Analysis of radar and gauge rainfall during the warm season in Oklahoma

Bin Wang[1], Jian Zhang[2], Wenwu Xia[2], Kenneth Howard[3], and Xiaoyong Xu[2]

[1] Wuhan Institute of Heavy Rain, China Meteorological Administration

[2] Cooperative Institute for Mesoscale Meteorology, University of Oklahoma

[1,2,3] National Severe Storms Laboratory, NOAA

1. Introduction

During June 2007 the Oklahoma state wide average rainfall set a new all time record of 9.1 inches. There were 92 separate reports of flooding with several mesonet stations' June rainfall total exceeding 17 inches. The record rainfall combined with a dense mesonet and seamless radar coverage provided a wealth of information for studying radar-gauge relationships in fine spatial and temporal detail. Over 25,000 5-minute radar-gauge observational pairs were examined for various factors such as the z/r uncertainties in relation to different precipitation regimes. Further, uncertainties in rainfall observations as a result of hail and wind were also investigated. The analysis results indicate a wide range of challenges and issues associated with radar-gauge comparisons. The results also suggest possible strategies in quantifying and mitigating the uncertainties in quantitative precipitation estimation that employ radar and gauge observations.

Corresponding author address: Jian Zhang, NSSL, 120 David L. Boren Blvd., Norman, OK 73072.
E-mail: jian.zhang@noaa.gov

2. Data and methodology

Thirteen precipitation events during June and July of 2007 are selected for this study based on 24-hr (12:00 UTC to 12:00 UTC) stage-IV analyses (Lin and Mitchell 2005). Table 1 below lists the dates, number of gauges with non-zero 24-hour rainfall, and domain average 24-hr precipitation accumulation of each case from the Oklahoma mesonet (Brock et al 1995) observations. The dataset used in the current study included gauge rainfall observations from 127 automated tipping bucket rain gauges in the Oklahoma mesonet and radar-based quantitative precipitation estimates using a scheme developed by Xu et al (2008). Both the Oklahoma mesonet and radar QPE data were sampled at 5 minutes interval and 1-hr and 24-hr precipitation accumulations were computed from the 5-min data. The dataset also includes variables associated with the radar QPE such as the radar hybrid scanning reflectivity (HSR), the height of the HSR (HHSR), and a diagnosed precipitation type ("PCP-flag"). Additional observations including relative humidity and wind speed from the Oklahoma mesonet were used in the current study as ancillary data.

The radar QPE data contains four groups of

Table 1. Date, number of gauges with non-zero rainfall and domain averaged 24-hr storm total rainfall for selected cases

Case No.	case date (month/date)	Number of gauges with non-zero 24-hr rainfall	domain average 24-hr rainfall (mm)
1	06/01-02	91	9.37
2	06/13-14	94	24.27
3	06/14-15	104	15.25
4	06/15-16	96	8.36
5	06/18-19	52	12.25
6	06/19-20	107	30.82
7	06/20-21	76	10.63
8	06/22-23	71	9.29
9	06/23-24	60	13.76
10	06/25-26	77	14.9
11	06/26-27	115	27.65
12	07/09-10	91	33.58
13	07/12-13	107	30.62

rain rates that were derived from four different Z-R schemes, among which three use a single Z-R relationship for the whole domain, and one uses spatial and temporal varying Z-R relationships based on the diagnosed precipitation type field (The "CST" scheme, Table 2). The three single Z-R relationships are a convective, a stratiform, and a tropical, respectively (Table 2). The CST approach uses all three Z-R relationships (Xu et al. 2008). The equations for each Z-R relationship are listed in Table 2.

The precipitation type field used in the CST scheme was derived based on multiple radar three-dimensional radar reflectivity structure and atmospheric environmental data from operational numerical weather prediction model analyses (Zhang et al. 2006; Xu et al. 2008). Five precipitation regimes were diagnosed and each of them was coded with a single digit flag: stratiform – 1, stratiform above freezing level – 2, convective – 6, hail – 7, and tropical – 9. Both the HSR and precipitation type fields are updated every 5 minute, and the HSR at each given grid cell is converted to a rain rate based on the precipitation type at the grid cell in the "CST" scheme. For all stratiform grid cells, either below or above the freezing level, the stratiform Z-R relationship is applied. For all convective and hail grid cells, the convective Z-R relationship is applied except that a 49dBZ cap is imposed for the hail cases. The tropical Z-R is applied to all tropical grid cells, also with a 49 dBZ cap. Additional details about the precipitation type analysis can be found in Zhang et al. (2006) and Xu et al. (2008).

Table 2. Equations for each single Z-R relationship

Scheme #	**Z-R relationship**	Equation	
1	**Convective**	$Z=300R^{1.4}$	(1)
2	**Stratiform**	$Z=200R^{1.6}$	(2)
3	**Tropical**	$Z=230R^{1.25}$	(3)
4	**CST**	Convective, Stratiform, and Tropical Z-Rs combined	

The focus of this research was to assess the radar QPE performance using radar-gauge biases at different time scales and to examine various issues related to radar-gauge comparisons. Conditional radar-gauge biases are computed using the following equation:

$$Bias^i_{\Delta t} = \frac{R^i_{r,\Delta t}}{R_{g,\Delta t}} \qquad (4)$$

where $R_{g,\Delta t}$ represents non-zero gauge rain accumulations for different time intervals, Δt, which can be 5-min, 1-hr or 24-hr. $R^i_{r,\Delta t}$ represents the co-located radar rainfall estimate computed using i^{th} Z-R scheme (Table 2), valid at the same time and accumulated for the same time intervals as the corresponding gauge data. The minimum non-zero amount recorded by a tipping bucket gauge in the Oklahoma Mesonet for a 5 minute period is 0.25 mm, while the minimum non-zero amount for $R^i_{r,\Delta t}$ could be less than 0.25mm/5 minutes based on Z-R conversions.

3. Radar-gauge comparison at 5-minute time resolution

3.1 Five-minute gauge rainfall intensity distributions

Five-minute gauge rainfall amounts are divided into 7 categories and the histogram for all cases (see Table 1) is shown in Fig. 1. It appears that the rainfall occurs at relatively small amounts with more than 50% of the 5-min rainfall amounts between 0.25~0.5mm. Nearly 80% of rainfall events are less than 1 mm in a 5-min interval.

3.2 Contributions of various 5-min rainfall intensities to 24-hr storm total rainfall

Figure 2 shows contributions of 5-min rainfall amounts to 24-h storm total rainfall for each case. Characteristics of this distribution are largely different from the frequency distribution shown in Fig.1. Even though 50% or more of the 5-min rainfall events occur within 0.25-0.5mm, their contributions to the storm total are not significant. The average contribution from these events to the 24-h storm total rainfall is only about 15% for all the cases. On the other hand, the higher amounts of 2mm and above contributed to more than 60% of the

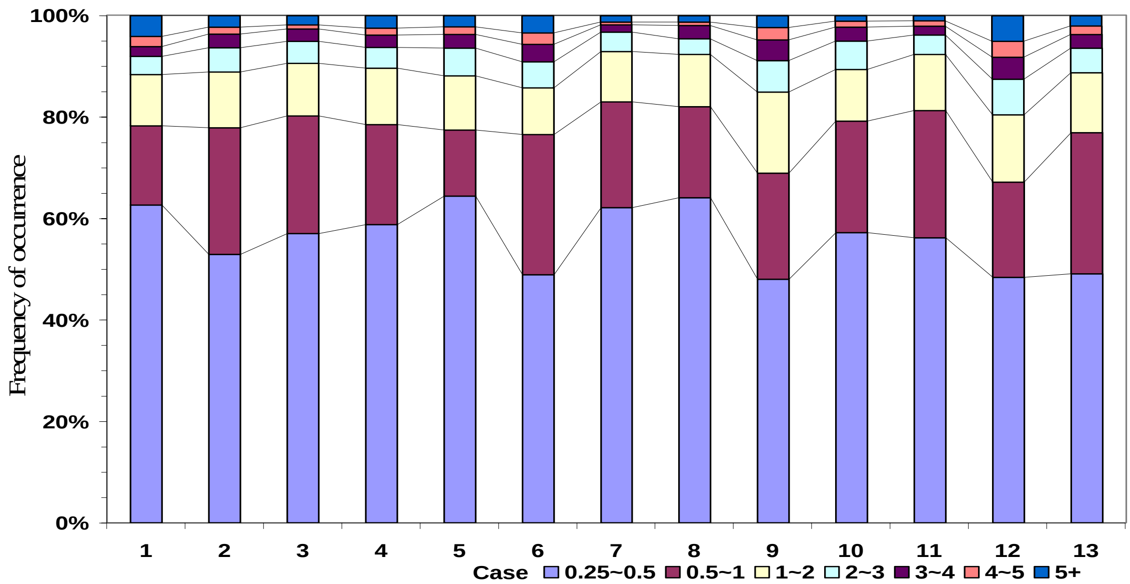

Fig 1. Histogram of different 5-min rainfall amounts (mm).

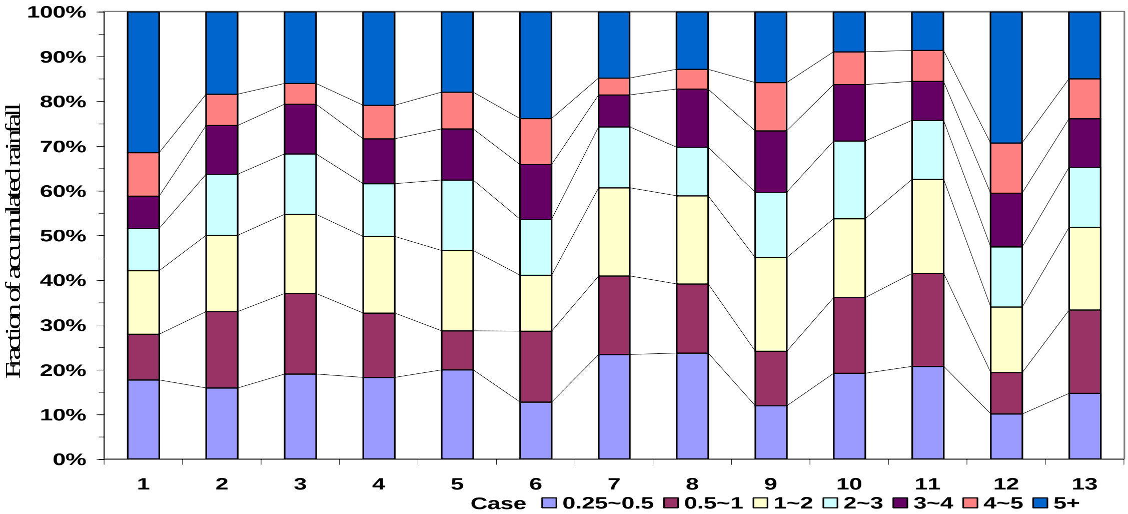

Fig 2. Contributions of various 5-min rainfall accumulations to the 24-h storm total.

total rainfall.

3.3 *Distributions of 5-min radar-gauge rainfall bias*

Five-minute radar-gauge biases for different Z-R schemes as a function of the 5-min rain gauge rainfall amounts are shown in Fig. 3. Large scatters of the bias exist below 48mm/hr (or 4 mm in 5 minutes), indicating large uncertainties of each radar Z-R scheme in estimating rainfall at the surface. The uncertainties are especially significant at rainfall intensities lower than 12mm/hr (1mm per 5 minutes). Biases for all four radar QPE schemes appear to converge as the 5-min rainfall amount increases, indicating that the uncertainties in radar QPE decreases as rainfall intensities increase. This finding is encouraging for the warning and prediction of flash floods using radar given flash floods most often occur at high rainfall intensities. Therefore the accuracy of radar QPE at high rainfall intensities is most relevant to the flash flood monitoring and detection.

For gauge 5-min rainfalls exceeding 4 mm (i.e., 48mm/hr), the CST and the tropical Z-T schemes performed significantly better than do the convective and stratiform Z-R schemes, where the latter showed a very large underestimation. Since flash floods are often associated with high-intensity rainfalls, obtaining accurate rainfall estimation at the high-intensity rainfall rates are obviously very important. Comparing Figs.3a and 3d with 3b indicates that the identification of tropical rainfall processes greatly reduced underestimation for rainfall events greater than 120mm/hr (10mm in 5-min). However, the average radar-gauge bias for these high rainfall events is still below 1 for both CST and single tropical Z-R schemes (Figs.3a and 3d), implies that 1) the tropical Z-R relationship used in the current radar QPE scheme is not fully representative of the precipitation efficiency; and/or 2) some of the tropical or warm-rain processes are not correctly identified. Further analysis is required to improve the CST scheme to address both 1 and 2.

Figure 4 shows mean bias curves for each Z-R schemes obtained by averaging biases with the same gauge 5-min rainfall. These curves highlight the overall performance of each Z-R schemes. On the average, the QPEs derived from single convective or stratiform Z-R relationship significantly

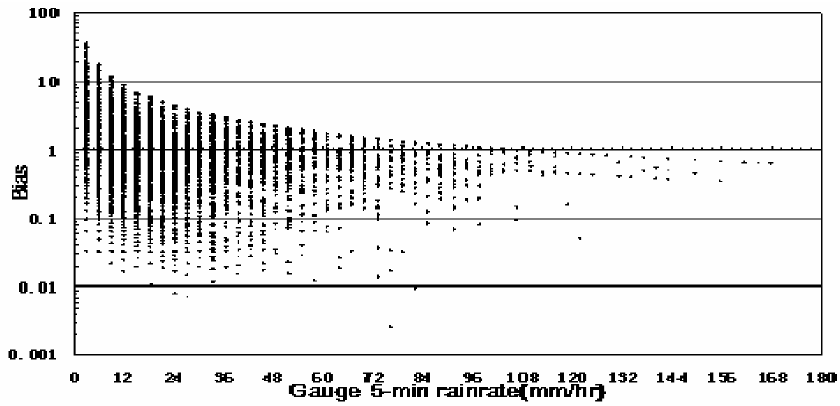

Fig. 3a

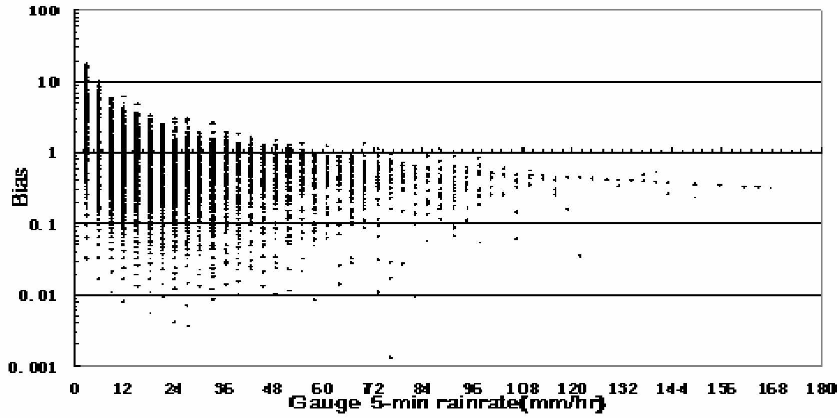

Fig. 3b

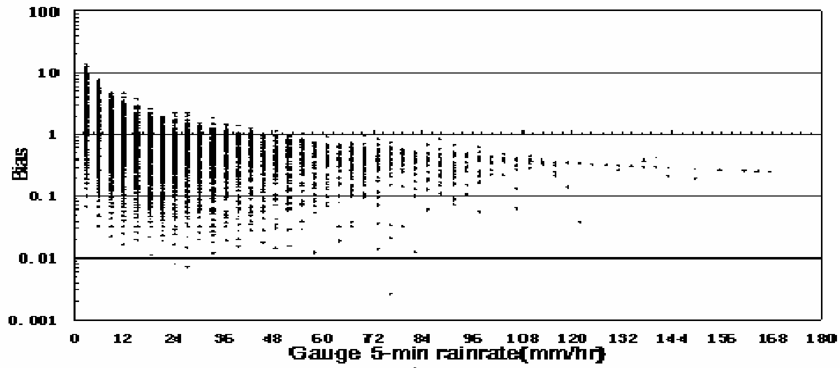

Fig. 3c

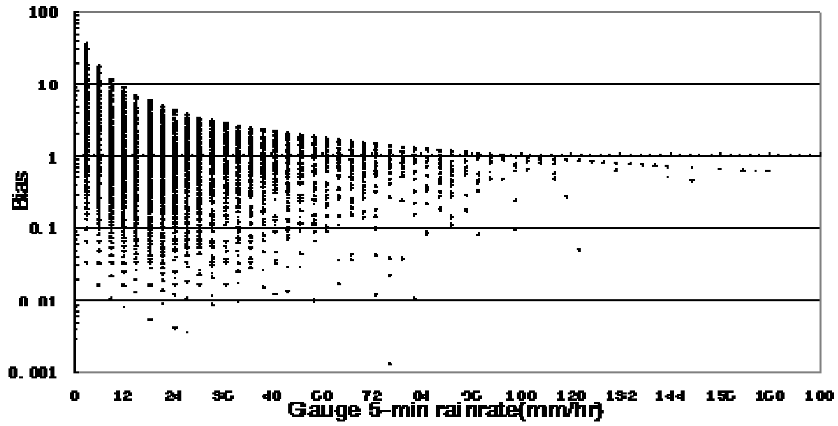

Fig. 3d

Fig. 3 Scatter plots of 5-min radar - gauge rainfall biases for the four Z-R schemes (a) CST, (b) Convective, (c) Stratiform and (d) Tropical.

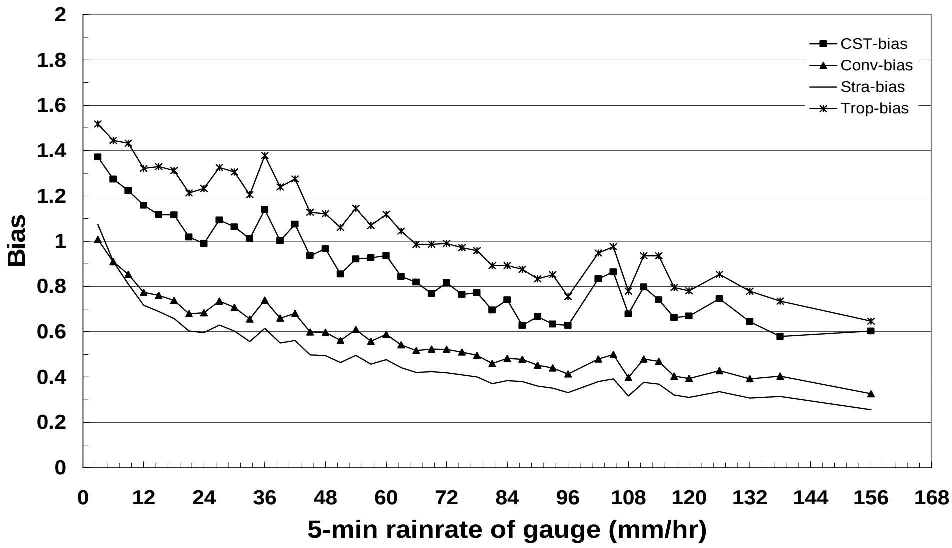

Fig. 4. Distributions of mean radar-gauge biases at different 5-min gauge rainfall intensities for the four radar QPE schemes.

underestimate rainfall except for very light amounts. The single tropical scheme provided best rainfall estimates (least biases) for the heavy rainfall events among all four schemes. This implies that most of the high intensity rainfall events during June and July 2007 in Oklahoma were predominately tropical-type rain process. Many floods/flash floods occurred in Oklahoma during the 2007 warm season, confirming that the high-intensity events were most likely high-efficient warm-rain type precipitation (Lapenta et al. 1995; Schumacher et al. 2005). However, the single tropical Z-R scheme significantly overestimates for the small rainfall events even though it provides better estimates at the higher amounts. The CST scheme has the capability of using a stratiform or a convective Z-R at the lower to medium rainfall amounts and a tropical or convective Z-R at the medium to higher amounts since it is based on a physically diagnosed precipitation type field. As a result, the CST scheme significantly improves the rainfall underestimation at large amounts with respect to the single convective and stratiform Z-R schemes, and it reduces overestimate for light rain events with respect to the single tropical Z-R scheme. These results clearly show that segregating different precipitation regimes and applying spatially varying Z-R relationships are necessary for accuracy.

4. Radar-gauge comparisons at 1-hr and 24-hr time scales

4.1 Radar-gauge bias for hourly rainfall

Hourly rainfall accumulations at each gauge site for the radar QPE schemes are derived by summing all the 5-min radar rain rates within a given one hour period regardless of whether the 5-min gauge rain rate was zero or not. Hence, 1-hour rainfall amounts might include some data points that were excluded from calculations of the 5-min radar-gauge biases presented above. The hourly accumulations from radar and from gauge are then used to compute hourly radar-gauge rainfall biases using Eqn. (1) with a condition that both are greater than zero.

Figure 5 shows distributions of the hourly radar-gauge biases for the four Z-R

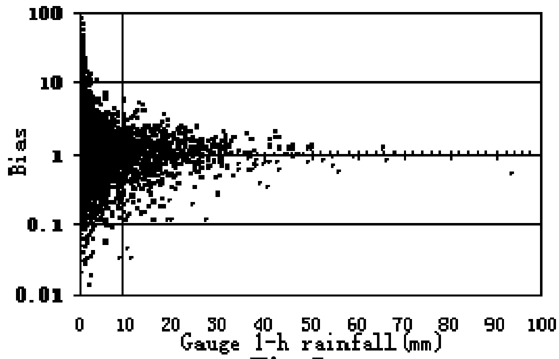

Fig. 5a

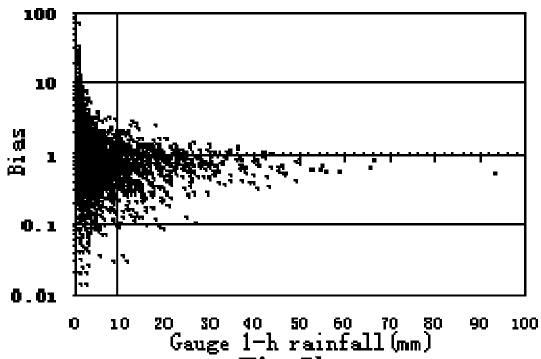

Fig. 5b

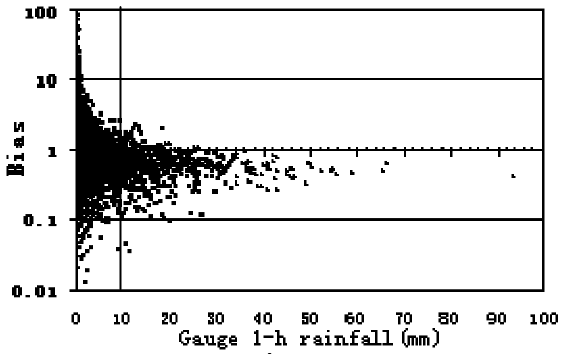

Fig. 5c

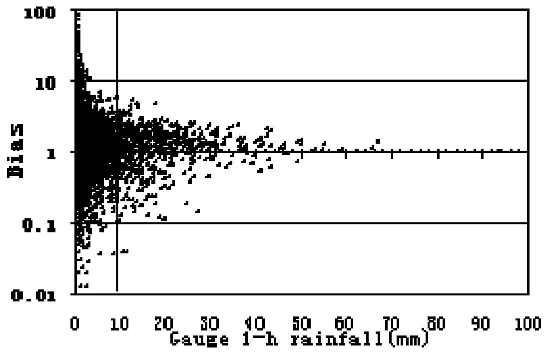

Fig. 5d

Fig. 5 Scatter plots of 1-hour radar-gauge biases for (a) CST, (b) convective, (c) stratiform and (d) tropical Z-R schemes.

algorithms with respect to different gauge hourly rainfall amounts. Biases from all four Z-R schemes showed a log-normal-type of distribution (Fig.5). Both the convective (Fig.5b) and stratiform (Fig.5c) Z-R schemes have an underestimation bias while the bias distributions and this tendency is more pronounced when the gauge 1-hour rainfall is larger than 10mm. The bias distribution for the tropical Z-R scheme, on the other hand, has a noticeable overestimation for rainfall amounts 10mm or higher. The bias distribution for the CST scheme is more concentrated around the bias value of one in comparison to the other schemes.

Comparing Fig. 5 vs. Fig. 3, the hourly radar-gauge biases, regardless of Z-R scheme, are higher than their 5-min counterparts, especially at light precipitation amounts. Detailed analyses of the radar and gauge data sets used to derive the hourly rainfall revealed that the increase in radar biases was due to the inclusion of non-zero 5-min radar rainfall data points that corresponded to zero 5-min gauge rainfall. These mismatching of points may be due to several factors: 1) the radar rainfall was derived from non-precipitating clouds or virga, or even from non-meteorological echoes due to imperfect reflectivity quality control; 2) the gauge is located at the edge of a storm and the radar observed rain at high altitudes drifted due to wind and not observed by the gauge below; 3) a report of zero from a bad gauge or communication failure while there is actually precipitation; 4) light rain that is observed by radar but not recorded by gauge when the 5-min rainfall accumulation is less than 1/100 of an inch, which is the minimum amount to trig the tipping bucket. A preliminary examination indicated that large amount of the mismatching points were due to factor 1), the radar rainfall was derived from non-precipitating clouds or from non-meteorological echoes as a result of insufficient reflectivity quality control. Further discussions on various factors impacting radar-gauge biases can be found in section 5.

4.2 *Radar-gauge bias for 24-hour rainfall*

The 24-hr radar-gauge rainfall biases are calculated using the same logic as for the hourly radar-gauge biases. The 24-hr radar and gauge rainfall accumulations were calculated by accumulating 5-min radar and gauge rainfall amounts, respectively. Mismatching points in the 5-min data sets (e.g., $R^i_{r,\Delta t}$ >0 but $R_{g,\Delta t}$ =0 or $R^i_{r,\Delta t}$ =0 but $R_{g,\Delta t}$ >0) are included in both accumulations. The radar-gauge biases for the four Z-R schemes are derived using Eqn. (1) for all the non-zero 24-h radar rainfall and non-zero 24-h gauge rainfall data pairs. Figure 6 shows distributions of the four sets of biases as a function of 24-h gauge rainfall amount. The bias distributions are similar to those of 1-hr rainfall, but with a narrower range of values from 0.1 to 10. The narrow range is likely a result that the longer term accumulations dampen random fluctuations and reduced uncertainties in the radar QPEs. For instance, underestimations and overestimations at different times during the 24-hr period may cancel out and subsequently resulted in better biases on the 24-hr time scale.

Radar QPEs from both the single convective and stratiform Z-R relationships still underestimate in medium to heavy rainfall events (e.g., > 40mm/day), but perform better at medium rainfall events than the

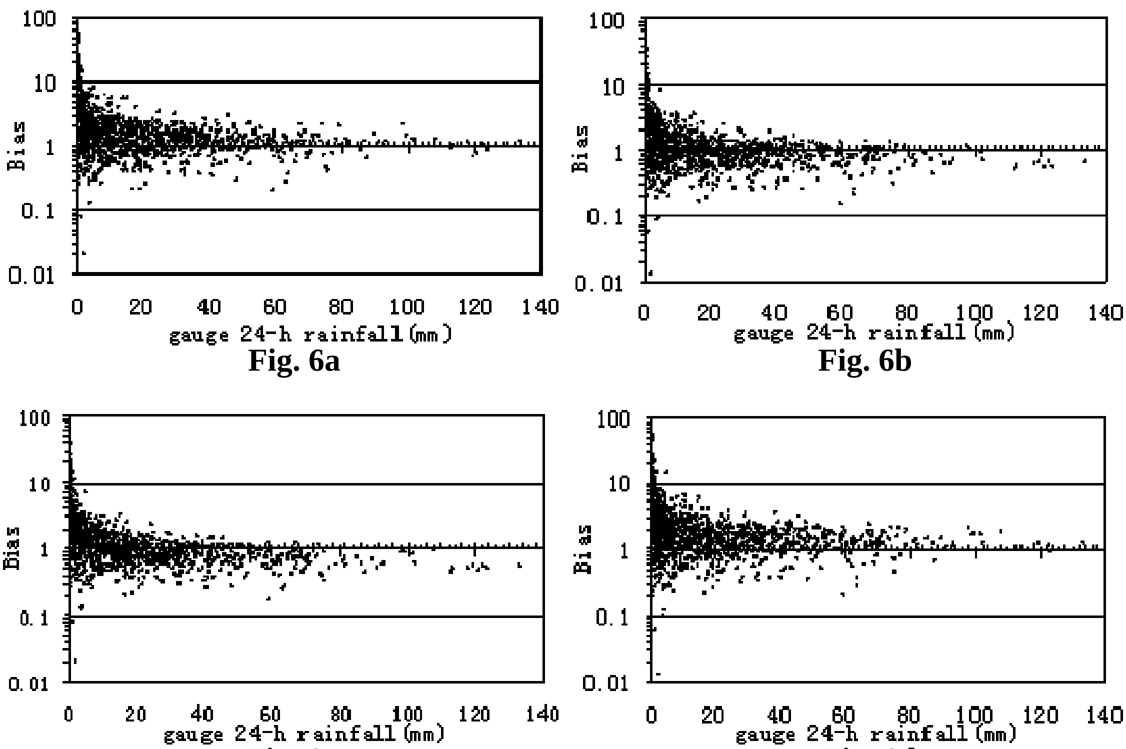

Fig. 6a Fig. 6b

Fig. 6c Fig. 6d

Fig. 6 Scatter plots of 24-hour radar-gauge rainfall biases for (a) CST, (b) convective, (c) stratiform and (d) tropical Z-R schemes.

1-hour QPEs. The improved performance may be a result that the underestimations due to inappropriate Z-R relationships and overestimations due to non-precipitation echoes during the 24-h period cancel each other out. The tropical Z-R scheme has a consistent overestimation at all the rainfall amounts. This degrading in performance does not necessarily indicate that the Z-R relationship is incorrect due to the same reasons just discussed. The CST scheme again showed the best performance among all four schemes with an average bias close to one for 24-h rainfall amounts above 50mm and a slight overestimation at the medium range of 20-50mm. The overestimation at small rainfall amounts may be further reduced by improving the radar reflectivity quality control and the rain-no rain segregation in the radar QPE schemes.

5. Preliminary analysis of various factors impacting radar-gauge biases

Large scatters in the radar-gauge bias distributions at all time scales, as shown in the previous section, clearly indicates that using one or even several Z-R relationships can never fully remove discrepancies between radar and gauge rainfall estimates/observations. The discrepancies are even more difficult to remove or reduce with light precipitation events because of the huge scattering of all radar QPEs (see Fig.3). There are many factors that impact the radar-gauge biases (Austin, 1987; Fulton et al., 1998; Medlin et al., 2007). On the radar side, these include radar data quality control to remove non-precipitation echoes, partial beam-filling and blockages, vertical profile of reflectivity, incorrect Z-R relationships, etc. On the gauge side, there are gauge data quality issues, wind-drifting effects, hail, etc. On combined aspect, these include different sampling characteristics for radar and for gauge. Preliminary investigations were conducted to examine a few issues associated with the radar-gauge discrepancies.

5.1 Uncertainties in Z-R relationships

Figure 7 shows a scatter gram of 5-min gauge rain rates versus radar HSRs for all non-zero gauge data in the 13 cases studied in this paper. The three Z-R relationships used in the radar QPE algorithms are superimposed on the scatter gram. Corresponding to each rain rates observed by gauges, there are significant spread of HSR values that deviate from any of the Z-R relationships. It reveals that there are large uncertainties in Z-R relationships due to complex microphysical processes. For any radar QPEs based on one Z-R, underestimation would occur when the real rain rate locates to the left of the Z-R curve and vise versa. It is necessary for any degree of QPE accuracy to use multiple Z-R relationships to encompass the range of the actual precipitation rates, and thus improving the radar QPE accuracy.

However, even with three Z-R relationships, there remains many rain rates outside the Z-R relationships (Fig.7). Further precipitation segregation would be necessary and new Z-R relationships derived. The dual-polarized radar variables have been shown to provide 3-D information on hydrometeor types and distributions, (Vivekanandan et al., 1999), and are forthcoming promising techniques for further improve radar QPEs.

5.2 Vertical profile of reflectivity

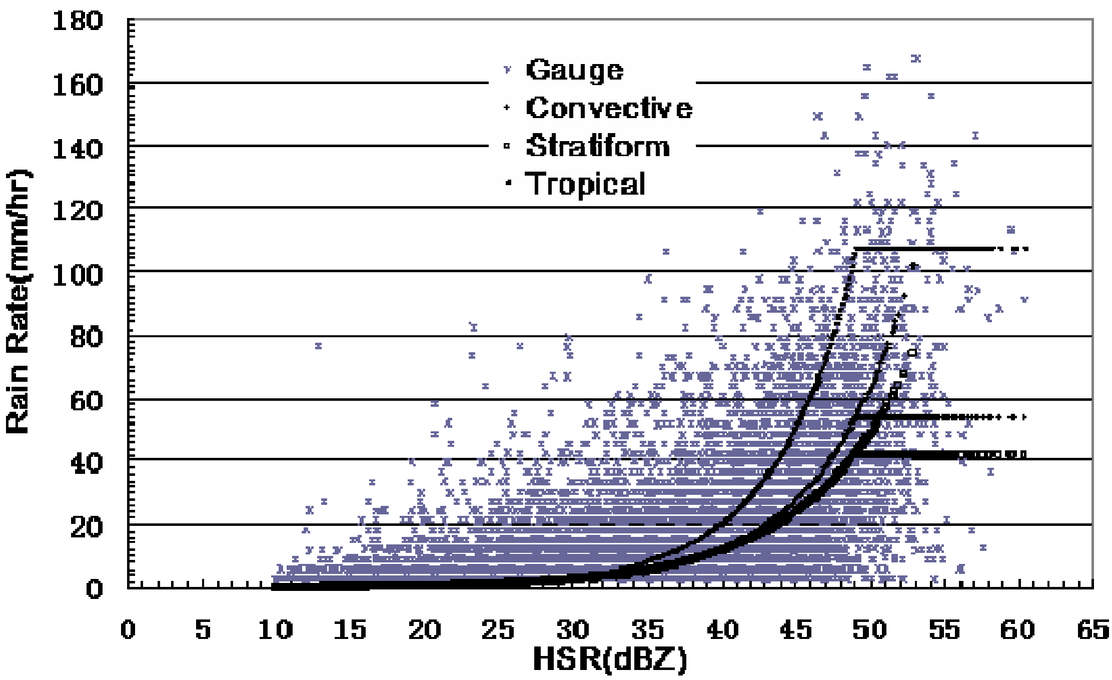

Fig. 7 Scatterplot of real 5-min rainrate of gauge and ideal 5-min rainrate derived from 3 kinds of Z-R relationships versus HSR.

Radar rain rates are derived from the radar hybrid scan reflectivity through Z-R relationships. The hybrid scan reflectivity (O'Bannon 1997, Fulton et al. 1998) is the lowest (in altitude) radar reflectivity observations that are not blocked by terrain. Due to the curvature of the earth's surface and the 0.5° elevation angle for the lowest tilt of WSR-88D scan strategies, the height of the lowest radar beam, and subsequently, the height of the HSR, increases with range. Therefore, there is a discrepancy between the radar observed rainfall, which is at the height of HSR in the atmosphere, and the rainfall observed by the gauge, which is at the ground. Assuming the Z-R relationship is perfect, the radar rainfall may still be different than the gauge observation if the vertical profile of reflectivity is not uniform between the ground and the height of HSR. Overestimation occurs when the HSR is located in the bright band in stratiform cloud. On the other hand, underestimations occur if the HSR is above the bright band and in the snow/ice cloud region, because reflectivity decreases rapidly above bright band (e.g., Fabry and Zawadzki 1995; Sánchez-Diezma et al 2000). Further underestimation can occur when the radar beam is above the cloud top.

Table 3 lists one-hour time series of 5-min rain rate observed by the Oklahoma mesonet gauge IDAB and rain rates derived from the four radar QPE schemes at 11:00UTC on Jun. 27, 2007. Additional radar variables and surface relative humidity (RH) for the same site and time are also listed. The value of -99 in HSR column represents no rainfall echo over the gauge.

Table 3 indicates that the radar detected very weak echoes even though the gauge recorded non-zero rain rate every 5 min through out the hour. The RH values were close to 100%, indicating that rainfall was likely occurring at the time. However, all four radar QPE schemes produced rain rates that are significantly smaller than what's observed by the gauge. Detailed examinations of radar data revealed that the

Table 3 Time series of 5-min rain rates from gauge IDAB and the four radar QPE schemes and a few ancillary variables on Jun. 27, 2007

Time	**Gauge (mm)**	CST (mm)	Conv. (mm)	Strat. (mm)	Trop. (mm)	HSR (dBZ)	HHSR (km)	RH (%)
11:05	**0.26**	0.05	0.03	0.05	0.03	19.2	4.14	96
11:15	**0.25**	0.00	0.00	0.00	0.00	-99	4.14	97
11:25	**0.51**	0.00	0.00	0.00	0.00	-99	4.14	97
11:35	**2.03**	0.03	0.03	0.03	0.03	16.7	4.14	97
11:40	**0.76**	0.05	0.03	0.05	0.03	19.2	4.14	97
11:45	**0.26**	0.04	0.03	0.04	0.03	18.8	4.14	97
11:50	**1.27**	0.05	0.03	0.05	0.03	19.2	4.14	97
11:55	**1.78**	0.08	0.06	0.08	0.07	22.4	4.14	97
12:00	**3.04**	0.10	0.08	0.10	0.10	24.5	4.14	97

underestimation was probably due to the non-uniform vertical profile of reflectivity issue. The height of the HSR for this location was 4.14 km, indicating that the radar beam was probably sampling the upper part of the precipitation clouds, where the echo was very weak (due to the overshooting). The microphysical process below this height might have produced evident rainfall. The rainfall was observed by the gauge at the ground, but not by radar. Therefore a large difference between the radar QPEs and the gauge observations was resulted.

5.3 Spatial scales of gauge records and radar estimates

The discrepancy between the spatial representations of gauge observations and radar estimate has long been recognized and investigated (Sieck et al., 2007). A gauge observation only represents a point at the ground, while a radar observation is a weighted average of return powers from hydrometeors in a volume that is 1° x 1 km x 1° in space. The spatial sampling difference increases with increasing range. Further, spatial scales of the precipitation system sampled by the radar and gauge will also have an impact on the discrepancy. The smaller the storm cells are, the greater the chance is that the gauge would 'miss' the storm while radar would not.

Table 4 shows a case that highlights the issue of the spatial discrepancy between gauge and radar rainfall data. The mesonet gauge TALI only recorded non-zero rainfall for one 5-min interval during a 25-minute period from 04:40 to 05:00 UTC on Jul 13,

Table 4 Time series of 5-min rain rates from gauge TALI and from the four radar QPEs and a few ancillary variables on Jul. 13, 2007

Time	Gauge (mm)	CST (mm)	Conv. (mm)	Strat. (mm)	Trop. (mm)	RH (%)	HHSR (km)	HSR (dBZ)
04:40	0	0.33	0.30	0.33	0.43	91	1.67	32.5
04:45	0.25	4.48	4.48	3.51	8.94	91	1.67	51.5
04:50	0	2.73	2.73	2.28	5.14	91	1.67	46
04:55	0	4.48	4.48	3.51	8.94	92	1.67	54.5
05:00	0	4.48	4.48	3.51	8.94	92	1.67	53.1

2007, whereas the radar observed relative strong rainfall consistently through out the period. According to the RH and HHSR time series, neither gauge nor radar appeared to be incorrect. Base tilt reflectivity image (Fig.8) from a nearby radar showed an evident precipitation cell over gauge TALI, and the gauge is located right at the edge of the small convective cell with a reflectivity of 50~55dBZ. The size of the radar bin (~167km away from the radar) is ~1km x 2.8km. Given the size of the storm, it was very possible that only part of the radar bin region was raining. The gauge was located in the non-precipitating area under the radar bin. However, the radar bin is large enough to detect the precipitation away from the gauge, and the resultant reflectivity was assigned to the whole radar bin region. The derived precipitation was then associated with gauge TALI, and large discrepancies were resulted.

6. Summary and conclusions

Radar QPEs derived from four different Z-R schemes was evaluated using the Oklahoma mesonet gauge observations. Radar-gauge biases were computed for 5-min, 1-hr and 24-hr rainfall accumulations for 13 precipitation cases during the warm season of 2007 in Oklahoma. Several factors that impact behaviors of radar-gauge biases were examined. From the study the following conclusions are drawn:

(1) 80% of the 5-min rainfall amounts less than 1 mm. However, these most frequently occurred rainfall amounts only contribute less than 30% of the storm total. More than 70% of the storm total rainfall comes from rainfall that have an intensity higher than 1mm per 5-min, or 12mm/hr.

(2) All four radar QPE schemes showed large uncertainties across all three time scales studied in this paper, with the largest uncertainty at the shortest time scale and the lightest rainfall intensity.

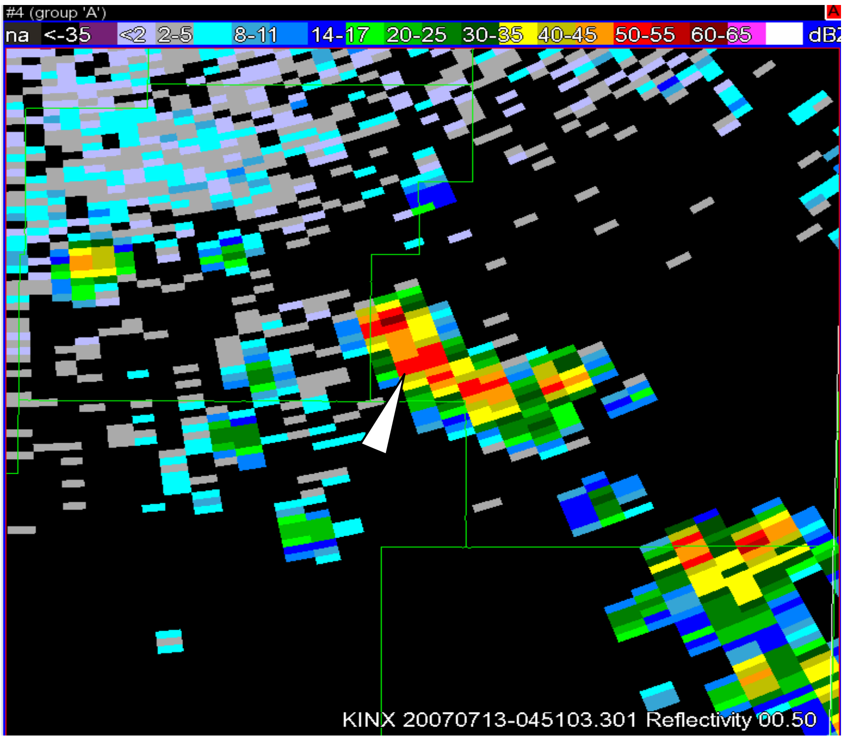

Fig. 8 Base reflectivity at 0.5° tilt from KINX (Tulsa, OK) at 04:51UTC on Jul. 13, 2007. The location of gauge TALI is marked by the arrow.

On the 5-min and 1-hr time scales, both the single convective and stratiform Z-R schemes had significant underestimation for medium to heavy rainfall events. The single tropical Z-R scheme significantly overestimated for light rainfall events even though it provided better estimates at higher amounts. The CST scheme significantly improved the rainfall underestimation at large amounts with respect to the single convective and stratiform Z-R schemes, and it reduced overestimation for light rain events with respect to the single tropical Z-R scheme. These results show the necessity of segregating different precipitation regimes and applying spatial and temporal varying Z-R relationships for accurate radar QPEs.

(3) The radar-gauge biases from all four Z-R schemes increased as the accumulation interval increases. The increase in radar/gauge biases were due to the large number of non-zero 5-min radar rainfall points associated with zero 5-min gauge rainfall. These mismatching data pairs were likely due to imperfect rain-no rain discriminations in the radar QPEs.

(4) Significant uncertainties exist in the Z-R relationship due to complex microphysical processes. A single Z-R equation is unable to represent actual precipitation distributions. Multiple Z-R relationships based on physically based precipitation type analyses are necessary for obtaining reasonably accurate radar QPEs.

(5) In addition to Z-R relationships and gauge observational errors, many factors impact the behavior of radar-gauge rainfall biases. Detailed analyses of radar, gauge, and atmospheric variables confirmed that non-uniform vertical profiles of reflectivity, wind drifting, and the spatial representation difference between radar and gauge observations are among these factors.

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