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The impact of reflectivity correction and accounting for raindrop size distribution variability to improve precipitation estimation by weather radar for an extreme low-land mesoscale convective system

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SUMMARY

Between 25 and 27 August 2010 a long-duration mesoscale convective system was observed above the Netherlands, locally giving rise to rainfall accumulations exceeding 150 mm. Correctly measuring the amount of precipitation during such an extreme event is important, both from a hydrological and meteorological perspective. Unfortunately, the operational weather radar measurements were affected by multiple sources of error and only 30% of the precipitation observed by rain gauges was estimated. Such an underestimation of heavy rainfall, albeit generally less strong than in this extreme case, is typical for operational weather radar in The Netherlands.

In general weather radar measurement errors can be subdivided into two groups: (1) errors affecting the volumetric reflectivity measurements (e.g. ground clutter, radar calibration, vertical profile of reflectivity) and (2) errors resulting from variations in the raindrop size distribution that in turn result in incorrect rainfall intensity and attenuation estimates from observed reflectivity measurements. A stepwise procedure to correct for the first group of errors leads to large improvements in the quality of the estimated precipitation, increasing the radar rainfall accumulations to about 65% of those observed by gauges. To correct for the second group of errors, a coherent method is presented linking the parameters of the radar reflectivity-rain rate (Z–R) and radar reflectivity-specific attenuation (Z–k) relationships to the normalized drop size distribution (DSD). Two different procedures were applied. First, normalized DSD parameters for the whole event and for each precipitation type separately (convective, stratiform and undefined) were obtained using local disdrometer observations. Second, 10,000 randomly generated plausible normalized drop size distributions were used for rainfall estimation, to evaluate whether this Monte Carlo method would improve the quality of weather radar rainfall products.

Using the disdrometer information, the best results were obtained in case no differentiation between precipitation type (convective, stratiform and undefined) was made, increasing the event accumulations to more than 80% of those observed by gauges. For the randomly optimized procedure, radar precipitation estimates further improve and closely resemble observations in case one differentiates between precipitation type. However, the optimal parameter sets are very different from those derived from disdrometer observations. It is therefore questionable if single disdrometer observations are suitable for large-scale quantitative precipitation estimation, especially if the disdrometer is located relatively far away from the main rain event, which was the case in this study.

In conclusion, this study shows the benefit of applying detailed error correction methods to improve the quality of the weather radar product, but also confirms the need to be cautious using locally obtained disdrometer measurements.

1. Introduction

Extreme precipitation events can have a huge socio-economic impact, especially when occurring in sloping and/or urban environments (Ogden et al., 2000; Creutin and Borga, 2003; Delrieu et al.,

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2005; Borga et al., 2007; Smith et al., 2005). For the future, it is anticipated that, as a result of climate change, extreme precipitation events will occur both at higher frequency and with larger amplitude (Solomon et al., 2007).

During the last decades, our understanding of extreme precipitation events has improved, both regarding its spatial and temporal behavior (e.g. Wilson et al., 1979; Pontrelli et al., 1999; Smith et al., 2007; Delrieu et al., 2009), its impact on the response of catchments (e.g. Gaume et al., 2003; Gaume et al., 2004; Magirl et al., 2007; Brauer et al., 2011), and the influence of urbanization (Smith et al., 2002; Zhang and Smith, 2003; Ntelekos et al., 2007; Javier et al., 2007). However, our ability to accurately measure intense precipitation in real time is still limited due to its small-scale variability and the limited spatial representativeness of rain gauge networks (Berne et al., 2004). Nowadays, ground-based remote sensing by means of weather radars is used to obtain a great deal of information on the spatial properties of precipitation systems in near real-time and at high resolution (Berenguer et al., 2005; Germann et al., 2006), making these instruments in principle ideal for measuring extreme precipitation events.

Unfortunately, precipitation estimation by weather radar is affected by multiple sources of error. In general, these can be subdivided into two main groups: (1) errors affecting the volumetric reflectivity measurements and (2) errors related to the conversion of the observed reflectivity values into rainfall intensity and attenuation estimates. The former type of error results from both internal characteristics of the weather radar (e.g. radar calibration errors, increase of beam height and volume with distance and the measurement aloft instead of at the surface) and from external environmental conditions (e.g. ground clutter and anomalous propagation, wet radome and signal attenuation, partial beam blockage, overshooting, and vertical profile of reflectivity). Overall, this type of error has a detrimental impact on the capabilities of weather radar to measure surface reflectivities (Collier, 1986a; Collier, 1986b; Andrieu et al., 1997; Creutin et al., 1997; Germann et al., 2006; Hazenberg et al., 2011a). The second type of error results from the conversion of the measured radar reflectivity into a rainfall intensity. In general the relationship between the radar reflectivity factor Z [$\mathrm{mm^6\,m^{-3}}$] and the rainfall intensity R [$\mathrm{mm\,h^{-1}}$] is assumed to follow a power law (Marshall et al., 1955; Battan, 1973):

$$Z = AR^b, \tag{1}$$

where the parameters A and b are typically fixed climatological values in an operational setting, although they actually vary with precipitation type (Fulton et al., 1997; Zhang et al., 2011; Zhang et al., 2012). As the physical properties of precipitation continuously change, so do the actual parameter values. Therefore, using fixed parameter values can result in erroneous precipitation estimates. To account for this conversion error, many operational systems make use of rain gauge networks to remove the overall bias in the weather radar precipitation product and/or optimize the two parameters in Eq. (1) (Steiner et al., 1999; Seo and Breidenbach, 2002). However, these techniques are difficult to apply for extreme rainfall measurement because of the spatially highly variable DSD characteristics coupled with the generally low density of most operational rain gauge networks. Also, scale issues that arise from comparing point to volume measurements complicate the direct use of rain gauges for weather radar applications (Kitchen and Blackall, 1992; Ciach and Krajewski, 1999a; Ciach et al., 2000).

During extreme rainfall intensities the transmitted microwave signal can be prone to attenuation, especially at X- and C-band frequencies (Delrieu et al., 1991; Delrieu et al., 1999). A power law similar to Eq. (1) is generally assumed between the radar reflectivity and the specific attenuation k [$\mathrm{dB\,km^{-1}}$]:

$$Z = Ck^d, \tag{2}$$

where the parameters C and d again depend on the local DSD and hence on the ambient climate as well as on the type of precipitation.

In principle both radar reflectivity, rainfall intensity and specific attenuation are dependent on the drop size distribution (DSD) of the precipitation system (Battan, 1973; Uijlenhoet and Stricker, 1999; Uijlenhoet, 2001). Since the DSD varies continuously due to collision, break-up and coalescence processes interacting with the large scale meteorological environment, the parameters in Eqs. (1) and (2) also vary in space and time in accordance with the DSD. Currently, it is impossible to obtain reliable real-time spatial estimates of the DSD, even with polarimetric radar. In practice, this information is therefore often obtained from disdrometer measurements. A main benefit of these instruments is that the measurements are not affected by scale problems, since all rainfall integral variables are obtained simultaneously. Therefore, in case no severe quality issues exist (Tokay et al., 1999; Tokay et al., 2013; Campos and Zawadzki, 2000; Uijlenhoet et al., 2006), these measurements can be directly used for weather radar applications (Austin, 1987; Steiner and Smith, 2004). However, a number of difficulties still arise due to the limited spatial representativeness of measured DSDs for the large-scale precipitation system aloft (Jaffrain and Berne, 2012a; Jaffrain and Berne, 2012b; Verrier et al., 2013). As a result, it is still unclear whether it is truly beneficial to use disdrometer information in real-time weather radar applications.

This study focuses on the combined effect of reflectivity error correction and conversion methods using the joint potential of both the volumetric weather radar and the disdrometer. Since a proper performance of weather radar is especially important for extreme precipitation events (Zhang and Smith, 2003; Delrieu et al., 2005; Borga et al., 2007), this study focuses specifically on an extreme low-land mesoscale convective system (MCS) observed over The Netherlands on 25–27 August 2010. For the eastern part of the country total event accumulations exceeded 150 mm (see Fig. 1), which corresponds to some of the largest rainfall sums ever recorded in the country, resulting in local (flash-)floods (Brauer et al., 2011). Unfortunately, the operational weather radar product was heavily affected by measurement errors and only registered about 30% of the actual precipitation. During the last decades a significant amount of research has focused on the impact of reflectivity error corrections (see for an overview: Krajewski et al., 2010; Villarini and Krajewski, 2010; Hazenberg et al., 2011a). A similar approach is followed here. However, instead of correcting for just a limited number of errors, here all known errors affecting the volumetric reflectivity measurements are systematically corrected for.

Instead of estimating the different power law parameter values directly from disdrometer measurements and applying these to convert radar reflectivities into rainfall intensities and specific attenuation estimates, a scaling-law theory (Sempere Torres et al., 1994; Uijlenhoet et al., 2003a; Hazenberg et al., 2011b) is applied to identify the intrinsic properties of the DSD. This allows estimating the parameters defined in Eqs. (1) and (2). The main benefit of this approach is that it provides a coherent parameter set and reduces the total number of independent parameters. As such, this paper also provides a complete analysis of the second type of weather radar measurement errors as defined above for extreme events.

This study is organized as follows. Section 2 provides a detailed overview of the event under investigation and the different precipitation measurements available. In Section 3 a complete overview of the different error sources affecting the weather radar measurements is presented, as well as the relations of the different power law parameters to the characteristics of the DSD. In Section 4 the