

Reviews of the paper “Application of bias correction methods to improve the accuracy of quantitative radar rainfall in Korea”

by

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General comments

The submitted paper talks about the comparison between weather radar data and gauge measurements in Korea. Gauge data are considered as truth. The main goal is to develop methods to correct the systematic bias, the random errors, and the range dependent bias which affects the radar rainfall estimates. The topic of the paper is one of the most discussed in radar hydrology. Several past works, such as those cited by the Authors, have already dealt with the same problem giving valuable contributions in the assessment of radar-gauge adjustment technique (see an additional reference list below for example). Even if the MFBC method (i.e. the mean field bias correction factor) is well known in the literature for many years, as well as the LGC method is the same methodology developed by Zhang et al. 2011, as mentioned by the Authors themselves, the submitted work surely gives a contribution to the aforementioned topic. In fact, the element of originality is constituted by the fact that Authors have investigated the variability of the correction factor as a function of rain type (all rainfall types, typhoon cases, Changma front, local torrential rainfall). However, the methodologies employed to correct Z bias and rainfall estimation bias were not explained in sufficient detail (I suggest Authors to introduce more references). In addition the LGC method is explained in a confused way, and Sect. 3 is poorly written. So it's my opinion that many parts of the paper should be rewritten (see specific comments and technical corrections). I also suggest to the Authors to submit the article to a revision concerning the English language. In conclusion, I believe that the manuscript is worth for publication after some major revisions.

Additional references.

- Sebastianelli, S., Russo, F., Napolitano, F., & Baldini, L. (2013). On precipitation measurements collected by a weather radar and a rain gauge network. *Natural Hazards and Earth System Science*, 13(3), 605-623, doi:10.5194/nhess-13-605-2013.
- Villarini, G., Mandapaka, P. V., Krajewski, W. F., and Moore, R. J.: Rainfall and sampling uncertainties: A rain gauge perspective, *J. Geophys. Res.*, 113, D11102, doi:10.1029/2007JD009214, 2008a.
- Villarini, G., Serinaldi, F., and Krajewski, W. F.: Modeling radar rainfall estimation uncertainties using parametric and nonparametric approaches, *Adv. Water Resour.*, 31, 1674–1686, 2008b.
- Berenguer, M. and Zawadzki, I.: A study of the error covariance matrix of radar rainfall estimates in stratiform rain, *Weather Forecast.*, 23, 1085–1101, 2008.
- Berenguer, M. and Zawadzki, I.: A study of the error covariance matrix of radar rainfall estimates in stratiform rain. Part II: scale dependence, *Weather Forecast.*, 24, 800–811, 2009.
- Seo, D. J., Breidenbach, J., Fulton R., O'Bannon, T., and Miller D.: Real-time adjustment of range-dependent biases in WSR-88D rainfall estimates due to nonuniform vertical profile of reflectivity, *J. Hydrometeorol.*, 1, 222–240, 2000
- Gorgucci, E., Scarchilli, G., and Chandrasekar V.: Calibration of radars using polarimetric techniques, *IEEE Trans. Geosci. Remote Sens.*, 30, 853-858, 1992.

Specific comments and technical corrections

P11429, title: I would suggest: “quantitative rainfall radar estimations” instead of “quantitative radar”.

P11430, line 1: I would say: “there are many potential sources of bias in rainfall estimation performed by a weather radar”; in fact there is only one bias that has multiple causes.

P11430, lines 1-6: you wrote: “This study classified the biases from the rainfall estimation process into the reflectivity measurement bias and the rainfall estimation bias by the Quantitative Precipitation Estimation (QPE) model and also conducted the bias correction methods to improve the accuracy of the Radar-AWS Rainrate (RAR) calculation system operated by the Korea Meteorological Administration (KMA).” The sentence is too long, please rephrase. I suggest writing: “This study classifies the rainfall estimation process overall bias into the reflectivity measurement bias (Z bias) and the rainfall estimation bias (R bias). It also conducted the bias correction methods to improve the accuracy of the Radar-AWS Rainrate (RAR) calculation system assessed by the Korea Meteorological Administration (KMA). The rainfall is estimated by a Quantitative Precipitation Estimation (QPE) model.”

P11430, lines 7-8: I suggest to write: “for the Z bias occurred when a weather radar measures the reflectivity this study ...” (a weather radar measures the reflectivity, not the rainfall).

P11430, line 8: please replace “the bias” with “a bias”.

P11430, line 10: please add the word “reflectivity” between the words “radar” and “corrected”.

P11430, line 11: you wrote: please delete the words “and then”.

P11430, line 13: I suggest hereafter to replace “rainfall estimation bias” with “R bias”.

P11430, line 13: I suggest to remove “by the QPE model” because it has already been said.

P11430, lines 15-18: you wrote: “For the rainfall types, although the accuracy of the Changma front and the local torrential cases was slightly improved without the Z bias correction the accuracy of the typhoon cases got worse than the existing results in particular. The sentence is too long. I suggest to write “However it needs to distinguish between precipitation types. In fact the accuracy of the Changma front and the local torrential cases was slightly improved without the Z bias correction. Vice versa, the accuracy of the typhoon cases got worse than the existing results”.

P11430, lines 18-20: the sentence is too long and it is not clear, please rephrase. I suggest to write: “Result obtained by the LGC method is better than that obtained by the MFBC method, due to the different rainfall biases applied to each grid rainfall amount in the LGC method.”. You have to define the meaning of “Z bias LGC_method” before, if you want to utilize it.

P11430, lines 20-23: the sentence is not clear, what did you mean? Perhaps you meant to say that the results are more accurate if you correct first Z bias and then R bias with the LGC method, especially for the typhoon case? Please rephrase.

P11431, line 1: I would replace “they play” with “playing”.

P11431, line 2: I would remove “process of calculating”.

P11431, line 3: what did you mean saying “radar data”? Perhaps you meant radar estimates of rain? Please specify.

P11431, line 5: I would remove “and” before the words “quality controls”.

P11431, lines 5-6: I believe that Z-R relationship parameter estimation as well as QPE model structures are sources of errors that don’t lead to a systematic bias but they lead to random errors (see below).

P11431, lines 8-9: I would change “because one of major reasons is” in “due to the fact”.

P11431, line 10: I would change “measured radar variables” in “radar measurables”.

P11431, line 12: I suggest the Authors to refer to a Z bias and to an R bias hereafter.

P11431, lines 11-14: I suggest the Authors to distinguish between the systematic bias (due to the lack of radar hardware calibration) and the others errors. The systematic bias occurs whenever a

radar makes a reflectivity measure and it is not dependent by both the spatial location of the sampling volume and the point in time when the measurement of reflectivity is made. Systematic bias (Villarini et al., 2008b) is not due to the loss of power which occurs when the signal propagates across the atmosphere, or when the radar beam is blocked by the ground, to the amount of backscattered power due to the ground detection, and to the increase in height with range of the sample volume. Beam-blocking, attenuation, ground clutter, and radar beam propagation geometry are sources of range-dependent bias (or error), whereas the choice of the relationship between Z and R is the sources of a random error, as mentioned by the Authors. In particular, temporal and spatial sampling errors are due to the radar beam propagation geometry, as detailed by Villarini et al., 2008a; Berenguer and Zawadzki, 2008, and Berenguer and Zawadzki, 2009. You can find an explanation of the different sources of error (such as systematic bias, random error, and range-dependent bias) in Sebastianelli et al., 2013 in which a gauge-adjustment technique is applied to define an adjustment factor to correct the radar range dependent error in comparison with rain gauges.

P11431, lines 11-14: Authors may specify whether the radar errors which are discussed are evaluated with respect to raingauges' measures or other.

P11431, lines 11-14: I suggest to add the following references:

- Sebastianelli, S., Russo, F., Napolitano, F., & Baldini, L. (2013). On precipitation measurements collected by a weather radar and a rain gauge network. *Natural Hazards and Earth System Science*, 13(3), 605-623, doi:10.5194/nhess-13-605-2013.
- Villarini, G., Mandapaka, P. V., Krajewski, W. F., and Moore, R. J.: Rainfall and sampling uncertainties: A rain gauge perspective, *J. Geophys. Res.*, 113, D11102, doi:10.1029/2007JD009214, 2008a.
- Villarini, G., Serinaldi, F., and Krajewski, W. F.: Modeling radar rainfall estimation uncertainties using parametric and nonparametric approaches, *Adv. Water Resour.*, 31, 1674–1686, 2008b.
- Berenguer, M. and Zawadzki, I.: A study of the error covariance matrix of radar rainfall estimates in stratiform rain, *Weather Forecast.*, 23, 1085–1101, 2008.
- Berenguer, M. and Zawadzki, I.: A study of the error covariance matrix of radar rainfall estimates in stratiform rain. Part II: scale dependence, *Weather Forecast.*, 24, 800–811, 2009.

P11432, lines 9-10: I would change “the bias of radar estimation” in “the radar estimation bias”.

P11432, lines 13-14: I would change “the bias by the QPE model” in “the bias which affects the rainfall estimation by the QPE model (R bias)”.

P11432, lines 14-15: it's my opinion that the sentence “because the measurement and estimation procedures of rainfall play and important roles to the accuracy of weather radar rainfall” is not necessary, so I suggest the Authors to remove it.

P11432, line 16: what the Authors define as Z bias is an overall error which includes the systematic bias, and the range-dependent bias due to beam-blocking, attenuation, ground clutter, and radar beam propagation geometry. It's correct?

P11432, line 19: concerning the random error due to the parameter of the Z-R relationship I suggest the Authors to add the following reference: Seo, D. J., Breidenbach, J., Fulton R., O'Bannon, T., and Miller D.: Real-time adjustment of range-dependent biases in WSR-88D rainfall estimates due to nonuniform vertical profile of reflectivity, *J. Hydrometeorol.*, 1, 222–240, 2000, in which the difference between the range-dependent bias and the mean field bias (due to both the random error related to Z-R relationship parameter and the lack of radar hardware calibration) is explained.

P11432, lines 20-21: in Section 2 both the correction methods of Z bias and R bias are described.

P11432, lines 21-23: the sentence is poorly written, I suggest to write: “Section 3 shows effects of methods used to correct Z and R bias on the rainfall estimation performed by the QPE model”. In addition I recommend the Authors to summarize here methods utilized to correct Z bias and R bias, as already done in the abstract.

P11433, lines 7-10: I suggest to write “ The Bislsan... was installed..., and was selected...” .

P11433, line 13: please replace “has” with “consists of”.

P11433, line 16: please replace “a reference” with “that reference”.

P11433, line 21: I would suggest to replace “a scan range of maximum 200 km” with “a scanning circle of 200 km radius”.

P11433, line 22: I would change “the radars” in “radars”.

P11433, lines 22-25: the sentence is too long, could you split it?

P11434, line 8: I would change “the parameters of the Z–R relationship” in “the Z–R relationship parameters”; in addition please delete “in real time” because it is mentioned after.

P11435, line 20: rain rate.

P11435, line 24: I would change “the measured reflectivity of the reference radar and the target radar” in “the reflectivity measured by the reference radar and that measured by the target radar”.

P11436, lines 4-8: I suggest the Authors to add the following reference: Gorgucci, E., Scarchilli, G., and Chandrasekar V.: Calibration of radars using polarimetric techniques, IEEE Trans. Geosci. Remote Sens., 30, 853-858, 1992.

P11437, line 2: I would replace “adjacent” with “close”.

P11437, lines 8-9: how it is estimated the attenuation? You used the differential propagation phase shift pattern? Could you add a reference for the used methodology?

P11437, line 10: what’s the methodology followed to estimate CAPPIs? You’re followed Sinclair and Pegram (2005)? Could you add a reference for the used methodology?

P11437, lines 11-15: Have you generated pairs of radars formed by the reference radar and a radar target? The two radars are located always at the same distance in each pair? For each couples you have calculated the reflectivity differences (only into the overlap area) between the two radar measures every 500 meters, from 1.5 to 3.5 km altitude. Moreover, the Z bias seems to be independent of ground clutter and bright band. It's correct?

P11438, lines 1-2: I would write: “... the bias correct factor ... is a mean field bias which is calculated as the ratio...”

P11438, line 14: what the Authors define as R bias is a mean field bias (see Seo et al., 2000) consisting only of a random error (due to the Z-R relationship parameter estimation, as well as to the QPE model parameters, and to the QPE model structure), which not includes the systematic bias (which is part of the Z bias). It's correct? In addition, G and R are calculated by referring to a rainfall event, for a certain period or to a point in time? Please clarify.

P11439, line 3: I would change “rainfall cases that occur locally” in “local bias which affect rainfall”; in addition please add “by radar” after the words “rainfall estimates”.

P11439, line 7: I would replace “as following” with “by the following”.

P11439, line 10: what did you mean with “pixels in the radars”? Perhaps you meant "radar pixels"?

P11439, line 17: r_j and g_j are rainfall amounts? How much is the length of the rainfall time series (collected by the radars and by the rain gauges)? A season? One year? A case study? Or other?

P11439, lines 5-21: this section is poorly written and therefore it is not clear. I suggest the Authors to introduce before the definition of every variable, preferably close to the related equations. For this reason, I suggest the Authors to proceed in the following order:

- 1) the Authors should first clarify what is D , and what rain gauges are chosen to calculate $r_{LGC,i}$.
- 2) the subscript i is equal to j ? If it's true please utilize only a subscript.
- 3) $r_{LGC,i}$ is calculated for each radar pixel? For each radar pixel you consider only rain gauges which are located at a distance $d \leq D$? If $d > D$ you don't correct the radar rainfall estimate?
- 4) for each rain gauge you calculate $e_j = r_j - g_j$
- 5) you attribute a weight w_j to the error; the weight depends on the rain gauges network density (introduce the general definition of w_j)
- 6) introduce the definition of α and the definition of w_j in the case of sparse rain gauges
- 7) finally introduce first the equation (7) and then the equation (6)

P11440, line 1: what is the name of the variable E_i ?

P11440, lines 5-6: it is absolutely not clear the criteria adopted by the Authors to determinate b and D ; how the stepwise method works? Can you add a reference?

P11440, line 8: n is the number of pixels? So m which is the number of rain gauges is different from n ? So we have two subscripts, i and j ? It's correct?

P11440, lines 9-10: given that D is the scan range of the radars while the AWSs are rain gauges, what did you mean with the maximum range D used by all AWSs?

P11440, line 13: I would replace "In sequence, because" with "Since".

P11440, line 16: I would change "The conditions of" in "The conditions checked by".

P11440, line 16: I would change "in a certain AWS" in "for a certain AWS".

P11440, line 17: I would change "that have" in "having".

P11440, line 19: I would change "the center" in "location".

P11441, line 1: what did you mean with thresholds? The thresholds are b and D ?

P11441, lines 23-26: you wrote: "In Fig. 8, after applying the Z biases to the RAR system, the accuracy of the rainfall estimates improved in the Root Mean Square Error (RMSE) and the correlation coefficient, which ranged from 7.37, 0.83, 7.21, and 0.84 mmh⁻¹ on average, respectively." I suggest to write: "Fig. 8 shows that after applying the Z biases to the RAR system, the accuracy of the rainfall estimates improved as shown by the Root Mean Square Error (RMSE), which passed from ... to ... and from ... to ..."

P11441, line 26: I would replace "As a result for each rainfall type" with "For each rainfall type".

P11441, line 26: I would delete "in the RMSE".

P11442, lines 1-3: I would write "... improved as showed by the RMSE which passes from..."; in addition the sentence is too long, please split it. Could you specify which index values in brackets refer?

P11442, line 4: I would write "... for typhoon cases decreases...".

P11442, line 9: I would write "... in these cases...".

P11442, line 10: August 10, 2012.

P11442, line 13: I would replace "It has been" with "For these reasons we proven".

P11442, lines 17-18: please delete "Since the rainfall estimates in the RAR system were improved by the Z bias correction in Sect. 3.1" because the sentence is redundant

P11442, line 19: please add the sentence "which results are shown in Sect. 3.1" after Z bias correction

P11442, line 26: I would write "table 4 shows result of the two R bias correction methods in terms of the accuracy..."

P11443, lines 2-4: I would write "The accuracy is improved by about 7.4% by considering RMSE values which pass from..."

P11443, line 5: I would replace "In the" with "By considering the"

P11443, lines 7-9: the sentence is poorly written; I would write "Therefore we proven that the accuracy of the radar rainfall estimates was improved with application of R bias corrections methods (applied after the Z bias correction) more than the case in which only the Z bias correction method is applied.

P11443, line 10: please replace "superior to" with "better than", and "the reason for this is that" with "because"

P11443, line 15: please replace "in the RMSE" with "in terms of RMSE"

P11443, line 17: I would change "in the RMSE improved over the Z bias" with "in terms of RMSE is greater than the Z bias accuracy"

P11443, lines 18-19: please replace "where inferior to" with "are less accurate with respect to"

P11443, lines 20-25: please check English grammar

P11444, lines 4-6: sentence too long

P11444, lines 12-14: you meant that in both A and B regions the rainfall estimates are increased?

P11444, line 15: slightly or strong? The two words have opposite meanings

P11444, lines 18-21: please check English grammar

P11444, lines 23-27: sentence too long

P11445, lines 8-20: please check English grammar

P11445, lines 21-22: I would delete “Since the rainfall estimates in the RAR system have been improved by the Z bias correction” because the sentence is redundant for me

P11445, line 23: I would delete “For results of the rainfall estimation bias correction methods” because the sentence is redundant for me

P11445, lines 23-27: please check English grammar

P11445, lines 27-29: sentence too long and incomprehensible; perhaps you meant “In fact in the MFBC method only one bias is applied to the whole area. Vice versa, in the LGC method it has a different bias for each radar pixel.”

P11446, lines 1-12: sentences too long and redundant; please check English grammar.

P11446, lines 12-15: not clear, what did you mean?