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Research papers

A Bayesian partial pooling approach to mean field bias correction of weather radar rainfall estimates: Application to Osungsan weather radar in South Korea

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ABSTRACT

The use of radar rainfall estimates has been limited by the lack of a reliable method of obtaining operationally accurate radar-based rainfall estimates and the associated potential errors embedded in the retrieval process. Moreover, the existing approaches have difficulty merging ground- and radar-based measurements due to spatial and temporal variations in bias as well as the uncertainties in model parameters that also can affect the overall bias. This study proposes a novel approach for radar rainfall estimates using a hierarchical Bayesian model (HBM) in the context of bias correction. In particular, three different variations (i.e. the partial-pooling model (PPM), complete-pooling model (CPM), no-pooling model (NPM)) of the HBM are explored to better characterize the bias correction factor and the associated uncertainty. In the case of the CPM, rain gauges are assumed to have a constant bias level over the spatial domain, which results in a significant increase in RMSE. Conversely, in the NPM approach, the parameters are independently estimated for each station, resulting in an increase in the uncertainty of the parameters caused by compensating for the estimates of other parameters; this approach also leads to a substantial increase in the RMSE. Here, we introduce the PPM approach, which aims to jointly estimate correction factors across all gauging stations, while considering the covariance structure of both parameters and model errors. The results obtained for the PPM show a noticeable reduction in the uncertainty of the parameters when compared to that of the NPM. We also note a decline in the bias of radar rainfall estimates. Finally, we further utilize the proposed PPM-based bias correction approach as an ensemble generator for simulation of radar rainfall estimates. The simulated rainfall ensembles can satisfactorily reproduce key statistical properties retrieved from ground reference measurements.

1. Introduction

The Korean Peninsula extends about 1100 km southward from the eastern part of the Asian continent, with a width of roughly 300 km. More than 60% of the land is mountainous, especially in the northern and eastern regions of the peninsula. Hence, sub-catchment areas are generally less than 500 km^2 and times of concentration are very short due to the steep slopes. Korea is part of the East Asia monsoon system and receives about two-thirds of its annual precipitation over the summer season, between late June and early September (Kwon et al., 2016; Lee et al., 2012). A marked spatio-temporal variation in precipitation has been observed, with complex spatial patterns resulting from the interaction of rainfall with the topography.

The flood-warning system, which largely depends on ground rain gauges, may be inadequate in areas where there is large spatial variability in precipitation (Jayakrishnan et al., 2004). Moreover, precipitation forecasts of numerical weather prediction models are often poor, especially in mountainous areas (Mendes and Marengo, 2010; Schwitalla et al., 2008). It is therefore difficult to predict and manage potential risks associated with floods and their consequences in South Korea. In this context, weather radar provides many advantages over ground-based rain gauges. For instance, weather radar can remotely estimate both precipitation and wind, with high spatio-temporal resolution and in regions where no ground-based data is available, such as oceans. This information can be used to improve the flood modeling process and early warning system. More specifically, weather radar offers the advantage of being able to continuously detect rainfall events over a relatively large area in real time, and document spatial rainfall patterns over unmonitored watersheds. Flash flood forecasts may benefit from weather radar due to its ability to quickly determine the

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spatial distribution of a storm over the area of interest.

Although the use of weather radar has many advantages, it is widely recognized that the direct use of weather radar precipitation data in hydrologic models is complicated by systematic bias in radar measurements (Bárdossy and Pegram, 2017; Biggs and Atkinson, 2011; Seo, 1998; Seo et al., 1999). Here, systematic bias can be defined as the consistent underestimation or overestimation of rainfall estimates (Einfalt et al., 2004). Therefore, correcting the systematic error (or bias) of radar data has been crucial to the use of radar-based precipitation in conjunction with hydrologic models (Yoo et al., 2014); errors are typically reduced by merging radar measurements with ground-based rainfall estimates (Einfalt et al., 2004).

In addition to systematic error, there are many different types of errors associated with the radar measurement, including nonlinearity between the echo intensity and the rain drops (Berne and Uijlenhoet, 2005; Kummerow, 1998; Lafont and Guillemet, 2004; Sassi et al., 2014), errors between the precipitation intensity and the radar reflectivity (Anagnostou et al., 1998; Steiner et al., 1999; Villarini and Krajewski, 2010a, 2010b), errors associated with the curvature of the earth's surface in a remote location from the radar site (Joss et al., 1990; Yoo et al., 2014; Yoo et al., 2010) and range-dependent bias related to systematic bias in space (Borga and Tonelli, 2000; Chumchean et al., 2004; Fulton et al., 1998; Seo et al., 2000; Zhang et al., 2014). A number of approaches to bias correction have been explored (Chumchean et al., 2004; Chumchean et al., 2006; Dai et al., 2015; Goudenhoofdt and Delobbe, 2009; Harrison et al., 2000; Hasan et al., 2014; Rabiei and Haberlandt, 2015; Seo and Breidenbach, 2002a; Thorndahl et al., 2014; Todini, 2001).

The gauge-radar (GR) ratio approach has been the most commonly used method for correcting the systematic bias of radar precipitation data. The GR ratio can be defined as the ratio of gauge precipitation to radar precipitation, and several variations and applications of the GR ratio approach have been presented over the last several decades (Anagnostou et al., 1998; Anagnostou et al., 1999; Borga and Tonelli, 2000; Chumchean et al., 2006; Collier, 1986; Habib et al., 2008; Hanchoowong et al., 2012; He et al., 2011; James et al., 1993; Smith and Krajewski, 1991; Wilson, 1970; Yoo et al., 2014). In view of the above, this study also used the GR ratio approach to correct the systematic bias. In part, previous efforts have been fueled by the increased availability of radar data as well as the recognition of many potential applications in the field of hydrology. However, merging ground- and radar-based measurements is a very complicated problem due to the fact that the bias is a function of space and time (Seo et al., 2000), and uncertainties in ground rain gauge measurements (Legates, 2000; Steiner et al., 1999; Villarini et al., 2008) can affect the overall bias as well. In these contexts, this study proposes a novel approach intended to preserve common features across ground rainfall gauges and to estimate uncertainty in the context of the bias correction process within a Bayesian modeling framework.

The existing bias correction approaches based on the GR ratio are routinely applied to radar-gauge pairs that are pooled across all gauges located inside the area of interest, which is termed as a complete-pooling model (CPM) in the Bayesian sense. The CPM assumes that the same GR ratios apply to all gauges for a specific radar rain rate, which excludes spatial variations among gauges (Devineni et al., 2013; Gelman, 2006a). Specifically, the CPM yields identical correction factors for all gauges, which is especially inappropriate for the case where there is significant spatial variation in the bias level. An alternative approach is to independently compute the GR ratio for each gauge location, which is called a no-pooling model (NPM) from a Bayesian inference point of view. The NPM treats each parameter as independent so that the model often overfits the data, leading to implausibly high estimates where data is particularly insufficient (Devineni et al., 2013; Kim et al., 2017). In other words, uncertainties associated with the parameters (i.e. GR ratios) are relatively high.

In this study, we propose a partial-pooling model (PPM) to estimate GR ratios at multiple stations within a regression framework. A radar rainfall ensemble generator is also developed using the posterior distributions of the GR ratios. Unlike the classical CPM and NPM approaches, the PPM provides more reasonable estimates, in which the model parameters are jointly estimated across multiple locations by accounting for correlations of both parameters and residuals across rainfall gauges. In this manner, correlated radar measurements from different locations may provide information on the estimation of bias-corrected rain rates by partial pooling of common information within a hierarchical Bayesian model (HBM) framework. Hence, the PPM approach theoretically yields lower uncertainty in parameter estimates by minimizing the independent parameters. Uncertainty in the bias-corrected rain rates can in turn be reduced in a similar way (Devineni et al., 2013; Kim et al., 2017; Kwon et al., 2011). PPM-type models have been used recently to estimate parameters and their uncertainties in hydrologic studies of extreme events (Kwon et al., 2008a; Kwon and Lall, 2016; Kwon et al., 2016; Lima et al., 2016a; Lima and Lall, 2009a; Lima et al., 2015; Najafi and Moradkhani, 2014; Renard and Lall, 2014; Sun et al., 2015). However, the use of Bayesian models for bias correction has not been well established in radar hydrology. There have been limited studies in the context of Bayesian modeling of radar measurements (Hossain et al., 2004; Seo and Smith, 1991; Todini, 2001), and the Bayesian models used in these studies are not equivalent to the one proposed in this study. Here, we attempt to use the existing formulation of GR methods – instead of modifying their functional forms – and employ a hierarchical partial pooling approach for the estimation of parameters (i.e., GR ratio) within a Bayesian framework.

In this section, we provided a brief overview of the past research. Ground rainfall data and radar measurements are summarized in the following section, and theoretical aspects of hierarchical modeling framework are described in Section 3. The results obtained from this study are presented and discussed in Section 4. Finally, we offer a summary and concluding remarks.

2. Weather radar and rain gauges

2.1. Weather radar measurement

The Korea Meteorological Administration (KMA) began the installation of its first modern weather radar on Mt. Kwanak in 1969. During the late 1980s, the government established a national weather Doppler radar network covering the entire Korean Peninsula, and 11 S-band weather radars are currently operated by KMA. In this study, the Osungsan radar (36°00′46″, 126°47′03″) was used to validate the proposed bias correction scheme. The original Osungsan C-band radar was installed in 1991 to monitor precipitation on the west coast of the Korean Peninsula. In 2007, it was replaced by an S-band weather radar, which offers more accurate precipitation estimates. Recently, dual polarization radar was adopted to improve the accuracy of precipitation estimates in South Korea. Detailed specifications of the Osungsan weather radar station are presented in Table 1.

The open radar product generator (ORPG) of the KMA weather

Table 1
Specifications of the Osungsan weather radar system used in this study.

Model Name	WSR-98D/S	
Latitude	36°00′46″	
Longitude	126°47′03″	
Observation distance	Effective	240 km
	Maximum	480 km
Antenna Speed	12°/s	
Bin Size	250 m	
Bin Number	957	
Altitude	231 m	
Frequency	2.735 MHz (S-band)	