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Title A STUDY OF SOME OBSERVED VARIATIONS IN RADAR Z-R RELATIONSHIPS WITHIN STORMS

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Raindrop-size distributions taken with methylene blue dyed filter paper recorders produced significantly different values of A in the "Z-R relationship", $Z = A R^B$, at various station locations in the OSU Mesometeorological Network for given types of storms. However, the raindrop-size distributions did not produce significantly different values of B of the Z-R equation at stations. For certain storms, calculation of a correlation coefficient revealed a moderate correlation between the values of the coefficient A and the elevations at stations. For any given value of R, the average Z-R equation of windward stations yielded a higher value of Z than the average Z-R equation of leeward stations. At stations located in valleys, there occurred the highest average Z values for given R values followed in order by the Z values for stations located on hillsides and those for hilltop stations in three of the four storms

analyzed. The analysis of covariance revealed no significant difference in the constants A and B at stations located in valleys during given storms. However, significant differences do appear between the values of A for hillside stations and those for hilltop stations. The highest coefficient of the Z-R equation occurred at different stations during different storms.

A STUDY OF SOME OBSERVED VARIATIONS IN RADAR Z-R RELATIONSHIPS WITHIN STORMS

by

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A STUDY OF SOME OBSERVED VARIATIONS IN RADAR Z-R RELATIONSHIPS WITHIN STORMS

I. INTRODUCTION

When an electromagnetic wave transmission from a radar encounters an area of rainfall, scattering occurs, and a very small percentage of the electromagnetic radiation returns toward the radar. If the cross-sectional area of the radar beam at the point of contact intercepts an area of rainfall having a cross-section equal to or greater than the radar beam, the average power received by the radar antenna $\overline{P}_r$ appears in the equation as (2, p. 30):

$$\overline{P}_r = \frac{\pi^5 P_t A_p^2 \theta \phi h |k|^2}{72 \lambda^6} \quad \frac{Z}{r^2} \tag{1}$$

where

P_t = The power transmitted by the radar, watts.

A_p = The apertural area of the radar antenna, m^2.

θ = The horizontal width of the radar beam, rad.

ϕ = The vertical width of the radar beam, rad.

h = The pulse length, m.

λ = The wave length of the radar, mm.

$|k|^2$ = The complex index of refraction, no units.

Z = The reflectivity factor, $mm^6\ m^{-3}$

r = The range of the meteorological target, m.

Now P_t, A_p, θ, ϕ, and λ relate to the properties of the radar set and remain constant, while $|k|^2$ remains constant for a given type of precipitation, and is close to unity for radar wavelengths greater than approximately 3 cm. Therefore, equation (1) expressed as

$$\overline{P}_r = C_1 \quad \frac{Z}{r^2} \tag{2}$$

remains valid for a given radar where C_1 indicates a constant. The reflectivity factor Z depends on the number and size of the raindrops in the radar beam, and appears as

$$Z = \sum_{vol} N_i D_i^6 \tag{3}$$

where N_i represents the number of spherical raindrops of diameter D_i, and $\sum_{vol}$ represents summation over a unit volume (2, p. 30).

From empirical studies made by others, a relation between Z and rainfall intensity R appears as

$$Z = A \left(\frac{R}{\frac{mm}{hr}} \right)^B \tag{4}$$

where R has the units of mm hr^{-1}, and A and B represent constants (7, p. 25). The coefficient A has the units of $mm^6 m^{-3}$, and the exponent B has no units. This equation will hereinafter be referred to the Z-R equation. Substituting equation (4) for Z into equation (2) yields

$$\overline{P}_r = \frac{C_2 R^B}{r^2} \tag{5}$$

where C_2 represents the product C_1 A. Thus one can make quantitative precipitation measurements at a point by knowing the constants A, B, and C_1, and the average power received by a radar from range r

$$R = \left(\frac{P_r \, r^2}{C_2} \right)^{\frac{1}{B}} \tag{6}$$

Investigators (8, 12, 13, 23) early found that the constants A and B varied from one storm to the next. However, they did not examine the variations in the values of A and B for a given storm at different locations. Since C_1 remains constant for any given storm, and since one could determine $\overline{P}_r$ and r from the radar, one can better estimate rainfall intensity at a point with radar if one knows how A and B vary with station location. This study seeks to determine any significant differences in A and B at various locations in the Oregon State University Mesometeorological Network for a given storm. The study also compares the differences in A and B at various locations for a given storm with other storms. Data collected in the Oregon State University Mesometeorological Network for the following dates provided the only data used:

29 December	1962
2 February	1963
2 March	1963
27 March	1963
28 March	1963

II. DATA COLLECTION AND REDUCTION

This study makes use of raindrop-size distributions collected at field stations in the OSU Mesometeorological Network. The majority of the field stations in the network lie to the west of Philomath on U. S. Highway 20 toward Newport and Oregon Highway 34 toward Waldport (Plate I). The observers did not operate at all of the same stations during the five storms. Observers equipped with altimeters, battery-operated fan psychrometers, rain gauges, filter papers, and hail recording panels took meteorological data while the Weather Radar Set AN/CPS-9 operated at McCulloch Peak. The observers exposed Whatman No. 4 filter papers rubbed with methylene blue dye to the rain for a period of a few seconds to collect raindrop-size distributions (7, p. 11). The observers recorded the exposure duration of the filter paper to the rain, time of day, filter paper number, station number, and other pertinent data on the back of each exposed filter paper. Drop-size sampling occurred at ten minute intervals and more often when rainfall intensities changed noticeably.

With the aid of calibrated circular templates, workers then measured the diameters of raindrop stains on each filter paper and tabulated the numbers of raindrop stains in each 0.2 mm diameter interval.

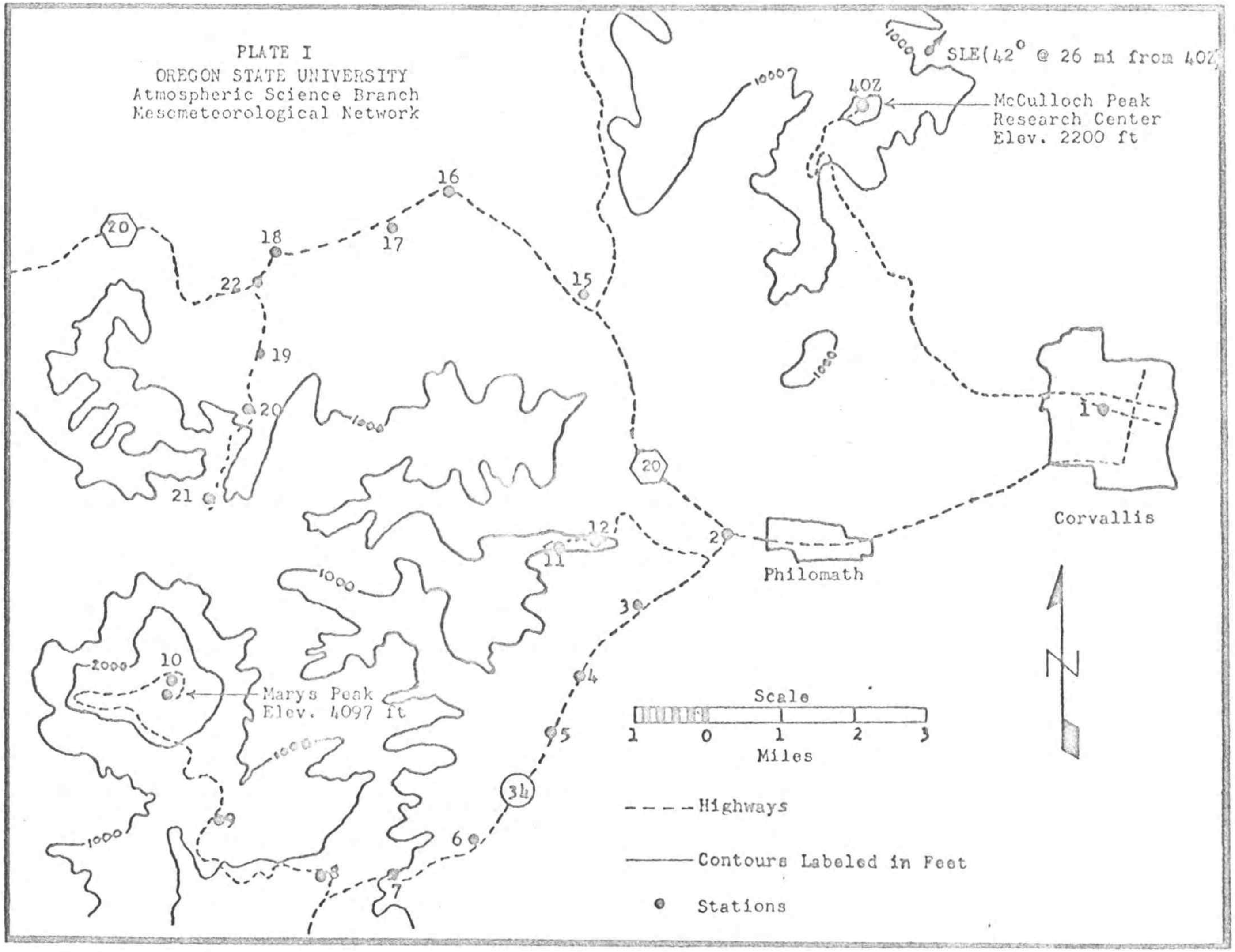
PLATE I
OREGON STATE UNIVERSITY
Atmospheric Science Branch
Mesometeorological Network
SLE(42° @ 26 mi from 40Z)
40Z
McCulloch Peak
Research Center
Elev. 2200 ft
1000
2000
Marys Peak
Elev. 4097 ft
20
34
1
2
3
4
5
6
7
8
9
10
11
12
15
16
17
18
19
20
21
22
Corvallis
Philomath
Scale
1 0 1 2 3
Miles
N
Highways
Contours Labeled in Feet
Stations

III. CALCULATIONS OF Z AND R VALUES FROM DROP-SIZE DISTRIBUTIONS

A. THEORY

The numbers of raindrop blots of different sizes on a sheet of filter paper exposed for a given time will provide data on the drop-size distribution of drops reaching the surface. However, this does not provide directly the distribution of different sized drops in a given volume at any instant. In order to determine the number of drops having diameters D_i per unit volume, one must make allowance for the different rates of fall of drops of given diameters because the depth of fall of raindrops varies with the size of the drops. A raindrop falling at its terminal velocity v_i descends a depth d

$$d = v_i t \tag{7}$$

during time t. If only one drop falls on a given horizontal area A_f in time t, the volume V enclosing that one drop appears as

$$V = A_f d = A_f v_i t \tag{8}$$

If N_i number of drops of the same diameter fell on a given area in time t, the number of drops per unit volume appears as

$$N_i/V = \frac{N_i}{A_f v_i t} \tag{9}$$

Thus, one can make approximations of the reflectivity factor Z defined as the sixth power of the diameters of all raindrops in a unit volume by using the numbers C_j of raindrop blots having average diameters $D_{\bar{j}}$ in each 0.2 mm diameter range, the filter paper area A_f, the terminal velocities $v_{\bar{j}}$ of the raindrops having average diameters $D_{\bar{j}}$, and the exposure duration t of the filter paper.

$$Z \doteq \sum_{j=0.2} \frac{C_j D_{\bar{j}}^6}{A_f v_i t} \tag{10}$$

or

$$Z \doteq \frac{\sum_{j=0.2} (C_j K_j')}{t} \tag{11}$$

where

$$\sum_{j=0.2} = \text{Summation over all 0.2 mm diameter ranges.}$$

$$K_j' = \text{The constants } (D_{\bar{j}}^6 A_f^{-1} v_{\bar{j}}^{-1}).$$

The constants K_j' appear in Plate II.

The numbers of raindrop blots of different sizes on a sheet of filter paper exposed for a given time will also provide data for calculations of rainfall intensity. The volume of rain falling on a given area per unit time defines the rainfall intensity R.

$$R = \frac{\text{Volume of Rain}}{A_f \quad t} \tag{12}$$

If one assumes spherical raindrops, the volume of a raindrop of diameter D_i equals

$$\text{Volume of Rain} = \frac{\pi D_i^3}{6} \tag{13}$$

Thus one can approximate the rainfall intensity by using the numbers C_j of raindrop blots having average diameters $D_{\bar{j}}$ in each 0.2 mm diameter range, the filter paper area A_f, and the exposure duration of the filter paper.

$$R \doteq \sum_{j=0.2} \frac{\pi D_{\bar{j}}^3 C_j}{6 A_f t} \tag{14}$$

or

$$R \doteq \frac{\sum_{j=0.2} (C_j K_j'')}{t} \tag{15}$$

where

$\sum_{j=0.2}$ = Summation over all 0.2 mm diameter ranges.

K_j'' = The constants $(D_{\bar{j}}^3 A_f^{-1} \pi 6^{-1})$.

The constants K_j'' appear in Plate II.

PLATE II

Computation plate for solving Z and R values

Average diameter (mm)	Number of drops C_j	Reflectivity constant K_j'	$C_j \times K_j'$	Rainfall constant K_j''	$C_j \times K_j''$
0.1		8.163×10^{-5}		3.845×10^{-2}	
0.3		2.976×10^{-2}		1.038	
0.5		0.159		4.806	
0.7		0.873		12.188	
0.9		2.892		28.030	
1.1		8.217		51.177	
1.3		18.763		84.474	
1.5		42.266		129.769	
1.7		79.452		188.903	
1.9		147.711		263.739	
2.1		259.308		356.085	
2.3		425.513		467.822	
2.5		668.787		600.781	
2.7		1026.80		756.811	
2.9		1517.41		937.757	
3.1		2236.09		1145.46	
3.3		2968.79		1381.74	
3.5		4403.24		1648.50	
Total					
$\frac{\text{Total}}{\text{Exposure Duration}}$			$\frac{mm^6}{m^3}$		$\times 10^{-3}\ \frac{mm}{hr}$

Station: ____________

Date: ____________

Time: ____________

Paper No. : ____________

Exposure duration: ____________ (sec)

B. DISCUSSION

One can obtain values for Z from either the radar or drop-size distributions. This study did not make use of radar for determining Z values at stations because the radar beam did not approach low enough to the surface to permit assuming no changes in the raindrop-size distributions from the radar beam to the surface. When the radar beam aims low the radar cannot distinguish between ground echoes and precipitation echoes. In order to get the rainfall intensity most representative of the calculated Z value, one must use the same drop-size distributions for calculating both Z and R values. Thus, this study made use of drop-size distributions collected at field stations to determine both the Z and R values (Table A-I to A-XV).

C. SOURCES OF ERROR

Splashing of relatively large raindrops upon contact with the exposed filter papers increases the numbers of smaller raindrop blots. Mason and Andrews (20, p. 349-353) found that a drop of 3.5 mm diameter produced approximately 57 smaller raindrops of 0.5 mm diameter or less. They also reported that raindrops having diameters of 2.5 mm or less produced very few drops by splashing.

Upon referring to the constants in Plate II, the percentage error in the Z value and R value caused by one drop of 3.5 mm diameter splashing 57 drops having the same diameter of 0.5 mm results in an error of 0.2% for Z and 16.3% for R. However, the actual percentage error in Z and R remains smaller since the 57 drops can also be smaller than 0.5 mm diameter. Also, the majority of observed raindrops had diameters smaller than 3.5 mm.

The author believes that the greatest error lies in the recorded exposure duration of sampling. A probable error of plus or minus one second can cause a percentage error in Z and R as high as 200% for recorded exposure durations of 0.5 seconds. This error increases with the increase in rainfall intensity because the observer must obtain drop-size distributions on the filter papers which can be measured. If the observer exposes the filter paper too long, one cannot distinguish between two different blots on the filter due to an over saturation of blots on the filter paper.

Filter papers exposed perpendicularly to the fall trajectories of the raindrops instead of horizontally to the ground cause errors in estimating the numbers of drops per unit volume. This error in sampling increases the numbers of drops per unit volume, and hence, overestimates the values of Z.

Conditions of strong downdrafts cause overestimations of Z values, and conditions of strong updrafts cause underestimations of Z values. This error results from the fact that Z relates inversely to the actual fall velocity of the raindrops (Equation 10), and that the constants used the terminal velocities of the raindrops.

IV. A COMPARISON OF CHANGES IN RADAR DATA OF $\overline{P}_r$ OVER STATIONS WITH CHANGES IN Z VALUES OBTAINED AT THE STATIONS

The Weather Radar Set AN/CPS-9 at McCulloch Peak provides data in decibels, db, which permit relating the actual signal strength $\overline{P}_r$ received compared to the signal P_o needed to produce a barely detectable indication on the RHI-Scope and PPI-Scope indicators with the receiver at maximum gain.

$$db = 10 \log \frac{\overline{P}_r}{P_o} \tag{15}$$

The camera records precipitation echoes on the PPI-Scope and RHI-Scope indicators automatically at pre-set receiver gain settings below the maximum receiver gain setting labeled "O db". For instance, if an echo begins to disappear at a gain setting labeled "-6 db", one knows that $\overline{P}_r$ exceeds P_o by +6 db.

Changes in $\overline{P}_r$ from a beam-filling target at a given range depend primarily on changes in Z at the given range

$$\overline{P}_r = C_3 Z \tag{16}$$

where C_3 indicates the product $C_1 r^{-2}$. The following equations show how changes in Z in the radar beam at a given range from the radar correspond to changes in $\overline{P}_r$ in db.

$$db_1 = 10 \log\left(\frac{\overline{P}_{r_1}}{P_o}\right) \tag{17}$$

$$db_2 = 10 \log \left(\frac{\overline{P}_{r_2}}{P_o} \right) \tag{18}$$

$$db_2 - db_1 = 10 \log \left(\frac{\overline{P}_{r_2}}{P_o} \right) - 10 \log \left(\frac{\overline{P}_{r_1}}{P_o} \right) \tag{19}$$

$$db_2 - db_1 = 10 \left[\log \left(\frac{\overline{P}_{r_2}}{P_o} \right) - \log \left(\frac{\overline{P}_{r_1}}{P_o} \right) \right] \tag{20}$$

$$db_2 = db_1 = 10 \log \left(\frac{\dfrac{\overline{P}_{r_2}}{P_o}}{\dfrac{\overline{P}_{r_1}}{P_o}} \right) \tag{21}$$

$$db_2 - db_1 = 10 \log \left(\frac{\overline{P}_{r_2}}{\overline{P}_{r_1}} \right) \tag{22}$$

$$db_2 - db_1 = 10 \log \left(\frac{C_3 \ Z_2}{C_3 \ Z_1} \right) \tag{23}$$

$$db_2 - db_1 = 10 [\log Z_2 - \log Z_1] \tag{24}$$

Thus, changes in $\overline{P}_r$ in db from targets at a given range should equal ten times the changes in the common logarithm values of Z.

For the storms on 2 March and 27 March, the author compared changes in $\overline{P}_r$ in db over two stations with changes in calculated Z values obtained at those stations. The expression on the right of equation (24) determined the changes in calculated Z values obtained at the stations. Since the camera recorded precipitation echoes on the RHI-Scope and PPI-Scope indicators automatically at fixed receiver gain settings, and not necessarily when the echoes over the station disappeared, the data provided by the radar represent limits of $\overline{P}_r$ in db. For example, if the camera records no echo over a station at a receiver gain setting labeled "-12 db" and on the succeeding gain setting labeled "-9 db" records an echo, one only knows that $\overline{P}_r$ ranges between +9 db and +12 db greater than P_o. Therefore, in calculating changes in $\overline{P}_r$ over stations, one can compute only the maximum possible change in $\overline{P}_r$. For example, if an initial echo disappeared between receiver gain settings labeled "-9 db" and "-3 db", and after a time disappeared between receiver gain settings labeled "-12 db" and "-9 db", the maximum possible change between successive values of $\overline{P}_r$ equals +9 db. If an echo appears at the lowest receiver gain setting, one does not know the limits of $\overline{P}_r$ and thus cannot calculate the maximum possible change of $\overline{P}_r$.

A simple numerical coefficient RR determined how well the changes in Z values obtained at the stations compare with the changes in $\overline{P}_r$ over the stations. The following rules state the criteria for solving RR.

$$RR = \frac{\sum (P\,Q)}{N} \tag{25}$$

1. If changes in $\overline{P}_r$ and Z values obtained at the ground have the same sign, let $P = 2.0$.

2. If changes in $\overline{P}_r$ and Z values obtained at the ground have opposite signs, let $P = 0.0$.

3. If the magnitude of change in Z in db exceeds the maximum possible change in $\overline{P}_r$, let $Q = 1.0$.

4. If the magnitude of change of Z in db remains smaller or equals the maximum possible change in $\overline{P}_r$, let $Q = 2.0$.

5. N represents the number of changes compared.

In determining how well changes in $\overline{P}_r$ over stations compare with changes in Z values in db obtained at the stations, $RR = 4.0$ indicates the best possible relation, and $RR = 0.0$ indicates no relation between $\overline{P}_r$ and Z since Z relates directly to $\overline{P}_r$ (Equation 24). A computed RR coefficient of 3.6 for a given station indicates a better relation between $\overline{P}_r$ and Z at the given station than a computed RR coefficient of 3.0 for another station.

The results (Table I) indicate a better relation between changes in both $\overline{P}_r$ and Z in db obtained at the ground for Station 18 than for Station 1. The results seem reasonable because the radar beam approached closer over Station 18 than over Station 1 by 300 feet, and therefore evaporation, coalescence, and wind shear could have affected the raindrop-size distribution from the radar beam less at Station 18 than at Station 1.

TABLE I

RR Calculation for Station 18 on 2 March 1963

Time (PST)	$\bar{P}_r$ over Station 18 (db)	Maximum possible change $\bar{P}_r$(db)	Z at Station 18 (mm^6m^{-3})	log Z	Z change (db)	(P x Q)
1550	9 to 12		39.9	1.600		
		+ 3.0			+ 3.30	2
1601	9 to 12		85.2	1.930		
		+ 9.0			+ 7.69	4
1610	12 to 18		500	2.699		
		Unknown			+ 8.31	4
1618	Greater than 18		3390	3.530		
		Unknown			- 5.30	4
1628	12 to 18		1000	3.000		
		- 9.0			-18.33	2
1640	9 to 12		14.7	1.167		
		+ 9.0			+21.89	2
1702	12 to 18		2280	3.356		
		- 6.0			- 0.56	4
1711	12 to 18		1990	3.299		
		- 6.0			- 2.69	4
1721	12 to 18		1070	3.030		
		- 6.0			-16.20	2
1731	12 to 18		25.7	1.410		
						28
						RR=3.11

RR Calculation for Station 18 on 27 March 1963

1339	13.02 to 14.86		525	2.720		
		+ 1.84			+ 2.88	2
1349	13.02 to 14.86		1020	3.008		
		Unknown			+ 4.90	4
1359	Greater than 19.48		3150	3.498		
		Unknown			+ 0.31	0
1408	14.86 to 19.48		3380	3.529		
		- 4.62			- 1.07	4
1418	14.86 to 19.48		2640	3.422		
		+ 4.62			+ 1.02	4
1429	14.86 to 19.48		3340	3.524		
		- 4.62			- 2.23	4
1438	14.86 to 19.48		2000	3.301		
		- 4.62			- 2.40	4
1448	14.86 to 19.48		1150	3.061		
		- 6.46			-12.98	2
1500	13.02 to 14.86		57.9	1.763		
						24
						RR=3.00

TABLE I (continued)

RR Calculation for Station 1 on 27 March 1963

Time (PST)	P_r over Station 1 (db)	Maximum possible change $\bar{P}_r$ (db)	Z at Station 1 (mm^6m^{-3})	log Z	Z change (db)	(P x Q)
1313	3.28 to 13.02	-13.02	209	2.318	- 5.10	4
1333	0.00 to 3.28	+13.02	64.2	1.808	- 4.72	0
1343	3.28 to 13.02	-13.02	21.9	1.336	+ 4.67	0
1353	0.00 to 3.28	+19.48	63.5	1.803	- 7.58	0
1411	14.86 to 19.48	+ 4.62	11.1	1.045	+14.38	2
1422	14.86 to 19.48	+ 4.62	304	2.483	+ 3.58	4
1432	14.86 to 19.48	+ 4.62	694	2.841	+ 0.84	4
1442	14.86 to 19.48	Unknown	842	2.925	+ 4.33	4
1453	Greater than 19.48		2280	3.358		18

RR=2.25

RR Calculation for Station 1 on 2 March 1963

Time (PST)	P_r over Station 1 (db)	Maximum possible change $\bar{P}_r$ (db)	Z at Station 1 (mm^6m^{-3})	log Z	Z change (db)	(P x Q)
1437	12 to 18	Unknown	890	2.949	- 3.68	0
1447	Greater than 18	"	381	2.581	-10.37	4
1617	12 to 18	"	35.1	1.544	- 9.47	0
1626	Greater than 18	"	3.95	0.597	+22.64	4
1638	Greater than 18	"	726	2.861	+ 6.78	4
1648	Greater than 18	"	3470	3.539	- 3.63	4
1658	Greater than 18	"	1500	3.176	+ 0.57	4
1708	Greater than 18	"	3090	3.490	-30.29	4
1717	Greater than 18		2.89	0.461		24

RR=3.00

V. DETERMINATION AND COMPARISON OF CONSTANTS IN THE Z-R EQUATION

A. THEORY

In order to determine and to compare the values of the constants A and B of the Z-R equation at stations, one can resort to the techniques of statistics summarized below.

Equation (4) written in the linear form appears as

$$\log Z = \log A + B(\log R) \tag{26}$$

or

$$Y = C + Bx \tag{27}$$

where Y represents log Z, C denotes log A, and x signifies log R. The method of least squares (18, Chapter 16) estimates C and B by minimizing the residual SS defined as the sum of squares of the deviations of the experimental log Z values, y, from the estimate of Y, $\bar{y}_x$, (18, p. 253), giving estimates of C and B designated c and b, respectively.

$$\sum (y - \bar{y}_x)^2 = \text{Minimum} = \text{Residual SS} \tag{28}$$

Although one can obtain different estimates of C and B (Equation 27) from data collected at stations during a given storm, this does not necessarily indicate the constants A and B (equation 4) differ significantly between stations because of inherent errors caused by sampling only part of the raindrops falling at each of the stations. Thus, one determines the equivalence of C and B at different stations by using the analysis of covariance (18, Chapter 19) which examines the equivalence of the estimates c and b at the stations under the following assumptions (18, p. 248): (A) The y values for any given R follow a normal distribution, (B) Equations (26) and (27) represent correct relationships, and (C) The variance of y for all values of R for any given storm remains equivalent at all stations. In general, the analysis of covariance using Snedecor's F-test measures the ratio of means of sums of squared deviations of c or b at each station from an average c or b from all stations divided by a pooled residual SS from all the stations.

$$F = \frac{\text{Mean} \sum (b-\bar{b})^2}{\text{Mean (Pooled Residual SS)}} \tag{29}$$

$$F = \frac{\text{Mean} \sum (c-\bar{c})^2}{\text{Mean (Pooled Residual SS)}} \tag{30}$$

One accepts the hypothesis that all values of B or C have single, identical values at all stations if the F-value approaches close to or equals zero.

The level of significance states the probability of rejecting a true hypothesis and the number of degrees of freedom DF defines the particular distribution the F-value follows if the hypothesis remains true. The variance of the array, s^2, gives a measure of scatter of the points from the best fitting line which represents the

Z-R equation at each station. Increasing scatter results in increasing s^2.

B. RESULTS

Calculated Z and R values from drop-size distributions collected at each of the operating stations during the entire observation period on a given date provided data for determining the constants A and B. The method of least squares yielded estimates of the constant A and the constant B at each of the operating stations for each of the five storms (Table II). The first analysis (18, p. 349) examined the equivalence of B at the operating stations for a given storm (Table III). Since the results of the tests revealed that B has a single, identical value at the stations, an average weighted exponent $\bar{b}$ represented the exponent B at each station for a given storm (18, p. 345). The average weighted exponent then yielded a different estimate of C, c', at each of the operating stations because the method of least squares uses the exponent in determining the value of c. The antilogarithm of the different estimates c' then estimates the coefficient A at each station (Table IV).

The F-test (18, p. 364) then examined the equivalence of A by examining the equivalence of the common logarithm value of Z at each station during a given storm (Table V). The Z-R equation (using the average R observed at all stations during a given storm) with the estimates c' and $\bar{b}$ solved for the Z value at each station during a given storm. Since the exponent at all of the stations on a given date has a single, identical value, the lines representing the Z-R equation at each station on a logarithmic graph parallel each other. Therefore, this test also determined the equivalence of the coefficient A at stations for a given storm. The results revealed that all stations did not have a single value of this coefficient at a significance level of 5% in each storm except the storm on 29 December.

Since the F-test revealed that both the exponent and coefficient at all operating stations on 29 December had identical values, the author combined the data from all the stations and obtained the constants of the Z-R equation applicable to all the stations.

$$Z = 192\ (R/\text{mm-hr}^{-1})^{1.13}$$

To determine whether any significant difference existed in the exponent at stations during different storms, the F-test examined the equivalence of B at ten stations, two stations from each storm. The results (Table VI) revealed that significant differences existed in the exponent at the stations during different storms.

Computing weighted averages from all the data obtained from all stations reporting on a given date yielded a single average Z-R

TABLE II

Z-R Relationships by Method of Least Squares

29 December 1962

Station	$Z = A\,(R/\text{mm-hr}^{-1})^B$ A	B	s^2
2	213	1.18	0.0043
15	339	1.28	0.0166
17	235	1.13	0.1390
22	94.3	0.97	0.0795

2 February 1963

Station	$Z = A\,(R/\text{mm-hr}^{-1})^B$ A	B	s^2
1	219	1.44	0.0635
2	233	1.42	0.0878
4	243	1.22	0.1095
6	230	1.49	0.0392
8	200	1.36	0.0781
9	221	1.57	0.0505
10	175	1.52	0.0689
15	187	1.50	0.0530
17	270	1.51	0.1159
18	257	1.30	0.0909
20	151	1.30	0.0608

2 March 1963

Station	$Z = A(R/\text{mm-hr}^{-1})^B$ A	B	s^2
1	365	1.30	0.0236
SLE	215	1.25	0.0489
15	406	1.29	0.0744
16	307	1.25	0.0428
17	214	1.04	0.2015
18	377	1.32	0.0213

27 March 1963

Station	$Z = A\,(R/\text{mm-hr}^{-1})^B$ A	B	s^2
1	289	1.38	0.0590
2	276	1.47	0.0487
5	274	1.50	0.0363
8	737	1.49	0.0562
9	456	1.41	0.0760
10	159	1.24	0.0358
11	364	1.44	0.0333
12	294	1.68	0.0244
15	306	1.43	0.0205
17	312	1.42	0.0277
18	277	1.33	0.0254
21	320	1.34	0.0254

28 March 1963

Station	$Z = A\,(R/\text{mm-hr}^{-1})^B$ A	B	s^2
1	404	1.41	0.1399
2	398	1.34	0.0148
4	286	1.35	0.0152
6	337	1.37	0.0175
15	236	1.30	0.0094
17	244	1.41	0.0213
18	373	1.43	0.0338

TABLE III

Summary of the Analysis of Covariance

Date	Source of variation	Sum of squares	Degrees of freedom	Mean square	F
29 December	Variation among b's	0.11797	3	0.03932	1.1606
	Pooled Residual	0.84701	25	0.03388	
2 February	Variation among b's	0.83807	10	0.08381	1.0925
	Pooled Residual	18.41130	240	0.07671	
2 March	Variation among b's	0.08656	5	0.01731	0.3944
	Pooled Residual	2.85299	65	0.04389	
27 March	Variation among b's	0.7166	11	0.06515	1.8057
	Pooled Residual	10.96848	304	0.03608	
28 March	Variation among b's	0.08139	6	0.01356	0.3711
	Pooled Residual	3.69082	101	0.03654	

REMARKS: The exponent B of the Z-R equation at all stations during a given storm has a single, identical value at the 5% level of significance.

TABLE IV

Coefficients of the Z-R Relationship at Stations Having the Exponent $\bar{b}$

2 February	$\bar{b}$=1.41	2 March	$\bar{b}$=1.27	27 March	$\bar{b}$=1.40	28 March	$\bar{b}$=1.36
Station	A	Station	A	Station	A	Station	A
18	261	15	399	8	617	2	402
6	242	18	381	9	453	1	392
9	238	1	357	11	364	18	359
2	234	16	315	12	332	6	340
4	225	SLE	207	17	317	4	287
1	220	17	205	21	316	15	262
17	217			15	311	17	238
10	194			1	294		
15	190			5	283		
8	188			2	274		
20	150			18	260		
				10	131		

TABLE V

Summary of the Analysis of Covariance

Date	Source of variation	SS_x	SP	SS_y	DF	Residual SS	Residual DF	Residual MS	F	Remarks
29 December	Among sample	0.68116	0.91618	1.31080	3	0.11307	3	0.0377	1.094	The coefficients at Stations 17, 15, 22, and 2 do not differ significantly from each other at the 5% level of significance with 3 and 28 degrees of freedom
	Within sample	10.90671	12.13771	14.47258	29	0.96493	28	0.0345		
	Total	11.58787	13.05389	15.78338	32	1.07800				
2 February	Among sample	2.00261	2.39750	3.90767	5	1.10640	5	0.2221	2.588	The coefficients at Stations 4, 6, 2, 15, 18, and 1 differ significantly from each other at the 0.5% level of significance with 5 and 138 degrees of freedom
	Within sample	38.95371	54.27272	87.46055	139	11.84440	138	0.0858		
	Total	40.95632	56.67022	91.36822	144	12.95510				
2 March	Among sample	8.09452	8.91218	10.44740	5	0.83140	5	0.1663	3.960	The coefficients at Stations 1, 18, 16, 17, SLE, and 15 differ significantly from each other at the 0.5% level of significance with 5 and 157 degrees of freedom
	Within sample	47.89026	60.79438	80.11509	71	2.93960	70	0.0420		
	Total	55.98478	69.70656	90.56249	76	3.77096				
27 March	Among sample	8.92594	9.78236	10.78477	5	0.75108	5	0.1502	4.521	The coefficients at Stations 8, 9, 11, 21, 17, and 15 differ significantly from each other at the 0.5% level of significance with 5 and 157 degrees of freedom
	Within sample	61.93613	86.26163	125.35817	158	5.21717	157	0.0332		
	Total	70.86207	96.04399	136.14294	163	5.96825				
28 March	Among sample	14.13614	20.44875	30.23409	6	0.72730	6	0.1212	3.349	The coefficients at Stations 1, 2, 6, 4, 18, 17, and 15 differ significantly from each other at the 0.5% level of significance with 6 and 107 degrees of freedom
	Within sample	37.04369	50.46724	72.62730	108	3.87221	107	0.0362		
	Total	51.17983	70.91599	102.86239	114	4.59951				

TABLE VI

Summary of the Analysis of Covariance

Source of variation	SS	DF	MS	F
Variation among b's	1.46009	9	0.16223	3.038
Pooled residual	8.11594	152	0.05339	

REMARKS: The exponents of the Z-R equations at Stations 17 and 22 on 29 December, 9 and 4 on 2 February, 18 and 16 on 2 March, 12 and 10 on 27 March, and 1 and 15 on 28 March differs significantly from each other at the 1.0% level of significance.

TABLE VII

Average Z-R Relationships of All Stations

Date	Average Z-R Relationships	s^2
2 February	$Z=214(R/mm\text{-}hr^{-1})^{1.41}$	0.0767
2 March	$Z=313(R/mm\text{-}hr^{-1})^{1.27}$	0.0439
27 March	$Z=309(R/mm\text{-}hr^{-1})^{1.40}$	0.0361
28 March	$Z=309(R/mm\text{-}hr^{-1})^{1.36}$	0.0365

equation valid for that body of data. Such an equation appears in Table VII for each of the following dates: 2 February, 2 March, 27 March, and 28 March.

C. DISCUSSION OF RESULTS

The results of the analysis of covariance reveal that the exponent B at all stations has a single, identical value but that the coefficient A does not have a single value for a given storm. Hence, curves for the Z-R equation at stations parallel each other but have different intercepts. One can only hypothesize as to why the exponent B has the same value for a given storm at stations. Since the exponent B has a single, identical value for a given storm, but changes from storm to storm, this value might depend upon the same factors which uniquely determine the different synoptic situations in those storms. With regard to the varying values of the coefficient A, one might also hypothesize that coalescence, evaporation, accretion, and wind shear (all of which can determine in part the value of A) depend on the synoptic situations.

Figures I to V show the highest and lowest value of the coefficient at the operating stations during each of the five storms. For given values of R, the difference in Z values between the two stations during a given storm exceeds the difference in average Z

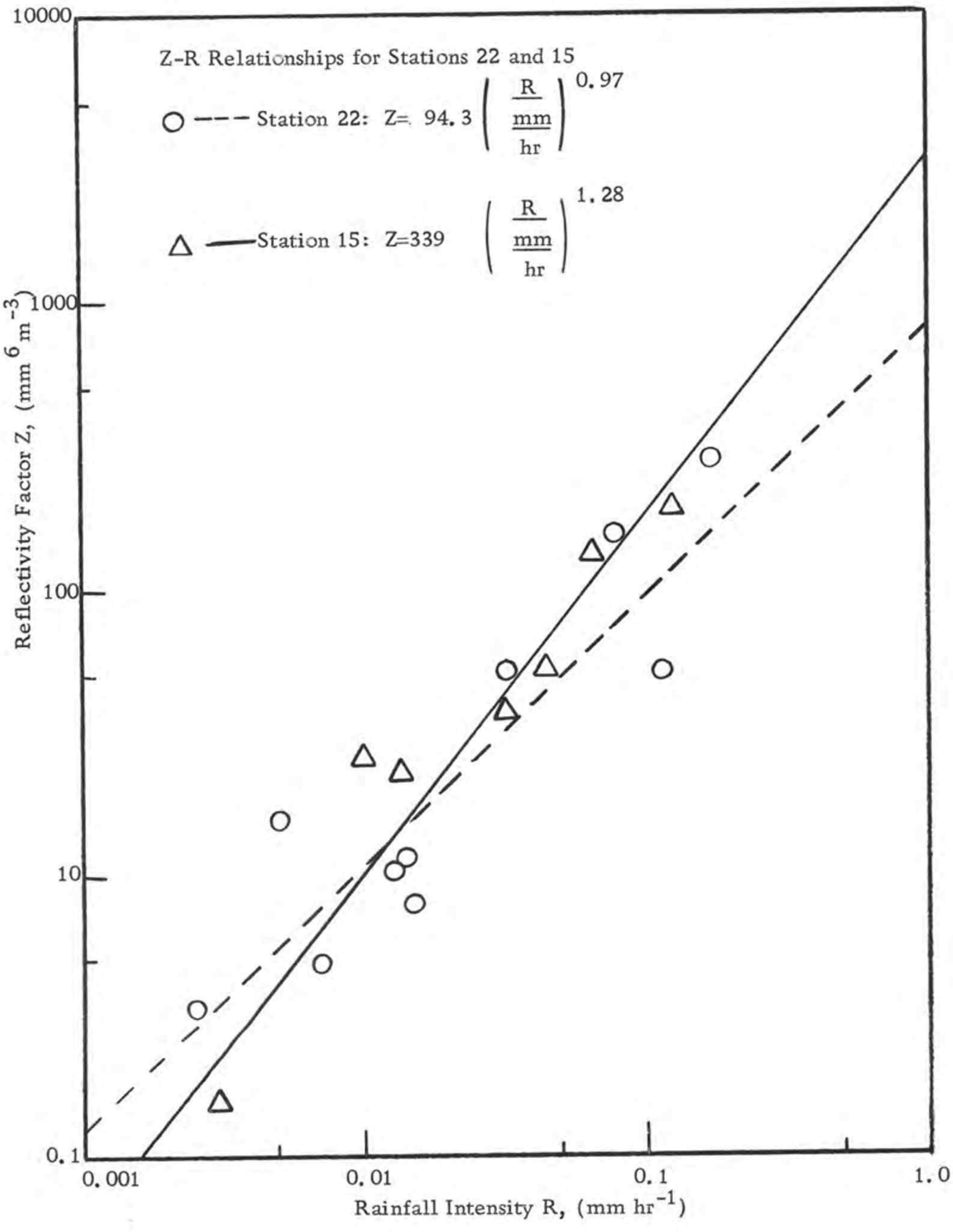

Figure I. Widest Variation in the Coefficient of Z-R Relationship for Stations on 29 December 1962.

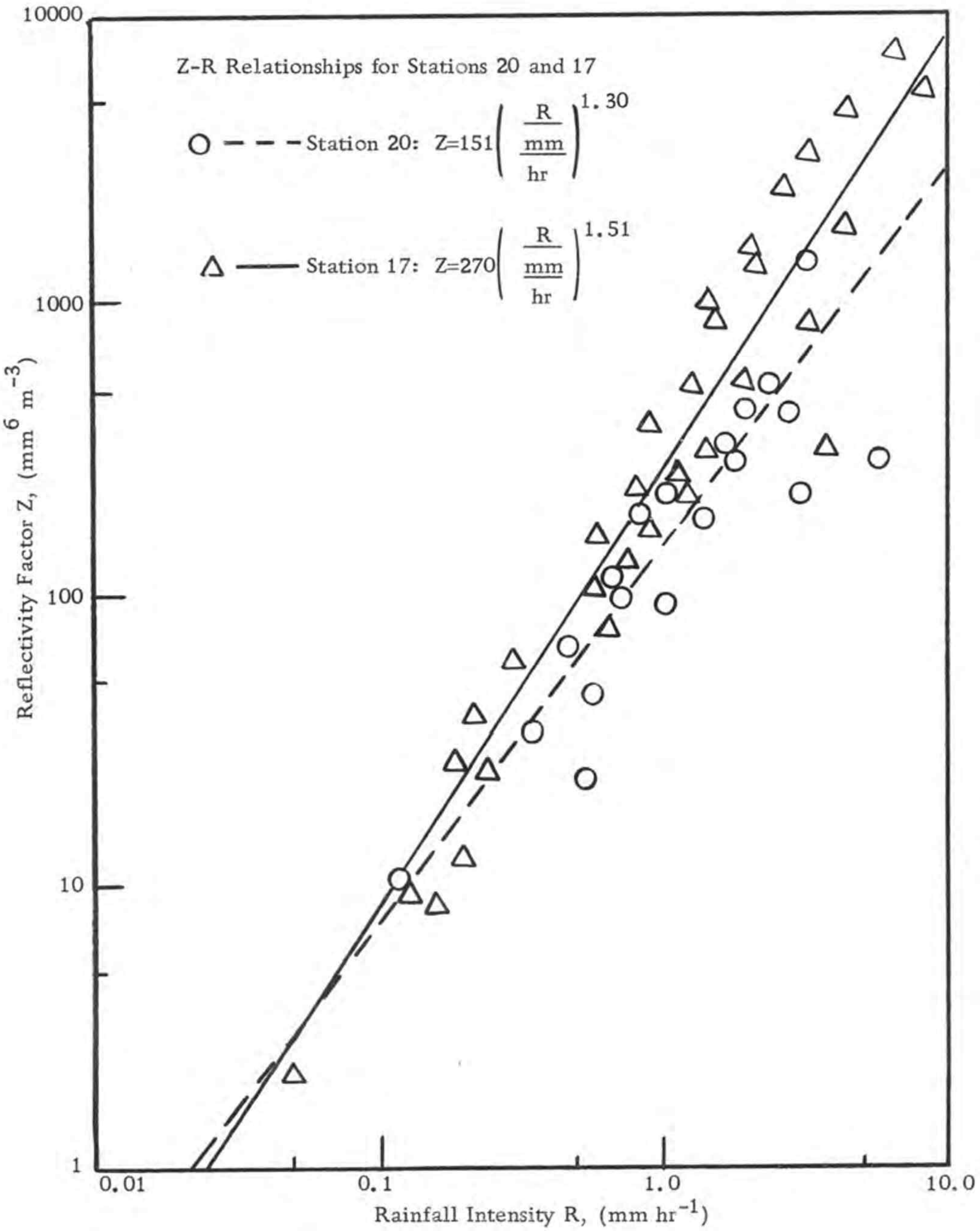

Figure II. Widest Variation in the Coefficient of Z-R Relationship for Stations on 2 February 1963.

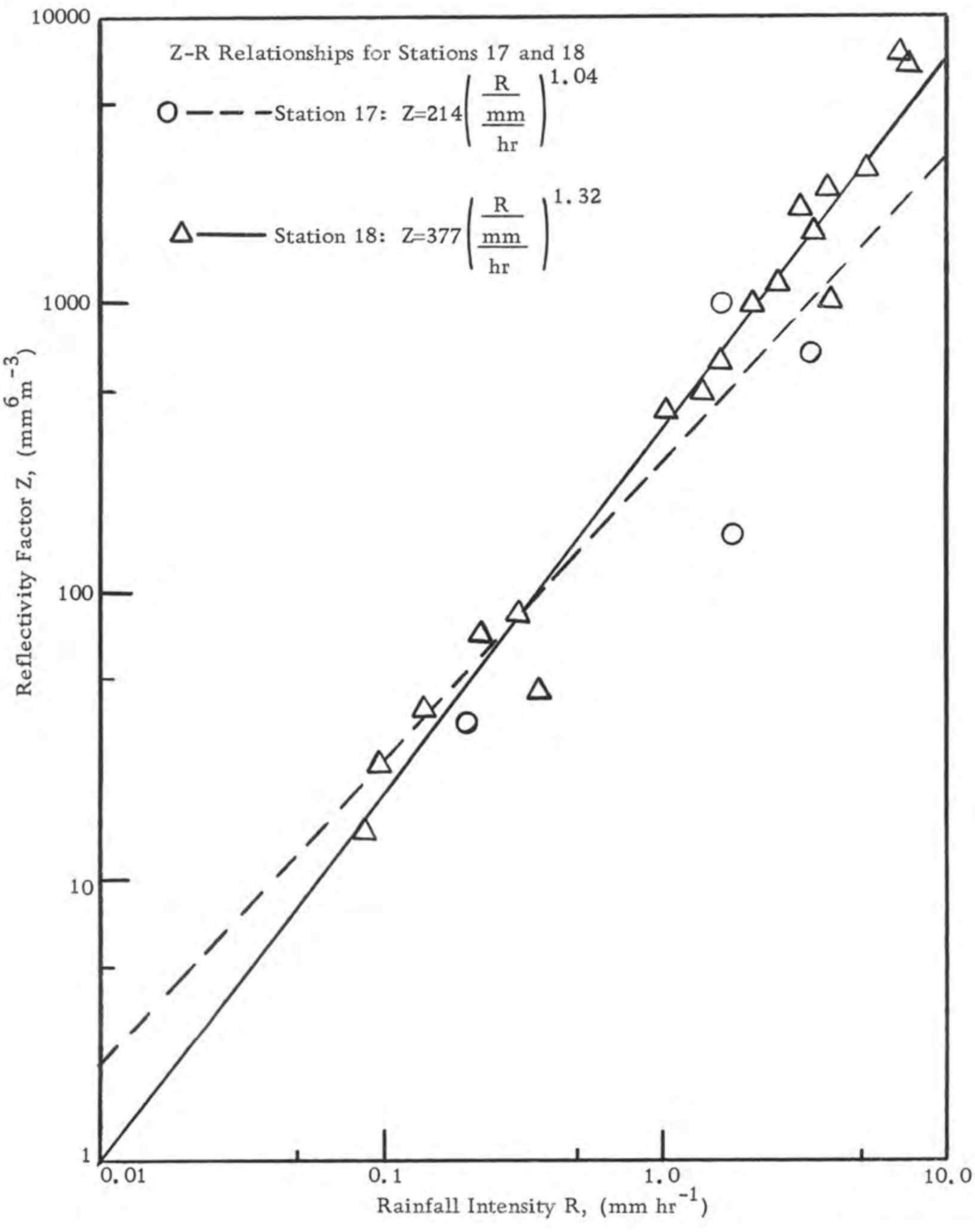

Figure III. Widest Variation in the Coefficient of Z-R Relationship for Stations on 2 March 1963.

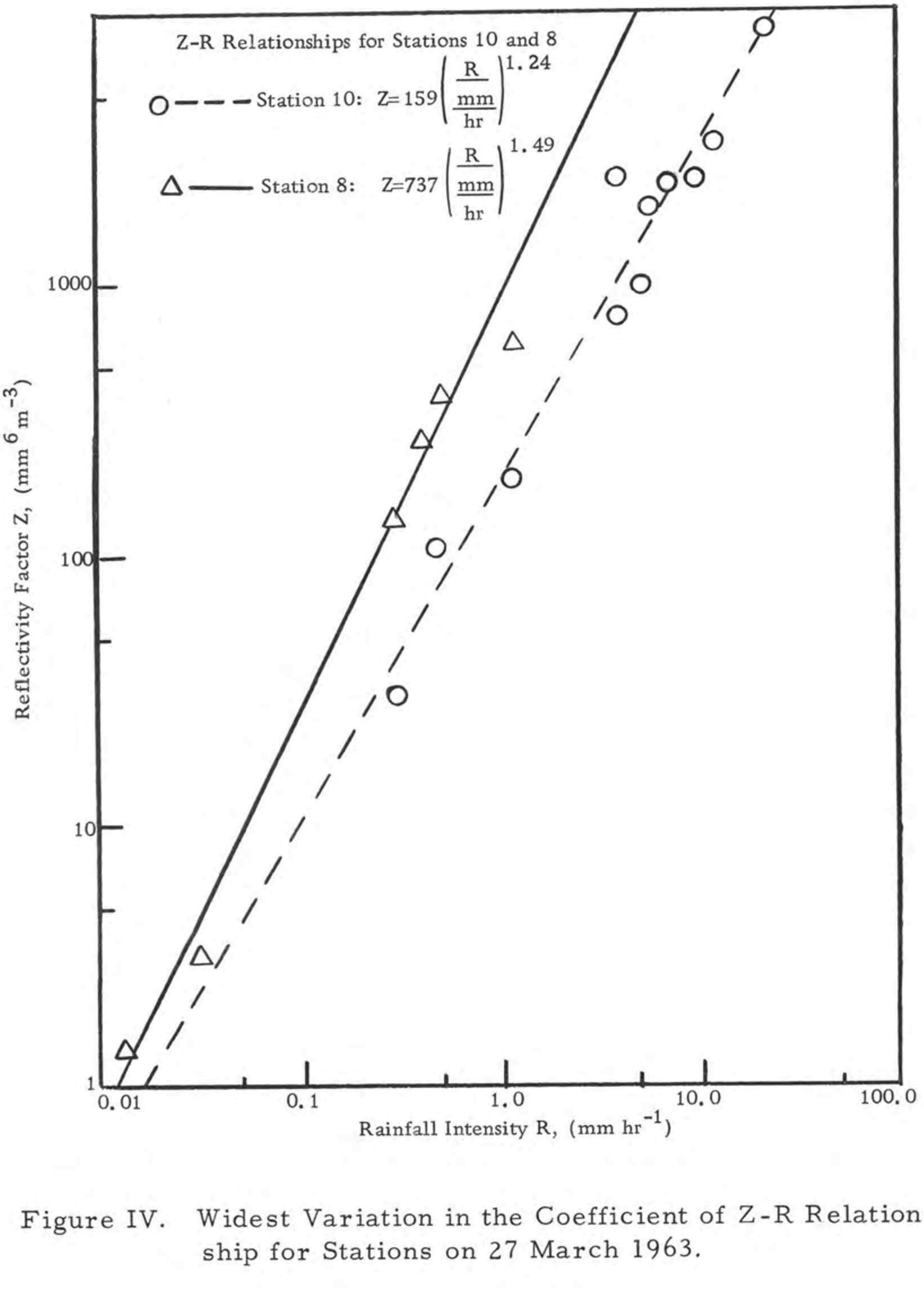

Figure IV. Widest Variation in the Coefficient of Z-R Relationship for Stations on 27 March 1963.

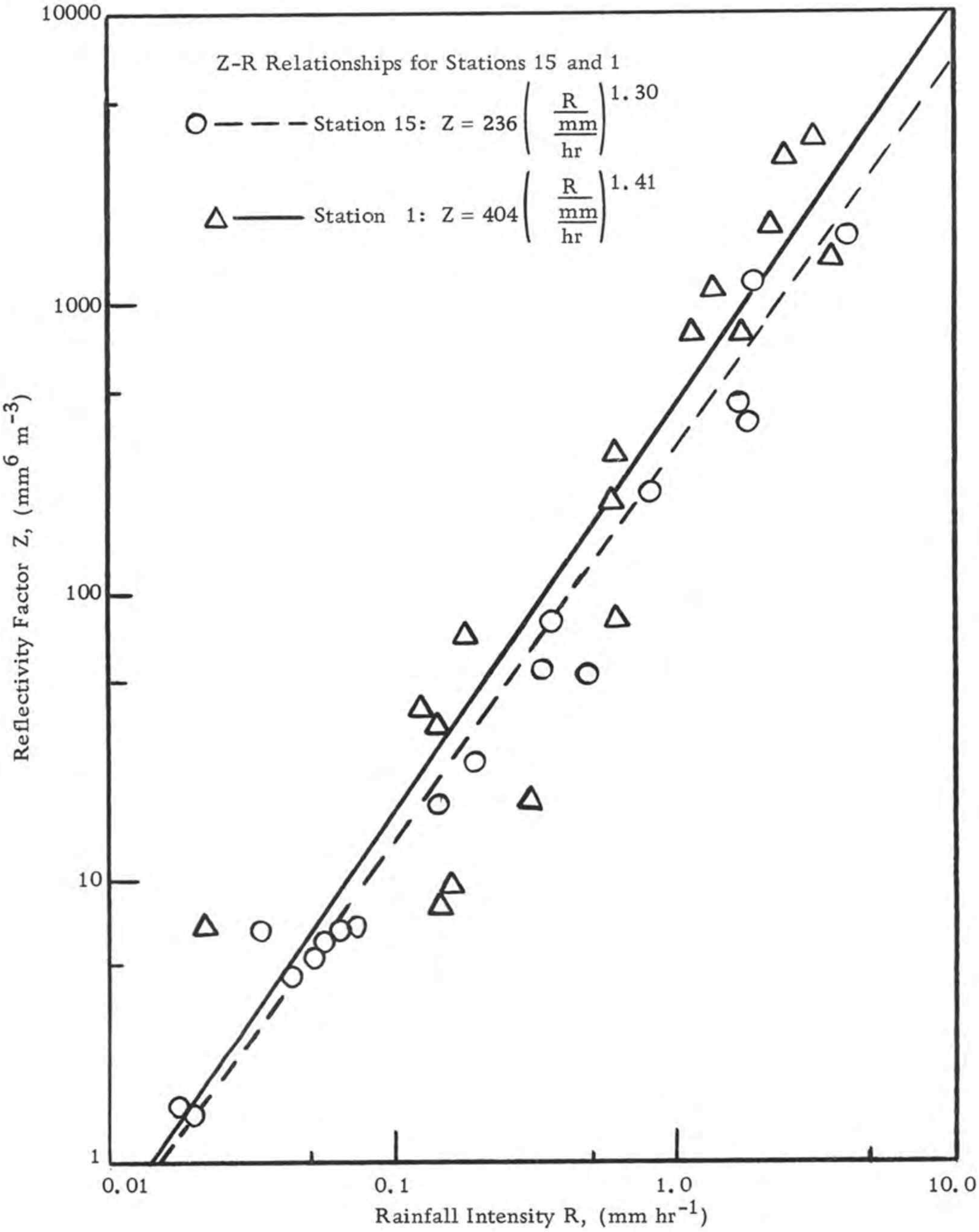

Figure V. Widest Variation in the Coefficient of Z-R Relationship for Stations on 28 March 1963.

values at all stations between storms (Table VIII).

Table IX summarizes the synoptic conditions of the five storms. This study did not examine the variations in A with the synoptic conditions associated with the type of storm, height of freezing level, stability index, and relative humidity because of inadequate data. Statistical study requires Z-R relationships at stations for many different storms having the same synoptic conditions in order to eliminate the random variations caused by sampling. For example, one may find A increasing with station elevation for two storms having the same synoptic condition. However, A at stations may then decrease with station elevation during the next two storms having the same synoptic condition as the two previous storms. Thus, if one concludes that the particular synoptic condition causes A to increase with station elevation from data collected during the first two storms, one makes a false conclusion.

To study the variations in the constant A at stations for a given storm, the author omitted the storm on 29 December because the constants A and B had single, identical values at all of the operating stations.

TABLE VIII

Decibel Differences at Various Rates of Precipitation Between Stations

Date	Stations	0.1 mm/hr	1.0 mm/hr	10 mm/hr	100 mm/hr
29 December	22 and 15	2.5 db	5.6 db	8.7 db	11.8 db
2 February	20 and 17	0.4 db	2.5 db	4.6 db	6.7 db
2 March	17 and 18	0.3 db	2.5 db	5.3 db	8.1 db
27 March	10 and 8	4.2 db	6.7 db	9.2 db	11.7 db
28 March	15 and 1	1.2 db	2.3 db	3.5 db	4.5 db

Average Z Values in mm^6/m^3 at Various Rates of Precipitation at all Stations

Date	0.1 mm/hr	1.0 mm/hr	10 mm/hr	100 mm/hr
29 December	14.3	193*	2600*	35100*
2 February	8.33*	214	5500	141000
2 March	16.8*	313*	5830	109000
27 March	12.3	309	7760*	195000*
28 March	13.5	309	7080	162000
Differences in Z values marked with * (db)	3.1 db	2.1 db	4.7 db	7.4 db

TABLE IX

Summary of Synoptic Conditions

Date	Type of storm	Height of freezing level	Stability index	Height of echoes	Relative humidity
29 December	Cold front	4300 ft	+12.5	20,000 ft	73%
2 February	Warm front	6500 ft	+ 3.0	25,000 ft	86%
2 March	Instability shower	3900 ft	+ 3.0	17,000 ft	83%
27 March	Warm front	4400 ft	+ 2.5	20,000 ft	87%
28 March	Cold front	2800 ft	+ 5.5	20,000 ft	71%

VI. OBSERVED VARIATIONS IN THE COEFFICIENT A WITHIN STORMS

A. INTRODUCTION

As mentioned earlier, this study seeks to determine how the constants of the Z-R equation vary with station location during a given storm. At the individual stations, the method of least squares yielded different values of the exponent B, but the differences resulted from sampling errors. Therefore, the exponent at all stations during a given storm has a single, identical value. Thus, one can better estimate rainfall intensity at a point with radar by determining how the values of A vary with station locations. The following sections examine how the coefficient A (from Table IV) varies with station elevation, windward or leeward location of stations, station topography, and time.

B. VARIATION WITH STATION ELEVATION

Several investigators (3, 4, 6, 12, 14, 16) studied the effect of accretion, coalescence, and evaporation on the constants A and B of the Z-R equation. Accretion and coalescence will increase the size and number of the larger drops while reducing the number of smaller drops. Evaporation decreases the size of all drops.

However, the ratio of surface area to mass of small drops exceeds the same ratio for large drops. Hence, starting with a given drop-size distribution, we can expect evaporation to reduce more rapidly the number of a given small diameter drop than of any larger size drop. Since a typical distribution has a peak in the number of the smallest diameter of drop, we must also expect proportionally greatest reduction in the number of the smallest drops than of larger drops. Investigators (1, 12) found (by computing the changes in given hypothetical drop-size distributions) that accretion and coalescence decrease the value of the coefficient A and increase the value of the exponent B. However, they found that evaporation increases the value of the coefficient and decreases the value of the exponent. Thus, one could expect A to vary with station elevation if either of the processes dominated during the observation period of a given storm since both coalescence and evaporation increase with the depth of fall of raindrops. One must assume that the raindrops form at a constant elevation above mean sea level, regardless of station elevation.

If accretion and coalescence affect the drop-size distribution more than evaporation during the observation period of a given storm, the value of A increases with station elevation. If evaporation dominates, the value of A decreases with station elevation. A correlation coefficient, r, determines whether a significant relation exists between A and station elevation (18, p. 267). A positive r indicates that the value of A relates directly to station elevation, while a negative r indicates that the value of A relates inversely to station elevation. A correlation coefficient close to or equal to plus or minus one indicates the existence of a significant correlation, and an r value equal to zero indicates the absence of a relationship.

Results

2 February

A calculated r value of -0.30 indicates a very weak tendency, if any, for A to vary inversely with station elevation.

2 March

The r value of +0.07 indicates hardly any tendency for A to vary directly with station elevation.

27 March

The r value of +0.58 indicates a rather weak direct dependency of A to station elevation, possibly the effect of accretion and coalescence.

28 March

The r value of -0.67 indicates a moderate tendency for A to vary inversely with elevation and thus to show that evaporation may have dominated during the observation period.

C. WINDWARD AND LEEWARD VARIATIONS

This section examines whether Z-R equations have higher values of A at stations located on the windward side of mountains than at stations located on the leeward side. The surface synoptic maps for the day yielded the wind direction, and the locations of stations on a topographic relief map determined whether to classify a station location as the windward or leeward side. Table X shows average weighted (18, p. 355) coefficients $\overline{A}$ found by averaging log A values at stations located on windward and leeward side of mountains, and weighted in proportion to the number of data points determining each value of A.

Windward stations have higher values of A than leeward stations for the four storms analyzed. This result suggests that windward stations experience different drop-size distributions from leeward stations. One can only hypothesize the reason for experiencing a different drop-size distribution on the windward side from that on the leeward side. The wind can lift the small drops from the windward side over the mountain to the leeward side. During ascent, the small drops may coalesce and fall on the windward side. The result of lifting then decreases the number of small drops and increases the number of large drops at the windward stations.

In order to determine whether this hypothesis results in a higher value of A at the windward side from that on the leeward side, one must compute the values of the coefficient A at two stations; one for the windward side and the other for the leeward side. To do this, first assume a hypothetical drop-size distribution for the leeward side. Then, eliminate the drops in the three smallest intervals of that assumed distribution and assume this modified distribution for the windward side. Such a procedure resulted in the following Z-R equations:

$Z=220(R/\text{mm-hr}^{-1})^{1.2}$	$Z=215(R/\text{mm-hr}^{-1})^{1.2}$
Modified Distribution	Hypothetical Distribution
Windward Side	Leeward Side

Although the windward distribution of raindrops did not have more large drops, the results of the computation still yielded a higher coefficient A for the windward side. Adding more large drops to the windward distribution increases the calculated Z value more than the R value, thus resulting in a still higher value of A. The value of Z increases more than R because Z depends on the sixth power of the diameter of the raindrops while R depends on the third power of the diameter.

TABLE X

Average Z-R Relationships for Windward and Leeward Stations

Date	Wind direction	Windward stations	Leeward stations	Average Z-R Relationship of windward stations	Average Z-R Relationship of leeward stations
2 February	SW	18, 8, 9, 17, 10, 1	15, 2, 4, 20, 6	$Z=218(R/mm\text{-}hr^{-1})^{1.41}$	$Z=205(R/mm\text{-}hr^{-1})^{1.41}$
2 March	NW	18, 15	1, 16, 17, SLE	$Z=390(R/mm\text{-}hr^{-1})^{1.26}$	$Z=263(R/mm\text{-}hr^{-1})^{1.26}$
27 March	SE	11, 12, 1, 2, 9	15, 17, 21, 18, 5, 10	$Z=374(R/mm\text{-}hr^{-1})^{1.40}$	$Z=296(R/mm\text{-}hr^{-1})^{1.40}$
28 March	SW	18, 17, 1	4, 6, 2, 15	$Z=322(R/mm\text{-}hr^{-1})^{1.36}$	$Z=318(R/mm\text{-}hr^{-1})^{1.36}$

TABLE XI

Average Coefficients at Topographic Regions

Date	Hilltop stations	Hillside stations	Valley stations	Hilltops $\bar{A}$	Hillsides $\bar{A}$	Valleys $\bar{A}$
2 February	10	8, 9, 17, 20	4, 6, 15, 18, 2, 1	194	195	227
2 March	None	17, 16	1, 15, 18, SLE	---	254	390
27 March	11, 12, 10	8, 9, 17, 21	5, 15, 18, 1, 2	251	409	284
28 March	None	17	4, 6, 1, 2, 15, 18	---	238	351

D. VARIATION WITH STATION TOPOGRAPHY

In order to study the effects of topography, consider the Z-R relationship grouped for stations on hillsides, hilltops, and valleys. Regions of relatively flat land surrounded by regions of relatively steep positive slope on at least two sides describe valley stations. One-tenth of the altitude from the floor of the valley to the lowest peak around the valley represents the upper limit of valley stations. Regions of relatively flat land surrounded by regions of relatively steep negative slope describe hilltop stations. Dropping one-tenth of the altitude difference from the peak to the floor of the most elevated valley on any side determines the lower limit of hilltop stations. All other regions represent hillside stations. For each of the four storms, Table XI gives the average coefficient $\overline{A}$ found by averaging log A values at stations from each topographic region.

In all of the four storms except the storm on 27 March, valley regions have the highest value of $\overline{A}$ followed in order by hillside and hilltop regions. In the case of 27 March hillside regions have the highest value of $\overline{A}$ followed in order by valley and hilltop regions.

Can the Z-R equation at one station from a topographic region represent the Z-R equation at other stations in the same topographic region? The analysis of covariance (18, p. 364) gives an answer by examining the equivalence of A at all stations in a given topographic region for each of the four storms (Table XII). The results of the analysis of covariance reveal no significant difference in A from one station to another at hillside regions on 2 March, and at valley regions on 2 February, 27 March, and 28 March at the 5% level of significance. The results indicate drop-size distributions at different valley stations yield single, identical values for the constants A and B during a given storm. Therefore, a radar could reliably approximate rainfall intensities in valley regions with just one rain gauge located in a valley. However, a radar with one rain gauge on a hillside or hilltop cannot approximate the rainfall intensities at other stations located on hillsides or hilltops.

E. VARIATION WITH TIME AND LOCATION OF STATIONS

Does the Z-R equation at a particular station as compared to another station always have a higher coefficient A during different storms? Consider the values of A at stations for given dates appearing in Table IV. The highest coefficient occurred at different stations during different storms suggesting that the constant A does not relate only to station location but also to other factors which change from one storm to the next. Interestingly, the rankings of A at stations on 27 March reverse on 28 March. The synoptic

TABLE XII

Summary of the Analysis of Covariance

Date	Source of variation	SS_x	SP	SS_y	DF	Residual SS	Residual DF	Residual MS	Residual F
2 February Hillside stations	Among sample	3.03736	3.85586	5.82181	3	1.00062	3	0.3335	4.034
	Within sample	27.52031	39.45474	63.75783	88	7.19319	87	0.0826	
	Total	30.55767	43.31060	69.57964	91	8.19381			
2 February Valley stations	Among sample	1.33628	1.77484	2.65933	5	0.30669	5	0.0613	0.818
	Within sample	57.50186	80.61235	124.33599	152	11.32485	151	0.0750	
	Total	58.83814	82.38719	126.99292	157	11.63154			
2 March Hillside stations	Among sample	0.99643	0.92448	0.85771	1	0.08912	1	0.0891	1.548
	Within sample	17.32091	21.39885	27.64298	22	1.20882	21	0.0575	
	Total	18.31734	22.32223	28.50069	23	1.29794			
2 March Valley stations	Among sample	4.64311	4.59999	4.91488	3	0.71569	3	0.2386	6.739
	Within sample	30.56935	39.39663	52.47211	49	1.69921	48	0.0354	
	Total	35.21246	43.99662	57.38699	52	2.41490			
27 March Hilltop stations	Among sample	2.34199	1.35609	0.95918	2	1.68298	2	0.8414	23.650
	Within sample	12.79023	18.57321	28.89238	55	1.92147	54	0.0356	
	Total	15.13222	19.92930	29.85156	57	3.60455			
27 March Hillside stations	Among sample	7.96119	8.71787	9.60836	3	0.61953	3	0.2065	5.517
	Within sample	48.31066	66.70161	95.94894	105	3.85529	104	0.0374	
	Total	56.27185	75.41948	105.55730	108	4.47482			
27 March Valley stations	Among sample	14.49137	19.64740	26.73709	4	0.12642	4	0.0316	0.837
	Within sample	71.12161	99.81417	145.93690	156	5.85474	155	0.0378	
	Total	85.61298	119.46157	172.67399	160	5.98120			
28 March Valley stations	Among sample	14.13533	20.46378	29.92940	5	0.38608	5	0.0772	2.020
	Within sample	29.58377	39.92428	57.24280	89	3.36366	88	0.0382	
	Total	43.71910	60.38806	87.16220	94	3.74974			

conditions on 27 March show a warm front passage, and the synoptic condition on 28 March show a cold front passage over the stations. This reversal in A suggests that different synoptic conditions could also affect the coefficient A at stations.

Using the best-fitting coefficient A at Station 17 on 27 March (Table II), the author found the exponent B of the Z-R equation for the raindrop population on each filter paper collected at Station 17 on 27 March. He then plotted B of each filter paper against time and rainfall intensity. The time cross-section shows wide variations in the exponent B from one filter paper to the next (Plate III).

F. DISCUSSION

The following discussion interprets the observed variations in the values of the coefficient A for given storms in estimating the rainfall amounts at stations using weather radar.

Equation (6), p. 3, shows that range-normalized radar signals $\overline{P}_{rn}$ of the same intensity from targets over stations can indicate different amounts of rainfall at those stations if they have different values for the coefficient A.

$$R = \left(\frac{\overline{P}_{rn}}{C_1 A} \right)^{\frac{1}{B}} \tag{31}$$

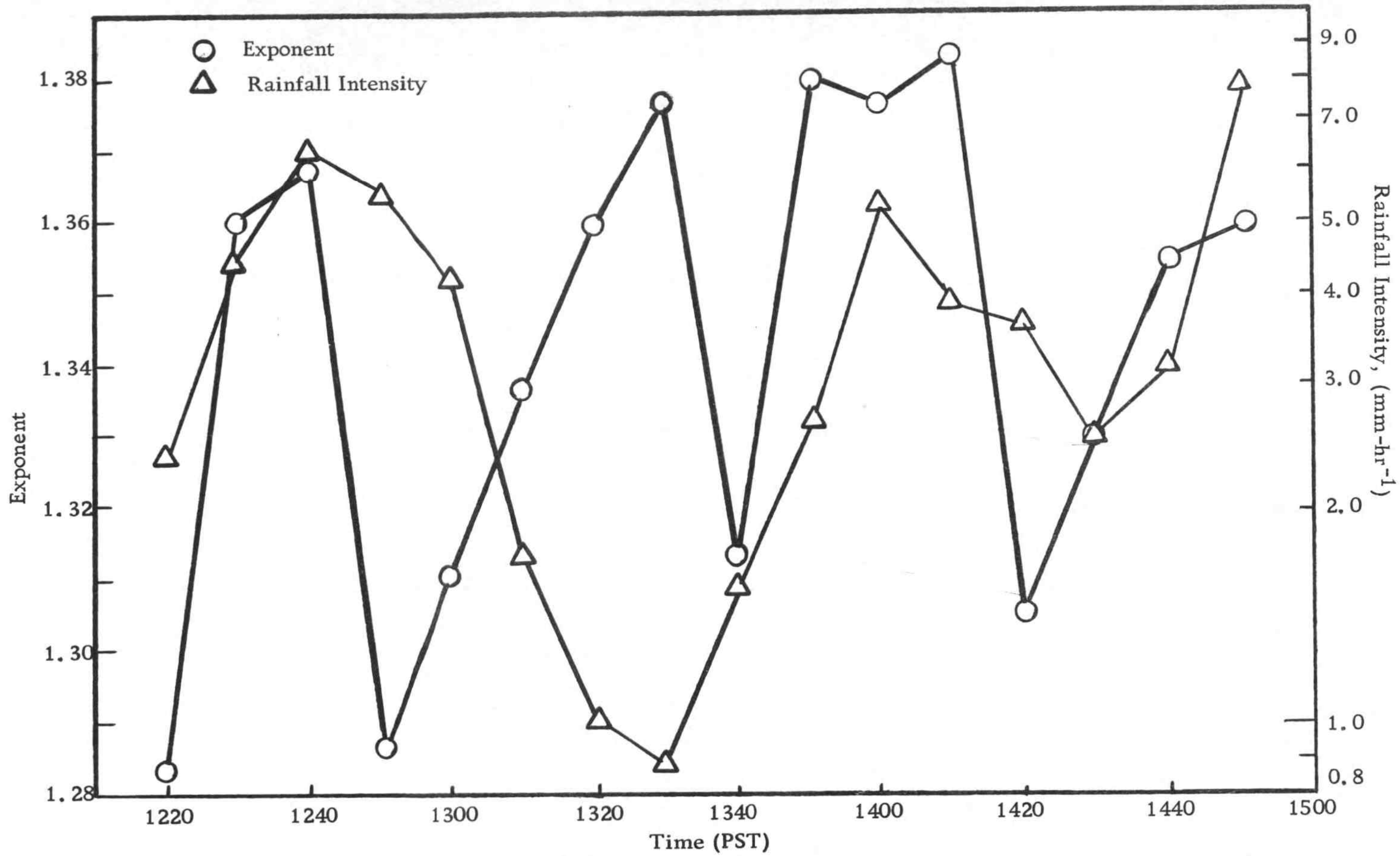

Plate III. Time Cross-section of Exponents and Rainfall Intensity for Station 17 on 27 March 1963 Obtained from Each Filter Paper. (Lines connecting points are for visual aids only.)

Here $\overline{P}_{rn}$ indicates the product $\overline{P}_r r^2$ in Equation (6). This of course assumes that the drop-size distribution does not change while falling from the radar beam to the station. For example, if the Z-R equation at a given station has a higher value of A than that of another station, all range-normalized radar signals of the same intensity over the two stations indicate the station with the higher value of A experiences a smaller amount of rainfall. Thus, for range-normalized radar signals having the same intensity from targets over stations, this study concludes that:

1. The amount of rainfall at leeward stations exceeds the amount of rainfall at windward stations.

2. The amount of rainfall on hilltops exceeds the amount of rainfall on hillsides and in valleys.

VII. CONCLUSIONS

This study concludes that:

1. Significant differences exist in the coefficient A but not in the exponent B of the Z-R equation at various locations in the OSU Mesometeorological Network during given storms.

2. For given values of R, the difference in values of Z between stations during a given storm exceeds the difference in average values of Z for all stations between storms.

3. The value of the coefficient A correlates moderately with station elevation during some storms.

4. The average Z-R equation has a higher coefficient $\overline{A}$ at windward stations than at leeward stations.

5. The average Z-R equation at valley stations has the highest coefficient $\overline{A}$ followed, in order, by the average values of A at hillside and at hilltop stations.

6. In three of the four storms analyzed, no significant differences existed in the coefficient A at valley stations.

7. The highest coefficient A occurs at different stations during different storms.

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APPENDIX

TABLE A-I

Z, mm^6-m^{-3}, and R, x 10^{-3} mm/hr^{-1}, Values for 29 December 1962

Station 17 n=10			Station 15 n=7			Station 22 n=10		
Time	Z	R	Time	Z	R	Time	Z	R
1506	0.103	1.221	1507	0.159	3.129	1500	1.075	13.100
1520	6.921	34.760	1522	2.485	18.210	1510	0.334	2.668
1530	2.880	25.930	1550	12.590	76.540	1515	1.648	5.391
1540	1.245	9.569	1600	19.930	117.900	1520	4.887	32.860
1550	39.630	176.900	1610	2.355	13.680	1525	0.477	7.115
1600	6.739	27.770	1620	5.556	42.630	1530	1.131	14.260
1610	14.000	81.870	1630	3.632	143.500	1535	5.137	115.100
1620	30.070	170.100				1540	0.786	15.380
1640	20.480	154.800				1545	28.320	171.500
1650	23.570	143.500				1550	14.700	81.283
			Station 2 n=6					
			1348	5.504	41.310			
			1520	50.130	298.700			
			1547	20.570	134.000			
			1553	5.086	50.480			
			1628	2.170	17.950			
			1745	0.549	6.976			

TABLE A-II

Z, mm^6-m^{-3}, and R, X 10^{-3} mm-hr^{-1}, Values for 2 February 1963

Station 4	n=23		Station 9	n=18		Station 6	n=20	
Time	Z	R	Time	Z	R	Time	Z	R
0950	4.814	15.900	1005	374.500	1431.000	1000	322.800	1382.000
1000	69.610	382.500	1020	539.400	1002.000	1010	1837.000	2284.000
1010	488.300	1408.000	1030	885.400	1921.000	1020	89.390	308.900
1020	486.100	1371.000	1040	737.000	1508.000	1030	1056.000	2480.000
1030	2204.000	3325.000	1050	4232.000	6428.000	1040	1344.000	2659.000
1040	544.900	1673.000	1100	4243.000	7468.000	1050	5114.000	6595.000
1050	2217.000	3500.000	1110	535.600	2253.000	1100	3760.000	7343.000
1100	3968.000	4437.000	1120	3350.000	4626.000	1110	1721.000	4284.000
1110	1792.000	3051.000	1130	1039.000	2804.000	1120	1119.000	4448.000
1310	43.400	592.800	1140	145.500	514.900	1130	1595.000	5160.000
1320	161.700	2020.000	1150	3660.000	7318.000	1140	1.346	43.970
1330	11.330	242.300	1200	1428.000	2045.000	1150	571.800	2625.000
1340	103.500	529.200	1210	4.517	130.800	1200	2458.000	4367.000
1410	389.500	3139.000	1220	907.300	4024.000	1210	129.500	1016.000
1415	551.800	3506.000	1300	237.800	1322.000	1220	150.800	555.900
1420	6464.000	10380.000	1310	75.320	784.000	1230	1077.000	3170.000
1430	412.500	2701.000	1320	114.600	623.100	1240	710.900	1912.000
1440	4882.000	9509.000	1330	57.620	438.644	1250	390.500	1345.000
1450	9502.000	13330.000				1300	3352.000	4644.000
1500	1178.000	4655.000				1310	103.200	633.900
1510	231.300	677.700						
1520	64.210	408.400						
1530	131.200	371.500						
Station 20	n=20		Station 8	n=22		Station 18	n=23	
1000	10.780	118.900	0950	42.150	233.900	1020	43.990	345.900
1010	332.700	1601.000	1000	306.700	1206.000	1030	977.800	2122.000
1020	231.100	1069.000	1010	1961.000	2521.000	1040	445.600	1335.000
1030	861.700	1429.000	1020	3254.000	4250.000	1045	2377.000	2861.000
1040	532.400	2296.000	1030	1769.000	3520.000	1055	1752.000	4088.000
1050	1388.000	3127.000	1040	31810.000	29880.000	1110	75.140	658.300
1100	427.900	2305.000	1100	1855.000	2824.000	1120	224.100	625.300
1110	99.710	730.300	1115	3074.000	9758.000	1130	811.800	2157.000
1120	289.100	1811.000	1150	700.400	3124.000	1140	68.790	297.100
1130	89.990	1043.000	1200	1425.000	5913.000	1150	629.800	1669.000
1230	33.940	348.900	1240	1122.000	2149.000	1200	2055.000	2996.000
1240	67.770	479.600	1330	18.370	236.200	1210	842.700	3653.000
1250	112.300	653.000	1350	425.500	4092.000	1220	214.600	1053.000
1300	189.900	811.800	1400	13.950	273.900	1230	156.400	162.500
1310	187.700	1354.000	1410	342.900	2581.000	1240	13.700	147.600
1350	24.360	533.300	1411	15310.000	36270.000	1245	84.940	391.400
1400	209.100	3084.000	1420	669.200	2847.000	1250	76.690	412.500
1410	46.560	547.000	1430	4807.000	16910.000	1300	273.900	805.700
1450	852.100	5086.000	1440	22350.000	21990.000	1310	99.130	758.800
1500	460.200	1941.000	1450	6869.000	0282.000	1400	195.700	2097.000
			1510	2943.000	9344.000	1410	2.455	50.710
			1511	3.274	42.550	1440	493.200	1250.000
						1450	235.400	2076.000

TABLE A-II (continued)

Z, mm^6-m^{-3}, and R, x 10^{-3} mm-hr^{-1}, Values for 2 February 1963

Station 17 n=32			Station 2 n=33			Station 15 n=35		
Time	Z	R	Time	Z	R	Time	Z	R
1004	106.800	572.800	1008	716.700	2665.000	1002	37.670	346.400
1010	32.590	307.400	1021	508.500	2122.000	1010	938.400	1864.000
1015	1036.000	1397.000	1029	222.100	1071.000	1020	451.300	1622.000
1020	320.600	1436.000	1034	778.900	2508.000	1030	287.400	1282.000
1030	243.100	838.400	1039	186.800	830.100	1040	1185.000	3242.000
1040	171.400	909.200	1047	2698.000	3304.000	1050	2341.000	3895.000
1045	1560.000	2114.000	1051	1871.000	3809.000	1100	2069.000	4639.000
1050	8412.000	7252.000	1109	1849.000	4967.000	1110	1744.000	4349.000
1100	147.300	1199.000	1059	821.400	1885.000	1115	661.500	3412.000
1110	272.200	1168.000	1119	29.270	298.100	1120	61.300	650.600
1120	301.900	630.200	1126	616.600	2557.000	1130	876.400	2728.000
1130	2562.000	2948.000	1127	3206.000	5519.000	1140	370.100	2164.000
1135	5714.000	7051.000	1129	26.950	90.960	1150	38.480	426.300
1140	215.100	637.500	1139	235.500	1206.000	1200	767.700	1945.000
1150	138.500	481.100	1153	240.400	1151.000	1210	2371.000	3324.000
1200	1325.000	2314.000	1157	4269.000	3773.000	1220	4861.000	8204.000
1201	3684.000	3122.000	1159	6524.000	14119.000	1230	116.700	566.500
1202	9.957	128.800	1207	6425.000	8095.000	1240	19.200	176.600
1210	740.500	2672.000	1210	936.800	1735.000	1250	8.538	144.600
1212	5566.000	9781.000	1215	2.237	53.730	1300	206.100	894.400
1220	475.000	1442.000	1220	1606.000	5320.000	1310	1838.000	3432.000
1230	1155.000	1155.000	1229	7.989	129.600	1315	1081.000	1848.000
1240	58.910	305.800	1237	1075.000	5524.000	1320	2251.000	4726.000
1250	949.800	1962.000	1241	147.100	704.300	1330	178.100	833.700
1252	2038.000	3211.000	1249	578.600	1360.000	1340	29.740	126.100
1300	3373.000	4870.000	1259	978.800	3074.000	1350	174.300	579.400
1310	222.200	857.900	1309	1768.000	2579.000	1400	3.909	125.200
1320	210.400	435.000	1320	54.310	665.900	1410	20.400	349.300
1330	2.239	52.530	1329	261.900	283.300	1420	15.900	230.900
1340	36.860	342.700	1330	0.633	23.640	1423	1176.000	5070.000
1350	12.510	205.500	1349	20.180	100.500	1440	156.300	1531.000
1410	8.481	162.400	1359	6.857	220.200	1450	1983.000	8066.000
Station 10 n=12			1400	143.600	1157.000	1500	609.100	3061.000
1032	1246.000	2355.000	Station 1 n=24			1510	21.790	301.600
1050	2494.000	5519.000	1030	1226.000	2477.000	1520	57.400	717.100
1110	1005.000	1742.000	1050	1355.000	3408.000	Station 1 n=24 (continued)		
1130	292.200	1839.000	1100	5448.000	6831.000	1350	0.631	17.130
1140	6921.000	8245.000	1110	7355.000	7392.000	1410	0.606	12.810
1210	405.700	2474.000	1120	2206.000	4914.000	1420	2.329	78.330
1230	15.670	228.100	1130	222.500	562.000	1430	212.600	1560.000
1250	2536.000	6221.000	1140	597.700	1952.000	1440	293.500	1696.000
1400	275.700	2464.000	1150	85.960	321.700	1450	1120.000	5250.000
1410	3055.000	5082.000	1250	2439.000	3877.000	1500	1906.000	3669.000
1430	1025.000	5138.000	1300	513.000	1975.000	1510	2949.000	7228.000
1500	244.300	949.300	1310	527.600	897.700	1530	157.200	640.800
			1320	243.900	1415.000	1540	111.500	1056.000
			1330	41.370	618.500	1542	664.400	2875.000

TABLE A-III

Z, mm^6-m^{-3}, and R, x 10^{-3} mm-hr^{-1}, Values for 2 March 1963

Station 18 n=20			Station 16 n=20			Station SLE n=14		
Time	Z	R	Time	Z	R	Time	Z	R
1550	39.940	129.900	1543	126.700	375.200	1310	11.710	73.870
1600	85.200	303.700	1545	32.730	251.100	1320	73.240	296.000
1604	927.000	1542.000	1550	4.510	37.700	1330	3.679	68.930
1605	1219.000	2674.000	1555	53.870	147.400	1420	1208.000	4934.000
1606	2977.000	4802.000	1600	2166.000	6956.000	1425	6910.000	16780.000
1610	500.800	1319.000	1605	8032.000	10740.000	1430	1343.000	2876.000
1615	649.600	1664.000	1610	983.700	3934.000	1435	18010.000	20010.000
1616	5655.000	8822.000	1615	0.150	2.004	1440	152.500	880.700
1620	1080.000	3960.000	1620	1105.000	2438.000	1445	640.300	1544.000
1625	1771.000	3712.000	1625	1053.000	1757.000	1450	1560.000	9047.000
1630	415.600	1047.000	1630	44.840	258.700	1455	588.300	3587.000
1635	44.490	350.400	1635	2.320	21.390	1500	3944.000	11630.000
1640	14.720	88.660	1640	61.540	204.800	1505	2327.000	5472.000
1701	2276.000	3084.000	1645	424.700	1436.000	1510	1180.000	5042.000
1705	272.100	3746.000	1650	427.800	910.100			
1710	6989.000	7368.000	1700	8.270	33.540			
1715	6407.000	6778.000	1705	93.810	358.500			
1720	1076.000	1968.000	1710	4.150	64.490			
1725	41.700	144.700	1715	18.820	205.900			
1731	25.690	99.320	1720	604.100	1507.000			
Station 1 n=10			Station 17 n=4			Station 15 n=9		
1420	6.929	47.020	1630	157.500	1853.000	1516	125.900	466.900
1440	890.300	2752.000	1700	1071.000	1625.000	1600	0.542	6.186
1450	391.100	1157.000	1720	717.500	3460.000	1606	163.900	265.800
1620	35.410	218.500	1730	36.980	200.600	1610	2611.000	2346.000
1630	3.946	23.770				1620	516.300	1383.000
1640	726.100	2334.000				1640	31.720	86.490
1650	3495.000	3934.000				1650	3621.000	7051.000
1700	1907.000	3190.000				1710	36.490	297.200
1710	3114.000	3878.000				1720	23.440	165.200
1720	2.888	26.010						

TABLE A-IV

Z, mm^6-m^{-3}, and R, x 10^{-3} mm-hr^{-1}, Values for 27 March 1963

Station 9 n=21			Station 5 n=24			Station 12 n=22		
Time	Z	R	Time	Z	R	Time	Z	R
1240	461.900	578.900	1220	1641.000	3706.000	1230	2078.000	3156.000
1250	282.500	578.000	1230	1182.000	3360.000	1240	1246.000	2614.000
1300	6.819	68.920	1240	2387.000	4253.000	1250	1488.000	2740.000
1321	268.200	648.000	1250	772.200	2730.000	1300	4189.000	4484.000
1330	140.100	501.600	1300	234.300	1187.000	1303	82.170	555.700
1337	306.900	526.300	1310	48.810	306.700	1310	202.900	718.900
1342	1523.000	1925.000	1320	36.020	226.600	1320	319.600	1265.000
1350	1676.000	1215.000	1330	6.585	67.280	1330	33.490	272.400
1400	347.600	692.600	1340	323.300	624.800	1340	129.100	499.900
1420	1209.000	1861.000	1400	31.980	256.800	1350	2813.000	2452.000
1430	1408.000	2830.000	1410	1381.000	2199.000	1400	513.800	1334.000
1440	1001.000	2182.000	1420	1770.000	2309.000	1410	998.300	2182.000
1450	5577.000	4650.000	1430	2528.000	2840.000	1420	1213.000	1880.000
1600	317.200	757.900	1440	9183.000	7685.000	1430	4166.000	3612.000
1610	31.040	242.000	1450	7269.000	7081.000	1440	2367.000	3571.000
1640	1268.000	3918.000	1500	1577.000	3270.000	1450	3045.000	3616.000
1650	507.900	1257.000	1610	783.900	2756.000	1500	3882.000	4785.000
1700	5.465	66.670	1620	904.700	3828.000	1610	169.200	590.600
1710	10.820	124.700	1630	33.230	305.600	1630	56.160	460.100
1720	11.040	25.130	1640	290.300	1295.000	1640	29.940	276.000
1730	4.998	64.200	1650	1351.000	3294.000	1650	1275.000	3712.000
			1700	1214.000	2197.000	1700	726.300	2530.000
			1710	227.300	970.900			
			1720	14.760	190.400			

Station 1 n=35			Station 1 n=35 (continued)			Station 2 n=29 (continued)		
1100	299.300	754.800	1523	0.001	0.569	1330	10.640	117.400
1110	186.900	869.300	1535	5.093	45.690	1340	53.920	310.300
1118	219.400	1060.000	1543	0.303	2.171	1341	6.726	64.110
1130	393.100	1170.000	1620	357.500	1119.000	1400	258.400	548.900
1142	3217.000	5067.000	1633	18.830	158.200	1401	537.500	1199.00
1152	1896.000	3111.000	1640	0.436	4.283	1410	100.700	460.100
1200	4381.000	6489.000	1650	0.370	5.501	1413	791.300	1228.000
1210	4493.000	6132.000	1700	107.800	681.900	1420	1068.000	2138.000
1220	291.400	1274.000	1710	0.936	23.580	1430	1336.000	3140.000
1230	3653.000	5612.000	1725	97.430	284.000	1435	2211.000	4411.000
1240	683.500	2387.000	1730	14.520	143.800	1440	1783.000	2888.000
1317	443.100	1018.000	1740	9.853	98.470	1500	5700.000	8256.000
1332	64.210	491.800	1803	80.500	478.200	1510	2.649	33.640
1340	21.770	186.600	Station 2 n=29			1520	4.376	105.100
1348	28.560	255.300	1210	1396.000	2720.000	1610	96.090	642.000
1355	63.500	314.400	1220	941.800	2244.000	1615	150.200	903.200
1410	11.060	79.920	1230	1246.000	3638.000	1620	267.400	2120.000
1420	302.100	1091.000	1240	566.400	2087.000	1630	36.540	435.400
1430	694.400	1908.000	1250	671.200	1756.000	1640	7.709	81.060
1440	842.300	2544.000	1300	1323.000	2463.000	1650	4862.000	3926.000
1502	1107.000	2122.000	1310	30.610	260.800	1700	767.600	3017.000
1510	1176.000	2557.000	1320	554.500	943.300			

TABLE A-IV (continued)

Z, mm^6-m^{-3}, and R, x 10^{-3} mm-hr^{-1}, Values for 27 March 1963

Station 21 n=50

Time	Z	R
1240	2526.000	4690.000
1245	2238.000	3400.000
1250	1101.000	2091.000
1255	1937.000	4421.000
1300	499.600	1283.000
1305	1951.000	3884.000
1310	272.700	1188.000
1315	493.600	1690.000
1320	72.160	423.800
1325	291.900	1024.000
1330	8.056	63.570
1335	117.600	383.700
1340	700.500	1620.000
1345	1238.000	1689.000
1350	184.900	922.600
1400	3389.000	3465.000
1410	2557.000	5433.000
1415	1983.000	3782.000
1420	4521.000	6883.000
1425	3485.000	4767.000
1430	3181.000	5887.000
1435	1196.000	2731.000
1440	893.200	1932.000
1445	1512.000	1981.000
1450	795.800	2213.000
1455	524.600	1562.000
1500	207.100	784.700
1505	1406.000	3754.000
1521	1.778	24.970
1545	0.199	3.912
1555	271.300	416.200
1600	120.600	471.200
1605	29.160	156.700
1610	563.200	881.000
1615	339.800	949.500
1620	5.638	88.420
1625	2.837	26.830
1630	41.780	377.600
1635	33.830	157.400
1640	901.700	2385.000
1645	1693.000	5120.000
1650	2539.000	4994.000
1655	9979.000	13650.000
1700	191.900	1079.000
1705	2270.000	3919.000
1710	1894.000	4701.000
1717	3859.000	6871.000
1720	1815.000	2957.000
1725	4169.000	7134.000
1730	538.100	1670.000

Station 17 n=32

Time	Z	R
1220	593.900	2352.000
1230	3365.000	4453.000
1235	3241.000	4545.000
1240	5372.000	6303.000
1245	2186.000	4291.000
1250	1899.000	4109.000
1300	1649.000	4172.000
1305	4863.000	6743.000
1310	686.300	1749.000
1315	469.600	1478.000
1320	413.800	1022.000
1330	389.600	871.800
1335	66.700	298.000
1340	465.200	1556.000
1345	400.200	1346.000
1350	1843.000	2629.000
1400	4791.000	5384.000
1410	3231.000	3853.000
1413	3783.000	3961.000
1420	1345.000	3651.000
1425	1603.000	3121.000
1440	1128.000	2618.000
1452	1868.000	3196.000
1500	6623.000	7798.000
1510	2.076	42.810
1558	22.710	114.800
1605	258.100	831.100
1620	101.200	878.700
1629	20.330	153.300
1643	766.200	2362.000
1649	1662.000	3772.000

Station 11 n=24

Time	Z	R
1225	1419.000	3188.000
1231	1124.000	2984.000
1240	1406.000	3078.000
1250	659.200	2121.000
1300	1571.000	2469.000
1310	119.000	519.000
1321	380.900	1216.000
1330	31.370	193.300
1340	69.320	392.700
1350	7.640	88.240
1400	784.200	1696.000
1413	352.300	744.300
1420	720.500	1115.000
1430	1981.000	2256.000
1440	3097.000	3309.000
1450	4272.000	6039.000
1500	1410.000	2641.000
1607	331.200	783.000

Station 15 n=31

Time	Z	R
1040	624.500	1788.000
1050	2403.000	3861.000
1100	1421.000	2385.000
1110	865.200	2228.000
1120	1212.000	2288.000
1130	1762.000	3850.000
1140	1342.000	3215.000
1150	4856.000	6625.000
1200	818.400	2250.000
1210	4677.000	3843.000
1220	168.800	1041.000
1230	486.900	1688.000
1240	1162.000	2223.000
1250	1121.000	2441.000
1255	2346.000	4640.000
1300	2627.000	3819.000
1310	38.670	211.500
1320	174.400	883.300
1330	37.030	267.800
1340	52.810	279.500
1347	458.600	881.800
1350	587.400	1891.000
1410	1156.000	2962.000
1420	2886.000	3791.000
1430	1015.000	3373.000
1440	2456.000	5889.000
1455	6830.000	7962.000
1500	255.200	695.400
1510	2.306	34.160
1519	129.000	553.900
1602	354.400	817.900

Station 11 n=24 (continued)

Time	Z	R
1611	61.440	267.900
1621	112.800	564.700
1633	10.770	85.690
1640	566.300	629.700
1650	1092.000	1732.000
1700	199.400	1093.000

Station 8 n=6

Time	Z	R
1250	552.800	1240.000
1300	3.103	31.590
1320	0.144	3.019
1340	243.500	433.900
1350	126.900	332.900
1400	748.000	582.100

TABLE A-IV (continued)

Z, mm^6-m^{-3}, and R. x 10^{-3} mm-hr^{-1}, Values for 27 March 1963

Station 18 n=42			Station 10 n= 12		
Time	Z	R	Time	Z	R
1220	1261.000	4467.000	1530	102.900	641.400
1230	1255.000	3297.000	1540	28.880	313.900
1235	4302.000	5882.000	1610	174.400	1297.000
1240	2035.000	4878.000	1620	1817.000	6025.000
1243	3060.000	6903.000	1630	717.600	2889.000
1247	2716.000	7673.000	1640	2300.000	7446.000
1251	2712.000	6193.000	1642	900.200	5638.000
1255	4450.000	6610.000	1645	3181.000	13000.000
1300	2672.000	5052.000	1655	2236.000	5009.000
1303	2555.000	5099.000	1707	8334.000	22740.000
1306	2618.000	6430.000	1710	2276.000	12210.000
1314	624.700	2380.000	1720	181.300	1246.000
1321	1116.000	4082.000			
1327	445.600	2289.000			
1328	1632.000	4390.000			
1342	524.900	1436.000			
1353	1024.000	1316.000			
1356	4566.000	6292.000			
1359	3147.000	4783.000			
1407	3385.000	4370.000			
1415	1419.000	3955.000			
1417	2639.000	4882.000			
1425	3338.000	6681.000			
1433	1966.000	5456.000			
1443	2246.000	5456.000			
1445	1150.000	2162.000			
1455	113.500	624.900			
1501	57.910	460.300			
1556	70.410	182.100			
1600	47.260	217.500			
1610	4.905	59.920			
1633	39.870	300.700			
1638	166.700	766.300			
1645	1016.000	2483.000			
1646	1114.000	3345.000			
1650	6473.000	7611.000			
1655	2599.000	4836.000			
1657	3095.000	5135.000			
1705	490.300	1404.000			
1710	2714.000	6069.000			
1721	439.900	2093.000			
1725	285.900	1109.000			

TABLE A-V

Z, mm^6-m^{-3}, and R, x 10^{-3} mm-hr^{-1}, Values for 28 March 1963

Station 6 n=20

Time	Z	R
1100	3389.000	5808.000
1115	3915.000	5808.000
1140	925.600	2876.000
1150	27.580	187.800
1210	79.400	428.400
1220	2116.000	3322.000
1230	2921.000	4995.000
1235	1174.000	2289.000
1240	3290.000	3723.000
1300	1846.000	4209.000
1310	4029.000	5683.000
1320	685.900	2059.000
1330	673.400	1083.000
1340	374.900	842.300
1350	1307.000	1900.000
1400	229.900	853.800
1440	3371.000	5203.000
1450	4523.000	8159.000
1452	12650.000	12500.000
1700	1819.000	4652.000

Station 1 n=17

Time	Z	R
1400	39.880	123.200
1510	3853.000	3226.000
1520	3152.000	2586.000
1530	1118.000	1488.000
1540	34.880	150.600
1550	302.200	639.100
1600	72.910	173.500
1854	6.376	22.010
1911	199.300	596.100
1920	77.750	657.800
1931	1925.000	2341.000
1940	774.000	1189.000
1951	805.200	1739.000
2000	8.270	146.800
2013	15.180	313.800
2032	1456.000	3720.000
2041	9.388	165.900

Station 18 n=14

Time	Z	R
1107	134.900	359.200
1120	109.800	487.400
1130	426.600	957.200
1145	134.600	375.100
1204	112.600	728.300
1217	69.240	269.100
1224	61.230	430.700
1234	125.800	458.900
1237	715.600	1096.000
1243	1464.000	2041.000
1251	64.440	247.300
1302	504.700	1290.000
1330	234.700	1034.000
1422	57.690	334.500

Station 2 n=8

Time	Z	R
1050	329.800	806.200
1100	5582.000	5384.000
1110	240.000	895.000
1150	78.650	262.200
1200	6.962	41.590
1220	46.150	237.900
1230	373.900	1129.000
1240	1436.000	2733.000

Station 4 n=16

Time	Z	R
1052	1.718	27.280
1100	151.600	725.800
1110	716.800	1697.000
1120	255.700	1622.000
1130	511.800	1359.000
1140	90.020	431.400
1150	260.200	900.700
1220	19.110	129.600
1250	691.600	2419.000
1300	2256.000	4486.000
1310	222.400	811.900
1320	63.700	318.200
1330	412.400	965.100
1340	65.160	295.700
1420	124.400	477.000
1450	136.900	574.200

Station 15 n=20

Time	Z	R
1130	456.200	1759.000
1140	52.220	527.700
1150	57.670	366.800
1205	3.791	35.030
1210	6.337	60.190
1220	6.764	69.500
1230	79.640	377.100
1240	224.900	859.000
1246	1858.000	4249.000
1250	1214.000	2098.000
1300	1.645	17.870
1310	381.900	1919.000
1320	25.040	207.500
1330	1.537	19.910
1340	4.731	51.170
1350	7.014	74.880
1400	4.516	44.140
1410	0.793	14.560
1420	5.464	53.000
1430	17.650	152.600

Station 17 n=20

Time	Z	R
1105	2081.000	4986.000
1118	270.500	1082.000
1127	378.400	1447.000
1139	167.500	944.200
1149	78.220	282.200
1209	85.460	586.600
1221	120.700	883.600
1226	98.220	604.700
1235	101.500	542.500
1239	853.000	1970.000
1242	1606.000	2905.000
1251	3526.000	5554.000
1259	95.160	610.700
1309	1775.000	3191.000
1321	8.589	74.280
1336	91.240	421.100
1349	1.821	26.260
1418	5.723	85.500
1428	91.800	743.800
1443	8.030	97.450

A. FORTRAN PROGRAMS FOR SOLVING Z AND R VALUES AND THE CONSTANTS OF THE Z-R EQUATIONS AT STATIONS

For future studies, one can save valuable time in computing the constants A and B at stations by using the following computer programs written in the FORTRAN language.

The data required for use of the first program includes the date, the station number, the time of the filter paper exposure, the exposure duration of each filter paper in seconds, and the numbers of raindrops in each 0.2 mm diameter range from each filter paper. This program solves for the Z and R value of each filter paper. For convenience, the first six columns of the punched data card indicate the year, month, and day. The data card punched as 630327 indicates 27 March 1963. The next two columns of the data card present the station number. Columns 9 to 12 show the time of exposure in PST followed by columns 13 to 15 which show the exposure duration. The next 44 columns present the numbers of raindrops in the first 11 0.2 mm diameter ranges of four columns per diameter range. The last 21 columns present the numbers of raindrops in the last seven diameter ranges of three columns per diameter range. For example, if one counted 2120 raindrops in the 0.2 to 0.4 mm diameter range and two raindrops in the 2.6 to 2.8 mm diameter range, columns 20 to 23 of the punched card and column 65 read 2120 and 2 respectively. This program will not solve the correct Z and

R value from a filter paper if raindrops have diameters larger than 3.8 mm. After entering the data cards into the computer, the computer punches the solutions on cards which include the date, time of exposure, station number, a value of Z in mm^6/m^3, and a value of R in mm/hr. The number of solution cards punched equals the number of data cards entered into the computer.

After sorting and grouping the solution cards of the first program into dates and stations, the solution cards serve as data cards for the program which solves for the constants of the Z-R equation at stations. Following a set of data cards for a station, the computer pauses and lights a panel to indicate to the operator the addition of a different set of data cards from a different station. The computer punches one solution card for each set of data cards. The solution card presents the constants A and B of the Z-R equation at each station, the station number, the date, and the variance of the array. The two programs appear in Table A-XVI and Table XVII. The statements R1 to R18 follow after Z18 but appear on the same lines as Z1 to Z18 to save space in this paper.

TABLE A-VI

FORTRAN Program for Finding Z and R Values

```
*0806

         Z1  = .8163E-4                           R1  = .345E-4
         Z2  = .2976E-1                           R2  = .1038E-2
         Z3  = .159                               R3  = .4806E-2
         Z4  = .873                               R4  = .1319E-1
         Z5  = .2892E+1                           R5  = .2803E-1
         Z6  = .8217E+1                           R6  = .5118E-1
         Z7  = .1876E+2                           R7  = .8447E-1
         Z8  = .4227E+2                           R8  = .1298
         Z9  = .7945E+2                           R9  = .1889
         Z10 = .1477E+3                           R10 = .2637
         Z11 = .2593E+3                           R11 = .3561
         Z12 = .4255E+3                           R12 = .4678
         Z13 = .6688E+3                           R13 = .6008
         Z14 = .1027E+4                           R14 = .7568
         Z15 = .1517E+4                           R15 = .9378
         Z16 = .2236E+4                           R16 = .1145E+1
         Z17 = .2969E+4                           R17 = .1381E+1
         Z18 = .4403E+4                           R18 = .1648E+1
    1    READ 100, NDA, NST, NTI, XT, C1, C2, C3, C4, C5, C6, C7, C8,
        1 C9, C10, C11, C12, C13, C14, C15, C16, C17, C18
  100    FORMAT (I6, I2, I4, F3. 0, 11F4. 0, 7F3. 0)
         Z=(Z1*C1+Z 2*C2+Z3*C3+Z4*C4+Z5*C5+Z6*C6+Z7*C7+Z8*C8+
        1 Z9*C9+Z10*C10+Z11*C11+Z12*C12+Z13*C13+Z14*C14+
        2 Z15*C15+Z16*C16+Z17*C17+Z18*C18)/XT
         R=(R1*C1+R2*C2 +R3*C3+R4*C4+R5*C5+R6*C6+R7*C7+R8*C8+
        1 R9*C9+R10*C10+R11*C11+R12*C12+R13*C13+R14*C14+
        2 R15*C15+R16*C16+R17*C17+R18*C18 )/XT
         PUNCH 200, NDA, NST, NTI, Z, R
  200    FORMAT (2X, 5HDATE=I6, 3X, 8HSTATION=I2, 3X, 9HTIME PST=
        1 I4, 3X, 2HZ=F10. 4, 3X, 2HR=F10. 4)
         IF (SENSE SWITCH 9) 10, 1
   10    STOP
         END
```

An example of a punched solution.

```
DATE=63027   STATION=8   TIME PST=1250  Z=    552.8014      R=      1.2312
```

SHOULD BE: "630327"
R.S. [illegible]
29 June '64

TABLE A-VII

FORTRAN Program for Finding Z-R Relationships

```
*0806
    1 C = 0.
      SR=0.
      SZ=0.
      SZR = 0.
      SQZ = 0.
      SQR = 0.
      D = .43429488
   10 READ 100, NDA, NSTA, Z, R
  100 FORMAT (7X,I6,11X,I2,21X,F10.4,5X,F10.4)
      C = C+1
      SR=SR+D*(LOGF(R))
      SZ=SZ+D*(LOGF(Z))
      SQR=SQR+(D*(LOGF(R)))**2
      SQZ=SQZ+(D*(LOGF(Z)))**2
      SZR=SZR+(((D*(LOGF(R)))*D)*(LOGF(Z)))
      IF (SENSE SWITCH 9)20,10
   20 B=(SZR-((SR*SZ)/C))/(SQR-((SR*SR)/C))
      A=EXPF((SZ/C-((B*SR)/C))/D)
      VAR=((SQZ-((SZ*SZ)/C))-B*(SZR-((SZ*SR)/C))))/(C-2.)
      PUNCH 200, NDA, NSTA, B, A, VAR
  200 FORMAT (5HDATE=I6, 4X,8HSTATION=I2,4X,2HB=F7.4,4X,
    1 2HA=F7.2,4X,9HVARIANCE=F7.5)
      PAUSE 13431
      GO TO 1
      END
```

An example of a punched solution

```
DATE=630327  STATION=8  B=   1.4881   A=     737.43  VARIANCE=.05622
```