Comparison of NEXRAD and Rain Gauge Precipitation Measurements in South Florida

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Abstract: The South Florida Water Management District (SFWMD) relies on a network of nearly 300 rain gauges in order to provide rainfall data for use in operations, modeling, water supply planning, and environmental projects. However, the prevalence of convective and tropical disturbances in South Florida during the wet season presents a challenge in that the current rain gauge network may not fully capture rain events that demonstrate high spatial variability. Next Generation Radar (NEXRAD) technology offers the advantage of providing a spatial account of rainfall, although the quality of radar-rainfall measurements remains largely unknown. The comparison of rainfall estimates from a gauge-adjusted, NEXRAD-based product developed by the OneRain Company with precipitation measurements from SFWMD rain gauges was performed for the Upper and Lower Kissimmee River Basins over a four-year period from 2002 to 2005. Overall, NEXRAD was found to underestimate rainfall with respect to the rain gauges for the study period, demonstrating a radar to gauge ratio of 0.95. Further investigation of bias revealed the tendency for NEXRAD to overestimate small rainfall amounts and underestimate large rainfall amounts relative to the gauge network. The nature of bias present in the data led to the development of a radar-rain gauge relationship to predict radar precipitation estimates as a function of rain gauge measurements. The intent of this paper is to demonstrate the importance of identifying systematic offsets which may be present in radar-rainfall data before application in hydrologic analysis.

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Introduction

The South Florida Water Management District (SFWMD) is one of five government agencies responsible for the oversight and protection of water resources in the State of Florida. The SFWMD service area extends south from Orlando, along the boundaries of the Kissimmee River Basin to Lake Okeechobee, and from the Atlantic Ocean to the Gulf of Mexico in South Florida. This region encompasses 46,439 square km (17,930 square miles) and boasts a population of over 7 million. Key features of the South Florida hydrosystem include Everglades National Park and the Kissimmee River, both sites of major restoration efforts; Lake Okeechobee, the nation's second largest freshwater lake; water conservation areas; coastal and estuarine systems; as well as expansive agricultural areas and urban districts (Fig. 1). The SFWMD manages this system through a complex network of water control structures, canals, and pump stations (Huebner et al. 2003; Pathak and Palermo 2006; SFWMD 2008).

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Precipitation in Florida is generally associated with convective, tropical, and frontal, or stratiform disturbances. The subtropical region of South Florida experiences two distinct rainfall periods as a result of seasonal variations in precipitation patterns: the wet season, which is in effect from June to October; and the dry season, which lasts from December to April. The months of May and November are considered transition months, and often demonstrate rainfall patterns characteristic of both the wet and the dry seasons.

The wet season is distinguished by hot, humid weather and the prevalence of convective and tropical rain events. Roughly two-thirds of the annual rainfall received at the SFWMD occurs during the wet season. Convective thunderstorms, formed as a result of sea-breeze effects, contribute the most to wet season precipitation and are capable of producing large amounts of rainfall over localized areas. Tropical systems such as tropical storms and hurricanes also produce intense rainfall of a highly variable nature, although the impact of precipitation effects is typically limited to the months of August, September, and October. Cooler temperatures and the influence of frontal systems mark the dry season, which is characterized by rainfall distributions of a relatively light and uniform nature.

The SFWMD maintains an extensive network of rain gauging stations in order to monitor rainfall and obtain precipitation data necessary for use in operations, modeling, water supply planning, and regulatory aspects of water management. Several limitations are known to exist with the current dependence on rain gauge technology, including introduction of error through the spatial extrapolation of point measurements to surrounding areas (Bedient and Huber 2002). The problem of accounting for spatial rainfall distributions is of particular concern in South Florida, where intense, highly variable convective and tropical

J. Hydrol. Eng., 2009, 14(3): 248-260

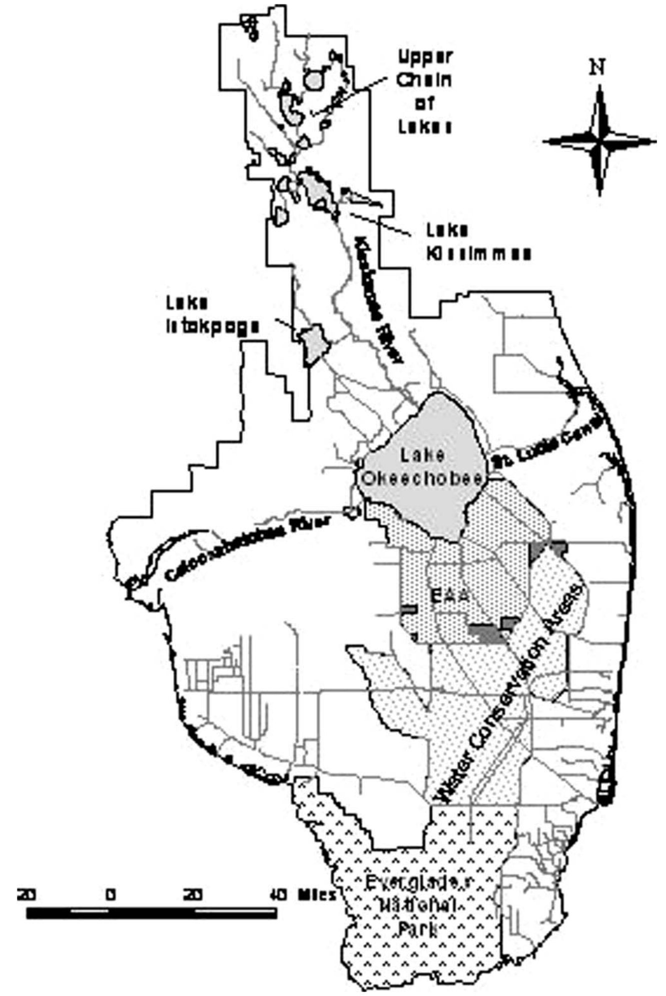

Fig. 1. SFWMD system features (SFWMD 2008)

rain events predominate in the wet season (Huebner et al. 2003; SFWMD 2008).

Next Generation Radar (NEXRAD) technology offers the advantage of providing water managers with a spatial and temporal account of rainfall variability, although the quality of radar measurements remains largely unknown. The SFWMD presently acquires NEXRAD-derived precipitation data from the OneRain Company in order to supplement data from the existing rain gauge network. However, before NEXRAD data can be successfully extended to applications involving operations and hydrologic analysis, the quality of radar-rainfall measurements must first be assessed.

Rain Gauge Measurement of Rainfall

Despite recent advances in remote-sensing technologies, such as radar and satellite, rain gauges remain the most common method for the measure of rainfall. The SFWMD operates a network of 279 active rain gauges of various types and reporting designations, as presented in Table 1. Limitations associated with rain gauge technology are well documented and include aspects of maintenance, calibration, and manual retrieval of data, which require that dedicated personnel arrive at individual rain gauge stations as often as daily. The presence of obstructions, such as vegetation, structures, and debris, presents an important source of systematic error in rain gauge measurements (SFWMD 2008; World Meteorological Organization 1996). Similarly, wind can have a significant impact on the amount of rainfall collected as Pathak (2001) reports that actual precipitation amounts may be underrepresented by as much as 1% per mile per hour (mph) of wind speed.

However, the most severe limitation in the reliance on rain gauge technology remains the fact that the rain gauge network cannot supply information about rainfall occurring between the gauges, and as a result, the network may not fully capture rainfall events demonstrating high spatial variability (Huebner et al. 2003). Several approximation techniques have been developed in an effort to estimate mean precipitation spatially; however, these methods rely upon mathematic or geometric representations of precipitation, which may or may not be indicative of actual rainfall characteristics. Consequently, the adoption of approximation methods may lead to the introduction of error (Bedient and Huber 2002). The SFWMD recognizes that highly variable convective and tropical storm events "may not be captured by the current district network" and that this represents a major limitation in the continued use of rain gauge technology (SFWMD 2008).

The SFWMD maintains a structured quality control process used to provide information about the quality of data produced at individual rain gauge stations. Rainfall and other hydrologic data are scrutinized and tagged in cases where data are missing or unreasonable, usually as a result of instrument malfunction or placement. The designation of a quality code is a central aspect of the SFWMD quality control scheme as it identifies missing precipitation records and data that may be otherwise compromised (SFWMD 2008).

Table 1. SFWMD Rain Gauge Attributes

Reporting designation	Data transfer	Gauge type	Data collection	Gauges used in NEXRAD calibration	Total number of SFWMD gauges	Number of gauges in study area
LoggerNet	Telemetry	Tipping bucket	Near real time	Yes	66	17
RACU	Telemetry	Tipping bucket	Near real time	Yes	71	7
MOSCAD	Telemetry	Tipping bucket	Near real time	Yes	7	0
ARDAMS	Phone lines	Tipping bucket	Daily	No	21	9
CR10	Manual	Tipping bucket	Monthly	Yes (since 2004)	60	10
Graphic Chart	Manual	Float type	Monthly	No	8	6
Manual Log	Manual	Standard	Daily	No	46	4
Total					**279**	**53**

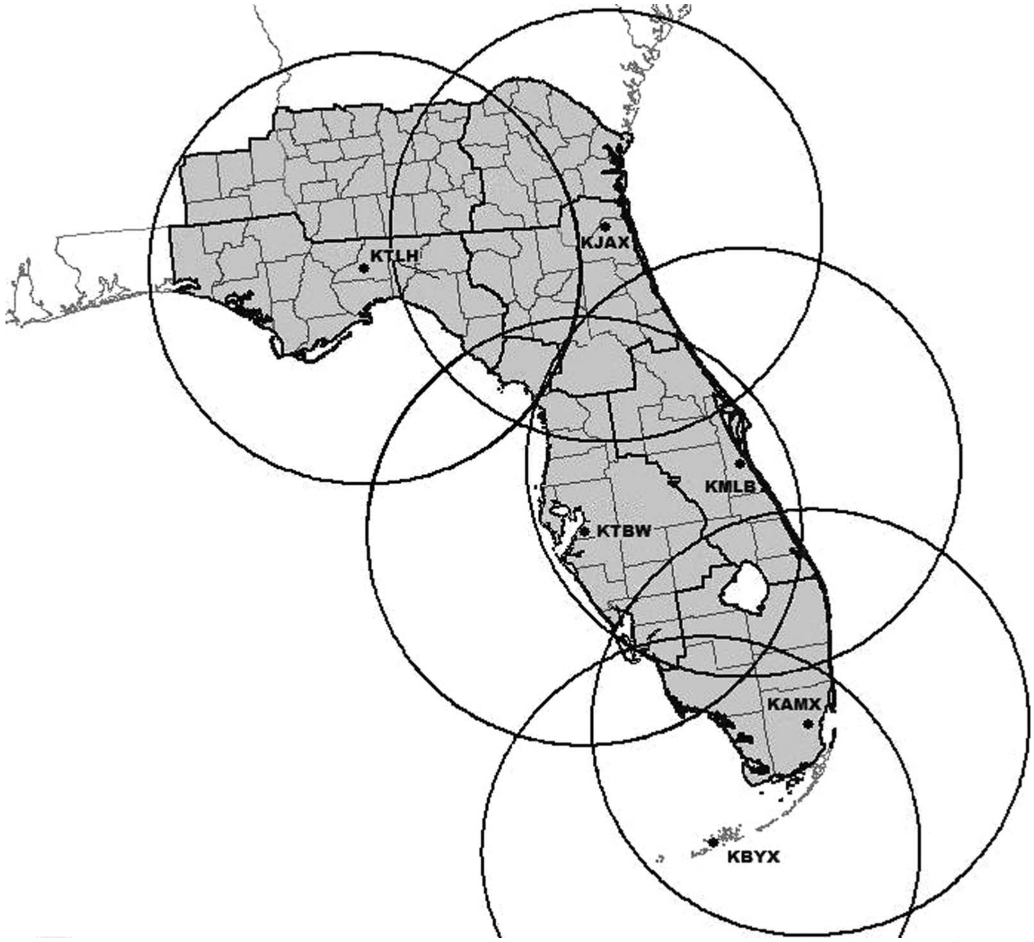

Fig. 2. Select Florida WSR-88D installations (National Weather Service 2007)

NEXRAD Rainfall Meteorology

NEXRAD, a product of the WSR-88D (Weather Surveillance Radar 1988) Doppler weather radar, is a promising technology which offers a spatial representation of rainfall distributions. Radar, or "radio detection and ranging," was originally developed as a method for the detection of aircraft. The use of radar was extended during World War II to provide information about weather systems when it was found that weather disturbances interfered with the principal objective of aircraft tracking. Weather radar has undergone sweeping advances since its inception, and the National Weather Service (NWS) has since relied on improved radar technology to detect and monitor weather conditions such as wind, rainfall, thunderstorms, lightning, tornadoes, and hurricanes (Bedient and Huber 2002; Doviak and Zrnic 1993).

NEXRAD was prototyped in 1988 at the National Severe Storms Laboratory in Norman, Oklahoma, and deployed for use nationally in 1992 under the controlling agencies of the NWS, the U.S. Air Force, and the Federal Aviation Administration (FAA). Currently, over 160 ground-based WSR-88D radar installations are in operation "providing nearly contiguous coverage across most of the United States" (Crum and Alberty 1993; Miller et al. 1999). Stations in Jacksonville (KJAX), Melbourne (KMLB), Tampa, (KTBW), Miami (KAMX), and Key West (KBYX) provide NEXRAD radar coverage for the SFWMD (Fig. 2). Radar can locate and track storms within a range of 200 to 400 km, depending on radio propagation conditions and nature of the weather system.

Doppler weather radars operate by emitting short pulses of microwave energy, which are focused in a narrow conical beam. The energy is scattered in all directions when a target, such as a building, airplane, bird or precipitation droplet, is encountered and a portion of the energy is returned to the radar antenna as an echo. The intensity of the returned signal is then related to the size of the object, and analyzed according to the time required for the pulse to reach the target and return back. This provides information regarding the range and Doppler velocity of the target relative to the radar. The WSR-88D detects and measures rainfall through conducting complete 360° volume scans of the atmosphere every 5–10 min. Sampling an entire atmosphere volume is achieved by using successively higher tilt angles (0.5–20°) for each sweep. The power from returned signals is related to the reflectivity of encountered raindrops through the use of the weather radar, or Probert-Jones equation

$$P_r = \frac{CLZ}{r^2} \tag{1}$$

where P_r=measured power; C=radar constant, which depends on beam width, power, wavelength, and antenna size; L=attenuation losses; Z=radar reflectivity ($\mathrm{mm}^6/\mathrm{m}^3$); and r=range, or

J. Hydrol. Eng., 2009, 14(3): 248-260

distance to the target (Battan 1973; Bedient and Huber 2002; Doviak and Zrnic 1993; Miller et al. 1999).

Radar meteorology (NEXRAD) may demonstrate several weaknesses since this technology relies on the measure of precipitation in the atmosphere, an approach that is fundamentally different from rain gauge sampling. Consequently, factors such as wind and evaporation present a challenge in the determination of rainfall as these may contribute to a change in sample volume during transport to the ground surface (Doviak and Zrnic 1993). Error can also result from attenuation of the 10 cm radar signal by precipitation, atmospheric gasses, and clouds; anomalous propagation, including cloud top overshooting; incomplete beam filling; and beam blockage (Battan 1973; Fulton et al. 1998; Miller et al. 1999; Wilson and Brandes 1979). Technical difficulties may arise periodically requiring that individual WSR-88D stations undergo maintenance or repair. Surrounding radar installations must provide coverage for the disabled radar when a station is taken out of service, thus increasing the likelihood for errors as the supplemental radars, in many cases, exceed the effective range of 230 km for precipitation (SFWMD, personal communication, 2006).

Selection of an appropriate Z-R relationship for converting reflectivity into rainfall rate is one of the most important factors influencing NEXRAD data quality. Bedient and Huber (2002) and Doviak and Zrnic (1993) illustrate the pronounced effect that altering the drop size distribution (DSD) and associated Z-R relationship even slightly has on the measured rainfall rate for a given reflectivity. Significant error may be introduced when the most fitting Z-R relationship is not applied for a particular rain event or when large variations in the DSD exist within the radar coverage area. Such differences have been shown to exist both within storms and between disturbances of different types, such as convective and frontal, or convective and tropical storms, which at times coexist in South Florida (Battan 1973; SFWMD, personal communication, 2006; Wilson and Brandes 1979).

Previous Studies

Lott and Sittel (1996) conducted an assessment of the accuracy of NEXRAD for five storm events, including Hurricane Gordon, which impacted Florida in November of 1994. Overall, it was found that NWS Level III precipitation estimates were too low for 80% of a total of 220 radar-rain gauge pairs investigated. In addition, it was observed that average NEXRAD rainfall estimates from the Melbourne, Florida NWS station represented only 65% of average rainfall measurements produced by the rain gauge network (29 total gauges) during Hurricane Gordon. This study established the need for improved radar accuracy and led to related advances in NWS radar processing. Johnson et al. (1999) compared mean areal precipitation values generated from Stage III NEXRAD data with those produced by the rain gauge network for several basins in the southern plains region. The study concluded that NEXRAD precipitation estimates were 5–10% less than rain gauge estimates overall for the three-year study period, and further that NEXRAD tended to underestimate rainfall for storm events. Bedient et al. (2000) focused on the comparison of streamflow hydrographs developed through the use of NEXRAD and gauge-derived precipitation data. The authors demonstrate that basin outflow modeled with unadjusted NEXRAD precipitation estimates are as accurate, or more accurate than outflow modeled on rain gauge measurements for three storm events impacting the Brays Bayou watershed in Houston, Texas.

Dyer and Garza (2004) considered the use of SFWMD rain gauges and Stage III radar-based rainfall data in producing mean areal precipitation estimates for Lake Okeechobee. The researchers concluded that mean areal precipitation amounts based on radar measurements were roughly 10–30% less than those produced by SFWMD gauges. Jayakrishnan et al. (2004) also investigated the accuracy of Stage III WSR-88D data in a direct comparison of radar and rain gauge-measured values over the Texas-Gulf basin. The authors demonstrate considerable variation in radar performance over the five-year study period as well as consistent underestimation of NEXRAD for the majority of rain gauge sites investigated. Neary et al. (2004) found that "operational Stage III radar precipitation products suffer from a systematic underestimation of surface precipitation amounts at both point and subbasin scales" in a comparison similar in nature to the Bedient et al. (2000) study for Tennessee. Further, the authors note that correction for systematic bias, which may be present in radar-rainfall data, should preclude the use of such data in hydrologic modeling applications. Xie et al. (2006) examined the effect of seasonality on the accuracy of Stage III NEXRAD radar data in central New Mexico. Results of the study indicate that for a seven-year period of record, seasonal rainfall amounts produced by NEXRAD were underestimated by 18–89% in the nonmonsoon season, and overestimated by 11–88% in the monsoon season.

Watkins et al. (2007) compared mean areal precipitation values derived from Stage III/MPE radar-rainfall data versus the rain gauge network for the Great Lakes region. The authors observed greater correlation between the datasets in the summer months, and that mean areal precipitation values resulting from NEXRAD were found to significantly underestimate rainfall in the winter months. Watkins et al. (2007) also recommend correction for seasonal/annual bias which may exist in the radar-rainfall data prior to implementation in hydrologic analysis. The studies presented illustrate the potential for NEXRAD rainfall measurements to demonstrate seasonal or annual bias relative to the rain gauge network. More specifically, several authors indicate a tendency for NEXRAD to underestimate rainfall overall or for certain storm events. The notion that the nature and severity of systematic offsets present in the radar-rainfall data may depend on measured rainfall intensity is further examined for the SFWMD.

OneRain NEXRAD Rainfall Data Product

The NEXRAD data product received at the SFWMD is processed by three separate entities: the NWS, Weather Services Incorporated (WSI), and the OneRain Company. Radar-rainfall measurements are developed through the use of an array of specialized algorithms, a process that begins at individual NWS NEXRAD installations. The radar data acquisition (RDA) unit, or physical WSR-88D radar, reports signals returned from successive atmosphere scans as reflectivity values. Clutter signals, such as those resulting from buildings and other ground targets are suppressed and data are then passed to the radar product generator (RPG). The determination of a fixed hybrid scan resulting from the assembly of successive volume scans performed by the radar is the first major stage of the precipitation processing system. The result of this operation is a composite scan consisting of reflectivity values for every location on a 1° by 1 km fixed polar grid, recognized as the NWS digital hybrid scan reflectivity (DHR) product (Fulton et al. 1998; Miller et al. 1999). Although the NWS provides for further processing of precipitation data, reflectivity data are intercepted at this stage by WSI in the case of radar-rainfall data destined for the SFWMD.

J. Hydrol. Eng., 2009, 14(3): 248-260

WSI employs several algorithms in order to further refine radar precipitation data for use. Clutter suppression procedures are used to correct for coarse beam blockage due to obstructions. The central step in this stage of processing involves the application of a Z-R relationship to generate rainfall rate information from reflectivity data. This is achieved through the use of an empirical lookup table, which assigns Z-R relations based on atmospheric and meteorological conditions. Data are also subjected to quality control measures, such as threshold detection and correction of outliers and range-dependent inaccuracies during this stage of processing. WSI facilitates the conversion of data from a polar configuration to a Cartesian grid format (2 km by 2 km pixels), which is different in orientation to the NWS hydrologic rainfall analysis project (HRAP) grid. Data mosaicing is also performed in order to account for areas or pixels covered by multiple radar stations and algorithms are applied to correct for radar stations that consistently run "hot" or "cold." The NEXRAD product generated by WSI is used to support network media outlets.

The OneRain Company acquires the radar-rainfall product from WSI to further improve upon the quality of precipitation data for use in hydrologic applications. Complex algorithms provide for additional quality control measures and advanced clutter suppression. The principal objective of additional processing involves the adjustment of radar-rainfall data with rain gauge measurements. The premise of gauge-correction involves the computation of a multiplicative bias factor to remove mean field bias from radar observations. Prior to 2004, gauge adjustment was accomplished through the use of the modified Brandes method. Recently, however, this algorithm was replaced in favor of a more sophisticated kriging technique. Rainfall data from select SFWMD gauges are used in the OneRain gauge-adjustment process. Data from telemetry-based gauges, or rain gauges that transmit data via the LoggerNet, RACU, and MOSCAD systems were used in gauge correction prior to 2004. Currently, data produced by telemetry-based gauges (LoggerNet, RACU, and MOSCAD) and CR10 gauge types are used in the gauge-adjustment scheme. Refer to Table 1, which identifies the rain gauges used in the OneRain gauge-correction process.

The SFWMD, along with three of the four other Florida water management districts, began acquiring NEXRAD radar precipitation data from the OneRain Company in July of 2002 through a competitive contract awarded to develop a corporate database and methods for data access. The use of a single vendor for processing NEXRAD data for the water management districts provided an opportunity to eliminate data discontinuities at district boundaries. Rainfall data produced by NEXRAD are used for operational purposes, and corporate access of 15-min (i.e., taken at 15-min time intervals) rain gauge-adjusted NEXRAD data by the SFWMD operations control center (OCC) was a major objective of the acquisition (Huebner et al. 2003; SFWMD 2008; Torrence, personal communication, 2006). Fig. 3 summarizes the NEXRAD data processing scheme as it applies to the SFWMD.

Methodology

The intent of the research was to compare NEXRAD precipitation data received at the SFWMD with corresponding rain gauge measurements in order to assess the relative performance of NEXRAD technology for different conditions. The study focused on the Upper and Lower Kissimmee River Rain Areas, located in the northern portion of the SFWMD service area. The Kissimmee

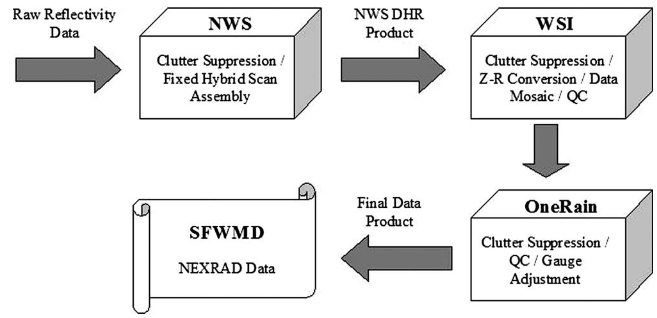

Fig. 3. NEXRAD data processing scheme

River Basin was selected as ongoing restoration projects require rainfall data for use in hydrologic models. The region also experienced the greatest influence, in terms of rainfall, of four tropical events impacting the State of Florida in 2004 and 2005, which proved useful in investigating the effects of extreme tropical rainfall on radar data quality.

The statistical comparison of NEXRAD and rain gauge measurements at the SFWMD was accomplished through the consideration of NEXRAD rainfall data produced for each 2 km by 2 km pixel containing an active SFWMD rain gauge and precipitation data generated by the corresponding SFWMD gauge. Daily time-interval rainfall data were selected for study as daily precipitation measurements represent the preferred time interval for hy-

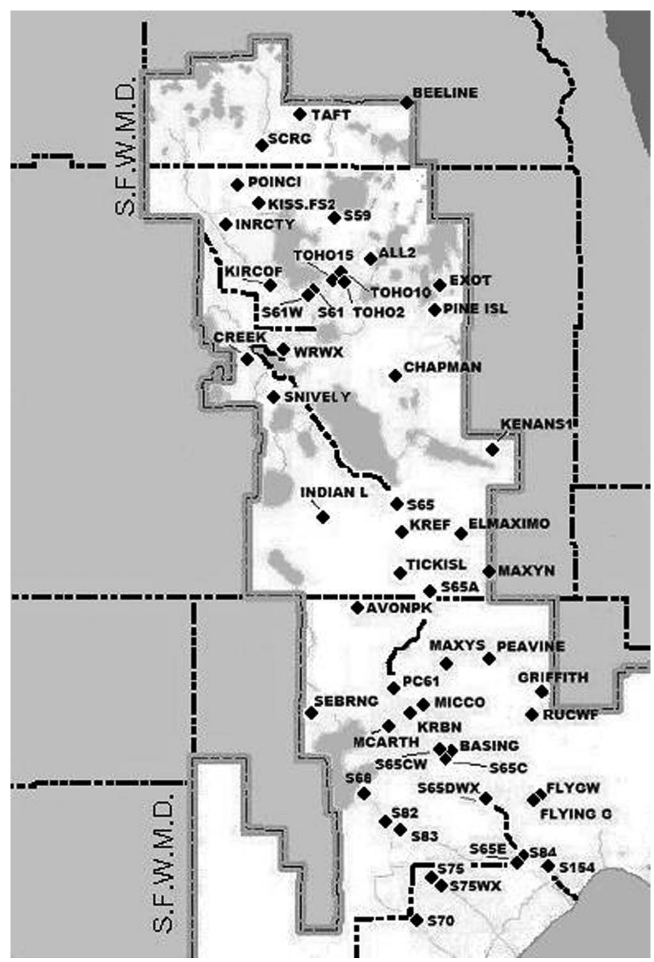

Fig. 4. Study rain gauge locations

Table 2. Kolmogorov-Smirnoff Test Results—Calibration Rain Gauges for the Period of Record

Station	n	Maximum vertical distance CDFs (in.)	Critical K-S statistic ($\alpha=0.01$) (in.)	Rainfall distributions from same population
AVON PK	369	0.491	0.120	False
GRIFFITH	138	0.391	0.196	False
KENANS1	327	0.514	0.127	False
KIRCOF	386	0.479	0.117	False
KRBN	338	0.547	0.125	False
PC61	333	0.574	0.126	False
PEAVINE	361	0.548	0.121	False
PINE ISL	391	0.509	0.116	False
POINCI	380	0.524	0.118	False
S59	393	0.570	0.116	False
S61W	382	0.560	0.118	False
S65CW	317	0.517	0.129	False
S65DWX	331	0.477	0.127	False
S68	329	0.538	0.127	False
S70	328	0.567	0.127	False
S75	338	0.574	0.125	False
S82	325	0.597	0.128	False
S83	316	0.589	0.130	False
S84	346	0.604	0.124	False
S154	343	0.548	0.124	False
SEBRNG	93	0.301	0.239	False
SNIVELY	382	0.523	0.118	False
TAFT	354	0.505	0.122	False
WRWX	376	0.532	0.119	False

Table 3. Kolmogorov-Smirnoff Test Results—Noncalibration Rain Gauges for the Period of Record

Station	n	Maximum vertical distance CDFs (in.)	Critical K-S statistic ($\alpha=0.01$) (in.)	Rainfall distributions from same population
ALL2	335	0.534	0.126	False
BASING	299	0.482	0.133	False
BEELINE	431	0.515	0.111	False
CHAPMAN	197	0.467	0.164	False
CREEK	356	0.522	0.122	False
EL MAXIMO	379	0.430	0.118	False
EXOT	402	0.555	0.115	False
FLYGW	289	0.547	0.136	False
FLYING G	360	0.569	0.121	False
INDIAN L	329	0.514	0.127	False
INRCTY	240	0.475	0.149	False
KISS.FS2	342	0.509	0.125	False
KREF	404	0.559	0.115	False
MAXYN	325	0.526	0.128	False
MAXYS	327	0.425	0.127	False
MCARTH	349	0.501	0.123	False
MICCO	375	0.571	0.119	False
RUCWF	342	0.550	0.125	False
S61	255	0.514	0.144	False
S65	303	0.465	0.132	False
S65A	290	0.448	0.135	False
S65C	272	0.426	0.140	False
S65E	315	0.511	0.130	False
S75WX	213	0.474	0.158	False
SCRG	383	0.548	0.118	False
TOHO2	368	0.565	0.120	False
TOHO10	403	0.521	0.115	False
TOHO15	391	0.524	0.116	False
TICK ISL	355	0.529	0.122	False

drologic analysis at the SFWMD. The daily time interval also makes use of the full compliment of data available from the rain gauge network. The period of January 2002 to December 2005 was identified for data comparison as the SFWMD began obtaining radar-rainfall data in 2002 (Huebner et al. 2003; SFWMD 2008). The rain gauges considered for the research are presented in Table 1 and visualized in Fig. 4 in relation to the study area.

Data Screening and Analysis

Data screening was performed in order to remove select data points from radar and rain gauge datasets prior to statistical comparison. This involved the sequential removal of tagged data and precipitation values of 0.01 in. of rainfall or less. The initial stage of processing involved the elimination of rain gauge and corresponding NEXRAD measurements when a SFWMD quality control tag accompanied the gauge value, indicating that rain gauge data may be missing or lacking in quality. The second and final stage in processing involved the removal of precipitation values less than 0.01 in. This component was included in order to avoid deceptive indications of statistical correlation produced by 0,0 pairs and also because rain gauges are not capable of discerning rainfall volumes less than 0.01 in. Details of the data analysis are presented below.

Comparison Statistics

Several statistics were computed in comparing NEXRAD and rain gauge rainfall quantities and characterizing the relationship between the datasets. Rain gauge measurements were selected as the independent variable for purposes of this study since rain gauge values are measured directly and radar-rainfall values are derived from reflectivity measurements. The Kolmogorov-Smirnoff (K-S) test was applied to determine the degree of similarity between the rainfall datasets overall, as well as seasonally. Linear regression was employed, accompanied by an analysis of correlation, in order to examine the suitability of a linear function in describing the relationship between NEXRAD and rain gauge measurements. Rainfall frequency distributions were generated for the datasets in order to study and visualize the precipitation data. Bias was computed as the difference between NEXRAD and rain gauge rainfall values, or

$$\text{Bias} = \text{Radar} - \text{Gauge}$$

and subsequent investigations of bias were used in the development of a radar-rainfall relationship. The root-mean-square error (RMSE) was calculated to determine goodness of fit for functions representing the data through the equation

$$\text{RMSE} = \left[\frac{\sum_{i=1}^{n} (y_i - y_i')^2}{n} \right]^{1/2} \quad (2)$$

J. Hydrol. Eng., 2009, 14(3): 248-260

Table 4. Kolmogorov-Smirnoff Test Results—Calibration Rain Gauges (Dry versus Wet Season Period of Record)

	Dry season period of record				Wet season period of record			
Station	*n*	Maximum vertical distance CDFs (in.)	Critical K-S statistic ($\alpha = 0.01$) (in.)	Rainfall distributions from same population	*n*	Maximum vertical distance CDFs (in.)	Critical K-S statistic ($\alpha = 0.01$) (in.)	Rainfall distributions from same population
AVON PK	131	0.133	0.201	True	238	0.271	0.149	False
GRIFFITH	45	0.109	0.344	True	93	0.196	0.239	True
KENANS1	139	0.205	0.195	False	188	0.238	0.168	False
KIRCOF	127	0.093	0.204	True	259	0.288	0.143	False
KRBN	131	0.160	0.201	True	207	0.300	0.160	False
PC61	98	0.096	0.233	True	235	0.381	0.150	False
PEAVINE	128	0.125	0.204	True	233	0.330	0.151	False
PINE ISL	147	0.133	0.190	True	244	0.284	0.148	False
POINCI	135	0.124	0.198	True	245	0.321	0.147	False
S59	134	0.140	0.199	True	259	0.323	0.143	False
S61W	130	0.128	0.212	True	252	0.330	0.145	False
S65CW	127	0.158	0.205	True	190	0.284	0.167	False
S65DWX	109	0.115	0.221	True	222	0.284	0.155	False
S68	112	0.118	0.218	True	217	0.322	0.156	False
S70	121	0.189	0.210	True	207	0.326	0.160	False
S75	115	0.145	0.215	True	223	0.335	0.154	False
S82	110	0.138	0.220	True	215	0.354	0.157	False
S83	111	0.136	0.219	True	205	0.348	0.161	False
S84	115	0.142	0.215	True	231	0.350	0.152	False
S154	125	0.157	0.206	True	218	0.353	0.156	False
SEBRNG	36	0.086	0.384	True	57	0.129	0.305	True
SNIVELY	129	0.115	0.203	True	253	0.311	0.145	False
TAFT	125	0.119	0.206	True	229	0.291	0.152	False
WRWX	143	0.128	0.193	True	233	0.290	0.151	False

where y_i=observed radar measurements; and y_i'=radar measurements predicted by the radar-rain gauge relationship. RMSE communicates improved ability of a function to fit the data as the computed value is minimized (Sprinthall 1997; Sheskin 2000).

Results (Skinner 2006)

The K-S test was executed for rainfall datasets associated with each study gauge (*n* equals number of data points for all analyses). Results indicate that the null hypothesis, or that NEXRAD and rain gauge precipitation distributions are derived from the same population, is rejected for the period of record study data (Tables 2 and 3). The assertion that the precipitation datasets are significantly different statistically (alpha error of 0.01) is an important finding as this validates further statistical comparison of the data. Similarly, the statistical dependence of NEXRAD and rain gauge datasets was examined for wet and dry season months, as shown in Tables 4 and 5 for calibration and noncalibration study rain gauges, respectively. The analysis revealed the tendency for the datasets to demonstrate less departure in the cumulative density functions in the dry season as opposed to the wet season.

Paired rainfall data were scrutinized, and linear regression was performed to determine the applicability of a linear function in describing the relationship between the datasets. The linear correlation between NEXRAD and rain gauge measurements proved substantial for most of the study gauges; however, the corresponding regression analysis exposed the tendency of the best-fit line to demonstrate a slope of less than unity and a positive, nonzero intercept. Further investigation revealed that pronounced deterioration in correlation was found to be the consequence of forcing the regression line through the origin, as demonstrated in Fig. 5. Regression lines established by plotting rainfall data from all gauge stations (Fig. 5) may indicate the presence of systematic bias as noted in previous studies including Johnson et al. (1999), Xie et al. (2006), and Watkins et al. (2007).

Rainfall frequency distributions were created in order to compare rain gauge and NEXRAD precipitation cata. Findings indicate rainfall distributions of a uniform shape, as indicated in Fig. 6 for the assembly of study data (all gauges). Fig. 6 shows that, for very low precipitation values (less then 0.10 in.), NEXRAD tends to record rainfall less frequently than the gauges. The figure also demonstrates that NEXRAD tends to measure rainfall more frequently in the low, 0.10–1.0 in. range, and measures rainfall less frequently in the high, 1.0–5.0 in. range.

Bias was examined in order to identify systematic offsets in the data and characterize the relationship between rainfall datasets. Overall, NEXRAD was found to underestimate rainfall by a total of 433 in., compared to a gauge total of 9,344 in., contributing to a radar to gauge (R/G) ratio of 0.95 for the assembly of study data (Table 6). R/G ratios computed seasonally and annually, also shown in Table 6, illustrate that while overall bias between datasets remains seemingly constant on a seasonal basis, total bias appears to diminish substantially on an annual basis, suggesting improvement in radar performance. Total bias was also computed for each study gauge over the period of

J. Hydrol. Eng., 2009, 14(3): 248-260

Table 5. Kolmogorov-Smirnoff Test Results—Noncalibration Rain Gauges (Dry versus Wet Season Period of Record)

	Dry season period of record				Wet season period of record			
Station	n	Maximum vertical distance CDFs (in.)	Critical K-S statistic (α=0.01) (in.)	Rainfall distributions from same population	n	Maximum vertical distance CDFs (in.)	Critical K-S statistic (α=0.01) (in.)	Rainfall distributions from same population
ALL2	123	0.137	0.208	True	212	0.313	0.158	False
BASING	108	0.130	0.222	True	191	0.278	0.167	False
BEELINE	159	0.139	0.183	True	272	0.304	0.140	False
CHAPMAN	63	0.076	0.290	True	134	0.279	0.199	False
CREEK	134	0.149	0.199	True	222	0.298	0.154	False
EL MAXIMO	154	0.134	0.186	True	225	0.230	0.154	False
EXOT	142	0.154	0.193	True	260	0.303	0.143	False
FLYGW	100	0.128	0.230	True	189	0.349	0.168	False
FLYING G	125	0.133	0.206	True	235	0.330	0.150	False
INDIAN L	86	0.085	0.249	True	243	0.359	0.148	False
INRCTY	72	0.104	0.272	True	168	0.304	0.178	False
KISS.FS2	120	0.129	0.210	True	222	0.313	0.155	False
KREF	145	0.136	0.191	True	259	0.315	0.143	False
MAXYN	113	0.129	0.217	True	212	0.314	0.158	False
MAXYS	124	0.125	0.207	True	203	0.220	0.162	False
MCARTH	108	0.097	0.222	True	241	0.327	0.148	False
MICCO	126	0.141	0.205	True	249	0.347	0.146	False
RUCWF	100	0.114	0.230	True	242	0.363	0.148	False
S61	76	0.106	0.264	True	179	0.392	0.172	False
S65	86	0.082	0.249	True	217	0.300	0.156	False
S65A	77	0.062	0.263	True	213	0.307	0.158	False
S65C	81	0.096	0.256	True	191	0.272	0.167	False
S65E	117	0.152	0.213	True	198	0.276	0.164	False
S75WX	77	0.123	0.263	True	136	0.253	0.198	False
SCRG	127	0.110	0.205	True	256	0.334	0.144	False
TOHO2	139	0.149	0.195	True	229	0.315	0.152	False
TOHO10	137	0.119	0.197	True	266	0.313	0.141	False
TOHO15	141	0.125	0.194	True	250	0.314	0.146	False
TICK ISL	112	0.101	0.218	True	243	0.335	0.148	False

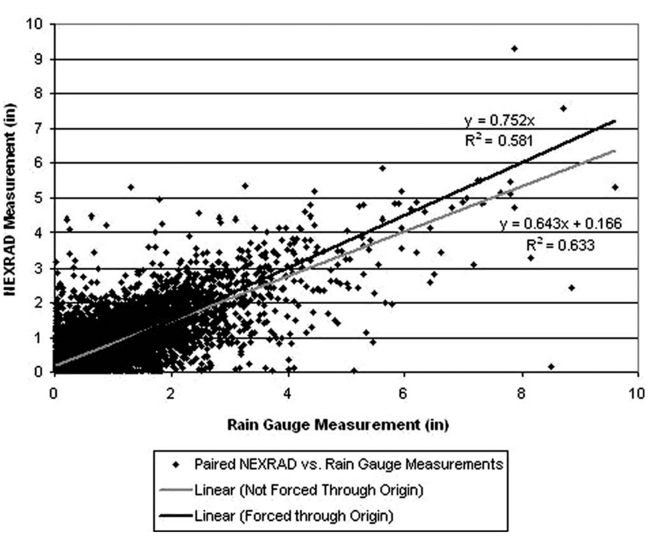

Fig. 5. Paired rainfall measurements with regression lines—study gauges for the period of record

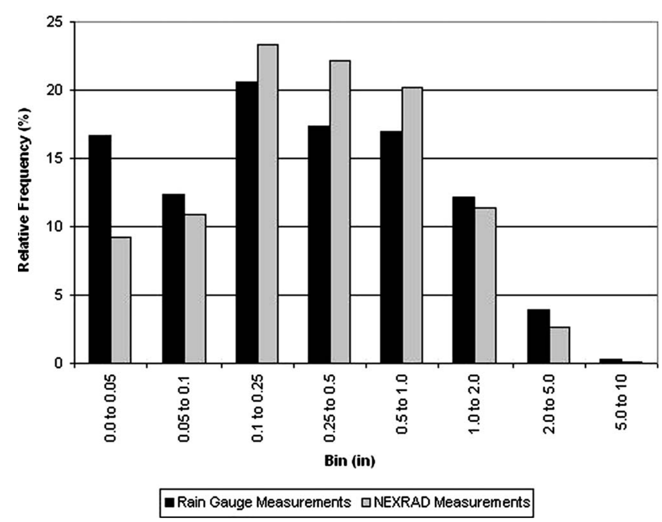

Fig. 6. Comparison of relative rainfall distributions—study gauges for the period of record

J. Hydrol. Eng., 2009, 14(3): 248-260

Table 6. Total Bias—Study Gauges for the Period of Record

Time period	n	Total depth for rain gauges (in.)	Total depth for NEXRAD (in.)	Bias (in.)	R/G
Period of record	17,605	9,343.6	8,910.2	−433.4	0.95
Dry season period of record	6,095	3,092.8	2,941.2	−151.6	0.95
Wet season period of record	11,510	6,250.8	5,969.0	−281.8	0.95
Annual (2002)	4,168	2,323.8	2,077.1	−246.6	0.89
Annual (2003)	4,605	2,088.8	1,929.8	−159.0	0.92
Annual (2004)	3,984	2,322.6	2,295.3	−27.3	0.99
Annual (2005)	4,848	2,608.4	2,608.0	−0.4	1.00

record, as presented in Tables 7 and 8 for calibration and noncalibration rain gauges, respectively. The tables indicate that data from the calibration rain gauges is less biased overall compared to data from the noncalibration rain gauges, which is an expected finding. Further, it is observed that NEXRAD tends to underestimate rainfall, in general, for the noncalibration gauges in the study area.

Despite the favorable indications of overall bias presented, results from the regression analysis indicate the presence of local systematic offsets in the rainfall data. The fact that the regression line does not pass through the origin and demonstrates a shallow slope supports the notion that NEXRAD may be biased high for low gauge precipitation amounts, and biased low for high gauge precipitation amounts. Mean rainfall was compared for various bins (rain gauge values) to test this assertion, as shown in Fig. 7. Results presented confirm that NEXRAD tends to overestimate rainfall for precipitation measurements in the low (less than 0.5 in.) range, and underestimate rainfall for precipitation measurements in the high (greater than 1.0 in.) range. Observations made by SFWMD meteorologists that radar tends to overrepresent rainfall for frontal, or stratiform disturbances, and under-represent rainfall for convective events, relative to the rain gauge network, also support these findings (SFWMD, personal communication, 2006).

The opposing nature of high- and low-range bias prompted the development of a prediction relationship to describe radar estimates as a function of rain gauge measurements. The tendency for NEXRAD to overestimate low-end rainfall and underestimate high-end rainfall suggests that a power relationship may be appropriate for representing the data. Moreover, a power function resolves the issue that the linear relationship, or linear regression line, does not pass through the origin for the assembly of paired

Table 7. Total Bias—Calibration Rain Gauges for the Period of Record

Station	n	Total depth for rain gauges (in.)	Total depth for NEXRAD (in.)	Bias (in.)	R/G
AVON PK	369	208.3	199.4	−8.9	0.96
GRIFFITH	138	83.0	82.0	−1.0	0.99
KENANS1	327	175.6	164.7	−11.0	0.94
KIRCOF	386	244.8	201.4	−43.4	0.82
KRBN	338	155.1	149.5	−5.6	0.96
PC61	333	167.9	155.1	−12.8	0.92
PEAVINE	361	208.8	187.8	−20.9	0.90
PINE ISL	391	222.1	214.8	−7.3	0.97
POINCI	380	195.4	197.6	2.2	1.01
S59	393	215.5	206.4	−9.1	0.96
S61W	382	194.9	202.7	7.8	1.04
S65CW	317	165.5	152.2	−13.4	0.92
S65DWX	331	179.4	154.0	−25.4	0.86
S68	329	159.9	175.4	15.6	1.10
S70	328	127.1	163.3	36.3	1.29
S75	338	157.7	171.8	14.1	1.09
S82	325	134.2	166.8	32.6	1.24
S83	316	127.4	180.7	53.3	1.42
S84	346	137.3	153.2	15.9	1.12
S154	343	132.1	145.8	13.7	1.10
SEBRNG	93	49.9	53.1	3.2	1.06
SNIVELY	382	222.1	200.2	−21.8	0.90
TAFT	354	221.7	186.9	−34.8	0.84
WRWX	376	209.9	191.1	−18.8	0.91
Mean	**332**	**170.6**	**169.0**	**−1.6**	**1.01**
Standard deviation	**72**	**47.4**	**37.7**	**22.7**	**0.15**

Table 8. Total Bias—Noncalibration Rain Gauges for the Period of Record

Station	n	Total depth for rain gauges (in.)	Total depth for NEXRAD (in.)	Bias (in.)	R/G
ALL2	335	161.4	171.9	10.5	1.07
BASING	299	166.7	138.5	−28.1	0.83
BEELINE	431	239.4	219.9	−19.5	0.92
CHAPMAN	197	115.3	93.2	−22.1	0.81
CREEK	356	211.8	197.6	−14.1	0.93
EL MAXIMO	379	278.0	190.6	−87.5	0.69
EXOT	402	198.5	210.8	12.4	1.06
FLYGW	289	139.0	138.3	−0.6	1.00
FLYING G	360	157.3	167.6	10.4	1.07
INDIAN L	329	185.3	187.3	2.0	1.01
INRCTY	240	124.6	130.2	5.6	1.04
KISS.FS2	342	197.2	190.1	−7.1	0.96
KREF	404	223.9	229.1	5.2	1.02
MAXYN	325	176.4	174.2	−2.2	0.99
MAXYS	327	248.3	148.4	−99.9	0.60
MCARTH	349	186.8	160.6	−26.2	0.86
MICCO	375	184.0	164.6	−19.4	0.89
RUCWF	342	158.8	154.1	−4.7	0.97
S61	255	149.3	128.6	−20.7	0.86
S65	303	173.6	156.7	−16.9	0.90
S65A	290	159.4	140.6	−18.8	0.88
S65C	272	152.2	119.7	−32.6	0.79
S65E	315	154.9	144.8	−10.1	0.93
S75WX	213	123.0	110.0	−13.0	0.89
SCRG	383	194.2	212.2	18.0	1.09
TOHO2	368	184.6	192.2	7.6	1.04
TOHO10	403	211.3	190.9	−20.4	0.90
TOHO15	391	209.0	194.3	−14.7	0.93
TICK ISL	355	184.4	197.1	12.7	1.07
Mean	**332**	**181.0**	**167.4**	**−13.6**	**0.93**
Standard deviation	**58**	**37.8**	**34.5**	**26.2**	**0.12**

J. Hydrol. Eng., 2009, 14(3): 248-260

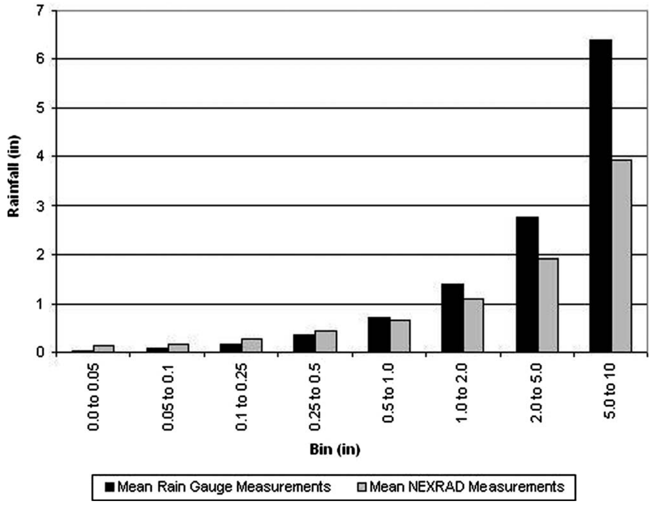

Fig. 7. Comparison of mean rainfall—study gauges for the period of record

rainfall data. Consequently, the investigation turned to the formulation of a power model of the form $y=ax^b$ to improve upon the linear relationship. Refer to Skinner (2006) for details relating to the development of a relationship between NEXRAD radar-rainfall data and rain gauge precipitation measurements in South Florida and associated constraints. The function

$$y = 0.9x^{0.9} \tag{3}$$

where y=daily time-interval NEXRAD measurement (in.); and x=corresponding daily time-interval rain gauge measurement (in.), was selected as an appropriate relationship to describe radar precipitation estimates as a function of rain gauge measurements for the SFWMD due to its ability to describe low- and high-range rainfall amounts.

Study gauges at Structure 61, Structure 65, Structure 65A, and Structure 65C were found to exhibit a poor degree of correlation ($r^2 < 0.40$) between precipitation datasets. The feature common to these gauges is that they constitute the four standard rain gauges located within the study area, and report rainfall as a 7 a.m. to 7 a.m. daily accumulation total, unlike NEXRAD and other gauge reporter types, which produce a midnight to midnight daily accumulation total. Poor correlation observed at these stations may or may not be entirely due to the discrepancy in reporting intervals. The relative inability of these gauges to provide information about the relationship between the two datasets, coupled with the fact that the SFWMD intends to abandon its standard rain gauges in favor of new tipping bucket installations, motivated the decision to disregard data associated with the standard rain gauges located within the study area for development of a radar-rain gauge relationship (SFWMD 2008). Data associated with the four standard rain gauges are not considered in the extreme (tropical) event analysis (Figs. 8 and 9 and Table 12).

Total bias could not be used as an accurate indication of radar performance due to the counteracting effects of local bias. Therefore, RMSE was employed to evaluate goodness of fit for all study gauges and assess the degree of the deviation of data from the formulated prediction function $y=0.9x^{0.9}$. Results summarized in Table 9 indicate better performance of the radar-rain gauge relationship in dry season months as opposed to wet season months as measured by RMSE. Noteworthy results were also obtained from the comparison of RMSE values on an annual basis

Table 9. Total RMSE for the Function $y=0.9x^{0.9}$—Study Gauges for the Period of Record

Time period	n	RMSE (in.)
Period of record	17,605	0.37
Dry season period of record	6,095	0.33
Wet season period of record	11,510	0.39
Annual (2002)	4,168	0.39
Annual (2003)	4,605	0.32
Annual (2004)	3,984	0.40
Annual (2005)	4,848	0.38

(Table 9) where it was discovered that, unlike findings presented for overall bias, RMSE does not decrease on an annual basis. Accordingly, improvement in radar performance is not observed annually and a pronounced degradation in data quality is observed in 2004 and 2005. The RMSE computed for these years may have been influenced by hurricane landfalls, as discussed in the next section. RMSE was also calculated for each study gauge over the study period, as shown in Tables 10 and 11 for calibration and noncalibration rain gauges, respectively. The tables reveal the expected outcome that rainfall data from calibration gauges demonstrate a better fit to the prediction model than data from noncalibration gauges.

Extreme Tropical Event Analysis

Four tropical events of magnitude impacted Central and South Florida in 2004 and 2005. Hurricane Charley made landfall on August 13–14, 2004; Hurricane Frances on September 5-6, 2004; Hurricane Jeanne on September 21, 2004; and Hurricane Wilma on October 24-25, 2005 (National Hurricane Center 2007). These events generated an appreciable amount of rainfall over the Kissimmee River Basin, and since high winds accompanied the storms, it was suspected that tropical rainfall demonstrated the most potential for deviating significantly from the established radar-rain gauge relationship. Precipitation data were examined on a monthly basis for 2004, which had the most active hurricane season for the study period, to test the hypothesis that radar performance is reduced by extreme tropical rainfall. RMSE was computed for August and September, months where Hurricanes Charley, Frances, and Jeanne impacted the Kissimmee River Basin, and compared against RMSE calculated for the summer months of June and July. Overall, it was found that greater values of RMSE were associated with the hurricane months (Table 12), indicating that tropical precipitation may have contributed to degradation in rainfall data quality observed in 2004.

However, it was decided that further investigation was warranted to determine if increased deviation from the prediction function observed for these months was solely the result of hurricane-related precipitation, or if convective rainfall could have contributed to this outcome. Daily precipitation data for the study gauges (excluding standard rain gauges) were plotted and examined for the two-month period from August to September in order to ascertain whether or not the greatest departure in rainfall measurements occurred during the hurricanes. Confidence intervals (95%) were employed as bounds for the developed radar-rainfall relationship to identify outliers. The assumption of a normal distribution of residuals led to the following equation describing the confidence intervals:

J. Hydrol. Eng., 2009, 14(3): 248-260

Table 10. Total RMSE for the Function $y=0.9x^{0.9}$—Calibration Rain Gauges for the Period of Record

Station	n	RMSE (in.)
AVON PK	369	0.32
GRIFFITH	138	0.32
KENANS1	327	0.39
KIRCOF	386	0.30
KRBN	338	0.24
PC61	333	0.26
PEAVINE	361	0.38
PINE ISL	391	0.32
POINCI	380	0.33
S59	393	0.34
S61W	382	0.34
S65CW	317	0.32
S65DWX	331	0.30
S68	329	0.30
S70	328	0.31
S75	338	0.25
S82	325	0.33
S83	316	0.40
S84	346	0.23
S154	343	0.25
SEBRNG	93	0.28
SNIVELY	382	0.34
TAFT	354	0.38
WRWX	376	0.31
Mean	**332**	**0.31**
Standard deviation	**72**	**0.05**

$$(\bar{x}-1.96s_x) < \mu < (\bar{x}+1.96s_x) \tag{4}$$

where $\bar{x}$ represents the sample mean of residuals (in this case the predication function itself); s_x=sample standard deviation of residuals; and μ=population mean of residuals (Kachigan 1986). Results from this analysis are visualized in Figs. 8 and 9 where outliers are identified for the assembly of study data from the calibration and noncalibration rain gauges, respectively.

The assessment of precipitation data from the 2004 hurricane season revealed several unexpected results. First, rainfall data not associated with tropical events produce a greater number of severe outliers than the hurricane data, which leads to the rejection of the assertion that hurricane-related precipitation is the primary cause of diminished data quality observed in August and September 2004 and that most outliers were produced as a result of hurricane conditions. Second, it is observed that most of the outliers present which are associated with tropical activity occurred during Hurricane Frances. Finally, it was found that several of the decided outliers relating to times of no tropical activity occur on the same day, September 26, 2004, 5 days after the landfall of Hurricane Jeanne. The SFWMD is currently investigating what may have contributed to this occurrence. Findings indicate that tropical precipitation data should not necessarily be discounted without further analysis of data quality in the comparison of radar-based and rain gauge datasets

Table 11. Total RMSE for the Function $y=0.9x^{0.9}$—Noncalibration Rain Gauges for the Period of Record

Station	n	RMSE (in.)
ALL2	335	0.25
BASING	299	0.48
BEELINE	431	0.31
CHAPMAN	197	0.32
CREEK	356	0.27
EL MAXIMO	379	0.56
EXOT	402	0.42
FLYGW	289	0.29
FLYING G	360	0.29
INDIAN L	329	0.34
INRCTY	240	0.31
KISS.FS2	342	0.27
KREF	404	0.31
MAXYN	325	0.38
MAXYS	327	0.56
MCARTH	349	0.32
MICCO	375	0.35
RUCWF	342	0.30
S61	255	0.66
S65	303	0.75
S65A	290	0.69
S65C	272	0.69
S65E	315	0.31
S75WX	213	0.36
SCRG	383	0.35
TOHO2	368	0.31
TOHO10	403	0.36
TOHO15	391	0.35
TICK ISL	355	0.32
Mean	**332**	**0.40**
Standard deviation	**58**	**0.14**

Conclusions (Skinner 2006)

The present study provides a comparison of NEXRAD-based precipitation estimates with rain gauge measurements for the SFWMD. Overall, it was determined that radar-rainfall data received at the SFWMD demonstrate considerable localized bias. More specifically, the data exhibit the tendency for NEXRAD to overestimate low-end data, which generally corresponds to stratiform precipitation, and underestimate high-end data, which is generally associated with convective/tropical rainfall. The SFWMD relies on accurate representations of rainfall for use in operations and water supply planning and therefore, a relationship

Table 12. Total RMSE for the Function $y=0.9x^{0.9}$—Study Gauges for the Summer Months of 2004 (Excluding Standard Rain Gauges)

Time period	n	RMSE (in.)
June 2004	599	0.329
July 2004	455	0.335
Aug. 2004	794	0.378
Sept. 2004	543	0.651
2004 (Annual)	**3,984**	**0.404**

J. Hydrol. Eng., 2009, 14(3): 248-260

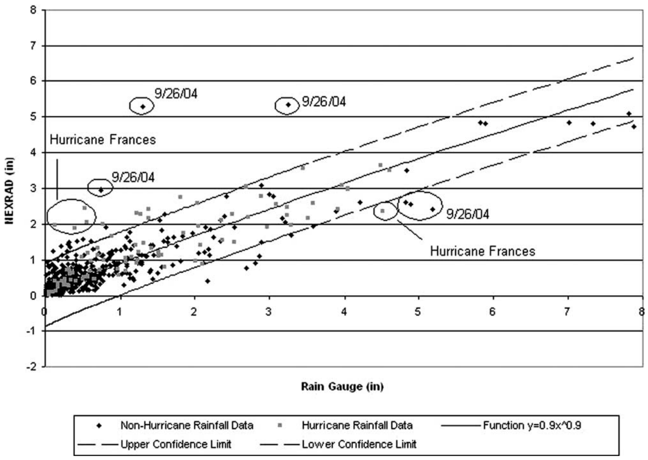

Fig. 8. Paired rainfall measurements for hurricane months in 2004—calibration rain gauges (excluding standard rain gauges) for August and September 2004

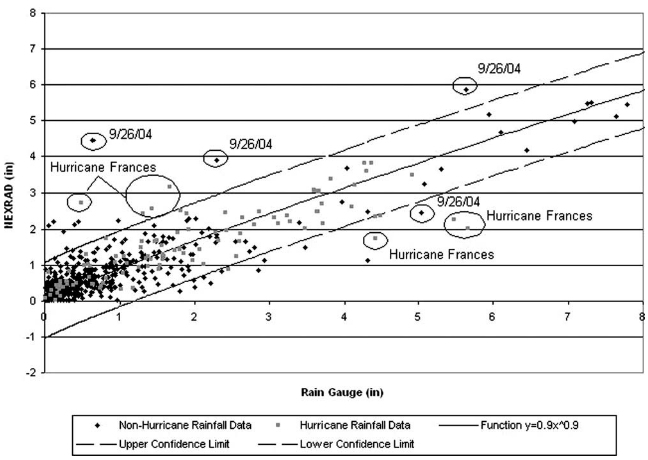

Fig. 9. Paired rainfall measurements for hurricane months in 2004—noncalibration rain gauges (excluding standard rain gauges) for August and September 2004

describing radar-rainfall estimates as a function of rain gauge measurements was developed. Subsequent investigations of RMSE revealed a pronounced increase in deviation of the rainfall data from the prediction function in 2004 and 2005. Since hurricane seasons in these years were exceptionally active, it was supposed that high winds associated with these extreme events could have contributed to the poor relative quality of NEXRAD-derived measurements observed. This hypothesis was refuted as it was discovered that most of the severe outliers produced during August and September, 2004 were not associated with hurricane conditions.

The goal of this work is to reiterate the importance of assessing the quality of radar-rainfall data prior to application in hydrologic modeling, as recommended by Neary et al. (2004) and Watkins et al. (2007). Likewise, the study aims to emphasize the importance of examining local bias contributions, which may exist concealed by favorable indications of overall or total bias. The research has also established the need for a follow-up study to include additional aspects of the comparison, which could not be included in the present study. The subsequent work should provide for the analysis of data from all of the SFWMD rain gauges (approximately 300 gauges) and include a geostatistical analysis of bias in order to further improve upon the accuracy of the developed radar-rain gauge relationship. Precipitation resulting from extreme tropical events and the associated effects on the derived prediction function requires further investigation and a comparison of precipitation measurements for various wind speeds is also suggested.

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J. Hydrol. Eng., 2009, 14(3): 248-260