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On the scale-dependent propagation of hydrologic uncertainty using high-resolution X-band radar rainfall estimates

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ABSTRACT

Radar precipitation estimates can improve hydrologic prediction over a range of spatial scales represented by both rural and urban basins. Flooding results from the combination of heavy precipitation and the distributed hydraulic and hydrologic characteristics of the basin. Accuracy and spatial scaling of radar estimated rainfall, and its impact at relevant hydrologic scales is an important determinant of hydrologic prediction accuracy and flood forecasting. Results of simulations using archival radar events are used to demonstrate the sources of uncertainty affecting site-specific flood forecasts within the distributed hydrologic model, Vflo. Radar data used in this analysis are derived from both S-band (NEXRAD/88D) and the Collaborative Adaptive Sensing of the Atmosphere (CASA), polarimetric X-band radars. X-band radars have the capability to provide higher spatial and temporal resolution than the conventional radars operating at S-band. However, compared to S-band, X-band radars have shorter wavelengths and suffer from attenuation, or even total extinction of the radar signal at short ranges from the radar. Degradation of precipitation mapping is a serious concern, especially in heavy precipitation over distances associated with watersheds prone to flooding. Compared to rain gauge accumulations, X-band radar polarimetric rainfall estimates were significantly degraded beyond about 15 km from the radars. With rainfall input derived from X-band radars, uncertainty in runoff volume scales with watershed area as a smooth monotonically decreasing function as area increases due to averaging of random errors in the input. Relative to estimates derived from S-band radar, unreliable hydrograph response was produced using X-band polarimetric rainfall estimates as input to a physics-based distributed hydrologic model, especially for watershed areas less than about 20 km^2.

1. Introduction

In recent years, with advances in polarimetric radar correction techniques, short wavelength radars (such as X-band) are able to acquire high-resolution data for quantitative precipitation estimation (QPE). In the US and elsewhere, there is interest in deploying networks of X-band radars in regions that experience high impact weather, such as high winds, floods, and tornadoes or where the *Next* Generation Weather Surveillance *Rad*ar (NEXRAD or WSR-88D) coverage is lacking or insufficient. A network of X-band radars would be able to provide near-ground observations to better observe weather in the lowest few kilometers of the atmosphere. Recent research and development by the Engineering Research Center, Collaborative Adaptive Sensing of the Atmosphere (CASA) is described by McLaughlin et al. (2005) who estimate that a network of approximately 10,000 such radars would be required to cover the contiguous U.S. with a radar spacing of 30 km. Several studies (Matrosov et al., 2002, 2005a; Anagnostou et al., 2004) over the last decade have looked at the utility of X-band radar in quantitative precipitation estimation (QPE). Krämer et al. (2009) and Berne et al. (2004) among others have investigated the utility of radar for hydrologic and hydraulic modeling applications, particularly relative to urban

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watershed scales. Indeed, the propagation of uncertainty in radar rainfall estimates in hydrologic models has been investigated as in Collier (1999). These studies have shown that X-band radars can overcome attenuation by using various schemes to correct for the attenuated radar signal. Many of these studies did not investigate accuracy of QPE with X-band radar beyond 15 km from the radar site, especially those reported by Matrosov et al. (2002, 2005a) and Anagnostou et al. (2004). The research reported herein examines the use of polarimetric X-band quantitative precipitation estimates (QPE) over watershed areas and how uncertainty scales with watershed size. Comparison of X-band rainfall estimates with a dense rain gauge network called the Oklahoma Micronet makes it possible to analyze rainfall estimates as a function of range from the radars. To test the scaling effects of the rainfall estimators, a watershed called Line Creek, located within an overlapping area of two X-band radars, is used to aggregate rainfall estimates and evaluate area-dependent watershed response.

1.1. Polarimetric rainfall estimation

Although correction techniques greatly mitigate signal attenuation issues and extend the usable range of X-band rainfall measurements, total signal loss can and does occur at short ranges when the signal travels through extended areas of rainfall, thus limiting the range of the radar. Although several polarimetric rainfall estimators exist by combining various polarimetric variables, there are two common estimators used in the X-band QPE studies mentioned previously.

Much like the form of any *Z–R* relationship, the specific differential phase estimator follows a power-law relationship,

$$R = aK_{DP}^{b} \qquad (1)$$

where, a and b are constants, R is rainfall rate (mm hr^{-1}), and K_{DP} is the specific differential phase measured in deg km^{-1}. Because estimates of K_{DP} are not affected by attenuation, radar calibration errors, errors in measuring transmitter power, beam blockage, and have a weaker dependence on details of raindrop size distributions compared to the reflectivity-based estimators, it has been widely used in rainfall estimation for both S- and X-band radars. However, due to the general noisiness of phase measurements (especially at lower rainfall-rates) and some dependence of K_{DP} estimates on the choice of the range interval used for deriving the phase derivative, K_{DP}-based approaches are better suited for retrievals of time (or space) integrated rainfall accumulations rather than for instantaneous rainfall rates (Matrosov et al., 2006). One advantage of X-band over S-band radar is that a significantly stronger differential phase shift is experienced, which is proportional to the radar frequency (for Rayleigh scattering). This amounts to an increase at X-band by a factor of 3 when compared to S-band (Matrosov et al., 2002). Due to stronger signal characteristics at X-band than S-band, K_{DP}-based rainfall estimators are able to detect and estimate rainfall rates in areas of light precipitation better at X-band frequencies. Matrosov et al. (2006) showed that K_{DP} values above 0.1 deg km^{-1} at X-band, which corresponds to about 26–27 dBZ, were useful, while at S-band, K_{DP} values were not useful until reflectivity levels reached 35–40 dBZ. Because of the uncertainties in K_{DP} estimates at low phase shifts, a *Z–R* relationship is often better for calculating rainfall rates below the mentioned thresholds (Matrosov et al., 2006 and Ryzhkov et al., 2005).

One source of uncertainty in $R–K_{DP}$ relationships is due to the variability of raindrop oblateness-size dependence since the commonly assumed equilibrium drop shape is not unique. This dependence results in a change of the coefficient in the $R–K_{DP}$ relationship, with little change to the exponent. Tuning the parameters of the $R–K_{DP}$ relationships, Eq. (1), requires knowing b, the shape factor or slope parameter of this dependence (Matrosov et al., 2006). Another polarimetric estimator used in the previous X-band QPE studies combines three polarimetric variables to estimate rainfall as,

$$R = Z_{eh}^{a}K_{DP}^{b}Z_{dr}^{-c} \qquad (2)$$

where, a, b, and c are constants; R is rainfall rate (mm hr^{-1}); Z_{eh} is the horizontal reflectivity (mm^6 m^{-3}); K_{DP} is the specific phase (deg km^{-1}); and Z_{dr} is the differential reflectivity in linear units. This polarimetric estimator (referred to as the *combined estimator* herein) suggested by Matrosov et al. (2002) implicitly accounts for changes in the shape factor, b, within the resolution volume when making an estimate of instantaneous rainfall rates and shows only modest sensitivity to the details of the drop size distribution. Since the combined polarimetric estimator in Eq. (2) utilizes power measurements, a correction technique must be applied to account for attenuation and differential attenuation of the radar signal.

1.2. Previous X-band QPE studies

Previous QPE studies using X-band radar, Matrosov et al. (2002, 2005a) and Anagnostou et al. (2004), have shown promise in the ability to accurately estimate rainfall at close range to the radar. Although the typical usable range of X-band radars is generally limited, each of the three studies only utilized disdrometer and rain gauge estimates within 15 km of the radar site to determine rainfall estimation accuracy. Matrosov et al. (2005a) suggested that a more thorough assessment of X-band QPE over a denser network of rain gauges at greater distances is desirable. Comparison of radar rainfall accuracy in these studies relies on bias and standard deviation of the radar estimate relative to rain gauge totals over some integration period, i.e. storm total or arbitrary time interval. In keeping with the previous studies by Matrosov and Anagnostou, the same equations used to assess uncertainty are used. The average relative bias and standard deviation are calculated for each event as,

$$bias = \left\langle \left(A_r - A_g\right)A_g^{-1} \right\rangle \qquad (3)$$

$$(sd)^2 = \left\langle \left(A_r - A_g\right)^2 A_g^{-2} \right\rangle \qquad (4)$$

where, brackets denote averaging; A is accumulation; and subscripts r and g refer to radar and gauge, respectively. Table 1 summarizes the variability of radar-gauge differences found in earlier studies for three geographically diverse regions, Wallops Island, VA, Fort Ross CA, and Iowa City IA. Results from Matrosov et al. (2002, 2005a) were computed using gauge and radar-derived rainfall on a storm total basis while results from