S.33 IMPROVING THE RADAR Z-R RELATIONSHIPS OVER PUERTO RICO

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1. Introduction

Improving rainfall estimates during heavy storms is especially important to save human lives and protect property. Warning people about the occurrence of flash-flood and/or the landslide events may help to mitigate their catastrophic effects. Puerto Rico (PR) has a dense rain-gauge network and during the rainy season severe rainstorms develop due to geographical location and complex orographical attributes. The easterly winds are coming from the eastern Atlantic during almost all year and play an important role bringing humidity into the island and stimulating orographical rainfall over the mountains of PR. Cold fronts dominate the weather pattern during wintertime. The tropical waves occur during the rainy season and frequently generate large amount of rainfall in the Caribbean basin. These tropical waves are largely the precursor of the tropical storms and hurricanes in the North Atlantic basin during the hurricane season (June to November). A validation algorithm was developed to enhance the NEXRAD-rain-rate measurements. A dense rain gauges network was installed in PR and collect data every 15 minutes. Radar data were aggregated to obtain 15 minutes of accumulation rainfall. PR was divided in 3 zones according to the distance from radar to rain gauge location for purposes of developing a radar correction factor. NEXRAD measurements over the western part of PR are frequently inaccurate. This is because reflectivity measurements are conducted at about 2000m above the surface as a result of the elevated location of the radar and a relatively high scan angle which was selected to minimize beam block by nearby mountains. The NEXRAD bias is measured with the purpose of developing a bias correction algorithm to improve rain rate estimations especially over the western part of PR. The bias correction algorithm will be based on high resolution observations obtained from Collaborative Adaptive Sensing of the Atmosphere (CASA) radar network that is being installed in the western part of PR. Although, the validation algorithm was developed by PR, it can be applied to other places characterized by tropical climate conditions.

The level of humidity in the atmosphere is measured by weather radar (reflectivity, Z, in dBz or mm^6 /m^3) and the accumulation of rainfall over a specific point in the surface is measured by a rain gauge (R, mm/h). The Z–R relationship relates the values of the measured reflectivity to the values of the rain rate according to an empirical expression, which is used to estimate rain rate from reflectivity measurements (Marshall et al. 1947). The Z-R relationship is derived by regression techniques and is used to convert the radar reflectivity Z (mm^6 /m^3) into the rain rate R (mm/h). The known relationship is given as follows:

$$Z = aR^b \tag{1}$$

where a and b are parameters that are empirically determined.

The effect of scale difference between radars and rain gauges is a relevant factor of uncertainty, as pointed out by Steiner and Smith (2004). This raises the specter of calibration to specific observing systems, which further undermines the generality of empirical Z–R relationships. Nevertheless, the simplicity of Eq. (1) is appealing and it continues to motivate research toward deriving general Z–R relationships.

Although there are several Z-R relationships, they cannot be directly applied to different areas. This is because the climate conditions are different and consequently the parameters *a* and *b* in the Z-R relationship will be different from one area to another. Consequently, there is no universal Z-R relationship that can be applied to all rainfall fields. The *Z-R* relationship determination can be derived by using two approaches; raindrop size distribution (DSD) and regression techniques. (Punpim, P. M., et al. 2008).For the first approach (DSD), *Z* and *R* are calculated directly by using raindrop size distribution data recorded by a disdrometer. Regression technique was applied in this study, the relationship was derived using reflectivity data measured by radar and accumulated rainfall recorded in 125 rain gauges distributed around the island of PR. A suitable relationship is then obtained by minimizing the errors between radar and rain gauge observations.

Application of weather radar to estimate rainfall has been widely used and documented by many authors. (Rosenfeld et.al., 1993; Rosenfeld et. al.,1994; Atlas et.al., 1997). There are other studies that have compared radar and rain gauge and have documented large discrepancies between both radar and rain gauges observations (e.g., Baeck and Smith 1998; Woodley et al. 1975).

Carefully attention was dedicated to rain gauge observations, and only the reliable rain gauge observations were selected to derive the Z-R relationships. In this study, PR was divided into three geographical regions, i.e, to capture the possible errors associated to distances between the radar and the rain gauges.

One of the objectives of this work was to study whether or not the distance of the rain gauge from the radar affects the rain rate estimation. Other objective of this work was to validate the weather radar locate in PR.

The second section of this paper describes the data source and the data collection process for rain gauges and radar. The third section describes the methodology and techniques used to perform validation and to determined the parameters used in the Z-R relationship. The fourth section presents the discrete and continuous validation results, in which rainfall observations area compared with rain rate estimations, and the fifth section presents some conclusions.

2. Data Collection

2.1 Radar Reflectivity Data

PR is an island located in the northeastern Caribbean between the Caribbean Sea and the North Atlantic Ocean, to the east of the Dominican Republic and west of the Virgin Islands. The National Weather Service (NWS) and National Oceanographic and Atmospheric Administration (NOAA) operates 158 high resolution Doppler weather radars including the one located in Cayey, PR. Rainfall estimation over PR is conducted by NEXRAD (Next-Generation Radar) the technical name is WSR-88D, which stands for Weather Surveillance Radar, 1988, and Doppler. Puerto Rico's NEXRAD is located in latitude 18.12°N and longitude 66.08°W with a height of 886.63m the maximum horizontal coverage is 462.5 km. NEXRAD base reflectivity data are updated every 5, 6, or 10 minutes, depending on whether the radar is in normal precipitation mode, storm precipitation mode, or clear air mode.

Base Reflectivity is an indirect measure of the intensity of precipitation occurring, and is reported in units of dBz (decibels). The radar emits pulses of energy into the atmosphere at regular intervals. When this energy impacts something (i.e. a raindrop, a snowflake, a mountain, etc.), some of the energy is scattered back to the radar dish. The amount of energy received back at the radar dish. The higher the dBz value the larger the object. Thus, large raindrops for example, produce high dBz values. In general, dBz values greater than 15 indicate areas where precipitation is reaching the ground; dBz values less than 15 usually are an indication of very light precipitation which in most cases is evaporating in the atmosphere before it reaches the ground. NEXRAD save the collected information in two formats: level II and level III. Level II data for PR are recently available; however, there were no level II data during the studied period (2002-2007). Thus, the Level III data were selected to perform validation.

2.2 Rain Gauge Data

PR has a rain gauge network that is administrated by the United States Geological Survey (USGS) and provides measurements every 15 minutes and includes 125 rain gauges with data available since January 2000. The rain gauge data were used to perform an accurate validation of the NEXRAD over PR.

Figure 1 shows the location of the radar, the spatial distribution of rain gauges, and the regions in which Puerto Rico was divided to perform the analysis. The black dot indicates the location of the NEXRAD and the red, blue and green stars show the location of the rain gauges for regions I, II and III, respectively.

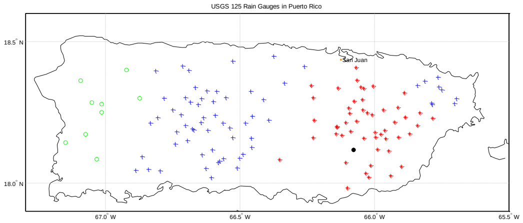

Figure 1 Location of the rain gauges and regions in Puerto Rico. *The black dot indicates the location of the NEXRAD and the red, blue and green stars show the location of the rain gauges for regions I, II and III, respectively.*

Table 1 shows the studied rainfall events. These nine events were selected because large amount of rain was observed, and some events caused floods and significant economical impacts over PR.

Table 1 Studied Rainfall Events

Rainfall Events
April 20, 2005
December 5-8, 2003
May 19-21, 2003
April 17, 2003
August 18, 2007
November 11-17, 2003
October 27-30, 2007
December 10-12, 2007
September 22, 2008

3. Methodology

The proposed methodology includes three major steps: (1) Identify the rain gauges that provide reliable information, (2) Divide PR in three regions according to the distance between the rain gauges and the radar with the purpose of developing the Z-R equations, and (3) Perform discrete and continuous validation.

3.1 Identifying reliable data

An automated procedure to filter reliable rain gauge data was implemented. This filtering procedure is a similar to the one suggested by Amatai (2000). The filtering parameters (P1 and P2) are calculated for each rain gauge separately. P1 is the correlation coefficient between the center radar pixel and the 5 minutes average gauge measured rain rate centered at the time of the radar scan. P2 is the rain gauge bias calculated from all the rain gauges combined. Thus, a rain gauge that exhibits a correlation coefficient less than 0.15 or a bias ratio outside of the interval [0.5, 2] was removed from the reliable data set.

3.2 Regression equations for each region

The conventional relationship for tropical regions was used as the reference calculation, and also for comparing the fitted regression equations. A power empirical relationship between the measured radar reflectivity and rain rate is used to convert the reflectivity into the rain rate. The conventional equation under tropical mode is:

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

The *Z-R* relationship for each region was developed using only reliable observations from each region. Parameters for each region were developed based on the nine rainfall events and using the following empirical equation.

$$Z = \alpha_i \, R^{\beta_i}, \qquad i = 1, 2, 3 \qquad (2)$$

Table 2 presents the values obtained for the parameters for each one of the regions. These values were obtained after selecting the observations for each region from the nine storms, and after applying the filtering algorithm. The analysis for each region varies depending of the number of stations included, but the regression process is the same for the three regions.

Table 2 Parameters obtained for each region

Parameters	Region I	Region II	Region III
α	164.551	188.358	200.989
β	1.336	1.286	1.364

Figures 2 to 4 show the time series of the cumulated rainfall for the rain gauges and the NEXRAD pixels in the corresponding region. These figures show evidences that the observed rainfall by the rain gauges are very close to the estimated rainfall by the radar.

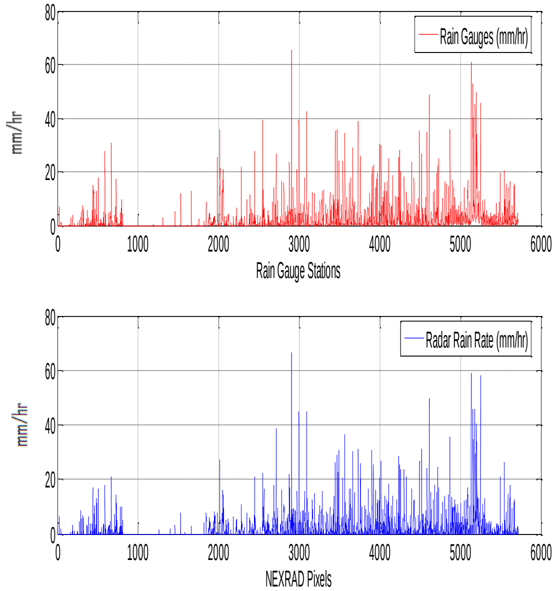

Figure 2 Time series of accumulated rainfall for the rain gauges and the NEXRAD pixels corresponding to Region I during the nine rainfall events.

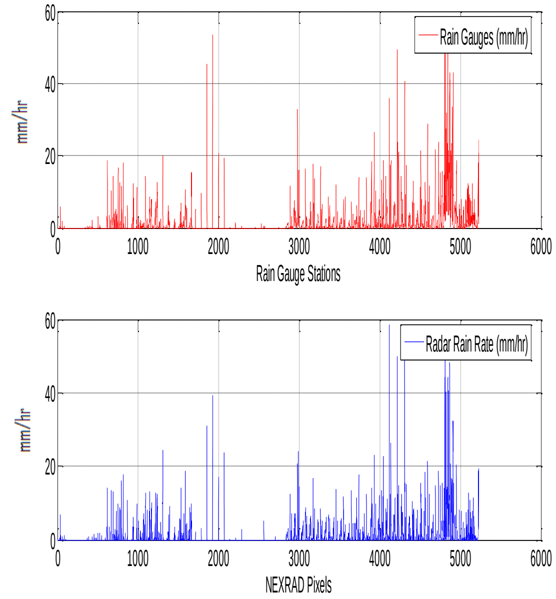

Figure 3 Time series of accumulated rainfall for the rain gauges and the NEXRAD pixels corresponding to Region II during the nine rainfall events.

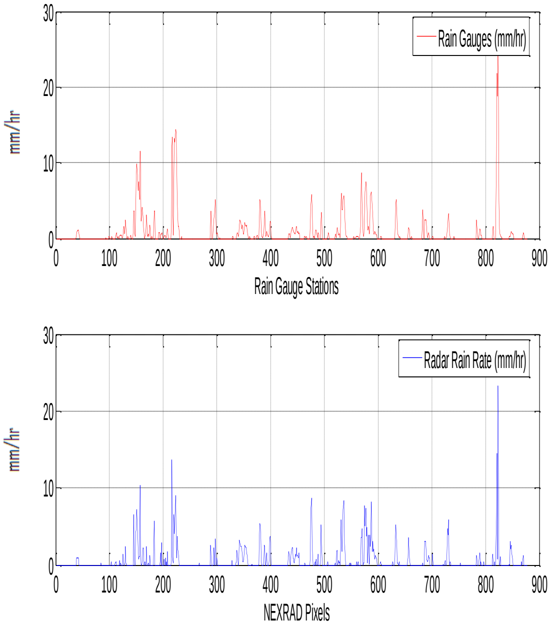

Figure 4 Time series of accumulated rainfall for the rain gauges and the NEXRAD pixels corresponding to Region III during the nine rainfall events.

3.3 Validation

Validation of the rainfall consists of comparing the radar rainfall (estimated) with observations (rain gauges) over the same time and space. The accuracy of rainfall estimates can be measured by decomposing the rainfall process as sequences of discrete and continuous random variables; i.e., the presence or absence of rainfall (discrete variable) and the amount of rainfall (continuous variable). The occurrence of rainfall events in a given area and at a particular time follows a Bernoulli process and consequently the estimation accuracy of rainfall events can be conducted by analyzing the contingency table. The typical scores that measure the accuracy of categorical forecasts are: hit rate (HR), probability of detection (POD), false-alarm rate (FAR), and discrete bias (DB). The continuous validation strategy consists of comparing the amount of rainfall that occurred at specific area in a particular time and the continuous measurements of accuracy are: mean absolute error (MAE), root mean squared error (RMSE), and continuous bias (CB).

Table 3 Contingency Table

		Rain Gauges	
		Yes	**No**
NEXRAD	**Yes**	*a*	*b*
	No	*c*	*d*

It is considered that the values provided by the rain gauges are the observed rainfall while the NEXRAD provides estimated rainfall values. The variable *a* in the contingency table is the number of times that the rain gauge identifies rainfall and the radar also identifies a rainfall at the same time and space. The variable *d* represents the number of times the rain gauge does not observe rainfall and the radar determines that there is no rainfall. The variable *b* indicates the number of times the rain gauge does not observe rainfall but the radar incorrectly indicates that there is rainfall. The variable *c* shows the number of times that the rain gauge detects rainfall but the radar incorrectly does not detect the rainfall.

3.3.1 Discrete Validation

To measure the accuracy and precision of the estimation a hit rate (HR), probability of detection (POD), false alarm (FA), and discrete bias (DB) were computed for each one of the Z-R relationship.

The hit rate is the fraction of the estimating occasions when the NEXRAD correctly determines the occurrence of rainfall event or no event. Probability of detection is the likelihood that the event would be estimated, given that it occurred. The false-alarm rate is the proportion of estimated rainfall events that fail to materialize. Bias is the ratio of the number of estimated rainfall events to the number of observed events (Wilks 1995).

$$HR = \frac{a+d}{a+b+c+d}$$

$$POD = \frac{a}{a+c}$$

$$FAR = \frac{b}{a+b}$$

$$DB = \frac{a+b}{a+c}$$

To analyze the results for the events a contingency table was created for the events analyzed. Table 4 presents the validation results.

Table 4 Validation Results

	Validation		
	Region I	**Region II**	**Region III**
Hit Rate	0.763	0.8	0.819
Probability of Detection	0.618	0.606	0.634
False Alarm	0.05	0.062	0.085
Discrete Bias	0.651	0.646	0.692

Table 4 shows that the hit rate exhibits a consistent small increment with distance. These unexpected results are may be influenced by the sample size that is lager in region I and smaller in region II and extremely small in region III. The probability of detection shows an expected small reduction in region II and an unexpected increment in region III. The discrete bias shows a consistent underestimation of the number of rainfall events in the three regions. The false alarm rate exhibits an expected consistent small increment with distance.

3.3.2 Continuous Validation

The accumulated rainfall across Puerto Rico was calculated to perform a comparison between the observed and estimated rainfall. The total rainfall is the accumulated rainfall obtained from the 125 rain gauges distributed around the island and the corresponding accumulated rainfall by the NEXRAD pixels at the same time and space.

Figures 5-7 show the scatter plots comparing the observed (rain gauges) and estimated (NEXRAD) accumulated rainfall every 15 minutes. From the continuous bias presented in tables 5 and 6 it can be observed that there is an underestimation by the NEXRAD, it is not clear if the underestimation is because of detection problems or because of an overestimation of the rain gauges.

Table 5 shows the errors obtained using the conventional equation for the tropical zone and table 6 shows the errors obtained by using the equation derived by each region. Tables 5 and 6 show that the derived equations for each region do not provide a significant improvement; i.e., it is not necessary to divide PR in different regions.

Table 5 Errors obtained using the conventional tropical equation

	Observed		
	Region I	**Region II**	**Region III**
MSE	14.184	12.895	4.108
MAE	1.93	1.79	1.01
Continuous Bias	0.664	0.679	0.752

Table 6 Error obtained using equation for each region

	Estimated		
	Region I	**Region II**	**Region III**
MSE	13.11	12.24	4.037
MAE	1.88	1.77	1.005
Continuous Bias	0.738	0.739	0.749

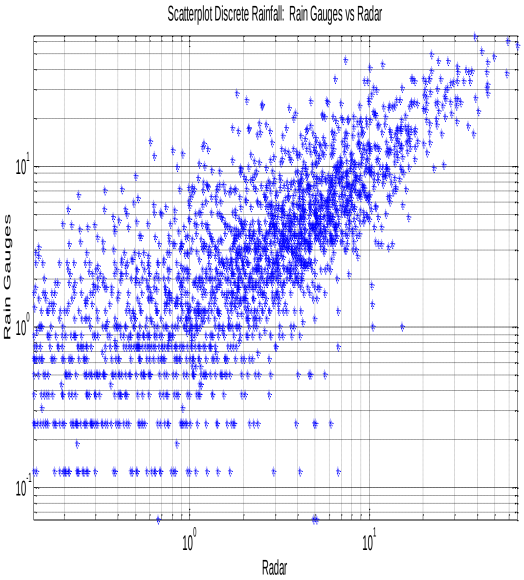

Figure 5 Comparison between the observed and estimated rainfall in Region I

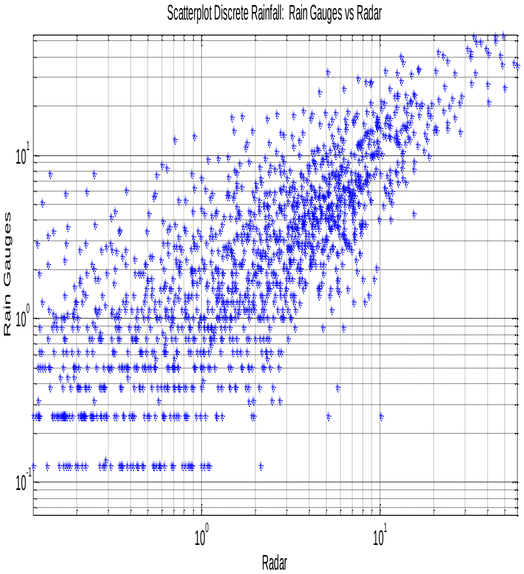

Figure 6 Comparison between the observed and estimated rainfall in Region II

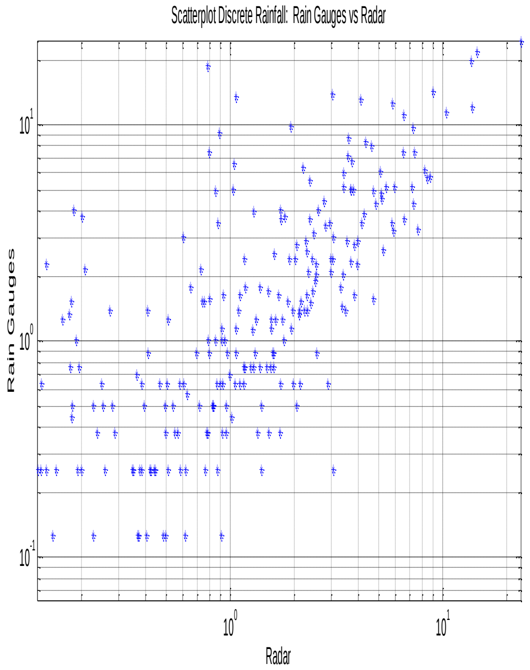

Figure 7 Comparison between the observed and estimated rainfall in Region III

4. Conclusions

It is important to select reliable observations to derive the parameters of the Z-R relationship. The filtering process contributes to improve the correlation between rainfall and reflectivity observations and reduces the bias estimation. Thus, in general the filtering process provides the possibility of deriving reliable Z-R relationship.

The measurement error due to the distance between the location of the rain gages and radar is may be smaller than the error associated to the sample size involved in the calculation. Thus, measurement error when there are large amount of observations is larger than when there are small amount of observations. Therefore is not worthwhile to segregate the study area and derive equations for different regions.

Discrete and continuous validation of the NEXRAD show that hit rate ranges from .76 to .82, which indicates that 76% to 82% of the time the radar attains the presence or the absence of rainfall events. The probability of detection range from 0.6 to 0.63, and the scores indicate that 60% to 63% of the times the radar detects the presence of rainfall events. The false alarm rate rage from 0.05 to 0.08, indicating that the radar incorrectly indicates the 5% to 8% of times that there are rainfall events when in reality there in not rainy event. The ideal value of the bias is the number 1, indicating an unbiased estimation. In this case the discrete bias range from .64 to .69, which indicates that the radar underestimate the number of rainfall events.

The continuous validation shows that the mean absolute error range from 1mm/h to 1.8 mm/h. This result indicates that the radar on the average provide and error that range from 1mm/h to 1.8mm/h.

Probably the estimation error due to the distance from the radar may be measured from a high resolution radars that are been installed in the western part of PR. These radars will have the capability of directly measuring at lower elevation the development of clouds and consequently the measurement error due to the distance from the radar will be measured.

Acknowledgements

This research has been supported by the NSF-ERC-CASA with a grant Number 0313747, NOAA-NWS grant number NA06NWS468001, and also by the University of Puerto Rico at Mayagüez. The authors appreciate and recognize the funding support from these institutions. Pedro L. Diaz director of PR-US Geological Survey provided the rainfall data from the PR rain-gauge network; we want to appreciate his invaluable contribution.

References

Amatai, E., 2000: *Journal of Applied Meteorology* Systematic Variation of Observed Radar Reflectivity-Rainfall Rate Relatons in the Tropics. **39** pp.2198-2208

Baeck, M. L., and J. A. Smith, 1998: Estimation of heavy rainfall by the WSR-88D. *Wea. Forecasting,* **13,** 416–436.

Brandes, E. A., J. Vivekanandan, and J. W. Wilson, 1999: A comparison of radar reflectivity estimates of rainfall from collocated radars. *J. Atmos. Oceanic Technol.,* **16,** 1264–1272.

Marshall, J. S., and W. M. Palmer, 1948: The distribution of raindrops with size. *J. Meteor.,* **5,** 165–166.

Punpim, P. M., Nutchanart . S., Climatological Z-R relationship for radar rainfall estimation in the upper Ping river basin. *ScienceAsia* **34,** 215–222.

Ramirez-Beltran, N.D., Kuligowski, R.J., Harmsen, E., Cruz-Pol, S., J.M. Castro, and Matos, I., Validation of Hydro-Estimator and NexRad over Puerto Rico.

Rosenfeld, D., Wolff, D. B. and Atlas, D. 1993 : *Journal of Applied Meteorology* General Probability Matched Relations between Radar Reflectivity and Rain Rate. **32** pp. 50-72.

Steiner, M., and J. A. Smith, 2000: *Journal of Applied Meteorology* Reflectivity, rain rate, and kinetic energy flux relationships based on raindrop spectra. **39** pp. 1923–1940.

Stellman, K. M., Fuelberg, H. E., Garza, R., Mullusky, M., An Examination of Radar and Rain Gauge-derived Mean

Areal Precipitation over Georgia Watersheds. *American Meteorological Society Journal.* 16(1), February 2001.

Wilks, D.S., 1995**:** *Statistical Methods in the Atmospheric Sciences: An Introduction.* Academic Press, San Diego, **467** pp. 65

Woodley, W. L., A. R. Olsen, A. Herndon, and V. Wiggert, 1975: Comparison of gauge and radar methods of convective rain measurement. *J. Appl. Meteor.,* **14,** 909–928.