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Hydrology and Earth System Sciences
Discussions

Interactive comment on "5 year radar-based rainfall statistics: disturbances analysis and development of a post-correction scheme for the German radar composite" *by* A. Wagner et al.

A. Wagner et al.

andreas.wagner@geo.uni-augsburg.de

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We greatly appreciate Prof. Uijlenhoet's valuable comments and suggestions which are very helpful for revising and improving our paper. Please find below our detailed answers addressing each concern of the reviewer and first modifications to improve the current manuscript.

General remarks

REFEREE#3: Generalization of the presented approach

The proposed correction scheme is largely statistical and empirical in nature. This begs the question: how generalizable are its results, beyond the reported improvements for the German radar composite? I have the impression that the presented outcome strongly depends on the specific aspects of the DWD radar processing algorithms (not taking into account VPR correction for instance), the specific character of precipitation systems in this part of Europe as compared to other parts of the world, as well as on the (tacit) assumption that rainfall estimates from rain gauges provide the "ground truth". A thorough discussion of these aspects, preferably in a discussion section preceding the conclusions, is important before the radar hydro-meteorological community would start using the presented methodology.

ANSWER: While our methodology is of general nature it is exemplarily applied for the German radar network. We will elaborate that more clearly in the introduction and refine the objective of this work (as outlined under the second general remark in more detail). Furthermore, we will discuss the aspects mentioned by the referee concerning the generalization of the presented approach in the revised version in Section 5 preceding the conclusion. In the following we will address these issues in more detail:
Our study addresses general basic radar problems with superordinate importance, such as beam widening, increasing beam-height with distance from the radar site, clutter effects and negative spokes. Regarding radar composites these problems are present in any other radar network, even though the scan strategies, the correction schemes on single radar images and the way of compositing might differ. We show in this study how these problems can be addressed, exemplarily for the German radar

network.
Our approach is by purpose statistical, empirical in nature and the algorithms are adapted for the specific aspects for the German radar composite; as our study deals with 16 radars in total and the product covers an entire country, the study is of relevance, also because other national radar networks have comparable radar problems.
The lack of a **VPR correction** scheme for individual radar images in DWD leads to significant modifications of areal patterns in long-term accumulated rain amounts visible in single radar and composite radar products (see Fig. 2, Fig. 4 and Fig. 11 in our submitted manuscript). Hence, this is a major part of our correction scheme. The importance of such an altitude correction in other parts of the world will vary due to the radar scan strategy, the used correction algorithms and the **character of precipitation systems**. The latter aspect (also mentioned by the referee) affects the vertical structure of precipitation. The melting layer as one dominant feature in this part of Europe and measurements of liquid and solid water in parallel may stronger demand for altitude corrections than the precipitation systems in tropical regions. Nevertheless, we think it is crucial to analyse the dependence of the frequencies of occurrence of radar reflectivities with range (or altitude) from the radar site as small systematic limitations may accumulate on a longer temporal scale. Comparable correction schemes can be deduced for a terrain-following scan (specific for DWD), a scan with the same elevation angle as well as for a CAPPI.
We are aware of the limitations related to **rain gauges** and that they do not **provide the "ground truth"**. Like any measurement technique rain gauge measurements are also affected by measurement errors and corresponding techniques have to be developed to meet these uncertainties. Since we use annually precipitation amounts of gauges for correction, random measurements play not so a dominate role in comparison to precipitation amount on a finer temporal scale. Additionally, the correction factor for each single radar area is averaged (median) over all associated pairs of values of rain gauges and corresponding radar pixels. After all, we do not assume single rain gauges

to be ground truth, but not to be dependent on radar beam height, clutter, spokes, etc. The special character of our correction scheme is its holistic methodology as mentioned by REFEREE#2. We do not correct single radar images, but accumulated results (e.g. accumulated frequencies of occurrence of reflectivities or annual rain amounts). In general, the correction steps are also adaptable to a shorter temporal scale, but at the current stage of this analysis we applied the algorithm on the annual time-scale. This is due to the high variability of the altitude dependence which can also decrease the quality on a short temporal scale as shown in Wagner et al. 2012. That is the reason why we focus on the improvement of the areal rain amounts by the correction scheme on an annual basis. We are aware that this annual correction may limit further possible applications, but systematic limitations within radar data can be highlighted this way.
To conclude, while our correction algorithm is of general nature; of course the transfer to other national radar networks would require regional adaptation.

REFEREE#3: Style of the manuscript

Finally, I feel the style of the manuscript, in particular the order in which the various aspects are being presented, requires a thorough round of editing. At certain moments, the paper reads more like a technical report than like a scientific publication, with relatively short sections and quite a number of repetitions. I am sure that with the experience of both co-authors, a significant improvement of the readability of the manuscript should definitely be achievable.

ANSWER: In order to improve the style of the manuscript, a comprehensive revision of the manuscript will be performed. The manuscript will be restructured within the methodology sections and the descriptions of the outcomes (Section 3 to Section 4).

In addition, we are going to improve the current descriptions of the methodology and outcome sections by adapting all text passages of Section 3 and Section 4 according to the new structure, by adding further information such as an additional flow chart for the correction algorithm, by deleting all repetitions and by avoiding technical abbreviations. We are also going to improve the current description of the objective to strengthen the motivation of our work, to highlight the relevance and to put this work in a more international perspective. The following main revisions will be performed:

Restructuring of the methodology section and the description of the outcomes

Section 3: "Analysis of disturbances in radar composite":
In Section 3.1 we will combine the short sections by removing the sub-section headlines (Step 1 . . .4) and improve the reference of the **Steps** to the analysed disturbances in Section 3.2. In Section 3.2 we will shift from a methodological structure (3.2.1, 3.2.2) to an organization by meteorological topics. The improved structure for Section 3 is as follows:
3 Analysis of disturbances in radar composites
3.1 Methods for the analysis of disturbances
3.2 Results of the analysis of disturbances in radar composites
3.2.1 Clutter analysis
3.2.2 Spokes analysis
3.2.3 Analysis of the variation with altitude
3.2.4 Analysis of the effects of the coordinate conversion method
3.2.5 Single areas vs. overlapping areas analysis
This restructure avoids repetitions as only one section of the variation with altitude in Section 3 remains. Additionally, we will underpin the description of the outcomes of this section by adding e.g. additional quantitative information:
(i) For the Section 3.2.1 a table of proportions of clutter pixels for each reflectivity

level and each radar system is added to the current manuscript (see our reply to REFEREE#2).
(ii) For the higher rain amounts in overlapping areas results from the more in-depth analysis will be shifted from Section 4 for the uncorrected data to Section 3.2.5.

Section 4: "Development and validation of a correction scheme":
For the development of the correction scheme a flowchart is added (see supplement to REFEREE#1) to improve the description of the correction algorithms and the comprehensibility of this section. In order to avoid repetitions and to improve the readability, we will also combine the respective sections in the current version of the manuscript where the correction steps are described separately for single radar areas and for overlapping areas. In Section 4.1 we will therefore shift from a methodological structure (4.1.1 to 4.1.3) to an organizational structure by meteorological topics:
4 Development and validation of a correction scheme
4.1 Modules of the correction scheme
4.1.1 Module 1: Altitude correction
4.1.2 Module 2: Spokes correction including rain patterns
4.1.3 Module 3: Adjustment to rain gauge data
4.1.4 Module 4: Clutter correction
We are aware, that the order of the correction steps differs from the order of the investigation steps, but both orders make sense from a logical point of view.
Conclusion: The discussion section mentioned in **"Generalization of the presented approach"** about the applicability of the presented approach will be given, here.

Refinement of the objective (Section 1)
We are going to improve the current description of the objective and straighten out that we address and correct common limitations of radar measurements. In addition we will put this work in a more international perspective (see suggestions of REFEREE#2

including our reply).
We are pursuing two objectives with our manuscript:
The first objective of this study is an identification and quantification of artificial effects in radar composite information that remained after certain corrections that may or may not have been applied at an earlier stage.
The second objective is the development and the validation of an a posteriori correction scheme in order to correct the results of a statistical analysis of rain echoes or the frequencies of heavy precipitation, hail or convective cells to derive hazard maps or spatial patterns of rain echoes on a temporal scale of at least one year.

Refinement of the data descripition (Section 2)
The discussion why we prefer the PX-product over the DX-product (mentioned by REFEREE#1 and REFEREE#2) will be given in the data section or alternatively in the discussion section preceding the Conclusion.

Specific remarks

REFEREE#3: *P.1766, l.4: I find the term "post-correction scheme" confusing. The term suggests that the authors have developed a scheme that works after the correction. I think what the authors mean is "a posteriori correction scheme", namely a correction scheme that works after the operational radar products have been produced.*
ANSWER: Our correction scheme is applied after the operational radar products have been produced. Hence, the term "a posteriori correction scheme" may better describe the issue. We will change that.
REFEREE#3: *P.1769, l.15-17: "some corrections are not applied in DWD, e.g. VRP-correction algorithms for single radar data or composite data" – why are such*

algorithms, which are known to provide significant improvement (e.g. Hazenberg et al., 2011; 2013), not applied by DWD?
ANSWER: In previous years (2002-2005) there had been some tests about VPR correction algorithms (Bartels et al., 2004) but none of them has been transferred to operational products. An algorithm had been developed by the author and was presented at the 32nd AMS Radar Conference (P7R.6). This algorithm has not been operationalized by DWD due to technical reasons. The present DWD strategy envisages a sweep-based object-oriented approach implicitly including the vertical profile.
We are aware of the limitations that result especially on a longer temporal scale that become obvious in our accumulated radar images. But this is our data basis we have to work with, calling all the more for an a posteriori correction.
REFEREE#3: *P.1770, l.24-25: So the last two columns of Table 1 represent "the minimum and maximum radar elevation at a distance of 128 km from the radar site". Given the small numbers, I doubt if these elevations are really expressed in meters. Shouldn't the indicated units be kilometers?*
ANSWER: That is correct. The elevations are expressed in kilometers. We will correct this mistake.
REFEREE#3: *P.1772, l.20: "a three-part Z/R relationship" – this relationship seems to be taken for granted. Can the authors provide any assessment of the appropriateness of this relationship and the systematic rainfall estimation errors that may be associated with it (e.g. Hazenberg et al., 2011; 2014)?*
ANSWER: Extensive measurements at Hohenpeißenberg until 2001 showed that one single Z-R relationship, namely the standard DWD relationship ($Z=256*R^{1.42}$) may lead to poor performances such as underestimations of rain rates for weak and overestimations for heavy precipitation due to the variable dropsize distributions of rainfall. A significant improvement was achieved by the presented three-part Z/R relationship which was firstly published only within an internal interim report (RADOLAN, 5. Zwischenbericht, April 2001). Since then, this relationship has been

used successfully in DWD's operational gauge adjustment routine. So one reason why we preferred this relationship is the potential comparability to RADOLAN rainrate products that are also derived by this relationship. It has meanwhile been corroborated by inverse hydrological modelling (Marx et al. 2006).

We acknowledge the works of Hazenberg et al. which focus, inter alia, on the variability of Z-R relationships with the help of disdrometers. For our approach the Z-R relationship helps to calculate the correct magnitude of the rain amounts taking into account main differences of DSD between light rain and heavy precipitation. The fine-tuning of rainrates is based on rain gauges measurements. We will elaborate that in the manuscript.

REFEREE#3: *P.1774, l.2: "frequencies of occurrence" – I presume these are actually frequencies of exceedance?*

ANSWER: First we create altitude classes depending on the altitude of each pixel within the range of one radar system. Then, we calculate the frequency of occurrence of radar reflectivities within a certain reflectivity level for a certain period (e.g. 3 years) of the corresponding pixels of one altitude class. As a last step we calculate the median of the frequencies of occurrence of radar reflectivities within such an altitude class. Hence, we think the term "frequencies of occurrence" is correct.

REFEREE#3: *P.1774, l.22-23: "the preferred allocation of pixels to one radar system within overlapping areas" – hence, in regions where two (or more) radars overlap, individual pixels area assigned to one radar only, not allowing for a weighted influence of individual radar systems?*

ANSWER: The value for one pixel is naturally only provided by one radar system, regarding one time step (maximum criterium). On a longer temporal scale, e.g. a certain fraction of measurements comes from radar system 1 and a certain fraction comes from radar system 2. If not the single radar images are corrected but accumulated images a weighted influence from both radar systems seems plausible.

We will change this sentence in the following way: "To derive the mean fraction of measurements provided by one radar system within overlapping areas the depen-

dency of frequencies of occurrence of radar reflectivities or rain amount on height is used, based on measurements."

REFEREE#3: *P.1776, l.17-18: "a differentiation between spokes with or without rain patterns is useful. This is done visually." What do you mean with "visually"? Is this an automatic or a manual procedure?*

ANSWER: We use an arbitrary threshold for this discrimination. The decision whether spokes include reliable rain patterns or not must only be made once based on accumulated radar images. Tests show that if the median of frequencies of occurrence of radar reflectivities within a spoke differs more than 50 % from the surrounded pixels the patterns within the spoke are not thrustworthy anymore. This threshold can be varied for other areas to use within an automatic procedure, and this automatic procedure would be able to run unsupervised. We, however, additionally perform a visual inspection of suspect spokes. The correction scheme inter alia is based on some empirical values or correction factors. The decision whether the patterns of one spoke is reliable or not is one of them. We will elaborate that in the manuscript.

REFEREE#3: *P.1787, l.13-15: "A significant overestimation of annual rain amounts based on the radar data compared to rain gauge data becomes apparent." – a RMSE of nearly 1200 mm per year is enormous. Please explain.*

ANSWER: We are most grateful for this hint. As a result, we checked carefully again our computer routines and indeed found a programming error within the Z/R subroutine. We accordingly did a full recalculation which lead to lower RMSE values and in general lower rain amounts. The RMSE for the individual years from 2005 to 2009 are the following (years in brackets): 954 mm/year (2005), 1204 mm/year (2006), 315 mm/year (2007), 300 mm/year (2008), 508 mm/year (2009).

The differences between the RMSE values for 2005 and 2006 ("push"-procedure) and the RMSE values for 2007, 2008 and 2009 ("pull"-procedure) are significant. One main reason for these higher RMSE values seems to be the "push"-procedure that leads to overestimations of the annual rain amounts and consequently to high RMSE values. These RMSE values may be discussed in Section 3.2.4 (Analysis of the effects of the

coordinate conversion method).
Additionally, the 516 pairs of values of rain amounts from rain gauges and from corresponding radar pixels also include radar patterns which are significantly influenced by altitude effects at the outer range of radar coverages or by clutter effects. This is one reason for high RMSE values, in general.
We will replace the figures that are affected by the error within the Z/R subroutine. The magnitude of the uncorrected rain amounts based on the radar composite will change but not their patterns. The results after applying the correction scheme are almost interchangeable with the previous results. The RMSE values for the application period (2005, 2006 and 2009) are 757 mm/year for the uncorrected rain amounts and 156 mm/year for the corrected rain amounts. For the validation period (2007 and 2008) the RMSE for uncorrected rain amounts is 296 mm/year and 176 mm/year for corrected rain amounts.

Editorial remarks

REFEREE#3: *P.1765, title: "disturbances analysis" –> "disturbance analysis" / "analysis of disturbances".*
ANSWER: we will change the title: "analysis of disturbances".
REFEREE#3: *P.1770, l.22, ref. to Table 1: I find the caption of this table (P.1794) too concise. Please explicitly explain the meaning of the numbers in all columns.*
ANSWER: We will change the caption in the following way: "General characteristics of the 16 weather radar sites contributing to the German radar composite with name and abbreviation. The location and the near-surface precipitation scan are characterized by the altitude of the radar site and the minimum and maximum altitude of the center of the radar beam at a distance of 128 kilometers."
REFEREE#3: *P.1771, l.1: "Each weather radar run" –> "Each weather radar runs".*

ANSWER: We will correct this sentence.
REFEREE#3: *P.1771, l.8, ref. to Fig.1: I find the figure captions in general too concise – as far as I am concerned figures plus captions should be self-explanatory.*
ANSWER: We will check that and change the caption of Figure 1 in the following way: "Overview of the German radar composite consisting of 16 radar sites. The locations of the radar sites are represented by their abbreviations in white letters. Their maximum ranges are marked by black rings. The colours indicate the mean altitudes of radar composite pixels due to the near-surface precipitation scan. The overplotted red-black (red-black and yellow-black) squares show the locations of the rain gauges used for comparing rain amounts for the evaluation (adjustment)".
REFEREE#3: *P.1771, l.25: "16 weather radar" –> "16 weather radars".*
ANSWER: We will correct this sentence.
REFEREE#3: *P.1773, l.23: "are inspected whether" –> "are inspected to investigate whether".*
ANSWER: We will correct this sentence.
REFEREE#3: *P.1778, l.8: Insert comma after "Adjacent radar systems".*
ANSWER: We will insert the comma.
REFEREE#3: *P.1786, l.23: "splitted" –> "split".*
ANSWER: We will correct this word.
REFEREE#3: *P.1788, l.22: You cannot start a sentence with "Whereas". This has to follow from the previous sentence: ", whereas".*
ANSWER: We will combine this sentence with the preceding one: "The radar sites of Emden, Neuhaus, Neuheilenbach and Munich provide results of only a very slight discrepancy between both data sets, whereas radar sites in or near bigger cities like the radar sites of Hamburg, Berlin or Frankfurt show differences of 50 % or more regarding annual rain amounts."

Literature

Marx, A., Kunstmann, H., Bárdossy, A., Seltmann, J.: Radar rainfall estimates in an alpine environment using inverse hydrological modelling. Adv. Geosci., 9, 25-29, 2006. http://www.adv-geosci.net/9/25/2006/adgeo-9-25-2006.pdf