considered low ($R_{i,t} < 2\text{mm day}^{-1}$) and all else high ($R_{i,t} >= 2\text{mm day}^{-1}$).

$$A_{\exp} = A \exp\left(R_{i,T} B\right) + C \qquad (7)$$

$$A_{power} = A R_{i,T}^{B} + C \qquad (8)$$

where A, B and C are constants and $R_{i,T}$ is the radar rainfall estimate.

Table 11 shows the optimized constants (A, B and C) for Equations (7) or (8) for the NAC approach for use with a single curve and for use with using multiple curves. Figure 5 shows the fitted curves with respect to the average gauge to radar ratio. As with the PWAF method, the value of the adjustment decreases with an increase in the intensity of the radar rainfall estimates. The results demonstrate that the NAC using either an exponential or a power law function can match the observed variability in the gauge to radar ratios. As expected, using two discrete curves (methods (3) or (4)) out-performed their respective single curves and the power law function out-performed the exponential function with respect to mean square error between the fitted values and the average gauge to radar ratio (Table 12).

4.2. Comparison with rain-gauges

Tables 13 and 14 show the performance of the NAC methods with respect to the comparison metrics for calibration and validation. Combining Tables 9, 10, 13 and 14, it is clear that

Table 11. Fitting constants for NAC (first subscript denotes whether an exponential or power law is used and the final subscript denotes the use of single or multiple curves).

Constants	A_{exp_s}	A_{power_s}	A_{exp_m} ($R_{i,T} >= 2$ mm day^{-1})	A_{exp_m} ($R_{i,T} < 2$ mm day^{-1})	A_{power_m} ($R_{i,T} >= 2$mm day^{-1})	A_{power_m} ($R_{i,T} < 2$mm day^{-1})
A	36.703	5.030	2.548	39.748	2.454	6.187
B	−3.239	−0.886	−0.515	−3.871	−1.083	−0.795
C	2.282	−0.299	1.142	3.293	0.924	−1.518

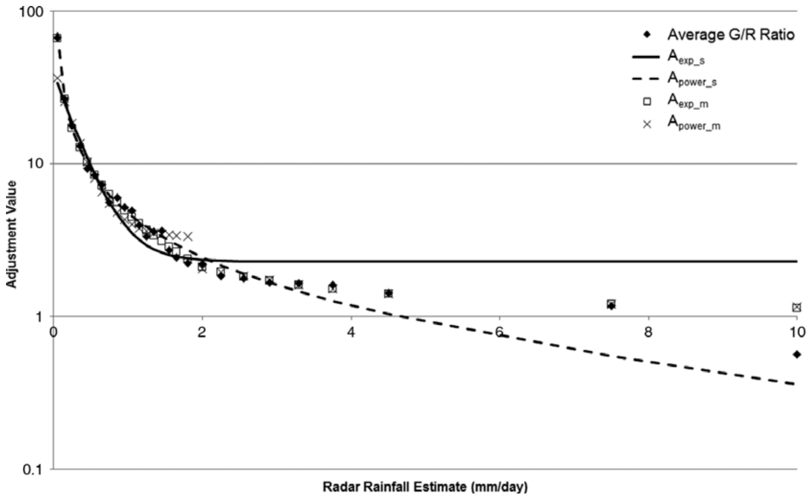

Figure 5. Nonlinear adjustment curve (NAC) fitting with respect to the average G/R ratio (the horizontal axis shows the daily radar rainfall estimate and the vertical axis shows the calculated adjustment values).

Table 12. Performance of NAC equations with respect to root mean square error (RMSE) and Pearson correlation (R^2).

	RMSE	R^2
A_{exp_s}	0.851	0.988
A_{power_s}	0.425	0.997
A_{exp_m}	0.594	0.995
A_{power_m}	0.344	0.998

Table 13. NAC comparison with rain-gauges for calibration, with respect to mean residual error (MRs), root mean square error (RMSE) and mean absolute error (MAE).

	MRs		RMSE		MAE
A_{exp_m}	−0.015	A_{power_m}	4.709	A_{exp_m}	2.759
A_{power_m}	0.033	A_{power_s}	4.709	A_{power_s}	2.755
A_{power_s}	−0.173	A_{exp_m}	4.742	A_{power_m}	2.779
A_{exp_s}	0.429	A_{exp_s}	5.410	A_{exp_s}	3.034

Table 14. NAC comparison with rain-gauges for validation, with respect to mean residual error (MRs), root mean square error (RMSE) and mean absolute error (MAE).

	MRs		RMSE		MAE
A_{exp_m}	0.123	A_{power_s}	4.663	A_{power_s}	2.734
A_{power_m}	0.211	A_{power_m}	4.708	A_{exp_m}	2.740
A_{power_s}	0.057	A_{exp_m}	4.720	A_{power_m}	2.794
A_{exp_s}	0.499	A_{exp_s}	5.295	A_{exp_s}	2.981

the NAC method performs very well compared to the other methods. For mean square error, the top three NACs outperform all the other estimates in both calibration and validation. With respect to mean residual errors, the NAC method produces the 2nd, 4th and 7th best estimates in calibration and the 2nd, 3rd and 7th best estimates in validation and is only bettered by another non-linear adjustment factor (PW9) in both cases. As with the PWAF method, the NAC method does not perform as well as the uniform method with respect to mean absolute error; however, it should be noted that the NAC estimates do outperform the PWAF estimates for MAE. The effect of using two curves instead of one is also visible in Tables 13 and 14. For the exponential function curves, the two curves produce better results than a single curve. With respect to the power law curves, the use of a single curve performs slightly better than using two discrete curves for mean square error in both calibration and validation and for mean residuals in validation.

5. Conclusions

This study introduced two new, nonlinear, radar adjustment methods (PWAF and NAC) for adjusting radar rainfall estimates with rain-gauge data and evaluated them for daily rainfall amounts. The PWAF method was compared to three different uniform single valued adjustment methods. The adjustment factors were calibrated over a 1 year period, and validated over an 18 month period.

The proposed piece-wise adjustment factor methods performed better than constant, uniform, adjustment methods in both calibration and validation for the mean residual and mean square error criteria. Of the nonlinear methods, the nonlinear adjustment curves (NAC) method out-performed the piece-wise adjustment factor (PWAF) method and both were better than uniform adjustment methods. For the uniform methods, the adjustment equation, Equation (3), which calculates the adjustment factor based on the ratio of total estimates of the raingauge to the radar, performed best across both methods. This method was also less sensitive to the non-zero thresholds.

The study also highlighted the effect of using thresholds when calculating adjustment factors. For the uniform single adjustments, with the exception of Equation (3), the choice of the minimum threshold had a large effect on the adjustment factor and, in turn, on the accuracy of the corresponding adjusted radar estimate. This study suggests that a threshold should be used and for daily adjustment factors this threshold should be greater than 1 mm day^{-1}.

For the PWAF method, the choice of the threshold interval bins is also important. This study suggests that the threshold intervals should be concentrated around the lower radar rainfall estimates. This was indicated by the observation that for each PWAF method the interval set that concentrated on the lower threshold performed better, i.e. PW1 performed better than PW4 or PW7.

For the NAC method, estimates obtained from a power law function perform better than those obtained from an exponential function. The choice of one or two equations depends on the choice of curve function. If using an exponential function, using two discrete equations produces better estimates than a single equation. However, for the power law function, a single curve can perform better than two discrete curves. The difference between using one power law function curve and two discrete curves is less than 2% with respect to mean square error.

Further work is suggested to investigate the performance of the piece-wise adjustment factor methods for sub-daily time-steps. The choice of intervals bins for sub-daily time-steps should also be investigated. The methods used to calculate the PWAF adjustments can also be further developed to calculate spatial adjustment factors.

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