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Radar Derived Rainfall and Rain Gauge Measurements at SRS

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EXECUTIVE SUMMARY

Over the years rainfall data for the Savannah River Site has been obtained from ground level measurements made by rain gauges. These instruments have inherent errors or biases that can impact the measured rainfall totals but are assumed as ground truth for most climatological and weather applications. With the development of weather radar technologies, various methods to derive rainfall totals from radar reflectivity values have been developed and have continued to improve. The Z-R relationship, which uses an exponential relationship to estimate rainfall rate based on radar reflectivity values, provides estimates of rainfall amounts (Z-R Level III) for locations within the radar's detection range. The recently developed Multi-Radar Multi-Sensor (MRMS) dataset combines reflectivity-based estimates using the Z-R relationship with a network of gauges and other rainfall estimates to produce a refined set of precipitation estimates for each grid point within its domain. Comparisons were done between gauge observations and radar estimates for various SRS locations to assess whether radar derived estimates are representative of rainfall measurements at the site. Results obtained show good agreement between radar derived amounts and ground measurements, with MRMS showing stronger correlations and lower spread than Z-R Level III estimates. Outliers and errors observed appear to be related to hydrometeor classification schemes. In general, MRMS proved to provide sufficiently representative estimates of daily rainfall amounts to replace existing SRS rain gauge measurements.

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LIST OF ABBREVIATIONS

SRNL	Savannah River National Laboratory
SRS	Savannah River Site
MRMS	Multi-Radar Multi-Sensor
QPE	Quantitative Precipitation Estimation
NPDES	National Pollution Discharge Elimination System
EPA	Environmental Protection Agency
HADS	Hydrometeorological Automated Data System
NSSL	National Severe Storms Laboratory
RMSE	Root Mean Square Error
CLM	Climatology
ATG	Atmospheric Technologies Group
NWS	National Weather Service

1.0 Introduction

Rainfall gauges have long been the trusted source for instantaneous, hourly, daily and other rainfall measurements for operational and research applications. Although radar derived estimates of rainfall have been available since the 1950's, these values are not widely used (Wilson and Brandes 1979). Gauges have generally been assumed to represent 'ground truth' and though they only represent a point in space, different methods to extrapolate and interpret measurements to represent a large spatial area are used. However, in truth, point coverage of gauges and extrapolation of measurements rarely represents the spatial and temporal distributions of rainfall, especially for highly variable and fast-moving rain events (Martinaitis, et al. 2015) (Goodrich, et al. 1995; Austin 1987). Intense convective cells tend to produce significant gradients across distances of less than 1 km and are therefore not well represented by most gauge networks (Steiner, et al. 1999; Wilson and Brandes 1979; Villarini, et al. 2008). Additionally, rain gauge data has been shown to contain certain errors or biases. Wedge rain gauges have measurement biases and errors associated with the sampling and reading method used, while tipping bucket gauges tend to suffer from mechanical or biological errors (such as animal litter or plant material growing or trapped on the instruments – which can be an issue with wedge gauges as well) that prevents accurate tips (Steiner, et al. 1999). Tipping bucket gauges have been shown to underestimate rainfall for the two extremes of the rain rate spectrum. Errors due to tipping bucket under catch during intense rainfall rate, where rainwater is lost between bucket tips, and strong wind events during which airflow around the gauge reduces catch area have been documented (Nystuen 1999; Sieck, et al. 2007).

Radar derived rainfall provides a three-dimensional distribution of rainfall intensity with a spatial resolution of 1-2 km and time resolution of 5-6 minutes, over a range of hundreds of kilometers. However, radar estimates also tend to have biases and errors. Possible errors of radar estimates are well documented in literature; some of them include missing rainfall intensification near the ground due to topography and beam height, and evaporation of rain below the cloud base (Zhang, et al. 2016; Steiner, et al. 1999; Wilson and Brandes 1979). Due to the lack of understanding of the nature of these possible biases and errors, radar derived rainfall did not become as strong of an operational tool as had been foreseen when originally developed for weather applications. However, improved techniques for radar estimates have been thoroughly studied and explored (Krajewski, et al. 2010; Sinclair and Pegram 2005; Villarini, et al. 2008). Today there is a much better understanding of the weaknesses and strengths of radar estimations, and a more robust set of empirical relationships between reflectivity and rain rate. These relationships take the general form: $Z = aR^b$ that relates radar reflectivity values (R) with rainfall rate (Z) and total rain amounts at a given time, with the constants *a* and *b* adjusted depending on assumptions made or event type classification.

Rainfall estimates from the Z-R relationship can be improved by correcting values with rain measurements from gauges or other instrumentation (Steiner, et al. 1999; Sinclair and Pegram 2005; Sun, et al. 2000). These improvements employ an ensemble of different sources of precipitation data (including gauge measurements, satellite estimates, radar estimates, and others) to process and generate enhanced radar derived rainfall estimations obtained from standard Z-R relationships (Zhang, et al. 2016). The Multi-Radar Multi-Sensor (MRMS) precipitation estimation tool was developed by National Severe Storms Laboratory (NSSL) and integrates Z-R data from approximately 180 radars over the U.S. and Canada with satellite data, lightning, rain gauge observations and other environmental information to provide precipitation estimates and products (Zhang, et al. 2016). The gauge data used on MRMS comes from approximately 7000 gauges that comprise the Hydrometeorological Automated Data System (HADS), measuring hourly values of rainfall (Zhang, et al. 2016). Figure 1 in Zhang et. al (2016) shows both the radar and gauge network coverage of MRMS. Savannah River Site (SRS) has access to both Z-R Level III and MRMS derived rainfall data sets used by the NWS through the NOAAPort Satellite data feed.

As part of the SRS meteorological monitoring network, the Atmospheric Technologies Group (ATG) maintains tipping bucket rain gauges located at A-, D-, P- and C-area, as well as a network of nine wedge rain gauges located around the site that provide daily rainfall totals (Figure 2-1). Data from the wedge gauges are used for many SRS applications, some of which include regulatory sampling of SRS streams for compliance with the EPA's National Pollution Discharge Elimination System (NPDES), hydrological and flood modeling, and facility engineering design and operations. The quality of the wedge measurements and the subsequent data transfer is of particular concern as many potential points of errors are identified. Different personnel with different backgrounds and training are assigned to the task of retrieving the data in the field. This enhances the likelihood of inconsistencies and errors in readings. Additionally, during certain types of events data retrieval is difficult, and when readings are made, the data reported includes a period greater than the established 24-hour period. Furthermore, the data is then reported by the field personnel to the SRS Operations Center point of contact who manually enters the data into an email that is sent to ATG. Personnel from ATG then conduct a general quality assurance (QA) review to eliminate the obvious flaws and then manually enter the values on the ATG database. Less obvious flaws such as: missing values (which are entered as a value of 0 inches by some of the readers), biased readings, or daily totals that cover periods greater or less than the prescribed 24-hour period, cannot be identified and therefore impact the quality and accuracy of this dataset.

Additionally, performing daily manual rain gauge readings involves a significant labor cost, hence an automated method of collecting this data is preferable. Our tipping bucket gauges mitigate some of these problems in that the measurements are generally more reliable, and the data can be directly transferred into our database with little to no human handling. These values still only provide point measurements and replacing all of the wedge gauges with tipping buckets presents budgetary and technical difficulties. Additionally, these instruments are prone to the errors mentioned above and discussed in literature. Therefore, having radar estimates of rainfall totals can facilitate revisions to current data collection methods, providing a substitute of, or supplement to, rainfall data measured on site.

A further motivation to compare our gauge data with radar derived rainfall values is that SRS rain gauges are not included in the HADS network that is used for MRMS Quantitative Precipitation Estimate (QPE) corrections; hence this study will provide an independent validation and verification of rainfall estimates provided by the MRMS data.

2.0 Methodology

This study focuses on two different types of radar derived rainfall: Z-R derived daily totals from a composite of local radars with range over our site, and MRMS gauge corrected daily rain estimates to evaluate how well they agree with measurements from our instruments. The composite of local radars used for the Level III Z-R estimates includes three radars: Columbia, SC, Charleston, SC and Peachtree City, GA (which is located twice as far from the center of the site than the other two radars). Radar rainfall estimates are obtained using nearest neighbor interpolation from all local radar grid points adjacent to the location of each rain gauge. No weighting of the data is done, i.e. all radar estimates are considered equally good regardless of the distance of the radar to the point in question. Level III data is available hourly, but rainfall estimates were obtained for a 24-hour period from 6 am through 6 am to replicate the measurement period encompassed by wedge rain gauge measurements.

The MRMS data used for this study corresponds to the gauge corrected quantitative precipitation estimate (Q3GC QPE), which includes a local gauge bias correction on the MRMS radar estimate that is done with a three-step process described in Zhang, et al. (2016). This method provided good radar derived rainfall estimates and proved to be effective in removing spatially consistent errors in radar QPEs (Zhang, et al. 2016). It is noted that the radar-gauge difference used in the correction scheme may not be representative of errors in areas not covered by the HADS network. Hence, Zhang warns that significant differences between radar estimates and independent validation gauges can occur and bias MRMS based estimates (Zhang, et al. 2016).

SRS rain gauges used in this evaluation are wedge and tipping bucket gauges. The wedge rain gauges are placed at multiple locations around SRS (Figure 2-1) and are read daily at approximately 6 am, measuring the rainfall amount accumulated over the previous 24-hour period. For this study we used data from gauges located at D-, C-, and A-area. The selection of these three areas was driven by the presence of a tipping bucket rain gauge near the wedge gauge location (i.e. within a mile or less of the wedge rain gauge). The P-area gauges were not considered for this study as these are used onsite to measure rainfall within the forest canopy, therefore the data is not considered representative for the present evaluation. The tipping bucket gauges are well maintained and calibrated routinely by ATG technicians, and data from these instruments undergoes a thorough quality assurance process. Hence, tipping bucket measurements will provide a secondary source of rainfall values to validate results obtained with wedge measurements. To maintain consistency with the wedge measurements, the 15-min values from the tipping bucket gauges were summed to give a 24-hour rain accumulation total (starting and ending at 6am) for each area.

In an effort to better understand the sources of differences between the rain gauges and the radar estimates, an event-based approach was used, in which dates when rainfall was measured with our tipping bucket rain gauges were identified and used to compare the rainfall amounts recorded by all other data sources. Rain events were selected over the course of September 2017-November 2018 to capture different types of rain processes (stratiform vs. convective, fast vs. slow moving, etc., based on the radar signature observed on the Level III data) and evaluate radar estimates for each type. Synoptic conditions, speed, duration and other event characteristics were included in the analysis to provide further insight into the behavior of radar estimates and gauge performance. Additionally, extreme rainfall events (i.e. more than 3 inches of rain) were not included in this analysis since these are not common over the area and would tend to positively bias the correlation coefficients (Townend 2002). Events associated with tropical cyclones (Hurricane Florence and T.S. Alberto) as well as stratiform rainfall associated with a cold air damming/over-running event were included to evaluate any radar QPE bias directly linked to these types of events. Most events observed, however, were associated with frontal systems or low-pressure systems moving over the region that fueled convection and passing rain showers (Table 2-1).

To evaluate agreement between the different datasets, a series of statistical tests were used on the data (goodness of fit correlations, root mean square error, and measurement ratio or bias). A linear fit was generated to depict the relationship between rainfall measurements and radar estimates and compare to a 1:1 correlation line. Comparisons were made between rainfall totals per site area for each product (Level III Z-R and MRMS) and each rain gauge type (wedge and tipping bucket) to identify which pair showed the best agreement.

Table 2-1. Description of Events Selected.

Date (end period)	Synoptic event	Precipitation Type	Notes	Duration
9/1/2017	Trough	Convective	Early afternoon. Various 1 hr events	1.5 hrs
10/9/2017	Low Pressure West	Convective	Afternoon. Various 1 hr events	4 hrs
12/21/2017	Frontal (stationary)	Stratiform	Afternoon and evening. Various systems	3 hrs (max)
1/13/2018	Front and Trough	Stratiform	Early afternoon. Various events	5 hrs (max)
1/29/2018	Frontal	Stratiform	Ongoing through the day. Various events	4+ hrs
2/5/2018	Frontal, strong squall line, severe	Convective	Morning	1. 5 hrs
3/7/2018	Frontal	Startiform	Morning and ongoing	>5 hrs
4/8/2018	Trough	Convective	Afternoon and Evening Thunderstorms	>5 hrs
4/16/2018	Squall line ahead of front	Convective	Afternoon and Evening Thunderstorms	>5hrs
4/24/2018	Front in the vicinity	Startiform	Multiple Events (ongoing)	>5hrs
5/18/2018	Low pressure	Convective	Early Afternoon. Various events	2.5
5/19/2018	Low pressure	Convective	Evening. One system	4 hrs
5/28/2018	T.S. Alberto, and trough	Convective	Evening/Overnight. Various events	4 hrs
6/12/2018	Low pressure	Convective	Afternoon/Evening (overnignt)	3 hrs (max)
6/23/2018	Local	Convective	Overnight. One system	1
6/26/2018*	Trough, Severe	Convective	Evening/Overnight. One system	3
9/16/2018	Hurricane Florence	Stratiform	Early morning to afternoon	3.5
9/17/2018	Remnants of Florence low	Stratiform	Overnight	1
9/18/2018	Frontal	Convective	Overnight. One system	1
11/10/2018	Stratiform	Stratiform	All day drizzle	>5 hrs
11/13/2018	Frontal- Stratiform (Wedge of cold air)	Stratiform	All day drizzle	> 5 hrs
11/14/2018	Wedge event	Stratiform	All day drizzle/mist	>5 hrs
11/15/2018	Wedge event	Stratiform	All day drizzle	>5 hrs

*Data only available for some of the D-area tipping bucket, other data was lost during event. Precipitation type based on Level III radar imagery for each date.

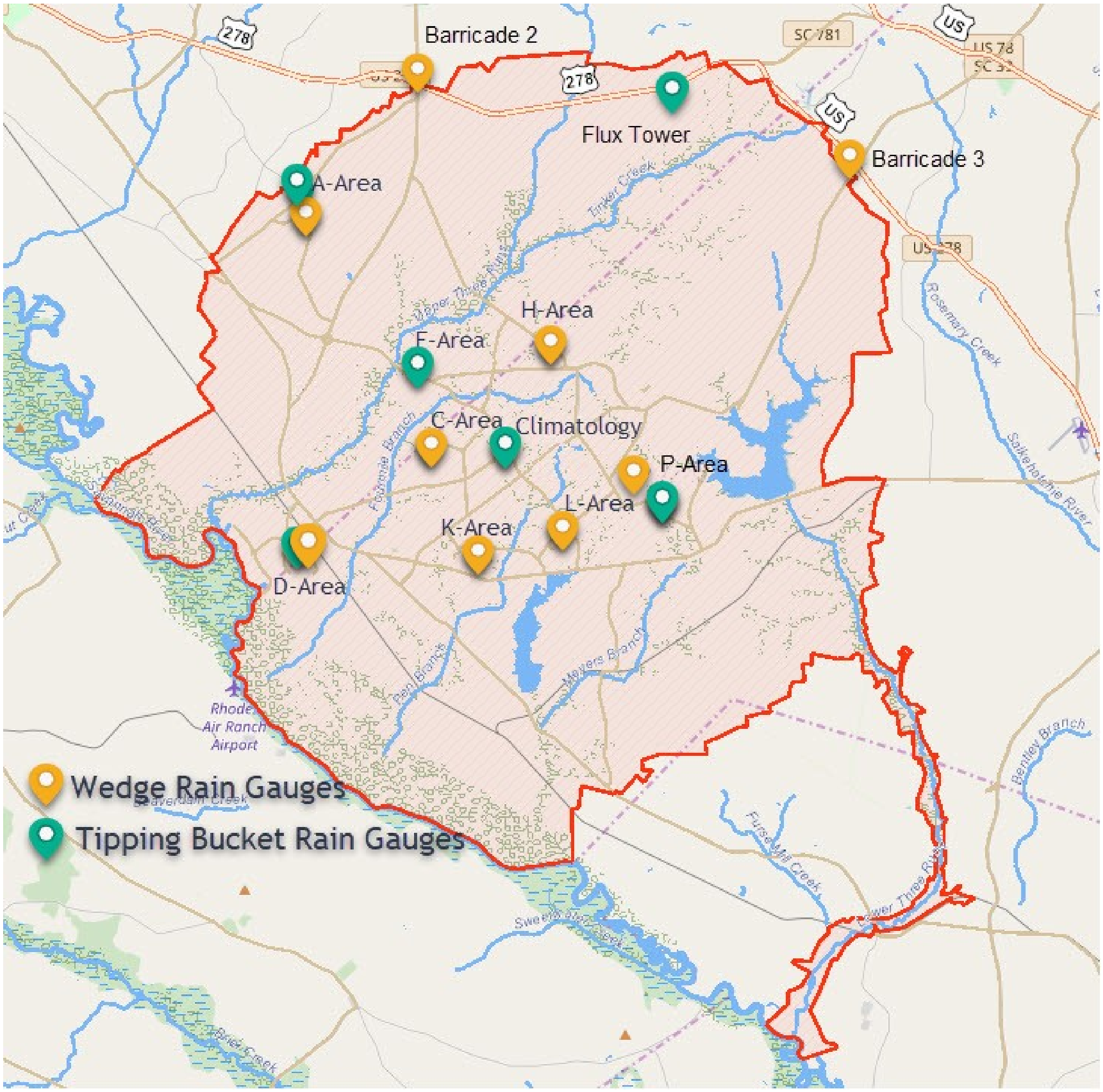


Figure 2-1. SRS Rain Gauge Locations.

3.0 Results and Discussion

Data collected for the selected rain events over the 15-month period suggests that values from both types of radar derived rain (Z-R Level III and MRMS data) are generally in good agreement with measured data (Table 3-1). Scatterplots, regression correlation coefficients, and RMSE values for each data pair show good agreement (Table 3-2 and Table 3-3). In fact, rainfall estimates derived from the Z-R relationship and MRMS dataset plotted against measurements from the corresponding area wedge gauges fit a linear relationship that is relatively close to the 1:1 correlation line, although a few outliers are observed at each location (Figure 3-1). All pairs of data had similar RMSE values, however correlation coefficients obtained between the MRMS data and the A- and D-area wedge gauge totals (Table 3-2) showed stronger agreement (0.9 and 0.8, respectively) compared to results obtained using the Z-R Level III estimates and wedge measurements (correlation coefficients of 0.87 and 0.5, for A- and D-area respectively). In contrast, correlation values for both radar derived rainfall estimates against the C-area wedge were comparatively low (correlation coefficients of 0.43 and 0.37 for MRMS and Z-R Level III estimates, respectively). Evaluation of event characteristics and gauge location could not explain why results for this area showed so much spread compared to the A- and D-area results. Further investigation found that the C-area wedge support bolt and the wedge were not appropriately secured, allowing the wedge to move by several degrees from the vertical with any outside interference (particularly wind). Additionally, the instrument has been placed within a short distance of many overhead obstacles which may be altering the rainfall amounts measured at this location.

Correlation coefficients obtained with radar derived estimates and tipping bucket measurements (Table 3-3) show a similar relationship: MRMS performs generally better than the Z-R Level III estimates. Low RMSE values are observed for the MRMS and tipping bucket data pair and scatterplots demonstrate less spread in the data. Additionally, correlation coefficients between the MRMS and tipping bucket data are higher than those obtained with the Z-R derived values. Particularly good results were obtained when comparing MRMS values to the A-area tipping bucket gauge measurements with values that resemble results obtained using the wedge gauge measurements (correlation coefficient of 0.95 and RMSE of 0.28). These results are relevant since the A-area instruments are well placed (and maintained) in an open and clear location without any nearby buildings or overhead obstacles. A correlation coefficient of 0.8 and a RMSE of 0.2 inches was obtained using the C-area tipping bucket measurements, which contrasts with the low correlation values obtained using the corresponding C-area wedge gauge data (Figure 3-2). Similar to the A-area tipping bucket, this instrument is placed in an open location without any nearby obstructions that could impact measurements. This demonstrates that the relatively large discrepancies observed between the C-area wedge and radar derived estimates are likely the result of the condition of the gauge and overhead obstructions, as noted above. Lower correlation coefficients were obtained between the D-area tipping bucket gauge and the radar derived data. Although this tipping bucket is placed on a smaller clearing that is closer to the forest canopy, it is thought that the clearing is large enough to prevent any overhead obstruction from the vegetation. Therefore, instrument placement does not seem to be the source of errors and biases observed at this location. Further below we discuss characteristics of D-area that may impact radar representation of rainfall reaching the surface.

In general, radar provided good estimates of ground rainfall totals and, of the two methods used, MRMS generates the most representative estimates of daily rainfall totals measured by the rain gauges at SRS. Results obtained using both gauge types are consistent with those previously found on similar studies. Both Zhang, et al. (2016) and Xu, et al. (2008) found correlation coefficient values of 0.8 and 0.9, respectively, when comparing 24-hr gauge accumulation totals and adjusted radar derived QPE estimates. In fact, results obtained using MRMS data and A- and C-area tipping bucket measurements (Figure 3-2) closely resemble values shown in Zhang, et al. (2016). The main difference between the two is that RMSE values obtained through the present evaluation are slightly lower than the values presented on Zhang's study. This is due to differences in the sample size, as well as the geographic area included in each study. Zhang, et al. (2016) used a larger sample size spread over a larger geographic area (Eastern Virginia) and focused on rainfall amounts over one single 24-hr period event - during the landfall of Hurricane Sandy. This provided more spread in their data and hence, higher RMSE values. For the present study we look at a comparatively small spatial scale and each station is evaluated independently but includes multiple 24-hr periods for specific rain events that occurred over approximately a year of sampling.

The bias observed from the various data pairs is obtained dividing the radar estimated amount by the amount measured by the gauge; this value helps highlight any tendency to over- or underestimate rainfall values for the two radar estimates. Assuming rainfall amount measured by the gauges is ground truth, a ratio larger (lower) than 1.0 would suggest radar overestimation (underestimation). Figure 3-3 and Figure 3-4 show that overestimation of rainfall totals by radar estimates tends to occur for rain events with low measured accumulation totals, i.e. radar tends to overestimate rainfall totals for events with measured amounts below 0.5 in. In contrast, events with rainfall totals of more than 0.5 inches showed ratios nearly equal to 1, i.e. radar estimates and rainfall measurements were in close agreement with measurements. These results are obtained for all radar-gauge pairs and areas evaluated, although results are shown here only for the MRMS data and C- and A-area tipping bucket rain gauges. These observations agree with previous studies by Xu, et al. (2008) and Zhang, et al. (2016).

There are several potential reasons why radar tends to overestimate gauge measurements for events with lighter rain rates and lower total amounts. Rain gauges have been shown to underestimate the actual rainfall amount totals for both extremes of the rain rate spectrum, this is particularly true for the tipping bucket gauge (Nystuen, 1999). Difference in the spatial scale of measurement has also been previously discussed as an inherent source of error: i.e. the catch area of the gauges (~1m) and the area of the radar estimates (~1km) differ and hence values are not expected to be an exact match for every rain event. As described by Austin in 1987, even if we had ideal conditions, i.e., error free rain gauge and radar measurements, discrepancies between the two are likely due to these scale differences:

"[...] radar samples almost instantaneously a volume of atmosphere which has a surface projection of several square kilometers, and measurements are repeated at intervals of several minutes, the gauge accumulates continuously rain falling on an area which is generally much smaller than a square meter. At any given instant, rainfall intensity often varies significantly over distances of less than a kilometer, while at any given point it may change during time intervals of a minute or less. Therefore, the rain sampled by the gauge may not be representative of that in the entire area beneath the radar-sampled volume. Similarly, rain rates observed instantaneously by the radar in any given measurement cell may not be representative of intensities during the intervals between observations."

Another possible source of error is that a radar beam detects droplets that are suspended in the air and for some rain events only a fraction of those suspended droplets falls to the ground as precipitation with the remainder evaporating before they reach the ground. This offers an explanation for the observed bias in radar estimates for D-area (Table 3-2 and Table 3-3). D-area is located within the lower portions of SRS near the river basin while A- and C-area are located over higher terrain. Given that the radar beam is measuring reflectivity values up to 100 feet higher above the surface over D-area compared to the other two sampling locations, rainfall estimates may not be fully representative of surface conditions at this location.

In addition, Zhang, et al. (2016) suggests that rain type classification methods of the MRMS data could misclassify some continental convective precipitation as tropical precipitation. Classification errors are important since Z-R Level III and MRMS datasets apply different Z-R relationships and corrections to the data based on how rain events are classified. This can explain, not only the bias ratio obtained for lower rainfall values, but it potentially explains outliers observed for some of the events discussed in this study. When date, season, synoptic conditions, and other event information was evaluated for these outlier events, no significant distinguishing characteristic in the events was found. In fact, outlier points on an individual gauge did not correspond to the same weather event as the outlier points observed for the other two gauges. Therefore, it is thought that the source of error must be a combination of the ground instrument and/or the method of estimating the rainfall, as well as the characteristics of the rainfall event itself at each measurement location.

A case study based on December 21, 2017 was evaluated. Rainfall totals for all site area wedge gauges and corresponding Z-R Level III data products for this event were reviewed for any information that could explain the discrepancy between radar estimates and measured values. During this event, radar estimates (Z-R Level III) significantly underestimated the rainfall measured by the instruments located at the northern and western portions of the site. In contrast, radar estimates for the rest of SRS were in very good agreement with ground measurements. Inspection of the Hydrometeor Classification product used to produce the Level III Z-R rainfall estimates showed that the radar identified one of the rain bands moving through as having hail or graupel (Figure 3-5). The rain band under this classification moved through the northwestern and center portion of the site, near the A- and D-area wedge locations before it was classified as heavy rain. Both MRMS and Level III Z-R data use Dual Polarization algorithms to identify and correct for "bright banding", which occurs in the melting layer and in the presence of water coated iced particles (e.g. hail or graupel). Water coated solid hydrometeors scatter radar energy more effectively and therefore can dramatically overestimate precipitation totals derived from radar. Therefore, corrections have been implemented to estimates from the Z-R relationship to eliminate errors due to this effect. However, our results suggest that the rain band was misclassified as containing ice particles and a correction was erroneously applied to the rainfall estimates producing the observed radar underestimation of rainfall totals on the western portions of the site (but not on the rest of the site, which was correctly classified as rain/heavy rain). It is thought that similarly, rainfall total over- or underestimation due to misclassification issues could likely explain outliers observed on this study.

The few outliers observed should not undermine the fact that radar derived values and gauge measured values have reasonably strong correlation coefficients and low RMSE, with results that are comparable to those obtained in similar published studies. Zhang, et. al (2016) had cautioned about possible differences when comparing MRMS data with data from independent gauges that are not part of its correction scheme, however this study demonstrates that the MRMS gauge correction method is robust and provides representative rainfall values even for an independent gauge network.

Based on these results, we conclude that radar derived rainfall is an acceptable substitute of wedge gauge data for applications at SRS. The MRMS derived values are the preferred source of radar derived rainfall estimates given our results. Data from SRS tipping buckets will continue to be collected and utilized for specific applications and for continued validation of MRMS estimates. It is expected that the areal estimates derived from radar will provide benefits for users that formerly extrapolated point estimates over a larger area for use in calculations, such as for watersheds runoff estimations, deposition studies, etc. There may be instances where the MRMS data may over or underestimate rainfall amounts due to hydrometeor misclassification, but event classification schemes are expected to improve in coming years as more data assimilation and QA techniques continue to be developed for this tool.

Lastly, studies have shown that radar derived data compares better with gauge measurements over longer periods of time. Upon inspection of monthly rainfall totals over approximately a year and half, good agreement between tipping bucket and MRMS values was observed. However, there are multiple instances where the MRMS tends to slightly underestimate rainfall amounts in comparison to wedge measurements. Therefore, it is expected that the long-term impact of the implementation of MRMS data as a substitute for the wedge measurements may result in a small decrease in the monthly and annual total rainfall amounts. This small decrease, likely due to smoothing over the 1 km area, will be more representative of amounts observed over larger portions of the site compared to data extrapolated from a single point estimate.

Table 3-1. Summary of Events Studied

Date (End Period)	D Area				C Area				A Area			
	Wedge	Tipping B.	Z-R	MRMS	Wedge	Tipping B.	Z-R	MRMS	Wedge	Tipping B.	Z-R	MRMS
9/1/2017	0.00	0.07	0.17	0.08	0.07	0.14	0.17	0.07	0.30	0.35	0.38	0.21
10/9/2017	0.82	0.82	0.75	0.67	0.80	0.59	0.85	0.89	0.60	0.64	0.55	0.59
12/21/2017	0.87	0.87	0.54	0.67	1.00	0.92	0.69	0.84	1.50	1.44	0.97	0.99
1/13/2018	0.98	0.98	0.56	0.86	1.15	0.85	0.64	0.80	0.90	0.98	0.64	0.70
1/29/2018	1.15	0.99	1.54	1.05	0.74	0.80	*nd*	1.04	1.30	1.30	0.85	1.23
2/5/2018	0.64	0.64	0.54	0.52	0.70	0.58	0.51	0.54	0.80	0.86	0.58	0.59
3/7/2018	1.20	1.20	1.18	0.83	1.10	0.98	*nd*	0.85	1.25	1.31	1.35	0.94
4/8/2018	1.36	1.33	0.87	0.90	0.68	0.70	*nd*	0.72	0.50	0.51	0.36	0.46
4/16/2018	0.75	0.75	1.72	1.06	1.15	1.16	*nd*	1.16	1.00	1.20	1.28	0.91
4/24/2018	1.59	1.08	1.52	1.27	0.80	1.01	*nd*	1.04	2.75	2.33	2.05	1.83
5/18/2018	1.04	1.04	0.70	0.68	0.36	0.93	0.42	0.38	0.40	0.41	0.32	0.37
5/19/2018	0.33	0.33	0.94	0.35	0.75	0.31	1.20	0.00	0.95	0.93	1.11	0.63
5/28/2018	1.48	0.35	0.94	1.36	0.38	0.45	0.81	1.24	1.50	1.65	0.81	1.41
6/12/2018	0.17	0.17	0.51	0.42	0.17	0.83	0.85	0.67	0.85	1.00	0.94	0.86
6/23/2018	1.24	1.21	1.11	0.96	1.20	*nd*	0.90	0.84	0.90	0.92	1.26	0.85
6/26/2018	0.58	0.60	1.91	1.48	0.62	*nd*	1.59	1.34	0.00	0.04	0.10	0.09
9/16/2018	0.41	0.35	0.13	0.24	0.25	0.26	0.17	0.30	0.50	0.58	0.25	0.30
9/17/2018	0.16	0.21	0.14	*nd*	0.50	0.11	1.09	0.74	0.07	0.03	0.00	
9/18/2018	0.09	0.10	0.45	0.53	*nd*	*nd*	*nd*	*nd*	0.25	0.22	0.48	0.76
11/10/2018	0.57	0.57	0.26	0.26	0.94	0.80	0.49	0.47	0.45	0.39	0.29	0.31
11/13/2018	0.70	0.70	0.53	0.77	0.70	0.86	0.65	0.78	1.60	1.56	0.99	1.15
11/14/2018	0.07	0.07	0.27	0.12	0.18	0.09	0.24	0.13	0.06	0.06	0.12	0.09
11/15/2018	2.05	2.05	1.06	1.71	0.82	1.82	1.10	1.73	1.80	1.98	0.99	1.57

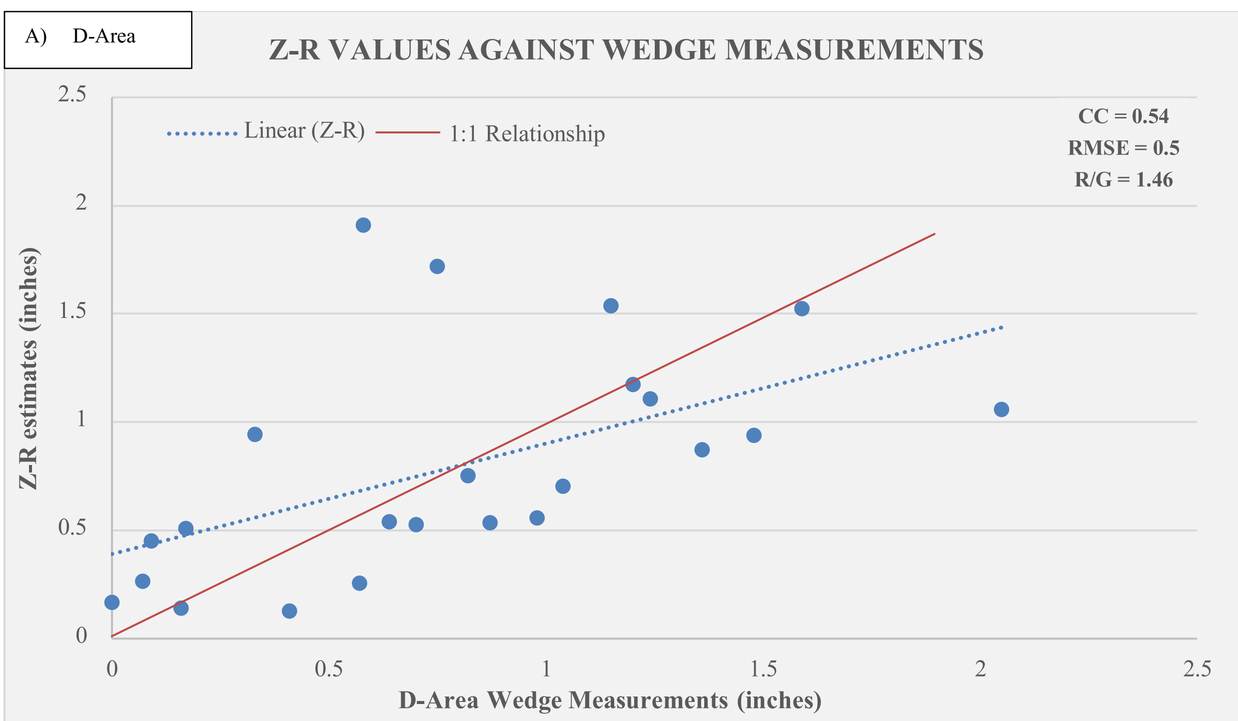
Days with no data are identified by *nd*.

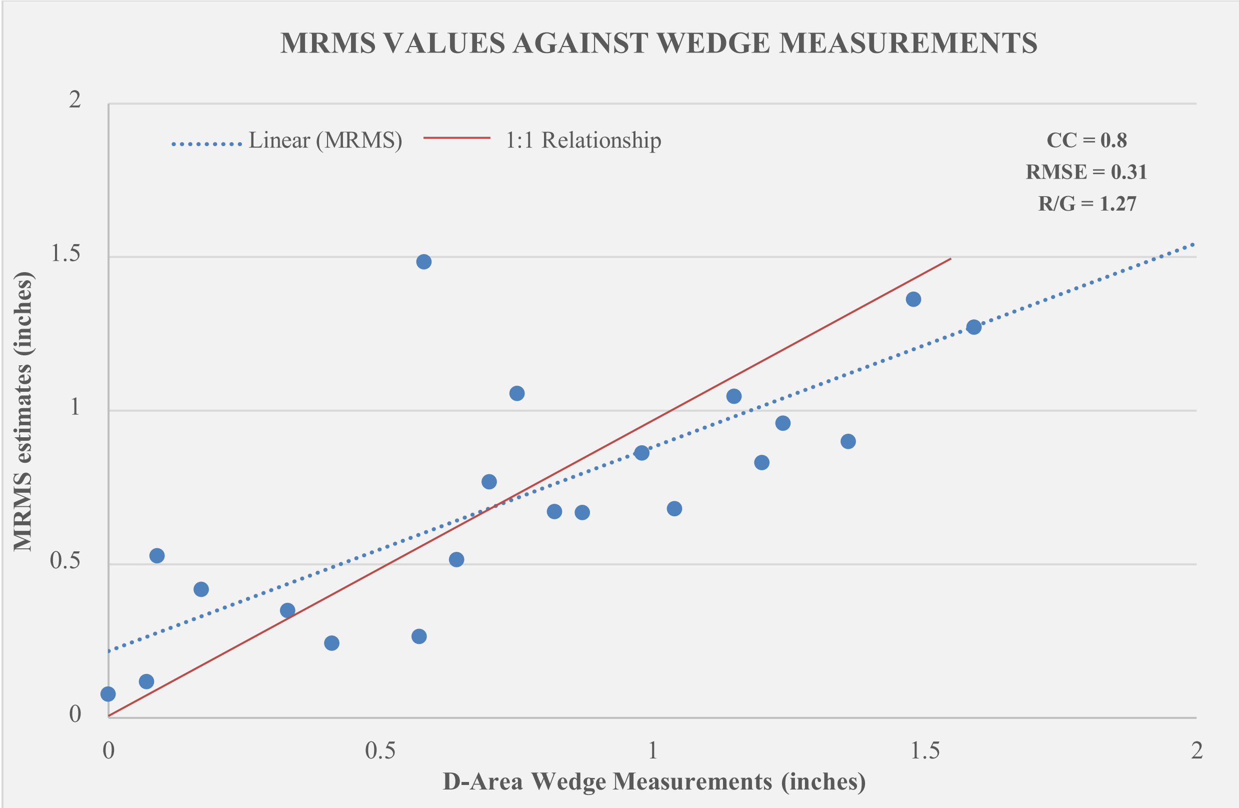
Table 3-2. Radar estimates and wedge measurement comparisons

Location	Stat. Tests	MRMS	Z-R
A-area	CC	0.94	0.87
	RMSE	0.30	0.52
	R/G	0.91	1.21
D-area	CC	0.80	0.54
	RMSE	0.31	0.50
	R/G	1.27	1.46
C-area	CC	0.43	0.37
	RMSE	0.41	0.52
	R/G	1.28	1.51

Table 3-3. Radar estimates and tipping bucket measurement comparisons

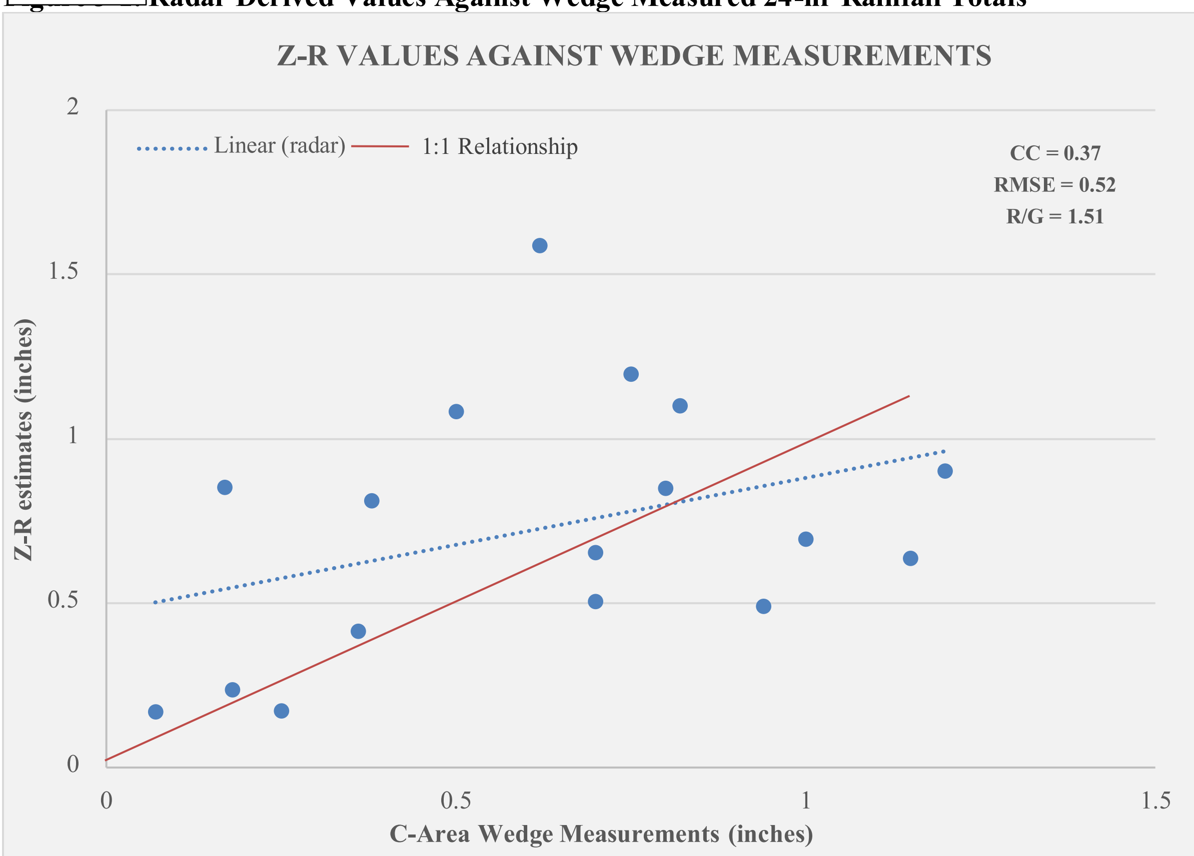
Location	Stat. Tests	MRMS	Z-R
A-area	CC	0.95	0.86
	RMSE	0.28	0.53
	R/G	0.96	1.33
D-area	CC	0.67	0.47
	RMSE	0.36	0.51
	R/G	1.40	1.59
C-area	CC	0.83	0.67
	RMSE	0.23	0.34
	R/G	1.09	1.42





B) C-Area

Radar Derived Values Against Wedge Measured 24-hr Rainfall Totals



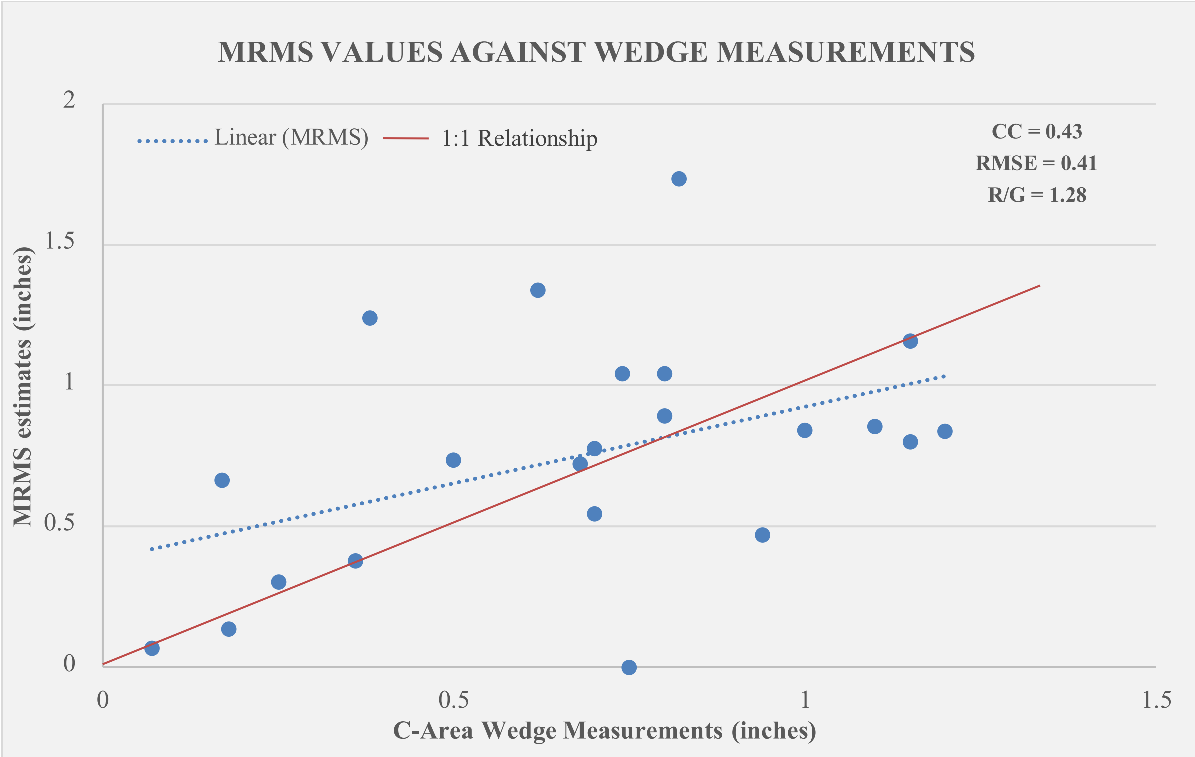
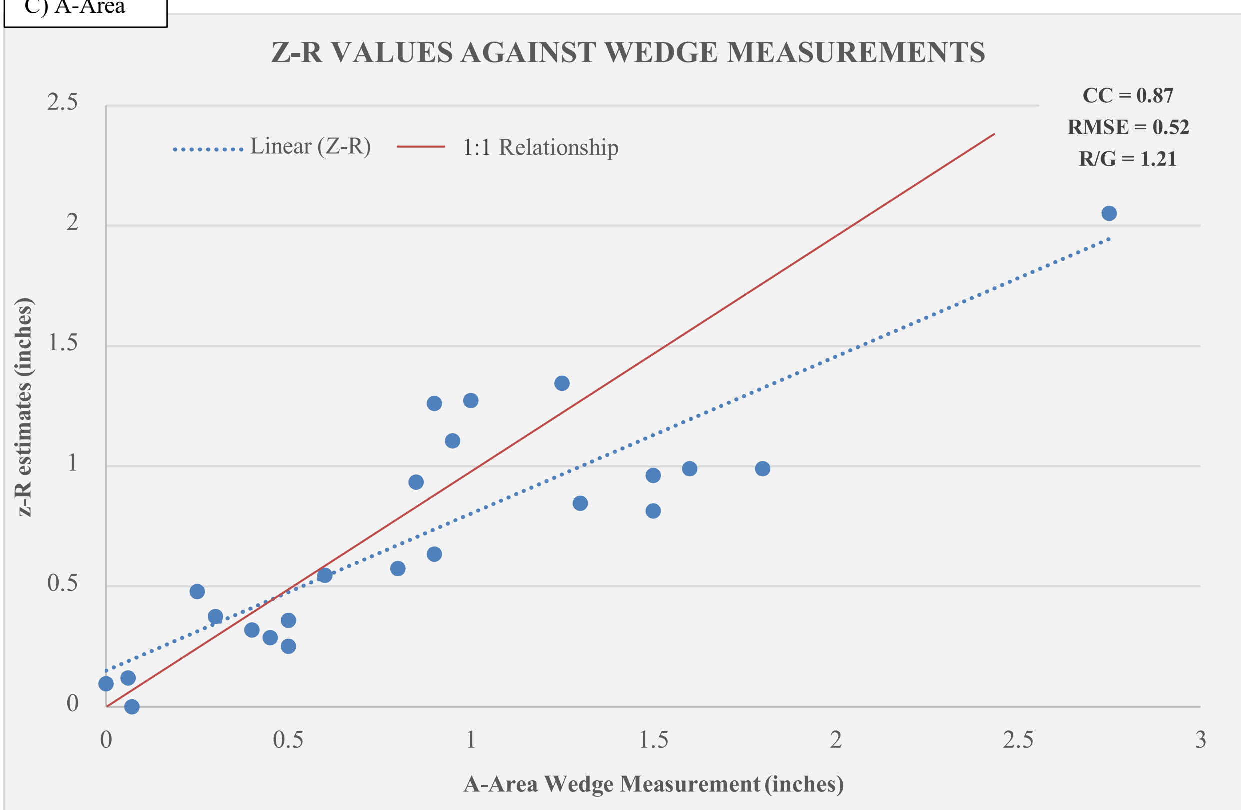


Figure 3-1. Radar Derived Values Against Wedge Measured 24-hr Rainfall Totals *(continued)*

C) A-Area



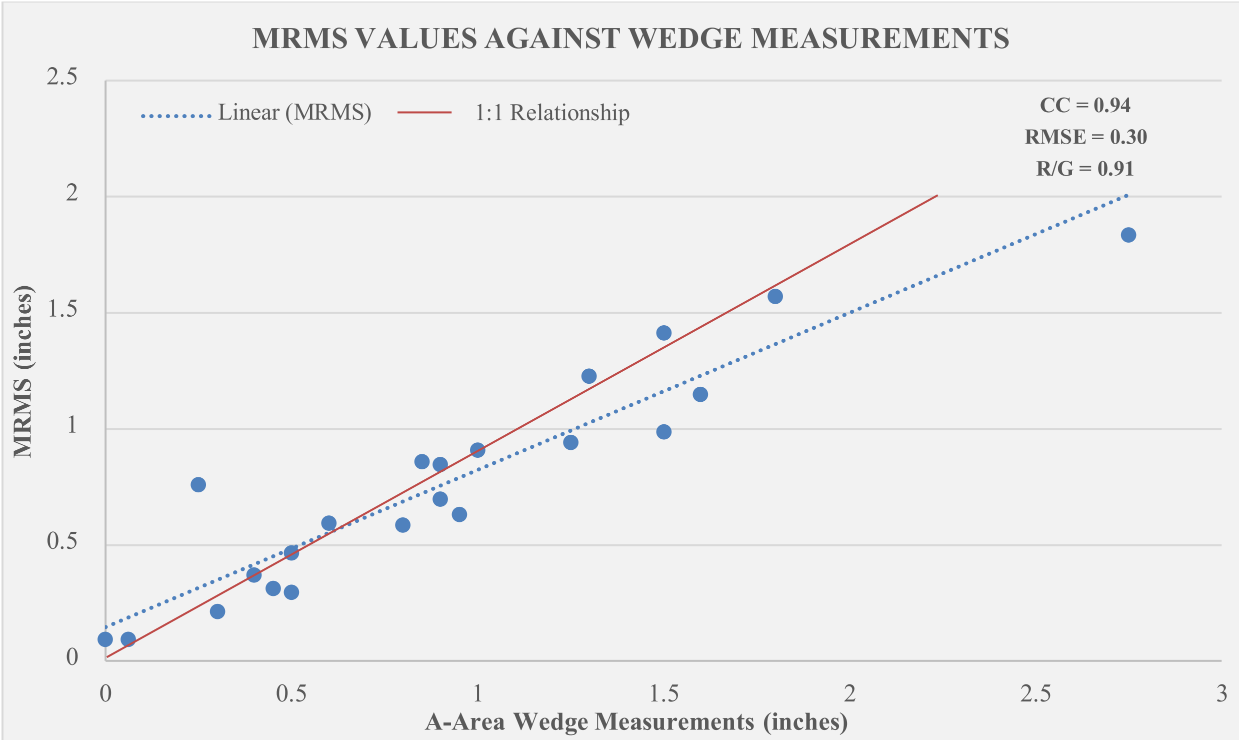
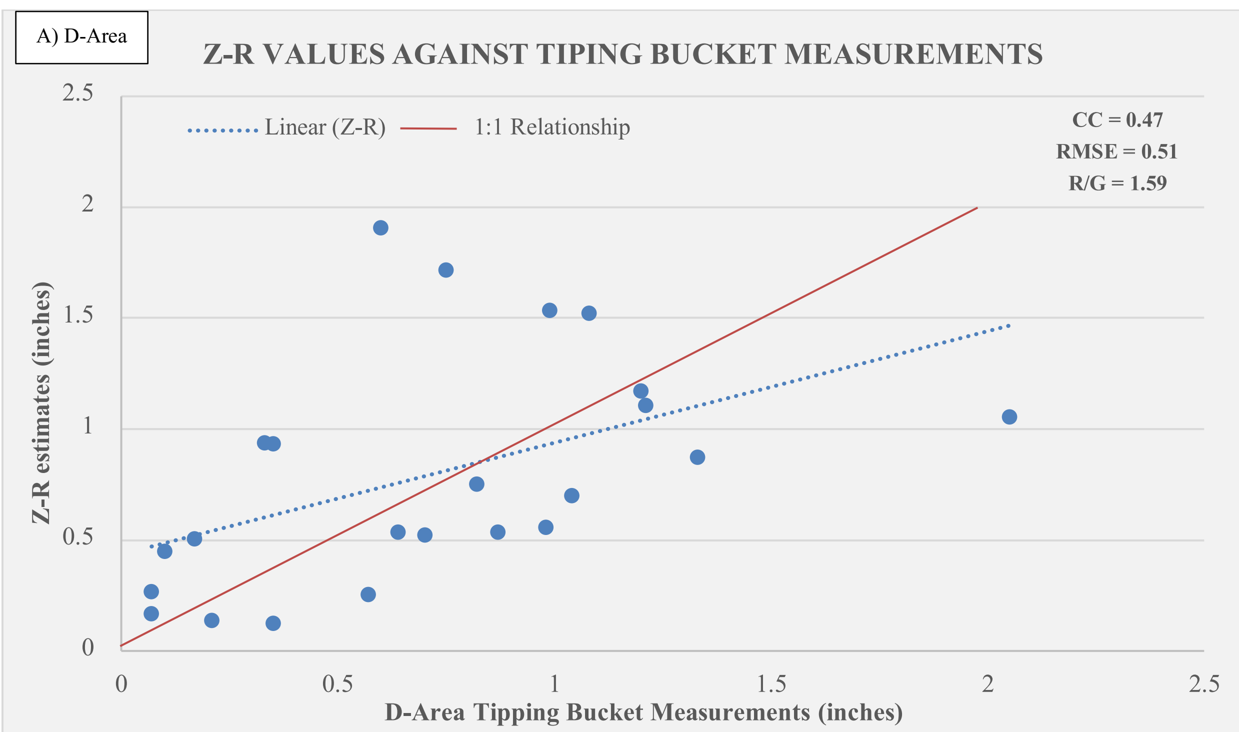


Figure 3-1. Radar Derived Values Against Wedge Measured 24-hr Rainfall Totals *(continued)*



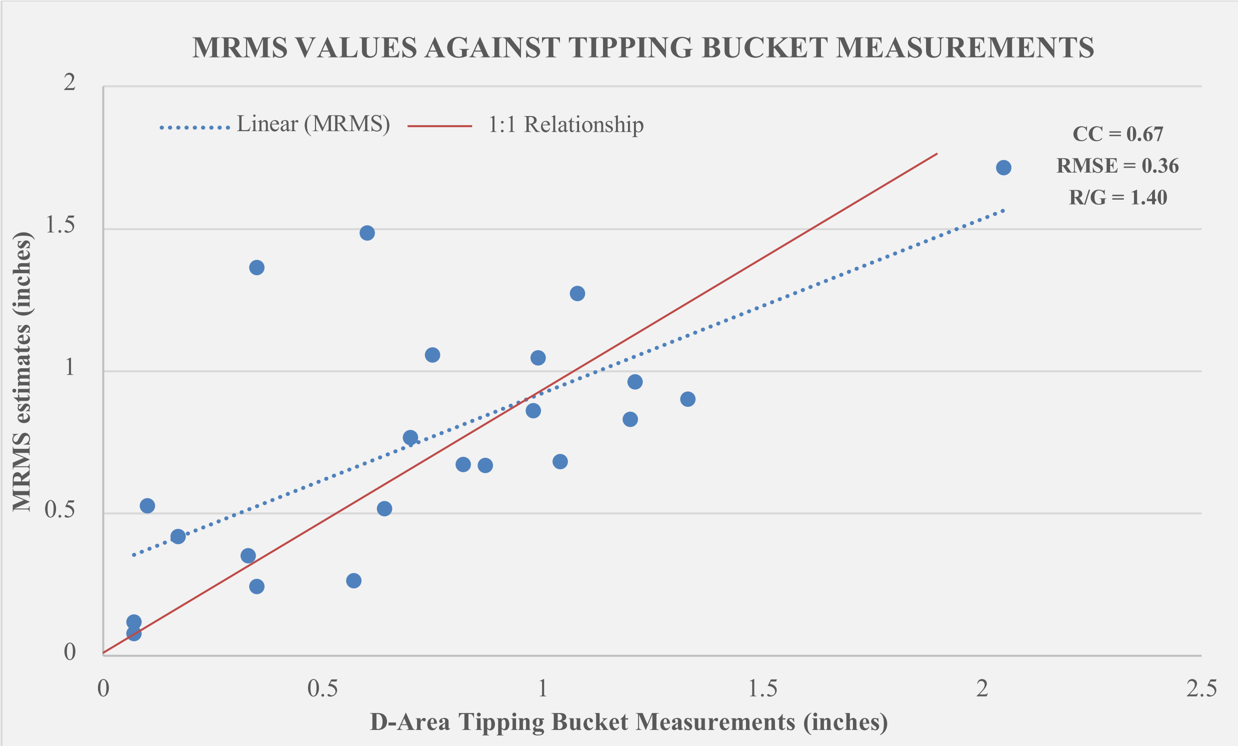
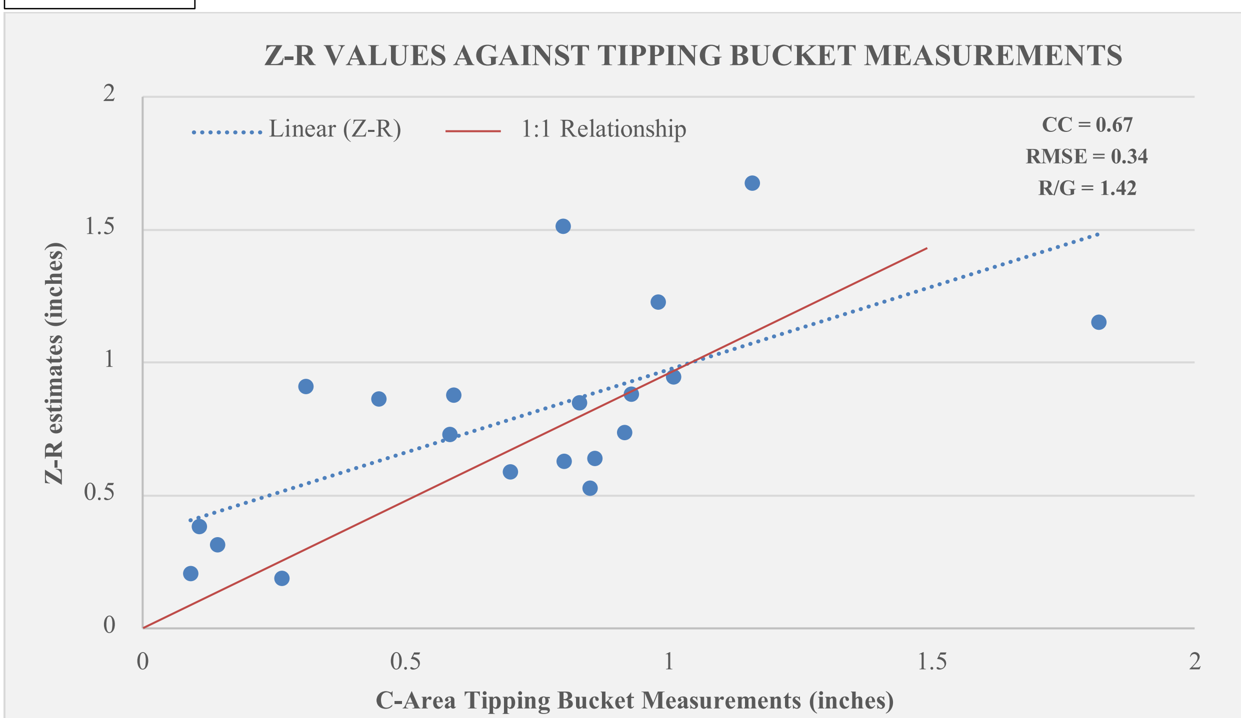
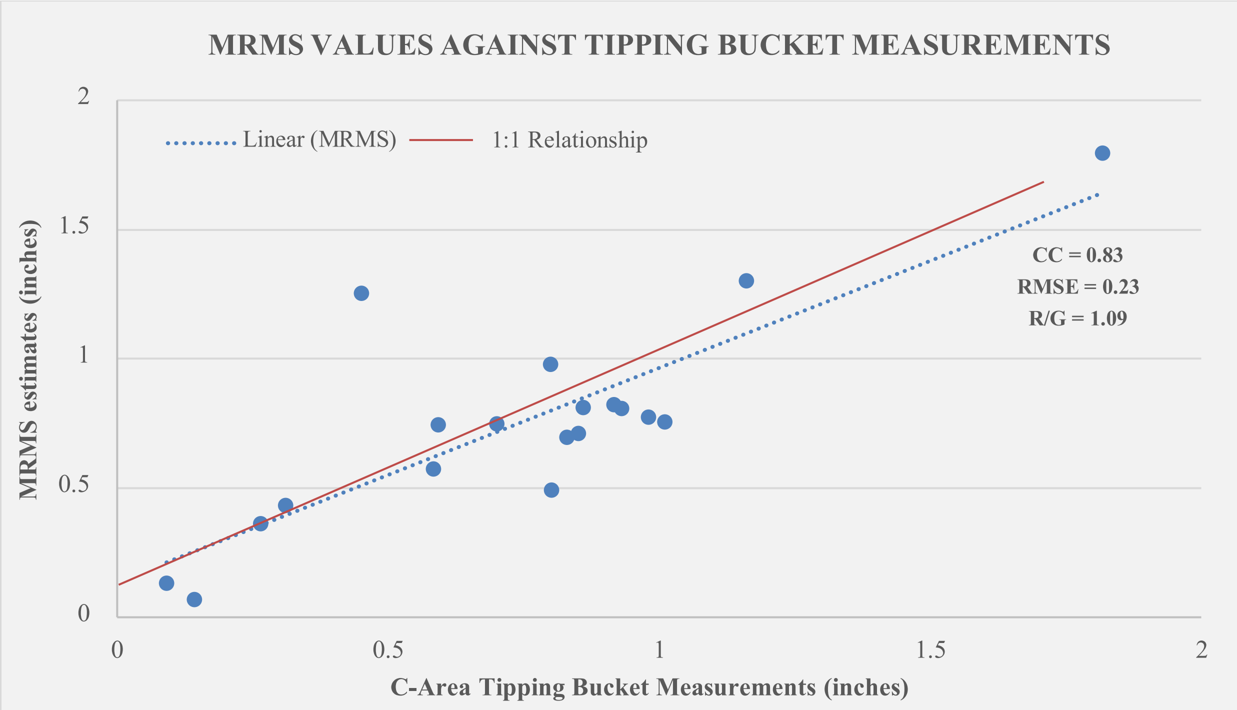


Figure 3-2. Radar Derived Values Against Tipping Bucket Measured 24-hr Rainfall Totals

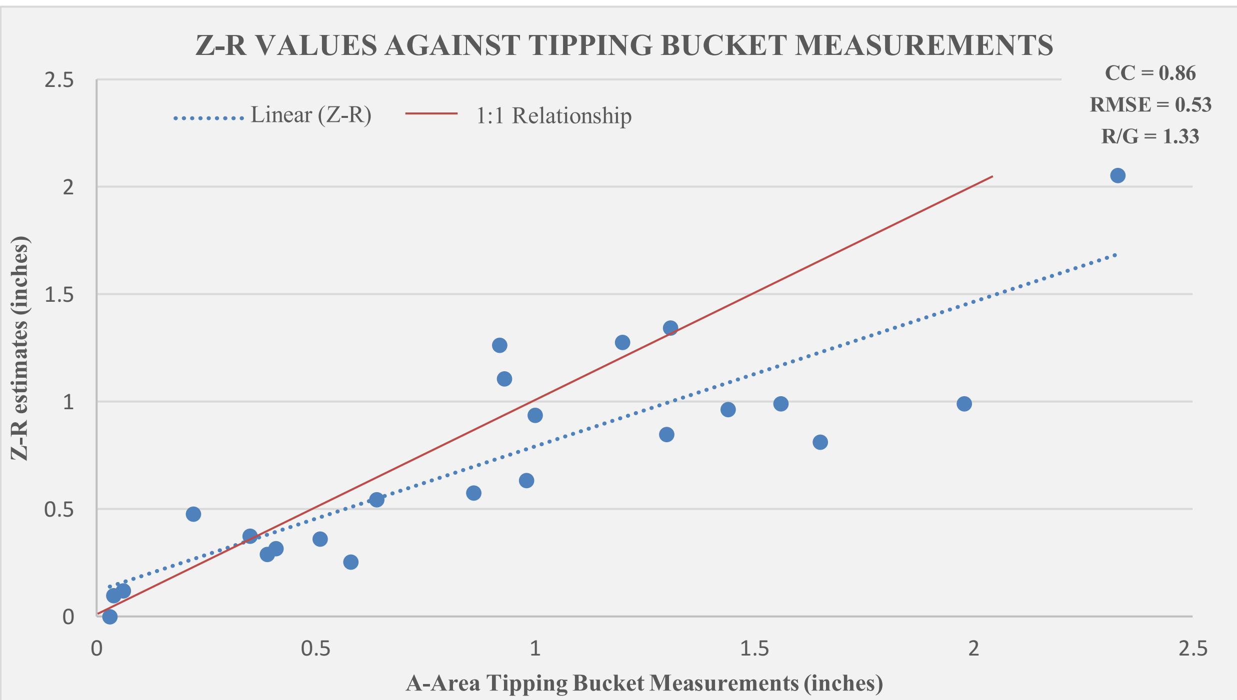
B) C-Area





C) A-Area

adar Derived Values Against Tipping Bucket Measured 24-hr Rainfall Totals



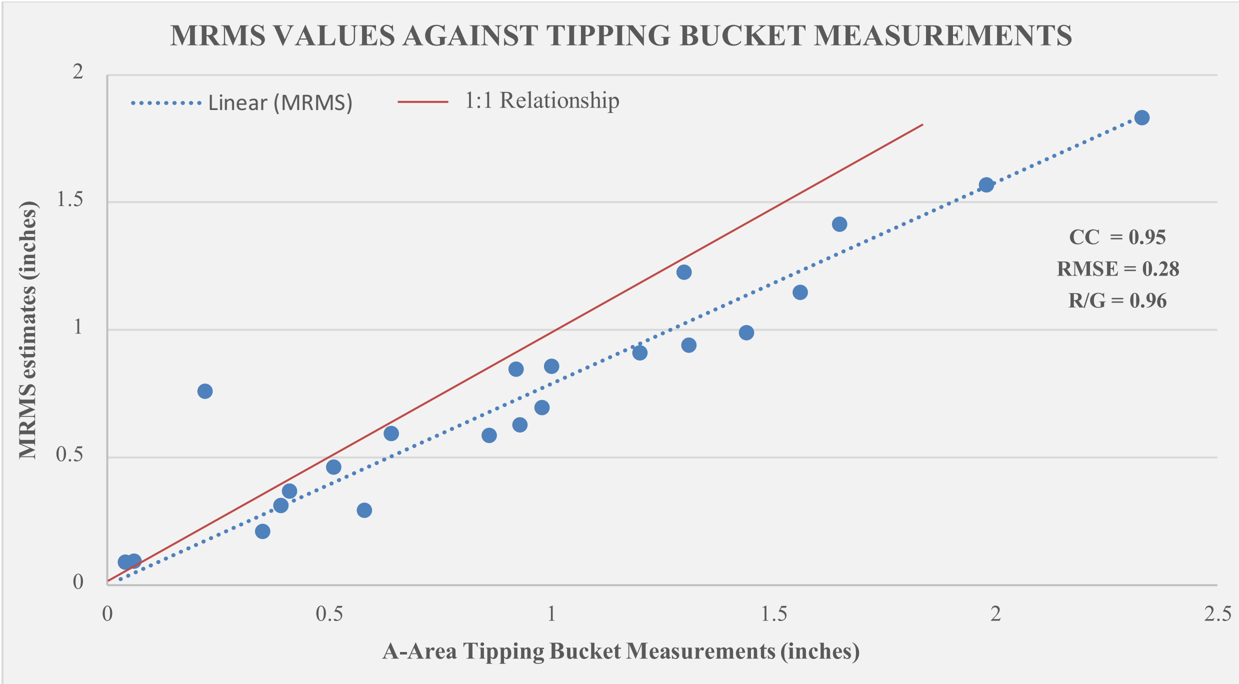


Figure 3-2. Radar Derived Values Against Tipping Bucket Measured 24-hr Rainfall Totals
(continued)

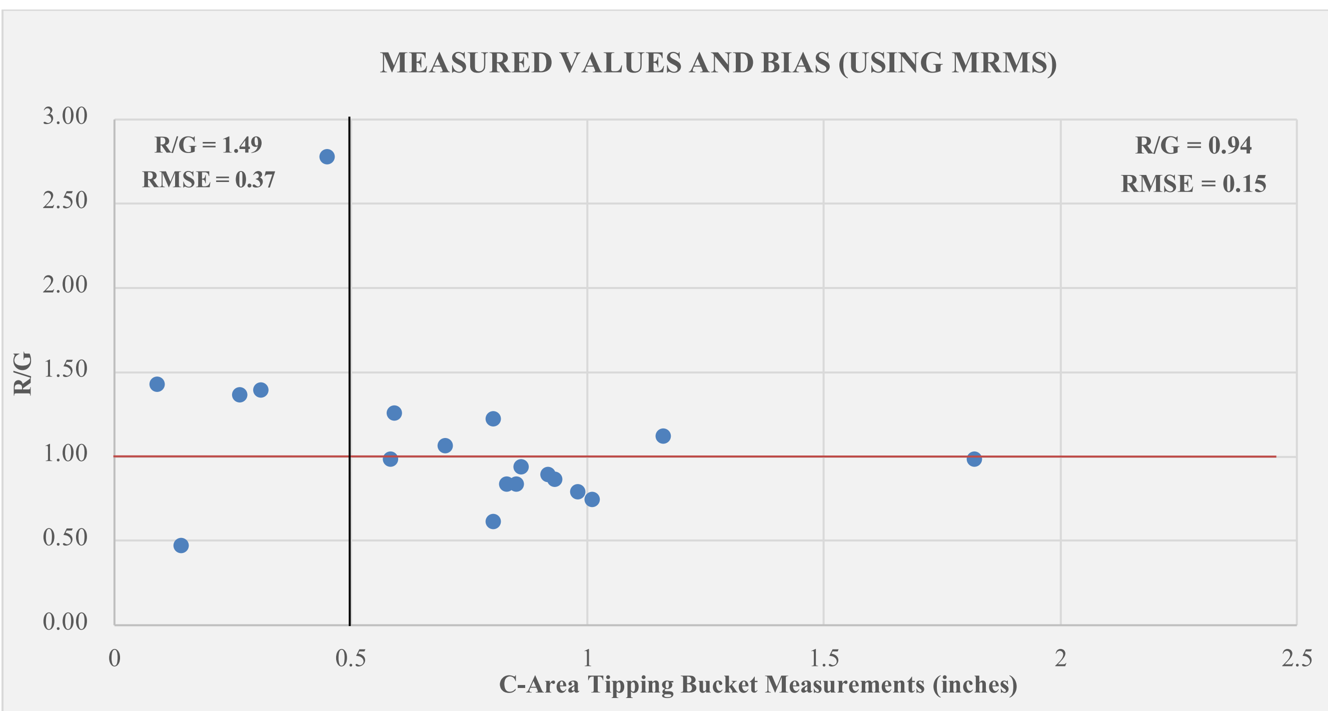


Figure 3-3. Accumulation Ratio (or Bias) for C-area Daily Total Amounts

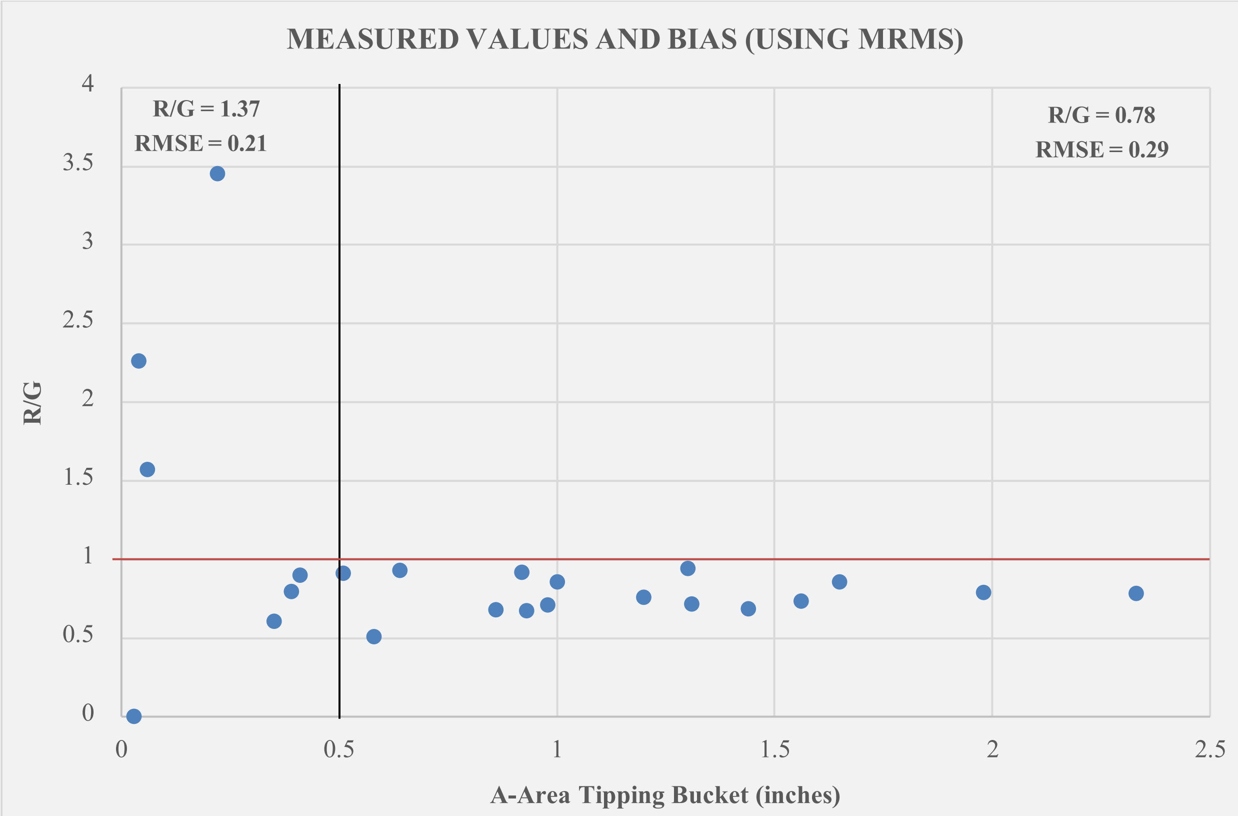


Figure 3-4. Accumulation Ratio (or Bias) for A-Area Daily Total Amounts

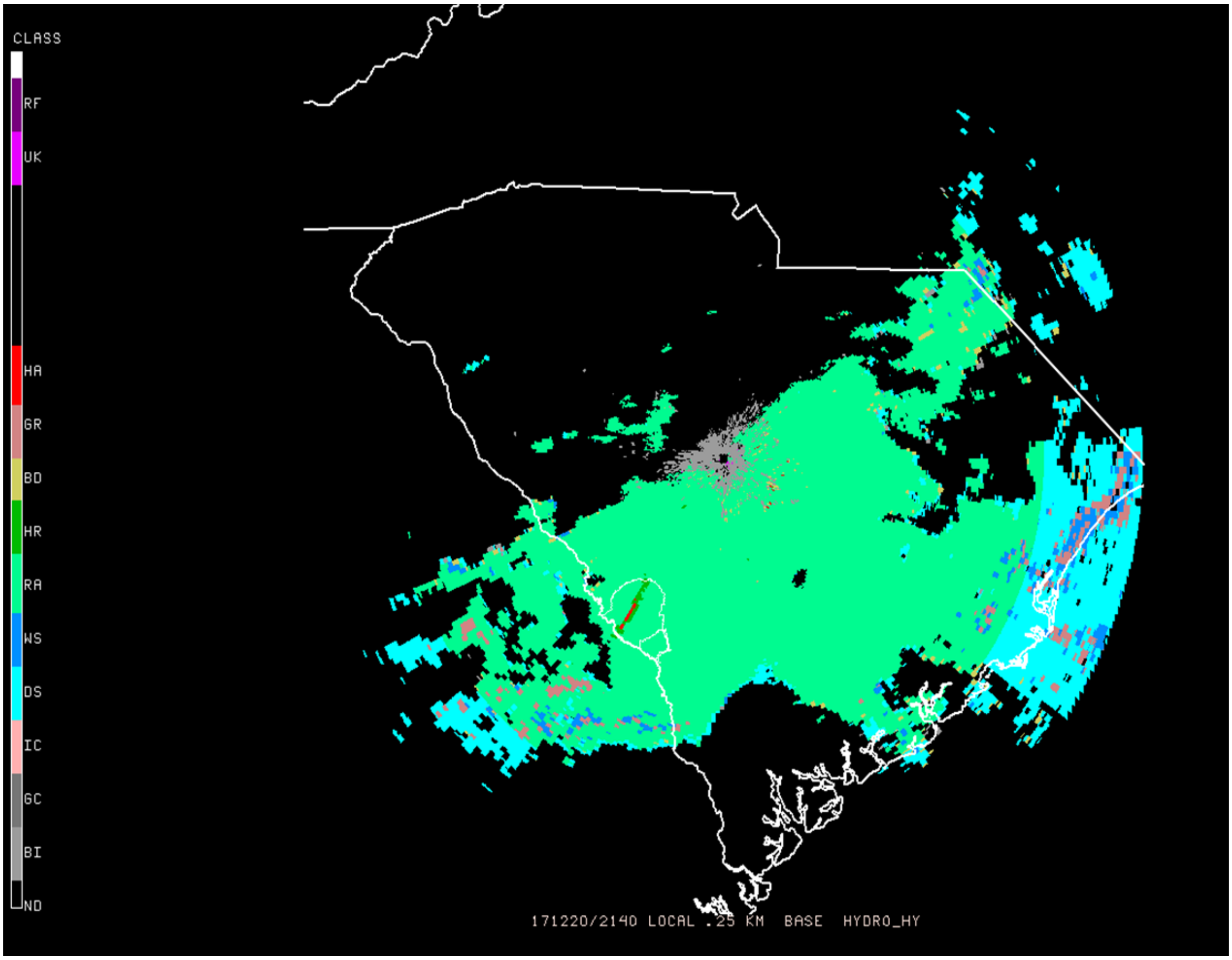


Figure 3-5. Hydrometeor Classification for the 12/21/2017 event. Red denotes areas classified as having hail or graupel.

4.0 Conclusion

Considering all sources of error that could impact both gauge and radar derived datasets, our results demonstrate that radar derived estimates of rainfall are now an acceptable alternative to ground rainfall measurements collected manually using wedge gauges. Key findings from this study show:

1) Correlation coefficients and mean error between radar derived rainfall estimates and gauge measurements demonstrate that radar estimates are in generally good agreement with gauge measurements.
2) MRMS gauge corrected rainfall estimates show better agreement with gauge measurements in comparison with Z-R Level III data.
3) The significant outliers and errors observed in the dataset are attributed to instrument placement and location and radar precipitation type misclassification.
4) Comparisons using ATG's rain gauges provided an independent validation for the MRMS dataset. Our results confirm the accuracy of the MRMS rainfall estimates and show they are representative of ground measurements even for locations that have not been included on the rain gauge database used for the QPE correction scheme.

Results support the use of radar derived estimates as a substitute for manually read wedge rain gauges. Of the two sources of radar derived data, the MRMS shows the best agreement with data from the tipping bucket gauges.

5.0 Future Work

Further studies will provide an assessment of radar derived rainfall against ground measurements over a longer timescale and a larger number of rain events. Additionally, future work will focus on the Hydrometeor Classification Scheme and evaluating how it impacts the agreement between the radar estimates and the rain gauge measurements. This will provide a robust background that will enable identification and, potentially, bias correction for locally problematic classification types.

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