ILLINOIS STATE WATER SURVEY
Meteorologic Laboratory
at the
University of Illinois
Urbana, Illinois

INVESTIGATION OF THE QUANTITATIVE DETERMINATION OF POINT AND AREAL PRECIPITATION BY RADAR ECHO MEASUREMENTS

Final Report

1 October 1961 - 30 September 1964.

Sponsored by
U. S. Army Electronics Research and Development Laboratory
Fort Monmouth, New Jersey

CONTRACT NO. DA-36-039 SC-87280

DA Task 3A99-07-001-01

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To record and analyze data on raindrop-size distribution in various parts of the world. These data will be correlated with appropriate radar parameters In order to improve the capability of radar in measuring surface rainfall intensities for Army applications such as radioactive rainout prediction, trafficability, and communications.

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PURPOSE

The object of this research is to study the utility of radar equipment in measuring surface precipitation, and to improve radar techniques in measuring precipitation for application by the Army to radioactive rainout prediction, trafflcability, and communications. Considerable effort is being directed toward determining the correlation between radar variables and actual rainfall quantities by means of raindrop-size distribution.

ABSTRACT

During the period of this contract, a raindrop camera was operated at Island Beach, New Jersey; Coweeta Hydrologic Laboratory, North Carolina; East Central Illinois raingage network; and for summer operation only at Mt. Withington, New Mexico, and Flagstaff, Arizona. The data obtained have been measured and preliminary calculations have been made.

The results of analysis of the relationships between rainfall rate and radar reflectivity are reported along with recommendations as to the appropriate relationship to be used under given conditions at various climatic regions. At a location such as Miami, Florida, a relationship determined by the thermodynamic instability is recommended. A single relationship is recommended for Majuro and Oregon where so far no stratification has made significant improvement.

The average drop size spectra from a number of locations are compared. Log normal curves best fit the spectra, but the parameters of the fitting curves do not seem to be orderly with rainfall rate.

PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

Three papers were presented at the Ninth Weather Radar Conference, Kansas City, Missouri, October 1961 and were included in the Proceedings. These papers were: "Attractive Forces Between Charged Drops and Their Effect on the Coalescence Process," by M. Fujiwara and E. A. Mueller; "Uncertainty in Rainfall Measurements Due to Drop Size Distributions," by E. A. Mueller; and "Effects of Stability on Drop Size Distributions," by R. M. Johnson.

Research Report No. 8, "Raindrop Size Distributions with Rainfall Types and Weather Conditions," by M. Fujiwara and Research Report No. 9B, "Raindrop Distributions at Miami, Florida," by E. A. Mueller were printed and distributed during the period of this contract.

"Liquid Water Content of Rain," by E. A. Mueller and A. L. Sims was presented at the Fifth Conference on Applied Meteorology, Atlantic City, New Jersey, March 1964 and at the Fourth Annual National Conference on Environmental Effects on Aircraft and Propulsion Systems, Trenton, New Jersey, September 1964. This paper was included as Appendix A of the Ninth Technical Report.

"Digital Computer as an Aid in Radar Data Reduction," by E. A. Mueller was presented at the Third Conference on Severe Local Storms, Urbana, Illinois, November 1963 and was included in the Proceedings.

Two papers were presented at the Eleventh Weather Radar Conference, Boulder, Colorado, September 1964 and were published in the Conference Proceedings. These papers are also included as Appendices to this Report. The papers are: "A Study of the Radar Precipitation Attenuation as Deduced from Drop Size Distributions," by E. A. Mueller; and "Case Studies of the Areal Variations in Raindrop Size Distributions," by A. L. Sims.

G. E. Stout and A. L. Sims visited USAERDL on June 24, 1964, to confer with technical personnel, and on September 1, 1964, E. A. Mueller visited USAERDL. September 14-18, E. A. Mueller and A. L. Sims attended the Eleventh Weather Radar Conference in Boulder, Colorado. On September 22-23, 1964, E. A. Mueller attended the Environmental Conference at Trenton, New Jersey, and visited USAERDL. The reader should refer to earlier reports for prior trips under this contract.

INTRODUCTION

Early attempts at measurement of rainfall rates by radar were not accurate enough for Army requirements. One of the major causes of the inaccuracy in early radar measurement of rainfall amount was determined to be the relationship between the radar signal and the rainfall rate. Much of the effort on this contract has been concerned with studying the variabilities in raindrop-size distributions and their effect on the radar rainfall relationship-.

Drop size distributions have been measured by the drop camera method in several locations around the world during the period of this contract and Contract No. DA-36-039 SC-75055. Some of this work is being continued on Contract No. DA-28-043 AMC-00032(E).

The raindrop camera samples one cubic meter of air space in about 13 seconds at intervals of every 60 seconds. Within this column all of the raindrops with diameters larger than 0.5 mm are measured by using semi-automatic calipers developed specifically for this purpose. The film data are projected on a screen so that the raindrop images are twice actual size. The measurement jaws of the calipers are then brought to the size of the image and a foot switch depressed. The measurement is entered automatically on IBM cards.

Each one-minute sample is approximately one cubic meter. The cards from the measurement table for each sample are processed to obtain the drop size spectra. A one-cubic-meter sample is large with respect to sampling volumes of other raindrop spectrometers, but still very small with respect to a radar volume. The problem of the representativeness of one cubic meter to the average radar volume of 10^6 to 10^8 cubic meters has not been determined. In an attempt to verify how adequate the sample is, the cameras were operated continuously at very close spacing during the summer of 1964.

These data have been considered for other Army applications such as tactical area radioactive rainout and visibility calculations. The data are also useful in cloud physics studies.

RADAR OPERATIONS

Three radars were operated during the Contract: the CPS-9, the TPS-10, and, during the summer of 1964, the M-33. No quantitative rainfall work was performed before the summer of 1964 since primary effort was directed toward the collection of raindrop size spectra data. Analyses were performed to determine the best possible relationships between rainfall rate and radar reflectivity from the drop size data. However, during the summer of 1964 when the drop cameras were located on the East Central Illinois raingage network, the radars were used to measure the Z values directly over the drop cameras. Since measurements of the drop size data have not been completed, these comparisons have not been made. The M-33 data will also be used to determine the rainfall amount which will be compared with the raingage amount. Unfortunately, no signal integrating device has been operated on the radar. However, some means of signal integration is planned for future operations.

In general, the radars operated successfully although both the CPS-9 and TPS-10 are requiring more maintenance as they become older. The radars were also used as an aid in short time forecasting for operations of the drop cameras. Data from the radars were used on studies being supported by the State of Illinois, the Crop-Hail Insurance Actuarial Association, and the U. S. Atomic Energy Commission.

RAINDROP CAMERA OPERATIONS

During the period of this contract, raindrop data for about one year were sampled at the Coweeta Hydrologic Laboratory, Franklin, North Carolina, and at Island Beach, New Jersey. A camera was operated briefly at Mt. Withington, New Mexico, during the summers of 1961-62 and at Flagstaff, Arizona in 1963. During the summers of 1963 and 1964, multiple camera experiments were conducted in Illinois. Some results of 1963 data collections are in Appendix A.

Three raindrop cameras were operated in the East Central Illinois raingage network from 1 May 1964 through 22 September 1964. Two of these were close together and were synchronized at a rate of 28 frames per minute per camera. This system has been described in greater detail in the Ninth Technical Report of this contract. The third camera was operated in the usual 7 frames per minute mode. It was located 2 miles south of the other two.

Because rain periods were infrequent, only 14 rolls of data were obtained during 1964 from each of the cameras in the synchronous operation, and 11 rolls from the third camera. Measurement of the film from the synchronized operation has been started.

RADAR. RAINFALL RELATIONSHIPS

One of the primary purposes of this contract was to determine the most reliable relationship between rainfall rate and the radar parameters from raindrop observations. For this purpose drop size data were gathered from various climatic regions around the world. Analysis of these data permits recommendations on the best radar relationships for a semi-tropical climate (Miami, Florida), a dry summer maritime climate (Corvallis, Oregon), and a tropical maritime climate (Majuro, Marshall Islands).

Raindrop size distributions are obtained by a photographic process. The optical system for the camera consists of a 29-inch parabolic mirror with a focal length of 4100 mm as the first element in a telecentric optical system. The second element is a 300-mm Schneider-Kreuznach Xenar lens. The aperture stop of this lens is placed at the focal point of the 29-inch parabola to reduce effects of perspective to a minimum. The sample volume is a right circular cylinder 14 inches high and 29 inches in diameter. After corrections due to the obstructions of the light path by the diagonal flat and necessary mirror mounts are made, the sampling volume becomes about 1/7 of a cubic meter. Ordinarily, the camera is operated for seven pictures in about 13 seconds and then remains quiescent for 47 seconds. The result is that a one cubic meter air space is sampled once every minute. The drops from these seven frames are measured and the rainfall rate and radar reflectivity calculated. One sample is considered to be the result of these calculations performed from a group of seven pictures. This is referred to as a one minute sample or one cubic meter sample.

The raindrop size data were used to calculate the rainfall rate, R, and the radar reflectivity, Z, for 3.2 cm wavelength. These R-Z points were entered onto IBM cards. The distribution of the sample with respect to the month of the year is shown in Table 1.

In analyzing the data, two methods were adopted: the first consisted of the commonly accepted procedure of finding the best (in the sense of least squares) linear relationship between the logarithms of R and Z; the second consists of tabulating for each 1 db interval in Z the maximum, minimum, and average rainfall rate. The logarithmic least squares method suffers from the disadvantage of forcing on the data a particular mathematical form. It also gives large weights to the rainfall rate variations in the small rate area, since the logarithmic deviations are large in this area. That is to say, the overall curve is highly biased by the large number of observations at rainfall rates less than 5 mm/hr. These rates are of less importance in determining total rainfall than the number of observations would indicate. The drop size spectra are also less accurate in this region since the total number of drops becomes small and the sampling noise becomes relatively more important. Furthermore, the logarithmic (or percentage) error is minimized by this procedure, and the percentage error in Z and R can be very large with only small error in the drop size spectrum. The advantage of the logarithmic least squares is that

TABLE 1

DISTRIBUTION OF DATA COLLECTION BY MONTHS

Location	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total	
Woody Island, Alaska	6	5	3	6	9	8	7	10	5	3	10	2	74	Days
	225	133	33	216	351	442	343	391	56	94	326	78	2688	Samples
Miami, Florida	7	1	9	4	7	3	8	12	9	6	6	7	79	Days
	394	66	306	46	448	82	207	250	128	189	184	206	2506	Samples
Majuro, Marshall Islands	4	1	7	20	11	12	7	11	7	4	5	6	95	Days
	81	44	67	445	215	524	271	457	208	96	63	81	2552	Samples
Corvallis, Oregon	12	1	10	16	-	9	-	-	-	-	-	11	59	Days
	501	8	198	358	-	203	-	-	-	-	-	435	1703	Samples
Bogor, Indonesia	14	4	15	13	5	1	-	-	-	-	12	12	76	Days
	426	55	333	253	63	16	-	-	-	-	239	494	1879	Samples
Champaign, Illinois	1	-	1	1	4	2	6	13	3	5	-	-	36	Days
	17	-	20	14	68	41	208	343	152	256	-	-	1119	Samples
Island Beach, New Jersey	6	9	6	7	5	13	9	7	5	8	8	4	87	Days
	199	501	236	298	121	486	292	122	92	287	326	187	3147	Samples
Coweeta, North Carolina	6	10	17	9	7	14	15	11	7	4	7	8	115	Days
	357	532	674	410	283	661	553	384	198	123	213	416	4804	Samples
										Totals			621	Days
													20,398	Samples

it is easily found and an estimate of the scatter can be easily made by use of the standard error of estimate or alternatively the correlation coefficient. Admittedly, these measures are not completely justifiable since the variation of the points around the regression line is not normally distributed. Nevertheless its use appears reasonable in estimating the relative reliability of the different stratifications which were made.

The second procedure of determining R-Z relationships provides a means of reducing the above criticisms at the expense of a loss of a closed form of the result and the ease of estimating the reliability of the estimate. If the ultimate use of the data is by means of a computer the introduction of a table of R-Z instead of an equation may not be a handicap. A complete discussion of the tabular data analysis can be found in the Eighth Quarterly Report on this contract and in the Seventh Quarterly Report on Contract DA-36-039 SC-75055.

In the analysis of the data by means of 1 db intervals of Z a second method of estimating the rate from the Z was investigated. This consisted of minimizing the function

$$\sum_i R_i \left| R_i - R^* \right|$$

where R_i is the observation of R and R* is the estimate of R from Z. This procedure tends to produce higher estimates of rate for a given Z. If, in the application to which the R-Z is applied, it is more serious to underestimate rather than overestimate a rainfall amount, the use of this type of weighting is indicated.

Various types of data stratification have been performed in order to reduce the scatter and improve the reliability of the amount of rainfall. The stratifications which were examined were by rain type (continuous rain, rain showers, and thunderstorms), by synoptic type (cold frontal, warm frontal, air mass, etc.), and by the thermodynamic instability from the prior radiosonde.

Miami, Florida - Logarithmic R-Z Relationships

Table 2 shows the results of the R-Z relationships determined for the data from Miami. The first column indicates the means of stratifying the data. The number of samples represents the total number of individual cubic meter samples in the analysis. The correlation coefficient is the coefficient from the logarithmic regression analysis. A and b are the regression coefficients as determined with Z as the independent variable. They are reported in the form

$$Z = AR^b$$

to conform with the usual means of representing the data. However, Z was chosen as the independent value since it is assumed that the use of these relationships will be in estimating the rainfall rate, R, from a radar measurement of the reflectivity. In these data the Z reported is the equivalent Z for 3.2 cm radiation. The Z for the larger drops has been corrected for Mie scattering. In general, the differences are small and the results should be applicable to all longer wavelengths without significant differences.

Examination of the table indicates an increase in the correlation coefficient for the stability classification. This classification was performed by considering the thermodynamic instability as determined from the radiosonde prior to the rainfall. The method chosen to evaluate the sounding consists in determining the expended or liberated energy resulting from lifting a parcel of air adiabatically from the surface and each 50 millibar level below 600 mb up to 100 millibar height. A measure of the liberated energy on a thermodynamic diagram is the area between the wet adiabat and the actual sounding temperatures. A computer program was written to calculate this area and the resulting positive area stability index (PASI) was used to classify the data. A more detailed discussion of the PASI investigation can be found in the final report on Contract DA-36-039 SC-75055.

Some order to the progression of the exponent in the regression coefficients can be noted. For stable conditions the lowest exponents are obtained. This is indicative of rainfall with small drops and relatively larger numbers. As the instability increases, the exponent becomes larger and finally remains nearly constant. The lowest correlation coefficient for any group was 0.95, and six of the ten groups were 0.97 or better. Synoptic classifications on the other hand had one small class with a 0.91, and only three of the eight classes had 0.97. Statistical tests of the improvement in these values yield a barely significant improvement for the stability classifications.

To evaluate the magnitude of error which might be made in estimating rainfall amount using these two methods of classification, several storms were chosen. A rainfall amount was estimated from each Z value according to one of the R-Z relationships. These estimated values of R were then compared with the true values of R measured. Since these data were not independent, i.e., the same points were used in determining the relationships, the method is not strictly valid. To some extent the results reflect the differences in finding a logarithmic least squares as opposed to fitting a curve which minimizes the deviations themselves. These results are presented in Table 3. This test also indicates that the stability criterion for choice of equations is somewhat superior to the synoptic classifications. It should be noted that on a storm basis using the best relationships, errors on the order of 20 percent can still be made in the total amount.

Florida - Tabular Relationships

Figures 1, 2, 3, and 4 contain tabulated values of the R-Z relationship.

In these figures, the column labeled Z is the radar reflectivity defined as ΣD^6 over the unit volume of one cubic meter. The units of this column are 10's of mm^6/m^3 (first entry Fig. 1 of 11.2 represents 112 mm^6/m^3). The Z intervals are one decibel apart and each row contains the data points whose Z values lie from 0.5 db below the indicated value to 0.5 db above the indicated value. It can be noted that some of the intervals are always empty.

This is due to the necessity of rounding and recording Z on cards as 000001 and 000002 which are 3 db apart. The second column is the best estimate of the rainfall rate, R*, subject to the minimization of $S = \sum_{i} R_i \left|R_i - R^*\right|$. This criterion tends to produce estimates of R which are weighted towards the higher rates and, thus, to overestimate more than underestimate. Columns 3 and 5 are the minimum and maximum rainfall rates for each of the Z intervals. The column headed R AVE is the average R defined as $\frac{1}{N} \sum_{i}^{n} R_i$ where N represents the number of samples in each interval. The column labeled S is the minimum sum corresponding to the R* reported. The columns labeled UNDER and OVER represent the extremes of error possible within the data set and are defined as

$$(\text{UNDER}) = \frac{R\ MAX - R^*}{R^*}$$

$$(\text{OVER}) = \frac{R^* - R\ MIN}{R^*}$$

The rainfall rate data from Miami and Majuro were rounded to the nearest mm/hr and entered on cards before this analysis was performed. It can be noted that a number of the lower Z intervals repeat values of R* = 1.0. It is apparent that if this region is of interest, a recalculation from the original drop size measurements to obtain lower readings of R will be necessary.

Examinations of the tables in Figures 1-5 lead to qualitative verification of the benefits to be derived from stratification of the data. It can be noted that the average OVER and UNDER values

TABLE 2

LOGARITHMIC LEAST SQUARES REGRESSION COEFFICIENTS FOR MIAMI

Class	Number of Samples	Correlation Coefficient	$Z = AR^b$ A	b
		No Classification		
All data	2507	.95	286	1.43
		Rain Type Classification		
Continuous Rain	911	.94	322	1.33
Rain Showers	696	.95	250	1.47
Thunderstorms	902	.94	224	1.51
		.94		
		Synoptic Classification		
Air Mass	467	.98	323	1.42
Pre-Cold Front	744	.95	280	1.49
Cold Front	187	.95	198	1.54
Warm Front	341	.96	403	1.24
Overrunning	196	.94	302	1.36
Easterly Wave	536	.97	296	1.35
Trough Aloft	80	.97	261	1.43
Pre-Cold Occlusion	40	.91	330	1.66
		.95		
		Stability Classification		
PASI < 0 (stable)	167	.96	324	1.27
PASI = 0	238	.95	352	1.30
1 < PASI ≤ 25	559	.95	358	1.31
26 < PASI ≤ 50	161	.97	420	1.41
51 < PASI ≤ 100	117	.97	206	1.42
101 < PASI ≤ 150	133	.98	313	1.39
151 < PASI ≤ 200	416	.96	304	1.41
201 < PASI ≤ 300	367	.97	307	1.41
301 < PASI ≤ 400	286	.97	295	1.36
> 400 (unstable)	136	.97	264	1.40
		.97		

TABLE 3

COMPARISONS OF PERCENTAGE ERRORS OF RAINFALL AMOUNTS
USING SYNOPTIC AND STABILITY CLASSIFICATIONS

Date	Synoptic Type	PASI Type	Total Rainfall mm	Error in Estimate (%) Syn.	PASI
8/28/57	Easterly Wave	300-400	31	16	19
5/5/58	Easterly Wave	150-200	62	-5	-4
5/23/58	Easterly Wave	25-50	50	-23	-4
11/27/57	Warm Front	200-300	44	-27	-20
12/23/57	Warm Front	1-25	36	0	10
9/19/57	Air Mass	300-400	78	4	3
10/10/57	Cold Front	150-200	49	35	8
		Average Magnitude		15.7	9.7

listed in Figure 4 for all of Miami are, in general, larger than the values listed in Figures 1 and 2. Admittedly, this is only a qualitative verification because of the sensitivity to the maximum and minimum value in each interval as a function of sample size. Sample calculations such as were performed for Table 3 indicate that the. results from the tabular output are not different from estimates obtained from the equation (see the Eighth Quarterly Report on this contract).

Oregon - Rainfall Rate-Reflectivity Relationship

Rainfall rate-reflectivity relationships have been determined from the Oregon data. In general, there was very little difference in the results regardless of classification schemes used. Table 4 presents the results of the logarithmic relationships. The highest rainfall rate that was measured was 27 mm/hr. When the data were originally measured, all minutes with rates less than 0.5 mm/hr were discarded. If there were less than 8 drops per cubic meter the sample was not measured. After the preliminary analysis, it became apparent that more detail would be required in the rainfall rate. All minutes which had previously been measured whose calculated rates were equal or greater than 0.1 mm/hr were added, but no additional measurements were made. This results in a slight weighting of the low rates to the larger number of drops and also does not show as many samples in the range 0.1 to 0.5 mm as were available.

The total scatter of points around the regression line is not greatly different from the scatter in the lower rate region of the Miami data, but since the variance of R and Z are both relatively smaller than from the total Miami data, the correlation coefficient is lower.

There is no benefit to be obtained by the synoptic, stability, or rain type classification. It is recommended that in a climatic area similar to Oregon a single R-Z relationship be used.

A tabular form of the R-Z relationship is found in Figure 4. Comparison of the over and under columns with the corresponding entries in the Miami table in Figure 4 supports the earlier statement that the total scatter is not different in Oregon and Miami for the low rates. In fact, if the average "over from 1.mm/hr to

TABLE 4.

LOGARITHMIC LEAST SQUARES REGRESSION COEFFICIENTS FOR OREGON

Class	Number of Samples	Correlation Coefficient	$Z = AR^b$ A	b
	No Classification			
All data	1636	.92	301	1.64
	Rain Type Classification			
Continuous Rain	600	.92	295	1.59
Rain Showers	218	.91	327	1.66
Thunderstorms	82	.95	339	1.64
Missing	736	.91	294	1.67
		.92		
	Synoptic Classification			
Air Mass	157	.95	322	1.62
Post Cold Front	204	.90	322	1.70
Overrunning	352	.92	307	1.56
Warm Front	158	.91	295	1.66
Warm Occlusion	175	.95	339	1.48
Pre-Warm Occlusion	151	.90	309	1.92
Post Warm Occlusion	320	.88	268	1.81
		.92		
	Stability Classification			
PASI $<$ 0	219	.88	286	1.73
PASI = 0	692	.93	305	1.67
1 $<$ PASI $\leq$ 25	411	.92	300	1.62
25 $<$ PASI $\leq$ 50	106	.91	308	1.52
		.91		

26 mm/hr is determined, Oregon has 0.62 error and Miami has 0.74.

The Oregon values of both A and b are larger than the corresponding values from Miami. This indicates that for equal rainfall rates the reflectivity at Miami is less than at Oregon, which requires Oregon to have larger drops than Miami. This appears to be true. The Increase In size can be noted in Figure 15 of a later section. The median scattering diameter is defined as the diameter', D_z, at which half of the scattering is due to drops larger than D_z. When D_z from Oregon is compared with Miami it is noted that the Oregon values are higher for all rates between 1 and 15 mm/hr. At rates between 15 and 25 mm/hr the D_z values from the two locations are equal, with a value around 2.6 mm. Miami D_z is about 2.2 for rates below 15 mm/hr while Oregon D_z remains high, around 2.6 mm.

Majuro-Rainfall Rate-Reflectivity Relationships

The data from Majuro were separated using the same classification schemes as were used at Florida and Oregon. As can be noted in Table 5, the separations did not produce significantly different relationships. Several classes were empty or had less than 50 samples and were discarded from the analysis. In general, the coefficient of R in the relationship is smaller than the coefficient at Florida and Oregon. The exponent is close to the value obtained at Florida. It is recommended that in a climatic area similar to Majuro, a relationship of $Z = 184\ R^{1.40}$ be used.

The tabulated form of the R-Z relationship is found in Figure 4 for the unstratified data and in Figure 5 for the PASI classification of the data. Analysis of several days of data In a manner similar to that used with the Miami data and presented in Table 3 is presented in Table 6. In these cases the percentage error tends to decrease with increased total rainfall amount. This

TABLE 5

LOGARITHMIC LEAST SQUARES REGRESSION COEFFICIENTS FOR MAJURO

			$Z = AR^b$	
Class	Number of Samples	Correlation Coefficient	A	b
	No Classification			
All data	2443	.95	184	1.40
	Rain Type Classification			
Continuous	952	.92	226	1.46
Rain Showers	1491	.97	146	1.42
		.95		
	Synoptic Classification			
Easterly Wave	1126	.95	196	1.38
Trade Wind Showers	239	.98	126	1.47
Intertropical Convergence Zone	1136	.95	196	1.38
		.96		
	Stability Classification			
50 < PASI ≤ 100	738	.96	191	1.40
100 < PASI ≤ 150	736	.94	172	1.41
150 < PASI ≤ 200	356	.92	234	1.36
200 < PASI ≤ 250	303	.97	143	1.41
250 < PASI ≤ 300	160	.92	207	1.47
PASI > 300	91	.97	153	1.38
		.95		

tends to emphasize the added percentage reliability that is obtained when larger numbers and longer times are used. More detailed information on the R-Z relationships from Majuro along with scattergrams of R-Z plots can be found in Quarterly Technical Report No. 1 on this contract.

TABLE 6

ERRORS IN USING THE ALL MAJURO RELATIONSHIP ON SELECTED STORMS

Date	Total Rainfall (mm)	Duration (minutes)	Error in Estimate (%)
4/24/59	5	40	-22
6/8/59	11	72	+6
6/9/59	10	60	+12
8/18/59	18	105	+8

Multlple Regression Analysis of R, Z, and Q

In the Ninth Technical Report on this contract there is a report on a study of the gain in accuracy that might be obtained by independently measuring the radar attenuation, Q, simultaneously with Z to predict R. This study was performed by means of multiple correlation of the logarithms of the variables and also with no transformation of the variables. In both cases, the residual or unexplained sum of squares was not significantly decreased by the addition of the Q variable. From these data it would not appear profitable to attempt to reduce the uncertainty in radar rainfall by means of measuring attenuation simultaneously. The relationship between Q, and R Is slightly better than between Z and R, so that measurements of attenuation would yield somewhat better estimates of rainfall. However, the difficulties inherent in measurement of attenuation far outweigh the slight gain in reliability.

AVERAGE DROP SIZE DISTRIBUTIONS

Under this and previous Army contracts, statistically significant collections of drop size distributions have been obtained at eight different geographical locations. The distribution of these data collections by location and months is shown in Table 1. Since there is a total of over 20,000 samples, some averaging of these data is appropriate in order to discover general trends and characteristics of the distribution curves. The data from each location were sorted by rainfall rate, then grouped into increments of rate, 1 mm/hr wide at the lowest rates and increasing in size at higher rates. At most locations above 50 mm/hr, groups of 10 samples each were used. The average number of drops per cubic meter in each .1 mm increment of drop diameter from .5 through 7.0 mm was calculated by the computer. From this average distribution the usual parameters were calculated. Average distributions for selected rates at Miami, Florida; Majuro, Marshall Islands; Corvallis, Oregon; Island Beach, New Jersey; and the Coweeta Hydrologic Laboratory, Franklin, North Carolina, are shown in Figures 6 through 10. On all the average distribution figures, N_S is the number of samples in the average; N_T is the average total number of drops per cubic meter, and R is the rainfall rate in mm/hr.

The average distributions are generally monomodal curves with modes occurring between 0.9 and 2 mm. Above the mode, the curves are very nearly straight lines on the semi-logarithmic plots. The number of drops decreases sharply for diameters less than the mode. The distributions are generally smoother and have a more systematic relation to rainfall rate at the low rates; at high rates, they are more erratic due to the smaller number of samples in the averages.

From these figures some geographical variations can be noticed. The New Jersey curves have some similarity to those of Majuro in the relative sharpness of the peak of the distributions; however, at the larger drop sizes, New Jersey has more drops than Majuro. The Miami distributions are generally similar to New Jersey at large drop sizes, but have broader modes located at larger drop sizes.

The average distributions for thunderstorms, rainshowers, and for continuous rain at Miami, Florida, are presented in Figures 11, 12, and 13. An interesting feature of the thunderstorm curves, Figure 11, is the rapid increase in small drops at rates above about 50 mm. Notice, for example, that the number of .7 mm drops increases from 1.7 at 43.6 mm/hr to 335 at 215.6 mm/hr. For the same change in rate, the number of 3 mm drops increases from 2.2 to only 18. This effect is also apparent on the curves for all Miami data, Figure 6, since at the high rates most of the rain came in thunderstorms.

In Figure 14, average total number of drops is plotted against the rainfall rate. Notice that the slope of the data for Miami increases beginning at 50 mm/hr.

The median volume diameter (as determined from the average distributions) is plotted against rainfall rate in Figure 15. It should be pointed out that both total number of drops and the median volume diameter are related much better to rainfall rate in the average plots than would be apparent from plotting individual one cubic meter samples.

FITTING EQUATIONS FOR DROP SIZE DISTRIBUTIONS

Several fitting equations have been proposed for drop size distributions. Probably the best known and most used one is that of Marshall and Palmer[1],

$$N_D = N_o \exp(-\lambda\ D) \qquad (1)$$

where N_D & D is the number of drops per cubic meter of diameter between D and D + & D mm, and N is the value of N_D for D = 0. N_O was considered constant with a value of 0.08 cm^{-4}. The parameter λ was related to rainfall rate by the equation

$$\lambda = 41\ R^{-0.21} cm^{-1} \qquad (2)$$

where R is the rainfall rate in mm per hr. These equations have been found very useful by many investigators due largely to their simplicity. However, the number of small drops is overestimated quite severely, and it has been found that much of the raindrop camera data is not fitted well by these equations with a constant N_O and with λ determined by Eq. (2).

Fujiwara[2], in Research Report No. 8 of this contract has proposed the equation

$$N_D = \alpha\,(D-D_o)^2 \exp[-\beta\,(D-D_o)^3] \qquad (3)$$

where a, (3, and D are empirical parameters. This equation fits the small drop portion of the distribution much better than Eq. (1) Attempts to fit it to distributions by computer have been reported in the Quarterly Technical Report No. 8 of this contract. These attempts were less than satisfactory.

Recently, the log-normal distribution has been re-examined as to its applicability to drop size distributions. The use of this distribution has been suggested by Levin[3]. Also, Matvejev[4] references the work of Kolmogoroff on this equation. Irani and Callis[5] use the log-normal distribution for particle size distributions in general. This distribution has the appearance of a Gaussian normal distribution if the frequency of occurrence is plotted against the logarithm of the drop diameter.

The log-normal distribution can be expressed in the following form for use with drop size distributions:

$$N_D\ \delta D = \frac{N_T}{\sqrt{2\pi}\,\ln\sigma}[\exp -(\frac{\ln D/D_G}{\sqrt{2}\,\ln\sigma})^2]\ (\ln\frac{D+\delta D}{D}) \qquad (4)$$

In this equation, N_D & D is the number of drops per m^3 of diameter between D and D + & D, and N_T is the total number of drops in the distribution. D_G is the geometric mean diameter of the distribution and is computed readily from the distribution by the equation

$$\ln D_G = \frac{\sum_{i=1}^{i=n} (n_i \ln D_i)}{N_T} \qquad (5)$$

The geometric standard deviation, σ, is then given by

$$\ln \sigma = \sqrt{\frac{\sum_{i=1}^{i=n} n_i (\ln D_i - \ln D_G)^2}{N_T}} \qquad (6)$$

The average distributions were fitted by computing In σ and In D_G using equations (5) and (6); then these values were used in Eq. (4) to calculate the "theoretical" points on Figures 6 through 13. In general, these points fit the data very well.

Attempts have been made to relate D_G and σ to R. The relationships are not as orderly as would be desired; further study is needed in this area.

PRECIPITATION ATTENUATION

In the Ninth Technical Report a study of the precipitation attenuation from drop size distributions was reported. It was suggested that attenuation be related directly to the Z parameter rather than to the R parameter. It was shown that if a 3.2-em wavelength is used for quantitative work that some correction (but not complete) produces better estimates of rainfall amount than ignoring the precipitation attenuation. The attenuation versus Z for Miami, Alaska, and Majuro are presented in tabular and graphical form in the Ninth Report. The attenuation versus rainfall rate for Miami is also shown and agrees with the Robertson-King data except at low rainfall rates.

MAJURO CONDENSATION LEVEL AND EVAPORATION EFFECTS ON DROP SIZE DISTRIBUTIONS

In the Fifth, Sixth, and Seventh Technical Reports a study of the average shape of the drop size spectra for different condensation levels was reported. Spectra obtained with high condensation levels are narrower and with higher total concentrations than are obtained from the lower condensation levels. It was shown that this is not an effect of drop evaporation below the cloud base since evaporation tends to broaden the distribution. Effects of evaporation were illustrated in the Seventh Technical Report and showed that only under very dry conditions with reasonably high cloud bases does evaporation materially change drop size spectra. The mechanism of continuing coalescence process below cloud base was discarded by reason of the larger total number of drops which are obtained from the high based clouds. It is assume that any wind sorting effects would not be active on the average Since the distributions considered are actually averages over several days, it would seem that wind sorting can be discarded. Raindrop break-up would possibly explain the differences in total number and also possibly the narrower spectra. However, break-up usually does not occur until the drops become quite large, and thus is thought to be of small importance. It is therefore tentatively concluded that different distributions are in existence at cloud base and are therefore due either to different cloud mechanisms or due to different times of growth or growth rates within the cloud.

ELECTROSTATIC FORCES BETWEEN CHARGED DROPS

In the Second Technical Report a discussion of the electrical forces between charged drops was reported. The effect of these forces on the coalescence process is considerable. The work that was initiated under this contract was expanded and continued on ARPA Grants No. DA-36-039 SC 62-G19 and DA-AMC-36-039 63-G2, "Investigation of Water Droplet Coalescence," and NSF Grant GP-2528, "Experimental and Theoretical Investigation of the Coalescence of Liquid Drops."

OVERALL CONCLUSIONS

Extensive analysis of raindrop size spectra have indicated that the radar's ability to measure rainfall will be ultimately limited to an accuracy on the order of 20 percent in storm rainfall total. This variability may eventually be reduced by data stratification by means of variables other than those investigated. Several variables that have been tried on a small scale which did not yield better results are level of free convection, level of condensation, windshear aloft. More profitable stratifications have been presented in the body of this report and in the earlier technical reports on this contract. For semitropical climate such as Florida, a stratification based on thermodynamic Instability is recommended. For a maritime tropical trade wind location such as Marshall Islands, and a dry summer maritime climate such as Oregon no stratification is recommended.

A study of the form of the drop size distributions was pursued during this contract. A coalescence distribution was used successfully to fit the drop size data from Oregon and Majuro, but it does not fit the Miami spectra. A log normal distribution was found to be a better fit for all of the data from all locations. This form of a fitting curve is recommended as the best. Computations using a log normal fitting curve are reasonably tractable, particularly if computing facilities are available for the initial fitting and determinations of the log normal parameters.

A study of the variability of R-Z relationship with location in respect to the center of the storm was conducted and reported in the Ninth Technical Report. It was found that in all but one case there was no difference that could be detected in the storm relationships.

RECOMMENDATIONS

All of the conclusions in this report are based on the assumption that one cubic meter sample is a statistically representative sample. This assumption should be verified by obtaining a larger sample of the same rainfall and comparing the larger volume with the one cubic meter volume. The data for this study were collected during the summer of 1964, and it is recommended that a further evaluation of them be undertaken.

At present there have been no results of any researchers in the field who can use a radar set for quantitative precipitation with an accuracy within the limits imposed by drop size spectra variations. Therefore, it i3 recommended that attention to radar data processing techniques and improved radar calibration procedures be initiated.

Data have been obtained from a humid continental climate typified by Franklin, North Carolina, and Island Beach, New Jersey. It is recommended that these data be subjected to stratifications and best R-Z relationships be obtained from them.

REFERENCES

1. Marshall, J. S. and S. McK. Palmer, 1948: The Distribution of raindrops with size. J. Meteor., 5, 165-166.

2. Fujiwara, Miyuki, 1961: Raindrop Size Distributions with Rainfall Types and Weather Conditions, Research Report No. 8, Contract No. DA-36-039 SC-87280.

3. Levin, L. M., 1954: Size Distribution Function for Cloud Droplets and Raindrops. Dok. Akad. Nank SSSR, 94, 1045. Trans. T263r of D. R. B., Ottawa, Can.

REPERENCES (cont'd)

4, Matvejev, L. T., 1964: On the Formation and Development of Layer Clouds. Tellus, 16, 139-149.

5. Irani, R. R. and C. p. Callis, 1963: <u>Particle Size</u>; <u>Measurement</u>, <u>Interpretation</u>, and <u>Application</u>, New York, John Wiley and Sons, 165 pp.

PERSONNEL

The following personnel were engaged in the research during the period of this report:

Name and Title	Starting Date	Hours Worked	Terminated
G. E. Stout Project Director	10/1/61	102	
Eugene A. Mueller Electronic Engineer	10/1/61	510	
Arthur L. Sims Research Assistant	5/13/63	1020	
Stanley G. Peery Electronics Technician II	3/1/63	1020	
Robert D. Vogt Scientific Assistant	8/12/63	142	9/17/64
Marian E. Adair Meteorological Aide I	9/24/62	340	
Edna M. Anderson Meteorological Aide I	10/1/61	1020	
Karen Sue Adair Laboratory Helper	6/17/63	28	6/5/64
Gustav A. Berquist Laboratory Assistant	2/18/64	65	5/21/64

PERSONNEL (cont'd)

Name and Title	Starting Date	Hours Worked	Terminated
Michael R. Goodale Laboratory Assistant	2/3/64	95	5/8/64
Doris M. Kaberline Card Punch Operator	2/10/64	460	9/25/64
Alfred S. Davis Research Assistant	5/24/64	202	8/31/64
William W. Lowe Laboratory Assistant	5/18/64	352	

N=409 MIAMI PASI NEGATIVE

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	1	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	17	.0	.00	.00
28.2	1.0	1.0	1.1	2.0	17	4.0	1.00	.00
35.5								
44.7	2.0	1.0	1.4	2.0	22	13.0	.00	.50
56.2	2.0	1.0	1.5	2.0	11	5.0	.00	.50
70.8	2.0	1.0	1.7	3.0	11	7.0	.50	.50
89.1	3.0	1.0	2.3	4.0	16	22.0	.33	.67
112.2	2.0	2.0	2.4	4.0	19	23.0	1.00	.00
141.3	4.0	1.0	3.7	6.0	19	65.0	.50	.75
177.8	4.0	2.0	4.3	7.0	23	118.0	.75	.50
223.9	4.0	3.0	4.6	9.0	34	180.0	1.25	.25
281.8	6.0	3.0	5.3	8.0	18	123.0	.33	.50
354.8	7.0	2.0	6.3	11.0	26	308.0	.57	.71
446.7	9.0	3.0	7.8	13.0	27	442.0	.44	.67
562.3	11.0	2.0	9.5	18.0	22	543.0	.64	.82
707.9	11.0	3.0	10.6	16.0	16	472.0	.45	.73
891.3	15.0	4.0	12.8	21.0	25	1092.0	.40	.73
1122.0	14.0	4.0	12.3	22.0	16	689.0	.57	.71
1412.5	24.0	12.0	20.6	29.0	9	975.0	.21	.50
1778.3	33.0	13.0	22.9	37.0	11	2050.0	.12	.61
2238.7	27.0	15.0	24.4	40.0	7	1188.0	.48	.44
2818.4	37.0	29.0	33.0	37.0	2	232.0	.00	.22
3548.1	33.0	10.0	24.3	44.0	6	1412.0	.33	.70
4466.8	38.0	25.0	36.7	47.0	4	785.0	.24	.34
5623.4	44.0	19.0	36.7	47.0	4	875.0	.07	.57
7079.4	87.0	61.0	74.0	87.0	2	1586.0	.00	.30
8912.5	59.0	18.0	46.4	74.0	8	4954.0	.25	.69
11220.2	65.0	40.0	52.5	65.0	2	1003.0	.00	.38
14125.4	99.0	63.0	81.0	99.0	2	2268.0	.00	.36
17782.8	77.0	49.0	63.0	77.0	2	1372.0	.00	.36
22387.2	110.0	91.0	100.5	110.0	2	1779.0	.00	.17
28183.8	190.0	81.0	140.3	210.0	3	20769.0	.62	.58
35481.3	173.0	173.0	173.0	173.0	1	.0	.00	.00
44668.3	212.0	115.0	211.0	306.0	3	39919.0	.44	.46
56234.0	319.0	319.0	319.0	319.0	1	.0	.00	.00
70794.5	324.0	181.0	252.5	324.0	2	25883.0	.00	.44
89124.9	466.0	466.0	466.0	466.0	1	.0	.00	.00
112201.7								
141253.5	722.0	566.0	644.0	722.0	2	88296.0	.00	.22

N=189 MIAMI PASI =0

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	1	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	3	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	2	.0	.00	.00
35.5								
44.7	1.0	1.0	1.2	2.0	5	2.0	1.00	.00
56.2	2.0	1.0	1.3	2.0	3	2.0	.00	.50
70.8	2.0	1.0	1.6	2.0	5	2.0	.00	.50
89.1	3.0	2.0	2.5	3.0	2	2.0	.00	.33
112.2	2.0	1.0	2.0	3.0	6	4.0	.50	.50
141.3	3.0	2.0	2.5	3.0	2	2.0	.00	.33
177.8	4.0	2.0	3.5	5.0	6	15.0	.25	.50
223.9	4.0	2.0	3.5	5.0	14	33.0	.25	.50
281.8	5.0	3.0	4.7	7.0	9	53.0	.40	.40
354.8	5.0	3.0	5.3	9.0	14	98.0	.80	.40
446.7	6.0	4.0	5.7	9.0	15	106.0	.50	.33
562.3	8.0	2.0	7.5	13.0	15	216.0	.62	.75
707.9	9.0	4.0	8.1	15.0	12	232.0	.67	.56
891.3	9.0	7.0	9.4	19.0	10	252.0	1.11	.22
1122.0	11.0	6.0	10.5	15.0	10	188.0	.36	.45
1412.5	19.0	17.0	18.7	22.0	4	134.0	.16	.11
1778.3	21.0	15.0	19.7	26.0	6	358.0	.24	.29
2238.7	33.0	4.0	25.9	61.0	11	3562.0	.85	.88
2818.4	27.0	10.0	24.6	37.0	14	1782.0	.37	.63
3548.1	36.0	15.0	33.7	59.0	6	2123.0	.64	.58
4466.8	43.0	27.0	37.5	45.0	4	802.0	.05	.37
5623.4	42.0	31.0	43.0	56.0	3	1125.0	.33	.26
7079.4	59.0	59.0	59.0	59.0	1	.0	.00	.00
8912.5	64.0	32.0	48.0	64.0	2	1024.0	.00	.50
11220.2	74.0	57.0	65.5	74.0	2	969.0	.00	.23
14125.4	54.0	54.0	54.0	54.0	1	.0	.00	.00
17782.8	34.0	34.0	34.0	34.0	1	.0	.00	.00

N=370 MIAMI PAST 1-25

Z	R*	R MIN	R AVG	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	1	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	1	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	3	.0	.00	.00
35.5								
44.7	1.0	1.0	1.0	1.0	11	.0	.00	.00
56.2	2.0	1.0	1.5	2.0	6	3.0	.00	.50
70.8	2.0	2.0	2.3	3.0	3	3.0	.50	.00
89.1	2.0	1.0	1.7	2.0	7	2.0	.00	.50
112.2	2.0	1.0	2.0	3.0	7	4.0	.50	.50
141.3	3.0	2.0	2.4	3.0	10	12.0	.00	.33
177.8	3.0	2.0	3.4	5.0	16	40.0	.67	.33
223.9	4.0	2.0	3.6	6.0	21	63.0	.50	.50
281.8	5.0	3.0	4.6	9.0	13	78.0	.80	.40
354.8	6.0	2.0	5.7	10.0	19	183.0	.67	.67
446.7	9.0	2.0	7.4	11.0	29	398.0	.22	.78
562.3	11.0	5.0	8.7	13.0	18	368.0	.18	.55
707.9	10.0	6.0	9.4	16.0	29	715.0	.60	.40
891.3	15.0	5.0	12.5	28.0	22	1564.0	.87	.67
1122.0	15.0	9.0	13.9	24.0	20	1314.0	.60	.40
1412.5	17.0	7.0	17.2	32.0	16	1982.0	.88	.59
1778.3	21.0	11.0	20.6	35.0	14	2384.0	.67	.48
2238.7	32.0	10.0	27.2	41.0	18	3542.0	.28	.69
2818.4	36.0	16.0	29.8	52.0	19	5059.0	.44	.56
3548.1	41.0	15.0	37.7	62.0	16	7164.0	.51	.63
4466.8	54.0	13.0	43.4	72.0	13	7370.0	.33	.76
5623.4	61.0	26.0	54.7	85.0	13	8026.0	.39	.57
7079.4	68.0	23.0	61.5	90.0	8	5710.0	.32	.66
8912.5	81.0	20.0	64.4	98.0	7	6172.0	.21	.75
11220.2	131.0	69.0	100.0	131.0	2	4278.0	.00	.47
14125.4								
17782.8	104.0	15.0	75.5	139.0	4	8840.0	.34	.86
22387.2	140.0	140.0	140.0	140.0	1	.0	.00	.00
28183.8	127.0	127.0	127.0	127.0	1	.0	.00	.00
35481.3	41.0	41.0	41.0	41.0	1	.0	.00	.00
44668.3	40.0	40.0	40.0	40.0	1	.0	.00	.00

N=169 MIAMI PASI 26-50

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
17.8								
22.4	1.0	1.0	1.0	1.0	1	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	12	.0	.00	.00
35.5								
44.7	1.0	1.0	1.1	2.0	19	2.0	1.00	.00
56.2	1.0	1.0	1.3	2.0	10	6.0	1.00	.00
70.8	1.0	1.0	1.0	1.0	6	.0	.00	.00
89.1	2.0	1.0	1.6	4.0	15	24.0	1.00	.50
112.2	2.0	1.0	1.5	2.0	6	3.0	.00	.50
141.3	4.0	2.0	3.0	5.0	7	21.0	.25	.50
177.8	3.0	3.0	3.5	5.0	8	18.0	.67	.00
223.9	4.0	2.0	3.6	7.0	8	43.0	.75	.50
281.8	4.0	2.0	3.8	6.0	6	27.0	.50	.50
354.8	4.0	3.0	3.5	4.0	2	3.0	.00	.25
446.7	4.0	3.0	4.3	6.0	3	15.0	.50	.25
562.3	11.0	5.0	8.0	11.0	2	33.0	.00	.55
707.9	10.0	3.0	6.5	10.0	2	21.0	.00	.70
891.3	14.0	7.0	10.5	14.0	2	49.0	.00	.50
1122.0	20.0	20.0	20.0	20.0	1	.0	.00	.00
1412.5	6.0	6.0	6.0	6.0	1	.0	.00	.00
1778.3	21.0	13.0	20.3	27.0	3	266.0	.29	.38
2238.7	21.0	8.0	19.7	30.0	4	394.0	.43	.62
2818.4	27.0	24.0	26.3	28.0	3	105.0	.04	.11
3548.1	26.0	9.0	17.5	26.0	2	153.0	.00	.65
4466.8	41.0	41.0	41.0	41.0	1	.0	.00	.00
5623.4	38.0	37.0	40.0	45.0	3	352.0	.18	.03
7079.4	43.0	43.0	43.0	43.0	1	.0	.00	.00
8912.5	56.0	33.0	49.3	59.0	3	936.0	.05	.41
11220.2								
14125.4	80.0	55.0	76.0	106.0	4	5262.0	.32	.31
17782.8	65.0	53.0	59.0	65.0	2	636.0	.00	.18
22387.2	90.0	88.0	97.3	116.0	3	3369.0	.29	.04
28183.8	154.0	56.0	110.5	155.0	4	11572.0	.01	.64
35481.3	176.0	77.0	137.7	192.0	4	18115.0	.09	.56
44668.3	119.0	80.0	99.5	119.0	2	3129.0	.00	.33
56234.0	220.0	33.0	126.5	220.0	2	6171.0	.00	.85
70794.5	104.0	93.0	127.0	184.0	3	15745.0	.77	.11
89124.9	49.0	49.0	49.0	49.0	1	.0	.00	.00
112201.7	305.0	73.0	197.0	305.0	3	36532.0	.00	.76
141253.5	82.0	82.0	82.0	82.0	1	.0	.00	.00
177827.6	204.0	204.0	204.0	204.0	1	.0	.00	.00

N=126 MIAMI PASI 51-100

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
17.8								
22.4	1.0	1.0	1.0	1.0	1	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	1	.0	.00	.00
35.5								
44.7								
56.2	2.0	2.0	2.0	2.0	1	.0	.00	.00
70.8								
89.1	3.0	3.0	3.0	3.0	3	.0	.00	.00
112.2	4.0	2.0	3.4	4.0	9	13.0	.00	.50
141.3	4.0	3.0	3.7	4.0	6	6.0	.00	.25
177.8	4.0	2.0	3.8	5.0	5	9.0	.25	.50
223.9	5.0	4.0	5.0	6.0	7	23.0	.20	.20
281.8	7.0	3.0	6.0	8.0	7	42.0	.14	.57
354.8	9.0	5.0	8.7	12.0	6	103.0	.33	.44
446.7	9.0	5.0	7.5	10.0	4	48.0	.11	.44
562.3	11.0	7.0	9.0	11.0	2	28.0	.00	.36
707.9	13.0	8.0	11.9	16.0	10	246.0	.23	.38
891.3	19.0	11.0	16.5	20.0	6	263.0	.05	.42
1122.0	19.0	10.0	18.1	27.0	9	537.0	.42	.47
1412.5	21.0	16.0	21.0	30.0	7	588.0	.43	.24
1778.3	23.0	20.0	23.7	28.0	3	203.0	.22	.13
2238.7	33.0	28.0	33.3	41.0	6	564.0	.24	.15
2818.4	38.0	6.0	26.5	46.0	4	917.0	.21	.84
3548.1	38.0	36.0	39.2	46.0	4	477.0	.21	.05
4466.8	50.0	28.0	43.0	55.0	4	1370.0	.10	.44
5623.4	59.0	29.0	54.6	70.0	5	2255.0	.19	.51
7079.4	52.0	41.0	52.4	65.0	5	1712.0	.25	.21
8912.5	79.0	60.0	74.7	84.0	4	1708.0	.06	.24
11220.2	76.0	76.0	76.0	76.0	1	.0	.00	.00
14125.4	115.0	115.0	115.0	115.0	1	.0	.00	.00
17782.8	113.0	91.0	102.0	113.0	2	2002.0	.00	.19
22387.2	15.0	15.0	15.0	15.0	1	.0	.00	.00
28183.8								
35481.3	196.0	196.0	196.0	196.0	1	.0	.00	.00
44668.3	153.0	153.0	153.0	153.0	1	.0	.00	.00

N=150 MIAMI PASI 101-150

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
17.8								
22.4	1.0	1.0	1.0	1.0	5	.0	.00	.00
28.2								
35.5								
44.7	1.0	1.0	1.0	1.0	2	.0	.00	.00
56.2	2.0	1.0	1.3	2.0	3	2.0	.00	.50
70.8	3.0	3.0	3.0	3.0	1	.0	.00	.00
89.1	2.0	1.0	1.8	2.0	5	1.0	.00	.50
112.2	3.0	2.0	3.2	5.0	5	12.0	.67	.33
141.3	3.0	1.0	2.5	4.0	4	8.0	.33	.67
177.8	4.0	2.0	3.4	6.0	5	23.0	.50	.50
223.9	4.0	2.0	3.3	4.0	6	10.0	.00	.50
281.8	13.0	3.0	8.0	13.0	2	50.0	.00	.77
354.8	5.0	4.0	6.0	10.0	4	54.0	1.00	.20
446.7	9.0	5.0	8.6	13.0	7	112.0	.44	.44
562.3	7.0	5.0	6.7	9.0	4	34.0	.29	.29
707.9	12.0	9.0	11.7	16.0	4	141.0	.33	.25
891.3	17.0	12.0	16.0	19.0	4	114.0	.12	.29
1122.0	15.0	8.0	13.9	18.0	8	315.0	.20	.47
1412.5	20.0	12.0	19.1	23.0	8	313.0	.15	.40
1778.3	24.0	10.0	19.8	27.0	6	561.0	.12	.58
2238.7	25.0	19.0	22.0	25.0	2	114.0	.00	.24
2818.4	26.0	10.0	20.2	28.0	4	369.0	.08	.62
3548.1	45.0	42.0	45.2	51.0	4	518.0	.13	.07
4466.8	56.0	8.0	43.6	63.0	5	1603.0	.12	.86
5623.4	69.0	52.0	63.3	69.0	3	885.0	.00	.25
7079.4	52.0	34.0	50.7	80.0	6	4534.0	.54	.35
8912.5	69.0	42.0	59.5	78.0	4	2816.0	.13	.39
11220.2	82.0	44.0	69.0	93.0	5	4089.0	.13	.46
14125.4	94.0	81.0	87.5	94.0	2	1053.0	.00	.14
17782.8	112.0	64.0	103.0	124.0	4	4563.0	.11	.43
22387.2	171.0	70.0	128.3	214.0	6	36916.0	.25	.59
28183.8	135.0	94.0	130.6	162.0	8	16942.0	.20	.30
35481.3	177.0	154.0	186.7	233.0	7	34018.0	.32	.13
44668.3	230.0	156.0	208.5	289.0	4	39884.0	.26	.32
56234.0	180.0	180.0	180.0	180.0	1	.0	.00	.00
70794.5								
89124.9	282.0	282.0	282.0	282.0	1	.0	.00	.00
112201.7	400.0	400.0	400.0	400.0	1	.0	.00	.00

KEY

Z = RADAR REFLECTIVITY IN mm^6/m^3

R^* = BEST ESTIMATE OF R BASED ON THE MINIMUM $\Sigma R_i |R^* - R_i|$ IN mm/hr.

R MIN = MINIMUM RATE IN EACH Z INTERVAL mm/hr.

R AVE = AVERAGE RATE IN EACH Z INTERVAL mm/hr.

R MAX = MAXIMUM RATE IN EACH Z INTERVAL mm/hr.

N = NUMBER OF ONE CUBIC METER SAMPLES IN EACH Z INTERVAL

$S = \Sigma R_i |R^* - R_i|$

UNDER = MAXIMUM POSSIBLE UNDERESTIMATE DEFINED AS $\frac{R\,MAX - R^*}{R^*}$

OVER = MAXIMUM POSSIBLE OVERESTIMATE DEFINED AS $\frac{R^* - R\,MIN}{R^*}$

FIG. 1 TABLES OF RAINFALL RATE VERSUS RADAR REFLECTIVITY FOR DIFFERENT POSITIVE AREA STABILITY INDICES (PASI) FOR MIAMI, FLORIDA.

N=402 MIAMI PASI 151-200

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	3	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	7	.0	.00	.00
28.2	1.0	1.0	1.1	2.0	9	2.0	1.00	.00
35.5								
44.7	1.0	1.0	1.1	2.0	11	2.0	1.00	.00
56.2	2.0	1.0	1.6	3.0	11	8.0	.50	.50
70.8	2.0	1.0	1.7	3.0	9	11.0	.50	.50
89.1	3.0	1.0	2.2	4.0	13	20.0	.33	.67
112.2	3.0	1.0	2.7	5.0	23	38.0	.67	.67
141.3	3.0	1.0	2.6	4.0	15	24.0	.33	.67
177.8	4.0	1.0	3.4	6.0	24	87.0	.50	.75
223.9	5.0	1.0	4.1	9.0	24	120.0	.80	.80
281.8	6.0	3.0	5.6	8.0	16	86.0	.33	.50
354.8	7.0	3.0	6.6	10.0	28	288.0	.43	.57
446.7	8.0	3.0	7.2	12.0	26	283.0	.50	.62
562.3	12.0	3.0	9.6	14.0	14	282.0	.17	.75
707.9	11.0	6.0	11.3	19.0	21	652.0	.73	.45
891.3	14.0	5.0	12.9	19.0	19	629.0	.36	.64
1122.0	16.0	4.0	15.2	22.0	12	556.0	.37	.75
1412.5	22.0	17.0	21.1	24.0	7	316.0	.09	.23
1778.3	25.0	5.0	19.8	30.0	10	788.0	.20	.80
2238.7	32.0	6.0	25.5	39.0	10	1591.0	.22	.81
2818.4	74.0	7.0	36.0	74.0	4	3122.0	.00	.91
3548.1	37.0	12.0	31.5	58.0	10	2730.0	.57	.68
4466.8	46.0	37.0	46.6	55.0	7	1084.0	.20	.20
5623.4	38.0	14.0	36.4	76.0	7	4103.0	1.00	.63
7079.4	77.0	18.0	59.6	80.0	7	4646.0	.04	.77
8912.5	75.0	16.0	66.8	98.0	9	7658.0	.31	.79
11220.2	93.0	18.0	66.6	95.0	5	4866.0	.02	.81
14125.4	102.0	60.0	108.7	221.0	7	33641.0	1.17	.41
17782.8	88.0	28.0	77.8	123.0	6	9355.0	.40	.68
22387.2	142.0	106.0	131.7	155.0	4	8063.0	.09	.25
28183.8	206.0	41.0	149.7	219.0	8	37604.0	.06	.80
35481.3	220.0	54.0	173.1	249.0	7	44772.0	.13	.75
44668.3	206.0	39.0	160.4	301.0	8	94457.0	.46	.81
56234.0								
70794.5								
89124.9								
112201.7								
141253.5	168.0	168.0	168.0	168.0	1	.0	.00	-.00

N=259 MIAMI PASI 201-300

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	2	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	2	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	3	.0	.00	.00
35.5								
44.7	1.0	1.0	1.1	2.0	16	2.0	1.00	.00
56.2	1.0	1.0	1.2	2.0	4	2.0	1.00	.00
70.8	2.0	2.0	2.0	2.0	2	.0	.00	.00
89.1	3.0	1.0	2.1	4.0	12	20.0	.33	.67
112.2	2.0	1.0	2.2	3.0	9	10.0	.50	.50
141.3	5.0	2.0	3.3	5.0	6	22.0	.00	.60
177.8	4.0	2.0	3.7	7.0	10	43.0	.75	.50
223.9	6.0	5.0	5.7	7.0	6	22.0	.17	.17
281.8	6.0	4.0	6.1	9.0	8	61.0	.50	.33
354.8	7.0	2.0	7.0	12.0	7	100.0	.71	.71
446.7	11.0	5.0	8.0	11.0	2	30.0	.00	.55
562.3	10.0	3.0	7.9	12.0	12	105.0	.20	.70
707.9	9.0	5.0	8.7	13.0	10	144.0	.44	.44
891.3	17.0	9.0	15.1	21.0	8	164.0	.24	.47
1122.0	19.0	10.0	17.7	26.0	14	1032.0	.37	.47
1412.5	21.0	12.0	19.0	30.0	7	586.0	.43	.43
1778.3	25.0	11.0	22.3	36.0	14	1662.0	.44	.56
2238.7	30.0	22.0	28.7	33.0	4	275.0	.10	.27
2818.4	33.0	5.0	24.2	44.0	14	2622.0	.33	.88
3548.1	36.0	8.0	25.4	37.0	5	809.0	.03	.78
4466.8	48.0	20.0	37.2	55.0	5	1944.0	.15	.58
5623.4	45.0	29.0	44.9	66.0	7	2450.0	.47	.36
7079.4	63.0	24.0	53.4	72.0	8	4538.0	.14	.62
8912.5	64.0	24.0	56.9	98.0	13	11470.0	.53	.62
11220.2	79.0	32.0	72.7	121.0	9	12404.0	.53	.59
14125.4	79.0	46.0	71.3	90.0	6	4600.0	.14	.42
17782.8	110.0	38.0	102.6	166.0	9	25005.0	.51	.65
22387.2	121.0	78.0	111.7	145.0	7	12730.0	.20	.36
28183.8	134.0	91.0	121.6	156.0	5	11344.0	.16	.32
35481.3	126.0	123.0	124.5	126.0	2	369.0	.00	.02
44668.3	168.0	80.0	147.3	194.0	3	12084.0	.15	.52
56234.0	284.0	160.0	273.0	375.0	3	53965.0	.32	.44
70794.5	71.0	71.0	71.0	71.0	1	.0	.00	.00

N=221 MIAMI PASI 301-400

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	2	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	4	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	2	.0	.00	.00
35.5								
44.7	1.0	1.0	1.0	1.0	9	.0	.00	.00
56.2	2.0	2.0	2.0	2.0	2	.0	.00	.00
70.8	2.0	1.0	1.5	2.0	2	1.0	.00	.50
89.1	2.0	1.0	1.9	3.0	7	9.0	.50	.50
112.2	3.0	1.0	2.6	4.0	5	8.0	.33	.67
141.3	4.0	2.0	3.2	4.0	4	7.0	.00	.50
177.8	5.0	2.0	3.6	6.0	5	24.0	.20	.60
223.9	6.0	3.0	5.2	7.0	8	30.0	.17	.50
281.8	6.0	3.0	5.1	8.0	7	44.0	.33	.50
354.8	7.0	4.0	6.4	10.0	14	134.0	.43	.43
446.7	8.0	5.0	7.9	13.0	14	187.0	.62	.37
562.3	11.0	5.0	9.4	13.0	13	260.0	.18	.55
707.9	13.0	6.0	11.2	15.0	14	363.0	.15	.54
891.3	12.0	6.0	12.0	24.0	10	490.0	1.00	.50
1122.0	17.0	3.0	15.4	22.0	14	706.0	.29	.82
1412.5	22.0	10.0	19.2	28.0	10	604.0	.27	.55
1778.3	28.0	13.0	25.1	35.0	11	1468.0	.25	.54
2238.7	27.0	20.0	24.7	27.0	4	190.0	.00	.26
2818.4	39.0	17.0	35.4	51.0	9	2808.0	.31	.56
3548.1	51.0	24.0	45.0	52.0	6	1212.0	.02	.53
4466.8	83.0	26.0	55.3	88.0	6	6846.0	.06	.69
5623.4	63.0	30.0	60.0	73.0	5	2430.0	.16	.52
7079.4	77.0	76.0	76.5	77.0	2	76.0	.00	.01
8912.5	77.0	65.0	76.3	93.0	3	2268.0	.21	.16
11220.2	88.0	69.0	84.0	95.0	3	1976.0	.08	.22
14125.4	124.0	73.0	101.0	138.0	5	12287.0	.11	.41
17782.8								
22387.2	124.0	98.0	125.8	151.0	5	12169.0	.22	.21
28183.8	117.0	116.0	139.7	186.0	3	12950.0	.59	.01
35481.3	216.0	171.0	193.5	216.0	2	7695.0	.00	.21
44668.3	110.0	110.0	110.0	110.0	1	.0	.00	.00

N=877 MIAMI CONTINUOUS RAIN

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	3	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	17	.0	.00	.00
28.2	1.0	1.0	1.0	2.0	29	2.0	1.00	.00
35.5								
44.7	1.0	1.0	1.3	2.0	42	22.0	1.00	.00
56.2	2.0	1.0	1.5	2.0	26	12.0	.00	.50
70.8	2.0	1.0	1.7	4.0	24	29.0	1.00	.50
89.1	2.0	1.0	2.0	4.0	39	59.0	1.00	.50
112.2	3.0	1.0	2.6	6.0	47	112.0	1.00	.67
141.3	4.0	1.0	3.1	6.0	47	138.0	.50	.75
177.8	4.0	1.0	3.8	7.0	44	174.0	.75	.75
223.9	4.0	2.0	4.2	9.0	62	319.0	1.25	.50
281.8	6.0	2.0	5.4	10.0	40	299.0	.67	.67
354.8	7.0	2.0	6.7	12.0	65	786.0	.71	.71
446.7	8.0	2.0	7.4	13.0	68	1040.0	.62	.75
562.3	10.0	2.0	9.2	18.0	45	977.0	.80	.80
707.9	12.0	3.0	11.0	16.0	48	1168.0	.33	.75
891.3	15.0	4.0	13.0	21.0	47	2012.0	.40	.73
1122.0	18.0	4.0	14.8	24.0	38	2411.0	.33	.78
1412.5	24.0	7.0	21.2	32.0	30	2732.0	.33	.71
1778.3	29.0	10.0	24.2	37.0	23	3692.0	.28	.66
2238.7	33.0	7.0	28.0	41.0	17	3304.0	.24	.79
2818.4	38.0	23.0	34.4	52.0	10	2020.0	.37	.39
3548.1	50.0	10.0	39.7	62.0	13	5254.0	.24	.80
4466.8	52.0	13.0	45.2	72.0	12	7378.0	.38	.75
5623.4	72.0	47.0	69.8	87.0	9	4888.0	.21	.35
7079.4	83.0	25.0	68.7	90.0	4	2542.0	.08	.70
8912.5	77.0	18.0	67.7	117.0	12	14642.0	.52	.77
11220.2	53.0	50.0	71.5	93.0	2	2150.0	.00	.46
14125.4	124.0	88.0	113.2	138.0	6	10331.0	.11	.29
17782.8	139.0	77.0	108.0	139.0	2	4774.0	.00	.45
22387.2	151.0	74.0	112.5	151.0	2	5698.0	.00	.51
28183.8	42.0	41.0	41.5	42.0	2	41.0	.00	.02
35481.3	216.0	171.0	193.5	216.0	2	7695.0	.00	.21

N=662 MIAMI RAIN SHOWERS

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	7	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	14	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	21	.0	.00	.00
35.5								
44.7	1.0	1.0	1.1	2.0	31	4.0	1.00	.00
56.2	2.0	1.0	2.1	9.0	17	13.0	3.50	.50
70.8	2.0	1.0	2.0	3.0	4	4.0	.50	.50
89.1	3.0	1.0	2.3	4.0	21	30.0	.33	.67
112.2	3.0	1.0	2.5	4.0	22	24.0	.33	.67
141.3	4.0	2.0	3.3	5.0	11	40.0	.25	.50
177.8	4.0	2.0	4.0	7.0	25	111.0	.75	.50
223.9	5.0	3.0	4.7	9.0	30	184.0	.80	.40
281.8	6.0	3.0	5.9	13.0	23	236.0	1.17	.50
354.8	7.0	2.0	6.0	10.0	28	276.0	.43	.71
446.7	9.0	4.0	8.1	13.0	36	594.0	.44	.56
562.3	11.0	3.0	9.2	14.0	35	684.0	.27	.73
707.9	10.0	5.0	9.9	19.0	37	1180.0	.90	.50
891.3	19.0	3.0	14.0	28.0	30	2014.0	.47	.84
1122.0	18.0	4.0	16.1	27.0	34	2432.0	.50	.78
1412.5	20.0	6.0	17.8	30.0	21	1663.0	.50	.70
1778.3	25.0	9.0	22.8	36.0	37	4454.0	.44	.64
2238.7	33.0	8.0	26.3	61.0	26	6648.0	.85	.76
2818.4	34.0	16.0	30.8	51.0	29	7897.0	.50	.53
3548.1	36.0	15.0	33.2	59.0	24	6443.0	.64	.58
4466.8	52.0	23.0	45.9	83.0	15	7370.0	.60	.56
5623.4	53.0	26.0	49.8	85.0	22	13390.0	.60	.51
7079.4	46.0	23.0	41.0	59.0	10	3846.0	.28	.50
8912.5	64.0	25.0	53.9	90.0	10	7647.0	.41	.61
11220.2	76.0	23.0	63.2	131.0	9	15683.0	.72	.70
14125.4	74.0	51.0	69.0	110.0	7	9013.0	.49	.31
17782.8	110.0	15.0	67.1	123.0	10	18729.0	.12	.86
22387.2	130.0	130.0	130.0	130.0	1	.0	.00	.00
28183.8	153.0	94.0	123.5	153.0	2	5546.0	.00	.39
35481.3	196.0	41.0	148.5	213.0	4	17464.0	.09	.79
44668.3	153.0	40.0	96.5	153.0	2	4520.0	.00	.74
56234.0	216.0	160.0	197.7	217.0	3	9177.0	.00	.26
70794.5								
89124.9	145.0	49.0	97.0	145.0	2	4704.0	.00	.66
112201.7								
141253.5	469.0	469.0	469.0	469.0	1	.0	.00	.00

N=869 MIAMI THUNDERSTORMS

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2								
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	9	.0	.00	.00
28.2	1.0	1.0	1.2	2.0	12	4.0	1.00	.00
35.5								
44.7	1.0	1.0	1.1	2.0	30	4.0	1.00	.00
56.2	1.0	1.0	1.2	2.0	10	4.0	1.00	.00
70.8	2.0	1.0	1.7	3.0	12	7.0	.50	.50
89.1	2.0	1.0	1.7	4.0	21	24.0	1.00	.50
112.2	3.0	1.0	2.5	5.0	24	40.0	.67	.67
141.3	3.0	1.0	2.4	4.0	20	36.0	.33	.67
177.8	4.0	1.0	3.3	6.0	32	89.0	.50	.75
223.9	4.0	1.0	3.9	7.0	35	134.0	.75	.75
281.8	5.0	3.0	4.9	14.0	22	254.0	1.80	.40
354.8	5.0	3.0	5.7	10.0	26	272.0	1.00	.40
446.7	7.0	3.0	6.6	11.0	30	346.0	.57	.57
562.3	9.0	3.0	7.8	13.0	24	452.0	.44	.67
707.9	11.0	3.0	9.9	16.0	35	896.0	.45	.73
891.3	13.0	4.0	11.3	20.0	32	1318.0	.54	.69
1122.0	14.0	3.0	13.1	22.0	34	1363.0	.57	.79
1412.5	20.0	10.0	18.2	30.0	19	1169.0	.50	.50
1778.3	20.0	5.0	17.1	35.0	27	3320.0	.75	.75
2238.7	29.0	6.0	25.6	39.0	27	3220.0	.34	.79
2818.4	31.0	4.0	25.7	74.0	33	9258.0	1.39	.87
3548.1	41.0	8.0	34.9	60.0	30	10280.0	.46	.80
4466.8	46.0	8.0	42.8	88.0	29	13798.0	.91	.83
5623.4	51.0	14.0	45.3	76.0	29	15536.0	.49	.73
7079.4	65.0	18.0	60.2	87.0	33	21098.0	.34	.72
8912.5	69.0	16.0	61.8	98.0	37	33114.0	.42	.77
11220.2	79.0	18.0	76.3	121.0	23	24692.0	.53	.77
14125.4	90.0	46.0	90.9	221.0	23	52937.0	1.46	.49
17782.8	104.0	28.0	94.1	166.0	20	51200.0	.60	.73
22387.2	120.0	15.0	113.5	214.0	30	95530.0	.78	.87
28183.8	154.0	41.0	137.6	238.0	32	166924.0	.55	.73
35481.3	181.0	54.0	168.0	249.0	22	132506.0	.38	.70
44668.3	212.0	39.0	170.8	306.0	22	244334.0	.44	.82
56234.0	284.0	33.0	235.2	375.0	6	86373.0	.32	.88
70794.5	203.0	71.0	189.9	359.0	8	132584.0	.77	.65
89124.9	466.0	287.0	374.0	466.0	2	51888.0	.00	.39
112201.7	305.0	73.0	247.7	400.0	6	74532.0	.31	.76
141253.5	566.0	82.0	384.5	722.0	4	219184.0	.28	.86
177827.6	204.0	204.0	204.0	204.0	1	.0	.00	00

KEY

Z = RADAR REFLECTIVITY IN $10\ mm^6/m^3$

R^* = BEST ESTIMATE OF R BASED ON THE MINIMUM $\Sigma\ R_i\ (R^* - R_i)$ IN mm/hr.

R MIN = MINIMUM RATE IN EACH Z INTERVAL mm/hr.

R AVE = AVERAGE RATE IN EACH Z INTERVAL mm/hr.

R MAX = MAXIMUM RATE IN EACH Z INTERVAL mm/hr.

N = NUMBER OF ONE CUBIC METER SAMPLES IN EACH Z INTERVAL

$S = \Sigma\ R\ (R^* - R_i)$

UNDER = MAXIMUM POSSIBLE UNDERESTIMATE DEFINED AS $\frac{R\ MAX - R^*}{R^*}$

OVER = MAXIMUM POSSIBLE OVERESTIMATE DEFINED AS $\frac{R^* - R\ MIN}{R^*}$

FIG. 2 TABLES OF RAINFALL RATE VERSUS RADAR REFLECTIVITY FOR DIFFERENT POSITIVE AREA STABILITY INDICES (PASI) CONTINUED FROM FIG. 1 AND FOR DIFFERENT RAIN TYPES FOR MIAMI, FLORIDA.

N=515 — MIAMI EASTERLY WAVE

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	2	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	9	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	1	.0	.00	.00
35.5								
44.7	1.0	1.0	1.0	2.0	21	2.0	1.00	.00
56.2	2.0	1.0	1.5	2.0	11	5.0	.00	.50
70.8	2.0	1.0	1.9	4.0	9	15.0	1.00	.50
89.1	2.0	1.0	2.0	3.0	22	27.0	.50	.50
112.2	3.0	1.0	2.8	6.0	23	55.0	1.00	.67
141.3	4.0	2.0	3.4	5.0	7	19.0	.25	.50
177.8	4.0	2.0	3.7	6.0	16	64.0	.50	.50
223.9	5.0	2.0	4.7	7.0	15	73.0	.40	.60
281.8	6.0	3.0	7.0	14.0	15	289.0	1.33	.50
354.8	7.0	4.0	6.8	10.0	25	222.0	.43	.43
446.7	9.0	5.0	8.2	13.0	25	383.0	.44	.44
562.3	11.0	6.0	9.7	14.0	32	583.0	.27	.45
707.9	14.0	6.0	11.9	17.0	25	729.0	.21	.57
891.3	15.0	3.0	13.7	24.0	31	1344.0	.60	.80
1122.0	18.0	4.0	16.6	26.0	34	2144.0	.44	.78
1412.5	21.0	10.0	19.9	30.0	25	1722.0	.43	.52
1778.3	26.0	9.0	25.0	36.0	26	3171.0	.38	.65
2238.7	27.0	4.0	25.0	38.0	13	2364.0	.41	.85
2818.4	38.0	10.0	33.6	51.0	13	3445.0	.34	.74
3548.1	44.0	14.0	38.1	60.0	15	5881.0	.36	.68
4466.8	55.0	13.0	47.3	83.0	16	8413.0	.51	.76
5623.4	71.0	29.0	59.7	87.0	15	11178.0	.23	.59
7079.4	69.0	25.0	57.9	83.0	9	6766.0	.20	.64
8912.5	82.0	42.0	76.1	117.0	13	12343.0	.43	.49
11220.2	82.0	32.0	70.9	95.0	7	6023.0	.16	.61
14125.4	101.0	73.0	99.5	138.0	11	23728.0	.37	.28
17782.8	149.0	38.0	85.3	149.0	3	9738.0	.00	.74
22387.2	151.0	74.0	129.4	214.0	7	37295.0	.42	.51
28183.8	156.0	41.0	127.8	238.0	9	51243.0	.53	.74
35481.3	205.0	154.0	191.2	233.0	5	20784.0	.14	.25
44668.3	257.0	110.0	221.5	289.0	4	31628.0	.12	.57
56234.0								
70794.5	359.0	203.0	281.0	359.0	2	31563.0	.00	.43

N=446 — MIAMI AIR MASS

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2								
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	6	.0	.00	.00
28.2	1.0	1.0	1.1	2.0	8	2.0	1.00	.00
35.5								
44.7	1.0	1.0	1.1	2.0	14	2.0	1.00	.00
56.2	2.0	1.0	2.2	9.0	10	68.0	3.50	.50
70.8	1.0	1.0	1.2	2.0	4	2.0	1.00	.00
89.1	3.0	1.0	2.2	4.0	14	20.0	.33	.67
112.2	3.0	1.0	2.4	4.0	17	24.0	.33	.67
141.3	3.0	1.0	2.5	4.0	20	32.0	.33	.67
177.8	4.0	1.0	3.4	7.0	21	78.0	.75	.75
223.9	5.0	1.0	4.6	6.0	18	60.0	.20	.80
281.8	5.0	2.0	4.9	8.0	16	92.0	.60	.60
354.8	8.0	3.0	6.0	10.0	18	234.0	.25	.62
446.7	8.0	3.0	7.1	10.0	25	213.0	.25	.62
562.3	10.0	3.0	8.1	13.0	16	297.0	.30	.70
707.9	11.0	5.0	10.0	15.0	24	564.0	.36	.55
891.3	14.0	5.0	12.7	19.0	10	391.0	.36	.64
1122.0	14.0	3.0	12.0	19.0	11	446.0	.36	.79
1412.5	18.0	12.0	17.4	21.0	5	243.0	.17	.33
1778.3	23.0	5.0	15.6	30.0	9	1124.0	.30	.78
2238.7	30.0	6.0	25.1	39.0	11	1468.0	.30	.80
2818.4	32.0	6.0	24.4	74.0	13	5179.0	1.31	.81
3548.1	46.0	12.0	33.8	58.0	12	4682.0	.26	.74
4466.8	53.0	20.0	46.3	88.0	10	6624.0	.66	.62
5623.4	52.0	15.0	48.1	76.0	8	4093.0	.46	.71
7079.4	63.0	18.0	48.1	80.0	14	12958.0	.27	.71
8912.5	64.0	16.0	58.0	98.0	13	11824.0	.53	.75
11220.2	78.0	18.0	68.7	95.0	14	14910.0	.22	.77
14125.4	102.0	51.0	95.5	221.0	11	42439.0	1.17	.50
17782.8	94.0	28.0	83.9	123.0	12	18465.0	.31	.70
22387.2	124.0	15.0	117.6	155.0	14	25136.0	.25	.88
28183.8	153.0	41.0	140.8	219.0	16	83256.0	.43	.73
35481.3	199.0	54.0	178.5	249.0	13	80343.0	.25	.73
44668.3	206.0	39.0	159.8	301.0	10	109730.0	.46	.81
56234.0	216.0	160.0	193.2	217.0	4	15657.0	.00	.26
70794.5								
89124.9	282.0	145.0	213.5	282.0	2	19865.0	.00	.49
112201.7	400.0	400.0	400.0	400.0	1	.0	.00	.00
141253.5	469.0	168.0	318.5	469.0	2	50568.0	.00	.64

N=176 — MIAMI OVERRUNNING

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	2	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	5	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	9	.0	.00	.00
35.5								
44.7	1.0	1.0	1.2	2.0	11	6.0	1.00	.00
56.2	2.0	1.0	1.9	3.0	7	5.0	.50	.50
70.8	2.0	1.0	1.7	2.0	4	1.0	.00	.50
89.1	2.0	2.0	2.0	2.0	2	.0	.00	.00
112.2	3.0	2.0	2.6	3.0	8	6.0	.00	.33
141.3	4.0	2.0	2.7	4.0	3	8.0	.00	.50
177.8	5.0	2.0	4.1	6.0	10	44.0	.20	.60
223.9	4.0	2.0	4.2	9.0	14	103.0	1.25	.50
281.8	6.0	3.0	5.7	9.0	15	110.0	.50	.50
354.8	7.0	2.0	5.8	9.0	15	134.0	.29	.71
446.7	10.0	2.0	7.5	12.0	10	157.0	.20	.80
562.3	14.0	7.0	12.0	15.0	4	62.0	.07	.50
707.9	12.0	5.0	11.6	19.0	10	326.0	.58	.58
891.3	14.0	8.0	13.9	28.0	11	787.0	1.00	.43
1122.0	11.0	10.0	10.7	12.0	4	32.0	.09	.09
1412.5	22.0	14.0	20.6	24.0	5	223.0	.09	.36
1778.3	29.0	25.0	28.0	30.0	3	130.0	.03	.14
2238.7	39.0	7.0	28.6	40.0	5	858.0	.03	.82
2818.4	37.0	29.0	33.0	37.0	2	232.0	.00	.22
3548.1	41.0	23.0	36.0	44.0	3	545.0	.07	.44
4466.8	52.0	52.0	52.0	52.0	1	.0	.00	.00
5623.4	47.0	33.0	40.0	47.0	2	462.0	.00	.30
7079.4								
8912.5	65.0	59.0	66.0	74.0	3	1025.0	.14	.09
11220.2								
14125.4	99.0	99.0	99.0	99.0	1	.0	.00	.00
17782.8	77.0	77.0	77.0	77.0	1	.0	.00	.00

N=337 — MIAMI WARM FRONTAL

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2								
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	3	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	3	.0	.00	.00
35.5								
44.7	1.0	1.0	1.0	1.0	2	.0	.00	.00
56.2	1.0	1.0	1.2	2.0	5	2.0	1.00	.00
70.8	2.0	2.0	2.0	2.0	1	.0	.00	.00
89.1	2.0	1.0	1.9	3.0	9	5.0	.50	.50
112.2	2.0	2.0	2.0	2.0	7	.0	.00	.00
141.3	3.0	2.0	2.4	3.0	13	12.0	.00	.33
177.8	3.0	2.0	3.4	5.0	14	35.0	.67	.33
223.9	4.0	2.0	3.9	6.0	17	45.0	.50	.50
281.8	5.0	4.0	5.2	7.0	5	25.0	.40	.20
354.8	7.0	3.0	6.5	10.0	13	145.0	.43	.57
446.7	8.0	4.0	7.6	13.0	25	373.0	.62	.50
562.3	9.0	2.0	8.2	13.0	21	375.0	.44	.78
707.9	11.0	4.0	10.2	16.0	25	614.0	.45	.64
891.3	15.0	5.0	12.8	22.0	17	963.0	.47	.67
1122.0	19.0	8.0	15.9	27.0	21	1635.0	.42	.58
1412.5	19.0	7.0	19.1	32.0	15	1593.0	.68	.63
1778.3	26.0	11.0	22.9	35.0	15	2242.0	.35	.58
2238.7	33.0	16.0	29.2	41.0	23	3915.0	.24	.52
2818.4	36.0	19.0	31.5	52.0	23	5507.0	.44	.47
3548.1	41.0	28.0	42.2	62.0	14	5931.0	.51	.32
4466.8	54.0	13.0	46.0	72.0	15	7386.0	.33	.76
5623.4	63.0	31.0	60.4	85.0	13	5312.0	.35	.51
7079.4	68.0	48.0	68.0	90.0	7	4523.0	.32	.29
8912.5	81.0	67.0	81.2	98.0	5	3552.0	.21	.17
11220.2	76.0	69.0	92.0	131.0	3	7688.0	.72	.09
14125.4								
17782.8	113.0	91.0	111.7	139.0	4	5552.0	.23	.19
22387.2	140.0	140.0	140.0	140.0	1	.0	.00	.00
28183.8	127.0	94.0	110.5	127.0	2	3102.0	.00	.26
35481.3	196.0	196.0	196.0	196.0	1	.0	.00	.00
44668.3	153.0	153.0	153.0	153.0	1	.0	.00	.00

N=702 — MIAMI PRE-COLD FRONTAL

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	4	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	6	.0	.00	.00
28.2	1.0	1.0	1.1	2.0	24	4.0	1.00	.00
35.5								
44.7	1.0	1.0	1.2	2.0	42	16.0	1.00	.00
56.2	2.0	1.0	1.4	2.0	16	10.0	.00	.50
70.8	2.0	1.0	1.9	3.0	16	18.0	.50	.50
89.1	2.0	1.0	1.9	4.0	27	36.0	1.00	.50
112.2	3.0	1.0	2.4	5.0	25	44.0	.67	.67
141.3	4.0	2.0	3.5	6.0	28	94.0	.50	.50
177.8	4.0	1.0	3.9	7.0	33	140.0	.75	.75
223.9	4.0	2.0	4.1	9.0	54	238.0	1.25	.50
281.8	4.0	3.0	4.4	8.0	26	142.0	1.00	.25
354.8	6.0	2.0	5.8	11.0	35	394.0	.83	.67
446.7	8.0	4.0	7.0	13.0	39	622.0	.62	.50
562.3	10.0	2.0	8.7	18.0	29	641.0	.80	.80
707.9	9.0	3.0	8.8	16.0	33	744.0	.78	.67
891.3	13.0	4.0	11.8	21.0	37	1818.0	.62	.69
1122.0	14.0	7.0	12.8	22.0	30	1367.0	.57	.50
1412.5	22.0	6.0	17.7	30.0	16	1926.0	.36	.73
1778.3	20.0	8.0	18.8	37.0	33	4475.0	.85	.60
2238.7	21.0	8.0	21.3	34.0	18	2690.0	.62	.62
2818.4	27.0	10.0	25.9	46.0	15	2798.0	.70	.63
3548.1	28.0	9.0	25.8	45.0	13	2446.0	.61	.68
4466.8	39.0	8.0	33.6	55.0	9	2680.0	.41	.79
5623.4	45.0	26.0	42.5	69.0	13	6748.0	.53	.42
7079.4	56.0	23.0	54.4	80.0	13	8383.0	.43	.59
8912.5	65.0	18.0	51.0	87.0	17	15800.0	.34	.72
11220.2	121.0	65.0	93.0	121.0	2	3640.0	.00	.46
14125.4	94.0	55.0	82.3	115.0	7	10858.0	.22	.41
17782.8	121.0	15.0	84.0	166.0	7	20064.0	.37	.88
22387.2	91.0	67.0	100.0	171.0	8	22140.0	.88	.26
28183.8	155.0	56.0	130.4	210.0	5	23254.0	.35	.64
35481.3	176.0	41.0	118.4	192.0	5	23650.0	.09	.77
44668.3	80.0	40.0	79.7	119.0	3	6241.0	.49	.50
56234.0	319.0	33.0	246.2	375.0	5	62158.0	.18	.90
70794.5	104.0	93.0	127.0	184.0	3	15743.0	.77	.11
89124.9	49.0	49.0	49.0	49.0	1	.0	.00	.00
112201.7	305.0	73.0	197.0	305.0	3	36532.0	.00	.76
141253.5	82.0	82.0	82.0	82.0	1	.0	.00	.00
177827.6	204.0	204.0	204.0	204.0	1	.0	.00	.00

N=183 — MIAMI COLD FRONTAL

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
11.2	1.0	1.0	1.0	1.0	1	.0	.00	.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	1	.0	.00	.00
28.2	1.0	1.0	1.0	1.0	2	.0	.00	.00
35.5								
44.7	2.0	2.0	2.0	2.0	1	.0	.00	.00
56.2	2.0	1.0	1.7	2.0	3	1.0	.00	.50
70.8	2.0	1.0	1.7	2.0	4	1.0	.00	.50
89.1	3.0	1.0	2.5	4.0	4	8.0	.33	.67
112.2	4.0	3.0	3.5	4.0	10	15.0	.00	.25
141.3	4.0	2.0	3.3	4.0	9	14.0	.00	.50
177.8	4.0	3.0	3.9	5.0	7	11.0	.25	.25
223.9	5.0	3.0	5.1	7.0	9	48.0	.40	.40
281.8	8.0	5.0	7.0	9.0	9	67.0	.12	.37
354.8	9.0	5.0	8.3	12.0	10	186.0	.33	.44
446.7	10.0	5.0	8.6	13.0	8	163.0	.30	.50
562.3	11.0	5.0	9.2	12.0	9	158.0	.09	.55
707.9	13.0	6.0	11.9	16.0	8	192.0	.23	.54
891.3	18.0	7.0	13.3	19.0	4	276.0	.06	.61
1122.0	16.0	6.0	14.9	21.0	8	337.0	.31	.62
1412.5	21.0	17.0	21.0	25.0	5	210.0	.19	.19
1778.3	19.0	11.0	17.2	21.0	5	210.0	.11	.42
2238.7	34.0	33.0	42.7	61.0	3	1680.0	.79	.03
2818.4	30.0	4.0	23.6	44.0	13	2950.0	.47	.87
3548.1	37.0	8.0	31.8	59.0	4	1932.0	.59	.78
4466.8	36.0	27.0	35.7	45.0	4	683.0	.25	.25
5623.4	42.0	39.0	44.8	56.0	5	1036.0	.33	.07
7079.4	59.0	49.0	57.3	64.0	3	810.0	.08	.17
8912.5	64.0	26.0	55.1	98.0	8	7729.0	.53	.59
11220.2	74.0	35.0	70.8	101.0	6	5295.0	.36	.53
14125.4	54.0	46.0	63.3	90.0	3	3608.0	.67	.15
17782.8	138.0	34.0	85.7	138.0	3	8041.0	.00	.75
22387.2	79.0	78.0	78.5	79.0	2	78.0	.00	.01
28183.8	156.0	91.0	123.5	156.0	2	9915.0	.00	.42
35481.3	126.0	123.0	124.5	126.0	2	369.0	.00	.02
44668.3	168.0	80.0	147.3	194.0	3	12084.0	.15	.52
56234.0								
70794.5	71.0	71.0	71.0	71.0	1	.0	.00	.00

KEY

Z = RADAR REFLECTIVITY IN $10\ mm^6/m^3$

R^* = BEST ESTIMATE OF R BASED ON THE MINIMUM $\Sigma\ R_i(R^*-R_i)$ IN mm/hr

R MIN = MINIMUM RATE IN EACH Z INTERVAL mm/hr.

R AVE = AVERAGE RATE IN EACH Z INTERVAL mm/hr.

R MAX = MAXIMUM RATE IN EACH Z INTERVAL mm/hr.

N = NUMBER OF ONE CUBIC METER SAMPLES IN EACH Z INTERVAL

S = $\Sigma\ R(R^*-R_i)$

UNDER = MAXIMUM POSSIBLE UNDERESTIMATE DEFINED AS $\frac{R\ MAX - R^*}{R^*}$

OVER = MAXIMUM POSSIBLE OVERESTIMATE DEFINED AS $\frac{R^* - R\ MIN}{R^*}$

FIG. 3 TABLES OF RAINFALL RATE VERSUS RADAR REFLECTIVITY FOR SYNOPTIC TYPES FOR MIAMI, FLORIDA.

N=2360 NORTH CAROLINA

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1	.1	.0	.1	.2	33	.1	1.00	1.00
1.4								
1.8								
2.2	.2	.1	.1	.2	31	.2	.00	.50
2.8	.2	.1	.2	.4	29	.3	1.00	.50
3.5								
4.5	.3	.2	.3	.8	44	1.6	1.67	.33
5.6	.4	.2	.4	.7	21	.9	.75	.50
7.1	.5	.2	.4	.6	13	.4	.20	.60
8.9	.5	.2	.4	.9	29	1.6	.80	.60
11.2	.7	.3	.6	1.3	46	6.6	.86	.57
14.1	.8	.2	.7	1.7	51	8.1	1.12	.75
17.8	.9	.3	.8	1.8	57	11.5	1.00	.67
22.4	1.2	.4	1.0	2.1	79	25.8	.75	.67
28.2	1.4	.5	1.3	2.5	71	39.7	.79	.64
35.5	1.7	.3	1.6	3.0	83	57.2	.76	.82
44.7	2.0	.4	1.8	4.2	85	90.2	1.10	.70
56.2	2.3	.7	2.1	4.4	96	124.9	.91	.70
70.8	2.7	.9	2.5	5.8	77	172.0	1.15	.67
89.1	3.0	.7	2.8	5.1	101	230.3	.70	.77
112.2	3.7	1.7	3.5	7.4	117	389.9	1.00	.54
141.3	4.3	1.0	4.0	9.5	123	607.4	1.21	.77
177.8	5.3	1.1	4.9	10.6	149	1062.3	1.00	.79
223.9	6.3	1.9	5.8	12.8	129	1394.8	1.03	.70
281.8	7.8	2.8	6.9	14.9	123	1690.2	.91	.64
354.8	8.4	2.2	7.8	17.8	103	1720.4	1.07	.74
446.7	10.7	1.5	9.6	20.4	90	2417.7	.91	.86
562.3	12.1	2.9	10.9	21.2	91	2851.7	.75	.76
707.9	15.0	5.7	13.8	29.0	94	4713.7	.93	.62
891.3	17.7	8.3	16.4	30.0	72	4694.3	.69	.53
1122.0	20.0	4.3	17.7	26.7	64	4431.7	.33	.78
1412.5	21.5	7.5	20.1	30.3	56	4603.2	.41	.65
1778.3	26.9	7.3	24.6	43.5	43	5825.7	.62	.73
2238.7	30.0	8.1	26.6	39.4	37	4951.3	.31	.73
2818.4	39.1	19.0	37.5	52.3	29	5060.7	.34	.51
3548.1	44.7	20.7	38.7	53.7	19	5124.6	.20	.54
4466.8	48.3	12.9	44.6	69.9	12	5497.7	.45	.73
5623.4	63.0	25.4	54.8	101.2	22	20455.0	.61	.60
7079.4	62.4	35.0	55.3	67.7	7	2958.5	.08	.44
8912.5	71.3	29.4	62.9	105.1	12	10833.4	.47	.59
11220.2	121.3	38.6	105.2	136.0	10	18996.7	.12	.68
14125.4	140.4	83.3	123.8	165.3	7	20855.1	.18	.41
17782.8	154.1	35.9	109.5	176.6	6	20137.8	.15	.77
22387.2	217.4	99.7	177.8	266.1	5	40667.7	.22	.54
28183.8	101.0	58.1	79.5	101.0	2	2492.5	.00	.42
35481.3	67.7	40.6	54.1	67.7	2	1100.3	.00	.40

N=2688 ALASKA

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1	.1	.1	.1	.2	70	.1	1.00	-.00
1.4								
1.8								
2.2	.2	.1	.2	.3	137	.8	.50	.50
2.8	.3	.1	.2	.5	115	1.7	.67	.67
3.5								
4.5	.3	.1	.3	.6	199	4.8	1.00	.67
5.6	.4	.1	.4	.9	103	4.1	1.25	.75
7.1	.5	.2	.5	.8	71	3.5	.60	.60
8.9	.5	.2	.5	.8	119	5.8	.60	.60
11.2	.6	.3	.6	1.0	187	12.7	.67	.50
14.1	.8	.2	.7	1.4	131	15.6	.75	.75
17.8	.8	.3	.8	1.7	164	23.6	1.12	.62
22.4	1.0	.4	1.0	2.1	177	77.1	1.10	.60
28.2	1.2	.4	1.1	2.4	149	43.5	1.00	.67
35.5	1.3	.3	1.2	2.9	150	61.3	1.23	.77
44.7	1.6	.6	1.5	3.1	156	73.3	.94	.62
56.2	1.9	.9	1.7	3.5	142	117.4	.84	.53
70.8	2.1	.7	2.0	3.7	117	131.1	.76	.67
89.1	2.3	.8	2.2	4.4	116	132.4	.91	.65
112.2	3.0	.7	2.8	7.8	111	263.6	1.60	.77
141.3	3.3	1.1	3.2	7.6	64	211.6	1.30	.67
177.8	3.4	.8	3.5	8.9	62	243.8	1.34	.79
223.9	4.2	2.0	3.8	6.7	36	139.9	.60	.52
281.8	5.2	1.9	4.7	9.3	32	239.0	.79	.63
354.8	5.3	2.1	5.2	10.9	28	225.4	1.06	.60
446.7	4.9	1.6	4.3	6.5	9	36.6	.33	.67
562.3	8.0	2.4	7.8	19.7	12	345.3	1.46	.70
707.9	9.3	2.7	8.1	12.0	7	112.5	.29	.71
891.3	9.6	4.1	7.9	9.6	4	31.9	.00	.57
1122.0	11.4	3.9	8.8	11.4	5	66.9	.00	.66
1412.5	13.0	5.2	13.6	25.7	6	394.6	.98	.60
1778.3	14.1	3.9	10.3	16.0	4	119.9	.13	.72
2238.7	16.6	15.9	16.9	18.5	3	49.3	.11	.05
2818.4	9.2	9.2	9.2	9.2	1	.0	.00	-.00
3548.1	6.5	6.5	6.5	6.5	1	.0	.00	-.00
4466.8								
5623.4								
7079.4								
8912.5								
11220.2	9.2	9.2	9.2	9.2	1	.0	.00	-.00

N=1706 OREGON

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1	.1	.1	.1	.1	3	.0	.00	-.00
1.4								
1.8								
2.2	.1	.1	.1	.1	4	.0	.00	-.00
2.8	.1	.1	.1	.2	7	.0	1.00	-.00
3.5								
4.5	.2	.1	.2	.5	10	.2	1.50	.50
5.6	.3	.1	.2	.6	6	.3	1.00	.67
7.1	.6	.2	.5	.7	7	.4	.17	.67
8.9	.6	.2	.6	.7	20	.7	.17	.67
11.2	.6	.2	.6	.8	38	2.1	.33	.67
14.1	.7	.2	.7	1.5	67	7.0	1.14	.71
17.8	.7	.2	.7	1.6	94	11.7	1.29	.71
22.4	.8	.3	.8	1.8	158	27.1	1.25	.62
28.2	1.0	.4	.9	1.8	109	32.6	.80	.60
35.5	1.1	.5	1.1	2.3	130	33.7	1.09	.55
44.7	1.3	.5	1.2	2.5	130	46.6	.92	.62
56.2	1.5	.6	1.5	3.9	101	72.3	1.60	.60
70.8	1.7	.8	1.7	3.7	112	46.8	1.18	.53
89.1	2.2	.9	2.1	5.1	104	127.0	1.32	.59
112.2	2.4	1.1	2.3	4.9	104	119.8	1.04	.54
141.3	2.8	.9	2.7	6.0	76	145.7	1.14	.68
177.8	3.5	1.2	3.3	7.1	87	252.4	1.03	.66
223.9	4.1	1.4	3.7	6.5	66	223.1	.59	.66
281.8	4.7	1.7	4.4	8.5	64	359.4	.81	.64
354.8	6.1	1.8	5.4	10.3	56	468.7	.69	.70
446.7	5.6	1.7	5.6	14.5	35	466.5	1.59	.70
562.3	6.5	2.6	6.5	19.9	34	692.9	2.06	.60
707.9	8.0	3.0	7.5	12.6	27	413.3	.57	.62
891.3	10.8	2.6	8.6	18.4	20	504.3	.70	.76
1122.0	11.1	2.7	9.5	15.6	20	574.3	.41	.76
1412.5	10.8	6.2	9.8	12.2	5	68.6	.13	.43
1778.3	24.2	7.0	14.4	26.1	5	418.5	.08	.71
2238.7	7.7	5.3	7.2	8.5	3	19.5	.10	.31
2818.4	21.5	21.5	21.5	21.5	1	.0	.00	-.00
3548.1	24.0	13.4	18.7	24.0	2	142.0	.00	.44
4466.8								
5623.4	4.2	4.2	4.2	4.2	1	.0	.00	-.00

N=1879 INDONESIA

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1	.1	.1	.1	.2	47	.1	1.00	-.00
1.4								
1.8								
2.2	.2	.1	.1	.3	45	.3	.50	.50
2.8	.2	.1	.2	.3	24	.2	.50	.50
3.5								
4.5	.3	.1	.3	.5	50	.9	.67	.67
5.6	.4	.2	.3	.6	20	.7	.50	.50
7.1	.4	.2	.4	.6	29	.7	.50	.50
8.9	.5	.2	.4	.8	44	2.1	1.00	.50
11.2	.5	.2	.5	1.0	59	4.5	1.00	.60
14.1	.7	.2	.6	1.1	41	4.0	.57	.71
17.8	.8	.3	.7	1.0	46	6.2	.25	.62
22.4	.9	.4	.8	1.6	72	12.6	.78	.56
28.2	1.0	.4	.9	1.9	55	14.1	.90	.60
35.5	1.2	.4	1.1	1.8	63	17.0	.50	.67
44.7	1.5	.6	1.4	2.6	50	25.0	.73	.60
56.2	1.6	.5	1.5	2.9	49	30.2	.81	.69
70.8	2.1	.8	1.8	3.1	56	46.5	.48	.62
89.1	2.2	.9	2.0	3.3	54	56.8	.50	.59
112.2	2.7	1.0	2.4	4.0	65	98.2	.48	.63
141.3	3.0	1.5	2.9	5.0	53	132.3	.67	.50
177.8	3.9	1.3	3.7	6.2	71	219.0	.59	.67
223.9	4.4	1.4	4.1	7.1	64	249.9	.61	.68
281.8	5.0	1.1	4.8	10.4	62	373.3	1.08	.78
354.8	6.4	1.6	6.0	9.3	61	468.2	.45	.75
446.7	7.6	1.3	7.0	11.7	45	517.5	.54	.83
562.3	9.1	1.9	8.0	12.8	54	784.3	.41	.79
707.9	10.7	5.6	10.3	17.5	58	1511.4	.64	.48
891.3	13.3	4.0	11.0	17.8	49	1418.8	.35	.70
1122.0	15.7	3.9	14.4	26.8	44	2229.5	.71	.75
1412.5	19.2	5.0	16.8	26.8	38	2449.6	.40	.74
1778.3	22.4	7.0	20.3	29.3	44	3513.6	.31	.69
2238.7	25.7	6.7	23.1	40.5	44	5925.7	.58	.74
2818.4	30.1	6.0	26.7	44.2	48	6265.5	.47	.80
3548.1	33.1	7.5	29.5	43.9	45	7753.9	.33	.77
4466.8	38.8	11.8	33.4	50.6	43	9773.4	.30	.70
5623.4	49.8	13.2	41.4	67.0	45	17928.0	.35	.73
7079.4	49.0	12.2	45.9	78.2	36	18292.7	.60	.75
8912.5	61.7	17.0	54.1	81.2	27	16394.3	.32	.72
11220.2	79.7	15.9	65.7	151.4	25	48959.3	.90	.80
14125.4	104.5	28.7	84.1	136.6	10	19098.0	.31	.73
17782.8	86.0	10.7	65.0	181.8	14	35079.7	1.09	.88
22387.2	118.8	18.7	75.5	203.8	10	40516.5	.72	.84
28183.8	202.0	133.5	201.7	202.0	2	19825.7	.00	.53
35481.3	74.6	40.7	70.0	94.7	3	3283.2	.27	.45
44668.3	129.5	98.7	125.6	148.5	3	5861.5	.15	.24
56234.0	72.3	72.3	72.3	72.3	1	.0	.00	-.00
70794.5	126.5	83.4	104.9	126.5	2	3544.5	.00	.34
89124.9								
112201.7	123.8	123.8	123.8	123.8	1	.0	.00	-.00

N=2461 MAJURO

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1								
1.4								
1.8								
2.2								
2.8								
3.5								
4.5								
5.6								
7.1								
8.9								
11.2	1.0	1.0	1.0	2.0	112	2.0	1.00	-.00
14.1								
17.8								
22.4	1.0	1.0	1.1	2.0	179	32.0	1.00	-.00
28.2	1.0	1.0	1.4	8.0	129	134.0	7.00	-.00
35.5								
44.7	2.0	1.0	1.8	8.0	190	259.0	3.00	.50
56.2	3.0	1.0	2.6	5.0	71	103.0	.67	.67
70.8	3.0	1.0	2.5	5.0	64	142.0	.67	.67
89.1	3.0	1.0	2.9	6.0	109	300.0	1.00	.67
112.2	4.0	1.0	3.7	7.0	146	570.0	.75	.75
141.3	5.0	1.0	4.4	9.0	120	752.0	.80	.80
177.8	6.0	2.0	5.1	12.0	124	1066.0	1.00	.67
223.9	7.0	2.0	5.0	12.0	143	1610.0	.71	.71
281.8	9.0	2.0	7.6	14.0	98	1478.0	.56	.78
354.8	10.0	2.0	8.7	15.0	166	2147.0	.50	.80
446.7	13.0	3.0	10.6	20.0	118	3438.0	.54	.77
562.3	14.0	4.0	12.4	21.0	104	3634.0	.50	.71
707.9	18.0	4.0	15.6	25.0	92	4371.0	.39	.78
891.3	21.0	5.0	19.1	29.0	74	4560.0	.38	.76
1122.0	24.0	7.0	21.6	32.0	87	6567.0	.33	.71
1412.5	29.0	10.0	25.9	37.0	62	6784.0	.28	.66
1778.3	33.0	4.0	29.3	47.0	63	9936.0	.42	.88
2238.7	37.0	16.0	35.9	52.0	54	9417.0	.41	.57
2818.4	44.0	7.0	41.4	59.0	41	9311.0	.34	.84
3548.1	51.0	13.0	48.5	67.0	47	13150.0	.31	.75
4466.8	55.0	7.0	52.8	80.0	33	14290.0	.45	.87
5623.4	65.0	23.0	55.6	86.0	24	17642.0	.32	.65
7079.4	77.0	16.0	70.9	96.0	25	17946.0	.25	.79
8912.5	86.0	53.0	83.1	102.0	14	12237.0	.19	.38
11220.2	93.0	75.0	90.5	102.0	8	4260.0	.10	.19
14125.4	129.0	86.0	117.6	149.0	10	22226.0	.16	.33
17782.8	121.0	89.0	121.5	171.0	8	21462.0	.41	.26
22387.2	123.0	113.0	118.0	123.0	2	1130.0	.00	.08
28183.8	248.0	177.0	212.5	248.0	2	12567.0	.00	.29
35481.3								

N=2506 MIAMI

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1								
1.4								
1.8								
2.2								
2.8								
3.5								
4.5								
5.6								
7.1								
8.9								
11.2	1.0	1.0	1.0	1.0	10	.0	.00	-.00
14.1								
17.8								
22.4	1.0	1.0	1.0	1.0	41	.0	.00	-.00
28.2	1.0	1.0	1.0	2.0	65	6.0	1.00	-.00
35.5								
44.7	1.0	1.0	1.1	2.0	104	30.0	1.00	-.00
56.2	2.0	1.0	1.6	9.0	55	95.0	3.50	.50
70.8	2.0	1.0	1.7	4.0	43	41.0	1.00	.50
89.1	2.0	1.0	2.0	4.0	85	121.0	1.00	.50
112.2	3.0	1.0	2.5	6.0	96	182.0	1.00	.67
141.3	3.0	1.0	3.0	6.0	81	226.0	1.00	.67
177.8	4.0	1.0	3.7	7.0	105	390.0	.75	.75
223.9	5.0	1.0	4.3	9.0	134	680.0	.80	.80
281.8	6.0	2.0	5.4	14.0	90	832.0	1.33	.67
354.8	7.0	2.0	6.3	12.0	125	1458.0	.71	.71
446.7	8.0	2.0	7.4	13.0	139	2086.0	.62	.75
562.3	10.0	2.0	9.0	18.0	116	2379.0	.80	.80
707.9	11.0	3.0	10.4	19.0	128	3620.0	.73	.73
891.3	15.0	3.0	12.8	28.0	115	5826.0	.87	.80
1122.0	17.0	3.0	14.5	27.0	111	6892.0	.59	.82
1412.5	21.0	6.0	19.2	32.0	72	6238.0	.52	.71
1778.3	25.0	5.0	21.2	37.0	90	12504.0	.48	.80
2238.7	31.0	4.0	26.3	61.0	72	13964.0	.97	.87
2818.4	33.0	4.0	28.3	74.0	76	21358.0	1.24	.88
3548.1	41.0	8.0	34.8	62.0	69	25390.0	.51	.80
4466.8	48.0	8.0	43.7	88.0	59	30390.0	.83	.83
5623.4	55.0	14.0	50.5	87.0	61	41818.0	.58	.75
7079.4	65.0	18.0	56.5	90.0	50	37740.0	.38	.72
8912.5	70.0	16.0	61.0	117.0	60	60039.0	.67	.77
11220.2	78.0	18.0	68.5	131.0	36	43422.0	.68	.77
14125.4	91.0	46.0	90.4	221.0	36	82434.0	1.43	.49
17782.8	110.0	15.0	86.5	166.0	32	76729.0	.51	.86
22387.2	121.0	15.0	113.9	214.0	33	104806.0	.77	.88
28183.8	153.0	41.0	131.5	238.0	36	181824.0	.56	.73
35481.3	192.0	41.0	167.1	249.0	28	161610.0	.30	.79
44668.3	206.0	39.0	164.6	306.0	24	259215.0	.49	.81
56234.0	220.0	33.0	227.7	375.0	9	132368.0	.70	.85
70794.5	203.0	71.0	189.9	359.0	8	132584.0	.77	.65
89124.9	282.0	49.0	235.5	466.0	4	117026.0	.65	.83
112201.7	305.0	73.0	247.7	400.0	4	74532.0	.31	.76
141253.5	566.0	82.0	401.4	722.0	5	264677.0	.28	.86
177827.4	204.0	204.0	204.0	204.0	1	.0	.00	-.00

KEY

Z = RADAR REFLECTIVITY IN $10\,mm^6/m^3$
R^* = BEST ESTIMATE OF R BASED ON THE MINIMUM $\Sigma R_i(R^*-R_i)$ IN mm/hr.
R MIN = MINIMUM RATE IN EACH Z INTERVAL mm/hr.
R AVE = AVERAGE RATE IN EACH Z INTERVAL mm/hr.
R MAX = MAXIMUM RATE IN EACH Z INTERVAL mm/hr.
N = NUMBER OF ONE CUBIC METER SAMPLES IN EACH Z INTERVAL
$S = \Sigma R(R^*-R_i)$
UNDER = MAXIMUM POSSIBLE UNDERESTIMATE DEFINED AS $\frac{R\,MAX - R^*}{R^*}$
OVER = MAXIMUM POSSIBLE OVERESTIMATE DEFINED AS $\frac{R^* - R\,MIN}{R^*}$

FIG. 4 TABLES OF R-Z COMPARISONS FOR NON-STRATIFIED DATA FROM ALASKA, OREGON, FLORIDA, INDONESIA, MAJURO, AND NORTH CAROLINA.

N=366 MAJURO PASI 1-75

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1								
1.4								
1.8								
2.2								
2.8								
3.5								
4.5								
5.6								
7.1								
8.9								
11.2	1.0	1.0	1.0	1.0	8	.0	.00	-.00
14.1								
17.8								
22.4	1.0	1.0	1.2	2.0	10	4.0	1.00	-.00
28.2	1.0	1.0	1.2	2.0	11	4.0	1.00	-.00
35.5								
44.7	2.0	1.0	2.1	3.0	17	19.0	.50	.50
56.2	2.0	1.0	1.8	3.0	5	5.0	.50	.50
70.8	3.0	1.0	2.1	4.0	8	14.0	.33	.67
89.1	3.0	2.0	2.7	4.0	13	12.0	.33	.33
112.2	4.0	2.0	3.3	6.0	26	76.0	.50	.50
141.3	3.0	2.0	3.4	6.0	14	42.0	1.00	.33
177.8	5.0	3.0	4.5	8.0	21	163.0	.60	.40
223.9	6.0	3.0	5.1	9.0	27	155.0	.50	.50
281.8	6.0	2.0	5.4	9.0	15	111.0	.50	.67
354.8	8.0	3.0	7.4	12.0	17	304.0	.50	.62
446.7	9.0	4.0	8.5	16.0	23	549.0	.78	.55
562.3	14.0	5.0	11.4	20.0	14	552.0	.43	.64
707.9	18.0	7.0	14.1	23.0	14	647.0	.28	.61
891.3	19.0	9.0	16.8	27.0	13	646.0	.42	.53
1122.0	20.0	7.0	19.4	28.0	17	1312.0	.40	.65
1412.5	27.0	19.0	26.8	33.0	13	722.0	.22	.30
1778.3	30.0	4.0	25.1	41.0	16	2619.0	.37	.87
2238.7	37.0	27.0	36.3	49.0	11	1844.0	.32	.27
2818.4	44.0	7.0	36.9	50.0	14	2959.0	.14	.84
3548.1	53.0	46.0	52.7	60.0	9	1634.0	.13	.13
4466.8	60.0	42.0	52.8	60.0	6	1903.0	.00	.30
5623.4	62.0	23.0	47.9	76.0	8	5297.0	.23	.63
7079.4	69.0	16.0	54.0	73.0	6	3224.0	.05	.77
8912.5	81.0	72.0	79.7	86.0	3	1379.0	.06	.11
11220.2	93.0	75.0	90.0	102.0	3	2268.0	.10	.19
14125.4	96.0	86.0	91.0	96.0	2	860.0	.00	.10
17782.8	111.0	110.0	114.0	121.0	3	1323.0	.09	.01
22387.2	123.0	113.0	118.0	123.0	2	113.0	.00	.08

N=518 MAJURO PASI 75-100

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1								
1.4								
1.8								
2.2								
2.8								
3.5								
4.5								
5.6								
7.1								
8.9								
11.2	1.0	1.0	1.0	1.0	19	.0	.00	-.00
14.1								
17.8								
22.4	1.0	1.0	1.1	2.0	44	5.0	1.00	-.00
28.2	2.0	1.0	1.5	5.0	29	72.0	1.50	.50
35.5								
44.7	3.0	1.0	2.1	4.0	27	44.0	.33	.67
56.2	3.0	2.0	2.8	4.0	11	15.0	.33	.33
70.8	3.0	1.0	2.3	5.0	11	34.0	.67	.67
89.1	4.0	2.0	3.3	5.0	15	31.0	.25	.50
112.2	4.0	2.0	3.7	7.0	22	77.0	.75	.50
141.3	4.0	1.0	4.2	7.0	25	103.0	.75	.75
177.8	6.0	2.0	5.4	9.0	25	143.0	.50	.67
223.9	7.0	3.0	5.6	11.0	20	315.0	.57	.57
281.8	9.0	4.0	8.5	12.0	13	173.0	.33	.56
354.8	11.0	3.0	8.8	13.0	15	292.0	.18	.73
446.7	13.0	6.0	11.9	17.0	9	133.0	.31	.54
562.3	13.0	4.0	11.5	17.0	19	534.0	.31	.69
707.9	18.0	4.0	14.7	24.0	15	742.0	.33	.78
891.3	21.0	7.0	16.9	29.0	15	1225.0	.38	.67
1122.0	24.0	9.0	21.4	32.0	17	1583.0	.33	.62
1412.5	27.0	10.0	24.3	31.0	13	1115.0	.15	.63
1778.3	31.0	15.0	29.7	42.0	13	1274.0	.35	.52
2238.7	36.0	21.0	36.0	48.0	11	2219.0	.33	.42
2818.4	44.0	24.0	42.7	52.0	9	1706.0	.18	.45
3548.1	50.0	22.0	46.7	55.0	12	2112.0	.10	.56
4466.8	59.0	45.0	57.0	68.0	7	2512.0	.15	.24
5623.4	76.0	25.0	58.6	86.0	5	4445.0	.13	.67
7079.4	82.0	47.0	77.9	94.0	7	5301.0	.15	.43
8912.5	88.0	67.0	84.0	102.0	3	3040.0	.16	.24
11220.2	88.0	88.0	88.0	88.0	1	.0	.00	-.00
14125.4	137.0	135.0	140.3	149.0	3	2271.0	.09	.01
17782.8	171.0	99.0	130.0	171.0	2	7299.0	.00	.42
22387.2								
28183.8	240.0	177.0	212.5	240.0	2	12561.0	.00	.26
35481.3								
44668.4	270.0	151.0	210.5	270.0	2	17767.0	.00	.44

N=413 MAJURO PASI 101-135

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1								
1.4								
1.8								
2.2								
2.8								
3.5								
4.5								
5.6								
7.1								
8.9								
11.2	1.0	1.0	1.0	2.0	28	2.0	1.00	-.00
14.1								
17.8								
22.4	1.0	1.0	1.1	2.0	27	4.0	1.00	-.00
28.2	2.0	1.0	1.6	6.0	24	42.0	2.00	.50
35.5								
44.7	2.0	1.0	1.5	3.0	27	15.0	.50	.50
56.2	3.0	1.0	2.2	5.0	17	32.0	.67	.67
70.8	3.0	1.0	2.2	4.0	15	20.0	.33	.67
89.1	3.0	1.0	2.8	6.0	19	74.0	1.00	.67
112.2	5.0	1.0	3.5	6.0	23	95.0	.20	.80
141.3	5.0	2.0	4.6	8.0	27	142.0	.60	.60
177.8	6.0	2.0	4.6	8.0	19	139.0	.33	.67
223.9	7.0	3.0	6.3	11.0	23	303.0	.57	.57
281.8	9.0	4.0	8.7	14.0	25	473.0	.56	.56
354.8	10.0	4.0	8.8	13.0	18	317.0	.30	.60
446.7	12.0	7.0	11.6	18.0	25	624.0	.50	.42
562.3	14.0	13.0	14.9	20.0	16	403.0	.43	.07
707.9	17.0	9.0	16.9	25.0	20	805.0	.47	.47
891.3	20.0	14.0	19.4	25.0	13	523.0	.25	.30
1122.0	24.0	13.0	21.4	27.0	14	849.0	.12	.46
1412.5	29.0	23.0	27.7	33.0	10	813.0	.14	.21
1778.3	31.0	23.0	31.6	38.0	7	684.0	.23	.26
2238.7	36.0	16.0	33.5	40.0	10	1227.0	.11	.56
2818.4	37.0	30.0	39.0	50.0	3	860.0	.35	.19
3548.1	54.0	28.0	47.0	59.0	3	1023.0	.09	.48
4466.8	62.0	62.0	62.0	62.0	1	.0	.00	-.00
5623.4	61.0	48.0	54.5	61.0	2	624.0	.00	.21
7079.4	73.0	73.0	73.0	73.0	1	.0	.00	-.00
8912.5								
11220.2	82.0	82.0	82.0	82.0	1	.0	.00	-.00

N=322 MAJURO PASI 136-150

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1								
1.4								
1.8								
2.2								
2.8								
3.5								
4.5								
5.6								
7.1								
8.9								
11.2	1.0	1.0	1.0	1.0	11	.0	.00	-.00
14.1								
17.8								
22.4	1.0	1.0	1.2	2.0	24	13.0	1.00	-.00
28.2	2.0	1.0	1.6	3.0	14	13.0	.50	.50
35.5								
44.7	2.0	1.0	2.0	3.0	18	23.0	.50	.50
56.2	3.0	2.0	2.7	3.0	7	4.0	.00	.33
70.8	4.0	2.0	3.3	4.0	10	17.0	.00	.50
89.1	3.0	2.0	3.3	5.0	10	23.0	.67	.33
112.2	4.0	2.0	4.3	7.0	26	79.0	.75	.50
141.3	6.0	4.0	5.6	7.0	8	25.0	.17	.33
177.8	6.0	2.0	5.5	9.0	10	85.0	.50	.67
223.9	7.0	3.0	7.2	10.0	25	188.0	.43	.57
281.8	9.0	3.0	8.4	11.0	14	163.0	.22	.67
354.8	11.0	5.0	10.0	15.0	18	406.0	.36	.55
446.7	13.0	4.0	10.2	16.0	20	523.0	.23	.69
562.3	14.0	5.0	11.5	19.0	24	895.0	.36	.64
707.9	13.0	5.0	10.9	20.0	14	704.0	.54	.62
891.3	21.0	5.0	15.6	28.0	8	106.0	.33	.76
1122.0	24.0	11.0	21.8	28.0	13	819.0	.17	.54
1412.5	29.0	11.0	24.1	35.0	10	1504.0	.21	.62
1778.3	34.0	12.0	29.2	47.0	13	2503.0	.38	.65
2238.7	44.0	33.0	40.7	45.0	3	408.0	.02	.25
2818.4	46.0	42.0	45.2	48.0	4	303.0	.04	.09
3548.1	51.0	13.0	46.6	67.0	8	3414.0	.31	.75
4466.8	52.0	46.0	52.6	61.0	5	927.0	.17	.12
5623.4	65.0	35.0	58.3	75.0	3	1000.0	.15	.46
7079.4	77.0	77.0	77.0	77.0	1	.0	.00	-.00
8912.5	99.0	99.0	99.0	99.0	1	.0	.00	-.00

N=452 MAJURO PASI 151-215

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1								
1.4								
1.8								
2.2								
2.8								
3.5								
4.5								
5.6								
7.1								
8.9								
11.2	1.0	1.0	1.0	1.0	19	.0	.00	-.00
14.1								
17.8								
22.4	1.0	1.0	1.0	2.0	31	2.0	1.00	-.00
28.2	1.0	1.0	1.2	2.0	25	13.0	1.00	-.00
35.5								
44.7	2.0	1.0	1.7	8.0	53	95.0	3.00	.50
56.2	3.0	1.0	2.8	4.0	16	22.0	.33	.67
70.8	3.0	1.0	2.3	5.0	13	32.0	.67	.67
89.1	3.0	1.0	2.6	4.0	28	58.0	.33	.67
112.2	4.0	1.0	3.5	7.0	29	133.0	.75	.75
141.3	5.0	2.0	4.5	9.0	27	198.0	.80	.60
177.8	6.0	2.0	4.8	10.0	27	216.0	.67	.67
223.9	6.0	2.0	5.4	12.0	22	275.0	1.00	.67
281.8	7.0	2.0	6.0	10.0	16	175.0	.43	.71
354.8	9.0	2.0	7.2	15.0	19	364.0	.67	.78
446.7	14.0	3.0	10.0	20.0	27	977.0	.43	.79
562.3	14.0	5.0	11.6	21.0	16	629.0	.50	.64
707.9	20.0	14.0	18.5	21.0	12	398.0	.05	.30
891.3	23.0	7.0	21.7	28.0	10	474.0	.22	.70
1122.0	24.0	17.0	22.9	27.0	9	514.0	.12	.29
1412.5	29.0	10.0	27.9	37.0	10	1332.0	.28	.66
1778.3	31.0	22.0	30.6	36.0	8	783.0	.16	.29
2238.7	38.0	29.0	36.7	42.0	8	904.0	.11	.24
2818.4	49.0	37.0	48.0	59.0	6	1504.0	.20	.24
3548.1	44.0	40.0	45.6	51.0	5	958.0	.16	.09
4466.8	51.0	7.0	35.2	52.0	4	983.0	.02	.86
5623.4	49.0	49.0	49.0	49.0	1	.0	.00	-.00
7079.4	85.0	70.0	77.5	85.0	2	1050.0	.00	.18
8912.5	97.0	94.0	95.5	97.0	2	282.0	.00	.03
11220.2	92.0	92.0	92.0	92.0	1	.0	.00	-.00
14125.4	129.0	91.0	114.2	144.0	4	8966.0	.12	.29
17782.8	133.0	92.0	112.5	133.0	2	3772.0	.00	.31

N=460 MAJURO PASI GREATER THAN 216

Z	R*	R MIN	R AVE	R MAX	N	S	UNDER	OVER
1.1								
1.4								
1.8								
2.2								
2.8								
3.5								
4.5								
5.6								
7.1								
8.9								
11.2	1.0	1.0	1.0	1.0	27	.0	.00	-.00
14.1								
17.8								
22.4	1.0	1.0	1.1	2.0	48	5.0	1.00	-.00
28.2	1.0	1.0	1.3	3.0	26	18.0	2.00	-.00
35.5								
44.7	2.0	1.0	1.6	4.0	48	45.0	1.00	.50
56.2	3.0	1.0	2.7	4.0	15	18.0	.33	.67
70.8	3.0	2.0	2.7	4.0	7	10.0	.33	.33
89.1	4.0	1.0	3.0	5.0	27	83.0	.25	.75
112.2	5.0	1.0	4.1	7.0	20	93.0	.40	.80
141.3	6.0	1.0	4.7	8.0	19	118.0	.33	.83
177.8	7.0	3.0	6.0	12.0	21	234.0	.71	.57
223.9	8.0	2.0	6.5	11.0	18	257.0	.37	.75
281.8	9.0	4.0	8.3	12.0	18	246.0	.33	.56
354.8	10.0	5.0	10.2	14.0	19	345.0	.40	.50
446.7	13.0	10.0	13.1	17.0	14	304.0	.31	.23
562.3	15.0	10.0	14.3	21.0	15	426.0	.40	.33
707.9	17.0	12.0	16.2	20.0	16	432.0	.18	.29
891.3	20.0	14.0	19.4	26.0	17	671.0	.30	.30
1122.0	24.0	15.0	23.6	31.0	17	1238.0	.29	.37
1412.5	23.0	12.0	24.0	33.0	6	672.0	.43	.48
1778.3	37.0	22.0	33.4	47.0	9	1740.0	.27	.41
2238.7	38.0	21.0	35.7	52.0	11	2217.0	.37	.45
2818.4	42.0	34.0	42.6	49.0	5	1075.0	.17	.19
3548.1	54.0	29.0	49.9	65.0	10	2895.0	.20	.46
4466.8	55.0	36.0	55.9	80.0	10	6020.0	.45	.35
5623.4	72.0	32.0	65.0	80.0	5	2265.0	.11	.56
7079.4	81.0	36.0	74.7	96.0	8	4486.0	.19	.56
8912.5	81.0	53.0	76.4	95.0	5	3462.0	.17	.35
11220.2	97.0	95.0	96.0	97.0	2	190.0	.00	.02
14125.4	116.0	116.0	116.0	116.0	1	.0	.00	-.00
17782.8	145.0	145.0	145.0	145.0	1	.0	.00	-.00

**** ALL INPUT DATA HAVE BEEN PROCESSED.
AT LCC 10005

KEY

Z = RADAR REFLECTIVITY IN $10 mm^6/m^3$

R* = BEST ESTIMATE OF R BASED ON THE MINIMUM $\Sigma R_i (R^* - R_i)$ IN mm/hr.

R MIN = MINIMUM RATE IN EACH Z INTERVAL mm/hr.

R AVE = AVERAGE RATE IN EACH Z INTERVAL mm/hr.

R MAX = MAXIMUM RATE IN EACH Z INTERVAL mm/hr.

N = NUMBER OF ONE CUBIC METER SAMPLES IN EACH Z INTERVAL

S = $\Sigma R (R^* - R_i)$

UNDER = MAXIMUM POSSIBLE UNDERESTIMATE DEFINED AS $\frac{R MAX - R^*}{R^*}$

OVER = MAXIMUM POSSIBLE OVERESTIMATE DEFINED AS $\frac{R^* - R MIN}{R^*}$

FIG. 5 TABLES OF RAINFALL RATE VERSUS RADAR REFLECTIVITY FOR DIFFERENT POSITIVE AREA STABILITY INDICES (PASI) FOR MAJURO.

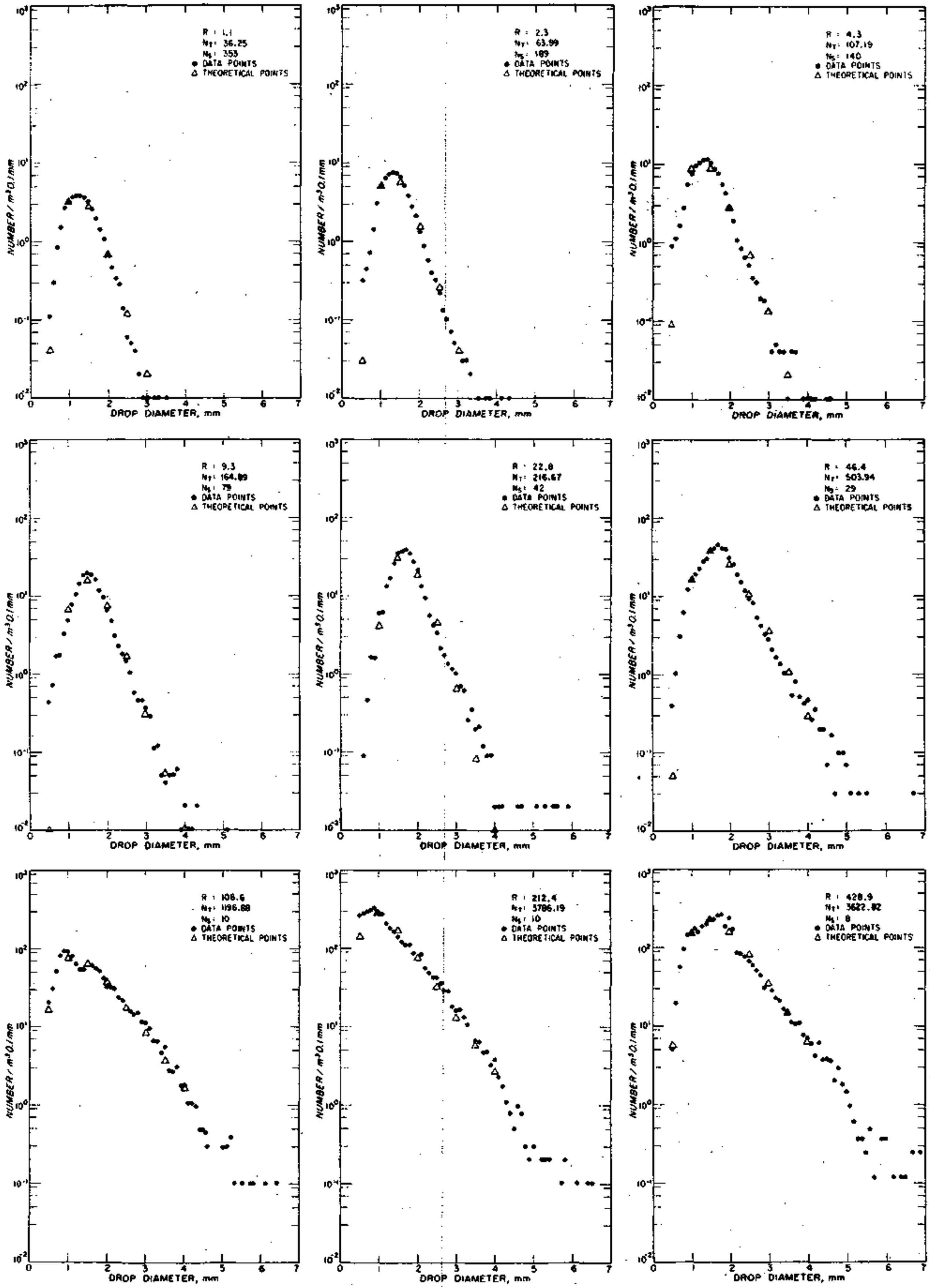

FIG. 6 AVERAGE DISTRIBUTIONS FOR ALL MIAMI, FLORIDA DATA

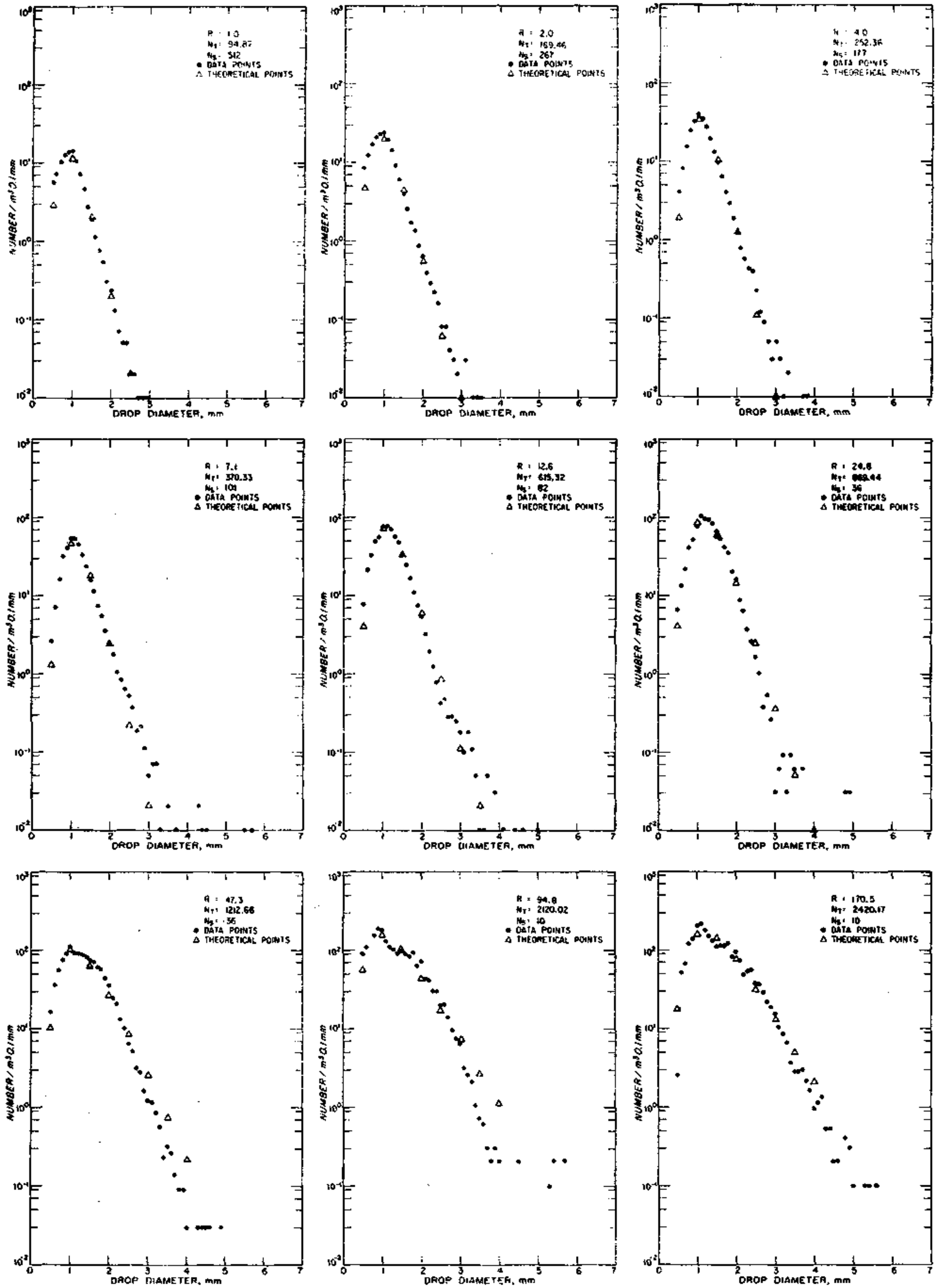

FIG. 7 AVERAGE DISTRIBUTIONS FOR MAJURO, MARSHALL ISLANDS

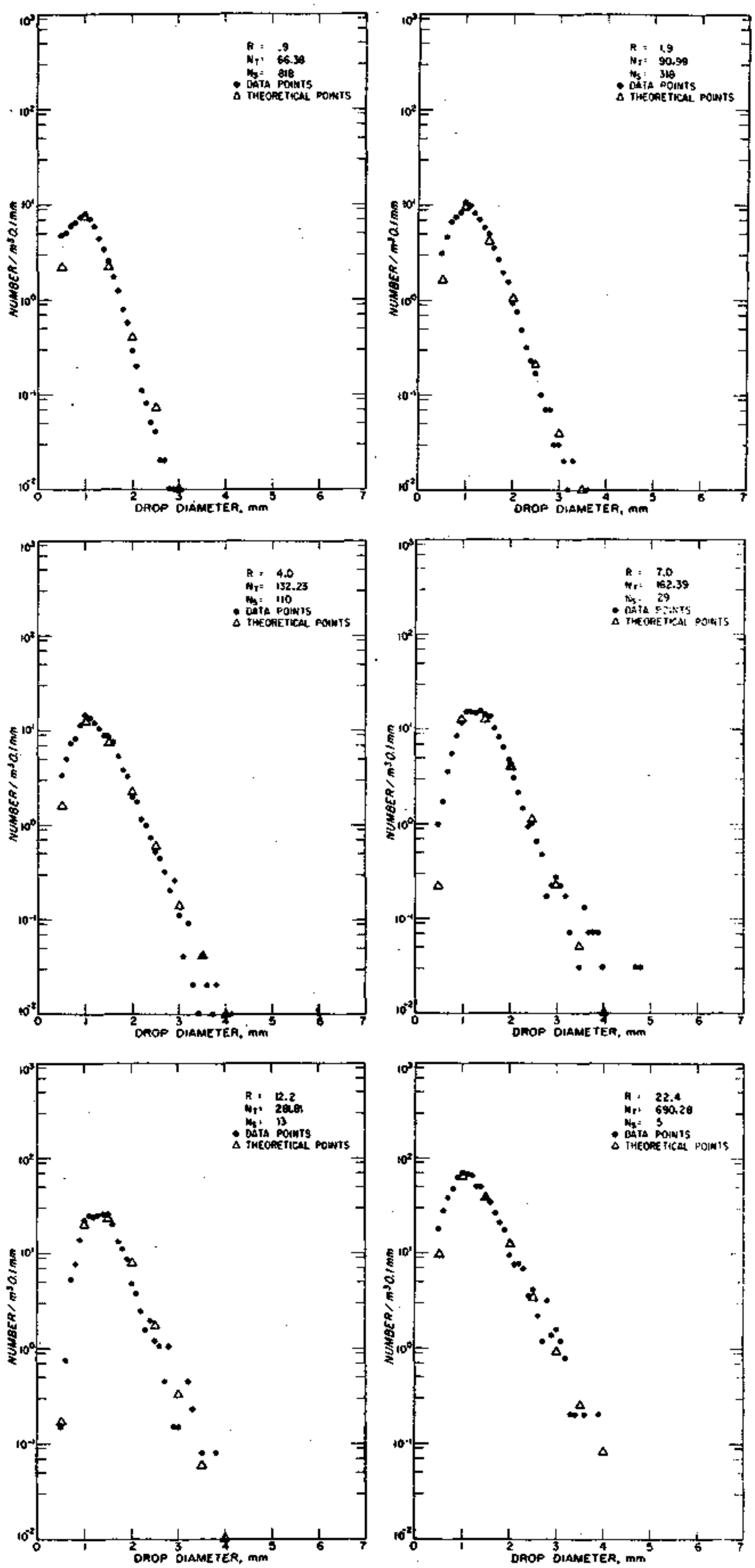

FIG. 8 AVERAGE DISTRIBUTIONS FOR CORVALLIS, OREGON

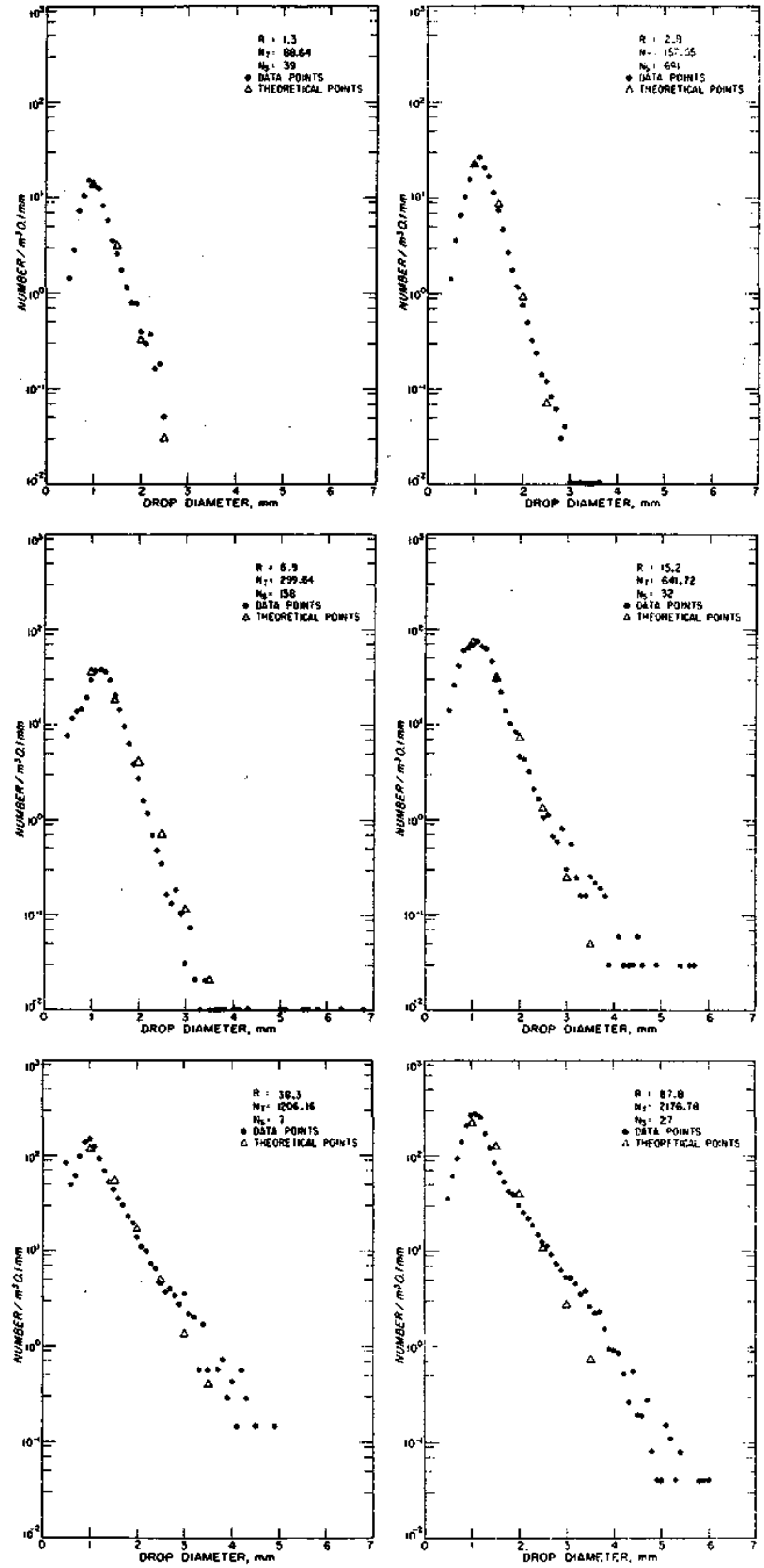

FIG. 9 AVERAGE DISTRIBUTIONS FOR ISLAND BEACH. NEW JERSEY

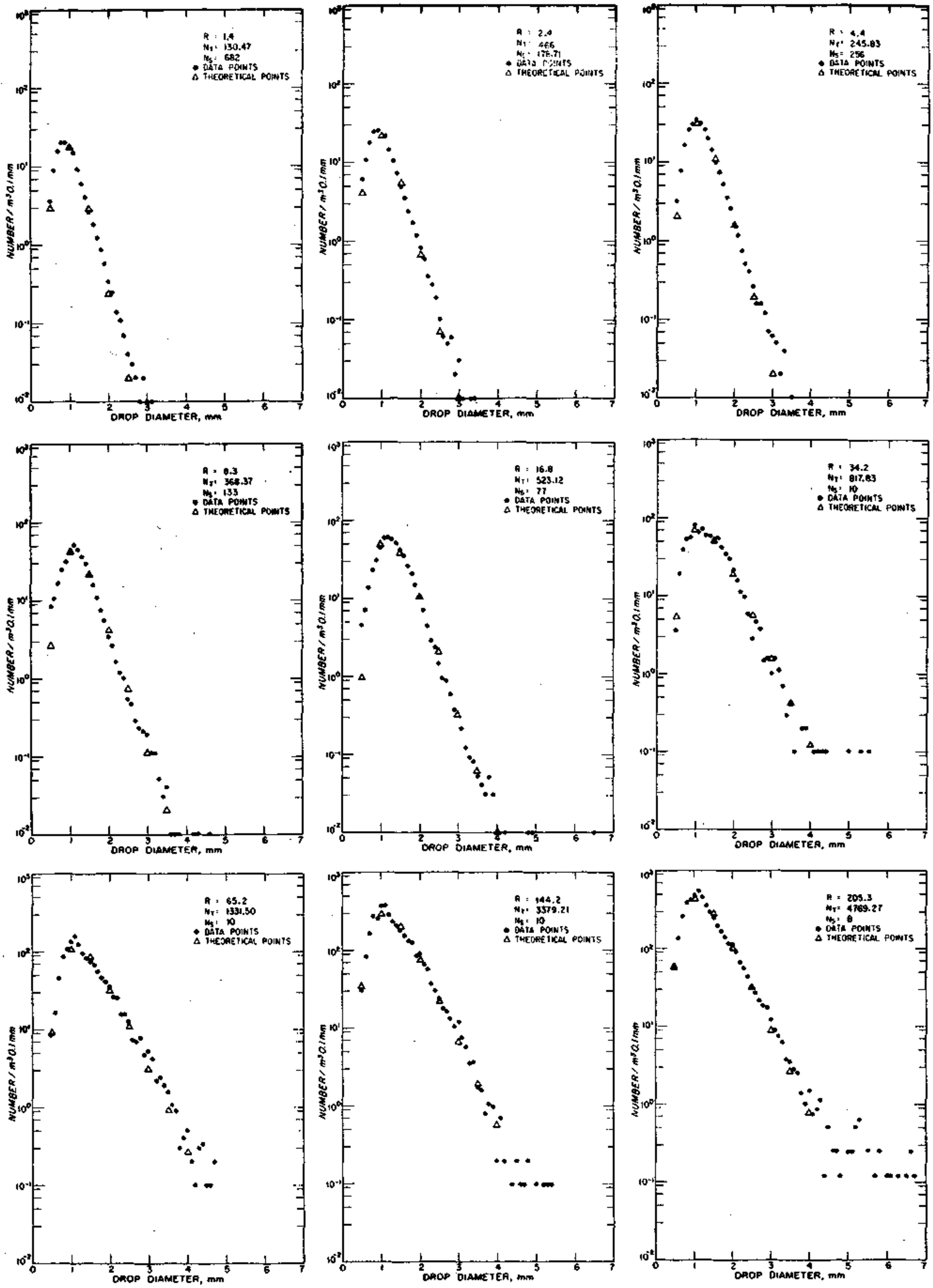

FIG. 10 AVERAGE DISTRIBUTIONS FOR COWEETA LAB., N. CAROLINA

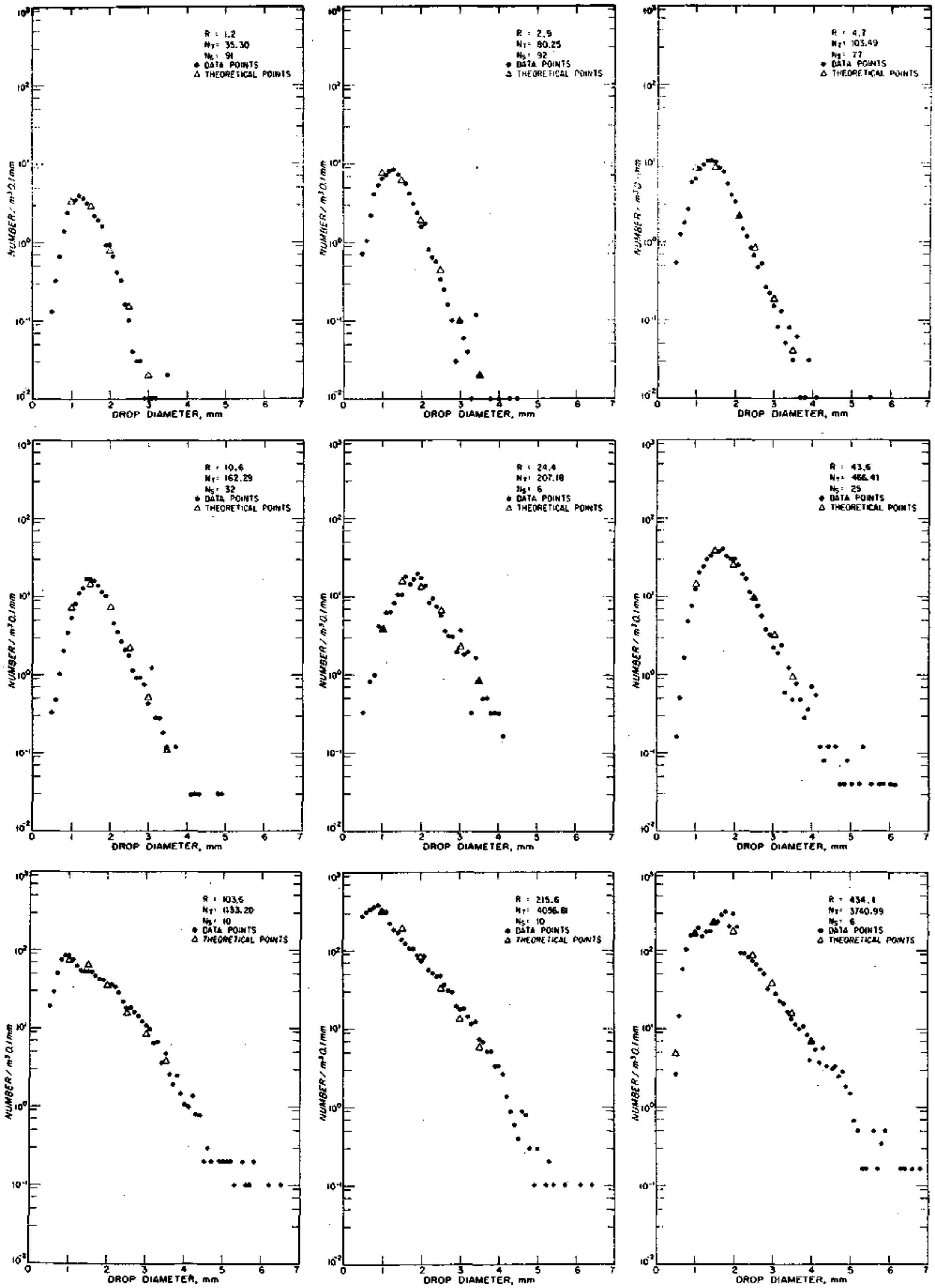

FIG. II AVERAGE DISTRIBUTIONS FOR THUNDERSTORMS AT MIAMI, FLORIDA

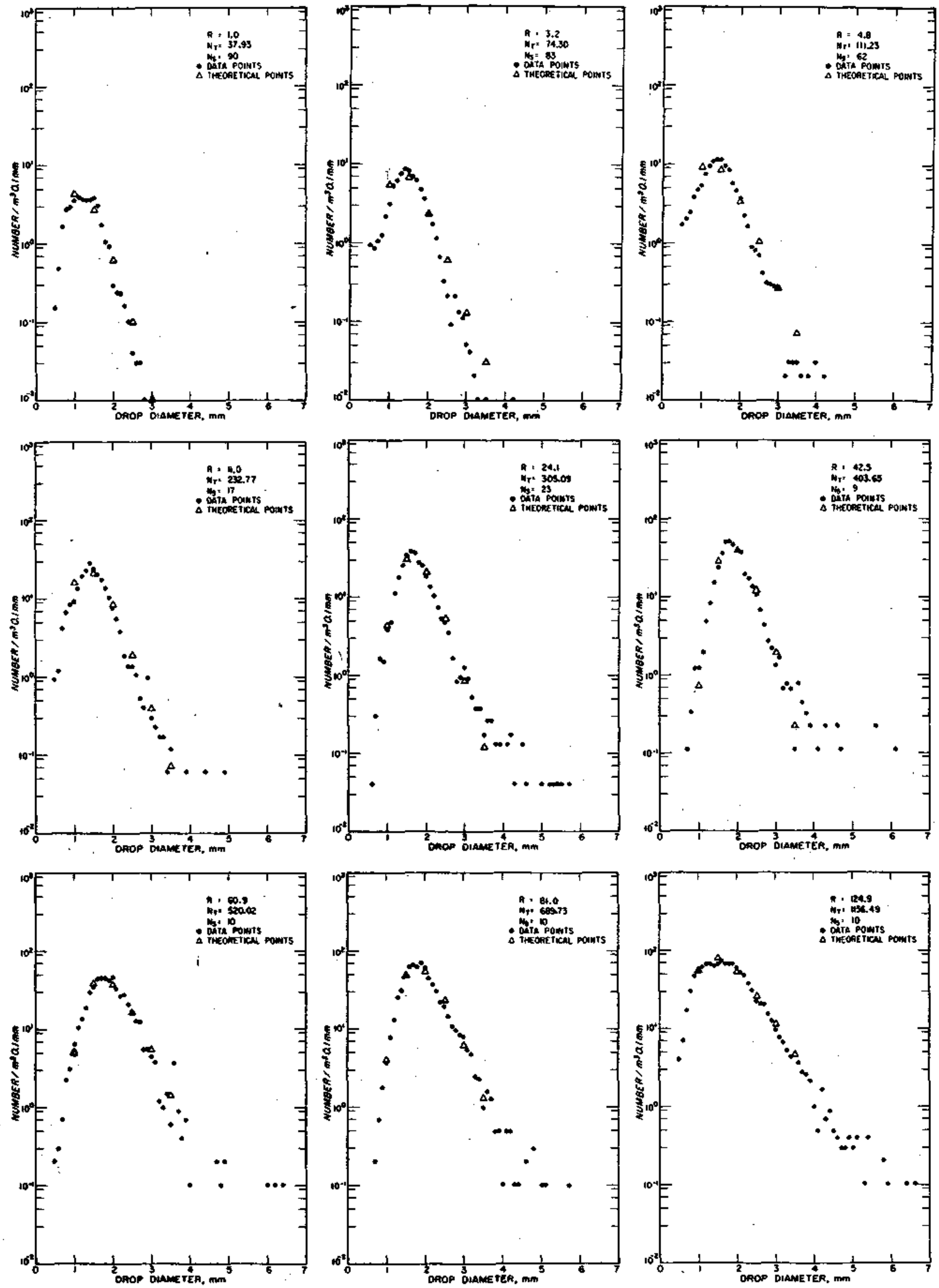

FIG. 12 AVERAGE DISTRIBUTIONS FOR RAINSHOWERS AT MIAMI, FLORIDA

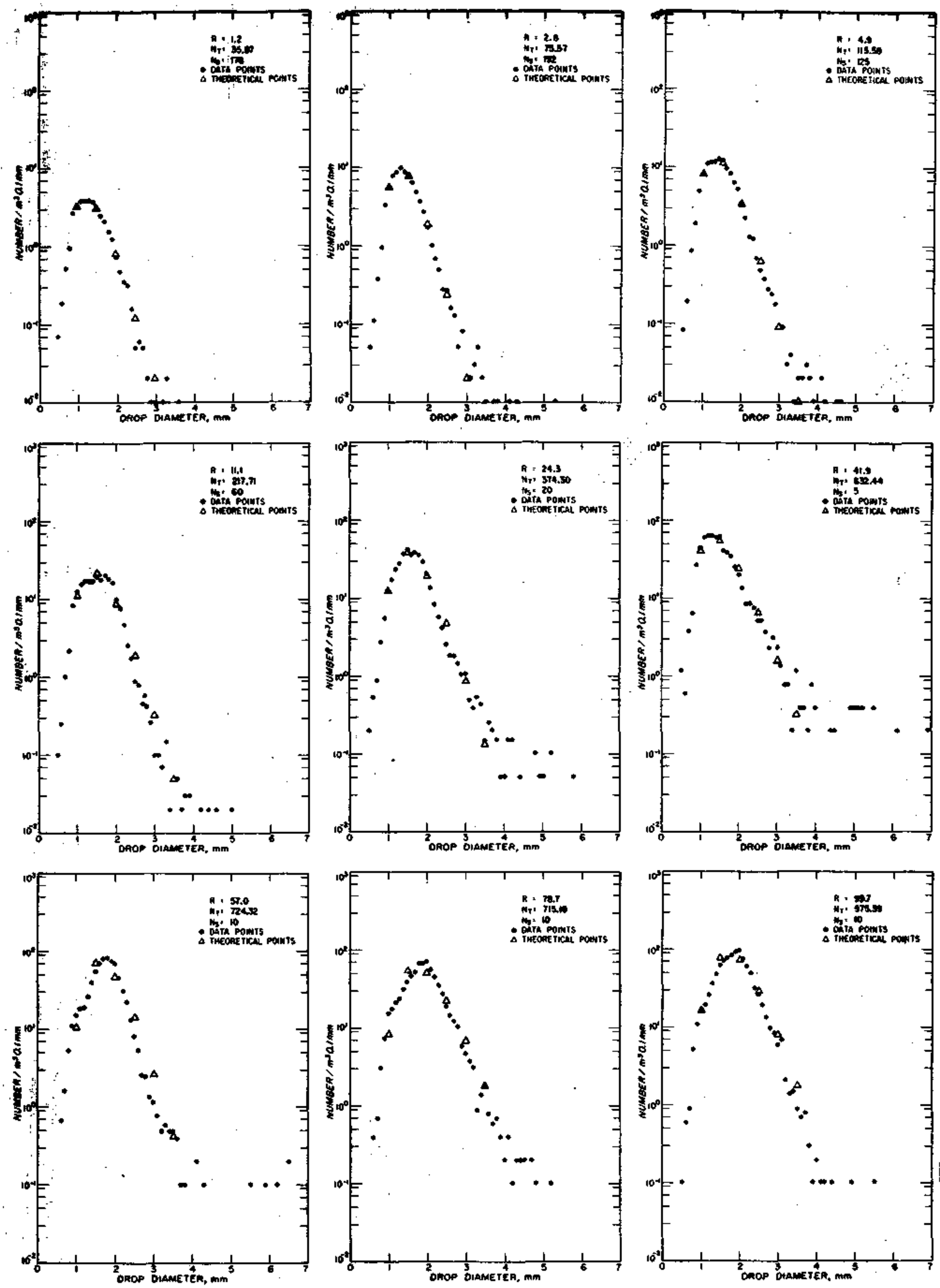

FIG. 13 AVERAGE DISTRIBUTIONS FOR CONTINUOUS RAIN AT MIAMI, FLORIDA

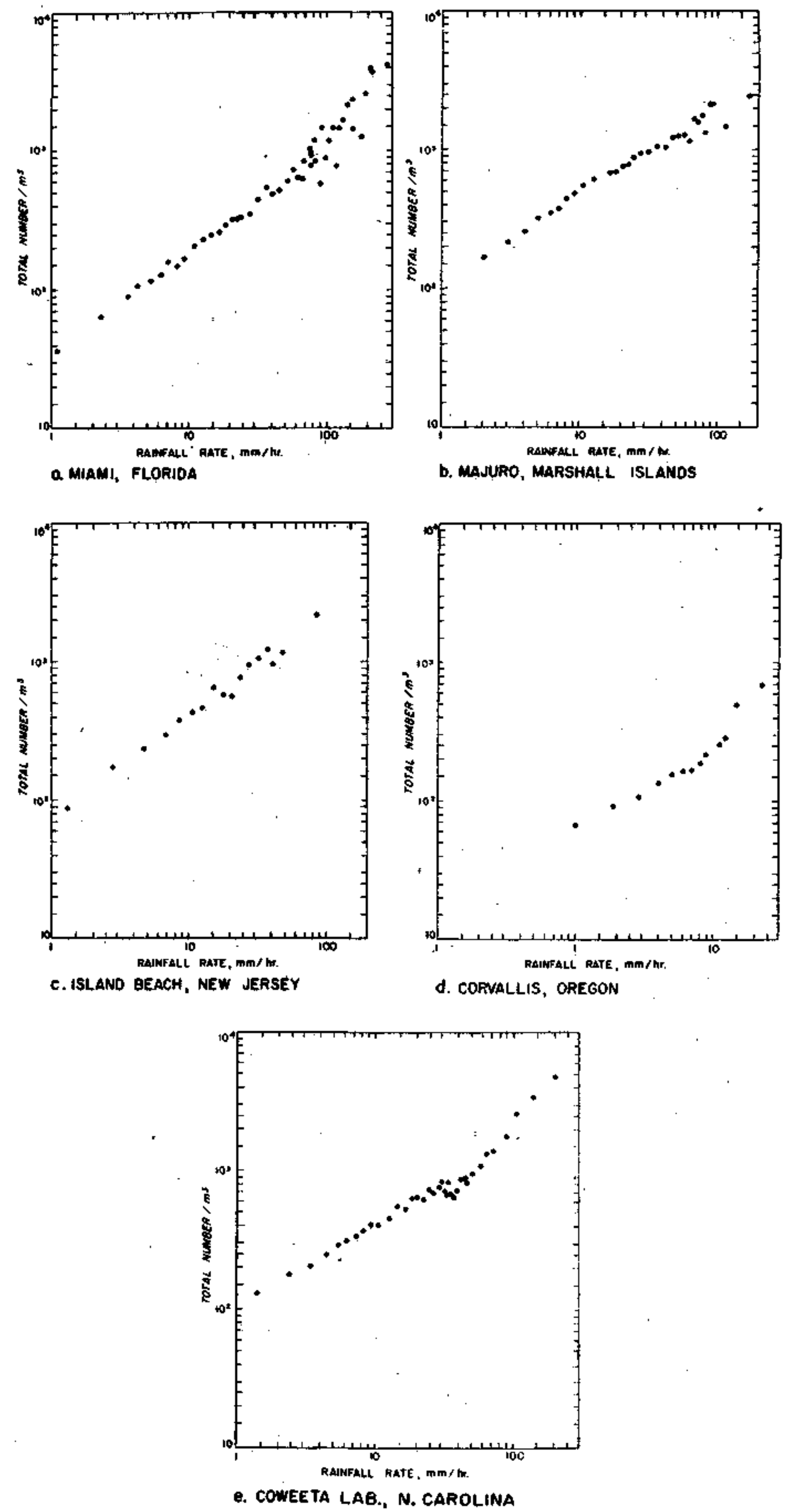

FIG. 14 NUMBER OF DROPS PER CUBIC METER VS. RAINFALL RATE

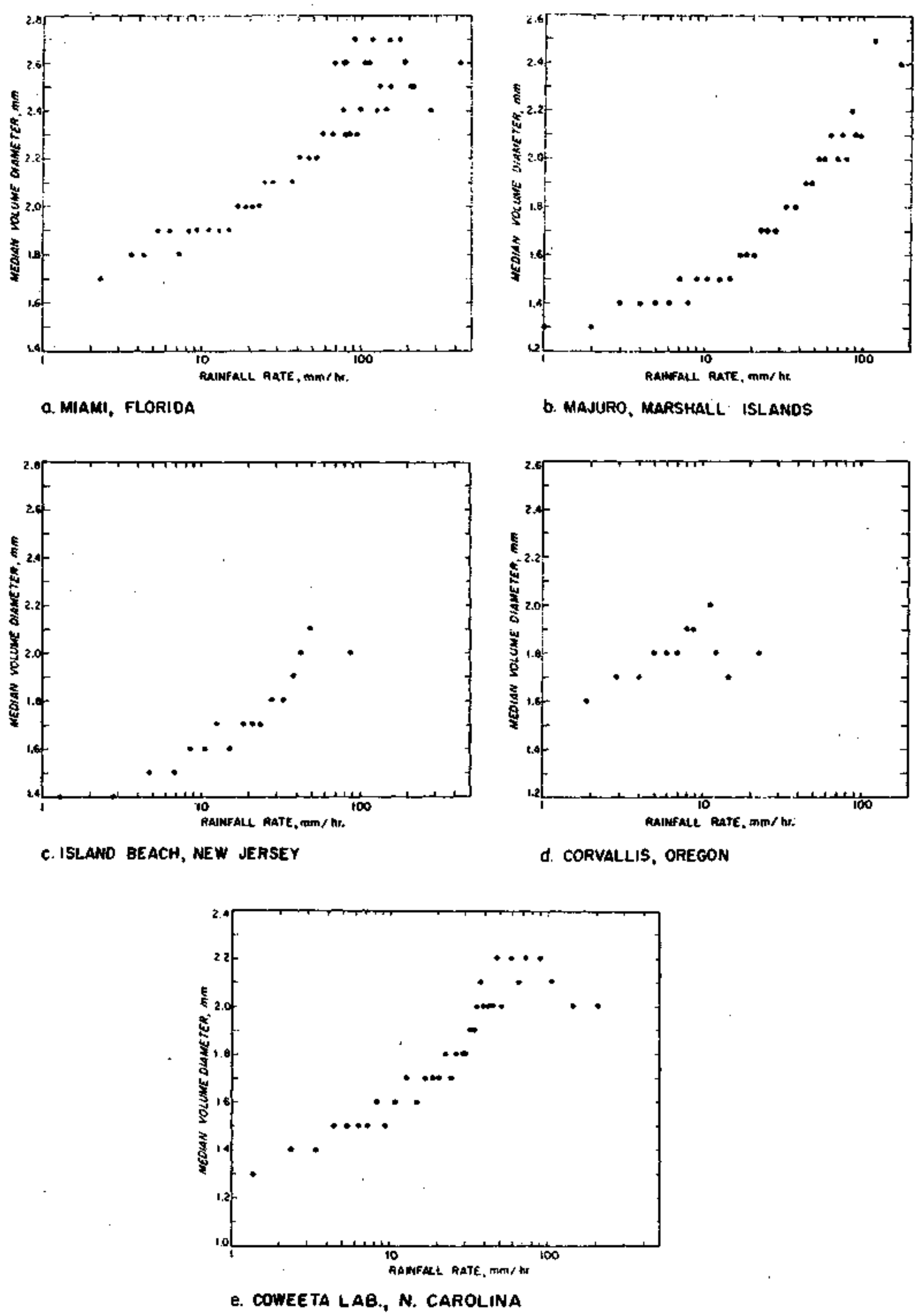

FIG. 15 MEDIAN VOLUME DIAMETER VS. RAINFALL RATE

Appendix A

CASE STUDIES OF THE AREAL VARIATIONS IN RAINDROP SIZE DISTRIBUTIONS'**

Arthur L. Sims
Illinois State Water Survey*

1. INTRODUCTION

During May through August, 1963, a study was conducted to investigate the variations in drop size distributions over an area, and to determine the reliability of measurement of the R-Z relationship at a single point for application to an entire storm. Previous drop size studies have generally used instrumentation only at a single point, and many studies have used Instruments having very low sampling rates.

The raindrop cameras used in this study are similar to the camera described by Jones and Dean (1953). The system consists of a telecentric optical system with a 29-inch parabolic mirror as its first element, and a 70-millimeter camera. The sampling volume is a right circular cylinder, 29 inches in diameter and 14 inches high, so that approximately 1/7 of a cubic meter is photographed on each frame. This volume is back-lighted by four FT 503 flash tubes, each delivering approximately 125 watt-seconds in 10 microseconds. A normal sample taken with this system consists of 7 frames, exposed approximately 2 seconds apart, so that a volume of about 1 cubic meter is observed in 13 seconds. A sample is obtained once each minute. The raindrop sizes are measured from the film, and from the measurements the distribution of drop sizes is tabulated. From the drop size distributions are calculated R, Z, M, the total absorption cross-section, and various median diameters.

For the 1963 study, two cameras were located 2 miles apart in a north-south orientation near the center of the East Central Illinois raingage network. These locations were under surveillance by the CPS-9 and TPS-10 radars located near Champaign, Illinois, 25 miles from the cameras. The northern camera was called "Camera A" and the southern one, "Camera C."

Eight cases were selected for detailed analysis. Three of these are presented here. The 15 May 1963 case is typical of the three continuous rain cases studied, and the 7 June 1963 case is typical of the four shower and thundershower cases. The 31 July 1963 case is quite different from any of the other cases observed.

2. CASE STUDIES

Rain of 15 May 1963. The light, continuous rain which fell on this date was associated with a stationary front in southern Illinois. The rain lasted 1-1/2 hour3, and the maximum rainfall rate observed was 8.6 mm per hour. The radar showed stratified echoes completely without cellular structure.

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**As presented at the 1964 World Conference on Radio Meteorology incorporating The Eleventh Weather Radar Conference, September 14-18, 1964 at Boulder, Colorado.

The R-Z plots for this case are shown in Figure 1. Each point represents a 1 cubic meter sample. Logarithmic least squares regressions were calculated for data from each camera and the resulting lines are shown. The relationships from each of the cameras are very similar. All the data can be fitted quite well by a single relationship,

$$Z = 439R^{1.46}$$

with a correlation coefficient of, .986.

Although considerable statistical noise is apparent in the drop size distributions for this case because of the 3mall number of drops per cubic meter, the distributions are very similar. No significant areal differences exist. All the drops observed in this rain were less than 3.0 mm in diameter.

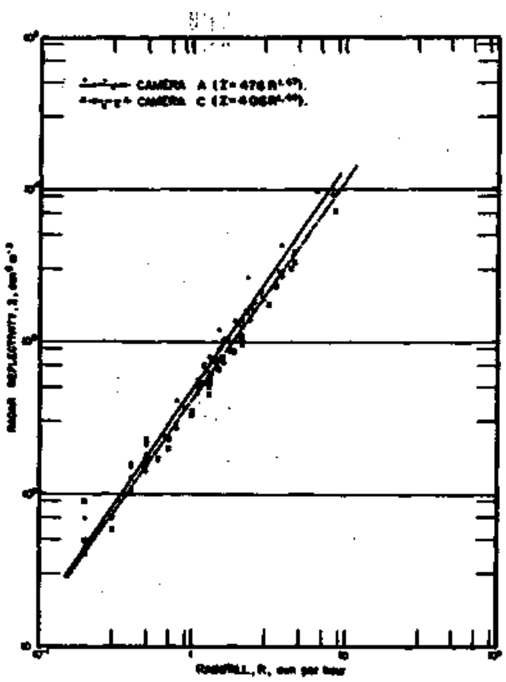

FIG 1 R-Z Plot for Cameras "A" and "C" for 15 May 1963. A Continuous Rain Case

Rain of 7 June 1963. Scattered night-time convective activity developed on this date in the warm air south of a quasi-stationary front in northern Illinois. This front was drifting slowly southward at this time. The thundershowers over the drop cameras moved in from the northwest. The exact character of these showers was not observable by radar because of attenuation of intervening showers.

Again, the R-Z relationships are very similar. Both lines in Figure 2 lie well within the scatter of points for either camera. The scatter of data points is greater than in the 15 May case; however, the regression lines are almost identical. A regression for all data points yields the equation $Z = 446R^{1.43}$. The correlation coefficient is .981.

Rain of 31 July 1963. A line of showers formed in the warm sector of a wave which had developed a day earlier on a stationary front. This line moved over the cameras from the west and was followed by an extensive area of continuous rain. The full extent of this rain area was not apparent on the radar data until the showers had passed to the east of the radar location. Rain began at the cameras at 0920 CST, became much lighter at 0930, and ended about 1115.

The raindrop photographs cover the last portion of the showers and about an hour of the continuous rain. Figure 3 shows the R-Z plots for this case. The R-Z points for camera C lie well along a single line. The points for camera A were much more widely scattered. In examining the time variation of these points and the distributions associated with them, it appeared to be appropriate to derive two lines for these data. During the early part of the sampling period (0925 to 0946), the points are along line A2 except for three minutes (0938 to 0940) when the points are along line A1. The rainfall rate generally decreased until 0949 when the rate increased, but this time the points were along line A1. The points were all clustered at the low rate end of the lines after 1000. On the figure. some sample average distributions of the observations enclosed by the curves are shown. Slightly smoothed average distributions were used as a means of reducing the statistical sampling noise inherent in a single 1 cubic meter sample. The distributions representing points along line A_1 are broad, straight-line types. However, along the other line, the distributions are much more narrow. These differences were evident in the individual distributions before averaging, as well as in the averages. Unlike most continuous rain distributions, samples along line A_1 contain some large drops. It is possible that the camera was at the edge of convective activity and large drops were being generated at this edge. Unfortunately, the radar was too badly attenuated to allow confirmation of this hypothesis.

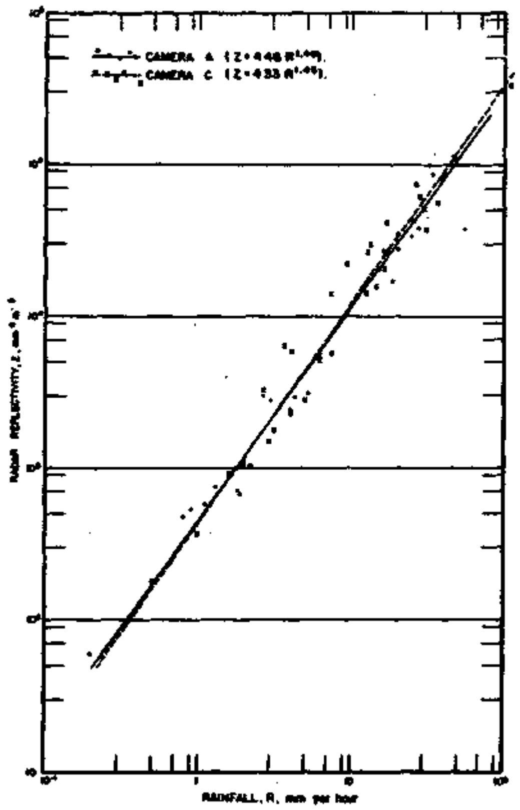

FIG 2 R-Z Plot for Cameras "A" and "C" for 7 June 1963, A Thunderstorm Case.

The types of distributions associated with the lines tend to suggest that A_1 is continuous rain and A_2 is showery rain. The timing also indicates this. However, the R-Z relationship for line A_1 has a higher coefficient and exponent than line A_2, indicating that for the same R, the Z is greater for the continuous rain, line A_1. This is the opposite of what has been generally observed, and of data published by Jones (1956). He reports a relationship of $Z = 311R^{1.43}$ for rain, and $Z = 435R^{1.48}$ for thundershowers. It should be noted, however, that these relationships are for data from several storms. This single 3torm is an unusual one. It is probable that situations producing similar relationships are rare.

This storm shows that it is possible to have within the same air mass and the same storm system two very different types of raindrop spectra producing quite different R-Z relationships. Also, on this occasion camera C, only two miles away, showed none of this duality.

3. CONCLUSIONS

This study suggests that usually an R-Z relationship determined from data taken at a single point is applicable to an entire storm. There are occasional cases where areal variations in raindrop size distributions are too great to be fitted well by a single relationship.

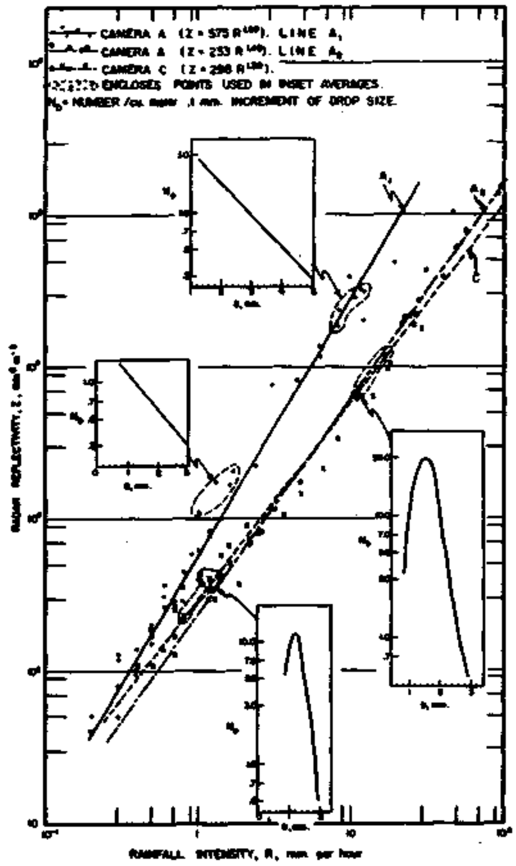

FIG 3 R-Z Plots for Cameras "A" and "C" for 31 July 1963. Insets show Average Distributions for Selected "A" Points.

4. REFERENCES

Jones, D. M. A. and Dean, L. A. (1953) A Raindrop Camera, Illinois State Water Survey, Urbana, Ill., Research Report No. 3 under Contract No. DA-36-039 SC-42446.

Jones, D. M. A. (1956) Rainfall Drop Size-Distribution and Radar Reflectivity, Illinois State Water Survey, Urbana, Ill. Research Report No. 6 under Contract No. DA-36-039 SC-64723.

Appendix B

A STUDY OF THE RADAR PRECIPITATION ATTENUATION AS DEDUCED PROM DROP SIZE DISTRIBUTIONS**

E. A. Mueller
Illinois State Water Survey*

1. INTRODUCTION

The relationships between the precipitation attenuation, rainfall rate, and the radar reflectivity have been studied. Raindrop size distributions from seven different geographical locations were available as basic data. Locations are: Miami, Florida; Corvallis, Oregon; Woody Island, Alaska; Majuro, Marshall Islands; Bogor, Indonesia; Island Beach, New Jersey; and Champaign, Illinois. Data from these locations were analyzed, and no significant differences In the relationships Involving attenuation were found. Therefore, only data from the three locations, Florida, Oregon, and Majuro, will be examined in this paper. The drop size spectra were obtained from the raindrop camera.

2. ANALYSIS PROCEDURE

The analysis consists of calculating the rainfall rate from each drop size spectrum from the raindrop camera by an equation of the form

$$R = \sum_{.5}^{8.0} \frac{\pi}{6} N_D D^3 v_D$$

where

R = rainfall rate in mm/hr
N_D = number of drop3 of size D
D = diameter of drops In mm
v_D = terminal velocity of a drop of diameter D

The value for v_D was obtained from Gunn and Kinzer.[1]

The radar reflectivity was calculated from

$$Z = \sum_{.5}^{8.0} N_D D^6$$

The attenuation was calculated from

$$Q_t = \sum_{.5}^{8.0} N_D Q_D$$

where

Q_D = the total scattering and absorption cross section for a drop of diameter D in mm^2

Q_t = the total cross section for a cubic meter sample

Q_D was obtained at 3.2 cm by use of F. T. Haddock's[2] calculation as reported by J. S. Marshall.[3]

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*This research is supported by the U. S. Army Electronics Research and Development Laboratory under Contract DA-36-O39 SC-87280.

**As presented at the 1964 World Conference on Radio Meteorology-incorporating The Eleventh Weather Radar Conference, September 14-18, 1964 at Boulder, Colorado.

After these parameters were calculated, the data were entered into IBM cards for correlating with one another. Each sample of Q_t, R and Z represents a drop size spectrum of 1 cubic meter of air space. The actual spectra as measured were from a volume that varied between 0.96 m^3 and 1.1 m^3. All values are corrected to 1.0 m^3.

3. RESULTS OF R-Qt COMPARISONS

Qt can be related to the attenuation A in db/km by the relation

$$A = 4.34 \cdot 10^{-3} Q_t$$

where Q_t is in mm^2/m^3. Since A is a more practical unit, A is used to compare R. Figure 1 is a plot on logarithmic axis of the R, A points. It was assumed that the attenuation is the dependent variable and the rainfall rate is the independent variable. Increments of 0.01 of the logarithm of R were chosen, and in each interval the average value of A was determined. The circles on the figure are the plots of these average points.

Two means of fitting of the data empirically were investigated. The linear relationship, which plots as a curve on log-log coordinates, of the least squares of all of the original points is plotted as the dashed line. This relationship fits the data very well for rainfall rates above 30 mm/hr. In this region the attenuation is most important. The logarithmic least squares fit to the data yields the best fit for low values of rainfall rate and attenuation. The average deviation for a constant R interval is about 1.0 db in attenuation. The average deviation tends to increase at the higher rates where the average deviation is of the order of 1.3 db. Average deviation at the lower rates is of the order of 0.5 db. This average scatter is considerably less than indicated by Robertson and King's[4] experimental points, which are ±3 db wide. This discrepancy is easily explained by the path length used by Robertson and King and their raingaging technique for determining the rainfall rate. The extremes of these data lie Just outside the Robertson and King limits with about a 3 db average. It is suggested that for practical use an attenuation relationship of $A = 3.10^{-2}R$ is acceptably accurate and easily used.

4. RESULTS OF Z-Q COMPARISONS

For radar measurement of rainfall rate, the attenuation is more appropriately estimated from the measured reflectivity of the rainfall rather than from the rainfall rate. To facilitate attenuation correction this relationship has been determined with Z as the independent variable and Qt as the dependent variable. Again, intervals of the independent variable of 0.1 db were chosen and the average Qt obtained from the sample points. Figures 2, 3, and 4 show the results from three locations. Although for convenience these are plotted on log-log scales, it is evident that the slope is nearly 1 and that they could be plotted on linear scales and result in a straight line relationship.

A logarithmic regression of Z and Q from the Miami data yields

$$Q_t = 1.15 \cdot 10^{-2} Z^{0.91}$$

with a correlation coefficient of 0.98, If it is assumed that the attenuation below a Z = 10^3 is of little importance (less than 0.025 db/km), a. fit to the data for Z in excess of 10^3 yields a linear regression of the form

$$Q_t = 6.75 \cdot 10^{-3} Z$$

This yields a value for Q that is always slightly larger than obtained from the logarithmic regression. For example, at Z = 10^3, Q is overestimated by 0.3 db, and at Z = 10^5, by 2 db. A better over-all estimate might be obtained by reducing the coefficient of Z, but it is believed that consistent overestimation is a better choice. The reduction of these relationships to linear relationships is admittedly forced to some extent. However, the scatter of the data does not preclude this possibility. The linear line always falls well within the scatter of points for values of $>10^3$. It does tend to underestimate the attenuation for very low values of Z, but the total attenuation obtained in a storm from these small Z values is so low that normal measurements would not detect the differences.

5. CONCLUSIONS

Although these data provide means for correcting 3.2 cm radar information for attenuation, caution must be observed in this application. However, some gain in accuracy of rainfall estimates can be expected by Judicious use of attenuation correction.

6. REFERENCES

1. Gunn, Rand Kinzer, G. D., The Terminal Velocity of Fall for Water Droplets in Stagnant Air. J. of Meteor., v. 6, 1949.

2. Haddock, F. T., Scattering and Attenuation of Microwave Radiation through Rain. Naval Research Laboratory, Washington, D. C. 1948 (unpublished manuscript).

3. Marshall, J. S., East, T. W. R., and Gunn, K. L. S., The Microwave Properties of Precipitation Particles. Scientific Report MW-7, McGill University, July 1952.

4. Robertson, S. D., and King, A. P., The Effect of Rain Upon the Propagation of Waves in the 1- and 3-centimeter Regions. Proc. of IRE, April 1946.

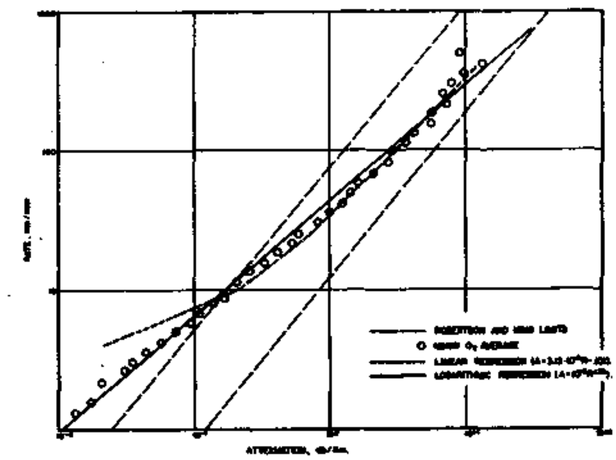

FIG 1 Attenuation versus Rainfall Rate from Miami

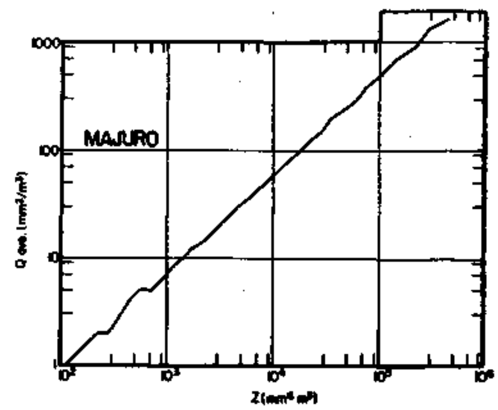

FIG 3 Attenuation Cross-Section versus Radar Reflectivity from Majuro

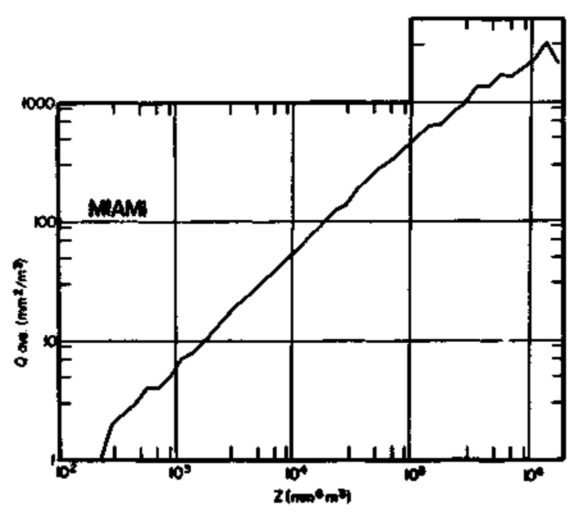

FIG 2 Attenuation Cross-Section versus Radar Reflectivity from Miami

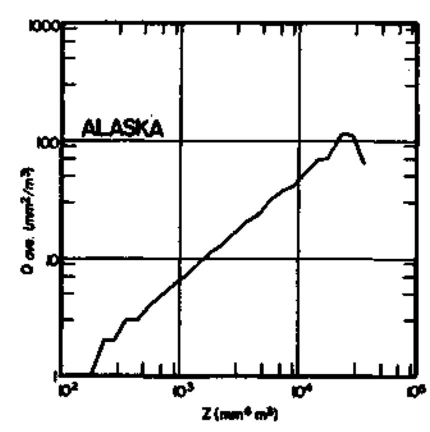

FIG 4 Attenuation Cross-Section versus Radar Reflectivity from Alaska

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3. REPORT TITLE

Final Report - Investigation of the Quantitative Determination of Point and Areal Precipitation by Radar Echo Measurements

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

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5. AUTHOR(S) (Last name, first name, initial)

Sims, A.L.
Mueller, E. A.
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8a. CONTRACT XXXXXXXXX. DA 36-039 SC-87280 b. PROJECT NO. 1VO-14501-B-53A-07 (formerly 3A99- c. 07-001-01) d.	9a. ORIGINATOR'S REPORT NUMBER(S) None 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None

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13. ABSTRACT

During the period of this contract, a raindrop camera vas operated at Island Beach, New Jersey; Coweeta Hydrologic Laboratory, North Carolina; East Central Illinois raingage network, and for summer operation only at Mt. Withington, New Mexico, and Flagstaff, Arizona. The data obtained have been measured and preliminary calculations have been made.

The results of analysis of the relationships between rainfall rate and radar reflectivity are reported along with recommendations as to the appropriate relationships to be used under given conditions at various climatic regions. At a location such as Miami, Florida, a relationship determined by the thermodynamic instability is recommended. A single relationship is recommended for Majuro and Oregon where so far no stratification has made significant improvement.

The average drop size spectra from a number of locations are compared. Log normal curves best fit the spectra, but the parameters of the fitting curves do not seem to be orderly with rainfall rate.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Meteorology Radar Echo Measurements Quantitative, Precipitation, Determination Rainfall measurements	N/A					

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