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Evaluation of radar precipitation estimates near gap regions: a case study in the Colorado River basin

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Radar precipitation estimation is very useful for hydrological and climatological studies. However, radar precipitation has inherent difficulty in estimating precipitation in mountainous regions. In developed countries such as the United States where there are extensive precipitation radar networks, gaps in the radar precipitation field are usually due to radar beam blockage by mountains. The goal of this study is to evaluate the performance of a daily radar precipitation field (Stage-II) against rain gauge measurements near radar gap areas in the Colorado River basin of the United States (southwestern Colorado, southeastern Utah, northeastern Arizona and northwestern New Mexico). We evaluated daily precipitation data for the years spanning from 2007 to 2009. Statistical score skills including correlation and bias are used for evaluation. Compared to gauge measurements, Stage-II fails to capture the altitude dependence of precipitation in the region. Bias analysis shows that Stage-II underestimates precipitation at higher elevation. Seasonal evaluations of Stage-II indicate that it underestimates cold season precipitation in the study area. Overall, the results show that the error in Stage-II precipitation estimates made within 100 km from the gap area, as measured against rain gauge measurements, is considerable, and caution is warranted for its use in hydrological and water management applications.

1. Introduction

The objective of this study is to provide some insight into the performance of radar precipitation estimates surrounding gaps in the Colorado River basin of the southwestern United States. Weather radar scans at different tilt angles. If more than 50% of a selected tilt angle scan is blocked, the next tilt angle scan will be used in the *Z*–*R* (radar reflectivity (*Z*) and rainfall (*R*)) relation. The *Z*–*R* relation is a mathematical equation used in radar precipitation estimation. In areas where high mountains are prevalent, there are permanent gaps in the radar precipitation field. Gaps may appear because radars have difficulty in eliminating ground echoes caused by blocking of radar beams by high mountains. Also, orographically enhanced precipitation occurring at relatively low altitudes limits the range of usable reflectivity to below the melting layer (Gourley et al. 2002). Above this level, the capacity of the Weather Surveillance Radar-1988 Doppler (WSR-88D) network to estimate precipitation is limited (Westrick, Mass, and Colle 1999). This in turn decreases the effective radar coverage area significantly. Even if the problem of beam attenuation by

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heavy precipitation is solved by using 10 cm wavelength radars as in the NEXt generation RADar (NEXRAD) network, radars suffer from anomalous signal propagation and bright band contamination. Bright band contamination occurs when radar beams intersect the freezing level of the cloud, which can lead to overestimation of precipitation by up to a factor of 10 (Gourley et al. 2002; Smith 1986).

Radar precipitation estimates are thus often erroneous close to high mountains despite corrections. The original WSR-88D algorithm considered quality controls isolated targets and ground clutter, tilt test and anomalous propagation and partial beam correction (Fulton et al. 1998) for the *Z*–*R* relationship. More recent studies developed a range dependent bias correction algorithm (Seo, Ding, and Fulton 2002), ground clutter removal using the radar echo classifier (REC) (Kessinger, Ellis, and Andel 1999), vertical profile of reflectivity (VPR) variability (Vignal and Krajewski 2001) and convective-stratiform separation algorithm (CSSA) (Seo, Ding, and Fulton 2002), which have been pivotal in addressing such difficulties. A fundamental improvement in accuracy of radar based quantitative precipitation estimation (QPE) is further expected with the implementation of dual polarization (Krajewski and Smith 2002). The implementation of dual polarization will also help classify different sources of errors in radar reflectivity data such as attenuation, non-uniform beam filling, partial beam blockage, biological scatter and receiver noise (Ryzhkov, Giangrande, and Schuur 2003; Schuur et al. 2003). Despite these efforts, the current study will show that the existing corrections near mountain gap areas are not sufficient to achieve reliable radar rainfall estimates. Evaluation of radar precipitation estimates using rain gauge measurements in mountainous regions has already been carried out in previous studies. For example, Young et al. (1999) evaluated the performance of radar precipitation estimates in the Appalachian Mountains. However, studies specifically near radar gap areas are limited. In addition, previous work has studied performance as a function of distance from the location of the radar, while the present study evaluates radar precipitation estimates as a function of distance to radar gaps, which provides a different perspective on where terrain and meteorological effects are likely to make current radar-derived precipitation estimates unreliable.

Errors in precipitation estimates propagate into hydrological, climatic and water resources management models. Hence, the error characteristics of precipitation products deserve emphasis. Calibration/validation and error analysis studies are significant in allowing for informed use of precipitation products.

2. Data and methodology

2.1. Radar Stage-II

Hourly radar Stage-II precipitation products downloaded from University Corporation for Atmospheric Research (UCAR) for the years 2007–2009 have been used in this study. The Stage-II product used in this study consists of radar only estimates. Stage-II products, a mosaic of more than 140 NEXRAD estimates for the conterminous US, are provided on a 4 km polar stereographic projection grid. There are two types of Stage-II products, ‘with bias removal’ and ‘without bias removal’. In this study, the ‘without bias removal’ products are used for analysis, so that the radar data are completely independent of the precipitation gauge measurements used here for validation. A region geographically bounded by 34° N–40° N and 105° W–113° W, comprising southwestern Colorado, southeastern Utah, northeastern Arizona and northwestern New Mexico (USA), was selected for this study (Figure 1). The study covers an area of about 480,000 km^2.

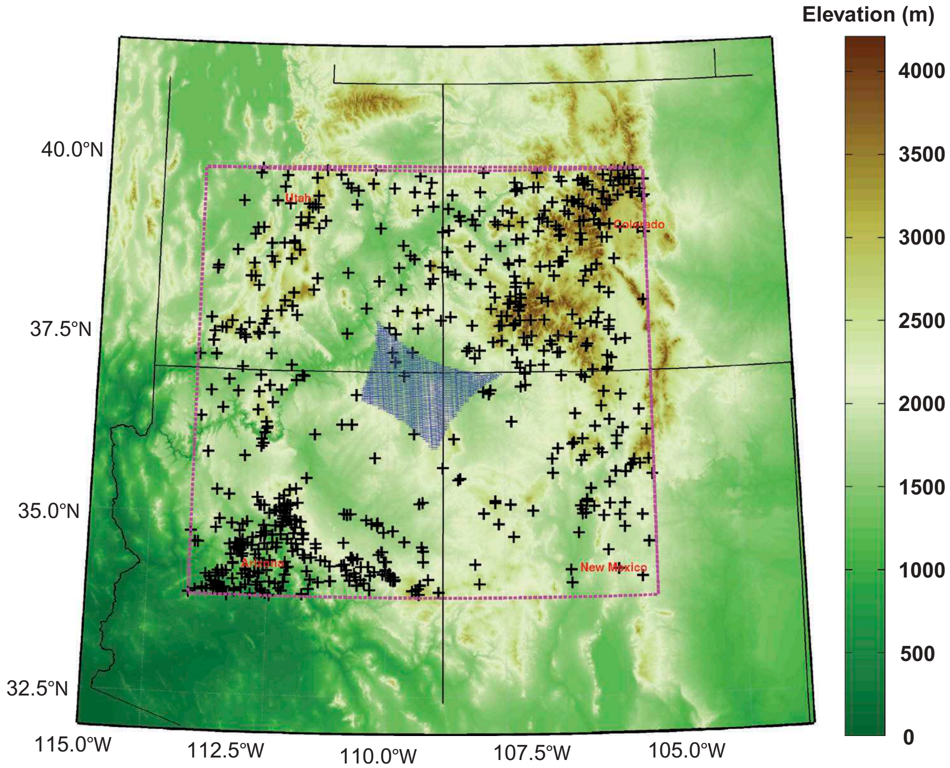

Figure 1. Study area. Crosses are the distribution of rain gauges used in this study from the NOAA Climate Prediction Center (CPC) Cooperative data sets (crosses); the area enclosed by the dashed magenta line is the study area; the area shaded in blue is the radar gap.

A few radar pixels registered precipitation values greater than around 100 mm day^{-1} for an extended period of time (more than 20 consecutive days). These pixels were confirmed as outliers by comparing their values with neighbouring pixels. We excluded these anomalous radar pixels in our analysis in order to concentrate on more typical radar outputs in mountainous areas, although if radar data are to be used in applications, it certainly would be important to identify and remove from consideration these pixels.

2.2. Rain gauges

All daily precipitation events from 2007 to 2009 are compared in this study between the radar product and available gauges. More than 600 rain gauges from National Cooperative (COOP) stations surrounding the radar gap area in the Colorado River basin are used for this study. The distribution of these rain gauges is shown in Figure 1. These gauges measure hourly, daily and event based precipitation in units of inches. We used daily accumulations of precipitation for this study. The rain gauges have the capacity of measuring as low as 0.01 inch h^{-1} (1 inch = 2.54 cm) rainfall rate. The distribution of the rain gauges around the gap is reasonably uniform. Therefore, the orientation of the rain gauges with respect to the gap is assumed to have minimal impact on the results.

3. Results

3.1. Radar-gauge scatter comparison

Correlation coefficients are the most commonly used statistical parameters to evaluate different precipitation estimates (Young et al. 1999; Dinku, Anagnostou, and Borga 2002; Zeweldi and Gebremichael 2009). Figure 2 shows scatter plots of radar rainfall measurements against rain gauge measurements. Comparisons are made based on daily rain gauge

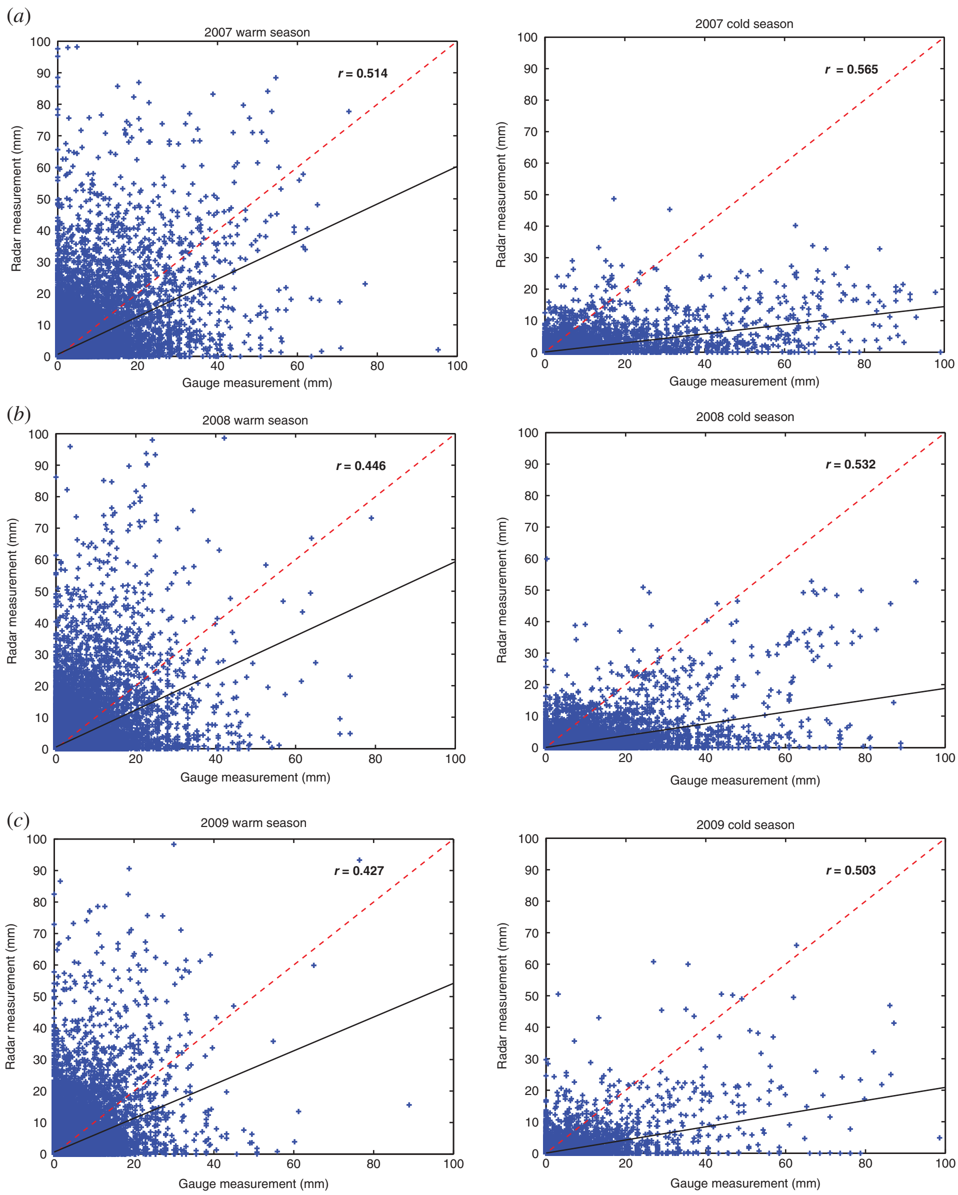

Figure 2. Scatter comparison between radar and gauge measurements. Warm season comparisons are shown on the left side and cold season measurements on the right. The red and black lines are one-to-one and least-square regression lines, respectively. r is the correlation coefficient.

measurements and the collocated radar pixel. We categorized the collocated radar and gauge data into warm- and cold-season measurements. Warm season is the time ranging from April to September whereas cold season is defined as the time period from October to March. From the scatter plots, significant variation between radar and gauge measurements is observed in both seasons. The maximum daily gauge value observed was about 125 mm in 2007 whereas for the collocated radar it was close to 170 mm. In all 3 years, radar measurements consistently underestimate precipitation during the cold season, when it often takes the form of snow. As can be seen in all of the cold-season scatter plots, the difference between radar and gauge measurements can reach up to 120 mm of precipitation per day. In the warm seasons, there is less systematic bias. In the cold seasons, radar-gauge correlation values of 0.565, 0.532 and 0.503 were observed for the years 2007, 2008 and 2009, respectively. In the warm seasons, similar correlations of 0.514, 0.446 and 0.427 were observed for the years 2007, 2008 and 2009, respectively, despite the lower systematic bias in this season (Figure 2). Temporal and spatial sampling differences between radar pixels and gauge measurements probably contribute to cause these low correlations. In addition, low correlations may have been caused due to the inability of the radar to capture the distribution of precipitation in this region. For example, Stage-II totally missed storms on days 335, 336 and 342 in 2007. We also noted that radar over-estimates the total precipitation in the warm season (Figure 3), unlike a previous study in a complex terrain in New York (Young et al. 1999). This may be related to the fact that the western and eastern US have different precipitation regimes in the warm season, with orography a more dominant factor in the West compared to the East.

3.2. Mean monthly precipitation comparisons

Figure 3 compares the mean monthly areal precipitation estimates from radar and rain gauge observations for the years 2007, 2008 and 2009. Observations from daily radar

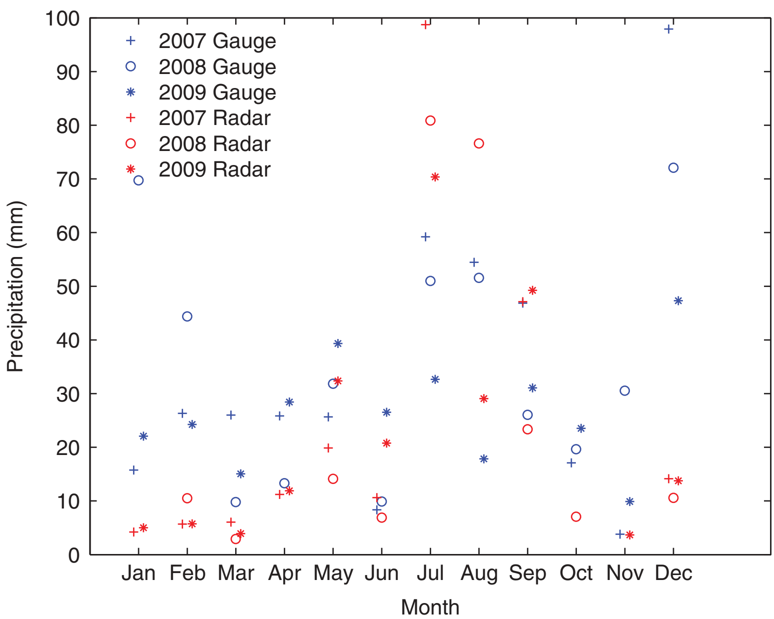

Figure 3. Mean monthly areal variations of radar and gauge measurements. Red and blue marks are gauge and radar measurements, respectively.

pixels that are collocated with rain gauges and rain gauges are accumulated to generate monthly values. The mean monthly areal precipitation from rain gauges ranges from approximately 0 mm in November 2007 to around 100 mm in December 2007. The radar product shows a similar minimum of approximately 0 mm in November 2007 and a maximum of about 100 mm in July 2007. Radars consistently overestimated the mean monthly areal precipitation in the summer time (June, July and August), except in June 2008 and 2009, and underestimated precipitation in the cold season (December–April). The mean monthly areal precipitation from the radar product shows pronounced seasonality with peaks in the summer seasons indicating July as the wettest month in the region, while gauges show inconclusive monthly variations.

3.3. Radar-gauge comparisons by altitude

Figure 4 shows the variation of precipitation estimates with altitude. The total precipitation in a year at a gauge location is calculated for rain gauges and collocated radar pixels. Radar precipitation estimates decrease with altitude while rain gauges show an increase in precipitation with elevation. The solid lines in Figure 4 are the locally weighted linear regression fits of the scatter data.

We plotted warm season mean difference in daily measurement between the radar and the gauge against the altitude of the gauge to see the variation of radar precipitation bias with altitude (Figure 5). This plot further confirms that at lower altitude the difference is positive, which means the radar overestimates precipitation. This may also be attributed to evaporation of hydrometeors before they reach the gauge (ground) level, however further study is needed to confirm the source of overestimation. As we go further up and close to the gap, the difference decreases to 0 around an altitude of 2 km above the mean sea level (AMSL). After this elevation, the radar underestimates precipitation, which is indicated by negative values in that plot. This may be because of partial beam blockage of the radar at higher altitudes.

A similar plot was made for cold season estimates (Figure 5). Like the warm season plots, the nature of bias is similar in all 3 years of studies. In the cold season, negative

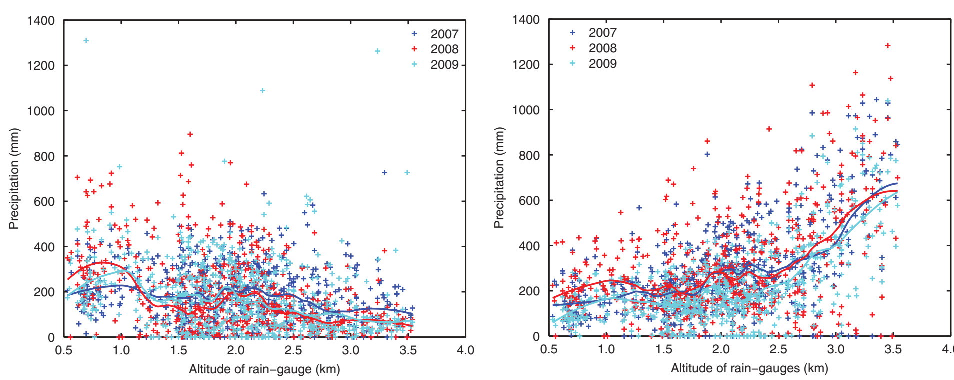

Figure 4. Total Stage-II (left) and gauge (right) precipitation estimates against elevation. Crosses are the total yearly precipitation of individual gauge and collocated radar pixel measurements, and solid lines are locally weighted linear regression fits.

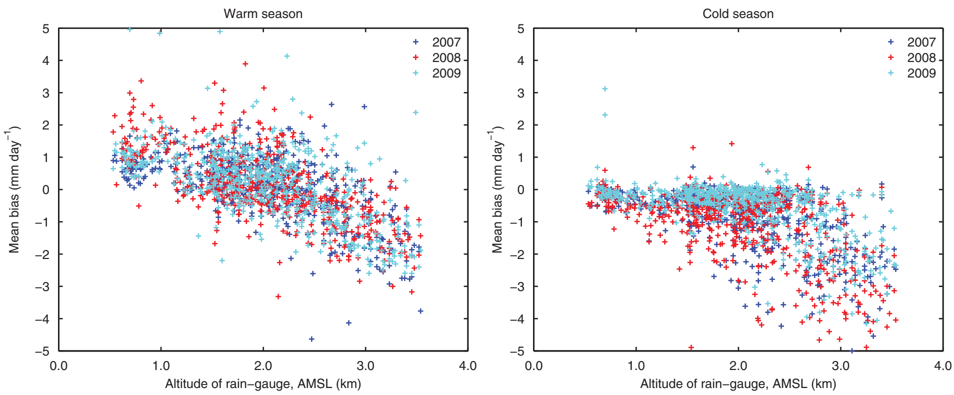

Figure 5. Variation of mean daily bias of radar precipitation estimates against rain gauge altitude above the mean sea level (AMSL).

mean bias dominates at all altitudes. This result further confirms that at high altitudes the radar underestimates precipitation.

3.4. Radar-gauge precipitation comparison versus distance from the radar gap

It is also worthwhile to evaluate radar estimates against the distance to the nearest gap pixel. The ratio of daily radar to gauge measurements is calculated at collocated locations. The calculated ratio values of the radar and the gauge are binned into 50 km ranges of distance from the Colorado plateau gap area. Figure 6 shows the mean logarithmic ratio of radar to gauge estimates versus distance of the collocated pixel to the nearest radar gap pixel. Figure 6 shows that the logarithms of the ratio values increase with distance from the nearest gap pixel. This means that estimates from the radar improve (precipitation underestimation becomes less severe) as we go farther from the gap. This result is consistent with previous studies that indicate that radar quality decreases with increasing range (Young et al. 1999; Dinku, Anagnostou, and Borga 2002). The figures also show that the radar performed poorly within 100 km from the periphery of the gap.

In addition, we also produced a plot of radar-gauge correlation coefficients as a function of distance from the gap area (Figure 7). According to Figure 7, the correlation improves with increasing distance from the gap before it stabilizes around 100 km.

4. Conclusion

The goal of this study was to evaluate the performance of the radar Stage-II precipitation estimates (Stage-II) near a gap area associated with high topography. A radar gap in the Colorado plateau was considered for the analysis. The study was carried out by collecting 3 years (2007, 2008 and 2009) of daily precipitation data from Stage-II and from COOP rain gauges. Based on the results for the mean correlation and altitude and season dependence of bias, Stage-II precipitation underestimates precipitation and shows a poorer correlation with gauge measurements within 100 km of the gap.

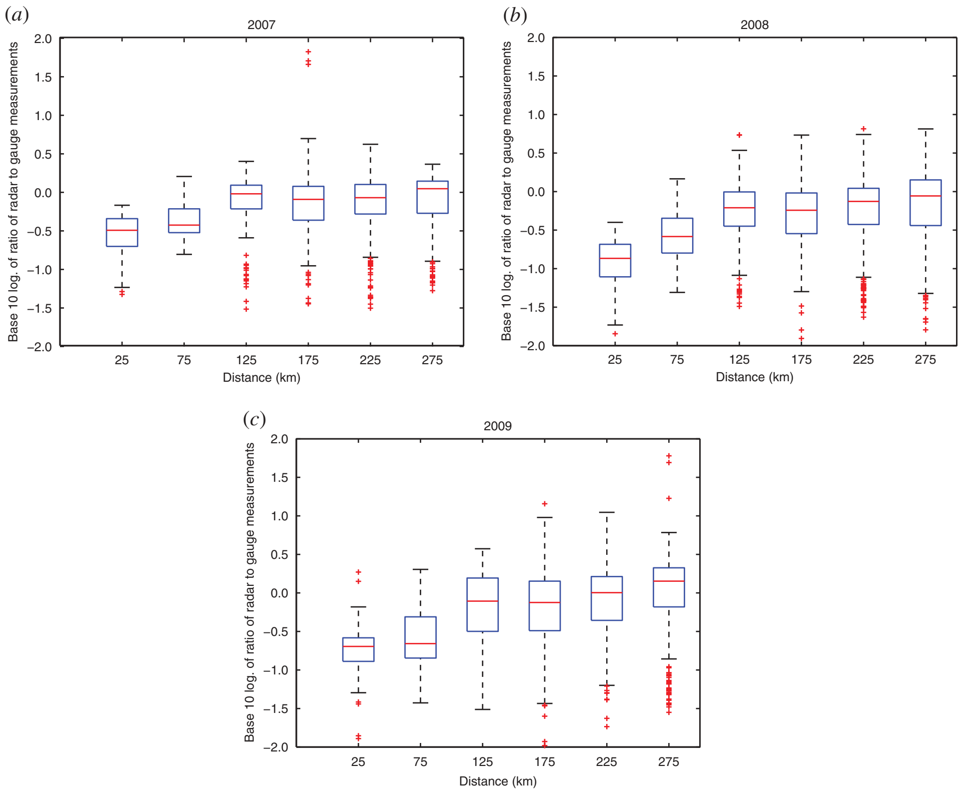

Figure 6. Mean logarithmic ratio of radar to gauge measurements. The red lines are medians. The edges of the boxes indicate the range between the 25th and 75th percentiles. The red crosses in the plot are outliers.

The analysis used precipitation pixels surrounding the gap with collocated gauges. A few collocated radar pixels registered a high amount of precipitation for an extended period of time (around 100 mm day^{-1}). These outlying pixels were discarded from the analysis because we saw them as clearly unreliable. Excluding these anomalous pixels, results show that Stage-II underestimates daily precipitation observations in the cold season and overestimates daily precipitation values in the warm season. Altitude-dependent comparisons show that precipitation in the radar product decreases with altitude whereas gauges measure increasing precipitation with altitude. Altitude dependent biases (radar-gauge) also indicate that in both the cold and warm seasons, negative mean bias increases with altitude. This result further confirms that at high altitudes radar underestimates precipitation.

In the near future, the dual-polarization of radar estimates will be implemented in the NEXRAD system by the National Weather Service, intending to improve radar precipitation estimates. Until then, precipitation estimates from radar Stage-II near radar gaps in the Colorado River basin may not be reliably usable for hydrologic studies without error (bias) adjustment. The distance from a radar gap area is shown to be an indicator of current radar product quality, with estimates close to a gap likely to be of poorer quality when evaluated against rain gauges.

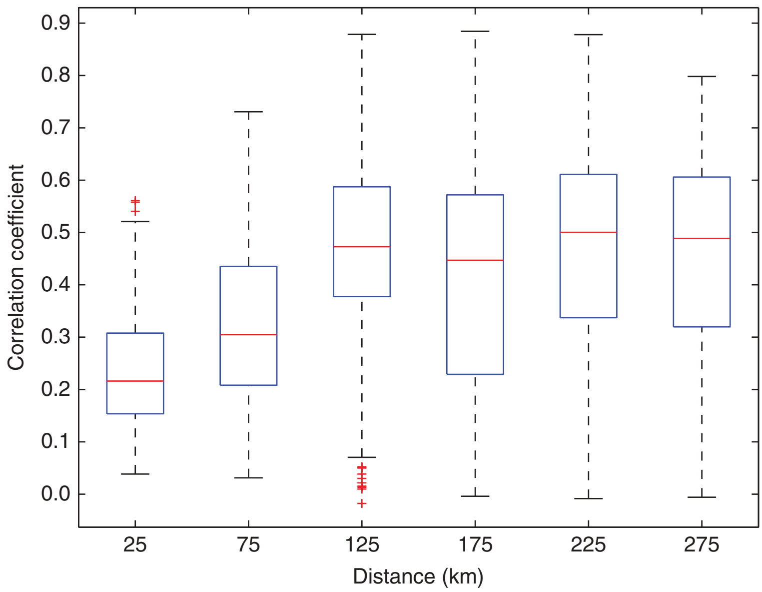

Figure 7. Correlation coefficient between radar measurements and gauge measurements. The red lines are medians. The edges of the boxes indicate the range between the 25th and 75th percentiles. The red crosses in the plot are outliers.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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