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Comparison of raingage and WSR-88D Stage III precipitation data over the Texas-Gulf basin

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Abstract

Precipitation is one of the most important hydrologic model inputs and is characterized by spatial and temporal variability. Traditionally, raingage networks have provided precipitation data for hydrologic studies. Weather radars like the WSR-88D estimate precipitation with high spatial and temporal sampling frequencies, but radar estimates suffer from errors due to several reasons. Assessment of the quality of radar precipitation data is necessary before the application of radar data in hydrologic studies and is important for improving radar data processing algorithms. Accuracy assessment of Stage III precipitation data from the WSR-88D network over the Texas-Gulf basin was performed for the period 1995–99 using 24-h accumulations from 545 raingages. Sampling differences between point raingage measurements and areal radar estimates were ignored. WSR-88D underestimated the five-year precipitation at a vast majority of the raingages. Difference in the total precipitation depth between radar and raingage was within ± 500 mm only at 42% of the raingages; the root mean squared difference was more than 10 mm at 78% of the raingages. Such large differences between both rainfall data sources will have significant implications for the hydrologic applications of WSR-88D Stage III data. Radar estimation efficiency was better than 0.50 at 71% of the First Order/FAA raingages and 41% of the cooperative observer raingages. Radar performance varied significantly over the years, and, in general, improvement in radar performance was observed, which is consistent with the on-going developments in WSR-88D data processing algorithms; however, an overestimation trend was identified during 1998–99. Evaluation of the quality of WSR-88D Stage III data and making necessary corrections are important before their application in hydrologic studies.

Keywords: WSR-88D; Next generation weather radar; Raingage; Precipitation; Accuracy assessment; Texas-Gulf basin

1. Introduction

Precipitation is one of the most important hydrologic model inputs and is characterized by high spatial and temporal variability. Traditionally, point precipitation measurements at raingages have been used with hydrologic models. Since raingages physically measure the depth of rainfall at the points of

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measurement, they generally provide good quality data. Still raingage measurements could involve various errors as discussed by Legates and DeLiberty (1993); Groisman and Legates (1994). Further, raingage networks are usually too sparse to capture the spatial variability of precipitation over the hydrologic system. The point measurements at the raingage location are usually extended over its area of influence (such as the Thiessen polygon around a raingage) in hydrologic studies, resulting in inadequate representation of precipitation spatial variability when the raingage network is sparse. This problem becomes more critical when simulating large river basins.

Weather radars such as the Next generation weather radar (NEXRAD) (formally known as the Weather Surveillance Radar-1988 Doppler (WSR-88D)) of the United States provide precipitation data with much better spatial and temporal sampling frequencies compared to raingages. A better representation of rainfall variability can be accomplished in a hydrologic model by using radar rainfall data. However, there are several possible sources of errors and possibilities of 'data contamination' in the measurement of precipitation by radars (Sauvageot, 1992; Smith et al., 1996; Ulbrich and Lee, 1999; Steiner et al., 1999; Legates, 2000). Hence, the quality of radar precipitation data over the study area should be assessed using raingage measurements before their application in hydrology.

There are several sampling and scale issues involved in comparing the areal estimates of radars and point measurements of raingages. Radar samples the three-dimensional rainfall field over large areas (1–2 km^2) at high temporal frequencies (5–6 min), while the sampling area of a raingage is of the order of 100 cm^2 only. Such large differences in the sampling areas between the two instruments pose a major problem for direct comparisons (Austin, 1987; Ciach and Krajewski, 1999; Steiner et al., 1999). In spite of this problem, raingage data are frequently used to evaluate and/or adjust radar rainfall estimates (See Section 2). WSR-88D precipitation data processing also involves radar data correction using hourly data from raingages under the umbrella of individual radars (Story, 1996; Fulton et al., 1998).

Hydrologic modeling efforts usually involve hourly or daily precipitation data obtained from the raingage networks. Comparison of Stage III WSR-88D precipitation data (Fulton et al., 1998; also see Section 3 for a brief description of the different stages of data processing by WSR-88D) available from the National Weather Service (NWS) of the United States with raingage data is necessary to evaluate the impact of the two precipitation data sources on model outputs. Johnson et al. (1999) found significant differences between the hydrographs simulated using WSR-88D and raingage data sets over a 1645 km^2 basin. In this study, we compare the Stage III WSR-88D precipitation data over the Texas-Gulf basin of the United States using daily precipitation data from a network of 545 raingages for a five-year period. The main focus of this study is to evaluate the Stage III precipitation data 'as available' from NWS for hydrologic modeling purposes. We do not discuss the reasons for the differences between both rainfall data sets and do not consider operational implementation of radar-raingage comparison to improve radar rainfall estimates. This study may serve as a benchmark for the evaluation and application of Stage III WSR-88D precipitation data and illustrates several operational and research issues that remain to be resolved.

2. Previous studies

A number of studies have been conducted on the evaluation of precipitation data from the WSR-88D or other radars using raingage networks. Smith and Krajewski (1991) compared the hourly Stage I WSR-88D data defined for 4 km^2 grids from the Norman, Oklahoma radar with the data from a network of twenty raingages for a rainfall event. They reported radar underestimation of the mean rainfall for all hours by a factor of 1.6–2.5 compared to the raingage mean. The variability of radar estimates as measured by the coefficient of variation was comparable to that of raingages and the correlation between raingage and radar observations was at least 0.70. Smith et al. (1996); Baeck and Smith (1998) reported that the range-dependent biases affected the hourly radar precipitation estimates within the range of a single WSR-88D; they compared the Stage I data from specific WSR-88Ds with raingage data. Significant underestimation of precipitation occurred at ranges beyond 100 km and within 40 km of the radar, and overestimation in the intermediate ranges. Such biases in WSR-88D estimates can adversely affect the Stage III products (Young et al., 2000). Smith et al. (1996); Young et al. (1999) found systematic differences between the precipitation estimates obtained by two different radars for the same area, indicating problems in radar calibration at individual radar sites; this would affect the quality of Stage III data. The gage-radar intercomparison study of Smith et al. (1996) suggested systematic underestimation of precipitation by WSR-88D at most raingage locations.

Lott and Sittel (1996) compared the storm-total precipitation calculated using the Stage III WSR-88D data with data from 220 raingages for five rainfall events. Radar underestimated precipitation by up to a factor of 2–3 at 80% of the raingage locations; the worst comparison was for one particular event with the Houston, Texas radar. They did not find any significant correlation between the distances of the raingage locations from the radar and the corresponding radar bias. Anagnostou et al. (1998) compared the Stage I data from the Tulsa, Oklahoma WSR-88D with data from a dense network of 240 raingages for a two-year period. The radar-gage correlation coefficients were less than 0.3 at several locations and were in the general range of 0.30–0.95. The bias-corrected Stage III WSR-88D data could be expected to produce better comparison with the raingage data. They also reported significant variations in the mean-field bias of radar estimates; the mean-field bias of warm season months was significantly less than that of cold season months.

Westrick et al. (1999) reported degradation of WSR-88D precipitation estimates due to partial or complete terrain blockage and 30–40% underestimation of precipitation by WSR-88D compared to the data from 130 raingages. Young et al. (1999) also reported beam blockage as a serious problem in mountainous terrain and nondetection and underestimation of precipitation by WSR-88D as issues of concern based on their radar-raingage comparison analyses. Baeck and Smith (1998) studied five extreme rainfall events using bias-adjusted WSR-88D data and reported that some parameters used in WSR-88D precipitation processing system were not adequate for estimating high rainfall events resulting in severe radar underestimation. They found the radar estimates for one storm event in eastern Texas to be lower by a factor of 2.0–5.5 compared to raingages. The same storm produced excessive flooding in Houston, Texas, and Bedient et al. (2000) analyzed this flood event using the data from the Houston WSR-88D and a raingage network. Comparing the radar estimates without bias correction to the raingage data, they found that the normalized differences ('bias') between radar estimates and raingage data ranged from -46 to $+79\%$.

Legates (2000) derived a Z–R relationship by analyzing radar-raingage data pairs for the Frederick, Oklahoma WSR-88D over a two-month period. His Z–R relationship increased the estimated rainfall rates by a factor of four over the standard Z–R relationship used in WSR-88D data processing; the estimated rainfall agreed closely with the gage data. He further noted that the standard Z–R relationship tends to overestimate light precipitation and underestimate heavy precipitation. Ulbrich and Lee (1999) showed that variations in Z–R relationship alone could not explain the systematic rainfall underestimation by WSR-88D. They found out that WSR-88D systematically underestimated the reflectivity factor itself and suggested that it was due to an offset in the radar constant.

Young et al. (2000) performed an evaluation of the WSR-88D multisensor precipitation estimates over the Arkansas-Red River basin of the United States over a five and half year period similar to our study. They found the range-dependent biases in the Stage III data to be lower in those regions of the basin with fewer raingages and radars. They also found evidence for possible systematic biases between the data from neighboring radars, systematic underestimation for specific beam radials due to partial beam blockage, and abnormally high precipitation accumulations in the Stage III data. Vignal and Krajewski (2001) describe the effect of the vertical profile of reflectivity (VPR) on the quality of WSR-88D estimates, inducing range-dependent errors in long-term accumulations. They evaluated two methods of correcting the VPR in radar data and the corresponding improvements in radar rainfall estimates through comparison with raingage data.

These studies highlight the various sources of errors in the WSR-88D rainfall estimates and the importance of radar calibration using raingage data to produce better quality precipitation data. They also indicate that the bias correction done in the precipitation processing algorithms of WSR-88D is sometimes not adequate and that the quality of WSR-88D rainfall data can significantly vary spatially and temporally over the study area. Underestimation of precipitation has been the major problem with WSR-88D. Since rainfall is the driving force behind all hydrologic processes, the quality of input rainfall data is very important in hydrologic modeling studies. Evaluation of long-term radar data is necessary for continuous time modeling of hydrologic processes in large watersheds.

In this study, we evaluate the Stage III WSR-88D precipitation data for 24-h accumulations using the data from raingages that are traditionally used for hydrologic modeling and are archived at the National Climatic Data Center (NCDC) of NWS. Young et al. (2000) suggest that these raingage data might be useful for evaluating radar estimates at longer timescales. In spite of the differences in spatial and temporal sampling between radar and raingage, most of the studies described in this section involve radar-raingage comparisons to varying degrees. The Stage II processing of WSR-88D data at the West Gulf River Forecast Center (WGRFC) also involves a bias adjustment based on the ratio of the sum of point raingage measurements and the sum of radar estimates over the 4 × 4 km grids containing those raingages (Greg Story, Personal communication, Hydrometeorological Analysis and Support Forecaster, WGRFC). Nevertheless, more detailed analysis than this type of comparison should be considered for a thorough investigation of the quality of Stage III WSR-88D data for hydrologic applications.

3. WSR-88D precipitation data processing at WGRFC

WGRFC's hydrologic forcast area includes the Texas-Gulf and Rio Grande river basins. The Hourly Digital Precipitation (HDP) array from a network of twenty-three WSR-88Ds is the product most extensively used by WGRFC. The raw HDP data obtained from individual WSR-88Ds through WSR-88D algorithm processing (Fulton et al., 1998) are considered the Stage I output. These data are defined for the Hydrologic Rainfall Analysis Project (HRAP) grids that are approximately 4 km × 4 km in size (Reed and Maidment, 1999). Original radar reflectivities are measured by volume scans over a fixed polar grid with a radial resolution of one degree in azimuth by 1 km in range. The convective Z–R relationship ($Z = 300\,R^{1.4}$) and the Rosenfeld tropical Z–R relationship ($Z = 250\,R^{1.2}$) are used in WGRFC to convert radar reflectivities into rainfall rates (Greg Story, Personal communication; Also see the technical paper at http://www.srh.noaa.gov/wgrfc/resources/projects/stageiii_paper/default.html). The rainfall depths are then calculated over the polar grids and averaged over the HRAP grids under the individual radar umbrella. These are the raw HDP data or Stage I precipitation data for individual WSR-88Ds. Refer to Fulton et al. (1998) for a detailed description of Stage I processing.

Stage II processing is performed at the WGRFC in Fort Worth, Texas, and it involves raingage bias adjustment factor calculation for individual radars based on available one-hour raingage reports. Since all raingage reports are not available immediately, this calculation is done for the current and previous hours. Hourly WSR-88D precipitation data are corrected (increased, decreased, or left unchanged) using a bias adjustment factor. These adjustment factors involve consideration of long-term raingage-radar differences (from a few hours for radars with more than 100 hourly reporting raingages up to one-year for radars with fewer than 10 raingages) and are meant to compensate for non-representative Z–R relationships of individual storms (Story, 1996; Greg Story, Personal communication. Also see the website mentioned earlier). This step produces the Stage II adjusted radar field for the HRAP grids. Next, a raingage-only analysis is done for the area under individual radars, which involves determining the rainfall field for the HRAP grids using available hourly raingage data with a 4 km radius of influence around each raingage in Texas and a 10 km radius of influence in New Mexico and Colorado. All HRAP grids within the circle of influence are assigned the same amount of rainfall measured at the raingage. This raingage-only rainfall field is merged with the Stage II adjusted radar field to produce the multisensor rainfall field for the HRAP grids under each radar.

In Stage III processing, the multisensor fields from all radars are overlaid onto one map to produce the hourly precipitation data for the entire WGRFC area.

The multisensor data for those HRAP grids under the umbrella of more than one radar are averaged together. This process is called mosaicking, and it has the benefit of compensating for the overestimation or underestimation of precipitation by a radar using better estimates of data from overlapping radars (Story, 1996). Refer to Crum and Alberty (1993); Klazura and Imy (1993); Smith et al. (1996), and Fulton et al. (1998) for further details on WSR-88D products and precipitation processing algorithms.

4. Study area and data sets

The study area considered for this analysis is the Texas-Gulf basin (the hydrologic cataloging unit 12 delineated by the United States Geological Survey), which includes several major rivers of Texas that drain into the Gulf of Mexico (Fig. 1). The total area of this hydrologic cataloging unit is approximately 468,000 km^2. Seventeen WSR-88Ds located in Texas, New Mexico, Louisiana, and Oklahoma cover this region (Fig. 1). The WSR-88D Stage III HDP data for this region are available through WGRFC starting from December 1994. HDP data from 1995 to 1999 were used in our analysis. Daily precipitation data from 545 weather stations located in and around this basin were collected for this five-year period as available from NCDC along with raingage location coordinates in latitude and longitude and daily rainfall observation times for individual months. There were missing raingage data for several months at a number of raingages during these years; the worst case was for 1995 with 47 raingages missing data for the entire year.

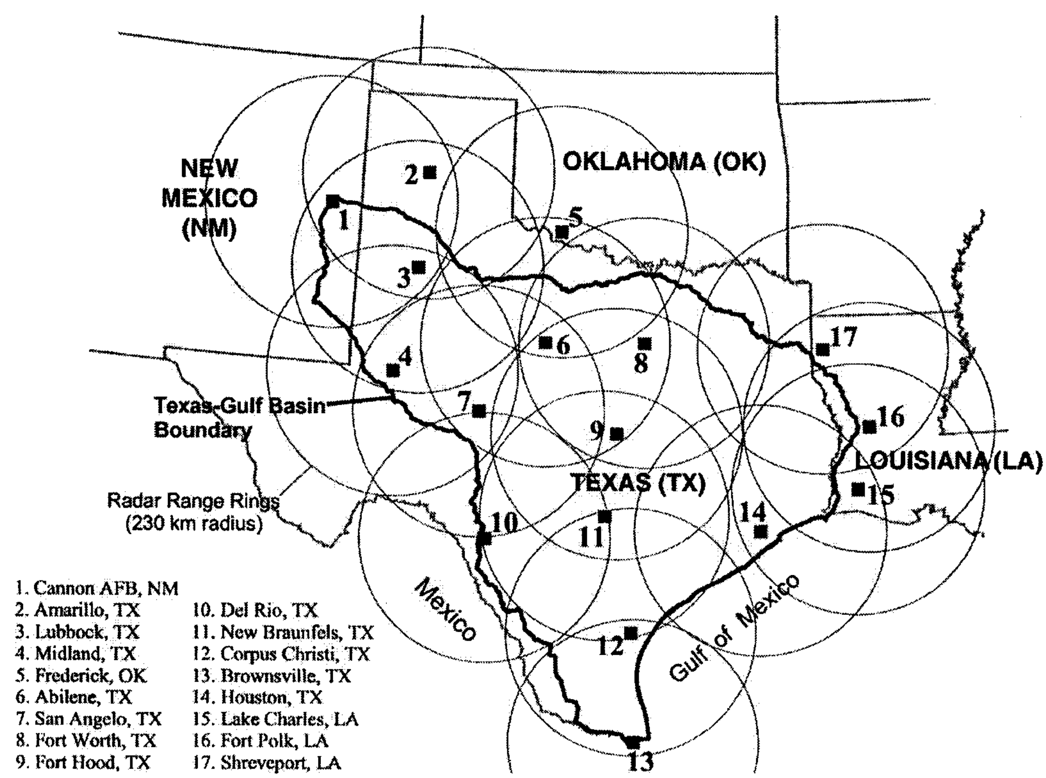

Fig. 1. Locations of the 17 WSR-88Ds covering the Texas-Gulf basin in the Southern United States.

5. Data processing

Since Stage III WSR-88D data are defined for the HRAP grids, we developed a HRAP grid map of the study area in a GIS environment in order to georeference the radar precipitation data. We modified the algorithm presented by Reed and Maidment (1999) to develop a HRAP grid map that would uniquely identify each HRAP grid. Raingage locations were overlaid on the HRAP grid map to determine the grid boxes on which they were located. The hourly WSR-88D precipitation data were extracted from the 1995–99 Stage III HDP files for the HRAP grid of each raingage. Normally, the daily data raingages record 24-h precipitation accumulation ending at the time of observation, and this is reported as the rainfall for the day of observation (Dingman, 1994). To create similar daily data sets for comparison, the hourly WSR-88D precipitation data of the HRAP grids were accumulated to 24-h depths depending on the rainfall observation time of the raingage located in the grid. For example, the rainfall observation time of Temple, Texas raingage is 7:00 AM local time, and it is located in the HRAP grid with lower left hand side HRAP coordinates of (589,203). The Stage III hourly data for this HRAP grid were accumulated from 7:00 AM on January 1, 1995 to 7:00 AM on January 2, 1995, and this 24-h depth was considered as the rainfall for January 2, 1995. Those days with missing WSR-88D data for any hour were excluded from the analysis. Daily precipitation data from the 545 daily data raingages were assembled in a similar format, excluding the dates with missing rainfall data. Then, the daily raingage data files and WSR-88D data files of corresponding HRAP grids were compared to create a new set of data files that included only those dates without any missing data for both raingage and radar. These 24-h precipitation data files formed the base data set for comparison and accuracy assessment of Stage III WSR-88D precipitation data.

6. Comparison statistics

The following statistics were computed using the 24-h precipitation data from the raingages and the data estimated by the WSR-88D network for corresponding HRAP grids.

1. Total Difference in precipitation (mm)

$$= \text{Radar total} - \text{Raingage total} \qquad (1)$$

2. Estimation Bias (%): This is the normalized difference between the radar estimate and the raingage measurement evaluated over long periods (one year or more). In other words, it is the ratio of the total difference to the raingage total precipitation.

$$\text{Estimation Bias (\%)} = 100 \times (\text{Radar total} - \text{Raingage total})/\text{Raingage total} \qquad (2)$$

3. Estimation Efficiency: This is the same as modeling efficiency, R^2, defined by Nash and Sutcliffe (1970) that is used widely for evaluating the performance of hydrologic simulation models (Martinec and Rango, 1989; ASCE Task Committee, 1993). This statistic is a good measure of the agreement between measured and modeled time series of variables like streamflow (Legates and McCabe, 1999). For radar-raingage comparison, the raingage data time series and the Stage III precipitation data times series are used in the equation for R^2 to calculate the estimation efficiency, as given by Eq. (3).

$$\mathrm{EE} = 1.0 - \left(\frac{\sum_{i=1}^{n} (R_i - W_i)^2}{\sum_{i=1}^{n} (R_i - R_m)^2} \right) \qquad (3)$$

where EE is the estimation efficiency; n is the number of days of comparison; R_i is the raingage precipitation for day i; R_m is the mean raingage precipitation over all days; W_i is the Stage III precipitation for the HRAP grid corresponding to the raingage location for day i. EE could vary from negative infinity to 1.0 (the ideal case when all W_i equal R_i).

4. Root Mean Squared Difference (RMSD) between the raingage measurements and the radar estimates.

Negative values of total difference and estimation bias mean underestimation of precipitation by radar network compared to the raingage, and positive values indicate overestimation. Estimation efficiency and RMSD were calculated for each raingage location as unconditional statistics with respect to zero rain (by including those days for which both raingage and radar measure zero rain) and as conditional statistics with respect to zero rain (by excluding days with zero rain). The comparison unconditional with respect to zero rain uses a relatively larger sample size and makes these two statistics artificially in favor of radar. Total difference and estimation bias are obviously not affected by unconditional or conditional calculations.

7. Comparison over the five-year period

Comparison of 24-h precipitation accumulations by the raingages and the corresponding Stage III precipitation estimates was performed for 1995–99. Quality of the raingage data should be an important consideration in studies that evaluate radar precipitation data using raingages (Steiner et al., 1999). The First Order (FO) weather stations of NWS and the airport weather stations operated by the Federal Aviation Administration (FAA) are equipped with better instruments and trained personnel, as are the weather stations of the US Army Corps of Engineers (COE) located at dam sites. There are 24 FO/FAA and 20 COE weather stations in the study area, all of which are located in Texas. Other cooperative observer raingages (COOP) include those operated by other state/federal agencies, local governments, radio stations, businesses, or citizens. There are 501 COOP raingages in and around the study area. The NCDC data from the COOP raingages are not available in real time for use in WSR-88D data processing and they constitute an independent source of data for comparison (Young et al., 2000), but they are the raingages normally used in basin-scale hydrologic studies. FO/FAA and COE raingages among others are included in WSR-88D data processing (Fulton et al., 1998). The radar-raingage comparison results presented here are stratified by the raingage category: FO/FAA, COE, or COOP.

7.1. Results of comparison conditional with respect to zero rain

By neglecting those days for which both gage and radar measure zero rain, 537 out of the 545 daily data raingages had more than fifty gage-radar data pairs (sample size) for comparison. Estimation bias calculation considered the total depth of precipitation over the entire five-year period. Tables 1–3 give the conditional comparison statistics for FO/FAA, COE, and selected COOP stations, respectively; they are arranged in the order of decreasing EE. Locations given in Table 3 represent the best and worst case comparisons for COOP stations and are evenly distributed throughout the study area so that they could represent all radar umbrellas.

Radar underestimation occurs at all FO/FAA stations except at Victoria Regional Airport, Texas (Table 1) where the raingage data are available only from 1999; the total difference was +300 mm at this station. The worst-case total difference of −3500 mm was at Houston NWS Office. This is an interesting result since the data from this raingage has been used in WSR-88D processing and both the raingage and the radar are physically located within the same office of NWS. Underestimation of precipitation by WSR-88D was revealed at all COE raingage locations, the worst-case total difference being −2930 mm at Town Bluff Dam (Table 2), and at 88% of COOP locations (Table 3). The estimation bias at COOP locations ranged from −57 to +60%. Thus, the WSR-88D network underestimated the total precipitation at a majority of the raingage locations, as found in previous studies. Such large differences between the radar-estimated precipitation depths compared to raingage measurements would severely impact the results of basin-scale water balance simulations and model parameter estimation. The five-year total difference was within ±500 mm at 42% of all raingages and the RMSD was more than 10 mm at 78% of the raingages.

A threshold EE value of 0.50 was considered for relative comparison of radar performance among the three categories of weather stations. A majority of FO/FAA and COE stations had an EE above 0.50 (Tables 1 and 2); this was the case only at 37% of COOP stations. This is an encouraging result since data from FO/FAA and COE raingage stations are generally considered to be of better quality;

Table 1
Comparison statistics conditional with respect to zero rain using raingage and Stage III WSR-88D daily precipitation data (1995–99) for First Order/FAA weather stations

Location	Total raingage rain (mm)	WSR-88D Estimation bias (%)	Estimation Eff. EE	RMSD (mm)
San Antonio Intl. AP, TX	3371	−9	0.92	5.3
Dallas-Ft. Worth Intl. AP, TX	4327	−10	0.88	5.2
Brownsville WSO AP, TX	3430	−16	0.88	7.1
Waco Reg. AP, TX	3998	−8	0.83	6.8
Houston Bush Intl. AP, TX	5798	−16	0.77	8.0
Dallas Love Field, TX[a]	3262	−18	0.76	7.2
Austin AP, TX	4146	−12	0.72	7.9
Fort Worth WSFO, TX	4400	−22	0.71	7.7
Lubbock AP Station, TX	2241	−20	0.67	6.3
Fort Worth Meacham Field, TX[a]	2574	−21	0.66	8.0
Port Arthur AP, TX	6504	−11	0.65	10.9
Corpus Christi WSFO AP, TX	3832	−15	0.63	11.0
College Station AP, TX[a]	2246	−23	0.61	9.2
Victoria ASOS, TX	5091	−7	0.59	11.4
Midland Intl. AP, TX	1251	−23	0.59	4.5
Houston Hobby AP, TX	5517	−38	0.57	11.5
McAllen Miller AP, TX[a]	961	−2	0.51	9.3
Abilene Reg. AP, TX	2767	−22	0.46	9.1
Palacios FAA AP, TX	5576	−16	0.39	17.4
Victoria Reg. AP, TX[b]	467	+65	0.14	8.8
Mineral Wells FCWOS AP, TX	3979	−9	−0.09	14.2
San Angelo WSFO AP, TX	2094	−26	−0.10	11.2
Houston NWSO, TX	7131	−49	−0.12	22.8
Hondo AP, TX[a]	831	−20	−0.32	11.6

[a] Raingage data missing for several months during 1995–99.
[b] 1999 only.

comparison statistics at other COOP stations might have been affected by the quality of the raingage data itself. But Steiner et al. (1999) noted that the quality of raingage data were sometimes poor even in an experimental watershed. The San Antonio 8 NNE, Texas station had the best EE of 0.97. Fig. 2(a) shows the scatter plot comparison at this COOP station; most of the data points fall very close to the 1:1 line, and its RMSD was the lowest. There was an extreme rainfall event at this station with a 24-h accumulation of 364 mm. Radar estimation for that day was 340 mm, which compares well with the raingage data. Since EE is sensitive to extreme values (Legates and McCabe, 1999), we repeated the analysis by neglecting this extreme event as an 'outlier'; the comparison is still good at this station with an EE of 0.90 and the RMSD dropped slightly (Table 3). The corresponding scatter plot in Fig. 2(b) also indicates good agreement between both data sets. Areal estimation of the 'true' rain field during such high rainfall events is critical for real-time flood forecasting and the comparison at this particular station indicates the potential of good-quality WSR-88D data for such applications. A poor comparison between radar and raingage data at Greenwood Fire Tower, Louisiana, is depicted in Fig. 3, while Fig. 4 shows the data scatter plot at Bardwell Dam giving the best comparison among COE raingages. Figs. 2–4 also indicate that the radar network estimated zero rainfall for several days when raingages measured up to 80 mm of rainfall. This suggests potential problems in WSR-88D data processing at specific radars and/or further processing in WGRFC. Such differences will have a significant impact on the results of hydrologic studies that use WSR-88D data.

Though Graham, Texas has as estimation bias of +15%, which is relatively better compared to Marshall, Texas, it has one of the worst EE values

Table 2
Comparison statistics conditional with respect to zero rain using raingage and Stage III WSR-88D daily precipitation data (1995-99) for Corps of Engineers weather stations

Location	Total raingage rain (mm)	WSR-88D estimation bias (%)	Estimation eff. EE	RMSD (mm)
Bardwell Dam, TX	4682	−5	0.76	8.6
Proctor Reservoir, TX	4138	−16	0.74	9.4
George Town Lake, TX	4535	−19	0.70	9.1
Somerville Dam, TX	4636	−21	0.67	9.0
Granger Dam, TX	3918	−26	0.65	8.2
Stillhouse Hollow Dam, TX	4545	−28	0.65	9.6
Canyon Dam, TX	3707	−42	0.63	8.6
Navarro Mills Dam, TX	4491	−14	0.60	10.9
Sam Rayburn Dam, TX	7201	−21	0.60	13.7
Grapevine Dam, TX	4146	−28	0.56	9.6
Lewisville Dam, TX[a]	3118	−32	0.56	11.2
Town Bluff Dam, TX	6808	−43	0.52	13.2
Benbrook Dam, TX	4153	−12	0.51	9.8
O. C. Fisher Dam, TX	2332	−25	0.47	8.0
Whitney Dam, TX	4060	−5	0.36	11.4
Hords Creek Dam, TX[a]	2653	−3	0.35	12.5
Waco Dam, TX	4160	−31	0.35	11.3
Joe Pool Lake, TX	5031	−45	0.33	14.6
Matagorda 2, TX	3347	−24	0.05	17.6
Canyon Dam No. 1, TX[a]	3215	−27	−0.51	29.0

[a] Raingage data missing for several months during 1995–99.

(Table 3). Such differences in the comparison statistics are due to the fact that EE involves day-to-day comparison while estimation bias considers the total depth of precipitation over the five-year period, averaging out the underestimations and overestimations for individual storms. Estimation bias calculation for shorter time intervals (yearly or monthly) may enable better evaluation. For example, the five-year estimation bias at Frisco, Texas was only −1%, which appears to be a good comparison. However, the monthly estimation bias at this location ranged from −40 to +85% and accordingly its EE is −1.30 and RMSD is about 24 mm.

Several pairs of nearby stations showed differing results. For example, the COOP station at Port Arthur City, Texas had an EE of −0.18 (Table 3) and the EE was 0.65 at Port Arthur airport (Table 1). Further, several nearby COOP stations themselves had very different comparison statistics. This result, again, indicates possible problems with the quality of raingage data at such COOP stations and stresses the importance of raingage data quality control before using them for comparison with radar data. Installation of two or more raingages as suggested by Ciach and Krajewski (1999); Steiner et al. (1999) at every station would enable detection of raingage data quality problems and development of improved raingage data sets for radar performance evaluation.

The spatial distributions of EE across the study area at FO/FAA, COE, and COOP stations are shown in Figs. 5–7, respectively. FO/FAA and COE stations with EE less than 0.50 (open symbols) are along the Gulf coast and in west-central Texas (Figs. 5 and 6), indicating potential problems in data processing with the WSR-88Ds covering these areas and the need for improvements. The majority of the COOP stations with an EE of 0.50 or better (solid symbols) are in the north- and south-central Texas; EE at most of the stations in the west, east, and coastal Texas regions are less than 0.50 (Fig. 7). The Gulf coast region and eastern parts receive the highest precipitation in Texas with an average annual precipitation of more than 1500 mm, while the west is a low precipitation zone (average annual precipitation less than 500 mm). This suggests that, in general, radar performance is poor in extremely wet and dry regions. Baeck and Smith

Table 3
Comparison statistics conditional with respect to zero rain using raingage and Stage III WSR-88D daily precipitation data (1995–99) for selected Cooperative Observer weather stations

Location	Total raingage rain (mm)	WSR-88D estimation bias (%)	Estimation eff. EE	RMSD (mm)
San Antonio 8 NNE, TX[a]	2172	−4	0.97	4.2
(San Antonio 8 NNE, TX without the 'outlier' shown in Fig. 2a)	1808	−3	0.90	3.9
Austin Water Trtmt. Plant, TX[b]	993	−21	0.81	5.6
Brenham, TX	5363	−22	0.70	11.6
Rosepine Res. Stn., LA	7474	−20	0.67	12.3
Concepcion 3 S, TX	2626	−8	0.67	10.7
Water Valley, TX	2286	−1	0.65	7.2
Marshall, TX	5588	−45	0.57	11.5
Clovis, NM	2377	−7	0.37	8.2
Santa Rosa 3 WNW, TX	2909	+9	0.28	12.7
Greenwood Fire Tower, LA	6447	−57	0.27	15.5
Clodine, TX	6079	−28	−0.06	18.3
Port Arthur City, TX	6317	−5	−0.18	20.9
Roscoe, TX	2340	+7	−0.20	12.2
Port O'Connor, TX	1517	+61	−0.58	22.2
Temple, TX	4040	−14	−0.58	23.4
Crossroads 2, NM[c]	1150	+4	−1.04	13.4
Frisco, TX	5043	−1	−1.29	24.2
Graham, TX	3724	+15	−1.45	21.4

[a] Raingage data missing for 1995–96.
[b] Sept. 1996-Aug. 1997 only.
[c] Raingage data missing for part of 1998 and 1999.

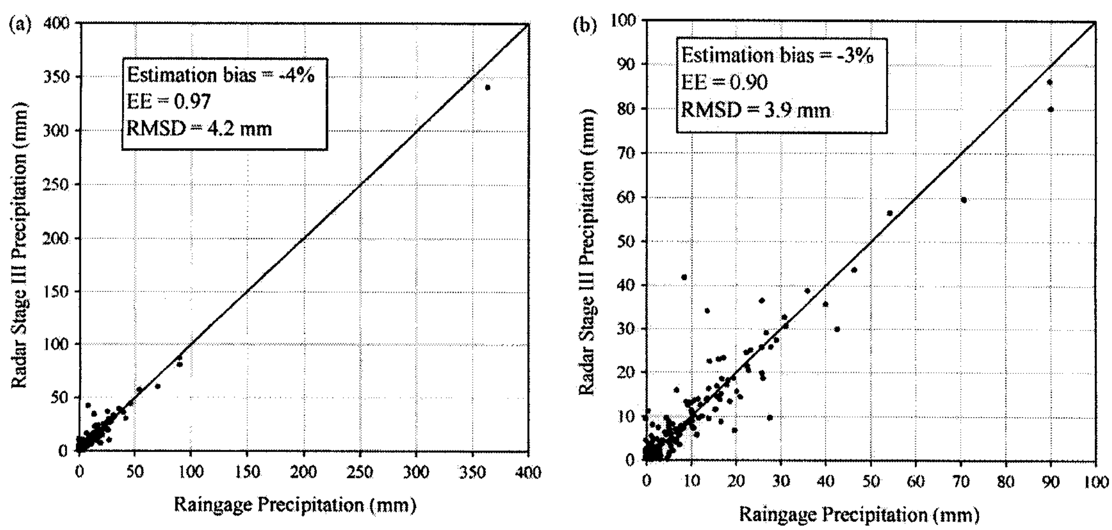

Fig. 2. Comparison of daily precipitation at San Antonio 8 NNE, TX (a) with the 'outlier'; (b) without the 'outlier'.

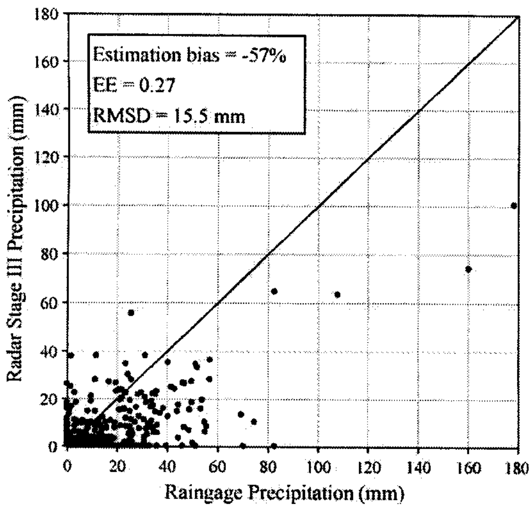

Fig. 3. Comparison of daily precipitation at Greenwood Fire Tower, LA.

(1998); Bedient et al. (2000) also reported poor WSR-88D performance for selected high-rainfall events of 1994, 1997, and 1998 in east Texas. Fig. 7 also indicates that the COOP stations with poor EE values are distributed throughout the study area.

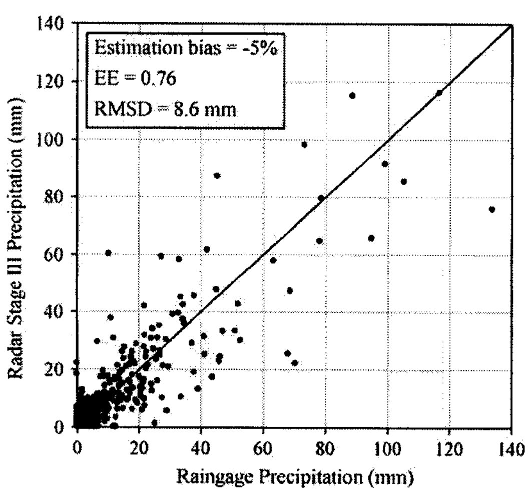

Fig. 4. Comparison of daily precipitation at Bardwell Dam, TX.

7.2. Results of comparison unconditional with respect to zero rain

Inclusion of days with zero rain in the comparison analysis obviously increases the sample size. Total difference and estimation bias statistics remain the same as before, but EE and RMSD become relatively favorable to radar because of increased sample size. For most of the raingage locations, these statistics were consistently better than those obtained by conditional comparison. For example, only 12% of COOP locations had negative EE with unconditional comparison, while it was 22% for conditional comparison. Similarly, EE was above 0.50 at 57% of COOP stations as opposed to 37% for conditional comparison. Mathematically, inclusion of zero values decreases the mean raingage rainfall R_m in Eq. (3) thereby increasing the denominator of the second term while the numerator remains the same. This in turn increases the EE value. Thus, inclusion of days for which both raingage and radar give zero rain puts the comparison statistics artificially in favor of radar when both instruments do not detect rain.

Based on the foregoing discussion, we conclude that hydrologists comparing precipitation data from radar and raingage networks using comparison statistics should use conditional statistics that are conservative leading to better quality assessment.

8. Year-to-year variation

We performed a year-to-year comparison of both precipitation data sets and found that there were major differences in the statistics calculated at all locations from year to year. In general, improvement in the performance of WSR-88D was observed over the years; comparison statistics for 1998 and 1999 showed significant improvements compared to 1995–97 period. The results of yearly comparison conditional with respect to zero rain are presented in Table 4. There was a significant improvement in radar performance during 1998; at least 78% of the FO/FAA and COE locations had estimation bias within ±20%. About 63% of COOP locations had estimation bias within ±20% during 1998 and 1999. There was also a significant increase in the number

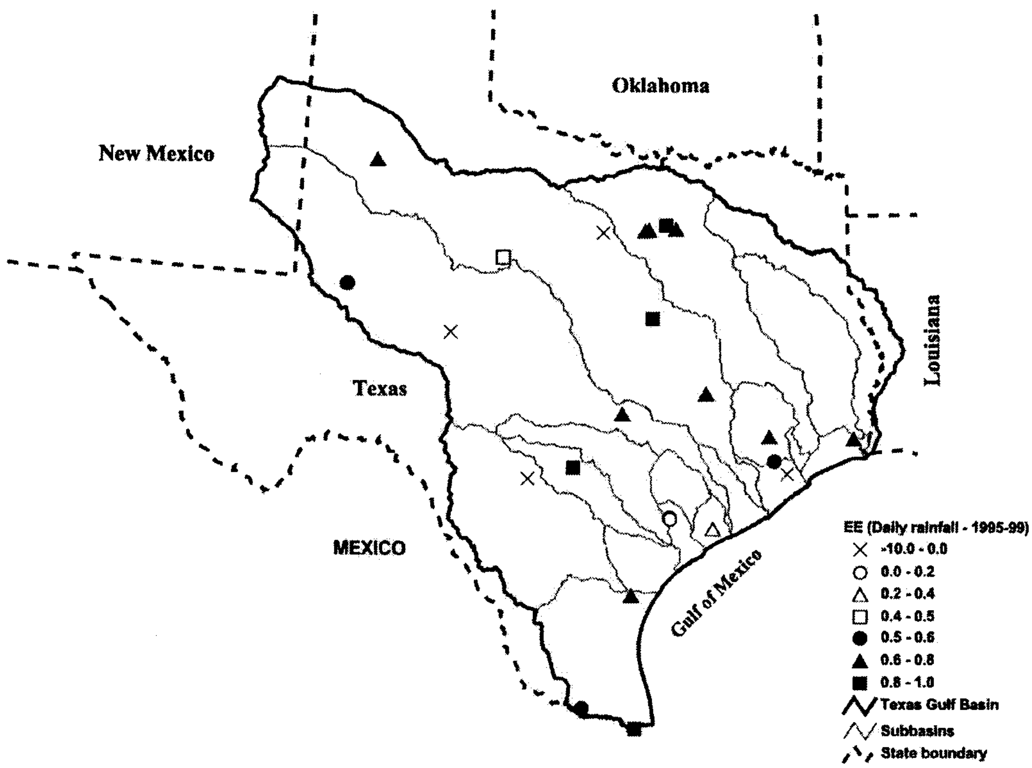

Fig. 5. Radar estimation efficiency at FO/FAA stations.

of locations with high overestimation (estimation bias > +20%) during 1998–99; this number increased from 7 to 149 for COOP stations. Similarly there was a significant reduction in the number of locations with high underestimation (estimation bias < −20%);–from 359 to 28–for COOP stations (Table 4). This indicates that radar underestimation errors are reduced significantly and this is consistent with the on-going developments and improvements being made to the WSR-88D precipitation processing algorithms by NWS during recent years. However, an increasing trend of rainfall overestimation is evident in the recent years. The proportion of COOP stations with an EE above the threshold value of 0.50 was the highest during 1997, but it dropped again during 1998–99 (Table 4) because of the overestimation problem at a large number of locations.

Table 5 shows the year-to-year variations in the comparison statistics for selected raingage locations. It includes the locations that had the best and worst comparisons as given in Tables 1–3. The yearly EE at the San Antonio International Airport, Texas with the best overall EE of 0.92 (Table 1), ranged from 0.56 to 0.96. Performance of WSR-88D was consistently poor at Houston NWSO, Texas. EE at Graham, Texas varied from −9.41 to 0.51; similar was the variation at Clovis, New Mexico. Thus, large variations between the Stage III precipitation data and raingage data over the years are evident, which will have significant implications for the application of Stage III data. Better quality control of the raingage data used for evaluating radar performance as done by Steiner et al. (1999) should be considered for future work.

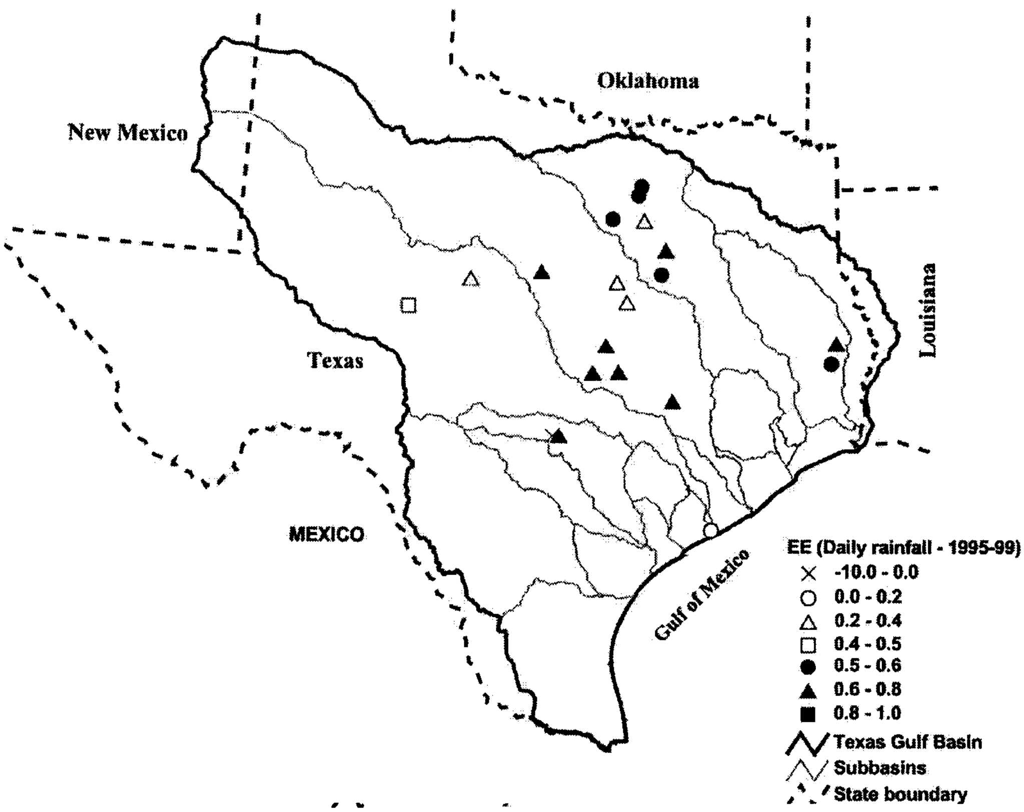

Fig. 6. Radar estimation efficiency at COE stations.

9. Sampling problems and georeferencing issues

As pointed out in Section 2, sampling errors are involved in the attempts to evaluate areally averaged radar precipitation estimates using point raingage measurements. Spatial variability of precipitation within the 16-km^2 HRAP grids is a key factor to be taken into account in this kind of post-comparison analysis and also in the WSR-88D data processing steps that use hourly gage measurements for radar bias adjustment. This is probably the main reason for the large discrepancies between WSR-88D and raingages at several weather stations considered in this study. Detailed and mathematically rigorous analysis of the effect of sampling errors such as those proposed by Morrisey (1991); Amani and Lebel (1998) among others, could be investigated to make better comparisons. The methodology described by De Michele et al. (2001) to derive areal reduction factors for point measurements of storm rainfall from its scaling properties could be adapted for reducing raingage-measured rainfall depths over the HRAP grid area before using them to evaluate WSR-88D data. Ciach and Krajewski (1999) present an error separation method to partition the differences between radar estimates and raingage measurements into the error of area-averaged radar estimate and the error due to the difference between the sampling areas of both instruments. This method could be investigated using the data from a hierarchical cluster network of raingages as suggested by them. Further, the quality of raingage data itself is another important factor.

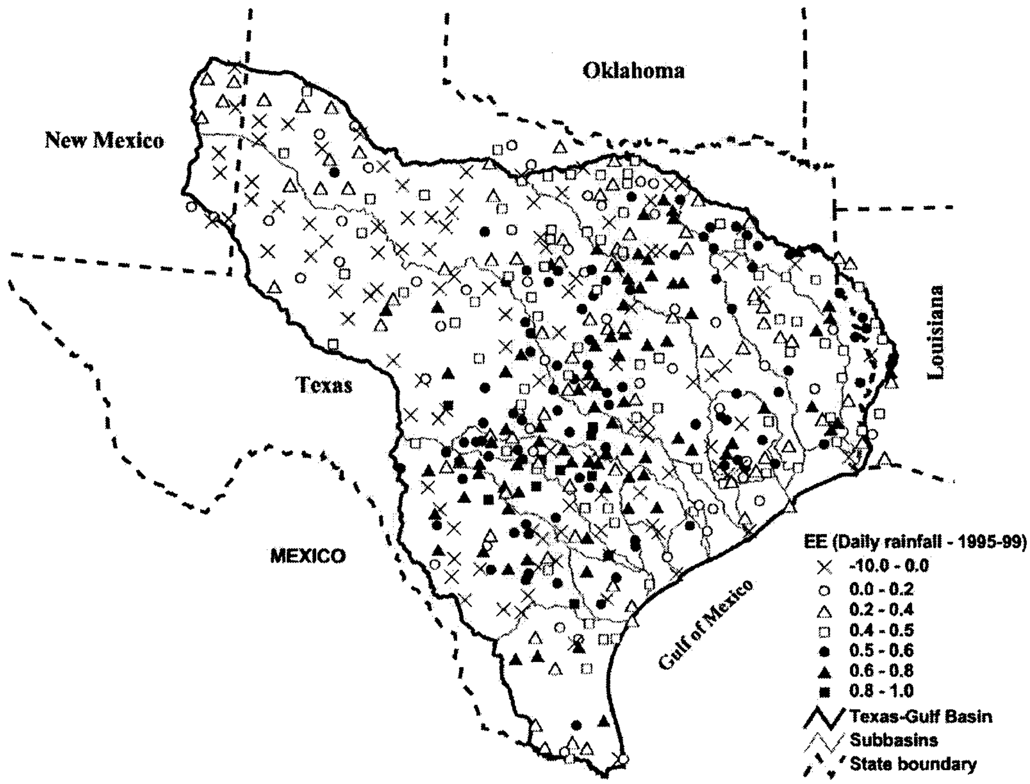

Fig. 7. Radar estimation efficiency at COOP stations.

Table 4
Performance of WSR-88D network over the Texas-Gulf basin by year

	Raingage category	1995	1996	1997	1998	1999
Percentage of locations having estimation bias within ±20%	FO/FAA	13	44	60	78	63
	COE	16	47	15	80	85
	COOP	20	39	26	64	63
Percentage of locations with EE >0.50	FO/FAA	39	65	85	78	79
	COE	58	68	65	60	65
	COOP	21	35	62	49	46
No. of locations with estimation bias > +20%	FO/FAA	0	1	0	3	8
	COE	0	0	0	1	1
	COOP	7	16	1	100	149
No. of locations with estimation bias < −20%	FO/FAA	20	12	8	1	1
	COE	16	10	17	3	2
	COOP	359	268	351	70	28

Table 5
Comparison statistics conditional with respect to zero rain for individual years at selected weather stations

Raingage category	Location	Statistic	1995	1996	1997	1998	1999
FO/ FAA	San Antonio Intl. AP, TX	EB (%)	−32	−25	−8	+4	+4
		EE	0.75	0.56	0.93	0.96	0.87
	Fort Worth WSFO, TX	EB (%)	−43	−21	−30	−8	−6
		EE	0.63	0.54	0.67	0.90	0.70
	Houston NWSO, TX	EB (%)	−55	−76	−45	−37	−33
		EE	−0.03	−0.18	0.01	−0.24	−0.27
COE	Bardwell Dam, TX	EB (%)	+1	−20	−9	−5	+9
		EE	0.67	0.67	0.77	0.79	0.81
	Sam Rayburn Dam, TX	EB (%)	−46	−44	−32	+2	+5
		EE	0.22	0.41	0.61	0.58	0.87
	Canyon Dam No. 1, TX	EB (%)	–	−16	−52	−16	−4
		EE	–	−0.82	0.37	−0.65	−1.23
COOP	San Antonio 8 NNE, TX	EB (%)	–	–	−10	0	−3
		EE	–	–	0.93	0.98	0.92
	Graham, TX	EB (%)	+18	+2	−14	+64	+11
		EE	−0.14	0.47	0.51	−9.41	−1.29
	Clovis, NM	EB (%)	−15	+2	−42	+3	+21
		EE	0.46	0.06	0.45	0.71	0.27
	Greenwood Fire Tower, LA	EB (%)	−80	−59	−60	−62	−39
		EE	−0.27	−0.21	0.44	0.08	0.49

EB: Estimation Bias; EE: Estimation Efficiency.

Legates and DeLiberty (1993) reported that errors in point raingage measurements due to wind and wetting losses on the interior walls of the instrument range between four and six percent over three-quarters of the United States. Groisman and Legates (1994) suggested correction procedures to reduce gage undercatch bias. Such methods could be investigated to improve the quality of raingage data used to evaluate radar estimates within the study watersheds.

Another key issue is the errors associated with georeferencing the WSR-88D precipitation data. The HDP data are averages of the original radar measurements within the 1-km × 1-degree polar bins over the 16-km^2 HRAP grids. Georeferencing errors are inherent to the process of conversion from polar coordinates to HRAP grid coordinates and to the use of the HRAP grid system. Reed and Maidment (1999) indicated that scale and shape distortions occur with the use of the HRAP grid system to map WSR-88D precipitation data, introducing errors in georeferencing the ranges at which radar detects precipitation. Mapping errors due to the combined effects of scale and shape distortions vary with the latitude. Their work confirmed that the discrepancies between the mapped range and the actual range of radar could vary from +1.6 to +3.1 km depending on radar orientation in 30–45° N latitude range.

The Texas-Gulf basin is located between 25 and 35° N latitudes. Based on the work of Reed and Maidment (1999), we calculated that the error in the mapped range in the Texas-Gulf basin could approximately be from +0.35 to +0.53 km when the radar is seeing east or west direction, +1.66 to +1.76 km when seeing north, and −2.73 to −3.55 km when seeing south. This error occurs at the maximum range of the WSR-88D (230 km) and should reduce as one gets closer to the radar location. Since the side of a HRAP grid box is approximately 4 km, mapping errors in the order of 2–3 km are significant and could move the location of actual volume scan of radar to the adjacent HRAP grid. We observed that, in several cases, the raingage was located near the edge of a HRAP grid and in such cases comparison using radar data of the HRAP grid containing the raingage would involve significant georeferencing errors. There is also an uncertainty in the mapped locations of raingages because of the precision of the latitude–longitude data (Fulton et al., 1998). These factors should also be taken into account in future work. Adjoining HRAP grids could be included in the comparison for such raingages, but this has the disadvantage of amplifying the sampling errors. Areal reduction factor for raingages as proposed by De Michele et al. (2001) is a promising solution for comparison at such raingages.

In spite of the pronounced sampling problems, we performed a comparison analysis for all raingages using the average WSR-88D precipitation over nine HRAP grids centered on the raingage location. In general, the comparison the statistics calculated using this 9-cell HRAP grid combination differed from those calculated using single HRAP grid as expected. The percentage of FO/FAA locations having the total difference within ±500 mm increased from 46 to 63%. Spatial averaging of precipitation had an averaging effect on radar performance; EE dropped at those stations with the highest EE values in single HRAP grid comparison and vice versa. Radar underestimation also increased at a majority of the raingages. This preliminary analysis indicates the effect of including adjacent HRAP grids in the comparison; use of 2-cell or 4-cell radar averages as appropriate may prove to be useful especially in watersheds with limited number of raingages.

10. Suggestions for WSR-88D data users

Suggestions for the users of Stage III WSR-88D precipitation data as available from NWS for hydrologic applications based on this study are given below.

1. Long-term comparison analysis conditional with respect to zero rain produces conservative statistics that would help better assess the quality of Stage III WSR-88D precipitation data.
2. Radar estimation efficiency is a useful measure of day-to-day comparison of radar data with raingage data.
3. Estimation bias over the five-year period indicates that the WSR-88D network underestimates precipitation at most of the FO/FAA and COE raingage locations, and at 88% of COOP raingage locations in the Texas-Gulf basin. The five-year total difference in precipitation depth between radar and raingage was within ±500 mm only at 42% of all raingages. The RMSD for 24-h accumulations was more than 10 mm at 78% of the raingages. Such large differences between both rainfall data sources will have significant implications for the application of Stage III WSR-88D data in hydrology. Radar estimation efficiency for 24-h accumulations was better than 0.50 at 71% of FO/FAA locations, 65% of COE locations and 37% of COOP locations. Spatial distribution of estimation efficiency across the Texas-Gulf basin indicates general regions of poor radar performance.
4. Radar performance varied significantly over the years, and in general, an improvement in performance was observed. Comparison statistics of 1998 and 1999 showed significant improvements compared to 1995 through 1997. At least 63% of FO/FAA locations had estimation bias values within ±20% during 1998–99, as opposed to only 13% of the locations during 1995; this increment was from 20 to 63% at COOP locations. About 80% of FO/FAA locations had estimation efficiencies better than 0.50 during 1998–99. These statistics indicate an improvement in the performance of WSR-88D network and it is the results of the improvements being made to the precipitation processing algorithms over these years.
5. An overestimation trend was evident in the recent modifications of WSR-88D algorithms. About 33% of FO/FAA locations and 30% of COOP locations indicated high overestimation (estimation bias >+20%) during 1999; this percentage was close to zero during 1995. A significant reduction in the percentage of raingage locations with high underestimation (estimation bias <−20%) was observed over these years; it reduced from 72 to 6% at COOP locations. This indicates a shift from the underestimating tendency of the WSR-88D to overestimation. In general, there was a reduction in the EE value at several locations during 1999 because of radar overestimation. Further improvements in the WSR-88D data processing are necessary.
6. Performance of the WSR-88D network varies significantly over the Texas-Gulf basin and also over the years. Hydrologists using the Stage III

WSR-88D precipitation data for their studies should evaluate the quality of data pertaining to the study area over the study period and make appropriate corrections to the Stage III data as precipitation data as necessary.
7. Sampling issues associated with the comparison between point and areal observations, georeferencing errors associated with WSR-88D data, and uncertainty in the precision of raingage locations are key factors that would affect radar data quality evaluation using raingages. More detailed analysis than what is presented in this study should be considered for future work.

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