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Bias adjustment and advection interpolation of long-term high resolution radar rainfall series

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SUMMARY

It is generally acknowledged that in order to apply radar rainfall data for hydrological proposes adjustment against ground observations are crucial. Traditionally, radar reflectivity is transformed into rainfall rates applying a fixed reflectivity – rainfall rate relationship even though this is known to depend on the changing drop size distribution of the specific rain. This creates a transient bias between the radar rainfall and the ground observations due to seasonal changes of the drop size distribution as well as other atmospheric effects and effects related to the radar observational technology. In this study different bias adjustment techniques is investigated, developing a complete 10-year dataset (2002–2012) of high spatio-temporal resolution radar rainfall based on a radar observations from a single C-band radar from Denmark. Results show that hourly adjustment mean field bias adjustment outperform daily mean field bias adjustment with regards to estimation of rainfall totals and peak rain rates. Furthermore, it is demonstrated that radar rainfall estimates can be improved significantly by implementation of a novel advection interpolation technique.

1. Introduction

Radar rainfall estimates serves a wide range of applications within hydrology, e.g. as input to hydrological models, in rainfall statistics, or in hydrometeorological analyses. For these purposes adjustment against ground observations are crucial in order to produce valid spatiotemporal series of high resolution and valid rainfall. Hence, the motivation for the present paper is to evaluate and compare different adjustment methods in order to develop a large dataset of accurate radar rainfall.

Traditionally, radar reflectivity (Z) is transformed into rainfall rates (R) applying a reflectivity–rainfall rate (Z–R) relationship (e.g. Marshall and Palmer, 1948; Wilson and Brandes, 1979; Fulton et al., 1998). This two-parameter power law function is known to depend on the changing drop size distribution (*DSD*) of the specific rain (or hydrometeors, Battan, 1973). The drop size distribution can be measured by high-resolution laser disdrometers at ground level and the radar reflectivity can succeeding be converted to rain rates using the measured drop size distribution. Distributed continuous, long-term disdrometer measurements are however seldom available and adjustment against ground observations must be performed using other methods. It is generally acknowledged to apply a fixed Z–R relationship regardless of a varying drop size distribution (e.g. Collier, 1986; Smith and Krajewski, 1991; Fulton et al., 1998; Seo et al., 1999; Krajewski and Smith, 2002; Borga et al., 2002 to acknowledge a few of the most cited publications within the research field). This creates a transient bias between the radar rainfall and the ground observations due to natural hydrometeorological variability and to some extent also due to attenuation effects, beam blockage effects, clutter, etc. (see for example Villarini and Krajewski (2010) for a comprehensive literature review on uncertainties in radar rainfall estimates). Furthermore, abrupt changes or drift of bias can originate from recalibration or replacement of radar hardware (Alfieri et al., 2010). There are issues with biases, which partially can be resolved using improved technology such as dual polarization measurements (Bringi and Chandrasekar, 2001), intercalibration of radar networks (Zhang et al., 2005; Lakshmanan et al., 2006), VPR correction (Vignal et al., 2000; Tabary, 2007; Bellon et al., 2005). In most cases this is, however, not possible on historical data sets as the fundamental radar operation data often is unavailable. It is therefore necessary to rely on adjustment against ground observations from rain gauges.

Sampling errors between point rainfall and areal observations from radars are by some authors considered to be a rather significant source of error (Kitchen and Blackall, 1992; Bringi et al., 2011). In a recent study, Bringi et al. (2011) showed when comparing point measurements from laser disdrometers to radar observations on a 4 km^2 pixel, the point to area difference (i.e. the variance reduction factor) is around 20% for rainfall accumulations larger than 1 mm h^{-1} and around 55% for rainfall accumulations larger than 6 mm h^{-1}. This error is entirely due to the rain gauge not

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being able to represent the areal measurement and will contribute to the overall error. Other authors have shown significantly lower errors comparing distrometer observations to radar observations (e.g. Nielsen et al., 2014). Whichever way, it is important to acknowledge the spatial sampling error.

Several authors have investigated and performed the bias adjustment on different timescales. The timescale depends on the application of the bias-adjusted radar data. If the data is used in fine scale hydrological modeling dominated by fast surface runoff, e.g. in urban areas with large impervious surfaces both spatial and temporal resolution of data needs to be small (e.g. as suggested by Einfalt et al. (2004): ~1 km and ~5 min and by Berne et al. (2004) ~2 km and ~3 min respectively). On the other hand, if radar data is applied in large scale catchment modeling dominated by subsurface flow, high resolutions in space and time becomes less crucial.

As argued by Krajewski and Smith (2002) the time integration should be small enough to represent hydrometeorological changes (basically the changes in drop size distribution), but on the other hand not too small leaving the bias dominated by random effects. Due to the latter, several authors apply hourly time integration as a minimum (e.g. Smith and Krajewski, 1991; Smith et al., 1996; Fulton et al., 1998; Ciach et al., 2007; Villarini and Krajewski, 2010; Habib et al., 2013; Wright et al., in press) although smaller values have been reported (e.g. Wood et al., 2000 and Villarini and Krajewski, 2009 who examine timescales down to 5 and 15 min, however with considerably scatter). Steiner et al. (1999) and Thorndahl and Rasmussen (2012) apply event based time integration, whereas Borga et al. (2002), Goudenhoofdt and Delobbe (2009), Thorndahl et al. (in preparation), Smith et al. (2012), Smith et al. (2013) used daily mean field bias adjustment. Wright et al. (in press) have recently proved that mean field bias adjustment with finer timescales (1-h as opposed to 24-h) improve rainfall estimates in extreme events (tropical cyclones) significantly.

In real time application of radar rainfall data, the adjustment on hourly or daily scales does not apply, therefore continuous adjustment methods have been proposed by Collier et al. (1983), Seo et al. (1999), Seo and Breidenbach (2002), Chumchean et al. (2006), Habib et al. (2013) using a fixed time window or volume for timestep by timestep bias adjustment.

Within the last 15 years methods have been developed in order not only to apply a constant mean field bias between radar and ground observations, but to allow the bias to change as a function of the rain rate (conditional bias). The concept of the conditional bias is to resolve problems of rain rate dependent biases especially during highly convective rainfall with rapidly changing drop size distributions. By applying a conditional bias, it is demonstrated e.g. by Ciach et al. (2000, 2007), Villarini et al. (2008) and recently Wright et al. (in press), that especially large rain rates can be converted from being severely underestimated to being comparable to rain gauge observations. The conditional bias has a strong seasonal dependency due to climatological variability over the year (however depending on the local climatology).

The bias adjustment methods described above all apply the mean field bias (*MFB*), signifying that the bias is assumed to be uniform in space. Some authors have investigated spatially non-uniform biases. For example: Krajewski (1987), Sinclair and Pegram (2005), Haberlandt (2007), Velasco-Forero et al. (2009) and Wang et al. (2012) who explore kriging or kriging with external drift as methods to interpolate rain gauge observations before calculating biases. This method has its advantage in areas with few or spatially inhomogeneous rain gauge observations. Some authors have performed bias adjustment of radar mosaics with interpolated rain gauge observations using Theissen polygons, e.g. Damant et al. (1983) and Johnson et al. (1999).

In order to handle bias changes as a function of the range from the radar due to incorrect attenuation adjustment, increasing sampling volumes, CAPPI layer generation, etc., Brandes (1975) and Michelson and Koistinen (2000), Michelson et al. (2000), have proposed different methods of range dependent adjustment.

Traditional meteorological radars scan the atmosphere in different antenna elevations in different time intervals, e.g. 5–15 min. As a result of this scanning strategy the variations of the rain is in principle unknown between the scans. In order to fill the gaps between the scans, and thereby increase the temporal resolution of the radar rainfall product Fabry et al. (1994), Delobbe et al. (2008), Tabary (2007), and Nielsen et al. (2014) have suggested to interpolate between scans using cross-correlation based advection interpolation. If this method is applied, it is possible to construct interpolated radar rainfall data with e.g. 1-min temporal resolution.

In hydrology long time series of rainfall data are essential in order to produce valid statistics. In rare cases high temporal resolution rain gauge series can extend 100 years (Ntegeka and Willems, 2008; Vaes et al., 2002), but in many countries several decades of rain gauge observations are available. With regards to continuous high quality radar observation the reported maximum periods are somewhat shorter e.g. in Baeck and Smith (1998): 14 years, Borga et al. (2002): 4 years; Germann et al. (2006): 7 years; Holleman (2007): 6 years; Goudenhoofdt and Delobbe (2009): 4 years; Overeem et al. (2009, 2010): 10 years; Villarini and Krajewski (2009): 7 years; Smith et al. (2012): 10 years; Thorndahl et al. (in preparation): 16 years, Wright et al. (in preparation): 10 years.

The aim of the present study is to develop a complete 10-year dataset (2002–2012) of high spatio-temporal resolution radar rainfall based on a radar observations from a single Danish C-band radar and a rain gauge network of approx. 65 rain gauges. A selection of the models described in the literature review above is applied in order to determine how the best possible radar rainfall estimates can be developed and to what extent uncertainties can be minimized. We aim the application of the dataset for urban hydrology (e.g. as applied in Thorndahl et al. (2013b) and Thorndahl and Rasmussen (2013)), hence we focus on high spatial resolution, small timescales variability, and estimation of extremes.

Based on the 10-year dataset we investigate and evaluate the following methods/issues:

- *Mean field bias adjustment* versus *spatially distributed bias adjustment*: This provides augmentation of the use of mean field bias adjustment throughout this study.
- *Mean field bias adjustment* with special focus on the temporal integration of radar – rain gauge pairs. We investigate daily and hourly bias adjustment and examine their performance with regards to different aggregation times of rainfall estimates. We assume that the minor sources of error, be it point-area sampling errors, temporal sampling errors, tipping bucket sampling errors, radar observational errors which has not been properly filtered (e.g. clutter, bright band, attenuation effects, etc.) is part of the overall uncertainty and is therefore part of the bias correction.
- We limit our study to historical data and discard methods of real time adjustment, such as continuous fixed time or volume adjustment.
- *Conditional bias adjustment* based on Ciach et al. (2000) and Villarini et al. (2008). Here we investigate the effect of a rain rate dependent bias adjustment method.
- Implementation of advection interpolation (Nielsen et al., 2014) in order to increase the temporal resolution of radar rainfall estimates.
- Investigation of the importance of the number of rain gauges applied in bias adjustment.