2.12 Inter-Comparison of Real-Time Rain Gage and Radar-Estimated Rainfall on a Monthly Basis for Midwestern United States Counties

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1. INTRODUCTION

Rain gages and radar have been used separately and jointly for many years to estimate rainfall. Rain gage measurements are typically used as ground truth measurements for rainfall, despite their known inaccuracies resulting from wind, poor exposures, instrument-based mechanical or data transmission problems, and errors associated with the spatial and temporal interpolation of gage reports. Radars, though providing better spatial resolution, have known problems related to the nature of the reflectivity-rainfall relationship, the location of the radar beam within the precipitating cloud, and other problems due to calibration, hail, anomalous propagation and ground clutter. These errors often are not uniformly distributed over the radar coverage area, as errors vary from storm to storm. Errors also may vary from radar to radar.

Hildebrand et al. (1979) indicated that for gage densities of better than 1 gage per 250-300 km^2, gage-alone and gage-adjusted radar estimates are of similar accuracy when compared to gage rainfall from densities of 1 gage per 30 km^2. However, they also indicated that for densities sparser than 1 gage per 250-300 km^2, gage-adjusted radar estimates of mean area convective rainfall may be more accurate than gage-alone estimates.

For many purposes, real-time or near-real-time rainfall over a large area such as the central Midwest is desired, but with the same time and point accuracy that is typically reserved for a small area with many gages. It is the intent of this paper to evaluate county-averaged rainfall estimates over the central Midwest region employing cooperative gage data and real-time gridded rain estimates based on WSR-88D radar and gages, to attempt to determine their relative accuracy on a monthly time scale.

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2. DATA AND ANALYSIS

Rainfall data was collected from three sources for this study: 1) hourly gridded precipitation estimates based upon hourly gages and the WSR-88D radars obtained in near real-time from the National Centers for Environmental Prediction (NCEP), 2) daily quality-controlled National Weather Service (NWS) cooperative raingage (QC_Coop) data from NCDC, and 3) daily real-time NWS cooperative raingage (RT_Coop) data. The area covered includes counties within nine states located in the central Midwest (Figure 1). The analysis period covers the summers of 1997-1999 and 2001. RT_Coop data, however, were archived beginning in 2001. The following describes these data sets.

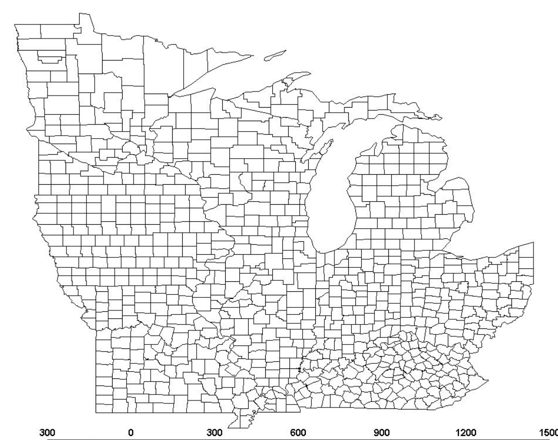


Figure 1. Counties included in study

Gridded (15-km) hourly precipitation estimates based on the NWS WSR-88D radar and rain gage observations have been obtained in near real-time from NCEP since March 1997. The gridded data are downloaded and summed over the 24-hour period, (0700 – 0600 CST). County averages are computed for the radar (unadjusted), gage, and multi-sensor fields (currently created from the unadjusted radar and raingage fields) for the central Midwest, and are stored for analysis.

The gridded radar rainfall fields for the central Midwest are a composite of data from some 30 WSR-88D radars. Where radar coverage areas overlap, grid values are averaged using an inverse distance weighting function. Fulton et al, (1998) provides a detailed description of the WSR-88D rainfall algorithm and a summary of possible radar and raingage errors.

Approximately 90 percent of the gages employed in the hourly gridded gage analysis are from Automated Weather Observing System (AWOS) sites, employing Fisher Porter (FP) Tipping-Bucket gages. Occasionally, extremely large county-averaged gridded gage rainfall values occurred. These extreme values were clustered together suggesting a bad gage value. An attempt was made to eliminate these values from the analysis. In 1997, there were no gridded gage estimates for Michigan.

The gridded multi-sensor field was developed to account for spatial inhomogeneities in the rainfall estimates, under the assumption that the radar mean bias error has been removed (Fulton et al., 1998). The technique detailed by Seo (1998) attempts to account for within-storm variability of rainfall and for variability due to the fractional coverage of rainfall (i.e. one instrument reports rainfall where the other does not). Similar to the elimination of extremely large county-averaged gage rains, some county values were also eliminated from the multi-sensor set, where the gridded values were clearly adjusted by bad gage values.

The QC_Coop data available some months after the fact were obtained from NCDC. The gages employed are either AWOS FP gages or the standard 8-inch nonrecording gages (SNRG). Only gages having 90 percent or more data reported during the period were employed. About 775 of the 858 counties in the study region contained at least one quality-controlled raingage. There were approximately 1500 cooperative gages reporting during this period. This resulted in an average of about two gages per county in counties with gages, or about one gage per 800 km^2. Reporting times of the cooperative gages vary, with some at midnight, many between 5 and 9 in the morning, and a few at other times of the day. Observing times are reported by the observer and can vary from day to day. All gages were employed in computing the QC_Coop monthly county averages.

RT_Coop data were collected daily during the summer of 2001. About 625 gages reporting between 5 and 900 LST were employed in this analysis. These data were largely from cooperative observers reporting SNRG amounts. Only about 530 of the 858 counties had at least one raingage reporting during the summer of 2001, with an average of about 1.2 gages per county or about one gage per 1300 km^2.

The QC_Coop data are the primary ground-truth in examining the utility of the RT_Coop and the NCEP gridded fields to provide accurate monthly county rainfall measurements. For all rainfall estimates, average monthly totals of 0.0 mm were eliminated from the analysis.

3. RESULTS

3.1 Monthly Rainfall Estimates, 1997-1999

Rainfall estimates summed for June, July, and August 1997-1999 are presented in Table 1. Monthly values were used in part because of the uncertainty in gage observation times. In the mean, the gridded data sets underestimate rainfall as compared to the QC_Coop data (Table 1, Figure 2). For all 9 months, the QC_Coop data mean rainfall totals were largest, and the gridded radar data, the smallest. The gridded gage data was generally most poorly correlated with the QC_Coop estimates. These results are borne out in plots of the monthly county rainfall totals (Figures 3a-c).

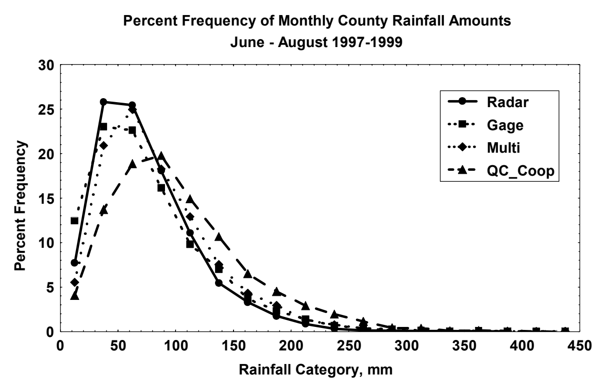


Figure 2. Percent frequency of occurrence of total monthly rainfall by rain estimate technique for June, July and August 1997-1999.

The multi-sensor gridded data were closest in mean value to the QC_Coop estimates of county rainfall. Note that the multi-sensor data also is better correlated with the QC_Coop data than both the gridded radar and gage data (Table 1). This suggests that except for areas where obviously bad gage data were employed, the techniques used by NCEP to compute the multi-sensor data in real-time is an improvement over the gage-only and radar-only gridded values.

Percent differences between the QC_Coop rainfall estimates and the gridded radar-based, gage-based and multi-sensor estimates were computed by ((QC – gridded) / QC) * 100). For these three data sets respectively, approximately 73, 74 and 85 percent of all differences are within ± 50 percent of the QC_Coop rain values.

	QC Coop	Radar	Gage	Multi-sensor
Sample	7139	7599	7234	7653
Mean	102.2	74.5	77.2	83.9
Std Dev	58.5	44.0	54.7	49.6
Linear regression equations relating the monthly QC_Coop and the gridded rainfall estimates.				
	Linear Regression		Linear Corr	
Radar	21.2 + 0.52 * QC		0.64	
Gage	16.1 + 0.60 * QC		0.59	
Multi-Sensor	17.5 + 0.65 * QC		0.77	

Table 1. County-averaged monthly rainfall (mm) statistics, for June - August 1997-1999.

It is generally known that radar underestimates rain in cold season stratiform rain cases. In high horizontal reflectivity gradient / high reflectivity convective rain cases typical of the Midwest during the summer, a radar overestimation is often observed (e.g. Klazura, 1999). Here however, the gridded radar data underestimate rainfall when compared to the QC_Coop data, and the underestimation increases for the larger monthly totals (Figure 3a-c).

One possible explanation that was considered to explain this underestimation of rainfall by the NCEP gridded radar field was individual radar biases due to calibration errors. There was spatial coherence in the pattern of differences between the radar and the QC_Coop estimates in each year, but they were not related to individual radars. The areas where differences were observed were larger than the coverage of individual radars. Further, the areas with the largest positive absolute differences were correlated with areas of larger total rainfall.

Possible reasons for rainfall underestimation by radar are suggested by Baeck and Smith (1998) for heavy rainfall events. These include too low a reflectivity threshold employed in the WSR-88D precipitation algorithm (53 dBZ), inappropriate radar reflectivity – rainfall (Z-R) relationships, insufficient sampling of the precipitation level by the radar beam, and wet radome attenuation. The Z-R relationship usually used by the WSR-88D radars ($Z=300R^{1.4}$) is similar to one ($Z=300R^{1.35}$) that was developed employing data from a dense raingage network in northeast Illinois in the late 1970's for the Hildebrand et al. (1979) study. It generally is suitable for convective rainfall within the Midwestern region. However, as drop-size distributions vary within a storm and as the radar beam does not uniformly sample the rain volume within a storm, the relative

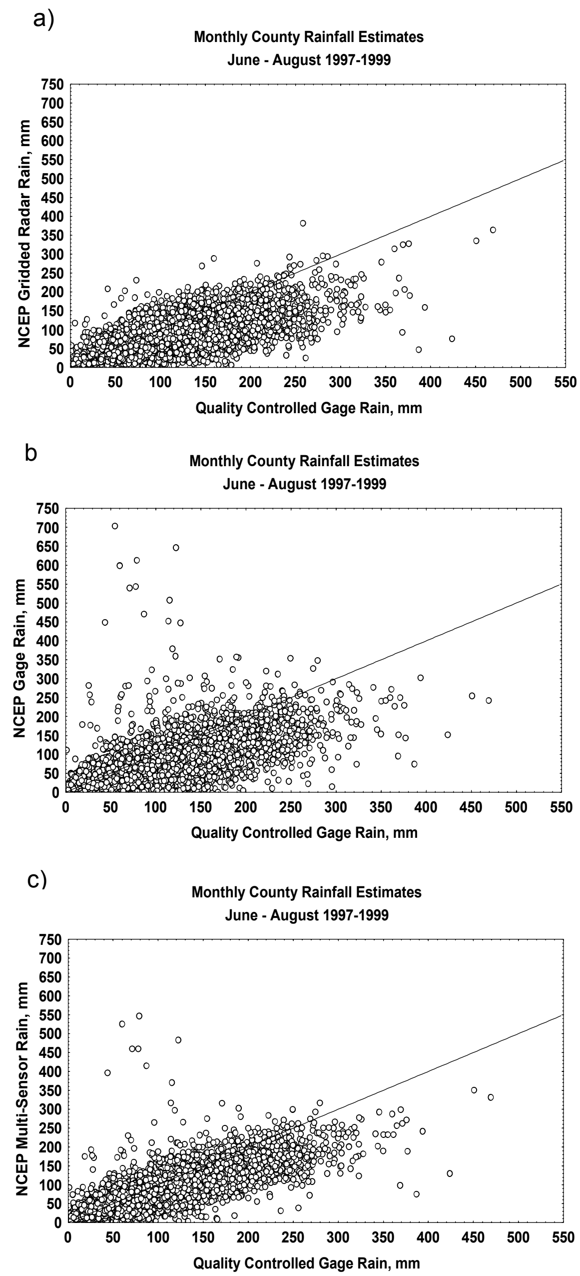


Figure 3. County-averaged monthly rainfall totals for the QC_Coop data versus the gridded fields for June, July and August 1997-1999

appropriateness of the Z-R equation and the impact of the other factors will vary from storm to storm, with distance from the radar, and with the particular scanning mode employed. One additional factor is that truncation errors in the WSR-88D precipitation algorithm have been found to result in a small but systematic underestimation of rainfall (Tim Crum, personal communication). The contribution by this latter factor, however, is small for larger rain-rates.

The underestimation by the gridded gage data also was unexpected. A possibly explanation for the underestimation is that the spatial density of gages may affect the gridded gage estimates. For sparser gage densities, large differences might occur if large gradients in rain were present in a county, i.e. if the gage was located in the peak or minimum rainfall area with a county. The median percent difference between the QC_Coop monthly estimates and the three NCEP gridded rain estimates, grouped by area per gage are presented in Figure 4. For counties with QC_Coop gage densities finer than 1 per 250 km^2, the gage and multi-sensor gridded fields correspond most closely to the QC_Coop estimates. The percent difference with the gridded gage field increases with decreasing gage coverage. For QC_Coop densities sparser than 1 per 2250 km^2, all three fields diverge from the QC_Coop data. No clear trend in bias due to gage density is found for the radar data, suggesting that the radar differences are unrelated to gage density, as is expected. The multi-sensor estimates are most closely related to the QC_Coop estimates and appear to compensate for differences related both to gage density and radar bias.

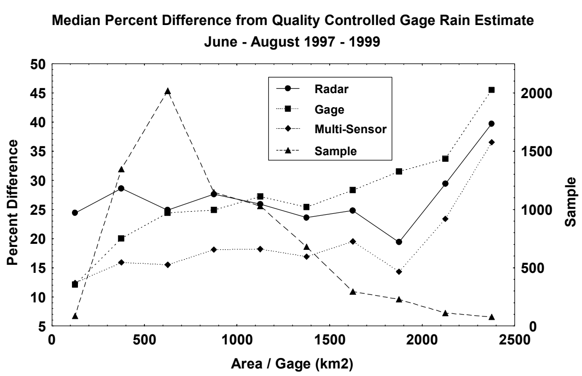


Figure 4. Median percent difference between the QC_Coop county-averaged monthly rainfall totals and totals from the gridded rain fields, for June, July and August 1997-1999. Sample size is indicated for the number of estimates in each area per gage category (increments of 250 km^2.)

3.2 *Monthly Rainfall Estimates, 2001*

In contrast to the 1997-1999 data, the mean rainfall estimates for the NCEP gridded fields were closer in value to the QC_Coop data in 2001 (Table 2, Figure 5). Differences in the mean county-averaged monthly total rainfall ranged from 10 to 15 mm for the summer months of 2001, rather than the 20 to 30 mm found in 1997-1999. Approximately, 89, 79 and 90 percent of the NCEP radar, gage and multi-sensor estimates fell within ± 50 percent of the QC_Coop rainfall estimates. One should note, however, that there were few monthly rainfall totals over 200 mm during 2001. Thus, there is some uncertainty in whether the improvement in agreement with the QC_Coop data found would extend to the highest rainfall totals.

	QC Coop	RT Coop	Radr	Gage	Multi-sensr
Sample	2322	1535	2574	2557	2574
Mean	96.6	77.0	86.3	80.8	86.9
Std Dev	46.6	46.5	40.9	45.7	41.2
Linear regression equations and Linear correlation relating the monthly QC_Coop, the RT_Coop and the gridded rainfall estimates.					
	Linear Regression			Linear Corr	
Radar	22.7 + 0.66 * QC			0.75	
Gage	22.4 + 0.60 * QC			0.62	
Multi-sensor	23.5 + 0.65 * QC			0.75	
Radar	50.7 + 0.49 * RT			0.56 (2001)	
Gage	51.2 + 0.40 * RT			0.39 (2001)	
Multi-sensor	53.2 + 0.46 * RT			0.50 (2001)	

Table 2. County-averaged monthly rainfall (mm) statistics, for June - August 2001.

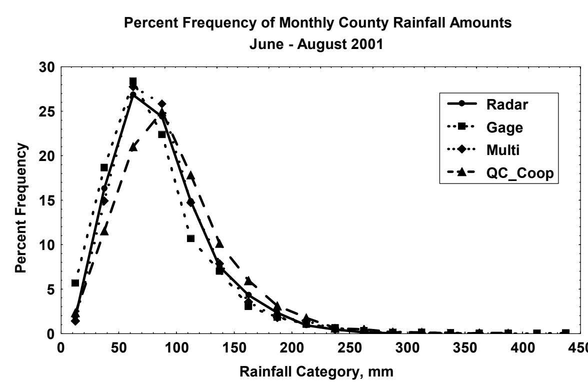
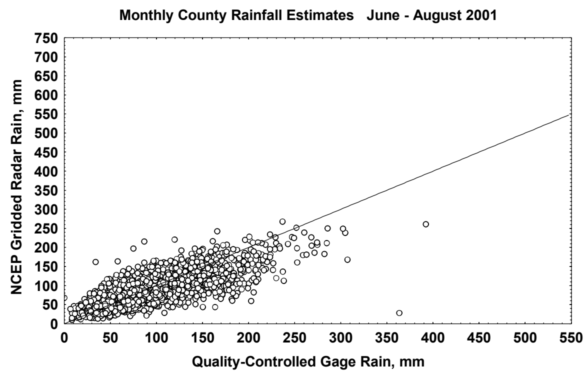


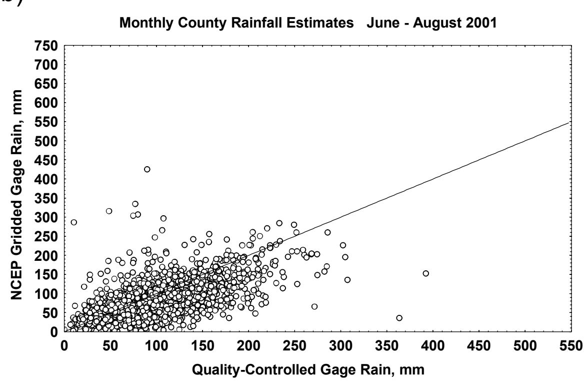
Figure 5. Percent frequency of occurrence of total monthly rainfall by rain estimate technique for June, July and August 1997-1999.

Of the NCEP gridded estimates, the radar estimates of 2001 were the most improved over the 1997-1999 results. Compared to the QC_Coop data, however, the gridded rainfall estimates still underestimate monthly rainfall, especially for the higher monthly rainfall totals (Figure 6 a,b,c). The improvement in the agreement between the gridded radar and QC_Coop estimates is most noticeable at low monthly rainfall totals (Figure 6a), but also is present at the larger rainfall rates. For monthly totals greater than 50 mm, some 57 percent of the differences exceeded 25 percent during 1997-1999, whereas in 2001, only 33 percent of the differences exceeded 25 percent. Improvement in the gridded radar estimates is likely the result of improvements in radar calibration and processing procedures. New occultation maps were installed, improving errors due to blockage of the beam by topographic features or other obstructions (Tim Crum, personal communication).

a)



b)



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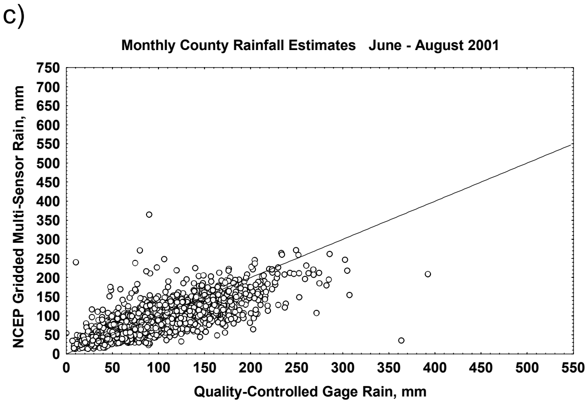

Figure 6. County-averaged monthly rainfall totals for the QC_Coop data versus the gridded fields for June, July and August 2001.

For 2001, there also is an improvement in agreement with the gridded gage data. However, there is considerable scatter in those values (Figure 6b) and in the gridded multi-sensor data (Figure 6c). The RT_Coop data were added to the analysis in 2001, in the hope that they might provide insight into the results for 1997-1999.

In the summer of 2001, the largest county-averaged total monthly rainfall differences were between the QC_Coop and the RT_Coop data (Table 2). Note the larger proportion of low monthly rainfall totals for the RT_Coop data in Figure 7. The correlation with the QC_Coop data was smaller for the RT_Coop data than with the radar and multi-sensor data, but the same as for the gridded gage data (Table 2).

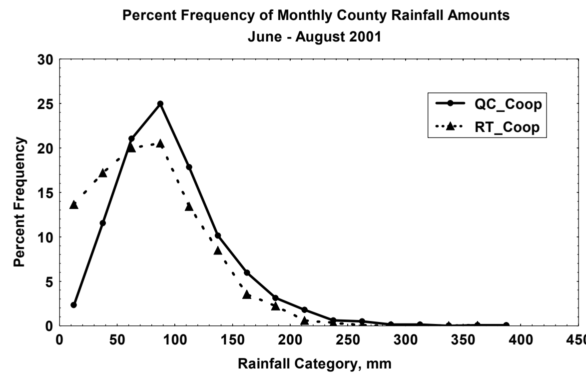

Figure 7. Percent frequency of occurrence of total monthly rainfall by rain estimate technique for June, July and August 1997-1999.

The QC_Coop data should be a better estimate than the RT_Coop because 1) the data have been quality-controlled and 2) the spatial density is greater. Because more gages are employed in the quality-controlled analysis, the largest rain values which cover relatively smaller areas in convective rainfall, are better sampled. The largest differences occurred between the QC_Coop and the RT_Coop when only one real-time reporting gage was found in a county. Of the counties with real-time reporting gages, 67 percent had an average of one or fewer gages per county. Of these counties, 52 percent had differences exceeding ± 25 percent when compared to the QC_Coop data. For counties averaging more than one gage, only 28 percent had differences exceeding ± 25 percent.

Some discrepancy was expected between the QC_Coop and the RT_Coop data. However, the magnitude of the bias (underestimation) was not expected (Figure 8). Groisman et al. (1999) found a reasonable comparison between daily-accumulated rainfall values of Fisher Porter (FP) gages and the standard non-recording raingages (SNRG), with an average ratio of FP to SNRG of 0.95, when missing data were excluded from the analysis. In fact, in examining Figure 8, it appears that many values do follow the 1:1 line. However, a large sample also underestimates the county rainfall.

One possible explanation for the large underestimation by the gridded gage data and the

RT_Coop data in comparison with the QC_Coop data may be the way missing data are treated. The description of the processing procedures for the hourly gage rainfall suggests that if any data is missing during an hour, the hour is reported as missing, and if any given hour is missing, the daily value is reported as missing (ASOS Users Guide, 1998). This would be consistent with an under-representation of rain for the gridded gage field, as many of the gages employed are the AWOS FP. For the RT_Coop data, sometimes rainfall reports from the SNRG are missing. The presence of missing data will always result in an under-representation of rain, and if missing data occur for many rainfall events, the underestimation could be large.

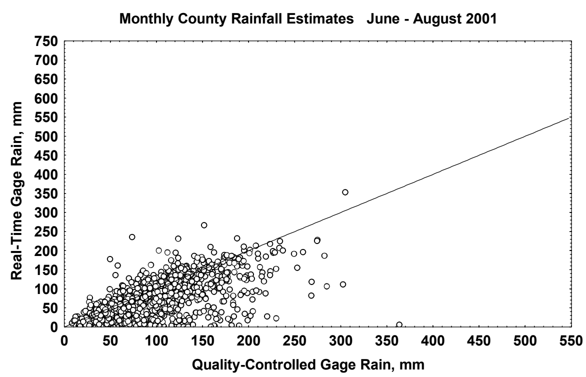

Figure 8. County-averaged monthly rainfall totals for the QC_Coop data versus the RT_Coop data for June, July and August 2001.

The multi-sensor estimates agreed best with the QC_Coop data in 2001. For monthly totals greater than 50 mm, in 1997-1999, approximately 45 percent of the gridded multi-sensor values fell within ± 25 percent of the QC_Coop rainfall total; in 2001, approximately 62 percent fell in this range.

4. CONCLUSIONS

A comparison of real-time rainfall estimates was undertaken. The analysis was carried out on a monthly basis due to the non-uniform observation times of the NWS cooperative gages. The QC_Coop data were employed as the ground-truth. Both the gridded gage and the RT-Coop based estimates underestimated the total rainfall. For both gage data sets, this was probably due to poor spatial density, and possibly due to the way missing data are handled. The real-time gridded gage, and hence the gridded multi-sensor data appeared to suffer occasional high values that might be eliminated with additional quality control tests. The gridded radar data appeared to underestimate rain, particularly for high rainfall values. There was a considerable improvement in the radar data (and hence the multi-sensor data) in 2001, that is likely due to changes in calibration and data processing procedures. These data may be further improved with planned changes in scanning procedures. In real-time, the NCEP multi-sensor data correspond most closely to the QC_Coop data.

5. Acknowledgements

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