An evaluation of WSR-88D rainfall estimates across Puerto Rico during Hurricane Debbie

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1. INTRODUCTION

The Weather Surveillance Radar-1988 Doppler (WSR- 88D) rainfall estimates have proven to be an invaluable tool for both hydrologic and hydrometeorological operations (Vieux and Benedient 1998; Baek and Smith 1998). The operational use of the TJUA radar has increased the issuance and accuracy of non-routine advisories, watches, and warnings at the WFO-San Juan, Puerto Rico since its commissioning in 1997 (Block 1998). The use of this operational tool needs to be carefully assessed, since depending on other factors, it tends to either underestimate or overestimate rainfall amounts. This paper evaluates the TJUA radar performance during the passage of Hurricane Debbie close to the island of Puerto Rico.

Hurricane Debbie affected the WFO-San Juan area of responsibility on August 22nd-23rd, 2000. Even though the eye-wall of Debbie passed about 40 miles north of Puerto Rico, some rain gages recorded storm total accumulation of more than 12 inches across the interior mountains and the southern slopes of the island. There were not any hurricane force winds observed across Puerto Rico. With only minimal tropical storm force winds over the island, the rainfall event associated with Debbie may be characterized as a convective high reflectivity gradient event and should be comparable with future tropical storms or strong tropical waves.

The WSR-88D precipitation processing system (PPS) converts reflectivity (Z) to rainfall rate (R) using a Z-R relationship. Radar-estimated rainfall amounts were compared with measurements from 126 rain gages. Linear regression was applied to the radar reflectivity values and rain-gage accumulations. The goal of this study was to find an alternative Z-R equation that would improve the accuracy of radar precipitation estimates for extreme rainfall events.

2. HURRICANE DEBBIE

On August 22nd 2000, the eye of Hurricane Debbie passed about 20 miles north of St. Thomas and 40 miles north of San Juan, Puerto Rico. The northern semicircle of its eye-wall contained the deeper convection and hurricane force winds. Whereas the southern semicircle appeared exposed on satellite imagery with minimal tropical force winds. As Debbie approached the U. S. Virgin Islands, deep tropical moisture trailed behind on its southeast quadrant forming an extended trough known as the "tail" of the hurricane. No hurricane force winds were recorded across the U. S. Virgin Islands and Puerto Rico. The WSR-88D radar showed a Velocity Azimuth Display (VAD) Wind Profile with southerly low level winds of 30-40 knots and a high reflectivity gradient. The "tail" of a Hurricane affected the islands directly with torrential rains. The heavy rainfall began the night of August 22nd and extended into the early morning of August 23rd when the tail of Debbie moved away from Puerto Rico. Radar detected convergent rain bands over the Caribbean sea moving on shore over the south coast continuing north into the interior highlands. The heavier precipitation fell across the steep southern mountain slopes causing several rivers to over flow their banks. In the interior mountains, heavy rain across the headwaters of north flowing rivers caused flash flooding in several municipalities along the eastern interior and north coast of the Island.

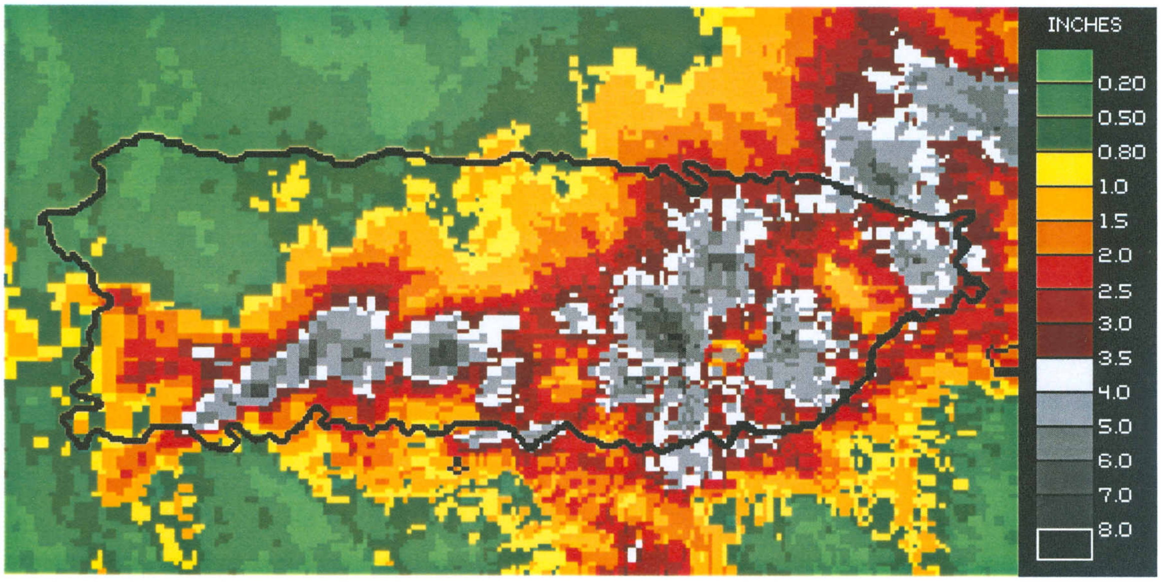


Figure 1. Storm Total Precipitation product (STP), (inches) after Hurricane Debbie.

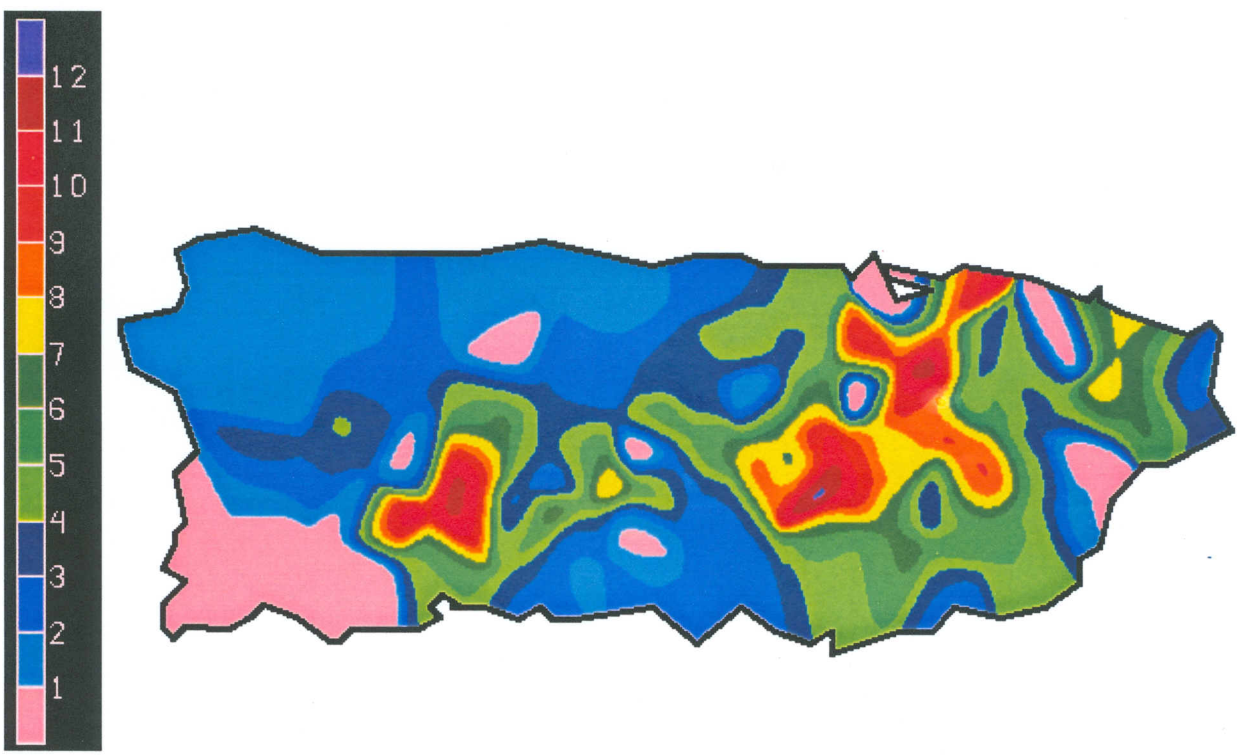


Figure 2. Shaded rain-gage isohyeths (inches) after Hurricane Debbie.

3. DATA

Puerto Rico is sampled by four rain gage networks with over 170 reporting stations combined. These include USGS, Alert, Metars, and cooperative observers networks. For this study 126 rain gages were used. The WSR-88D Storm Total Precipitation (STP) product was saved immediately after the rainfall event. Due to the spatial resolution of 1° azimuth angle by 2 square kilometers, radar estimated values were chosen from pixels over or adjacent to the latitude and longitude of the gage that best matched the gage value. Rainfall estimates were analyzed with respect to their range from the Radar Data Acquisition (RDA), and gage elevation from mean sea level.

The NWS Radar Operational Center (ROC), formerly Operational Support Facilities (OSF), and the Adaptable Parameter Working Group (APWG) authorized WSR-88D sites to select from five PPS Z-R relationships to improve radar rainfall estimates depending on the season, geographical location, and expected weather type. The relationships and their recommended use are listed in Table 1. The Z-R equation used by the PPS algorithm during Debbie was the Rosenfeld Tropical:

$$Z=250R^{1.2} \quad (1)$$

where Z is the reflectivity, and R is the rainfall rate.

Table 1. List of Z-R relationships available and approved by ROC for most types of precipitation events.

RELATIONSHIP	RECOMMENDED USE	2ND RECOMMENDATION
Marshall-Palmer $Z = 200R^{1.6}$	General stratiform precipitacion	
East-Cool Stratiform $Z = 130R^{2.0}$	Winter stratiform precip. east of continental divide	Orographic rain-East
West-Cool Stratiform $Z = 75R^{2.0}$	Winter stratiform precip. west of continental divide	Orographic rain-West
WSR-88D Convective $Z = 300R^{1.4}$	Summer deep convection	Other non-tropical convection
Rosenfeld Tropical $Z = 250R^{1.2}$	Tropical convective systems	

The PPS automatically removes erroneous reflectivities such as anomalous propagation, ground clutter, and outliers. As pointed out by Austin (1986), significant discrepancies might occur between radar estimates and gage rainfall amounts because of the differences in sampling modes. The WSR- 88D PPS algorithm produces STAGE I rainfall estimates with a spatial resolution of 1° azimuth angle by 2 km radial distance, and sampling is made almost instantaneously with repeated measurements in intervals of 5 or 6 minutes in precipitation mode. On the other hand, gages continuosly accumulate rain falling on an area smaller than half a square meter. Also, heavy rain may fall within less than a kilometer from a rain gage without depositing any amount at nearby gages. Therefore, radar precipitation estimates may not be representative of surface rainfall.

Because of the complex mountainous terrain, the TJUA radar detects localized ground clutter over several areas. A ground clutter suppression technique is used to filter those non-meteorological, ground-based targets that otherwise would produce false reflectivity echoes affecting the PPS algorithm estimates. Ground clutter suppression may also affect rainfall accumulation by removing power contribution of hydro-meteorological targets. This technique is applied on stationary echo returns, thus hydro-meteorological targets moving perpendicular to the radar beam may be filtered as well.

Inaccurate precipitation estimation are also affected by the lack of detection by the radar beam. As the radar beam samples the atmosphere, the scanned volume lowest height increases as the square of the range from the RDA. The elevation angles of the radar beam used by the PPS to estimate rainfall rates are the lowest four tilts: 0.5°, 1.5°, 2.4°, and 3.4°. In addition, the WSR-88D site (TJUA) is located on a mountain top at an elevation of 2,900 feet above sea level. Thus, the effect of radar beam overshooting rain clouds at all ranges would contribute to additional radar underestimation.

Another factor to consider is the radar calibration. Joe and Cynthia Christman (1999) from OSF discussed the importance of radar calibration for accurate rainfall estimates. They point out that using the tropical equation, a 40 dBZ return with a -4dB reflectivity error would cause the PPS algorithm to estimate a 0.85 in/hr rainfall rate instead of the 1.83 in/hr rate that is actually occurring. An underestimation of one inch or less per hour becomes extremely significant over the life of the event. Conversely, a positive error in the reflectivity would result in overestimated precipitation accumulation errors.

Figure 3 shows a scatterplot of all radar-gage pairs of estimated rainfall after Debbie. The solid line represents the one to one correlation line. Notice how the greater gage rainfall amounts (75 mm or ~ 3 inches) are underestimated by radar using the Rosenfeld Tropical equation.

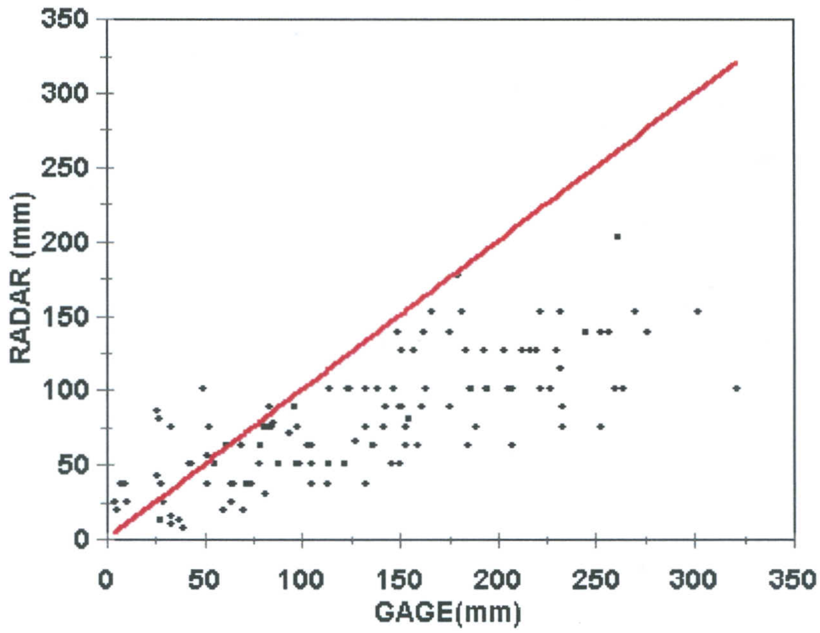


Figure 3. Scatterplot of all radar vs. gage accumulation values. Solid line represent perfect correlation. Radar rainfall estimates were calculated from the Z-R relationship $Z = 250\ R^{1.2}$.

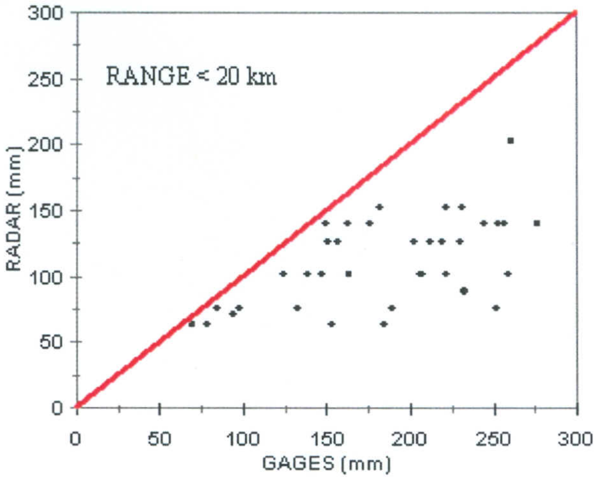
In order to determine if any relationship exists between radar rainfall estimates and distance from the RDA, scatterplots for each valid radar-gage pair were constructed at different ranges with respect the RDA (Figure 4). The range categories selected were 0-20, 20-35, 35-50, and >50 km from the RDA. The G/R ratio is defined by Wilson and Brandes (1979) as the sum of the observed amounts at all gages with rainfall divided by the sum of the radar estimates for those gages. G/R ratios were calculated at different ranges from the RDA(Table 2) and radar-gage pairs were plotted vs. range from RDA (Figure 5). Valid radar-gage pairs were also plotted vs. gage elevations (Figure 5). The G/R ratio is the mean radar bias factor given by:

$$G/R = (G_1 + G_2 + \ldots G_i)/(R_1 + R_2 + \ldots R_i) \qquad (2)$$

Table 2. gage to radar ratios from their corresponding range (km) from RDA, using $Z=250R^{1.2}$.

Ranges	0 - 20 km	20 - 35 km	35 - 50 km	> 50 km
G/R	1.68	1.71	1.58	1.4

a)



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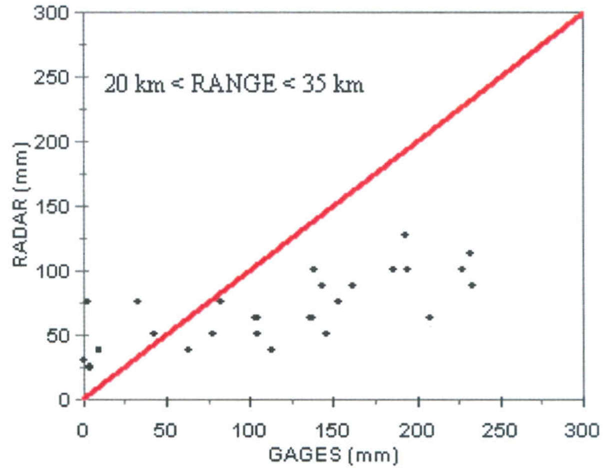

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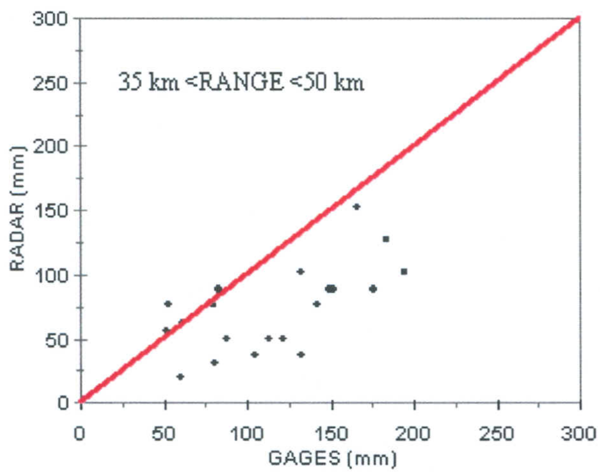

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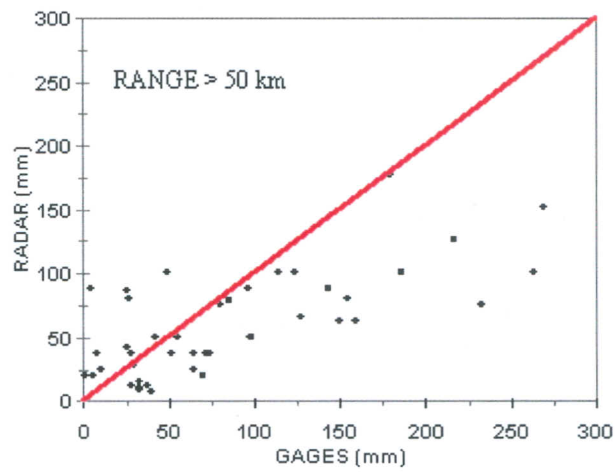

Figure 4. Scatterplots radar vs. gage rainfall estimates a) 20 km, b) 20-35 km, c) 35-50 km, d) >50 km from RDA. Radar rainfall estimates calculated from Z-R relationship $Z = 250R^{1.2}$

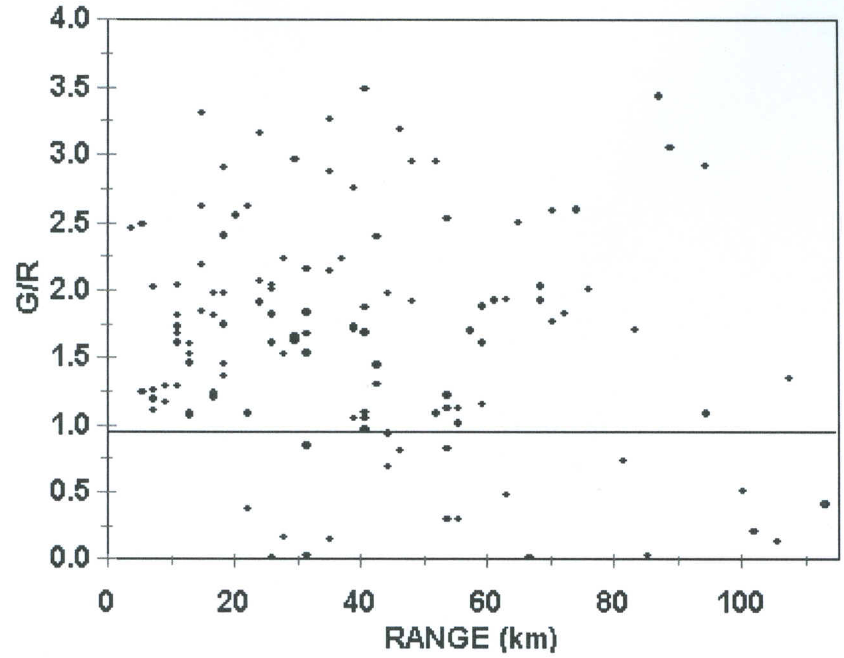

Figure 5. Ratio of total gage rainfall over total radar rainfall vs. Distance of the rain gage location from the RDA. Radar rainfall estimates were calculated from the Z-R relationship $Z = 250R^{1.2}$

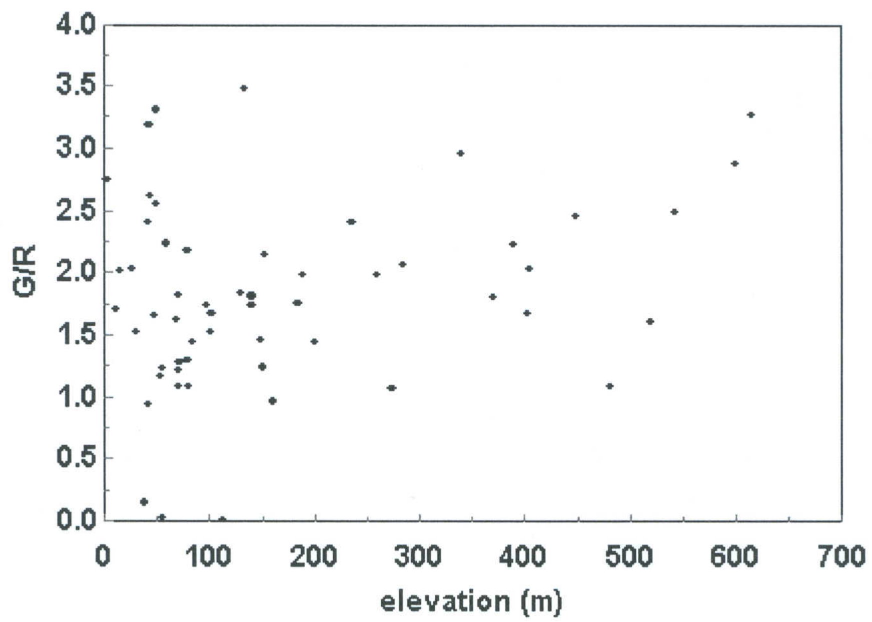

Figure 6. Ratio of total gage rainfall over total radar rainfall vs. gage elevation.

4. RESULTS AND DISCUSSION

From the Z-R equations suggested by the ROC, the Rosenfeld tropical relationship provides the closest estimation for the precipitation that occurs over Puerto Rico. As shown in Figure 1, the Z-R equation tends to underestimate rainfall accumulations exceeding 63.5 mm (2.5 inches) at all ranges. Only few gage accumulations of less than 63.5 mm indicated radar overestimation. From 126 gage-radar comparisons, only 13 % of the gage-radar pairs show a good correlation mostly between the range of 50 to 75 mm (2 to 3 inches). The G/R ratios for this Z-R relationship used during Debbie(Table 2) show an average underestimation of about 63%. At far ranges from the RDA (>50 km), the G/R ratio (G/R=1.40) shows slightly less underestimation than at the nearest ranges (G/R=1.4). gage to radar ratios were plotted against gage elevation (Figure 5). Although most stations are located at or below 150 meters from sea level, no clear indication could be seen that the gage altitude played a role in the radar underestimation.

Tim D. O'Bannon (Adaptable Parameter Meteorologist at ROC) developed a quick calculation that uses the G/R bias to estimate an unbiased coefficient in the Z-R equation. This technique consists in dividing the current multiplicative coefficient (250) by the bias (1.63) raised to the power coefficient (1.2):

$A' = A/((G/R)^b$ $\qquad$ $A' = 250/(1.63)^{1.2}$ $\qquad$ $A' = 1.39$

Since Level II base data is not available at the TJUA site due to hardware problems, this technique could optimize the multiplicative coefficient (A) in the tropical Z-R relationship, improving rainfall accumulation estimates especially after long term rain events.

5. CONCLUSION

The equation $Z = 250R^{1.2}$ provides accurate rainfall estimates for events with rainfall accumulations of near 75 millimeters (4 inches), but underestimates for rainfall accumulations higher than 125 millimeters (>5 inches). Similar results have been documented in 1999 by Gottschalck et al., with the KMIA radar site severely underestimating high convective rainfall rates in South Florida. G/R ratios do not show any correlation of radar rainfall underestimation at farther ranges from the RDA perhaps due to the hybrid scan algorithm removing the sampling errors associated with the radar beam and the range from the RDA. As shown in Figures 4 and 5, ranges from the RDA and rain-gage elevations appear not to be an influence in the radar rainfall underestimations. Three factors have been identified to have significant effects on the accuracy of precipitation accumulation estimates. 1) Erroneous radar calibration. 2) The high altitude location of TJUA radar may contribute to the beam overshooting effect of low orographic enhanced rain formed on the windward side of the mountains. 3) Ground clutter suppression, designed to filter non-meteorological, ground-based targets may also affect rainfall accumulation by removing power contributed by hydro-meteorological targets.

Doviak and Zrnic (1993), suggested the use of a more appropriate Z-R relationship to help compensate for errors in radar calibration. The underestimation effects of beam overshooting and undesirable filtering from ground clutter suppression can be counterbalanced by adjusting the Z-R equation such that radar rainfall estimates border on gage observations. A more appropriate Z-R equation would provide more accurate radar rainfall accumulations by compensating for those factors which affect the WSR-88D in Puerto Rico.

We recommend to test this possible alternative to the Z-R equations ($Z=139R^{1.2}$) to seek for accurate rainfall estimates during events with conditions similar of Hurricane Debbie. Even though, smaller rainfall amounts may be overestimated, it is much more imperative to have early detection of heavy rainfall at the local warning office. The use of an alternative Z-R equation represents an excellent tool to compensate for the underestimation bias produced by the aforementioned factors. Although data was obtained from a single case study, the alternative Z-R equation should be tested in future hurricanes, tropical storms, or strong tropical waves.

6. REFERENCES

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