Validation of NWS Stage IV Multi-Sensor Precipitation Estimates (MPE) in the Mid-Atlantic Region

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Abstract

Multi-Sensor Precipitation Estimates (MPE) is a regional multi-sensor hourly surface rainfall product that was developed for input into hydrologic forecast models and decision-making systems for river forecasting, flood and flash flood warning, and other hydrologic monitoring purposes. MPE result from merging operational radar, automated gauge, and Geo-stationary satellite rainfall estimates following quality control and bias adjustment. MPE are superimposed over a nominal grid size of 4 square kilometers termed Hydrologic Rainfall Analysis Project (HRAP). Stage IV is a final stage term used to describe nationwide mosaicking of manually-edited, regional MPE products produced by each of River Forecast Center (RFC) on an hourly basis. Stage IV is a readily available operational product which makes it attractive to validate various satellite rainfall estimates including NASA's Tropical

Rainfall Measuring Mission (TRMM) multi-sensor precipitation analysis. Prior to the use of Stage IV as a validation product, the accuracy of Stage IV products should be validated with independent observations. In that regard, this study compares Stage IV rainfall with a rain gauge network that was located in Eastern Virginia, Delmarva, and northeast North Carolina. The rain gauge network consisted of 28 sites where each site had dual or triple gauges. Interestingly, three-fourths of the sites were at the coast. In fact, one-fourth of the sites were located at Wallops Island, Virginia where the maximum site spacing was approximately 6 km. As a result, two MPE pixels each had three gauge sites at Wallops Island, while the rest of the MPE pixels had only a single gauge site. The gauges were operated by the TRMM satellite validation office during 2004-2007 and were not in included in Stage IV. Each site was in operation at least one year and quality control of the gauges has been completed as part of this and previous study. A rainfall statistical package including correlation coefficients and biases were run between gauge and MPE rainfall for one-, three-, and six-hour, daily and monthly time scales. The statistical package was also applied between gauges and neighboring eight MPE pixels, and between the nine MPE pixels themselves. The results indicate that agreement between MPE and gauge rainfall is reasonable at a given site on an hourly basis, and agreements between the two increase with increasing integration time scale. Several thresholds were also applied to the gauge rain totals to emphasize higher rain totals which are significant in hydrological applications. Based on our knowledge, the evaluation of Stage IV or previous versions (Stage I, II, III) has been done at other locations, but not in a coastal area and where rainfall can be dominated by tropical cyclones, frontal systems, and isolated thunderstorms.

Introduction

Due to its natural temporal and spatial variability, capturing rainfall intensity and accumulation can be very challenging. Current technology including satellites, radar systems, and surface rain gauges provide opportunities for researchers to accurately assess rainfall events for use in forecasting, modeling, and other important public measures. The National Weather Service operates approximately 160 Weather Surveillance Radars-1988 Doppler (WSR-88D) radar stations throughout the continental United States and other select overseas locations as part of the Next Generation Radar (NEXRAD) program. These operational radars provide rainfall monitoring coverage over most of the United States with the exception of some locations in western areas where radars are sparser. Since the commencement of the NEXRAD program in the late 1980's, radars have become more heavily relied upon due to their high temporal and spatial resolution. These capabilities, which far exceed pin point surface rain gauges, allow for faster processing of data which in turn can provide faster prediction of extreme weather events. On the other hand, due to known biases that often result in radar measurement surface rain gauges are still considered to be a true measurement of ground rainfall. In order to assess this radar error, biases are adjusted through use of rain gauge and sometimes even satellite measurement. The resulting product of merging these rainfall data sources is called multi-sensor precipitation estimates (MPE). Validation of MPE data continues to be of importance for further improvement of bias adjustment algorithms and accuracy of rainfall measurement. Many studies have been done in the validation of radar estimates through use of independent surface gauge data which were not used in the bias correction procedure. In regards to a coastal validation analysis, does MPE data compare differently to gauge data when assessed at coastal rather than inland locations? Does

averaging surface gauge measurement within the same area give better results when comparing to MPE data? Answers to these questions can prove to be useful in the further application and improvement of MPE product.

Study Site and Regional Precipitation

The rain gauge network consisted of 28 sites where each site had dual or triple gauges. The sites were located in Eastern Virginia, Delmarva Peninsula, and northeast North Carolina. Approximately three-fourths of the sites were at the coast while one-fourth of the sites were located at Wallops Island, Virginia (Figure 1). The maximum site spacing on the island was approximately 6 kilometers. Rain gauge data was available from mid 2004 through January 2007. Each site was in operation at least a year within this 2.5 year period (Figure 1). Five of the rain gauge stations (Painter, VA; Oyster, VA; Williamsburg, VA; Petersburg, VA; Holland, VA) were relocated at some point during this period. Oyster, VA is not shown in the map as a relocation site because its relocation did not fall outside of the original pixel. Also, the station located at Murfreesboro, NC was shutdown in 2005 and reinstated at the Melfa, VA site.

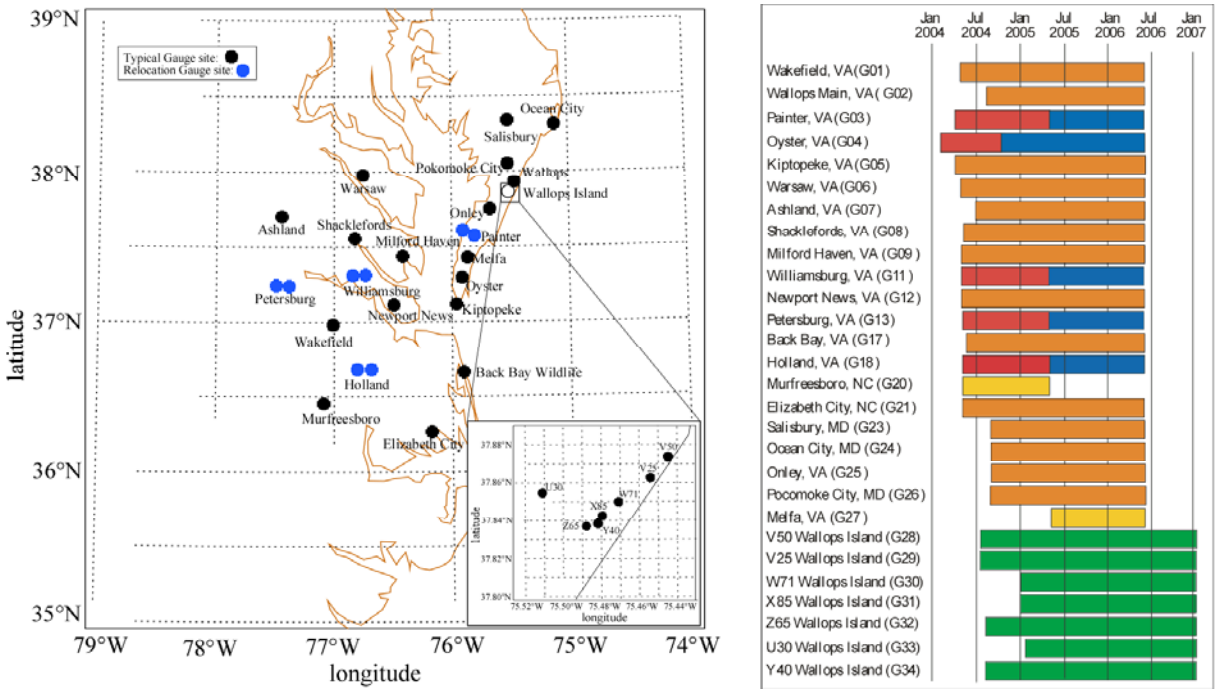

Figure 1: (Left) Gauge station map showing locations of all sites. (Right) Data period available for each gauge station along with times at which relocation took place.

All rain gauges were tipping buckets and manufactured by MetOne Instruments. The instrument had a maximum resolution of 0.254 millimeters corresponding to one tip. Operation and maintenance of the gauge network was done by the NASA's TRMM satellite validation office. A quality assessment of the rain gauges has been done in a prior study. This assessment was used in determining which gauge, at each site, consistently provided better quality data. One downside to tipping bucket rain gauges is the inability of the gauge to determine whether rainfall actually caused the tipping mechanism to tip or something else. Due to the physical climate of the region, much of the winter precipitation occurs in the form of snow, sleet, or partially frozen water droplets. In order to avoid difficulties in determining whether rain gauge tips occurred as a result of rainfall or melting snow, controversial winter days were taken out of the analysis.

Radar Rainfall Data

Radar rainfall data used in the current study are based upon Stage IV products of the National Center for Environmental Prediction (NCEP). Stage IV radar-rainfall estimates are based on mosaicking of regional MPE which are developed at the National Weather Service River Forecast Centers. Using real-time rain gauge observations, the MPE algorithm applies correction factors to the radar data to reduce mean-field and local biases that are inherent in the radar-only rainfall estimates (Seo and Breidenbach, 2002, Seo et al., 1999). Occasionally, geo-stationary satellite rainfall estimates are used along with rain gauge observation in this process. Thus, MPE is a product of merging of operation radar, automated gauge, and geo-stationary satellite data. The rain gauge network used in this study was not part of the developed bias adjustment process of MPE data, which made it a good candidate for validation and comparison. Stage IV data are provided over the 4x4 km^2 HRAP national grid system where each pixel corresponds to an MPE value. The base timestep of MPE data is hourly. MPE data was accumulated from hourly into 3-, and 6-hourly, daily, and monthly timesteps for further analysis. MPE Pixels with at least one rain gauge station within were extracted along with the surrounding eight pixels. The center pixel, which was the actual pixel that the gauge station was within was termed the middle center (M.C.) pixel. The surrounding eight pixels were given labels depending on whether it was located on top of or below the center and also if it was located to the left or right of the middle center pixel. Due to a maximum gauge site spacing of 6 kilometers at Wallops Island, two pixels each had three stations while the seventh station was located within a different pixel. Of the stations which were not at Wallops Island, each was located within its own MPE pixel.

Results

A statistical package including Pearson's correlations coefficient, standard deviation of the difference, as well as normalized weighted absolute and non-absolute biases were performed during this study.

Pearson's Correlation Coefficient

$$r = \frac{Cov(l1, l2)}{(Var(l1)Var(l2))^{1/2}}$$, where $l1$ is gauge and $l2$ MPE

Standard Deviation of the Difference

$$STD_{Diff} = [\mathrm{var}(l1) + \mathrm{var}(l2) - 2\,\mathrm{cov}(l1, l2)]^{1/2}$$

Normalized Weighted Absolute/ Non-absolute Bias

$$Wt.\ Abs.\ Bias = \sum_{i=1}^{N} \frac{\omega_i |l1_i - l2_i|}{l1_i} \quad , where \quad \omega = \frac{l1_i}{\langle l1 \rangle \times N}$$

N is the number of hours within the sample

Comparison of MPE and rain gauge data was performed through the following scenarios; gauge versus MPE middle center pixel, averaged gauge versus MPE middle center pixel, gauge versus MPE middle center pixel with respect to given thresholds, and also MPE middle center pixel versus surrounding pixels.

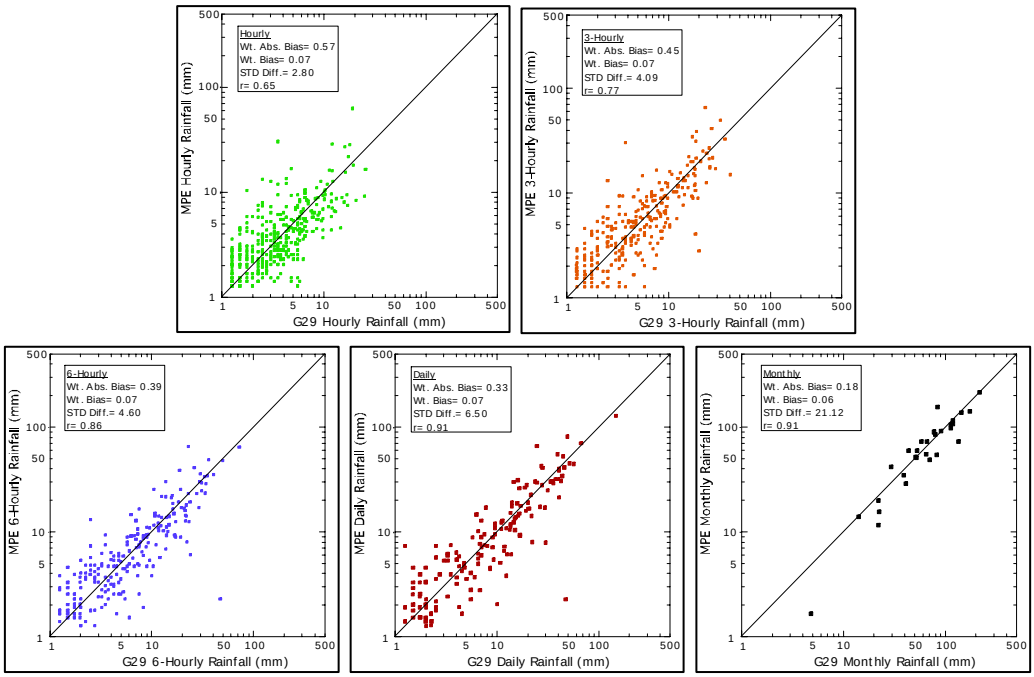

Figure 2: Gauge station 29 vs. MPE (middle center) pixel at hourly, 3- , and 6-hourly, daily, and monthly timesteps.

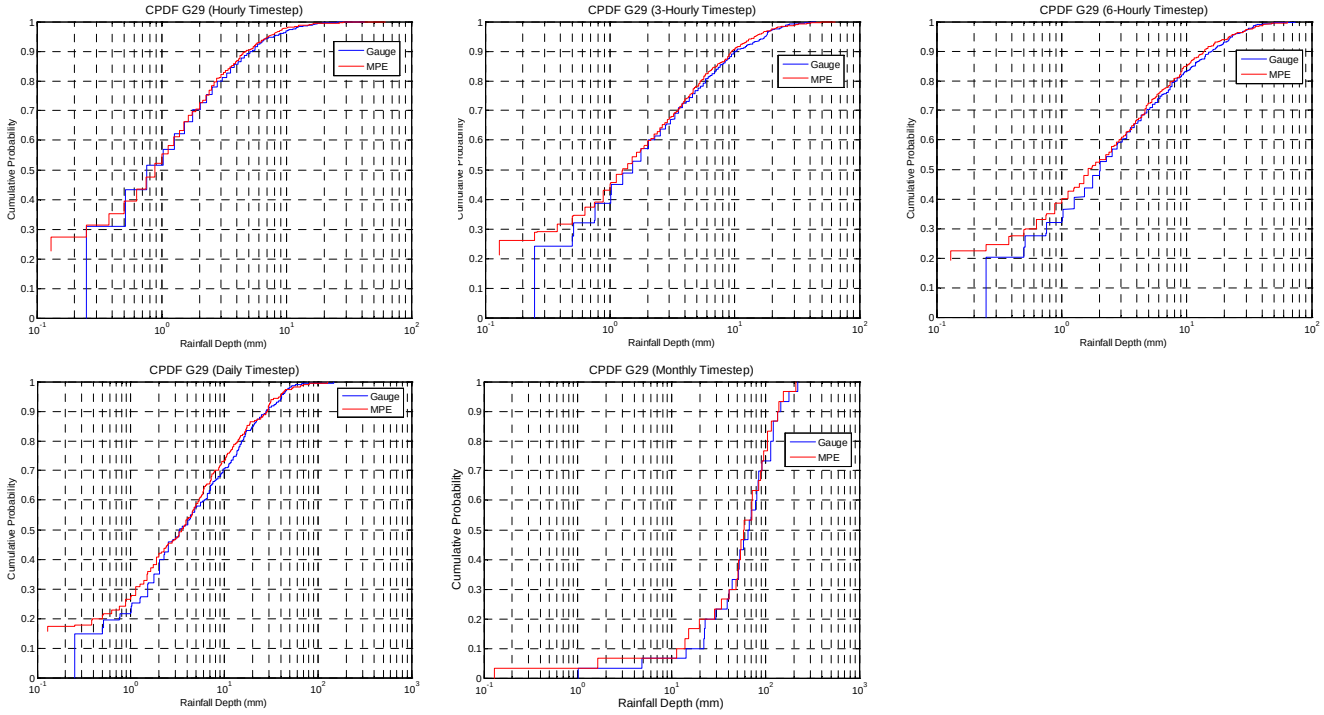

Figure 3: Cumulative Probability Distribution Functions (CPDF) for Gauge 29 at hourly, 3 - , and 6-hourly, daily, and monthly timesteps.

Figure 2 gives a comparison of gauge versus MPE data for the middle center pixel at each timestep, while figure 3 shows corresponding cumulative probability distribution functions. The timestep accumulations were based upon the hourly timestep only. Gauge station 29 was used in the analysis because it was a gauge site located at Wallops Island near the coast and contained more than one gauge station within the pixel. Correlation coefficients continued to rise as the time step was increased from hourly to monthly. The monthly correlation was fairly high (0.91), which may have been due to the bias averaging effect occurring within the data. With a correlation coefficient of 0.65 and standard deviation of difference equal to 2.80, gauge and MPE data seem to have fairly large differences at an hourly timestep. These differences may be partially due to the spatial and temporal variability of rainfall within the region. Another factor may be the limited amount of quality control available on hourly MPE data. Possible use of the 6-hour MPE product, due to its higher level of quality control, may have given better results.

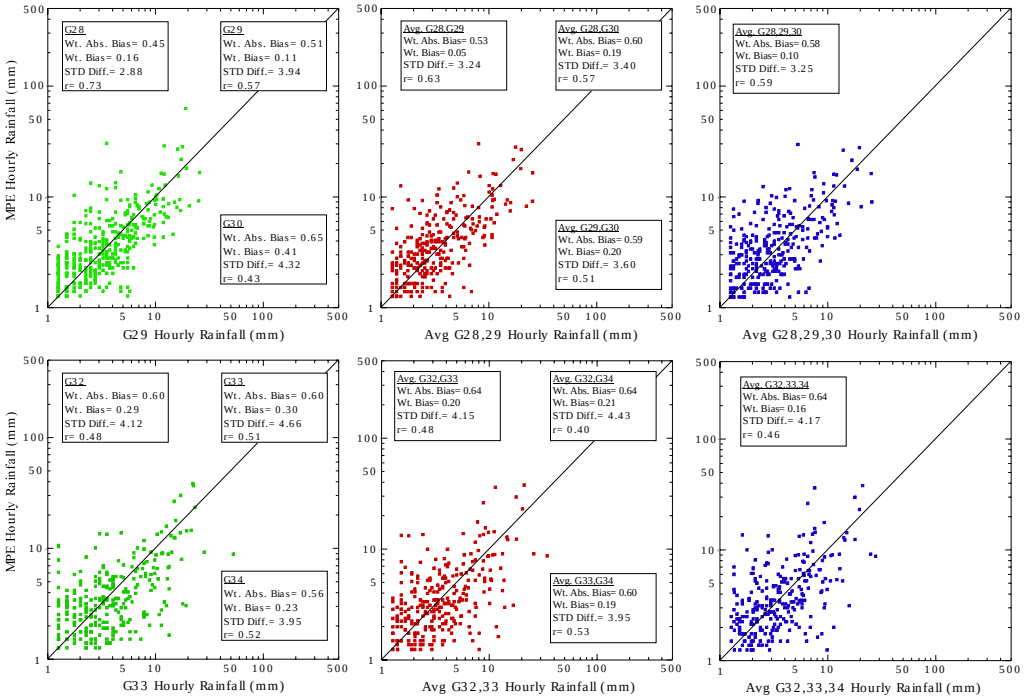

Figure 4: Scatter plots of averaging gauge measurements on Wallops Island versus corresponding MPE pixel. Statistical measures are also provided. (Top row) Pixel 1 contains G28, G29, and G30. (Bottom row) Pixel 2 contains G32, G33, and G34.

Figure 4 depicts various gauge averaging scenarios of two coastal pixels. Averaging two and three gauges within the same MPE pixel was compared to statistics of only one gauge versus MPE. This analysis could only be done at Wallops Island due to the close proximity of the gauges to each other (within 6 kilometers). The same scenarios were performed for the second pixel containing the other three gauge sites. Noticeable statistical differences can be seen in the single gauge versus MPE plot. Differences as much as 30% in correlation and 1.44 mm in the standard deviation of the difference are seen. By using two gauges as a representation of rainfall within the pixel, not as much variability is seen in correlation and standard deviation of the difference between each of the three two-gauge scenarios. Weighted absolute and non-absolute biases are fairly low (0.45 and 0.16 respectively) in the one-gauge plot while minimal weighted bias decreasing is seen in the two and three-gauge analysis. By averaging all three gauges within the pixel, the correlation seems to stay approximately the same. As a result, it seems as though two gauges represented rainfall within the pixel with as much accuracy as three gauges. The same statistical analyses can be seen for the second pixel with three gauges.

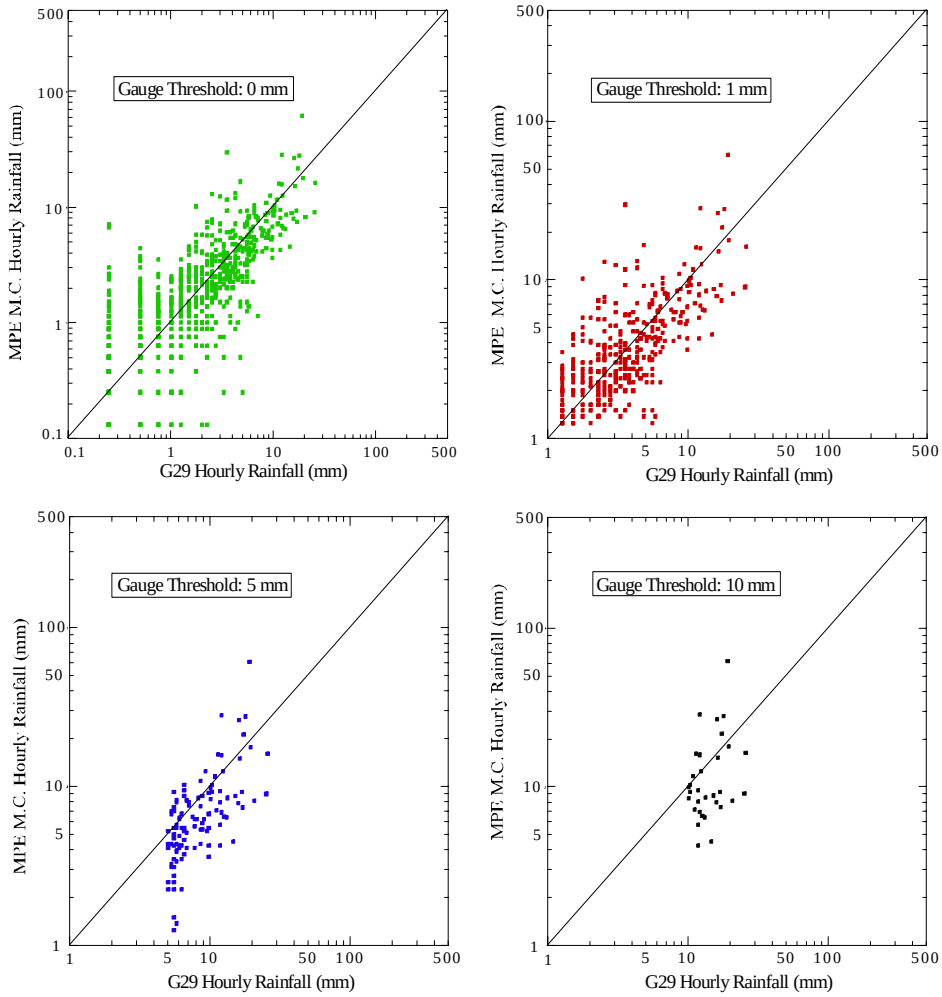

Figure 5: Hourly scatter plots of Gauge 29 versus MPE (middle center) pixel at 0, 1, 5, and 10mm gauge threshold.

Scatter plots at an hourly timestep for four different thresholds are shown in figure 5. Visual inspection of the 0 mm threshold scatter plot shows vertical straight line features. This may be due to the limiting thresholds of gauge and MPE measurement. Gauge measurement, which has a threshold of 0.254 millimeters, has vertical features a little further away from zero than does MPE vertical features. This would be true since MPE has a finer resolution than gauge does. By looking at the various threshold levels, we can see instances in which gauge measurement above a certain level corresponds to lower MPE measurement. For

example, when gauge measurement is above a threshold of five we find MPE measurement as low as 1 and 2 millimeters. Much of the same occurs at a threshold of 10mm.

Gauge 29	Gauge Threshold: 0 mm				Gauge Threshold: 1 mm			
Pixels Compared	Correlation	Std Diff.	Non-normalized Wt. Abs. Bias	Non-normalized Wt. Bias	Correlation	Std Diff.	Non-normalized Wt. Abs. Bias	Non-normalized Wt. Bias
M.C./M.L.	0.83	1.97	3.06	1.54	0.79	2.79	3.49	1.78
M.C./M.R.	0.89	1.59	2.47	1.93	0.87	2.24	2.81	2.24
M.C./T.C.	0.95	1.05	1.66	1.00	0.95	1.44	1.86	1.15
M.C./T.L.	0.77	2.32	3.61	1.63	0.73	3.27	4.08	1.87
M.C./T.R.	0.93	1.28	2.06	1.50	0.93	1.72	2.31	1.73
M.C./B.C.	0.97	0.90	1.34	0.23	0.96	1.24	1.49	0.27
M.C./B.L.	0.89	1.63	2.55	0.89	0.87	2.27	2.89	1.06
M.C./B.R.	0.78	2.20	3.49	2.05	0.73	3.10	3.96	2.38

Gauge 29	Gauge Threshold: 5 mm				Gauge Threshold: 10 mm			
Pixels Compared	Correlation	Std Diff.	Non-normalized Wt. Abs. Bias	Non-normalized Wt. Bias	Correlation	Std Diff.	Non-normalized Wt. Abs. Bias	Non-normalized Wt. Bias
M.C./M.L.	0.66	5.46	6.14	3.89	0.53	9.80	11.18	7.24
M.C./M.R.	0.83	4.09	4.45	3.80	0.79	7.14	7.76	7.25
M.C./T.C.	0.94	2.53	2.95	1.97	0.94	4.11	4.75	3.36
M.C./T.L.	0.57	6.40	7.14	4.07	0.42	11.51	12.86	7.22
M.C./T.R.	0.94	2.54	3.16	2.47	0.95	3.93	5.00	4.32
M.C./B.C.	0.95	2.19	2.27	0.59	0.95	3.36	3.49	1.02
M.C./B.L.	0.83	4.01	4.60	2.81	0.78	6.96	8.08	5.09
M.C./B.R.	0.59	5.94	6.65	4.30	0.46	10.17	11.60	8.36

Table 1: Gauge 29 statistical table of MPE versus MPE analysis over 0, 1, 5, and 10mm gauge thresholds.. Nine pixels (middle center and 8 surrounding pixels) M: middle; T: top; B: bottom; C: center; L: left; R: right;

The statistical package was also applied to the MPE data of each gauge site and surrounding MPE grid pixels (Table 1). Average gauge comparisons versus MPE data were discussed earlier to show if variability of rainfall within one pixel was significant. Furthermore, the analysis can be produced on a larger scale by comparing MPE pixel data to surrounding MPE pixel data. Non-normalized weighted biases were calculated in this analysis based upon the actuality of neither MPE pixel being the reference. One characteristic we can see in the statistics is the low correlation associated with pixels diagonal to the center pixel. An example would be seen at a threshold of 5mm in which we see the top-right and bottom-right pixels with a correlation of less than 60% when compared with the center pixel. Correlation decreases and standard deviation of the difference increases as the threshold is

increased from 0 to 10mm. This may be a result of short-lived convective thunderstorms producing large amounts of rainfall over small areas.

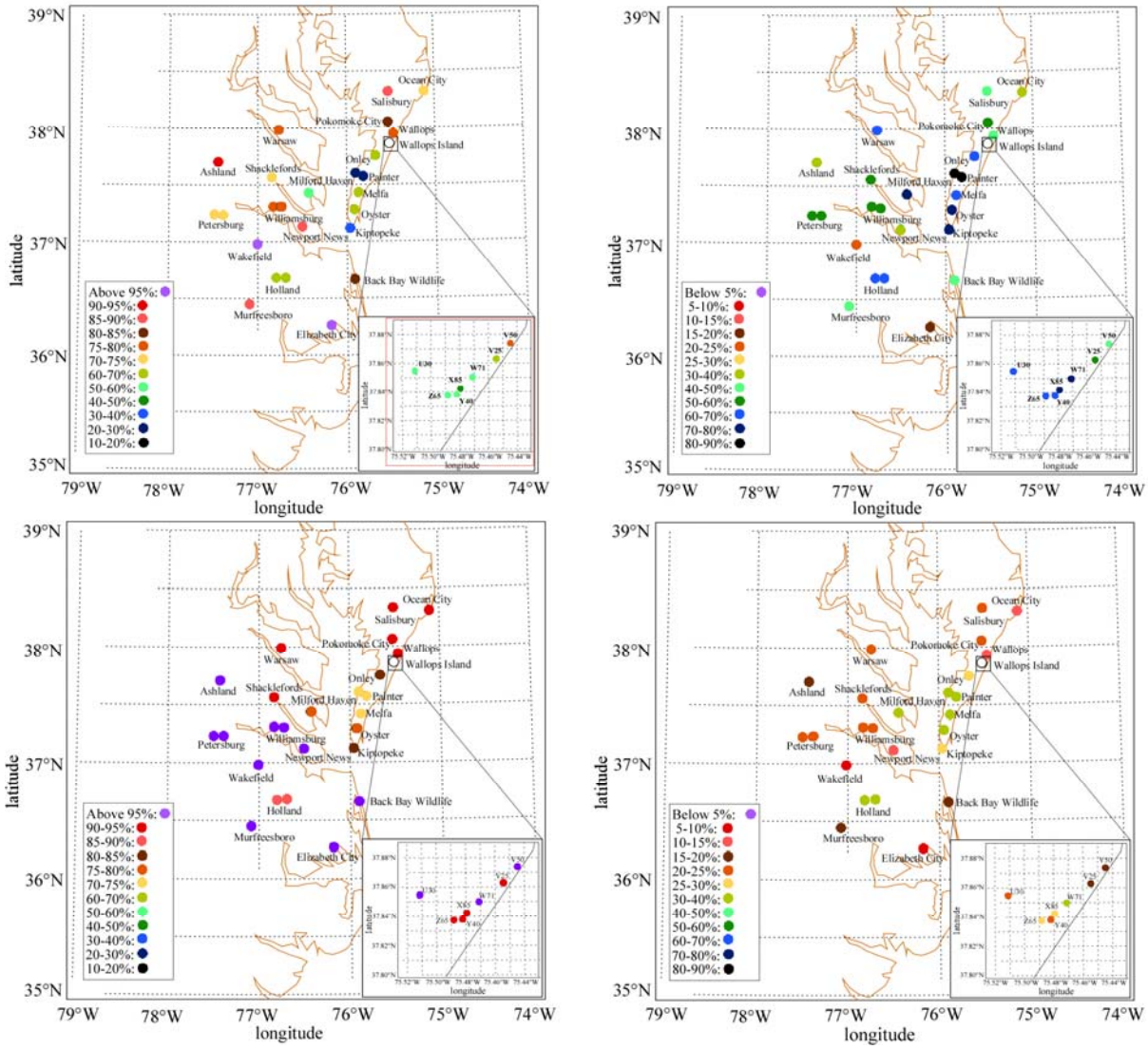

Figure 6: Gauge location maps showing correlation (left column) and weighted absolute bias (right column) color bars for hourly (top) and monthly (bottom) timesteps.

A spatial representation of statistics is useful in determining whether gauge station location has an affect on its comparison against MPE data (figure 6). Cooler colors represent higher weighted bias and lower correlations and the opposite is true for warmer colors. On

average, gauges stations along the coast seem to have lower correlations than do inland gauge stations at an hourly timestep. Statistics seem to improve at the monthly timescale over all gauge stations, with many inland gauges showing over 95% correlation. Inland gauges still show signs of higher correlation and lower weighted absolute bias than coastal gauge stations.

Summary and Future Analysis

Accumulation of rainfall from hourly to a monthly timestep tended to mask or "average" the bias inherent in the hourly statistics. Correlation and weighted absolute bias maps showed slight correlation trends between coastal and inland gauges in comparison to MPE data. Increased humidity and variability in weather conditions may be of significance in these resulting trends and should be further studied. Variability of rainfall in the coastal MPE versus MPE analysis was somewhat high. Analyzing specific storms within the region on a storm scale could provide knowledge as to the variability of rainfall near the coast as apposed to inland. Also, the gauge 29 hourly threshold analysis showed results of low MPE rainfall measurement when gauge measurement was high. This was especially true at the 5mm gauge threshold. Looking into what part of the year these low MPE measurements occurred might provide more insight. Based upon the Stage IV MPE to rain gauge analysis, MPE data would be a useful source in the validation of TRMM rainfall measurements for inland areas. Also, further review of this study could provide needed results for extended validation of TRMM rainfall measurements in coastal areas.

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