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Enhancement of radar rainfall estimates for urban hydrology through optical flow temporal interpolation and Bayesian gauge-based adjustment

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SUMMARY

Rainfall estimates of the highest possible accuracy and resolution are required for urban hydrological applications, given the small size and fast response which characterise urban catchments. While radar rainfall estimates have the advantage of well capturing the spatial structure of rainfall fields and its variation in time, the commonly available radar rainfall products (typically at ~1 km/5–10 min resolution) may still fail to satisfy the accuracy and resolution – in particular temporal resolution – requirements of urban hydrology. A methodology is proposed in this paper, to produce higher temporal resolution, more accurate radar rainfall estimates, suitable for urban hydrological applications. The proposed methodology entails two main steps: (1) Temporal interpolation of radar images from the originally-available temporal resolutions (i.e. 5–10 min) to finer resolutions at which local rain gauge data are commonly available (i.e. 1–2 min). This is done using a novel interpolation technique, based upon the multi-scale variational optical flow technique, and which can well capture the small-scale rainfall structures relevant at urban scales. (2) Local and dynamic gauge-based adjustment of the higher temporal resolution radar rainfall estimates is performed afterwards, by means of the Bayesian data merging method. The proposed methodology is tested using as case study a total of 8 storm events observed in the Cranbrook (UK) and Herent (BE) urban catchments, for which radar rainfall estimates, local rain gauge and depth/flow records, as well as recently calibrated urban drainage models were available. The results suggest that the proposed methodology can provide significantly improved radar rainfall estimates and thereby generate more accurate runoff simulations at urban scales, over and above the benefits derived from the mere application of Bayesian merging at the original temporal resolution at which radar estimates are available. The benefits of the proposed temporal interpolation + merging methodology are particularly evident in storm events with strong and fast-changing (convective-like) rain cells.

1. Introduction

Rainfall estimates of the highest possible accuracy and resolution are required for urban hydrological applications, given the small size and fast response which characterise urban catchments (Berne et al., 2004; Collier, 2009; Fabry et al., 1994; Liguori et al., 2012; Ochoa-Rodríguez et al., in press). Due to their ability to well capture the spatial characteristics of rainfall fields and their evolution in time, radar rainfall estimates are playing an increasingly important role in urban hydrological applications (Krajewski and Smith, 2002; Krämer et al., 2007; Schellart et al., 2012; Villarini et al., 2010; Wang et al., 2011a). However, the operational radar rainfall products provided by national weather services (typically at ~1 km/5–10 min resolution) may still fail to meet the demanding requirements of urban hydrology, both in terms of accuracy and resolution.

As regards accuracy, since radar quantitative precipitation estimates (QPEs) are an indirect measurement of rainfall, they are subject to multiple sources of error. Firstly, radar reflectivity

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measurements, from which QPEs are subsequently derived, may be affected by factors such as radar beam blockage, attenuation, ground clutter and anomalous propagation of the signal (Collier, 1996; Einfalt et al., 2004; Harrison et al., 2000). A number of corrections are usually applied in order to reduce errors arising from these sources; however, it is virtually impossible to have error-free reflectivity measurements. Additional errors arise in the conversion of reflectivity measurements (Z) to rainfall rates (R), which is usually done using the Z–R relationship, $Z = aR^b$ (Marshall and Palmer, 1948). The variables a and b can be theoretically linked to rain drop size distribution and are generally deduced by physical approximation or empirical calibration based upon long-term comparisons (Collier, 1986; Krajewski and Smith, 2002). However, the highly dynamic nature of rain drop size distribution, even within a single storm event (Smith et al., 2009; Ulbrich, 1983), renders the use of a static Z–R relationship – as used for single-polarisation radars – imperfect, especially when extreme rainfall rates are observed (Einfalt et al., 2005; Goudenhoofdt and Delobbe, 2013). In the case of dual-polarisation radars (dual-pol radars hereafter), dual-polarisation parameters provide useful information which enables significant reduction of some of the sources of error mentioned above (especially detection of non-weather echoes and improved attenuation correction), as well as a dynamic adjustment of the Z–R relationship according to drop-size distribution; this results in much more accurate rainfall rate estimates (Bringi and Chandrasekar, 2001). Dual-pol radars are being deployed in a number of countries around the world (e.g. Sugier and Tabary, 2006; Chandrasekar et al., 2009; Bringi et al., 2011; Wang et al., 2011b; Kim et al., 2012; Vasiloff, 2012; Berkowitz et al., 2013), and it is likely that in the near future most existing single-pol radars will be upgraded to dual-pol. However, despite the advantages of this new technology and the better QPEs that can be achieved with it, dual polarisation will not change the limitations inherent to radar, such as the fact that rainfall is measured indirectly, often well above the ground and often far away from the radar, which results in beam broadening and range degradation.

The uncertainties in QPEs propagate through hydrological and hydraulic models and their effect is particularly evident at the small scales of urban catchments (Collier, 2009; Schellart et al., 2012; Vieux and Bedient, 2004). Gauge-based adjustment of radar QPEs has proven effective to reduce these errors and improve the accuracy of the estimates, thus improving their applicability for hydrological applications (Harrison et al., 2009). However, most gauge-based adjustment methods have been tested and applied at large spatial and temporal scales (Anagnostou and Krajewski, 1999; Cole and Moore, 2008; Fulton et al., 1998; Germann et al., 2009; Gerstner and Heinemann, 2008; Goudenhoofdt and Delobbe, 2009; Harrison et al., 2009; Seo and Smith, 1991; Todini, 2001). Relatively few tests have been conducted at urban/small scales and all of them have concluded that at these scales more dynamic and localised adjustments are required (Borup et al., submitted; Sinclair and Pegram, 2005; Wang et al., 2013b). In fact, at urban scales, commonly used coarse-scale methods such as Mean Field Bias (MFB) correction have proven to be insufficient, while other more dynamic and higher (statistical-) order methods (e.g. geostatistical methods) have exhibited a better ability to reproduce fine-scale rainfall structures and dynamics (Wang et al., 2015).

With regards to the resolution of radar QPEs, recent studies suggest that the currently commonly available resolutions (i.e. ~1 km/5–10 min) may be insufficient for urban-scale applications. In fact, the effect of insufficient spatial–temporal information of rainfall inputs on urban hydrological simulations may be as significant as that caused by insufficient accuracy. This is especially the case when the drainage area of interest is small (Gires et al., 2014, 2012; Schellart et al., 2012; Wang et al., 2012). Therefore, the impact of rainfall data resolution should not be ignored in urban hydrology. Although the spatial and temporal resolution of rainfall inputs are strongly related, a number of studies have suggested that the latter generally constitutes a more critical factor than the former (Ochoa-Rodríguez et al., in press; Singh, 1997; Thorndahl et al., 2014) and that temporal resolutions of ~1–2 min (i.e. below those currently available) are required for urban hydrological applications, while spatial resolutions of ~1 km (i.e. close to those currently available) appear to be sufficient. The predominant effect of temporal resolution, as well as the above mentioned resolution requirements for urban hydrological applications are illustrated in Fig. 1 (adapted from Ochoa-Rodríguez et al., in press). Moreover, it is often the case that local rain gauge (RG) records are available at temporal resolutions finer than those of radar QPEs. However, in order to perform local gauge-based adjustments, the RG records are usually aggregated to the temporal resolution of radar QPEs, thus losing valuable information. In fact, for small-scale applications, recent studies suggest that performing gauge-based adjustment of radar QPEs at shorter time intervals leads to better results than doing so at longer intervals (Borup et al., submitted; Thorndahl et al., 2014). Traditional strategies for obtaining higher temporal resolution radar QPEs include changes in radar scanning and sampling strategies (Delobbe et al., 2008; Gill et al., 2006; Sadjadi, 2000; Tabary, 2007; Zhang et al., 2005) and stochastic downscaling (Deidda, 2000; Gires et al., 2012; Gupta and Waymire, 1993; Koutsoyiannis and Onof, 2001; Marsan et al., 1996; Pegram and Clothier, 2001; Segond et al., 2006; Tessier et al., 1993; Wang et al., 2010). The former is not always possible, due to hardware and operational limitations. With regards to the stochastic temporal downscaling, albeit applications exist that meet the high temporal resolution requirements mentioned above (~1–2 min; e.g. Gires et al., 2014), they result in large ensembles, which are difficult to use operationally, given the runtimes associated to urban hydrodynamic models (Leandro et al., 2014). More recently, an advection based temporal interpolation method, combined with MFB correction, has been proposed by (Nielsen et al., 2014; Thorndahl et al., 2014). Although this method has shown to improve the performance of hourly and daily radar QPEs (assessed through comparison against ground rain gauge measurements), its performance at sub hourly scales was inconsistent. The unsatisfactory performance at smaller scales may be explained by the way in which storm movement is estimated in advection-based techniques, as well as by the MFB-based adjustment techniques that were employed, which may be insufficient to well capture and preserve the small rainfall structures relevant at urban scales (Gao et al., 1999; Germann and Zawadzki, 2002; Van Horne, 2003; Laroche and Zawadzki, 1995; Rinehart and Garvey, 1978; Wang et al., 2013b; Weickert and Schnörr, 2001; Wilson et al., 2004).

In this paper a methodology is proposed for producing accurate radar rainfall estimates with high temporal resolution, suitable for urban hydrological applications. Similar to the method proposed by Nielsen et al. (2014), the procedure proposed herein entails two main steps: (1) temporal interpolation of radar images, followed by (2) gauge-based adjustment of radar QPEs at short time intervals (1–2 min). Nonetheless, different from Nielsen's method, the techniques employed in this study to carry out the aforementioned steps are particularly well suited to capture and reproduce small-scale rainfall structures, thus making the proposed method more appropriate for urban hydrological applications. For the first step, a novel temporal interpolation technique, based upon the multi-scale variational optical flow technique, is proposed to generate high temporal resolution (i.e. 1–2 min) radar