J9.2 DEVELOPING A HIGH RESOLUTION PRECIPITATION DATASET FOR FLORIDA HYDROLOGIC STUDIES

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1. INTRODUCTION

Water resources are exerting an ever-increasing impact on society. This is especially evident in areas where a growing population exceeds the natural water supply such that water shortages ensue. To manage and maintain a successful water balance, accurate rainfall measurements are needed. Florida's precipitation occurs primarily during the summer months, generally associated with typical sea breeze-induced thunderstorms, but occasionally due to tropical systems such as hurricanes. This summer-time convection sometimes produces very heavy rainfall in short periods of time (> 1 in./h) over relatively localized areas. Such variability emphasizes the challenges of accurately describing and understanding the nature of Florida's precipitation.

It is economically unfeasible to maintain a network of gauges that fully captures the scale of rainfall in regions such as Florida. To overcome some of the gauge placement issues, remote sensing techniques have been introduced. Although radar has been utilized to estimate rainfall for several decades (e.g., Baeck and Smith 1998; Austin 1987; Doviak 1983; Wilson and Brandes 1979; Brandes 1975; Huff 1967), it was not until recently that radar has become a vital tool in hydrologic and atmospheric studies (e.g., Seo and Breidenbach 2002; Young et al. 2000; Seo et al. 1999; Fulton et al. 1998). In 1988 the National Weather Service (NWS) developed the operational Weather Surveillance Radar Doppler (WSR-88D). Although first deployed in 1991, most of the WSR-88D radars became operational by 1996 (Fulton et al. 1998).

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The WSR-88D provides reflectivities at high spatial (1 km range, 1-degree azimuth) and temporal resolution (scans every 6 min.) and an aerial coverage out to 230 km from the radar site. The main algorithm responsible for producing rainfall estimates from the reflectivities is the Precipitation Processing Subsystem (PPS) (Fulton et al. 1998).

Although radars provide excellent spatial and temporal resolution, there are several concerns. A major limitation is knowing the specific reflectivity-rain rate (Z-R) relation to use at a particular location. In addition, radars send out pulses of energy at various elevation angles, with the lowest angle (0.5°) generally being most desirable. However, the low level beams can be compromised by blockages or obstructions. Another inherent problem involves atmospheric refraction and the curvature of the Earth which cause the width and depth of the radar pulse to increase with increasing distance. At large ranges from the radar, the beam may either overshoot relatively low-top stratiform precipitation events, or the beam may be improperly filled. During the cold season ice particles falling through the melting layer in a cloud causes the outer surface to melt while the inner core remains ice. This appears as bright banding on a radar display which produces erroneously high rainfall amounts (Klazura et al. 1999; Anagnostou and Krajewski 1998; Doviak and Zrnic 1993; Smith 1986). Finally, it was recently discovered that precipitation amounts may have been universally underestimated in the PPS algorithm due to slight truncations during the computation of rainfall totals (Hydrology Laboratory 2000, 2002). The problem is worse during longer-term stratiform events rather than brief, more intense convective events.

Many studies have compared the spatial and temporal capabilities of radar-derived precipitation with gauge measurements (Austin 1981, 1987; Seed and Austin 1990; O'Bannon 1998; Klazura et al. 1999). Ratios of gauge-derived to radar-derived rainfall accumulations (G/R) have been computed to test the accuracy of the radar; however, the different sampling volumes of rain gauges and radars complicate this comparison. An 8-in. diameter point gauge measurement typically is compared with a 4 x 4 km^2 radar area, resulting in an area difference of over one million times. In a study comparing the two methods in an Oklahoma mesonetwork of gauges, Fo et al. (1998) showed that radar-derived rainfall underestimated gauge-derived rainfall by ~40% when compared to single point gauge observations. Other studies have shown that gauge and radar values were nearly the same during convective events, but varied as much as ~50% during stratiform events (Klazura et al. 1999). Thus, radar-derived estimates during stratiform events were approximately half the amount of gauges. Other studies have shown similarly large differences between gauge and radar-derived estimates (e.g., Baeck and Smith 1998; Woodley et al. 1975).

To address some of these large differences between measurements, gauges can be used to "correct" radar-derived rainfall estimates. A multiplicative bias can be calculated by dividing total gauge-derived rainfall by total radar-derived estimates and then applying the bias to the original radar-derived estimates to "correct" the radar-derived amount. As a result, the quantitative error of the radar is reduced (Smith and Krajewski 1991). Unfortunately, mean field radar biases may not represent the entire radar area, and they can differ from hour to hour, storm-to-storm, or even within a single storm (Seo et al. 1999).

The National Weather Service's Hydrologic Research Lab (HRL) recently developed a new scheme known as the River Forecast Center Wide Multi-sensor Precipitation Estimator (RFC-wide MPE), commonly denoted MPE (Breidenbach and Bradberry 2001). Using rain gauge data, the MPE software calculates bias correction factors each hour for each radar to improve remotely sensed precipitation values. MPE combines the quantitative strengths of rain gauges closest to each grid point with the enhanced spatial and temporal resolution of radar-derived precipitation.

This paper describes our efforts to create a six-year historical database of rainfall for Florida using the MPE methodology. It is an extension of previous work by Mroczka (2002) and Quina (2003). We first describe an objective rain gauge Quality Control (QC) procedure that compares the gauge data with corresponding raw radar data before the gauge data are input to the MPE. Results of the MPE algorithm then will be demonstrated by examining spatial fields of the computed rainfall and through a statistical analysis using independent gauge data.

2. DATA AND METHODOLOGY

2.1 Precipitation Data Sources

The primary data sources for this study were hourly rain gauge and radar data for the years 1996 through 2001. Five Florida Water Management Districts (WMDs) supplied hourly tipping bucket rain gauge data (Fig. 1). The South Florida Water Management District (SFWMD), the Southwest Florida Water Management District (SWFWMD), and the St. John's River Water Management District (SJRWMD) cover the Florida peninsula, contributing 275, 166, and 181 gauges, respectively. In addition, the Florida Panhandle contains the Northwest Florida Water Management District (NWFWMD) and the Suwannee River Water Management District (SRWMD), contributing 30 and 23 gauges, respectively. When combined, the five Florida WMDs maintain a network of approximately 675 hourly rain gauges. However, due to gauge quality issues in the SWFWMD, far less than their original 166 gauges were utilized as described later. Some areas in Florida contain a very dense gauge network (southeastern Florida), while other areas have a relatively sparse gauge network (the southwest and panhandle areas of Florida). In addition to the WMD gauge network, the NWS Office of Hydrology (OH) supplied data from 48 gauges. This OH gauge network is relatively sparse compared to the Florida WMD network (Fig. 1).

Radar-derived precipitation data were obtained from the Southeast River Forecast Center (SERFC), covering the 28 NWS radars within their area of responsibility. Figure 2 shows the ten WSR-88D radars providing coverage over Florida. Previously known as Hourly Digital Precipitation (HDP) data, the data now are denoted the Digital Precipitation Array (DPA). The DPA product has a resolution of approximately 4 km and uses the 131 x 131 local Hydrologic Rainfall Analysis Project (HRAP) grid at each radar site. No information was available for December 1999 or April and December of 2001 due to lost/missing data (Bradberry 2003, personal communication).

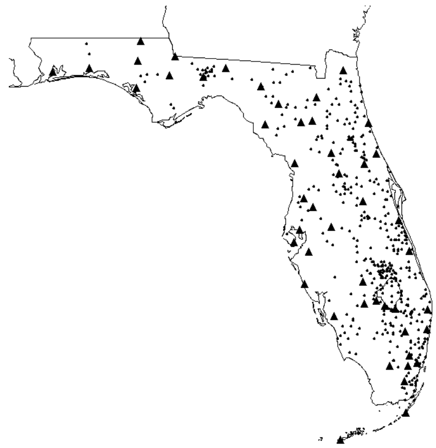


Figure 1. The Florida Water Management District (WMD) gauge network is shown as filled circles, and the National Weather Service (NWS) Office of Hydrology (OH) gauge network is shown as triangles.

Figure 2. Ten WSR-88D radars providing coverage over Florida.

2.2 River Forecast Center-wide Multi-sensor Precipitation Estimation (MPE) Algorithm

The MPE software optimally combines gauge- and radar-derived precipitation estimates (Breidenbach and Bradberry 2001). MPE originally was designed to operate in the Advanced Weather Interactive Processing System (AWIPS) environment at NWS and River Forecast Center (RFC) offices. However, Mroczka (2002) and Quina (2003) converted this operational software from an INFORMIX driven environment to one primarily using flat files for use on workstations at Florida State University. Since most grid points within the computational area are covered by more than one radar, the installation providing the best coverage for each 4 km grid point must be determined. This was done by first constructing a seasonal composite rainfall analysis for each of the 28 SERFC radars using four years of DPA data (1996-1999) (Mroczka 2002; Quina 2003). The seasonal composites revealed areas of beam blockage due to obstructions, together with the reliable range of each radar. The radar masks based on these seasonal composites define the region of reliable observations within each radar domain. The MPE software then uses the individual masks to select the radar providing the best coverage of each 4 km HRAP grid point.

The MPE algorithm produces several individual products. The first product is the gauge-only mosaic (denoted GMOSAIC) in which objective analysis is used to estimate rainfall optimally at each 4 x 4 km^2 grid cell from the nearby gauges. The single Optimal Estimation (OE) technique described by Seo (1998a; 1998b) employs a version of kriging to estimate rainfall amounts from the gauges. The GMOSAIC approach can be illustrated as

$$GMOSAIC_{ij} = G_1W_1+G_2W_2+G_3W_3+G_4W_4, \qquad (1)$$

where W_x is the weight of each gauge G_x, with the sum of all weights equaling one. This OE technique has been shown to be more accurate and less biased than the reciprocal distance squared method that is more commonly used (Seo 1998a). Although the scheme is configured for the four nearest gauges, both the number of gauges used as well as the radius are adaptable parameters that can be changed.

An MPE product without any gauge influence is the radar-only mosaic (RMOSAIC). RMOSAIC is simply the DPA data for each hour that are mapped onto the national HRAP grid. This product utilizes the radar masks mentioned earlier to determine which radar's estimate should be assigned to each grid cell in the mosaic. The RMOSAIC procedure locates the best available radar for each grid point that has data, no beam blockage, and the lowest beam height.

Although radars provide excellent temporal and spatial coverage of rainfall, their inherent limitations can produce erroneous amounts. To minimize errors associated with radar-derived rainfall, area wide biases are calculated by comparing radar-derived values with corresponding rain gauge values. The MPE product that utilizes both gauge- and radar-derived rainfall is the bias-adjusted radar mosaic (BMOSAIC). Mean field radar-wide biases are calculated each hour for each radar. This hourly computation is performed by dividing the sum of gauge values within a radar mask by the sum of the corresponding radar-derived values at those grid cells containing gauges,

$$\boldsymbol{Bias}_a(\boldsymbol{k}) = \frac{\sum_{j=k-l}^{k} \sum_{i=1}^{n(j)} \boldsymbol{g}(\boldsymbol{j}, \boldsymbol{u}_i)}{\sum_{j=k-l}^{k} \sum_{i=1}^{n(j)} \boldsymbol{r}(\boldsymbol{j}, \boldsymbol{u}_i)} \qquad (2)$$

where $Bias_a(k)$ is the mean field bias for each hour k and each radar a, $g(j,u_i)$ and $r(j,u_i)$ contain the i^{th} positive gauge/radar pair at hour j, n(j) represents the number of gauge/radar pairs at each hour j, and l represents the lag in hours (memory span). MPE requires a minimum number of gauge/radar pairs to calculate a radar-wide bias. An adaptable parameter, this study utilized ten pairs in the bias computations. If ten gauge/radar pairs are not available at the current hour, MPE uses pairs from previous hours. By using recursive estimation via exponential smoothing, biases can be estimated over longer time periods, ranging from hourly to daily to weekly to seasonally (Seo et al. 1999). The best mean field bias available for each radar domain then is determined by comparing how recent the bias computation is against the number of gauge/radar pairs. Further details of bias computation using recursive estimation via exponential smoothing can be found in Smith and Krajewski (1991) and Seo et al. (1999).

Once a suitable bias correction factor has been calculated for each radar at the current hour, the original radar-derived rainfall estimates (RMOSAIC) are multiplied by that bias. This produces the bias-corrected radar mosaic field (BMOSAIC), in which the radar is used primarily for spatially distributing the rainfall, while the gauges are used to calibrate the radar-derived amounts using the relationship

$$BMOSAIC_{ij} = Bias_a(k) * RMOSAIC_{ij}, \qquad (3)$$

where $BMOSAIC_{ij}$ is each cell of the BMOSAIC product.

The final product of the MPE algorithm is the multi-sensor mosaic field called MMOSAIC. The MMOSAIC product is a merger of the hourly gauge reports with the bias-corrected radar field (BMOSAIC) to optimize the use of each sensor, while simultaneously reducing the error associated with each. MMOSAIC is calculated on the same 4 x 4 km^2 HRAP grid, using the same scheme described in the GMOSAIC product. The procedure calculates a grid cell's rainfall using the relation

$$MMOSAIC_{ij}=G_1W_1+G_2W_2+G_3W_3+ G_4W_4+BMOSAIC_{ij}W_5, \qquad (4)$$

where W_{1-4} is the weight for each gauge (G_x) determined by its proximity to the particular grid cell (Quina 2003). Like GMOSAIC, the closer (farther) a gauge is to an evaluated cell, the greater (smaller) its weight. The bias-corrected radar weight (W_5) increases as a function of distance from the nearest gauge, with the sum of all weights equaling one. If a gauge is located within a grid cell, that cell is assigned the gauge's value. If a grid cell contains two or more gauges, the gauge values are averaged and assigned to the cell.

Mroczka (2002) and Quina (2003) developed a stratiform versus convective precipitation test within MPE after determining that a single set of adaptable parameters was unsatisfactory. Specifically, the type of precipitation (stratiform or convective) was determined by calculating the standard deviation of radar-derived rainfall (RMOSAIC) over the Florida peninsula each hour. Only cells reporting rainfall were considered. Results of the standard deviation then were used to select key adaptable parameters. Convective precipitation generally is localized and relatively intense, producing a relatively large standard deviation. Conversely, stratiform precipitation typically is more uniform and lighter in intensity, yielding a smaller standard deviation. The type of precipitation can vary greatly from hour to hour and even during a single hour. For this study, a standard deviation greater than or equal to (less than) 0.11 in. defines convective (stratiform) precipitation.

Once the nature of the precipitation is determined (convective/stratiform), one of two sets of adaptable parameters is used within MPE to account for the varying nature of the precipitation. These adaptable parameters affect the relative weights of radar- and gauge- derived precipitation. The "gauge radius of influence" (ROI) represents the radial distance (in km) over which each gauge exerts an influence. For this study, the convective ROI was set at 30 km, while the stratiform ROI was set at 40 km. The lag-0 indicator cross-correlation and the lag-0 conditional cross correlation parameters are used to assign relative weights to gauges and radars (Breidenbach and Bradberry 2001). Both of these correlation parameters can range from zero to one, with zero yielding the GMOSAIC product, and one producing the BMOSAIC product. Hence, greater correlation values produce a greater influence by BMOSAIC, while smaller values yield a greater influence from the gauges. Since convective (stratiform) rainfall events generally are heavy (light) and spotty (uniform), more weight should be given to BMOSAIC (GMOSAIC). Following this methodology, both correlation parameters were set at 0.925 for convective precipitation and to 0.65 for stratiform precipitation. Various sensitivity tests of these parameters showed the values chosen to be most optimal for the Florida peninsula (Quina 2003).

3. RAIN GAUGE QUALITY CONTROL

3.1 Problems Encountered

We utilized rain gauge data from all five Florida's WMDs, together with a supplemental dataset provided by the NWS OH, a total of over 700 gauges (Fig. 1). A detailed inspection of the original gauge data showed varying degrees of quality.

The SFWMD provided 275 operational gauges for this study. The SFWMD had performed its own quality control check on their data. Hourly rain gauge values were assigned one of several different quality control (QC) indicators to document the resulting output of their procedure.

The SRWMD supplied 23 gauges, comprising a relatively sparse network and not covering the entire study period. In fact, gauge data were supplied only for the years 1998 through 2001, with only minimal useable data during 1998 and 1999. There was no documentation of a QC procedure having been applied to the data. A major quality control issue was discovered regarding the timing of the SRWMD data. Specifically, the time attributed to a gauge observation often did not agree with the radar-observed timing (i.e., they seemed to differ by plus or minus one hour). This timing problem did not appear with all gauges and did not appear to span the entire period of record. However, no specific documentation about these problematic gauges was provided. Therefore, the data had to be examined carefully to identify those gauges having the timing problem and to determine the time periods over which they occurred.

Examination of the data included correlating each gauge's data against the hourly RMOSAIC values for every month of the dataset--a very time consuming task. Table 1 gives two examples of these correlation tests for different months. The "original" columns contain correlations from the original dataset as provided by SRWMD (beginning time stamp). The "original + 1" columns contain correlations after an hour was added to the gauge time stamp, transforming it to an ending time stamp. Clearly, most gauges are better correlated with the radar-derived precipitation when the time stamp is altered. Two gauges in May 2001 (e.g., gauge "2319800" and "241") may have had the correct time stamp in the original dataset (Table 1). The time stamp assigned to the radar data also was confirmed during this process.

Correlation tests performed for every gauge of the SRWMD dataset revealed a few gauges (~ 1%) where the original time stamp might have been correct (i.e., the two correlations were very close to one another as in the two May 2001 cases in Table 1). However, there was no systematic pattern with these cases. For example, a gauge might appear to have a beginning time stamp one month, although the next month(s) would appear to have an ending time stamp (Table 1). Since so few gauges might have had the correct original time stamp, all gauges were changed to an ending time stamp.

The SJRWMD provided 181 rain gauges, and like SFWMD, they had performed their own QC procedure to screen suspect data. Some of the data were missing over a period of hours but an accumulated total was reported at the end of the missing period. Mroczka (2002) and Quina (2003) attempted to distribute accumulated gauge values over the missing periods by applying an interpolation scheme based on radar-derived rainfall estimates. Specifically, their scheme first would identify the accumulated gauge event. It then would inspect the hourly radar-derived precipitation at the gauge location and attempt to distribute the gauge's accumulated rainfall in proportion to the radar's hourly values. Although this method initially showed promise, the results were deemed too uncertain to be used with confidence. Hence, the accumulations were removed from the dataset prior to any further analysis.

Table 1. Individual SRWMD gauge correlations with the RMOSAIC radar product for May and August 2001.

	May 2001		August 2001	
Gauge ID	***Original (Beg. Time)***	***Original + 1 (End Time)***	***Original (Beg. Time)***	***Original + 1 (End Time)***
2319800	0.571	0.509	0.247	0.736
2320500	0.090	0.982	0.375	0.604
2321500	0.059	0.794	0.256	0.829
2323500	0.222	0.899	0.279	0.715
210	0.157	0.647	0.161	0.419
229	0.110	0.541	0.050	0.384
235	-0.003	0.626	0.084	0.968
240	0.191	0.722	0.143	0.884
241	0.743	0.508	0.129	0.808
246	0.542	0.637	0.288	0.728
252	0.234	0.715	0.073	0.719
254	0.024	0.840	0.045	0.569
263	0.135	0.445	0.180	0.715
270	0.042	0.729	0.197	0.829
287	0.427	0.932	0.148	0.635
Averages	**0.236**	**0.702**	**0.177**	**0.703**

Another issue with the SJRWMD data was whether the proper time stamp had been assigned to the hourly gauge amounts, as described earlier for the SRWMD data. Therefore, the SJRWMD gauges were correlated with radar data in an attempt to verify the time stamp (as in Table 1). The tests revealed the time stamp to be the beginning of the collection hour for all gauges.

The NWFWMD provided 30 gauges spanning the Florida panhandle. The District had not applied QC procedures to their data, and several major formatting issues needed to be addressed. MPE requires hourly rain gauge amounts for effective use; however, much of the NWFWMD data were provided in sub-hourly increments. That is, the data were recorded at 5- 10- 15- 30- or 60-min time intervals. Although NWFWMD personnel provided a detailed listing of gauges and their respective data interval recordings, many problems still existed. For example, some gauges that were specified to contain only 5-min data increments actually had other data intervals intertwined within the 5-min increments (i.e., 15-min summations for some hours, but 5-min for most others). Since this appeared to occur randomly, substantial effort was spent identifying the different situations for each gauge and correcting them by calculating hourly accumulations.

The SWFWMD provided 166 gauges over the western portions of the Florida peninsula. These data have high spatial resolution, similar to the SFWMD and SJRWMD. However, initial examination of the SWFWMD gauge dataset showed a large number of gauges reporting with a non-hourly time stamp, with most in the form of 12 h accumulations. There also was a large number of cases in which the data contained a time stamp greater than or less than one hour. Segregating the 12 h accumulations into hourly amounts would have yielded significant uncertainty. Hence, the 12-hourly gauges were removed from the dataset. It should be noted that at one time or another, all of the SWFWMD gauges reported some non-hourly amounts, but only those particular hours were removed. Thus, only those gauges that reported hourly remained. This initial QC step removed 79 gauges from the original 166 that were provided, leaving 88 gauges to be examined further. Additional problems with these data are described in a later section.

The NWS OH gauge network was relatively sparse compared with the Florida WMD network. These data had been quality controlled by the NWS. Analysis of the OH data revealed that about 85% of the gauges reported at a resolution of only 0.1 in. (not 0.01 in.). Not only was the resolution to the nearest 0.1 in., but the hourly amounts also were truncated. For example, if a gauge reporting to the nearest 0.1 in. actually received 0.09 in. of rain during an hour, a value of zero would be reported that hour. Unless additional rainfall occurred prior to the end of the day, no rain would be recorded that day (Tollerud 2000).

3.2 Florida State's Quality Control Procedures

A detailed examination of the WMD and OH gauge data showed that an additional, substantial quality control effort still was needed since manual inspection revealed many cases of unusual and unacceptable amounts. An objective QC procedure would be required due to large amount of gauge over the multi-year period.

In attempting to devise an appropriate QC procedure, there were many discussions with personnel at the NWS OH. Several of their procedures were investigated but found to be unsatisfactory for our use. For example, a "buddy check" procedure was attempted. However, since Florida's rainfall is very localized, many values were flagged as being suspicious when they actually appeared quite reasonable. A temporal consistency check procedure was investigated to identify "stuck" rain gauges (zero values occurring during rainfall). After individually summing daily gauge and radar rainfall values, differences between the two are checked against a set of criteria. This technique also provided unacceptable results, again due to the highly variable nature of Florida rainfall.

Another attempt at quality controlling rain gauge data was to plot gauge data onto corresponding radar imagery (RMOSAIC). Based on several test cases of this method, it was soon abandoned since it was deemed too subjective and too time intensive because every hour required manual inspection.

We developed a QC procedure that objectively compared hourly gauge values with raw radar-derived values (i.e., RMOSAIC before any modifications). Specifically, each hourly gauge value was compared to the 4 x 4 km^2 radar-derived estimate whose area contained the gauge. This proved to be a fruitful approach since the gauge data were objectively compared with an independent source (the radar) and since the high-resolution radar data are more likely to detect Florida's spotty rainfall patterns than the gauge networks (e.g., the "buddy check" procedure). To the authors' knowledge, this type of objective evaluation of gauge data against radar values has not been reported previously. Figure 3 is a flow chart of this scheme, and the following sections detail the various steps of the procedure along with justifications for choosing some of the adaptable parameters that are contained within. We state at the outset that there is no perfect scheme for quality controlling precipitation data.

Since gauge and radar precipitation values must be positive, any hours with missing data were immediately removed from the dataset. Hence, only hours with both gauge amounts (G) and radar-derived estimates (R) greater than or equal to zero were passed through the procedure. The remaining non-zero data then were evaluated against four additional criteria that are discussed individually below (numbered at the top of Fig. 3).

1) *R = 0, G > 0 Condition*

Step 1 of the QC procedure (Fig. 3) evaluated hours when the gauge reported rainfall, but the radar did not. If a gauge reported rainfall, but the encompassing 4 x 4 km^2 radar grid cell exhibited no rain, the radar area around the gauge was expanded to include the eight surrounding HRAP grid boxes (12 x 12 km^2). This criterion hereafter will be denoted the "9-pt. test", while the maximum radar-derived estimate within the nine grid boxes will be denoted "R_{max}". This expansion in the test area was designed to consider cases when a gauge was located at the boundary of an HRAP grid cell and that gauge marked the edge of the precipitation area. When the gauge reported rainfall, but all nine radar values indicated zero rainfall (R_{max} = 0.00 in.), a sliding scale was established to determine whether the gauge value was acceptable. A gauge threshold was determined for comparison with the surrounding radar pixels (12 x 12 km^2). Specifically, the hourly gauge value was kept when its value was less than or equal to 0.40 in. of rain (an adaptable parameter), even though R and R_{max} equaled zero. We hypothesized that rainfall exceeding 0.40 in. in an hour likely was convective. Therefore, the radar should detect this rainfall since convective clouds generally extend relatively high in the atmosphere (Baeck and Smith 1998). Conversely, if an hourly gauge value was less than 0.40 in., the precipitation more likely was stratiform in character, and the radar beam could overshoot the relatively low echo tops, giving a zero value. Due to the potential for considerable uncertainty in comparing a point gauge value to a radar-derived 4 x 4 km^2 area, the 0.40 in. minimum gauge threshold was chosen rather generously.

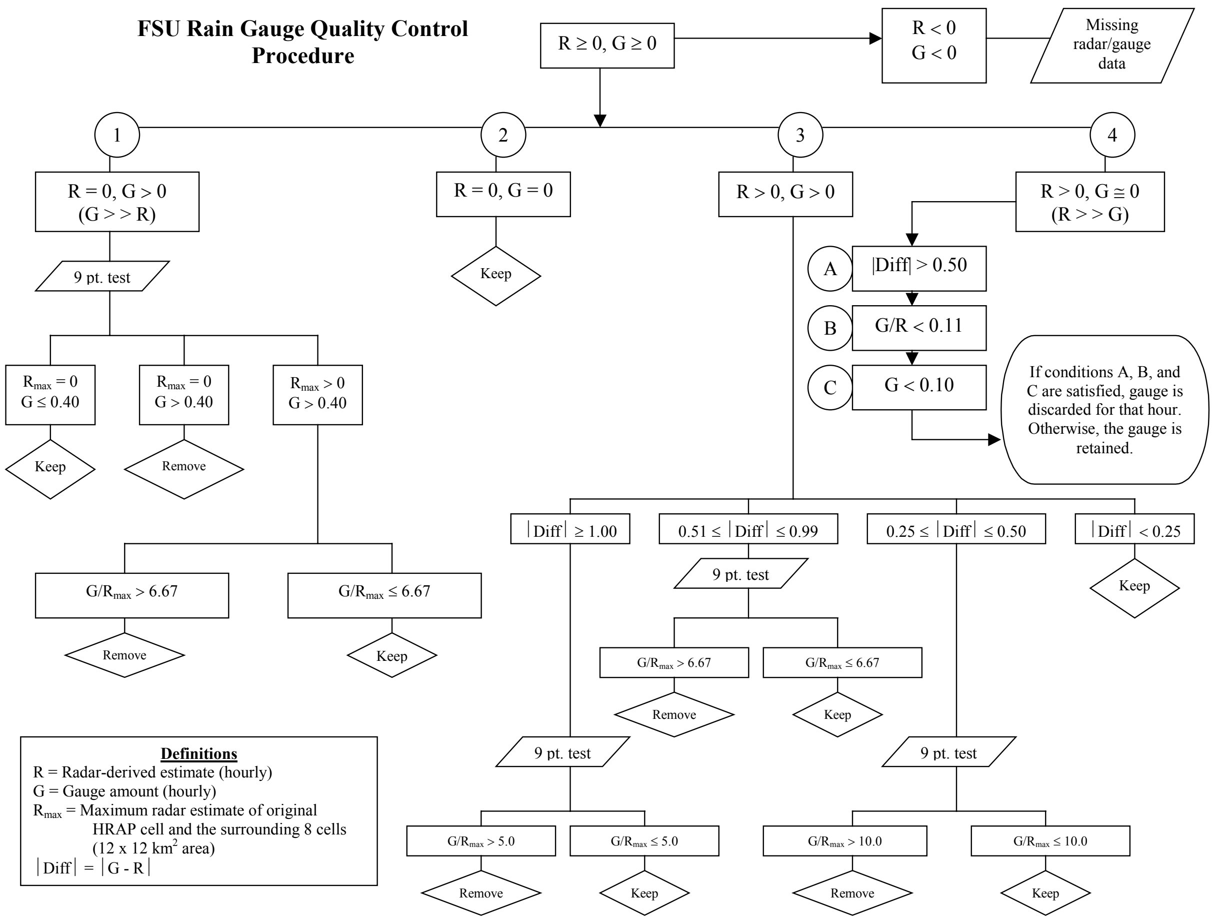


Figure 3. Rain Gauge Quality Control (QC) Procedure Flow Chart.

Those cases where R_{max} equaled zero but the gauge exceeded 0.40 in. were removed from the dataset. Since hourly rainfall amounts greater than 0.40 in. were assumed to be convective, at least one (or more) radars should have detected these events if the radars were operational. A random inspection of the peninsula radars for various examples of this scenario (not shown) revealed no bad scans or missing periods that would explain R_{max} = 0. Therefore, the gauge value was assumed to be erroneous.

When R_{max} was greater than zero and the gauge value exceeded the 0.40 in. threshold, an analysis of the bias (G/R_{max}) determined if that gauge hour should be removed. This criterion handles cases when the radar detected no rain in the gauge's HRAP box, but it was detected nearby. The parameters for this bias criterion were chosen subjectively after an extensive manual inspection of several test months. After ranking all hours in which this scenario occurred, it was determined that gauges with the greatest 15% of the bias values would be removed, while the remaining 85% of the cases would be kept. This corresponded to a threshold of G/R_{max} = 6.67. For example, if a gauge reported an hourly rainfall of 0.60 in., the encompassing radar grid cell detected no rain, and the nearby R_{max} = 0.08 in., then the resulting bias (G/R_{max}) would be 7.5. Hence, the gauge would be removed for that hour. Although this may seem like a harsh test considering that the difference between the gauge and R_{max} was only ~ 0.5 in., it should be noted that this amount occurred in a nearby grid cell, not the original radar grid cell. By extending the bias calculation to a nearby grid cell (the "9-pt test" for determining R_{max}), we acknowledge that there may be gauge placement issues with respect to the precipitation and that the precipitation likely is moving over different grid cells. This prevents the gauge from mistakenly being removed because the original radar grid cell detected nothing; whereas precipitation did in fact, occur nearby.

During the summer season months, Step 1 accounted for approximately 25 % of the total gauge hours that were removed. However, during the winter season, Step 1 accounted for approximately 80-90 % of the total removed gauge hours (this will be explained in Step 3 of the QC procedure). Nevertheless, results from Step 1 revealed many cases where gauge values were large (often exceeding 1 in.) although the nine encompassing radar-derived values were zero. These gauge values were removed from the dataset. Although some gauge hours from each WMD exhibited this problem, it was most prevalent with data from the SWFWMD. Examples of the more glaring situations are illustrated in Table 2. An examination of hours before and after each example (Table 2) showed no apparent timing issues in either the gauge or radar data. One should note that four different gauges in Table 2 recorded the same rainfall (i.e., 2.55 in.) at different times. Inspections of other gauges showed this same amount (2.55 in.) to be reported on many occasions. Since the probability of exactly the same heavy rainfall amount occurring at numerous gauges at different times is very low, the value appears invalid. These unexplained gauge amounts appear attributable to some systematic problem with the gauge system (e.g., a measurement conversion from mm to in.). It should be emphasized that the radars were checked in these cases and appeared to be functioning properly.

Table 2: Step 1 of the FSU QC procedure containing examples of removed gauges when the gauge reported greater than 0.40 in, while both R and R_{max} equaled zero.

Gauge ID	**Date/Time**	**Gauge**	**Radar**	**R_{max} (9-pt)**
R0038700	0610199917z	2.14 in.	0.00 in	0.00 in.
R0038700	0711199920z	2.44 in.	0.00 in.	0.00 in.
R0038700	0715199901z	2.55 in.	0.00 in.	0.00 in.
R0051200	0719199900z	4.00 in.	0.00 in.	0.00 in
R0038800	0805199900z	2.55 in.	0.00 in.	0.00 in.
R0019400	0818199921z	2.55 in.	0.00 in.	0.00 in.
R0005200	0907199907z	3.74 in.	0.00 in.	0.00 in.
R0048000	0927199921z	2.55 in.	0.00 in.	0.00 in.

2) R = 0, G = 0 Condition

Step 2 of the QC procedure (Fig. 3) considered hours when both the radar and gauge indicated no rainfall. Although both methods recorded zero rainfall, this does not necessarily mean that either is correct due to spatial and temporal considerations. However, with no other conflicting information, these hours were retained in the dataset.

3) *R > 0, G > 0 Condition*

Step 3 of the QC procedure (Fig. 3) evaluated hours when both the gauge and radar values were non-zero. The difference between the two sources determined whether the gauge value was retained or deleted. Those hours when the difference between the gauge and radar (| Diff |) was less than 0.25 in. were retained. This minimum difference threshold (0.25 in.) was deliberately set less than the 0.40 in. threshold for Step 1 since the original radar cell reported positive rainfall.

Differences between radar and gauge amounts greater than the 0.25 in. threshold were separated into three additional categories (Fig. 3): 1) between 0.25 in. and 0.50 in., 2) between 0.51 in. and 0.99 in., and 3) greater than or equal to 1.00 in. In each case, the gauge values underwent the 9-pt test and were classified as either good or bad according to the additional bias criterion check (G/R_{max}) described earlier. The bias threshold parameters again were chosen subjectively after manual inspections of the data revealed the appropriate acceptable and unacceptable differences between gauge and radar amounts.

For gauge and radar differences less than or equal to 0.50 in. but greater than or equal to 0.25 in., only the gauges with the largest biases were removed. As described earlier for Step 1, extending the bias to include the nearby radar grid cells accounts for gauge location with respect to the precipitation, in addition to moving precipitation. Since both the gauge and radar reported rainfall, only those situations with the greatest 10% of the bias values based on all nine grid boxes were removed ($G/R_{max} > 10.0$). For example, if a gauge reported 0.55 in. and the radar reported 0.03 in. of rainfall in an hour, the minimum acceptable radar amount in the nine grid cells (R_{max}) would be 0.05 in. ($G/R_{max} = 11$). If $R_{max} = 0.04$ in. in this case ($G/R_{max} = 13.75$), the gauge hour would be removed. Inspections of these scenarios revealed that the nearby radar grid cells generally had a greater rainfall than the gauge's grid cell. Therefore, R_{max} would be greater than R, the bias would meet the acceptable criterion, and the gauge would be kept. Very few gauge hours were removed due to this criterion.

When the gauge and radar difference was between 0.51 in. and 0.99 in (or > 1.00 in.), the same methodology was applied. After the 9-pt test, a gauge was removed when the bias (G/R_{max}) criterion exceeded 6.67 (5.0). This value corresponds to the greatest 15% (20%) of the biases. The remaining 85% (80%) of the cases were kept. We decreased the percentage bias criterion for the larger gauge-radar differences between a gauge and radar (> 1.00 in.) to include a larger range of suspect data. For example, if the gauge reported 2.30 in. of rainfall in an hour, and the radar reported 0.40 in., the minimum acceptable radar amount in the nine grid cells would be 0.46 in. If $R_{max} = 0.45$ in. in this case, that gauge hour would be removed.

It should be stressed that since both the gauge and radar reported positive rainfall, it was very difficult to determine whether a given gauge value was correct or incorrect. Hence, few gauge values were deleted in this step. Only extreme differences between a gauge and radar caused a gauge to be removed. Examples of large differences whose gauge hours were removed from the SFWMD and the SJRWMD data are illustrated below (Table 3).

Table 3. Example of gauges removed during Step 3 of the FSU QC procedure.

Gauge ID	Date/Time	G	R	| Diff |	R_{max}	G/R_{max}
LXWS+R	0203199802z	0.68 in.	0.05 in.	0.63 in.	0.09 in.	7.6
SIXL3+R	0918199921z	0.91 in.	0.06 in.	0.85 in.	0.08 in.	11.4
02651475	0704200118z	1.35 in.	0.16 in.	1.19 in.	0.21 in.	6.4
30233130	0914200122z	0.91 in.	0.09 in.	0.82 in.	0.11 in.	8.3

4) R > 0, G = 0 Condition (R>>G)

The final scenario is when the gauge reported no rain, but the radar did report rain (Fig. 3). However, the QC procedure did not have to consider this scenario since the MPE scheme, as configured by the NWS, automatically deletes these gauges. The advisability of this step can be debated on the basis of gauge placement within the HRAP grid cell. However, we believed it was best to follow the MPE scheme as utilized by the NWS.

An extension of Step 4 revealed many cases when the gauge reported very small amounts (e.g., 0.01 in.) while the radar reported much larger amounts (e.g., 1.5 in.). Although both the gauge and radar reported positive rainfall, the gauge values appeared unrepresentative of the area-wide rainfall. Thus, three additional criteria were established to determine whether the gauge should be removed from the dataset. The conditions establishing removal were: 1) the difference between the gauge and radar amounts must be greater than or equal 0.51 in. (Condition A in Fig. 3); 2) the bias between the gauge value and the encompassing radar (G/R) value must be less than 0.11 (Condition B), and 3) the gauge value must be less than 0.10 in (Condition C). Since gauge placement issues within a 4 x 4 km^2 grid cell could account for such large differences, gauges only were discarded if all three conditions were satisfied that particular hour. These criteria were chosen subjectively after extensive testing of these cases. By establishing the three additional conditions for this situation, we believe we removed the most suspect gauge data, while preserving most of the representative cases.

These additional conditions of Step 4 (A, B, C when R >> G) removed the most gauge data of the entire FSU QC procedure. Gauge malfunctions (clogs) and placements coupled with very localized convective events are the likely cause of this situation. About 75% of the entire summer flagged (removed) hours were attributed to these three additional conditions. Conversely, few gauge hours were removed because of these three criteria during winter, likely due to the relatively uniform, stratiform type of precipitation. Random examples of gauges from the SFWMD and SJRWMD that were removed by these conditions are illustrated in Table 4 below.

Table 4. Examples of removed gauges for the three additional conditions applied to Step 4 when G > 0, R > 0, and R >> G.

Gauge ID	Date/Time	Gauge	Radar	R_{max} (9-pt)
LZ40+R (SF)	0624200023z	0.01 in.	2.79 in.	4.42 in.
ENR301+R (SF)	0708200000z	0.01 in.	1.86 in.	3.51 in.
60406091 (SJR)	0711199822z	0.04 in.	1.05 in.	1.44 in.
70271003 (SJR)	0801199921z	0.05 in.	1.97 in.	3.13 in.

Although the above (R >> G) situations might occur due to moving precipitation and gauge placement issues, extending the radar search area to the surrounding eight grid cells (the 9-pt test) minimizes the number of valid cases that are flagged. Because at least one of the surrounding grid cells had an even higher radar-derived estimate (R_{max}) than the encompassing cell (R), the much smaller gauge values do not appear representative of the area wide rainfall. Hence, those gauges hours were removed from the dataset.

It should be emphasized again that there is no perfect QC procedure. Inevitably, good gauge data sometimes will be mistakenly removed, while suspect gauge data sometimes will be retained in situations where it should have been removed. There is no way to always distinguish between accurate and erroneous gauge amounts. Steiner et al. (1999) notes that this is especially true in an operational environment and for sparse gauge networks. Nonetheless, we believe that this objective procedure is superior to any of the alternatives that we investigated and provides high quality gauge data as input to the MPE procedure for calculating bias corrections to the radar data.

3.3 Florida WMD QC Results

Results of the QC procedure just described are presented according to the source of the gauge data. The numbers of removed gauges from the four Florida WMDs, excluding SWFWMD, which will be discussed later in this section, are seen in Table 5a. Each monthly value represents the number of removed gauges from each of the four WMD datasets. Rainy hours (Table 5b) were defined as a gauge reporting an hourly total greater than or equal to 0.01 in. The percentage of removed gauge hours then was calculated by dividing the removed hours by the total rainy hours (Table 5c). One should note the asterisks in several entries, denoting that radar data for these months either was missing or problematic, in which case no QC analyses were performed.

Examination of the results (Table 5) shows that the amount of deleted data generally is less than 1%; however, values for the summer months are slightly greater at 1-2%. Although this small percentage might not seem to justify our comprehensive QC procedure, the removed gauge hours could represent a relatively large volume of rainfall. That is, using erroneous gauges to calculate a bias adjustment of radar-derived rainfall estimates can produce significant errors.

Since the three additional conditions in Step 4 (A, B, C) of the QC procedure removed the most gauges (where G << R), we believe that we eliminated many of the situations that would most severely impact the bias calculations in MPE. The additional deleted data represent an attempt to remove the other types of largest differences between gauge and radar-derived estimates. MPE results based on the original gauge data are compared with those from the quality controlled data in the next section.

Table 5. QC results of a) removed gauge hours, b) rain hours, and c) percentage of removed gauge hours for the Florida WMD (excluding SWFWMD) gauge network from 1996 through 2001. (Excluding December 1999, April and December 2001 due to missing radar data.)

a)

	Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Total***
1996	5	2	23	7	54	98	42	55	33	24	2	4	349
1997	2	11	12	41	48	121	81	79	35	7	14	20	471
1998	19	34	32	18	29	51	80	73	84	35	101	11	567
1999	21	19	4	41	76	167	95	134	75	80	56	****	771
2000	58	9	23	48	23	145	264	151	240	46	21	15	1043
2001	13	5	41	****	71	177	182	126	210	49	44	****	918
Total	118	80	135	155	301	759	744	618	677	241	238	53	**4119**

b)

	Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Total***
1996	4118	1893	9831	2785	6058	9526	5805	7833	5811	10252	2200	3881	69993
1997	5468	3438	5703	11921	7981	14918	10886	11331	13308	4390	6572	11140	107056
1998	6293	8479	6499	2551	3885	3496	9990	9214	14610	5134	8844	5690	84685
1999	8192	4346	2768	5033	7189	22004	9477	13366	20237	18625	5593	****	124771
2000	6219	4757	7480	6935	2408	11610	13414	10642	17715	9228	4615	5864	100887
2001	5818	3206	14948	****	9240	16561	19641	15223	27116	11472	8943	****	132168
Total	36108	26119	47229	29225	36761	78115	69213	67609	98797	59101	36767	34516	**619560**

c)

	Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Mean***
1996	0.12%	0.11%	0.23%	0.25%	0.89%	1.03%	0.72%	0.70%	0.57%	0.23%	0.09%	0.10%	0.42%
1997	0.04%	0.32%	0.21%	0.34%	0.60%	0.81%	0.74%	0.70%	0.26%	0.16%	0.21%	0.18%	0.38%
1998	0.30%	0.40%	0.49%	0.71%	0.75%	1.46%	0.80%	0.79%	0.57%	0.68%	1.14%	0.19%	0.69%
1999	0.26%	0.44%	0.14%	0.81%	1.06%	0.76%	1.00%	1.00%	0.37%	0.43%	1.00%	****	0.61%
2000	0.93%	0.19%	0.31%	0.69%	0.96%	1.25%	1.97%	1.42%	1.35%	0.50%	0.46%	0.26%	0.86%
2001	0.22%	0.16%	0.27%	****	0.77%	1.07%	0.93%	0.83%	0.77%	0.43%	0.49%	****	0.59%
Mean	0.31%	0.27%	0.28%	0.56%	0.84%	1.06%	1.03%	0.91%	0.65%	0.41%	0.57%	0.15%	0.67%

With summer-time small-scale convection contributing the most to Florida's annual rainfall, it is reasonable that a greater number of gauge hours is removed during these months. It should be noted that most of these data had been quality controlled to some extent by their respective districts prior to our receipt of them. Thus, these results show our removal of data in addition to what had already been deleted by the Florida WMDs.

QC results for the 88 gauges from the SWFWMD are shown in Table 6. One should note that the SWFWMD gauges were flagged approximately ten times more often than gauges from the other Florida WMD (Table 5). This finding was very disturbing, and we became increasingly suspicious of all the SWFWMD gauge data. Even gauge hours that passed the QC criteria still could be incorrect. Therefore, we used one final method to examine the extreme differences between the SWFWMD gauge-derived observations and radar-derived estimates. Rain gauge amounts were compared to observed streamflow in the vicinity of those suspect gauges. Streamflow data in the area of selected suspect gauges confirmed our results about the apparently erroneous gauge amounts. For the cases examined, streamflow was not influenced by large gauge amounts. For example, in situations where a gauge reported a very heavy rainfall (e.g., > 3 in./h), the observed streamflow showed no corresponding increase in volume. Therefore, we concluded that those gauges had indeed reported erroneous rainfall, in agreement with our QC findings.

Table 6. QC results of a) removed gauge hours, b) rain hours, and c) percentage of removed gauge hours for the SWFWMD gauge network from 1996 through 2001. (Excluding December 1999, April and December 2001 due to missing radar data).

a)

	Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Total***
1996	2	14	24	15	18	60	41	53	34	23	2	0	286
1997	7	5	12	36	10	34	55	69	60	29	46	0	363
1998	53	69	69	7	24	26	129	93	141	16	17	0	644
1999	53	7	22	14	73	172	106	162	173	94	63	****	939
2000	22	17	27	39	11	303	337	284	214	13	30	3	1300
2001	12	7	262	****	66	346	587	249	537	60	0	****	2126
Total	149	119	416	111	202	941	1255	910	1159	235	158	3	**5658**

b)

	Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Total***
1996	545	231	659	320	419	864	564	731	515	620	111	0	5579
1997	290	236	313	734	235	471	715	626	850	549	808	32	5859
1998	705	1345	742	133	388	192	1231	956	1899	271	591	0	8453
1999	553	226	320	482	739	2715	1421	2163	2441	2221	805	****	14086
2000	1135	530	647	904	283	3411	3398	2903	3246	379	1464	475	18775
2001	1206	1056	4013	****	828	4529	6115	3726	7288	1375	680	****	30816
Total	4434	3624	6694	2573	2892	12182	13444	11105	16239	5415	4459	507	**83568**

c)

	Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Mean***
1996	0.37%	6.06%	3.64%	4.69%	4.30%	6.94%	7.27%	7.25%	6.60%	3.71%	1.80%	0.00%	4.39%
1997	2.41%	2.12%	3.83%	4.90%	4.26%	7.22%	7.69%	11.02%	7.06%	5.28%	5.69%	0.00%	5.12%
1998	7.52%	5.13%	9.30%	5.26%	6.19%	13.54%	10.48%	9.73%	7.42%	5.90%	2.88%	0.00%	6.95%
1999	9.58%	3.10%	6.88%	2.90%	9.88%	6.34%	7.46%	7.49%	7.09%	4.23%	7.83%	****	6.62%
2000	1.94%	3.21%	4.17%	4.31%	3.89%	8.88%	9.92%	9.78%	6.59%	3.43%	2.05%	0.63%	4.90%
2001	1.00%	0.66%	6.53%	****	7.97%	7.64%	9.60%	6.68%	7.37%	4.36%	0.00%	****	5.18%
Mean	3.80%	3.38%	5.73%	4.41%	6.08%	8.43%	8.74%	8.66%	7.02%	4.49%	3.37%	0.16%	5.36%

Based on these various investigations, we were tempted to delete all of the SWFWMD gauge data. However, that was not feasible because the MPE procedure requires some gauge data to calculate the radar biases. Our guiding principle was to use fewer quality gauges instead of a larger number of suspect gauges. Therefore, we devised a procedure to identify the best of the SWFWMD gauges. We ranked the 88 SWFWMD gauges by the number of times each was flagged by the QC procedure, and then performed a manual inspection of the gauge data. The objective was to establish a cutoff value for gauges to be kept versus those to be deleted. The gauges that were flagged the least were assumed to be most accurate. Unfortunately, results of the ranking did not reveal a clear distinction between "good vs. bad" gauges. Instead, the various gauges exhibited a relatively uniform increase in the number of hours that were flagged.

After an extensive analysis of the data, we decided to keep the best 30% of the reporting (operational) gauges for each particular year. The 30% threshold was chosen since it allowed the minimum number of gauges needed for MPE calculations. For example, during 1999, 73 gauges reported hourly rainfall amounts. Of these 73 gauges, the best 30% to be kept yielded 22 gauges as input to MPE. This procedure represents our attempt to make best use of what appears to be an error-laden dataset from the SWFWMD.

The OH dataset contained many gauges (~ 85%) that reported and truncated rainfall amounts to the nearest 0.10 in. (not 0.01 in.). In addressing this issue, we increased non-zero gauge amounts by 0.05 in. to minimize some of the error associated with the truncation. This is an imperfect solution to the problem. Since amounts less than 0.10 in. had been reported as 0.00 in., there was no feasible way to distinguish between hours with truly zero amounts from those less than 0.10 in. but reported as zero. After applying the 0.05 in. increase to all gauges reporting at least 0.1 in., the data were input to the QC procedure described previously. Results (not shown) indicated that the percentages of removed hours are approximately 4-5 times greater than for the Florida WMD network (Table 4c), with the greatest amounts also occurring during summer. Thus, the OH data appear to be less reliable than those from the Florida WMDs (with the exception of SWFWMD data).

4. RESULTS

4.1 Seasonal Product Comparisons

To compare and evaluate the various MPE-derived precipitation estimates, hourly grid point values were summed for each season of the study period (1996 through 2001). Warm season months consisted of April through September, while cold season months included October through March. Spatial depictions of four MPE products (RMOSAIC, GMOSAIC, BMOSAIC, and MMOSAIC) then were generated. Results for two warm seasons and one cold season are presented here.

The RMOSAIC product is derived using the best available radar for each HRAP grid point within the domain. Based on the radar masks described earlier, together with the availability of the various radars each hour, MPE assigns a radar to each 4 x 4 km^2 HRAP grid cell. An example of the four radars covering the Florida peninsula is given in Fig. 4. Once MPE assigns the proper radar to each grid cell, the various radars' DPA data are composited to produce the RMOSAIC field. The MPE procedure then continues to create the other products as described earlier.

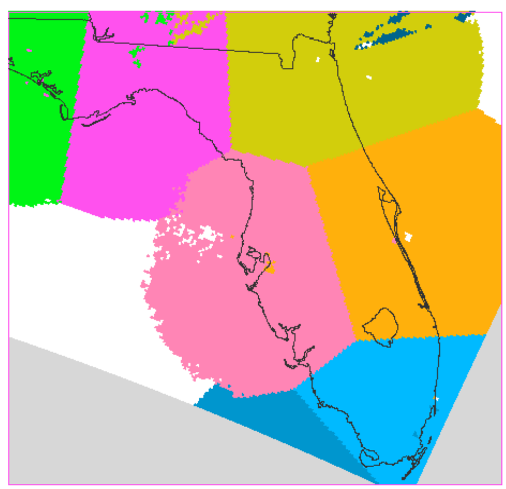


Figure 4. An example of the radar coverage areas over Florida (0100 UTC 1 January 1998).

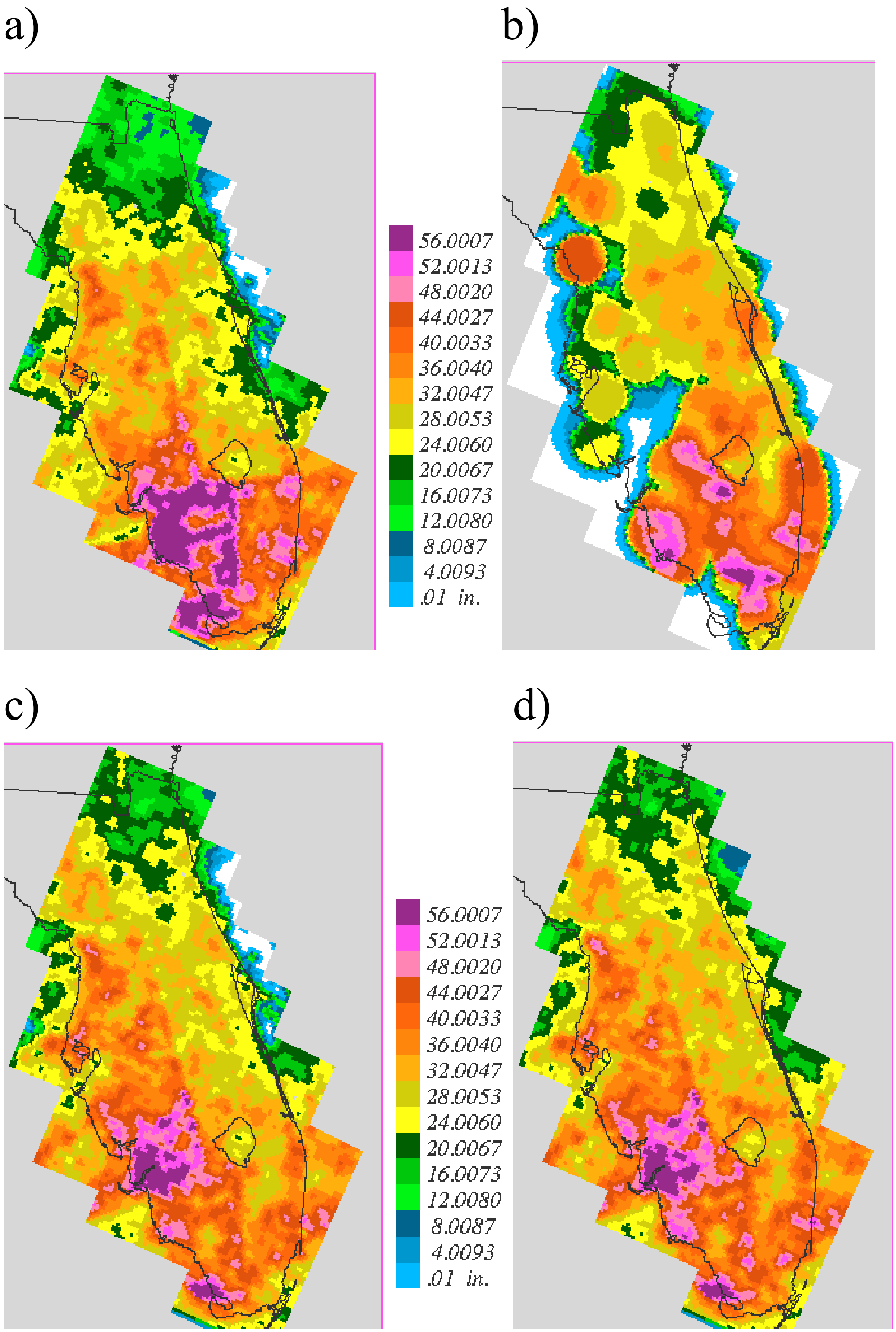


Figure 5. Rainfall totals (in.) for the period April – September 1999. The totals represent output from a) RMOSAIC, b) GMOSAIC, c) BMOSAIC, and d) MMOSAIC.

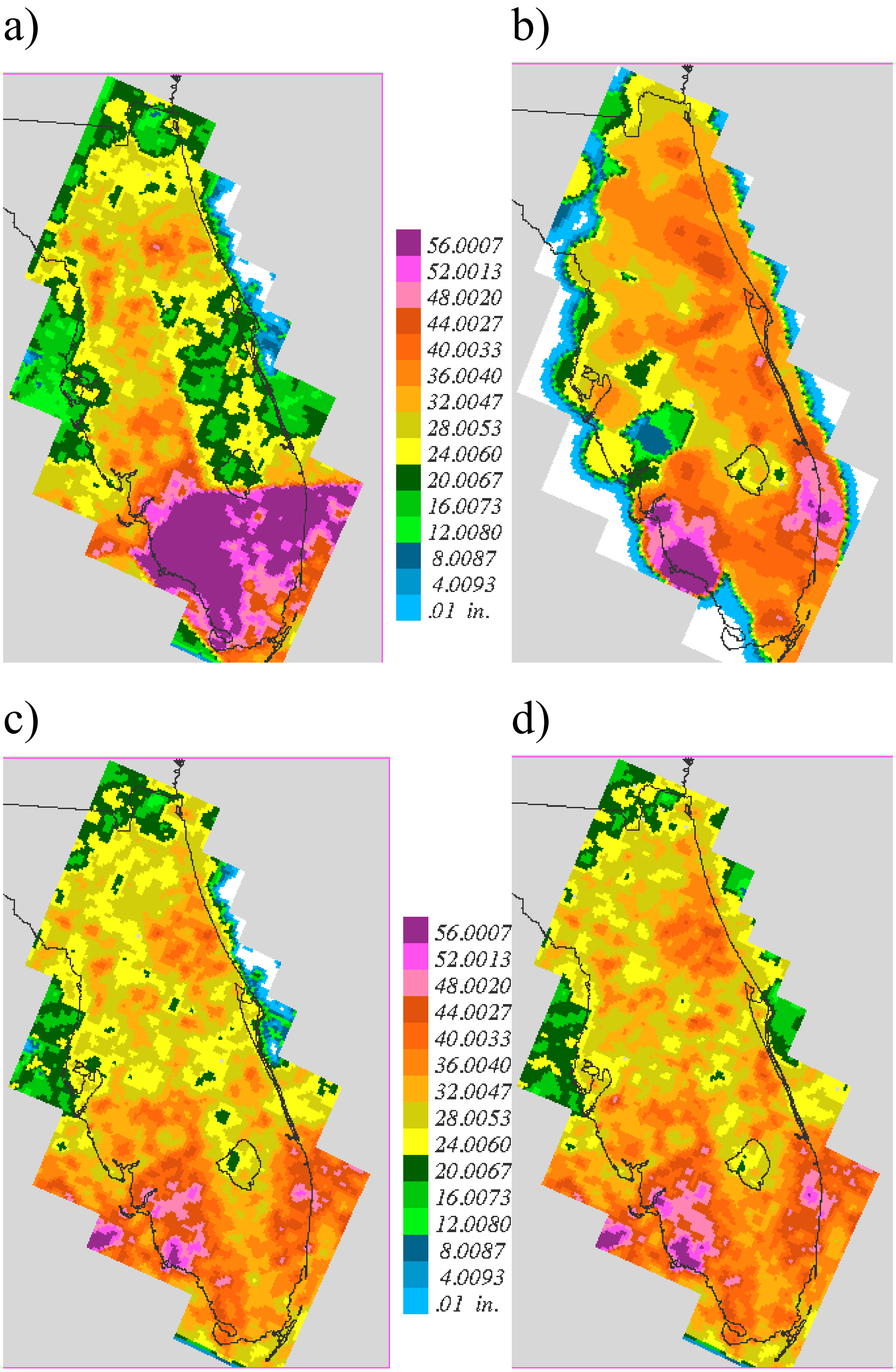


Figure 6. Rainfall totals (in.) for the period May – September 2001. The totals represent output from a) RMOSAIC, b) GMOSAIC, c) BMOSAIC, and d) MMOSAIC.

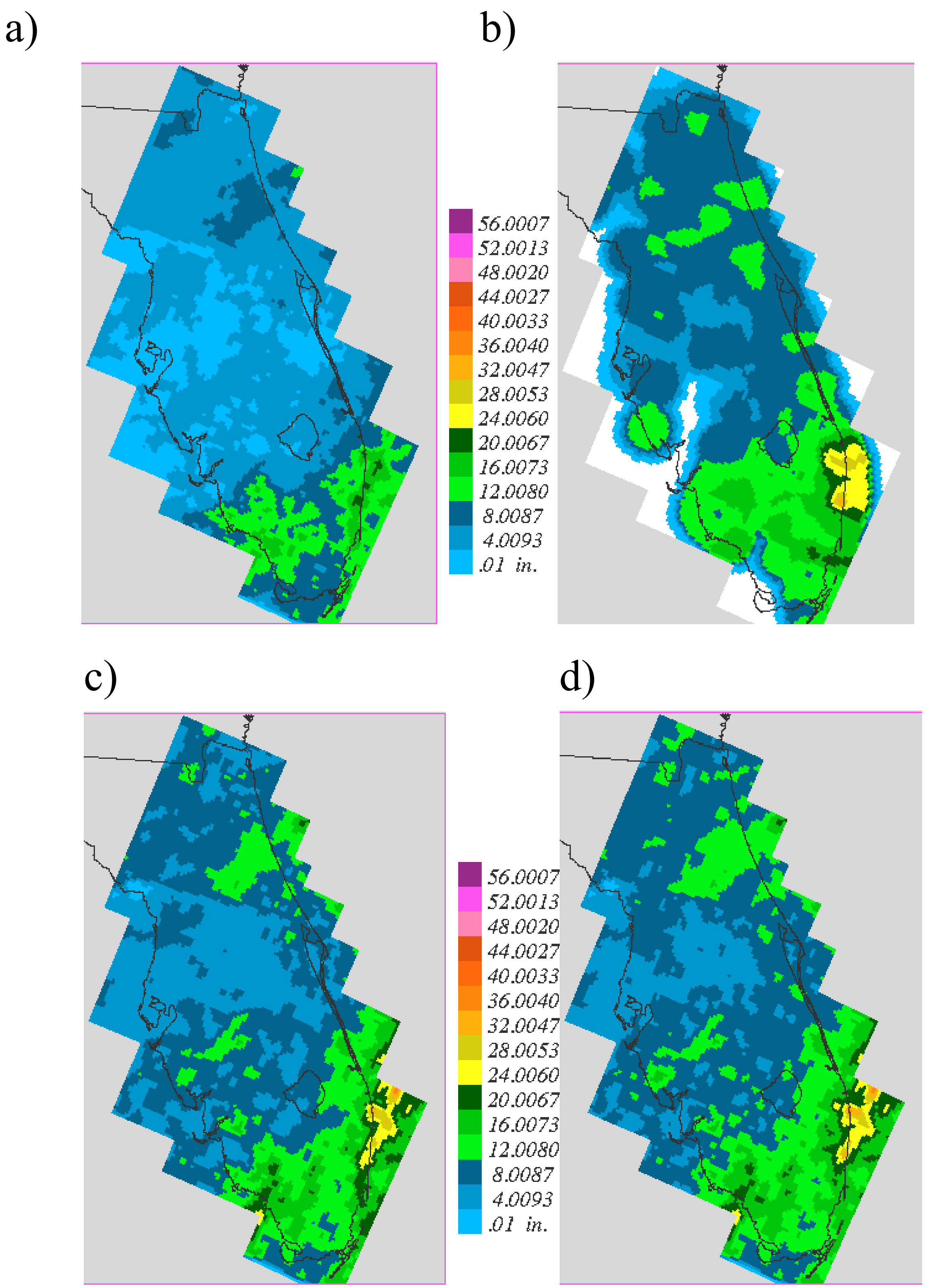


Figure 7. Rainfall totals (in.) for the period October 1998 – March 1999. The totals represent output from a) RMOSAIC, b) GMOSAIC, c) BMOSAIC, and d) MMOSAIC.

RMOSAIC fields for our period of study are shown in panels a) of Figs. 5-7. One should note the distinct lines of demarcation that are evident over the peninsula during some warm seasons (e.g., Figs. 5a and 6a). These lines correspond to boundaries in the radar index product (Fig. 4). For example, during the warm season of 2001 (Fig. 6a), the Melbourne (MLB) radar (Fig. 2) appears "cold" (underestimation of radar-derived rainfall) compared with the surrounding radars, while estimates from the Miami radar (AMX) appear too large ("hot").

Two factors appear to explain these distinct gradients between radars. One possibility involves the Z-R relationship used at each radar site. Utilizing a tropical Z-R relationship during non-tropical conditions will yield an overestimate in rainfall. Personnel at NWS-Miami confirmed that the AMX radar predominantly operated in the tropical Z-R mode during the warm season of 2001 (Fig. 6a). In addition, poor calibration at a radar site can contribute to the "lines" in the precipitation pattern. Since each radar has its own calibration, improper calibrations will yield a discontinuity at the boundaries. Although distinct lines of demarcation between radar boundaries are most clearly evident during some warm seasons, the winter season months also can exhibit this feature, but to a lesser degree. Not every old or warm season exhibits discontinuities between radars. In Fig. 7a for example, there are no distinct gradients that can be attributed to the particular radar being used. RMOSAIC shows reasonable rainfall patterns with the appropriate spatial detail.

In summary, the RMOSAIC maps provide an excellent spatial depiction of Florida rainfall; however, actual values sometimes appear suspect due to improper calibrations or Z-R relations.

The GMOSAIC product of MPE utilizes only gauges in its calculations. Since gauges generally are considered to be "ground truth", they are used in many meteorological and hydrological operations. However, an analysis of the GMOSAIC maps during the study period illustrates some of the shortcomings of using gauges alone. As noted earlier, a gauge value is assigned a certain radius of influence (ROI). Figure 5b shows individual gauge amounts being assigned to circular ROI regions in the northwestern portion of the domain where there are relatively few gauges. Conversely, the GMOSAIC field is much smoother in areas with a dense gauge network, e.g., the eastern and southern parts of the domain.

Another noticeable characteristic of the GMOSAIC field is the effective coverage area of the gauges. Although the SWFWMD maintains a dense gauge network, we were forced to delete much of their data because of the quality control issues described earlier. This effect is clearly noticeable as the bare area between Tampa and Lake Okeechobee (e.g., Fig. 5b). Although this lack of gauges affects the bias calculations in MPE, it is nonetheless better to use fewer, higher quality gauges, than more, less-quality gauges.

The warm season GMOSAIC fields show many cases where large differences exist between adjacent gauges (Fig. 5-6b). Although one could argue that suspect data had passed through our QC procedure, such patterns can be seen throughout the GMOSAIC images, suggesting that they are due to the highly variable convective rainfall.

The cold season GMOSAIC analyses exhibit a more uniform rainfall pattern than during the warm season. Despite some relatively heavy amounts in southeastern Florida (e.g., Fig. 7b), cold season rainfall typically is fairly uniform across the peninsula, with amounts generally ranging between 8 – 12 in. One should note that the GMOSAIC amounts tend to be greater than those from the radar during the cool seasons (Fig, 7a vs. Fig. 7b), probably due to the radar beam frequently overshooting the relatively low tops of stratiform clouds. A goal of the MPE procedure is to reduce these radar underestimates.

The BMOSAIC product of MPE blends the GMOSAIC and RMOSAIC products to maximize the strengths of both gauges and radars. BMOSAIC is based on a radar-wide bias for each radar that is applied to the original radar-derived (RMOSAIC) estimates, thereby removing the area-wide biases for each radar. One noticeable characteristic of BMOSAIC is its ability to greatly reduce the "hot/cold" issues contained in the original RMOSAIC fields (Figs. 5c and 6c). However, in Fig. 5c, a slight discontinuity still exists even after the bias adjustment. This line of demarcation will be described further in subsequent sections. During the cold season (Fig. 7c), values of BMOSAIC are greater than those from the RMOSAIC, showing the adjustment provided by the gauges.

The final product of MPE (MMOSAIC) incorporates gauge values (GMOSAIC) with the bias-corrected radar values (BMOSAIC) to calculate local adjustments. The c) and d) panels of Figs. 5-7 show that differences between BMOSAIC and MMOSAIC are subtle. Several adaptable parameters within MPE define the relative strengths of the input gauges and the radars, while simultaneously minimizing the adverse affects of each source alone. We rigorously tested many combinations of three key adaptable parameters within MPE--the “gauge radius of influence” (ROI), the lag-0 indicator cross-correlation, and the lag-0 conditional cross correlation. Consulting with personnel at NWS OH, they proposed modifications to the adaptable parameters to maximize the desirable effects of MPE (Seo 2004, personal communication). After implementing these changes, the final set of adaptable parameters was chosen (described earlier).

The summer 1999 period was the focus of many test runs (Fig. 5). Our goals were to achieve the most representative MPE products, and possibly to remove the line of discontinuity through central Florida. This straight “line” is evident in the RMOSAIC, BMOSAIC, and MMOSAIC maps (Figs. 5a, c, d). Since much of the SWFWMD gauge data had been deleted, the “line” is due partly to sparse gauge data being input to MPE to calculate radar-wide biases. However, the “line” also exists in the radar data (RMOSAIC, Fig. 5a), probably due to calibration issues. The demarcation was not expected in the BMOSAIC and MMOSAIC fields (Figs. 5c, d) since the MPE scheme is designed to correct the radar data with corresponding gauge data. The “line” appears to coincide with the index masks between the Tampa (TBW) and MLB radars (Fig. 4). Discussions with NWS OH personnel revealed that similar demarcation problems have been discovered in other areas of the country. They are most noticeable at longer time scales (e.g., monthly, seasonally, or yearly) (Bradberry, 2004, personal communication).

We believe that there also is some real enhancement of precipitation over central Florida during summer 1999. This is suggested by the enhanced GMOSAIC values in central Florida (Fig. 5b). On relatively light wind days, the Atlantic and Gulf Coast sea breezes often converge over the central portion of the state producing a maximum of precipitation down the spine of Florida. Thus, we believe that the north-south “line” in Fig. 5d is partly “real”, and partly due to MPE’s inability to remove all of the area-wide radar biases. This one season illustrates all of the inherent problems with gauges, radars, the MPE scheme, and even the natural variability of Florida rainfall.

MPE does an exemplary job of removing radar index lines during the warm season of 2001 (Fig. 6). RMOSAIC exhibits a sharp discontinuity between radars (Fig. 6a); however, both the BMOSAIC and MMOSAIC fields (Figs. 6c and 6d, respectively) exhibit a reasonable depiction of peninsula precipitation. Thus, the gauge corrections applied by MPE achieve their goal.

4.2 MPE Verification

To verify the MPE-derived rainfall estimates, they must be compared with an independent data source. A set of independent gauge observations was created for selected periods (May – September 1999, May – September 2001, and October – February 1998-99) to evaluate statistically the strengths and weaknesses of each product. The ten gauges comprising the independent data set were distributed throughout the Florida peninsula (Fig. 8). The ten gauges included five from the NWS OH (to the 0.01 in.), two from the SJRWMD, two from the SFWMD, and one from the SWFWMD. These gauges were removed from the original dataset, and the MPE procedure was re-run. MPE results at the sites of the ten removed gauges then were compared with the actual gauge values.

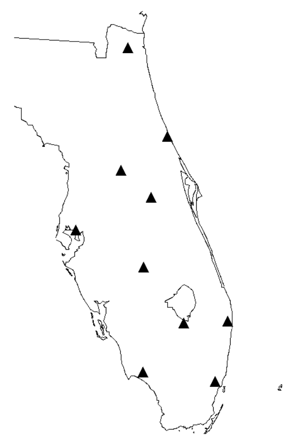


Figure 8. The ten gauges used as verification sites over the Florida peninsula.

The hourly rain gauge data that were deleted were paired with their encompassing 4 x 4 km^2 HRAP grid cells. These hourly pairs also were summed to daily and monthly totals. To be considered a pair, either a gauge or at least one of the five MPE products (MMOSAIC, RMOSAIC, etc.) must have reported rainfall (at least 0.01 in.).

Before attempting to verify the MPE products, the effects of rainfall variability and its role in producing differences between gauge accumulations and radar-derived rainfall estimates must be considered. The natural spatial (and temporal) variation of precipitation within a 4 x 4 km^2 HRAP grid cell compared to an 8-in. diameter rain gauge presents a sampling problem. Quina (2003) presented correlograms of gauge-to-gauge rainfall to define precipitation variability within the dense South Florida gauge network. The area of the SFWMD mesonetwork used for this comparison consisted of 79 gauges between 26˚ – 27˚ N and 80˚ – 81˚ W for the years 1996-2000.

Figure 9 is Quina's (2003) gauge-to-gauge correlogram of hourly precipitation values. The agreement between gauges decreases rapidly with increasing gauge-to-gauge distances, with r < 0.20 beyond 30 km. The average correlation at just 10 km is approximately 0.45. Corresponding correlograms by Young et al. (2000) for the Oklahoma mesonetwork showed an average correlation of 0.45 at a gauge separation distance of 30 – 40 km. Hence, the spatial variability of precipitation appears greater in Florida than in Oklahoma. At a gauge-to-gauge distance of only 4 km, the average correlation between two gauges is approximately 0.68 (Fig. 9). Thus, large rainfall variability is possible within even our 4 x 4 km^2 radar grid areas (Quina 2003), especially during summer, due to the convective nature of Florida's precipitation. This extreme variability makes it very difficult to evaluate 4 x 4 km^2 MPE products properly against gauge data.

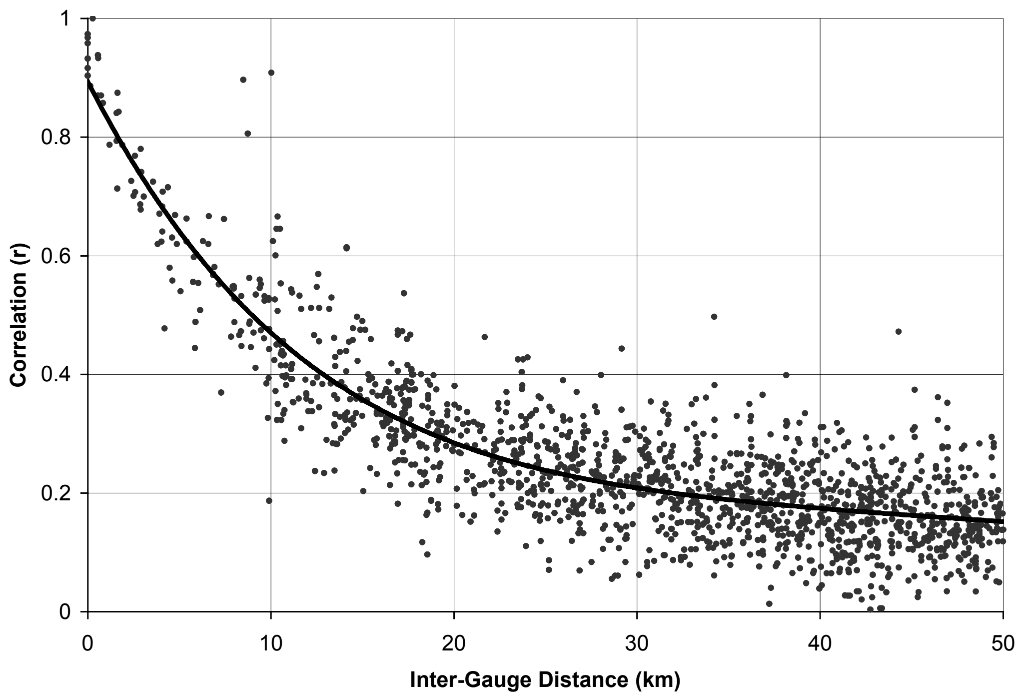


Figure 9. Correlogram of hourly precipitation totals for 1996 – 2001 gauge data. The solid line represents the least squares fit line (After Quina 2003).

4.3 Warm Season 1999

The warm season of 1999 (Fig. 5) was chosen for further investigation since it was the wettest season of the study period and since it illustrated many of the inherent problems associated with gauges, radars, the MPE scheme, and rainfall variability. It should be noted that April has been excluded from the warm season analysis. April typically is a transition month from more stratiform precipitation to a more convective type, whereas our goal was to focus on the convective aspects of Florida rainfall. Thus, the case focuses on the warm season months of May – September 1999.

Since Florida rainfall can be highly variable, evaluating hourly rather than daily or monthly sums is the most rigorous test of MPE performance. Rainfall variations tend to average out over daily or monthly periods. Comparison of the hourly MMOSAIC product with the independent gauge observations shows that the two versions of data agree reasonably well (Fig. 10a). The correlation is 0.72, with an overall seasonal bias of 0.003 in. (4.9%) between the gauges and the final MPE product (MMOSAIC), indicating a relatively small overestimation by MMOSAIC. Although the individual points generally appear well distributed on both sides of the 1 to 1 line, there is some underestimation of the larger gauge totals (e.g., gauge values > 1 in.). The RMSD for this season also shows relatively good agreement between the independent gauges and the MMOSAIC product (i.e., RMSD = 0.14 in.).

An evaluation of the daily and monthly scatter diagrams shows improved results (Figs. 10b and 10c, respectively). The underestimation of the larger gauge totals is reduced in the daily and monthly comparisons. The greater biases are attributed to larger rainfall totals when accumulating the hourly totals over the longer time periods; however, the scatter between the two will be smaller. This is evident by correlations of 0.72 and 0.94, for the hourly and monthly comparisons, respectively. On the other hand, the biases tend to increase over longer time periods, although the percent bias remains the same. Daily and monthly percent biases (4.9%) are the same as the hourly data because overall differences between MMOSAIC and the gauges are the same at any time scale. The RMSD values also increase over longer time scales (monthly value of 1.36 in. vs. 0.14 in. and 0.30 in, for the hourly and daily periods, respectively), in large part due to the increasing rainfall totals over these longer time periods.

a) Hourly Accumulations

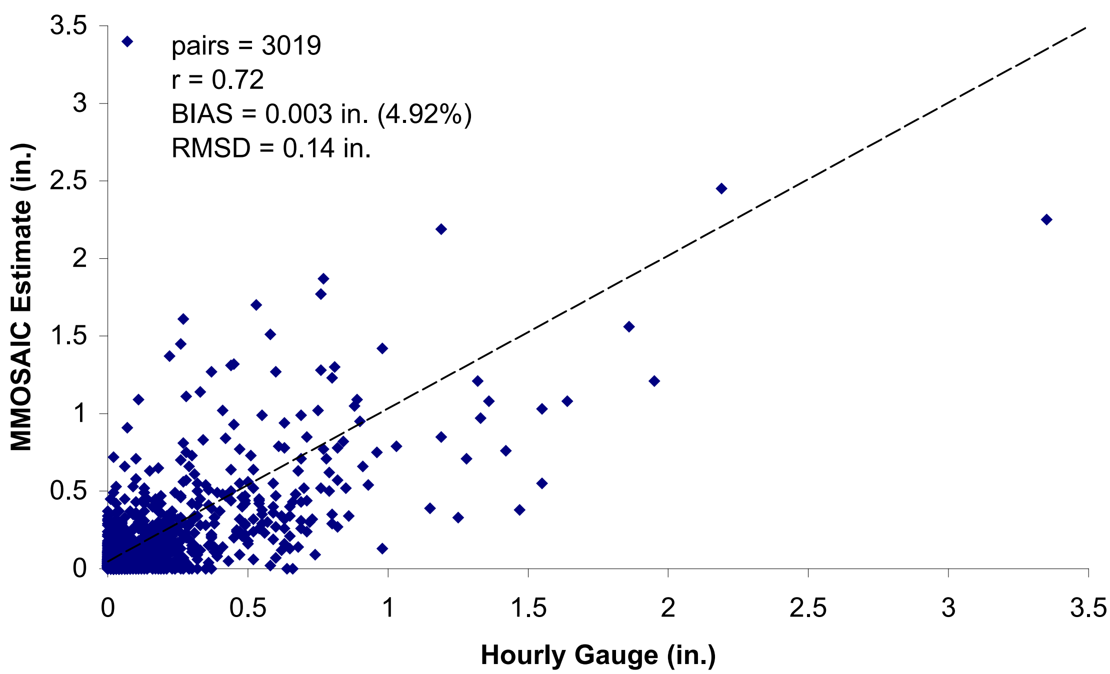
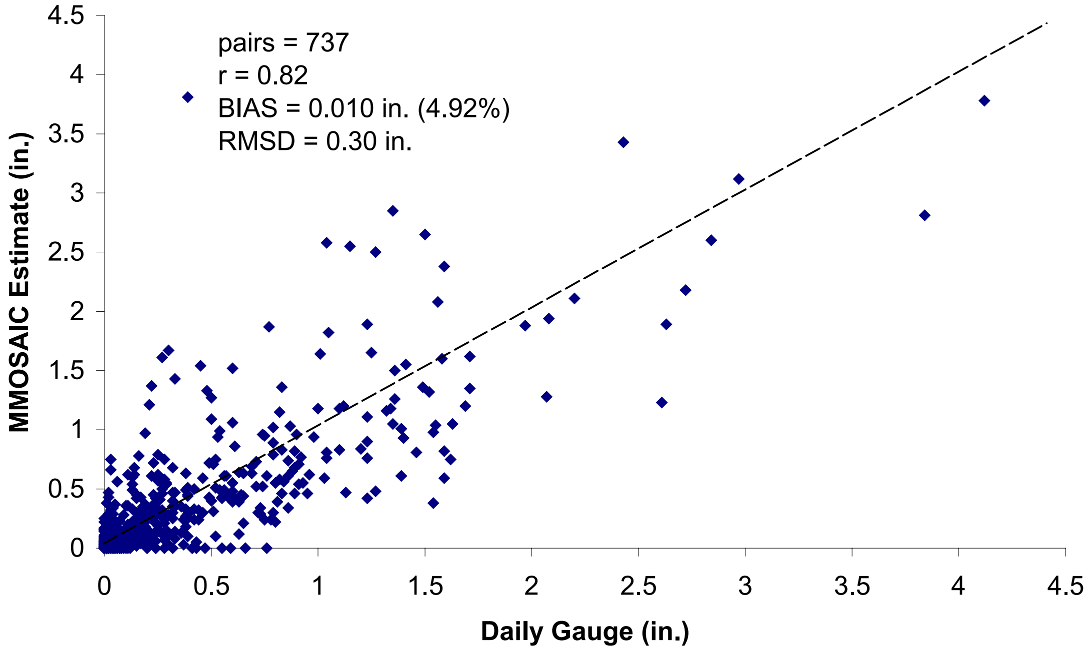


Figure 10. Scatter plot of a) hourly, b) daily, and c) monthly MMOSAIC vs. gauge amounts for ten independent gauges from May through September 1999.

b) Daily Accumulations



c) Monthly Accumulations

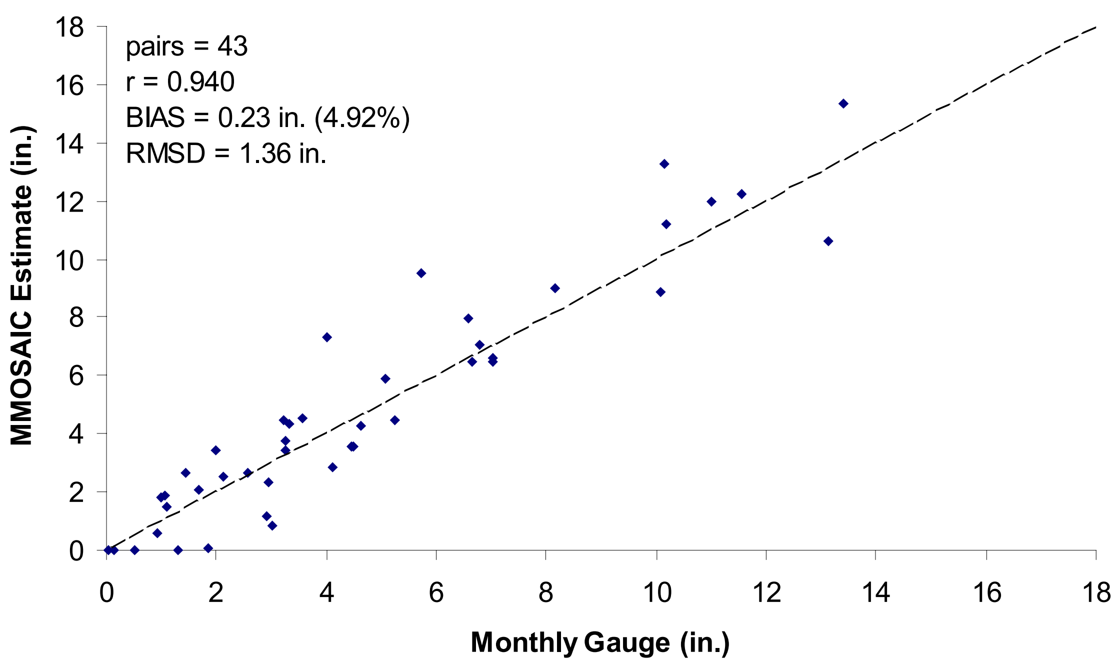


Figure 10. Continued.

Further comparisons show that the 4 x 4 km^2 MPE product underestimates the larger rainfall events (Fig. 11). The plot of gauge-minus-MMOSAIC differences versus the independent hourly gauge accumulations illustrates this underestimation for gauge accumulations greater than ~ 1 in. For values less than 1 in., there is a relatively close scatter of gauge-minus-MMOSAIC pairs about the zero line, although MPE clearly underestimates the larger rainfall events. However, one must remember that since we are comparing 8-in. gauge values to corresponding 4 x 4 km^2 grid values, MPE is expected to underestimate the larger gauge amounts. Since heavy rainfall events typically are localized, a point gauge location is not expected to represent an entire 4 x 4 km^2 grid cell. Thus, MPE appears to achieve its goals with the heavy rain events.

To quantify results of this case (May – September 1999), mean areal precipitation (MAP) was calculated for each radar area over the peninsula (Fig. 4). Table 7 illustrates differences between the four radars (e.g., Jacksonville (JAX), Melbourne (MLB), Tampa (TBW), and Miami (AMX). MAP was calculated for each of the MPE products (MMOSAIC, BMOSAIC, RMOSAIC, and BMOSAIC). Before examining these results, it should be emphasized that there is no standard for comparison. However, we consider MMOSAIC to be the most representative of area-wide rainfall. In examining average MAP over the peninsula, BMOSAIC and MMOSAIC show relatively similar results (e.g., averages of 30.26 in. and 30.48 in. for BMOSAIC and MMOSAIC, respectively). The RMOSAIC product yields the smallest average for the peninsula (29.54 in.), while the GMOSAIC field produces the greatest MAP (33.59 in.). Thus, the MAP for MMOSAIC is between the values of its two inputs (RMOSAIC and GMOSAIC).

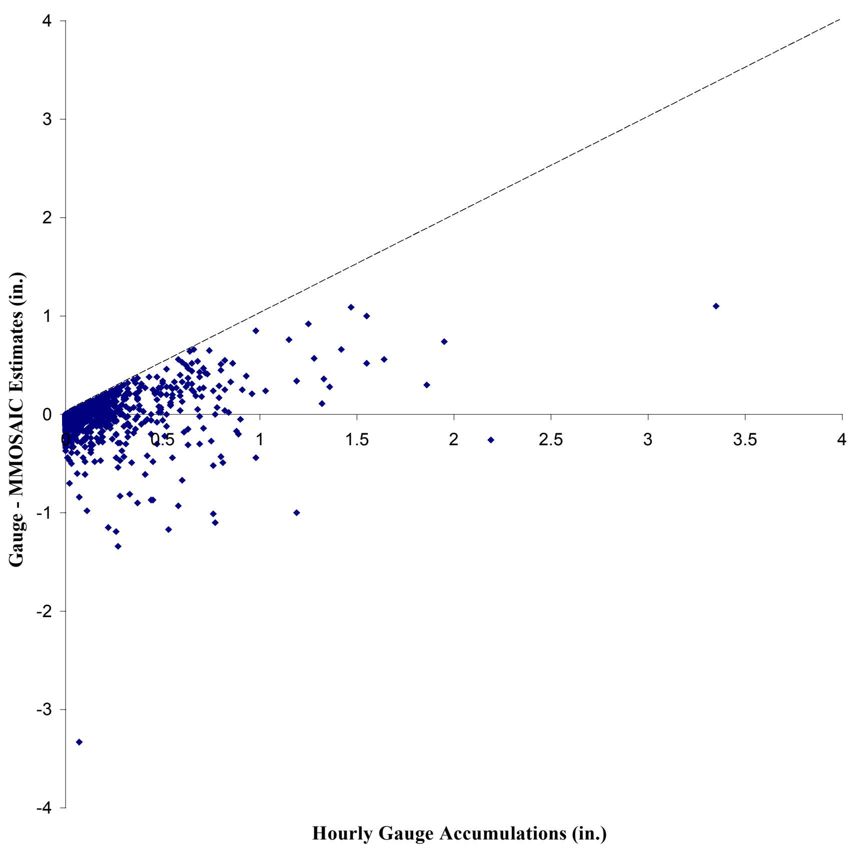


Figure 11. Gauge-minus-MMOSAIC difference vs. hourly gauge accumulations for May through September 1999.

Table 7. Mean Areal Precipitation (MAP) over the AMX, JAX, MLB, and TBW radar areas during May – September 1999 for the MPE products MMOSAIC, RMOSAIC, BMOSAIC, and GMOSAIC.

	MMOSAIC	RMOSAIC	BMOSAIC	GMOSAIC	AVERAGE
JAX	21.33 in.	17.32 in.	21.27 in.	25.58 in.	21.38 in.
MLB	28.13 in.	26.39 in.	28.17 in.	32.42 in.	28.78 in.
TBW	33.76 in.	30.00 in.	33.77 in.	33.84 in.	32.84 in.
AMX	38.69 in.	44.45 in.	37.83 in.	42.50 in.	40.87 in.
AVERAGE	30.48 in.	29.54 in.	30.26 in.	33.59 in.	*30.97 in.*

4.4 Quality Controlled vs. Original Gauge Comparisons

It is important to determine the impact of our gauge quality control procedures within MPE. Therefore, the same period (May – September 1999) was evaluated using the original dataset provided by the Florida WMDs and the NWS OH, i.e., before our quality control. The same methodology explained previously was used, the only difference being the data input to MPE. Figures 10 and 12 show a marked difference between the runs utilizing the quality controlled data and the original data. Hourly MMOSAIC based on the raw gauge data exhibits a positive bias of 0.020 in. (29.3%) (Fig. 12a). This represents a six-fold percentage increase over the bias of the quality-controlled data (bias = 0.003 in., 4.92%) (Fig. 10a). The correlations also are notably lower for the raw data (0.50 vs. 0.72) compared with the quality-controlled data. Even the longer time periods show poorer quality output from MPE using these original data (Fig. 12b and c). For example, there is greater scatter with the raw data (r = 0.64 and 0.80 for the raw vs. 0.82 and 0.94 for the quality controlled data, for daily and monthly time scales, respectively). The biases also are considerably greater for these longer time periods. The raw gauge data exhibit biases of 0.08 in. and 1.47 in.; while the quality controlled gauge data have biases of 0.01 in. and 0.23 in. for daily and monthly values, respectively.

Figure 12 illustrates the importance of utilizing accurate gauge data in the MPE procedure. Our objective QC procedure eliminated many gauge errors that would have corrupted the bias calculations. If no QC analysis had been performed on the gauge data, results of the case study would take the form of those in Fig. 12--an undesirable outcome.

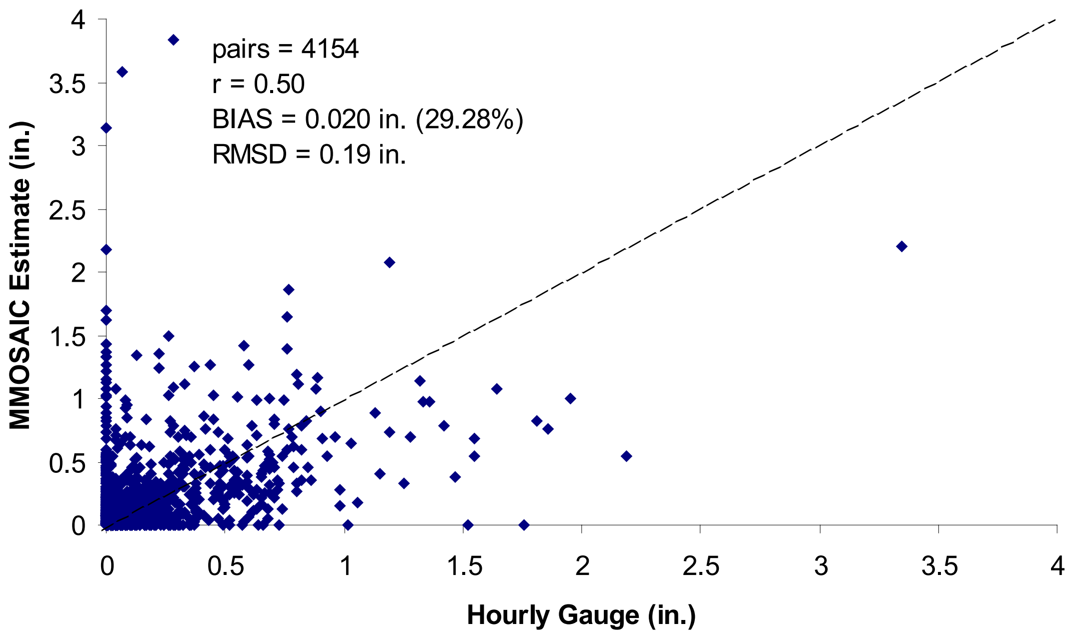
4.5 Warm Season 2001

The analysis of the May – September 2001 warm season (Fig. 13) generally shows similar results to those of the previously described 1999 period (Fig. 10). An important difference between the two warm seasons is the change in hourly bias values (Fig. 13a). The bias during 2001 is greater and now shows an underestimation instead of the overestimation seen in 1999 (Fig. 10). Specifically, the hourly MMOSAIC bias is -0.01 in. (-12.2%). However, correlations between the independent gauge observations and MMOSAIC remain high (e.g., r = 0.75) compared with the 1999 case (r = 0.72) (Fig. 10). Also, compared with the 1999 case, the RMSD remains the same at 0.14 in.

Evaluating the MMOSAIC product against the independent gauge observations at longer time scales produces similar results (Figs. 13b and c). The MMOSAIC product is well correlated with the gauges (r = 0.90 and 0.94 for daily and monthly accumulations, respectively); however, the biases are consistently greater and negative than during the 1999 warm season case (i.e., -0.04 in. and -0.82 in. for the daily and monthly biases, respectively). Also greater is the RMSD for the monthly time scale (i.e., 1.81 in.), while the daily RMSD for both cases remains at 0.30 in. Further examination of the underestimation by the hourly MMOSAIC product is seen in Fig. 14. The underestimate of large gauge totals noted during the 1999 warm season (Fig. 11) also is clearly visible during 2001. However, following the same reasoning described previously, some underestimate is expected since the heavier rainfall events at point locations generally do not represent rainfall over a much larger area.

MAP again was calculated for each of the peninsula radars (Table 8). Not surprisingly based on Fig. 6a, the RMOSAIC MAP over the Miami radar coverage area (AMX) is almost 20 in. greater than its MMOSAIC counterpart. The GMOSAIC product again produces the largest area-averaged amount (i.e., 37.49 in.) when compared with the other products. MMOSAIC MAP yields smaller average MAP than both the GMOSAIC and RMOSAIC (i.e., 32.91 in. vs. 37.49 in. and 33.39 in., respectively).

a) Hourly Accumulations



b) Daily Accumulations

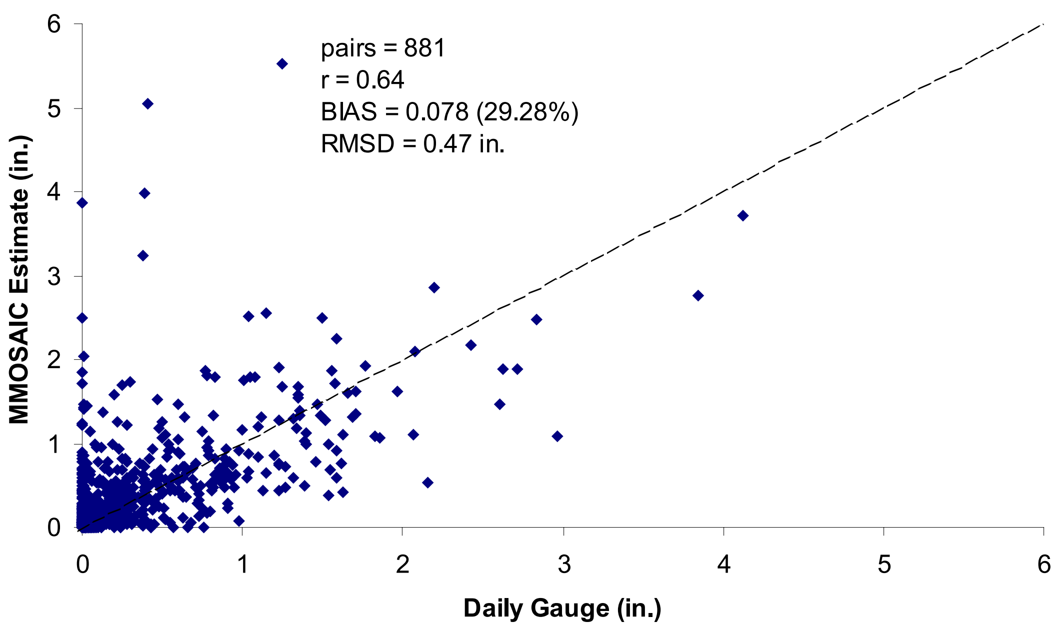


Figure 12. Scatter plots of a) hourly, b) daily, and c) monthly MMOSAIC vs. gauge amounts for ten independent gauges from May through September 1999 using Raw Gauge Data.

c) Monthly Accumulations

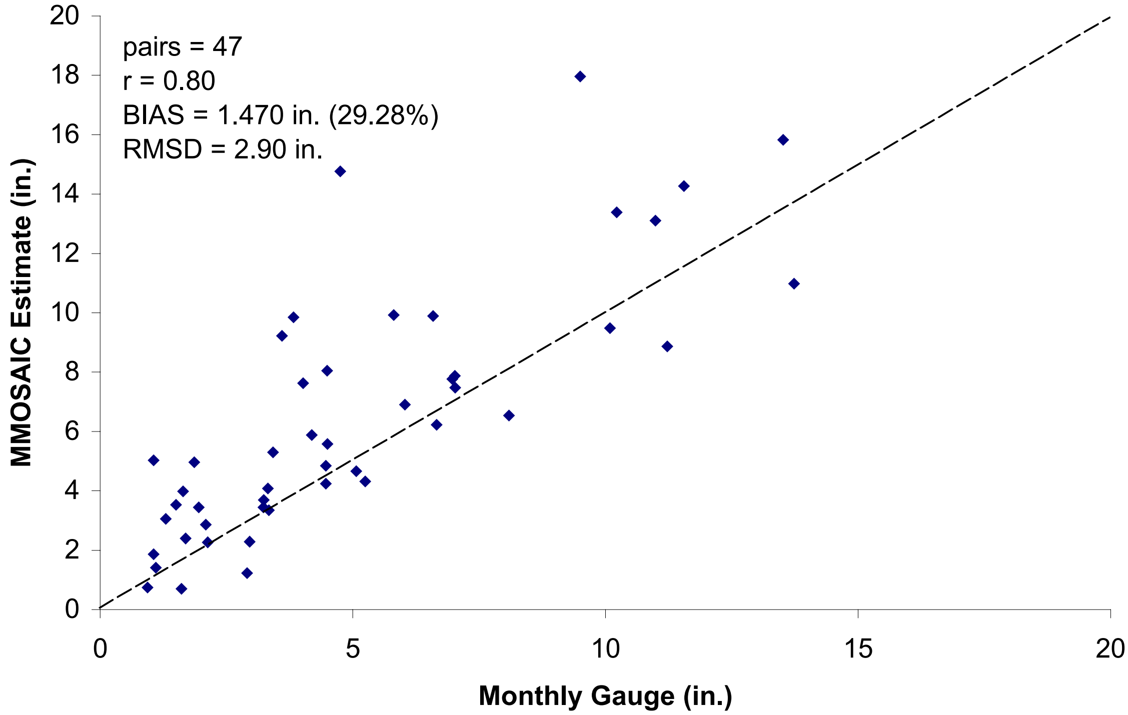
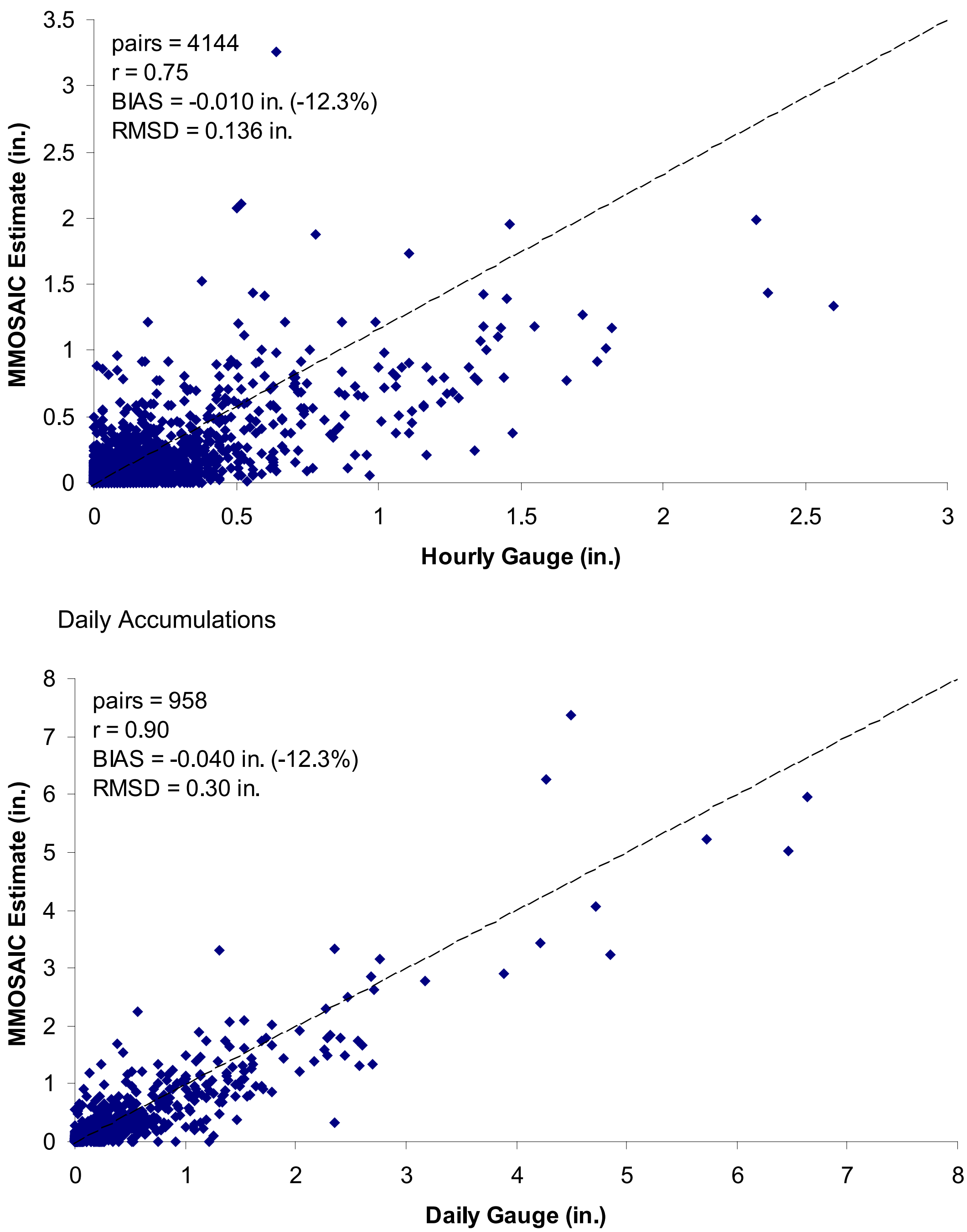


Figure 12. Continued.

a) Hourly Accumulations



b) Daily Accumulations

Figure 13. Scatter plots of a) hourly, b) daily, and c) monthly MMOSAIC vs. gauge amounts for ten independent gauges from May through September 2001.

c) Monthly Accumulations

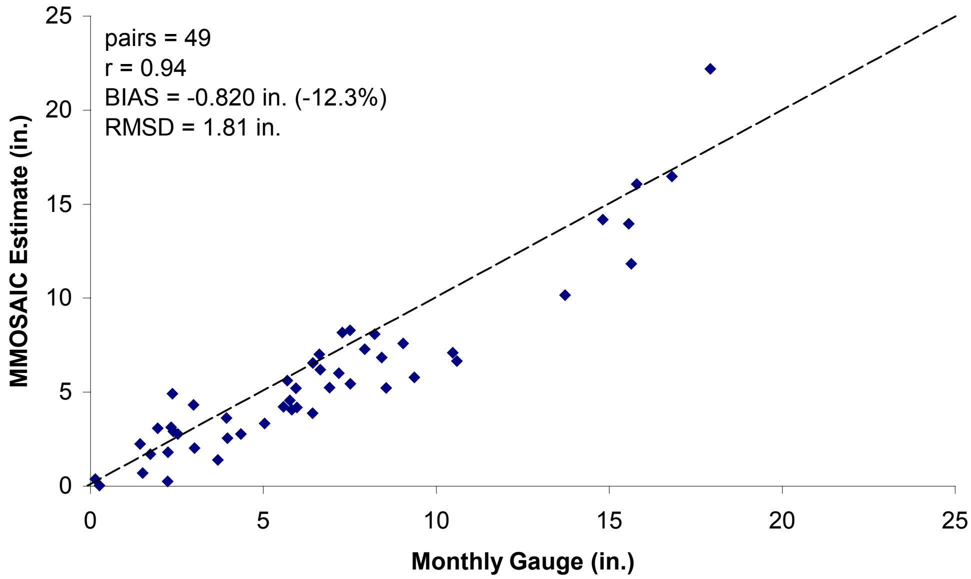


Figure 13. Continued.

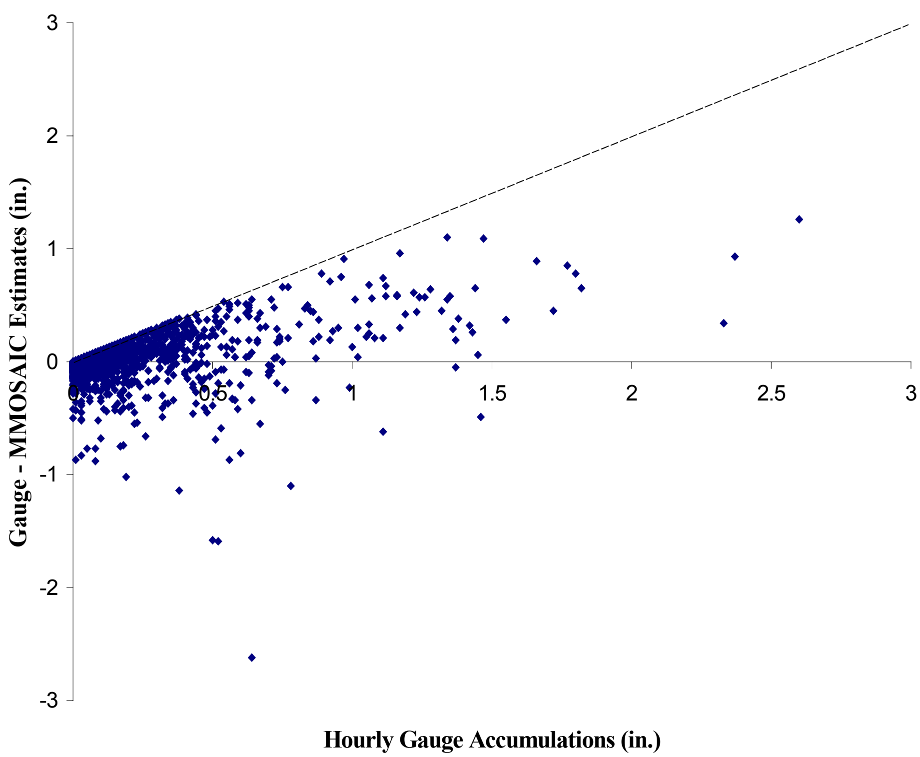


Figure 14. Gauge-minus-MMOSAIC difference vs. hourly gauge accumulations for May through September 2001.

Table 8. Mean Areal Precipitation (MAP) over the AMX, JAX, MLB, and TBW radar areas during May – September 2001 for the MPE products MMOSAIC, RMOSAIC, BMOSAIC, and GMOSAIC.

	MMOSAIC	RMOSAIC	BMOSAIC	GMOSAIC	AVERAGE
JAX	25.78 in.	22.59 in.	24.97 in.	33.74 in.	26.77 in.
MLB	33.86 in.	24.29 in.	33.69 in.	37.11 in.	32.24 in.
TBW	32.28 in.	29.48 in.	31.93 in.	34.27 in.	31.99 in.
AMX	39.71 in.	57.18 in.	38.68 in.	44.84 in.	45.10 in.
AVERAGE	32.91 in.	33.39 in.	32.32 in.	37.49 in.	*34.03 in.*

4.6 Cold Season 1998-99

The cold season of October through February 1998-99 also was evaluated. Figure 15 shows relatively good agreement between the MMOSAIC hourly product and the ten independent gauge observations. Correlations are higher for this case (r = 0.86) than during the two warm season cases (Figs. 10 and 13). The bias is -0.005 in. (-8.1%). Gauges are expected to represent area-wide rainfall conditions better during the cold season's relatively uniform stratiform type precipitation, compared to the convective warm season, and GMOSAIC's noticeably smaller biases (0.004 in. (6.6%) vs. 0.012 in. (19.3%) avg. of two warm seasons, not shown) are consistent with that assumption. In addition, many studies have shown that radars can overshoot the relatively low echo tops of stratiform type precipitation, therefore completely missing many of the cold season rainfall events (Doviak 1983; Austin 1987; Baeck and Smith 1998; Fo et al. 1998; and Fulton et al. 1998).

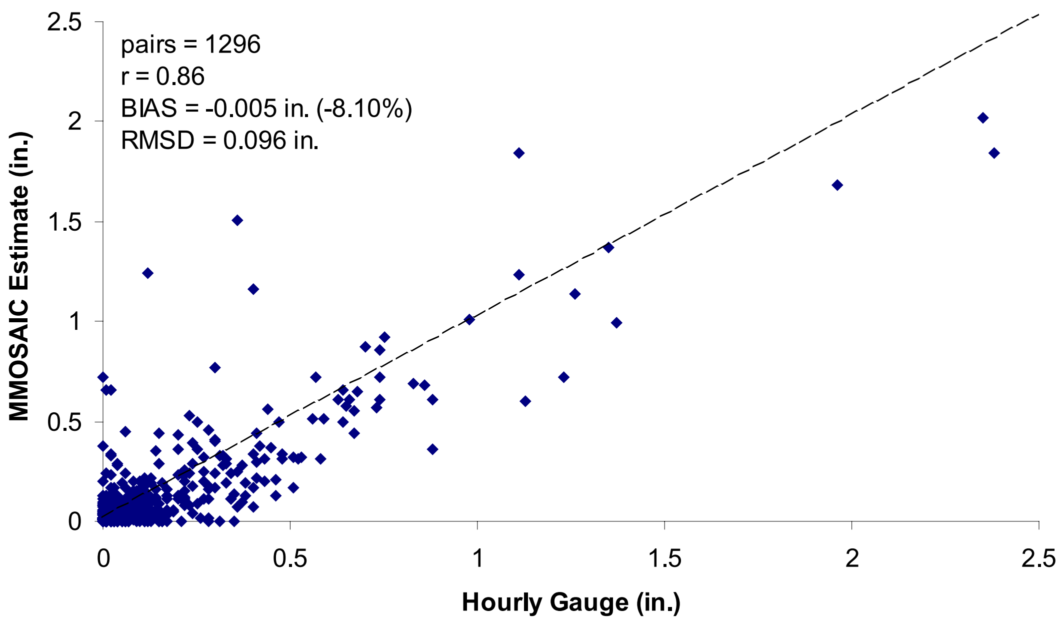
Examination of longer time scales also shows good results. Both daily and monthly MMOSAIC values correlate with the independent gauges at 0.96 (Fig. 15b and c). Biases are relatively smaller than during the warm season months (Figs. 10 and 13) with cold season biases of -0.02 in. (8.1%) and -0.17 in. (8.1%) for daily and monthly time scales, respectively. Not surprisingly, the RMSD increases over longer time periods, but is still smaller than during the warm seasons (i.e., monthly RMSD of 0.77 in. for the cold season vs. an average warm season monthly RMSD of ~ 1.60 in.).

There is little underestimation of the larger rainfall amounts during the cold season. Figure 16 shows more points about the zero line than during the warm season (Figs. 11 and 14). This improved estimate of larger amounts probably is due to the more widespread nature of cold season precipitation. Thus, gauge amounts are more representative of the 4 x 4 km^2 radar (HRAP) areas during the cold season.

MAP calculations for this period are shown in Table 9. In contrast to the warm season months (Tables 7 and 8), MMOSAIC yields the largest amounts of the products (12.00 in.). Conversely, RMOSAIC produces the smallest values (7.57 in.). This is likely due to the radars tending to overshoot the low, more widespread stratiform precipitation. This suggests that less confidence be given to the RMOSAIC product during cold season events. Conversely, gauges typically represent widespread precipitation quite well, and therefore have been assigned more weight by the adaptable parameters during stratiform precipitation than during convective precipitation (Section 2). The fact that GMOSAIC and MMOSAIC differ only slightly (i.e., 11.64 in. and 12.00 in., respectively) is evidence of that different weighting.

In summary, MPE appears to perform better during the cold season than the two warm seasons described earlier. However, as noted earlier, some of the disagreement between gauges and MPE values is attributable to the different sampling areas of gauges vs. radars. This aspect is less pronounced during the often-widespread precipitation of the cold season.

a) Hourly Accumulations



b) Daily Accumulations

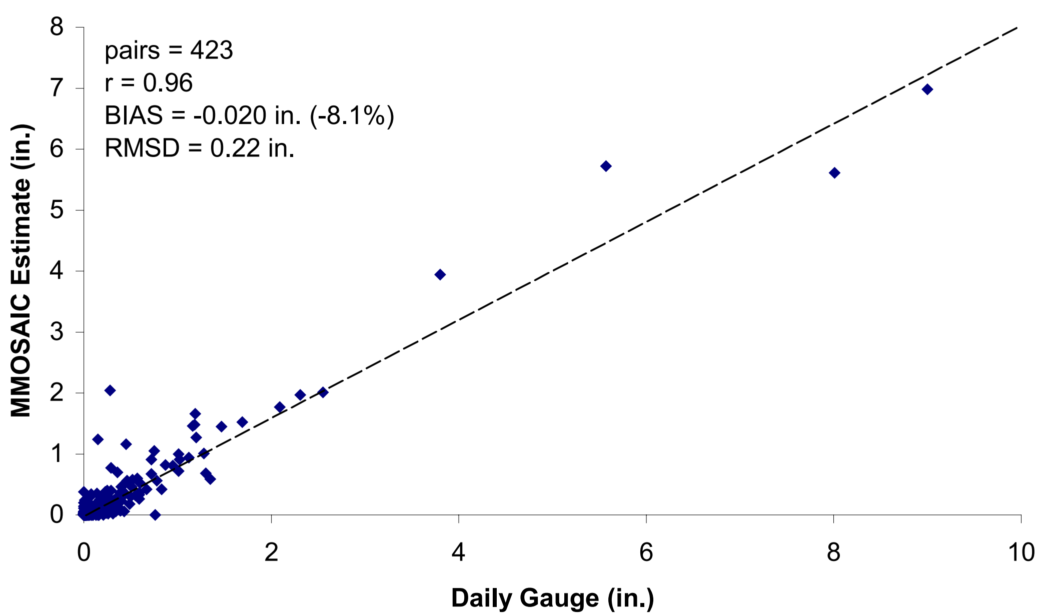


Figure 15. Scatter plots of a) hourly, b) daily, and c) monthly MMOSAIC vs. gauge amounts for ten independent gauges from October through February 1998-1999.

c) Monthly Accumulations

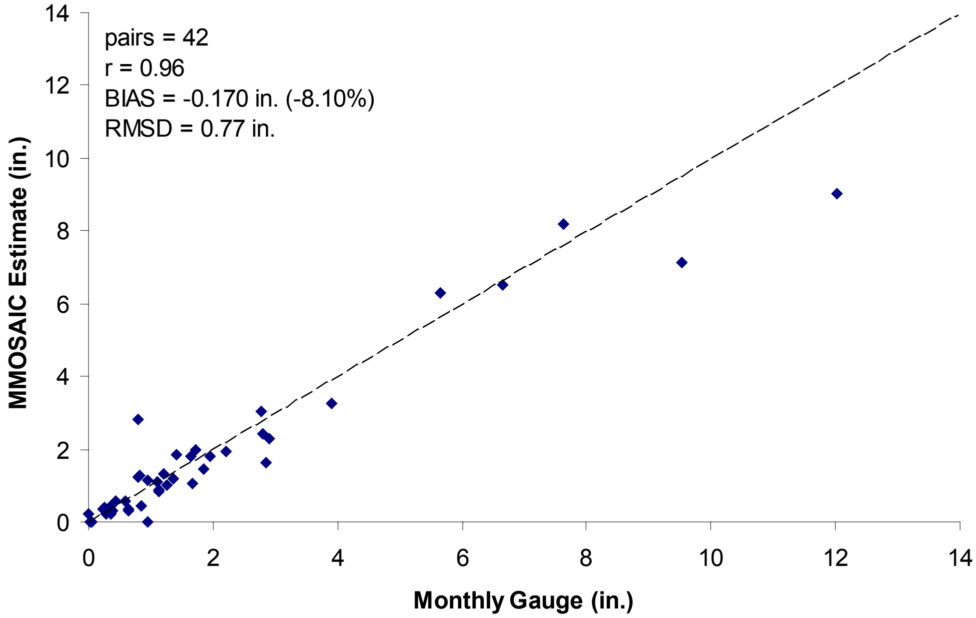


Figure 15. Continued.

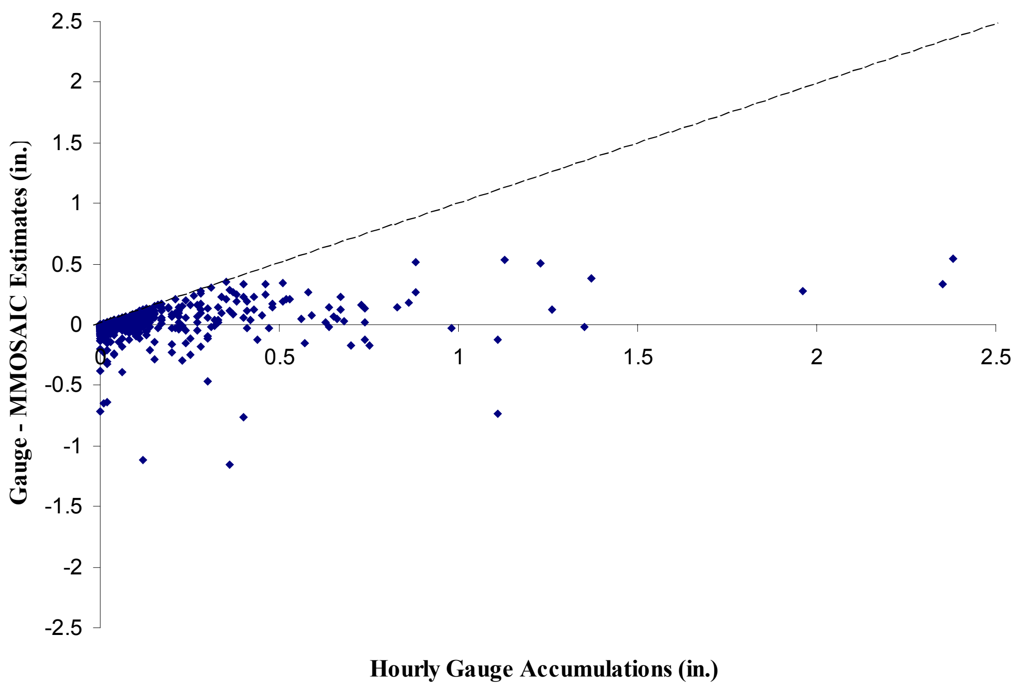


Figure 16. Gauge-minus-MMOSAIC difference vs. hourly gauge accumulations for October through February 1998-99.

Table 9. Mean Areal Precipitation (MAP) over the AMX, JAX, MLB, and TBW radar areas during October – February 1998-99 for the MPE products MMOSAIC, RMOSAIC, BMOSAIC, and GMOSAIC.

MAP	MMOSAIC	RMOSAIC	BMOSAIC	GMOSAIC	AVERAGE
JAX	10.89 in.	7.05 in.	10.58 in.	9.95 in.	9.62 in.
MLB	14.71 in.	7.71 in.	14.25 in.	10.32 in.	11.75 in.
TBW	6.93 in.	3.58 in.	6.70 in.	9.83 in.	6.76 in.
AMX	15.50 in.	11.92 in.	15.11 in.	16.46 in.	14.75 in.
AVERAGE	12.00 in.	7.57 in.	11.66 in.	11.64 in.	*10.72 in.*

5. SUMMARY AND CONCLUSIONS

A high-resolution historical precipitation dataset for 1996 through 2001 has been developed for the Florida peninsula. The Multisensor Precipitation Estimator (MPE) software from the National Weather Service (NWS) was used to combine the relative strengths of radar- and gauge-derived precipitation, while lessening the inherent limitations of each. The gauge accuracy at a point is blended with the spatial details provided by the radar.

A dense network of rain gauge data (675 gauges) was provided by the five Florida Water Management Districts (WMDs). In addition, the NWS Office of Hydrology (OH) contributed data from an additional 48 gauges. Radar-derived precipitation data were from the Weather Surveillance Radar 1988 Doppler (WSR-88D). The Digital Precipitation Array (DPA) that is output from the WSR-88D consisted of hourly rainfall estimates over the Southeast River Forecast Center's (SERFC) area of responsibility (28 radars), and were mapped to the 4 x 4 km^2 Hydrologic Rainfall Analysis Project (HRAP) grid array.

A major component of the study was to develop rigorous quality control (QC) procedures for the rain gauge data. Our objective QC procedure compared rain gauge observations with their encompassing 4 x 4 km^2 radar-derived grid value. To the authors' knowledge, this is the first such attempt described in the literature. The QC procedure consisted of four main scenarios that considered all possible combinations of gauge (G) and radar (R) amounts. These four scenarios were 1) $R = 0$, $G > 0$; 2) $R = 0$, $G = 0$; 3) $R > 0$, $G > 0$; and 4) $R > 0$, $G \approx 0$. As part of Steps 1 and 3, radar-derived comparisons were extended outward to include the surrounding eight 4 x 4 km^2 grid cells. This accounted for gauge placement and precipitation movement issues within an HRAP grid box that could produce large differences between gauge- and radar-derived values.

One of the inherent problems with any QC procedure (or any precipitation analysis) is that rainfall at a point only represents that location and not necessarily a larger area. For example, when 8 in. diameter gauge values are compared to 4 x 4 km^2 radar values, the difference in area is over one million times. Correlograms by Quina (2003) revealed hourly correlations to be approximately 0.7 at inter-gauge distances of only 4 km. Based on these sampling issues, the QC procedure was designed to remove only those gauges with the largest differences with the encompassing radar-derived value.

The QC procedure removed approximately 1% of the Florida WMD gauge data and about 3-4% of the NWS OH gauge data. Gauge data from some of the WMDs appeared superior to those from others. Although these amounts may not seem to justify such an extensive effort, bias calculations in the MPE scheme were found to be severely corrupted when the QC was not performed. Careful inspection of the removed data revealed many instances when the gauge reported a very heavy rainfall amount (> 1 in./h), while the encompassing radar-derived value (and the surrounding eight radar-derived values) reported nothing. However, most of the removed gauge data occurred when the radar reported a heavy rainfall amount (> 1 in./h), while the gauge within that same grid cell reported a near zero value. Although this situation could occur, these values did not appear representative of the area-wide rainfall. There is no perfect way to assess the quality of rainfall amounts accurately; however, the gauge hours retained through the QC procedure are considered to be the best product available.

The gauge product resulting from the QC procedure, together with the radar data, were input to the MPE scheme to develop the high-resolution precipitation database over the Florida peninsula. MPE requires that numerous adaptable parameters be selected to maximize its performance optimally. These parameters can vary regionally, temporally, and throughout the course of a storm. Extensive sensitivity testing determined the optimum choice of parameters.

Images of seasonal totals were created to evaluate the four different precipitation products produced by MPE. These products included a gauge-only optimal estimation scheme (GMOSAIC), a radar-only scheme (RMOSAIC), a radar-wide bias adjustment scheme (BMOSAIC), and the final multisensor product (MMOSAIC). Many of the inherent problems of gauges and radar were illustrated with these seasonal images.

In some of the RMOSAIC images, lines of demarcation were evident that coincided with the effective radar coverage areas (masks) that were calculated by MPE. The lines corresponded to situations when a particular radar appeared “hot/cold” (over/underestimated rainfall). Improper radar calibration in conjunction with the Z-R relationship being used likely caused these “lines” between radar areas. Nonetheless, the RMOSAIC patterns contained intricate spatial details about the variability of Florida rainfall.

The GMOSAIC fields showed the effects of having gauge networks of varying density across the peninsula. The GMOSAIC analyses also revealed the highly variable nature of Florida rainfall.

The bias-adjusted BMOSAIC fields considerably reduced the lines of demarcation evident in the RMOSAIC images, while maintaining high spatial detail. Thus, BMOSAIC was successful in reducing most radar-wide biases.

The final MPE product, MMOSAIC, was similar to the BMOSAIC analysis. However, subtle differences did exist since local adjustments were made during the calculations. In summary, the MPE procedure appeared to perform as designed, utilizing the strengths of point accurate gauge data and the spatial detail of radar data to produce an analysis that is superior to each input alone.

To evaluate the performance of the MPE final product statistically, the MMOSAIC 4 x 4 km^2 values were compared against independent verification gauges (not used in the original product calculations) for selected cases during 1999 and 2001. Ten gauges over the peninsula were removed to create this independent dataset. MPE’s 4 x 4 km^2 values at the removed gauges were compared with these gauge values; hourly, daily, and monthly comparisons were made.

In the May through September 1999 case, there was generally good agreement between the MMOSAIC estimates and the independent gauges (i.e., r = 0.72, bias = 0.003 in. (4.9%), and RMSD = 0.14 in.). These results compared favorably with those from a second case (May – September 2001), yielding similar correlation and RMSD values. However, the bias became an underestimate (i.e., r = 0.75, RMSD = 0.14 in., and bias = -0.010 in. (-12.3%)). These hourly comparisons are the most severe test of the MPE procedure. An examination of longer time scales (e.g., daily and monthly totals) for both warm seasons showed even closer agreement between the gauges and MMOSAIC. During heavy rain events, MMOSAIC values generally were less than those from the gauges. However, this is expected since heavy rain events often are localized, i.e., not uniform over a 4 x 4 km^2 area.

Analysis of a cold season period (October – February 1998-99) revealed a stronger statistical relation between the MPE final product and the independent gauges than during the warm season (i.e., r = 0.86, bias = -0.005 in. (-8.10%), and RMSD = 0.096 in.). Values of mean areal precipitation (MAP) over the Florida peninsula showed that RMOSAIC severely underestimated the gauge-derived values. This occurred because radars typically overshoot the low echo tops of stratiform rain, and hence often underestimate area-wide rainfall. Conversely, gauges are expected to detect this more uniform, stratiform type of precipitation. The MMOSAIC product was a major improvement over the radars during this cold season.

The impact of the QC procedure on the MPE products was investigated during the warm season of 1999 (May – September) by rerunning the MPE software using the original raw gauge data before quality control. Results showed a six-fold increase in the hourly bias percentages of MMOSAIC for the quality-controlled data vs. raw original data (i.e., bias = 29.28% vs. 4.92%). Thus, if the erroneous (unrepresentative) gauge data had not been removed, the bias calculations and resulting MPE products would have been severely corrupted.

This study emphasizes the need for extensive quality control of all input gauge data before any analysis. Performing quality assurance on input data will ensure maximum efficiency of the MPE procedure. The objective QC procedure described here is not a perfect scheme; however, it appears to detect those gauges that are most likely erroneous. As noted by Steiner et al. (1999), quality control of all data is the single most important step of any precipitation analysis. Although MPE is state of the art software, quality input data must be provided to ensure success!

Further research on this high-resolution historical rainfall dataset will extend the coverage to North Florida and the panhandle and to those parts of Georgia and Alabama whose waters ultimately pass through North Florida. The period of record will be extended through 2004. In addition, we beginning to use the dataset in various hydrologic studies of the area.

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