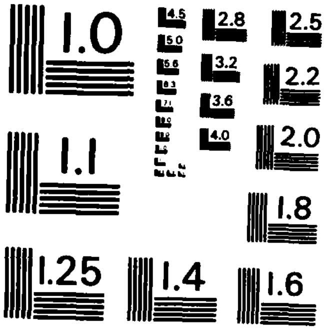
AD-A160 463 TIME DURATIONS OF RAIN RATES EXCEEDING SPECIFIED 1/1
THRESHOLDS(U) AIR FORCE GEOPHYSICS LAB HANSCOM AFB MA
R D BERTHEL ET AL. 24 MAY 85 AFGL-TR-85-0122

UNCLASSIFIED F/G 4/2 NL

END
FILMED
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(12)

AFGL-TR-85-0122
ENVIRONMENTAL RESEARCH PAPERS, NO. 918

Time Durations of Rain Rates Exceeding Specified Thresholds

ROBERT O. BERTHEL
VERNON G. PLANK

24 May 1985

ATMOSPHERIC SCIENCES DIVISION PROJECT 6670
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MA 01731

"This technical report has been reviewed and is approved for publication"

FOR THE COMMANDER

Arnold A. Barnes, Jr.
ARNOLD A. BARNES, JR., Chief
Cloud Physics Branch

Robert A. McClatchey
ROBERT A. McCLATCHEY, Director
Atmospheric Sciences Division

This document has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify AFGL/DAA/LYC Hanscom AFB, MA 01731. This will assist us in maintaining a current mailing list.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

AD-A160 463

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFGL-TR-85-0122 ERP, No. 918	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Air Force Geophysics Laboratory 6b. OFFICE SYMBOL (If applicable) LYC	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code) Hanscom AFB Massachusetts 01731	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
62101F	6670	12	06

11. TITLE (Include Security Classification)
Time Durations of Rain Rates Exceeding Specified Thresholds

12. PERSONAL AUTHOR(S)
Berthel, Robert O., and Plank, Vernon G.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Scientific Interim	FROM 1983 TO 1985	1985 May 24	34

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Rain Rate Variability Data Averaging Attenuation

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Rainfall may hamper military operations in ways as diverse as the visual detection of enemy movements to the attenuation of sophisticated, electro-optical, weapon-guidance systems. Thus, it would obviously be advantageous to have the ability to predict probable rain-rate intensities from forecast information or, for planning purposes, from climatological data.

The rain investigation detailed in this report was conducted with the objective of developing a method for estimating durations and occurrences of rates of specified intensities. Our data base consisted of 185 events taken from 31 days of rain-rate measurements. The rate variability of each event was mathematically defined and we found that the individual variabilities did not depend upon the amount of rain or the length of time rainfall occurred. Analysis revealed that variability could be expressed as a percentage of time that rain rates were equal to or exceeded specified threshold levels that were relative to their mean values and could be described by an equation set. (over)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Robert O. Berthel	22b. TELEPHONE NUMBER (Include Area Code) (617)861-2942	22c. OFFICE SYMBOL LYC

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

the author

19. Abstract (Contd)

it was

(< or =

> or =

Although the diversity of the data negated all attempts to estimate the frequency that specific rate intensities occurred, ~~we have~~ shown that averaged rain-rate data (≤ 10 min) changed predictably with relative measures. Thus, we have deduced a method by which rain-rate variability, in terms of the percentage of time the rates are ≥ intensity levels relative to their means, may be estimated from knowledge or deduction of two parameters, the mean and maximum rates.

Preface

The authors wish to express their appreciation to the individuals responsible for the operation of the rain-rate meter and the acquisition of the data used in the analyses; Mr. Anthony J. Matthews, T. Sgt. Dennis L. LaGross and M. Sgt. Stephen Crist (retired). Thanks are also extended to S. Sgt. Debra Douglass for the data reduction and Mrs. Carolyn Fadden for typing the manuscript.

Contents

1. INTRODUCTION 1
2. DATA DESCRIPTION 3
3. DATA ANALYSIS 3
4. EFFECTS OF DATA AVERAGING 19
5. FINDINGS 24

Illustrations

1. Number Distribution of Time Periods in the 185 Rain Events 4
2. Number Distribution of the Averaged Rain Rates 4
3. Number Distribution of the Maximum Rain Rates 5
4. Number Distribution of the Coefficients of Variation 6
5. Plot of $\sqrt{R_{rm}}$ vs the Coefficients of Variation for the 185 Events 7
6. Theoretical Curve Showing Number Distribution With Rain Rates 8
7. One Hour of Rain Rates Having a Coefficient of Variation of 50. 1 9
8. Number Distribution of Rain Rates From the Data Plotted in Figure 7 9

9. Rain Rates From a 41-Min Shower Having a Coefficient of Variation of 50 11

10. Number Distribution of Rain Rates From the Data Plotted in Figure 9 11

11. Percentages of Time That the Rain Rates Were ≥ R_r of 1.0, 1.6, and 2.5 for the Coefficients of Variation of the 185 Events 13

12. A Plot Showing the T_p vs R_r Mathematical Relationships That Describe the Rain-Rate Data of Figure 7 14

13. Exponents From the Percentage vs R_r Relationships of Eq. (7) for Each Coefficient of Variation From the 185 Events 15

14. Coefficients From the Percentage vs R_r Relationships of Eq. (7) for Each Coefficient of Variation 16

15. Estimated Percentages of Time That Rain Rates are Equal to or Larger Than Various Relative Intensity Levels for Specified Coefficients of Variation 17

16. Comparison Showing Percentage of Time That $R \geq R_r$ From Rain Rates of Figure 7 and Those Calculated Using Eqs. (10) and (11) 18

17. Comparison Showing Percentage of Time that $R \geq R_r$ From Rain Rates of Figure 9 and Those Calculated Using Eqs. (10) and (11) 18

18. Ten-Min Averaged Rain Rates From the Weight Data Used in the 30-sec Averaged Rates of Figure 7 21

19. A Comparison of Estimated and Measured T_p Values for Two Averaging Periods 22

20. A Plot of the Exponents of Eq. (13) for Various Averaging Intervals 24

21. Estimated Percentages of Time That Rain Rates are Equal to or Larger Than Specific Relative Intensity Levels for Various Coefficients of Variation 26

Tables

1. Time Periods Where Rain Rates $\geq$ Various R_r Levels for 1 hr of Continuous Rain on 13 August 82 10
2. Percentages of Time That Rain Rates Were $\geq$ Various R_r Levels for a 41-min Shower on 25 August 82 12
3. Standard Error of Estimates From the Comparison of T_p's From the 185 Events to the Estimates Calculated Using Eqs. (10) and (11) 17
4. Standard Error of Estimates From the Comparison of T_p's From 16 Events > 1 hr to the Estimates Calculated Using Eqs. (10) and (11) 19
5. Number of Occurrences Where $R \geq R_r = 1$ From Six Events Having Similar Coefficients of Variation and Different Times 19
6. Number of Occurrences Where $R \geq R_r = 1$ From 12 Events of 1-hr Duration With Different Coefficients of Variation 20

Time Durations of Rain Rates Exceeding Specified Thresholds

1. INTRODUCTION

The attenuation of electromagnetic energy caused by rainfall has posed problems in the operational efficiencies of many weapon-guidence, surveillance, and communication systems and continues to be a concern in those currently in design or development. Depending upon the intended use, each such system operates on a specific wavelength or series of frequencies that may show different degrees of attenuation with various intensities of rainfall. Different rain conditions may require the choosing between systems and/or frequencies to insure effective operation. The ability to predict the performance of a particular system in any anticipated rain situation would thus be advantageous.

A performance evaluation of any system requires a two-step effort with the first being the definitive knowledge of the attenuation that is experienced from using particular frequencies in respect to the absolute rain rates. This information may then be associated with real-time measurements, forecast projections, or past climatological records of operational areas to predict periods and degrees of attenuation.

(Received for Publication 22 May 1985)

The attenuation of a particular frequency can be determined by the direct measurement of the electromagnetic energy that is propagated through rain of known rates over prescribed path lengths. Since rain intensities may vary considerably within short time periods, detailed records of rain rates along the line-of-sight are essential for accurate attenuation determinations. This is not an insurmountable problem however, now that instruments are available for the high-resolution measurements of rain rates. One such device was designed and constructed at the Air Force Geophysics Laboratory and a detailed description of the instrument and the techniques used in the data reduction have been reported.[1,2]

The more immediate problem is the prediction of rain rates on which to base attenuation assessments. The most idealized scenario would be a perfect forecast of the time-resolved, rate structure of an impending rain situation. In this case, the times where attenuation becomes a problem could easily be defined by noting when the rain rate reaches or exceeds a critical intensity. This, of course, is beyond the ability of any present forecasting technique, whether it be by humans or computers. Realistically, the best that can be provided now are estimations of total rainfall, time duration, and some possible rate intensities.

Climatological records are available for most operational areas and they provide past information on the number of rain situations, total and mean amounts, and rain rates, although the listed rate measurements would, more than likely, be averaged values over long time periods of 5 min to 1 hr or more. These statistics may be used to provide gross estimates of attenuation but until a reasonably accurate, rain-rate prediction method is devised, attenuation assessments will remain inadequate.

This report describes our investigation into rain-rate variability. Our data base consisted of 31 days of high-resolution, rain-rate measurements taken at Hanscom Air Force Base (HAFB) during 1982 and 1983. The study was approached from the viewpoint of the operational commander who has to predict the efficiency of his system from forecast information and that of the engineer who has to design the most efficient system for use in some specified area whose weather history can be found in the climatological records. Both concerns can be reduced to one common question, "How often and for how long will a particular system suffer attenuation while operating in a rain situation that can only be described by forecast or climatology?".

---

1. Plank, V. G., and Berthel, R. O. (1983) High Resolution Snow and Rain Rate Measurements, Reprints of the Fifth Symposium on Meteorological Observation and Instrumentation, AFGL-TR-83-0107, AD A128296.

2. Berthel, R. O., and Matthews, A. J. (1984) Rain Rate Determinations from Electronic Weight Measurements: Instrument Description and Data Reduction Techniques, AFGL-TR-84-0212, AD A150765.

2. DATA DESCRIPTION

The 31 days of rain-rate measurements that were taken at HAFB during the summer and fall seasons of 1982 and 1983 consisted of periods of rain that varied from a few minutes to ~ 5 hr. The maximum recorded rate was 84 mm hr^{-1}.

It was decided that the data that were to be used in the analysis would only include those periods when it was actually raining measureable amounts. Thus, a trace of rain having a rate of 0.127 mm hr^{-1} (0.005 in. hr^{-1}) was designated as a lower limit. After applying this limitation, the data were divided into two categories with (1) numerous instances of rain having durations less than 1 hr and (2) 16 instances of rainfall lasting longer than 1 hr.

In the first category, no rain instance was considered for time periods of < 5 min. These cases had fewer points for statistical evaluation and were invariably those of extremely light rain and it was found that those particular conditions were amply represented by numerous cases of > 5-min duration. In the second category, the rain data were analyzed in periods of 1 hr maximum. For example, if the duration were 4 hr, it would be treated statistically as four 1-hr cases. If the duration were 4 hr 45 min, it would be treated as four events of 1 hr and one event of 45 min. (The > 1-hr time periods are discussed separately later in the analysis.)

When the measurements from the 31 days were subjected to these limitations, 185 events with time periods between 5 and 60 min were designated as the data base for analysis. Each event consisted of a 30-sec averaged[2] rain-rate reading for each 3-sec interval throughout the event period. The number distribution of the 185 events with respect to time, mean rain rate ($\overline{R}$), and maximum rate (R_m) are shown in the histograms of Figures 1 through 3.

3. DATA ANALYSIS

The objective of the investigation was to use these high-resolution, rain-rate data in an attempt to discover and/or devise the means of predicting the variability of rainfall from standard weather observations or from climatological records.

Variability can be loosely classified by describing the rain type as widespread or homogeneous with little variability, showery with moderate variability, and rates that vary considerably as in thunderstorms. A more precise measure is that of standard deviation (σ), a value that is calculated from the 3-sec rates for each particular event. When σ is multiplied by 100 and divided by the mean rate, it becomes a relative measure where σ is expressed as the percentage of the mean value as

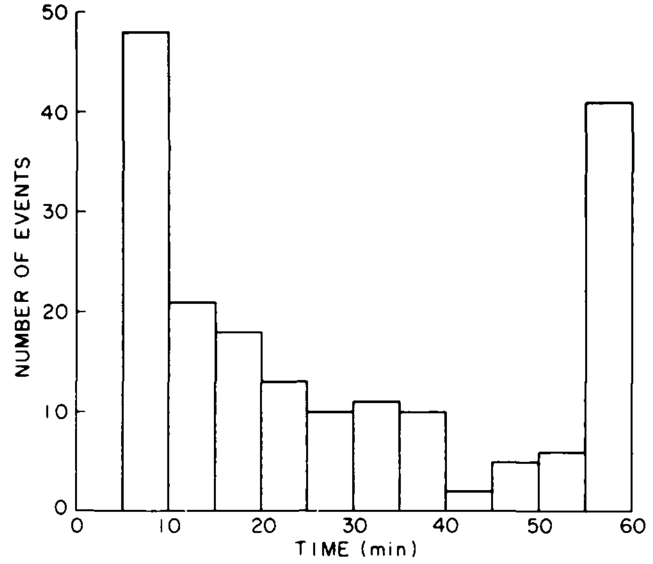


Figure 1. Number Distribution of Time Periods in the 185 Rain Events

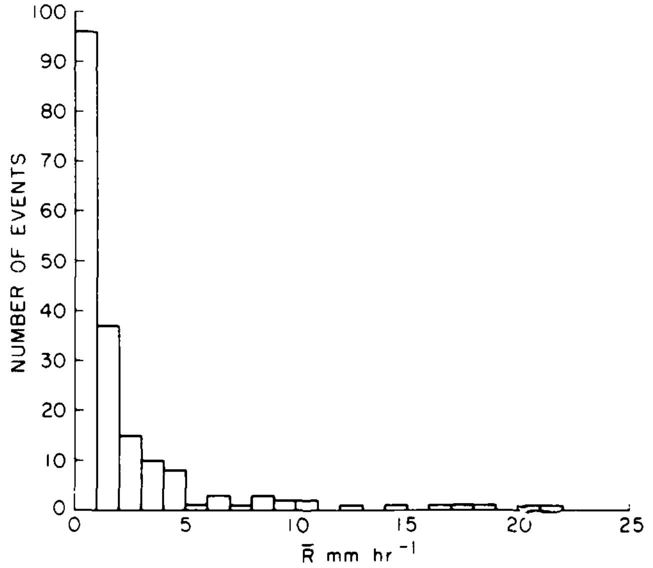


Figure 2. Number Distribution of the Averaged Rain Rates

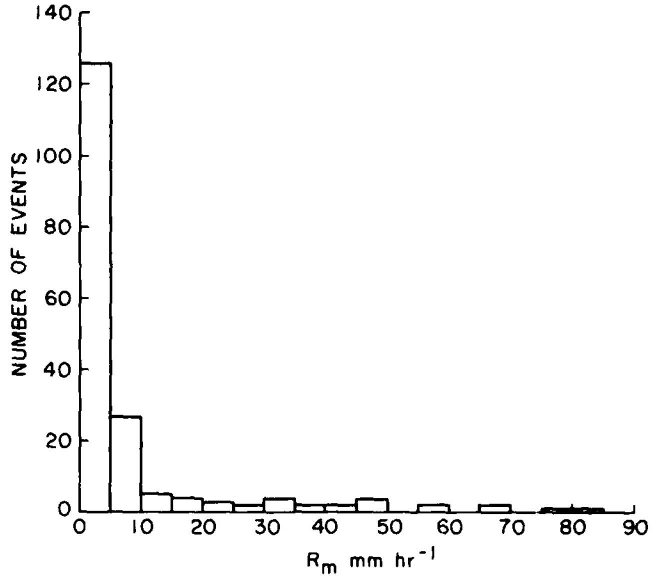


Figure 3. Number Distribution of the Maximum Rain Rates

$$V = \frac{100\,\sigma}{\bar{R}}\,\% \tag{1}$$

and is referred to as the coefficient of variation.[3] It was decided that V would give the best, unbiased description of any given rain situation with values $< \sim 60$ representing homogeneous, ~ 60 to ~ 100 the showery, and $> \sim 100$ the more diverse events. The number distribution of V's for the 185 events is shown in Figure 4.

Although V provides a mathematical definition of the rain-rate dispersion contained within a data set, that number, by itself, does not sufficiently describe the characteristics of a particular set of absolute rain intensities for use in assessing the effects of rate variability. For this, V has to be related to other parameters of the rate data and variability expressed in terms of duration and/or frequency of occurrence with respect to absolute rates.

When $\bar{R}$ and R_m were compared to V, very little correlation was evident. This suggested that amounts of rain, whether they are in terms of the average, total or maximum rates, are not good indicators of variability. However, if R_m is made relative to $\bar{R}$ as $R_m/\bar{R}$ and then compared to V, the correlation improves

---

3. Wessel, R. H., and Willet, E. R. (1963) Statistics as Applied to Economics and Business, Holt, Rinehard and Winston, New York.

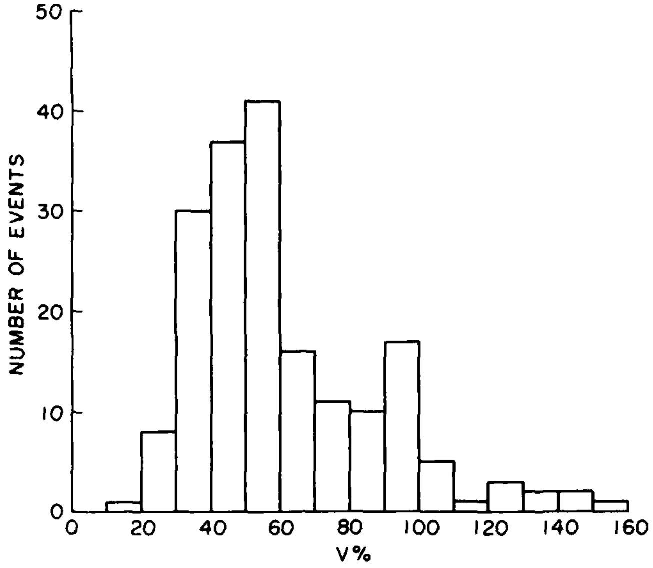


Figure 4. Number Distribution of the Coefficients of Variation

considerably. It thus became apparent that any rate-prediction scheme would have to be expressed as the relationship (R_r) of the rates (R) to their means as

$$R_r = \frac{R}{\bar{R}} \tag{2}$$

with the maximum relative rate being

$$R_{rm} = \frac{R_m}{\bar{R}} \quad . \tag{3}$$

An estimate of the R_{rm} value for a given V can be made by using the linear regression relationship of

$$\sqrt{R_{rm}} = 1 + 0.0109\ V \quad . \tag{4}$$

The plot in Figure 5 shows the $\sqrt{R_{rm}}$ and V values from the 185 events. The dashed lines indicate the standard error of estimate (SEE) limits of ± 0.074. If Eq. (4) is solved for V as

$$V = 91.7\ (\sqrt{R_{rm}} - 1)\ \% \quad . \tag{5}$$

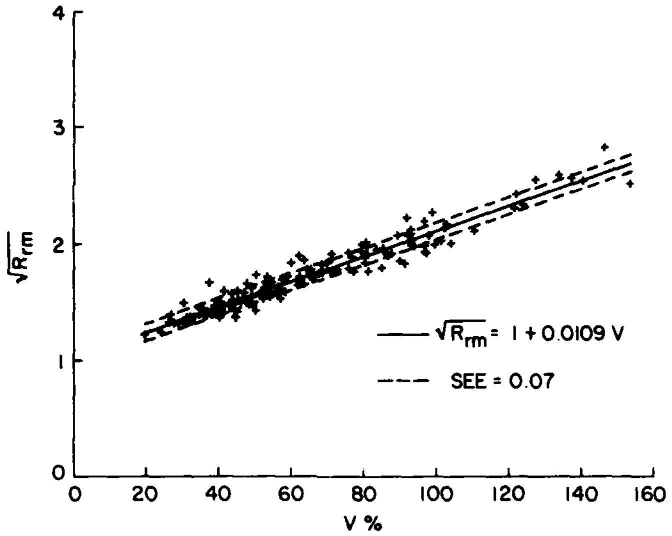


Figure 5. Plot of $\sqrt{R_{rm}}$ vs the Coefficients of Variation for the 185 Events

we now have the means to determine V from knowledge of R_m and $\bar{R}$.

R_r and R_{rm} as defined in Eqs. (2) and (3) are dimensionless ratios and are used as such in the equations throughout this report. However, they can be considered as factors of the mean value as $R = R_r \bar{R}$ and $R = R_{rm} \bar{R}$ with R having units of mm hr^{-1} when comparing relative and absolute rates as used in the following explanation of the analytical concept. (Rain rates less than their mean values are, in all probability, not germane to attenuation problems and only R_r's > 1 are considered in these analyses.)

The coefficient of variation, in that it is the relative measure of σ, is a rigidly defined mathematical quantity. When applied to a normal bell-shaped curve, 68 percent of the points in the data set will be included in plus and minus one standard deviation from the mean value. Thus, if we consider a theoretical rate distribution with a V = 50 that forms a normal curve with $R = 1.5\,\bar{R}$ being the upper σ limit, the relative rate can be expressed as $R_r = (\bar{R} + \sigma)/\bar{R}$ or 1.5. In this distribution, the values of $R = 0$ to $1.5\,\bar{R}$ contain 84 percent of the points, whereas the points $> R = 1.5\,\bar{R}$ are 16 percent of the total number. Any value of R_r can similarly be defined up to R_{rm} and the percentage larger than the level can be calculated. Figure 6 illustrates this principle and shows several R_r levels and the percentages of points that are above those values.

Experimental data seldom form normal distributions thus, some deviation from this rule can be expected. However, if one compares rain-rate events having the same V, one would expect reasonable agreement in the percentage of points

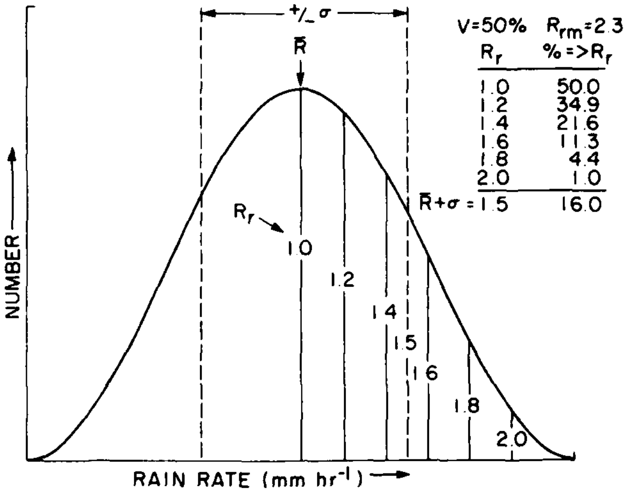


Figure 6. Theoretical Curve Showing Number Distribution with Rain Rates. The dashed vertical lines indicate ± one standard deviation and the R_r relative relationships are indicated by the solid line

within the ± σ limits. Continuing this line of reasoning, one should also find a comparable percentage of points above any level that is defined relative to the mean. Since each point of a rain-rate plot from our instrument represents a 3-sec time interval, it follows that the percentage of time that the rates are ≥ any specific R_r level should also be comparable.

Figure 7 shows 1 hr of rain rates that were determined from weight measurements obtained at HAFB on 13 August 1982. (Because of the 30-sec averaging, the total time is actually 3570 sec or 0.992 hr.) The calculated V for this event is 50.1. The horizontal lines represent various levels of R_r, where a value of 1 is the mean of the data. A trace along any of these lines will delineate the times when the rate becomes equal to and rises above that level and another when it falls below. A complete line scan results in one or more time periods when $R \geq R_r$ and the summation of the periods give the total amount of time. When time is expressed as a percentage of the total time of the event, it allows comparisons to be made between events.

Table 1 lists the specific time periods that the rates in Figure 7 were ≥ the various R_r levels. The differences in these values and those from the normal curve of Figure 6 are the effects of the "non-normal", natural distribution as presented in Figure 8.

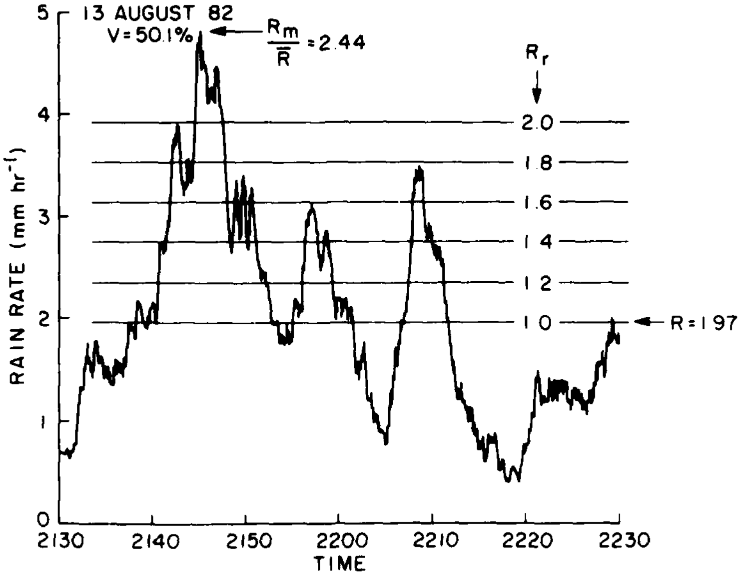


Figure 7. One Hour of Rain Rates Having a Coefficient of Variation of 50.1. The horizontal lines indicate various levels of R_r

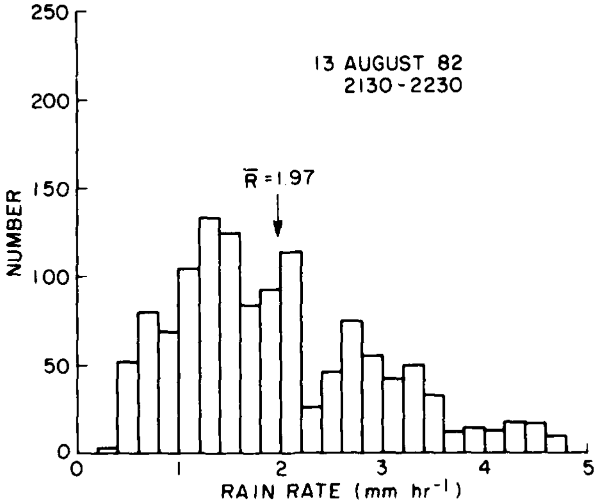


Figure 8. Number Distribution of Rain Rates From the Data Plotted in Figure 7

Table 1. Time Periods Where Rain Rates ≥ Various R_r Levels for 1 hr of Continuous Rain on 13 August 82

13 August 82	Time 2130 - 2230 (3670 sec)	
$\bar{R}$ = 1.97 R_m = 4.79	R_{rm} = 2.44	V = 50.1%
Time	sec	% of Total
2138.3 - 2139.2	50.6	1.4
2139.6 - 2153.0	800.8	22.4
2155.2 - 2201.5	387.8	10.9
2206.8 - 2211.8	297.9	8.3
1537.1 sec or 43.1% ≥ R_r of 1.0		
2140.6 - 2152.2	691.3	19.4
2156.2 - 2159.3	182.6	5.1
2207.5 - 2211.2	222.0	6.2
1095.9 sec or 30.7% ≥ R_r of 1.2		
2141.5 - 2148.4	413.1	11.6
2148.6 - 2150.1	92.7	2.6
2150.3 - 2151.2	50.6	1.4
2156.4 - 2157.8	81.5	2.3
2158.4 - 2158.9	25.3	0.7
2207.7 - 2210.0	137.7	3.9
800.8 sec or 22.4% ≥ R_r of 1.4		
2141.9 - 2148.0	368.1	10.3
2148.8 - 2149.1	16.9	0.5
2149.6 - 2150.0	22.5	0.6
2150.5 - 2150.8	16.9	0.5
2207.8 - 2209.1	75.9	2.1
500.2 sec or 14% ≥ R_r of 1.6		
2142.1 - 2143.1	56.2	1.6
2144.4 - 2147.8	199.5	5.6
255.7 sec or 7.2% ≥ R_r of 1.8		
2144.6 - 2147.5	171.4	4.8
171.4 sec or 4.8% ≥ R_r of 2.0		

Figure 9 shows the rain rates for a 41-min shower on 25 August 1982 and the distribution of the rates are shown in Figure 10. The V derived from these rates, 50, is nearly identical to that of Figure 7 although the $\bar{R}$ of that case was 2.7 times larger and the rate distribution obviously different. However, the percentages of time that the rates were ≥ the various R_r levels as listed in Table 2 are comparable to those of Table 1.

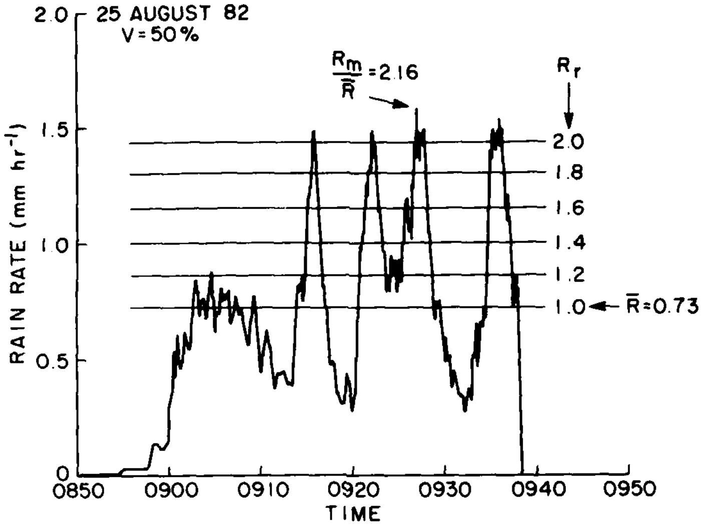


Figure 9. Rain Rates From a 41 Minute Shower Having a Coefficient of Variation of 50. The horizontal lines indicate various levels of R_r

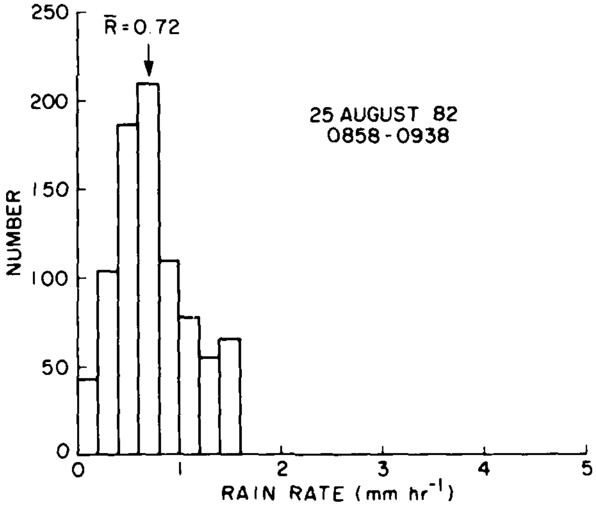


Figure 10. Number Distribution of Rain Rates From the Data Plotted in Figure 9

Table 2. Percentages of Time That Rain Rates Were ≥ Various R_r Levels for a 41-min Shower on 25 August 82

25 August 82 Time 0857:30 - 0938:30 (2456 sec)

$\bar{R}_r = 0.73$ $R_m = 1.58$ $R_{rm} = 2.16$ $V = 50\%$

R_r	Time (sec) ≥ R_r	% of Total Time
1.0	1109.9	45.2
1.2	716.5	29.2
1.4	539.5	22.0
1.6	382.2	15.6
1.8	247.3	10.1
2.0	89.9	3.7

The 185 events were processed in the identical manner as described for those of Figures 7 and 9. The percentages of time that the rates were ≥ R_r were then plotted vs the corresponding V's. Figure 11 shows the plots for $R_r = 1$, 1.6, and 2.5 The solid lines indicate the trend of the data.

The line of "best fit" for $R_r = 1$ over the range of V's from ~20 to ~160 can be described by

$$T_p = 52.7\, e^{-0.00474\, V}\ \% \quad , \tag{6}$$

where T_p is the percentage of time that the rates were equal to or larger than the mean values. If the rate distributions of the 185 events all formed normal curves, T_p would equal 50 percent for each case. The deviation from 50 percent can be attributed to "non-normal" or skewed distributions (Figures 8 and 10) and the slope of the line marking the trend in the upper diagram of Figure 11 indicates that the skewness increases with larger V's. The trend lines in the other two plots show a changing curvature with increasing R_r.

The relationship of T_p with R_r was then investigated and it was found that

$$T_p = C\, e^{-E\, R_r}\ \% \tag{7}$$

for ~ 90 percent of the R_r values or, in other words, for $R_r = 1$ to $0.9\ R_{rm}$. The remaining ~ 10 percent of R_r's, from $R_r = 0.9\ R_{rm}$ to R_{rm}, have percentages that decrease linearly to ~ 0 at R_{rm}. These relationships are shown in Figure 12 for the rain rates of Figure 7. The dashed line in this plot is the semi-log regression line derived from the T_p - R_r values from $R_r = 1$ through 2.2. The solid line shows the linearly interpolated T_p's from $R_r = 2.2$ to $R_{rm} = 2.44$.

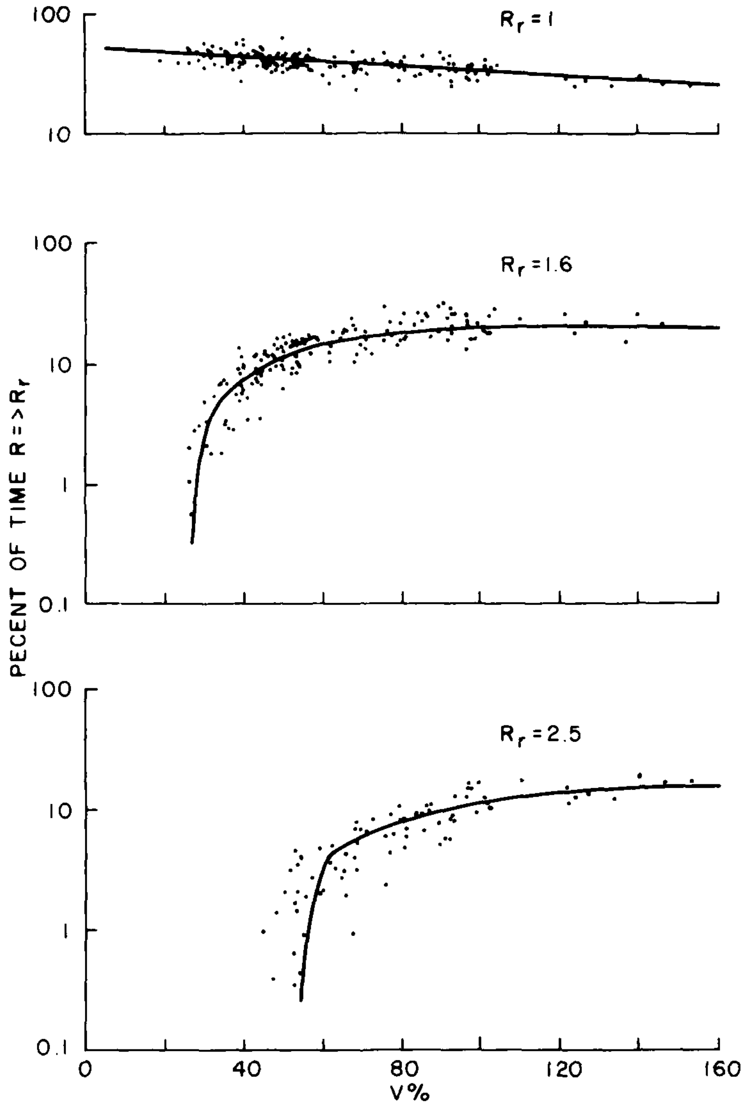


Figure 11. Plots Showing the Percentages of Time That the Rain Rates Were $\geq R_r$ of 1.0, 1.6, and 2.5 for the Coefficients of Variation of the 185 Events. The data trends are indicated by the solid lines

Although scatter was evident in both the derived E and C values of Eq. (7) for the ~90 percent R_r grouping, all of the 185 events had correlations > 0.95 with 95 of them > 0.99. When E was plotted vs V as in Figure 13, a log-log relationship of

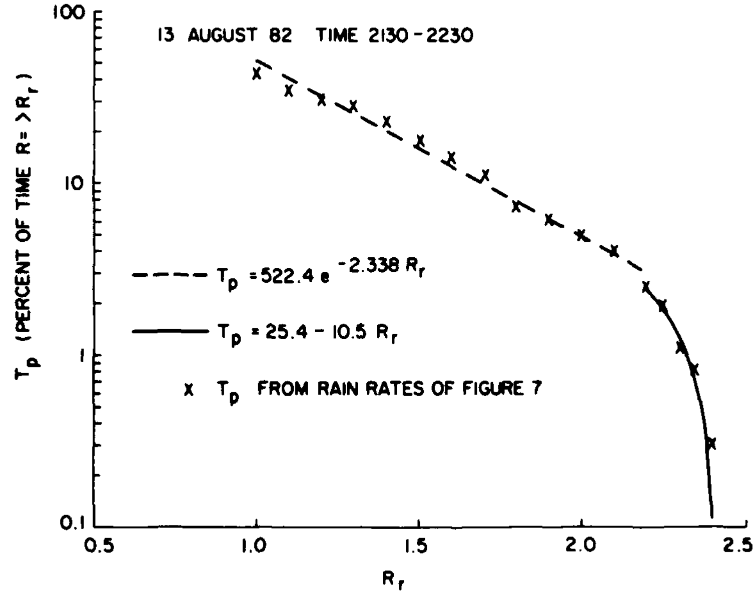


Figure 12. A Plot Showing the T_p - R_r Mathematical Relationships That Describe the Rain Rate Data of Figure 7

$$E = 437.2\, V^{-1.37} \tag{8}$$

described the data in the best manner and is shown by the solid line. The dashed lines represent the SEE of the log values, ± 0.096.

The values of C from the 185 events for the ~ 90 percent R_r grouping are plotted vs V in Figure 14. The solid line in this plot was derived by substituting Eqs. (6) and (8) in Eq. (7) for R_r = 1 and solving for C as

$$C = 52.7\, e^{437.2\, V^{-1.37}} - 0.00474\, V \quad . \tag{9}$$

The SEE (ln) for these data was 0.667.

When Eqs. (8) and (9) are used in place of E and C in Eq. (7), a general equation incorporating both V and the initial 90 percent of R_r's can be derived as

$$T_p = 52.7\, e^{437.2\, V^{-1.37}(1 - R_r) - .00474\, V} \quad \%. \tag{10}$$

The interpolated T_p values for the remaining ~ 10 percent of the largest R_r's are described by the equation

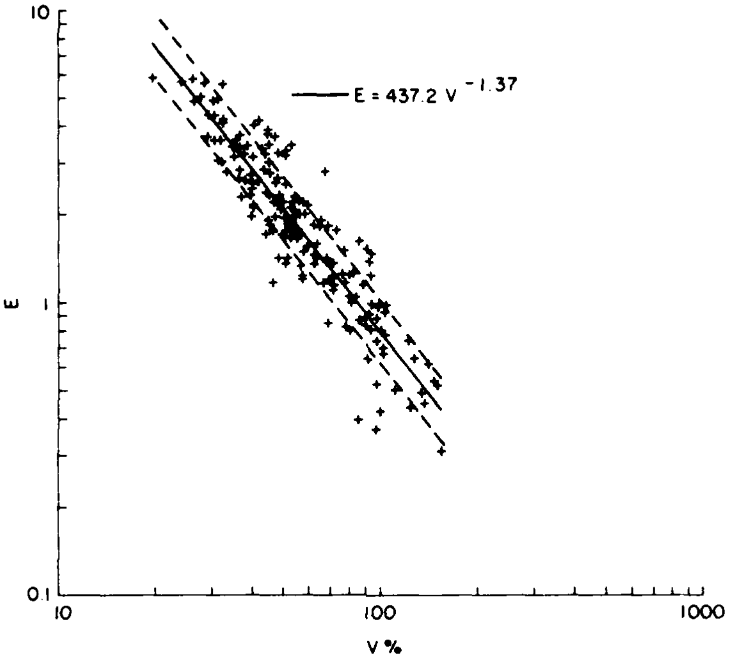


Figure 13. Exponents From the Percentage vs R_r Relationships of Eq. (7) for Each Coefficient of Variation From the 185 Events. The solid line was derived from a least-squared regression analysis and the dashed lines show the standard error of estimate

$$T_p = 52.7\, e^{\frac{437.2\, V^{-1.37} (1 - .9\, R_{rm}) - .00474\, V}{(R_{rm} - .9\, R_r)}} \% \% \qquad (11)$$

Figure 15 shows estimates T_p vs V curves for various R_r levels that were calculated using Eqs. (10) and (11). Figures 16 and 17 show the T_p's that were derived from the rain rates of Figures 7 and 9 compared to the estimated values calculated using Eqs. (10) and (11). [As a matter of interest, if Eq. (10) were applied to the upper σ limit in Figure 6 where $R_r = 1.5$ for $V = 50$, the estimated $T_p = 14.9$ percent compared to the actual 16 percent.] Table 3 lists the SEE of the empirical T_p's from the 185 events for several R_r levels when compared to the estimated T_p curves.

As mentioned previously, there were 16 days with continuous rain data ranging between ~ 1.5 and ~ 5 hr. Since these 16 events had rain rates that varied substantially throughout the time of rainfall, they were originally divided into periods with maximum times of 1 hr as explained in Section 2. The rates from each of these long-time periods were now processed as individual events to test

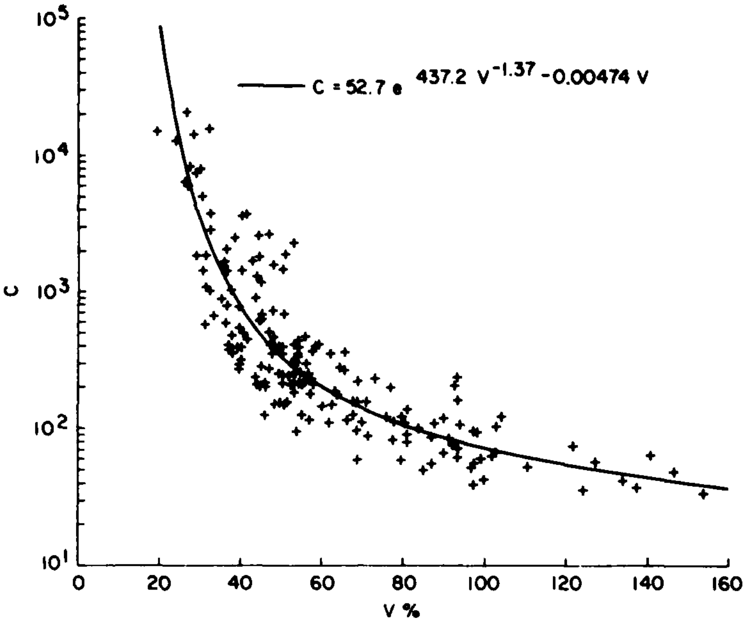


Figure 14. Coefficients From the Percentage vs R_r Relationships of Eq. (7) for Each Coefficient of Variation. The solid line was derived using Eq. (9)

the validity of the equation set for times > 1 hr. The results of this analysis are compared to the estimated values in Table 4 and show that the statistics that describe the < 1-hr rain events are also applicable to times > 1 hr.

Although Eqs. (10) and (11) can be used to predict the amount of time that the rain rates exceed specific levels of intensity, the number of occurrences during the total time period still remains a question. An occurrence, in this case, is defined as a period of time starting when $R \geq R_r$ and ending at $R < R_r$.

When one considers a normal curve with a specified V as in Figure 6, it is apparent that the total number of points in the distribution can be raised or lowered (changing the values of the y axis) with no effect on the total percentages of time for the various R_r levels although the actual number of points will be different. This would seem to indicate that the number of occurrences where $R \geq R_r$ should increase in accordance with longer time periods for events of the same V. However, when we compared six events of similar V's (52 to 56) that ranges in time from ~ 9 min to ~ 5 hr, we found vast differences in the number of occurrences at all R_r levels. Table 5 lists these events for $R_r = 1$.

If we consider Figure 6 once again, this time keeping the total number of points constant thereby conserving the total area under the distribution curve, it is again apparent that the profile of the normal curve would become more shallow

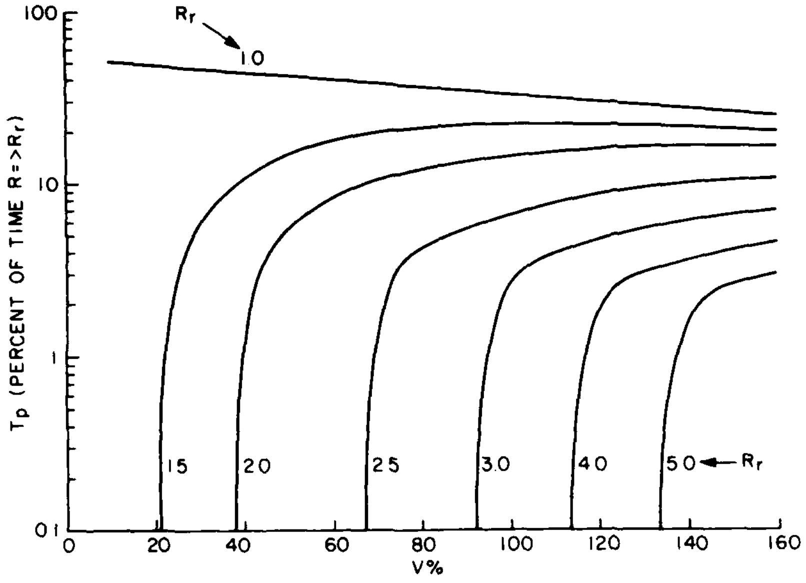


Figure 15. Estimated Percentages of Time That Rain Rates are Equal to or Larger Than Various Relative Intensity Levels for Specified Coefficients of Variation

Table 3. Standard Error of Estimates From the Comparison of T_p's From the 185 Events to the Estimates Calculated Using Eqs. (10) and (11)

R_r	SEE %	No. Used in Analysis
1.0	5.56	185
1.2	5.42	185
1.4	4.33	183
1.6	3.38	174
2.0	2.98	137
2.5	1.98	89
3.0	1.50	56
3.5	1.21	40
4.0	1.15	23
5.0	0.91	10

as V increases. Thus, one might deduce that for identical time periods the number of occurrences at any specified R_r should decrease with increasing V's. A comparison of events with identical time and differing V's shows a slight tendency towards a lower number of occurrences for the larger V's but the dispersion is so

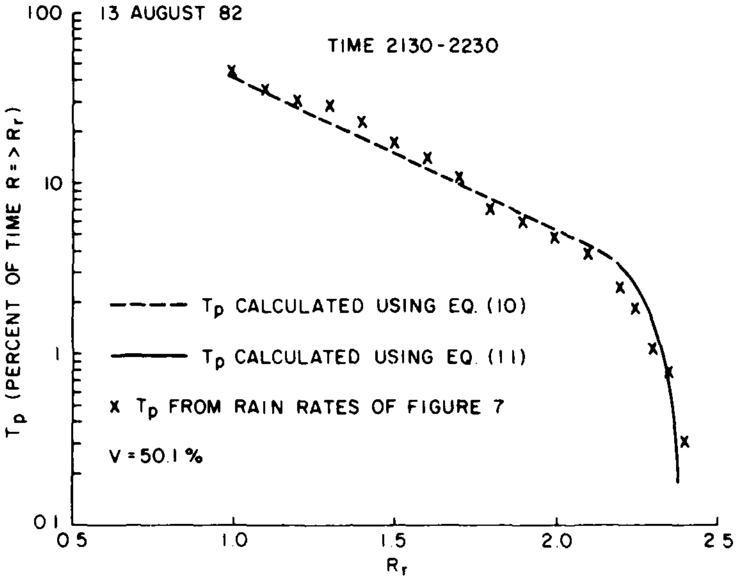


Figure 16. Comparison Showing Percentage of Time That $R \geq R_r$ From Rain Rates of Figure 7 and Those Calculated Using Eqs. (10) and (11)

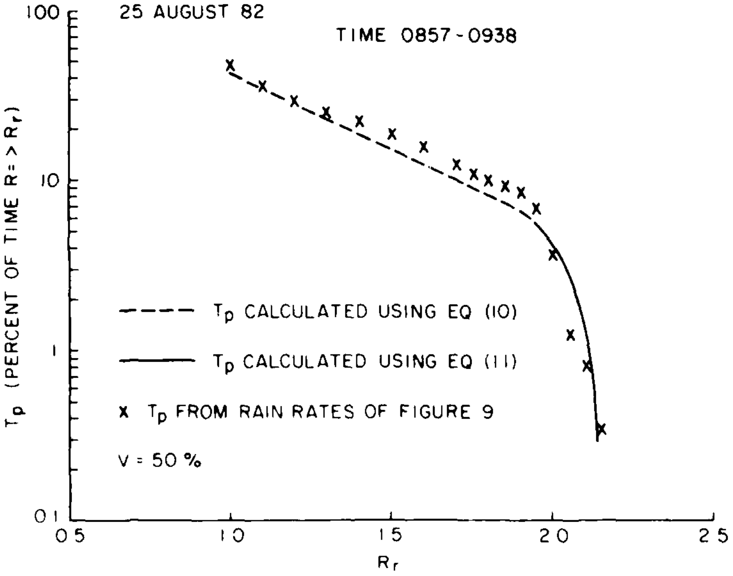


Figure 17. Comparison Showing Percentage of Time That $R \geq R_r$ From Rain Rates of Figure 9 and Those Calculated Using Eqs. (10) and (11)

Table 4. Standard Error of Estimates From the Comparison of T_p's From 16 Events > 1 hr to the Estimates Calculated Using Eqs. (10) and (11)

R_r	SEE %	No. Used in Analysis
1.0	4.16	16
1.2	4.43	16
1.4	4.07	16
1.6	3.55	16
2.0	2.98	16
2.5	2.03	14
3.0	1.33	12
3.5	0.96	8
4.0	0.74	7
5.0	0.29	5

Table 5. Number of Occurrences Where $R \geq R_r = 1$ From Six Events Having Similar Coefficients of Variation and Different Times

Date	Total Time hr min sec	V %	No. of Occurrences	T_p Where $R \geq R_r = 1$ %	T_p [Eq. (10)] %
9 August 82	9 19	56.1	6	44.0	40.4
27 May 83	21 59	52.3	15	40.7	41.1
12 October 83	56 46	56.0	5	40.8	40.4
13 August 82	1 48 31	54.1	18	38.8	40.8
20 July 82	3 20 29	55.1	79	39.3	40.6
16 July 83	4 58 28	55.9	15	46.2	40.4

great that no definite conclusion can be drawn. Table 6 lists 12 events of 1-hr duration that show this dispersion at the $R_r = 1$ level.

Because of the diversity of the data as evidenced in Tables 5 and 6, we have been unable to devise a means to reasonably estimate the number of occurrences.

4. EFFECTS OF DATA AVERAGING

As previously mentioned, the rain rates used in the preceding analyses were determined from 3-sec weight data subjected to 30-sec averaging. This averaging interval was found to be optimum for our particular rain-rate meter in that it

Table 6. Number of Occurrences Where $R \geq R_r = 1$ From 12 Events of 1-hr Duration With Different Coefficients of Variation

Date	V %	No. of Occurrences	T_p Where $R \geq R_r = 1$ %	T_p [Eq. (10)] %
16 May 83	27.5	13	46.6	46.3
16 May 83	31.3	6	50.5	45.4
26 May 83	32.4	37	48.1	45.2
26 May 83	41.6	41	47.0	43.3
12 August 83	45.1	5	45.1	42.9
12 October 83	50.9	11	39.7	41.1
13 August 82	53.6	4	44.1	40.9
9 August 82	63.6	10	37.8	39.0
12 October 83	83.8	5	30.7	35.4
28 June 83	96.9	5	28.9	33.3
12 October 83	127.5	5	27.8	28.8
12 October 83	133.9	1	25.7	27.9

reduced noise while retaining the characteristic variability of the rain data. Averaged rates from 3-sec weight data are found by

$$R = \frac{[w_{(0+\eta)} - w_{(0-\eta)}]}{A\,\rho\,\eta/600} \qquad (12)$$

where Δv is the weight ± η time increments from w_0, A is the collection area in mm^2, ρ is the density of water in g mm^{-3}, and the time between the weight readings is $2\,\eta \times 3$ sec/3600 sec hr^{-1} or $\eta/600$ hr. When w_0 advances one point at a time through the 3-sec weights and $\eta = 5$, a 30-sec running-mean (RM) averaging results. The continuous 3-sec weights may also be used to average in the more conventional manner when Eq. (12) is applied as w_0 advances in increments of 2η. Thus, the averaging period may be easily changed by varying η.

Figure 18 shows the 30-sec averaged rates as in Figure 7 and the determinations from a 10-min RM averaging of the same weight data. The closed circles are the six readings that would result from measurements made every 10 min. As averaging increases, the rate variability is suppressed and substantial differences may be present in the values of the minimum, maximum, and V. The 30-sec RM values divided by the 10-min RM in this figure give a V ratio of 2.36, a minimum rate ratio of 0.44, and 2.35 for R_m ratio.

The determination of precipitation rates from electronic-weight measurements has a decided advantage over other rate measuring methods in that rate values from any desired averaging interval may be easily calculated from the 3-sec data base. In comparison, one other widely used instrument, the tipping-bucket gauge, records when the bucket fills to a specified capacity and dumps the

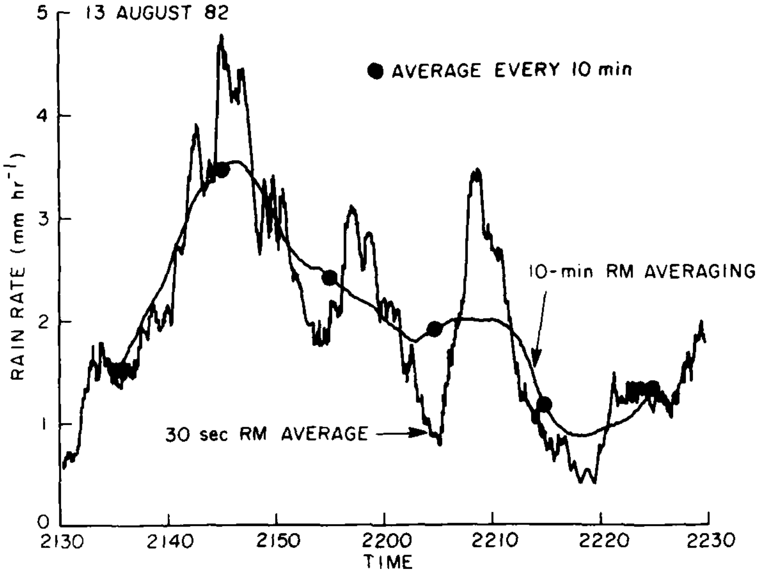


Figure 18. Ten Minute Averaged Rain Rates From the Weight Data Used in the 30-sec Averaged Rates of Figure 7

collected water. This gives time periods with considerable differences in light and heavy rain situations. Thus, the recorded rate data from these type measurements are already averaged over varying, non-consistent time intervals with long periods in light rain conditions and short-time intervals in heavy.

Accurate averaging may be of considerable importance in the determination of attenuation. For illustration, we can consider the rate profiles in Figure 18. The rate at any given time on the curves in this figure represent the amount of rainfall at some particular point on the earth's surface that is centered along a path length defined by the wind speed and averaging period. For example, if the wind velocity during this hour of measurements were a constant 1 m sec^{-1}, any 30-sec rate would represent the rainfall occurring over a 30-m distance in the wind direction. The 10-min averages would describe 600 m.

We may assume a hypothetical scenario where attenuation measurements were being conducted during the 1-hr rate determinations of Figure 18. We may further assume that the path length was a known-fixed distance parallel to the wind direction, the wind speeds were being recorded, and the rates were obtained from a rain-rate meter (our precipitation weight-measuring type) situated at mid range. With these stipulations, it is apparent that the weights could be averaged in accordance with the wind speed to produce rates that correspond to path length distances. The resulting rate structure would be that causing the attenuation.

The importance of averaging caused us to check the application of Eqs. (10) and (11) that were derived using 30-sec data for the estimation of T_p to those rates determined from longer averaging periods.

The weight data that produced the 30-sec rates of Figures 7 and 9 were averaged over various time periods from 1 to 30 min. The V's and R_{rm}'s resulting from the averaging were then used in Eqs. (10) and (11) to give estimated T_p's that were compared to the measured values. The comparisons showed reasonable agreement for averaging intervals up to 10 min as evidenced in the examples of the 2-min rates for the 13 August 82 and the 10 min for the 25 August 82 data (Figure 19). The T_p's derived from > 10-min averaging did not conform to the estimated curves and, at this time, we have no definitive explanation to offer.

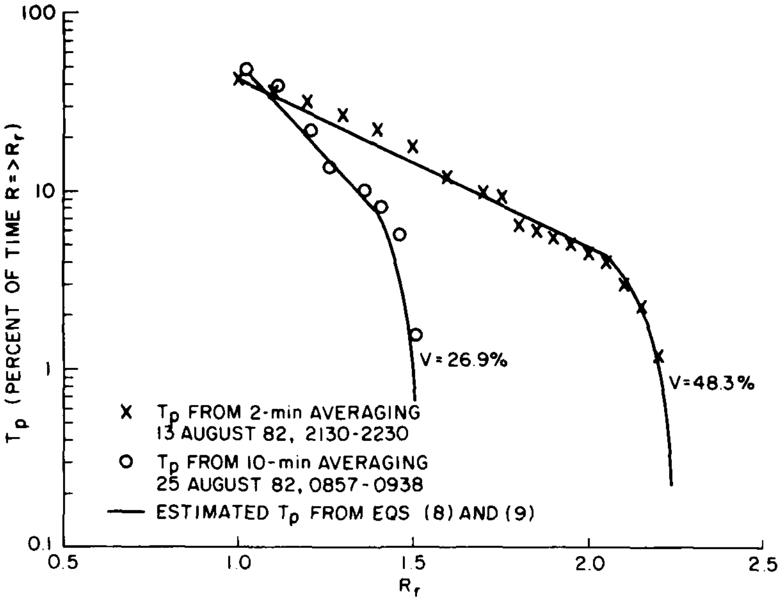


Figure 19. A Comparison of Estimated and Measured T_p Values for Two Averaging Periods

Thus, for rain rates averaged ≤ 10 min, the V, $\bar{R}$, and R_m of the data set may be used for estimating T_p. Rate data consisting of a sufficient number of points to produce a valid statistical analysis can give the values of those parameters. Hourly or 6-hr weather station measurements can not supply this information nor can climatological data. But, if one could determine V from knowledge of averaging time, $\bar{R}$ and R_m (R_{rm}), values that may possibly be deduced from forecasts or climatology, estimates of T_p may be calculated. We thus decided to investigate the differences in the signatures of rain rates averaged over various time periods.

Out of the 185 events used in the T_p analysis, 63 were > 40-min duration and gave a sufficient number of points for a statistical evaluation from 30-min RM averaging. These events were averaged at time intervals from 1 to 30-min or from η = 10 to 300 in Eq. (12). We had hoped to define changes in V and R_{rm} with averaging time or with respect to the resulting V or R_{rm} from averaging. No correlation was found.

However, when the V's and R_{rm}'s were compared, they formed linear relationships similar to the 30-sec data shown in Figure 5 as

$$\sqrt{R_{rm_a}} = 1 + E_a V_a \quad , \tag{13}$$

where the subscript "a" refers to a specific averaging period. For time intervals ≤ 10 min, the exponents of Eq. (13) (E_a) can be expressed as

$$E_a = 0.0102\ T_a^{-0.089}\ \text{min}^{-1} \tag{14}$$

with a SEE (log) = 0.007 as shown in Figure 20. T_a is the time of the averaging period in minutes. This plot also shows the non-conformity in the > 10-min averaging.

Substituting Eq. (14) into Eq. (13) yields a general equation

$$\sqrt{R_{rm_a}} = 1 + 0.0102\ T_a^{-0.089}\ V_a \tag{15}$$

that may be used to estimate the R_{rm} from the V of averaged data (≤ 10 min) or to find the estimated V of the data set when R_{rm} is known by

$$V_a = \frac{\sqrt{R_{rm_a}} - 1}{0.0102\ T_a^{-0.089}}\ \% \quad . \tag{16}$$

When Eq. (16) is applied to the 10-min RM averaged data of Figure 18 in which R_{rm} = 1.71, the estimated V = 36 vs the actual 37.1. Using the six points from the conventional 10-min averaging, the R_{rm} = 3.48/1.96 = 1.78 and the estimated V = 39.1.

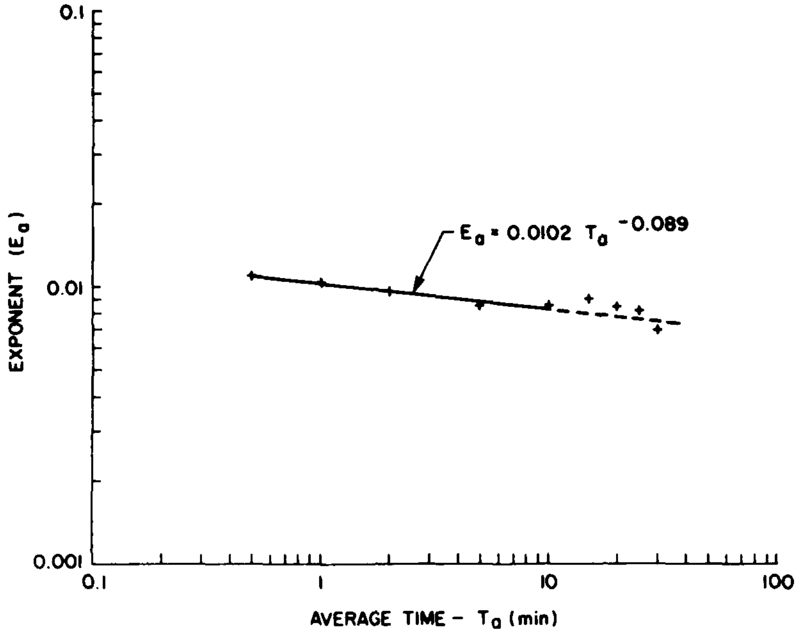


Figure 20. A Plot of the Exponents of Eq. (13) for Various Averaging Intervals

5. FINDINGS

Intensities of rainfall may vary considerably from one rain situation to another giving rain-rate profiles showing small changes over long-time periods or large changes occurring within a few seconds. Since many endeavors are affected by relatively short periods of rainfall above specific levels of intensity, such as the attenuation experienced by electro-optical sensing systems, the ability to predict some measure of the rate variability from forecast information could prove essential. Also, evaluations of system performances in given geographical areas may be possible if estimates of rate intensities could be deduced from statistical climatological information.

The rain investigation detailed in this report was conducted with the objective of establishing a method to predict the durations and frequency of specified rate intensities from limited inputs such as those obtained from forecasts or climatology. Our data consisted of 31 days of measured rain rates from which 185 separate events were isolated. These events were defined and classified as to their rate variabilities in terms of the coefficient of variability (V). We found that V had no dependence upon the amount of rainfall that occurred but did change predictably with the relative measure of the ratio of the rates (R) over the mean values ($\bar{R}$) as $R/\bar{R}$. Analysis of the 185 events using various relative rate-intensity levels showed that the time the rates were equal to or exceeded the relative levels varied with V and could be mathematically modeled or described by an equation set. We also found that the relationships of the relative maximum rates and their corresponding V's varied predictably with averaging period up to 10-min time intervals.

Thus, we have deduced a method by which rain variability, in terms of percentage of time the rates are ≥ intensity levels relative to their mean values, may be estimated from knowledge or deduction of two parameters, the mean and maximum rates.

For example, if one could obtain the mean and maximum rain rates that have occurred or are forecasted to occur during a specified time period, one may apply the relative maximum rate (R_{rm}) and time interval (T_a) in Eq. (16) to estimate the coefficient of variation for that particular situation. The estimated percentage of total time that the rain rates are equal to or become larger than any relative value (R_r), where R_r is the factor above the mean, may then be determined from the plots of Figure 15 or calculated using Eqs. (10) and (11). In this scenario, one might find it more convenient to estimate T_p using the isolines of V from the plot of T_p vs R_r from Figure 21.

On the negative side, we failed to devise the means to estimate the frequency of occurrence for rates rising above relative levels. Neither could we find a method to relate the change in variability from different averaging periods.

Although the equations in this report have been developed for averaging periods ≤ 10 min, the data from longer time intervals may be used to provide less accurate values of percentage of time if one takes into account that the estimated results may be low by as much as 25 percent at the relative level of 1 to 60 percent when approaching the relative maximum level.

Finally, we recognize the fact that the rain data used in the preceding analyses were obtained at one geographical location and do not necessarily represent the particular characteristics found in other global areas. However, since we classified each rain situation using a mathematical definition of relative variability and used relative values of rain rates in the analyses, we believe that the equations presented herein may be applicable in other rain situations regardless of location.

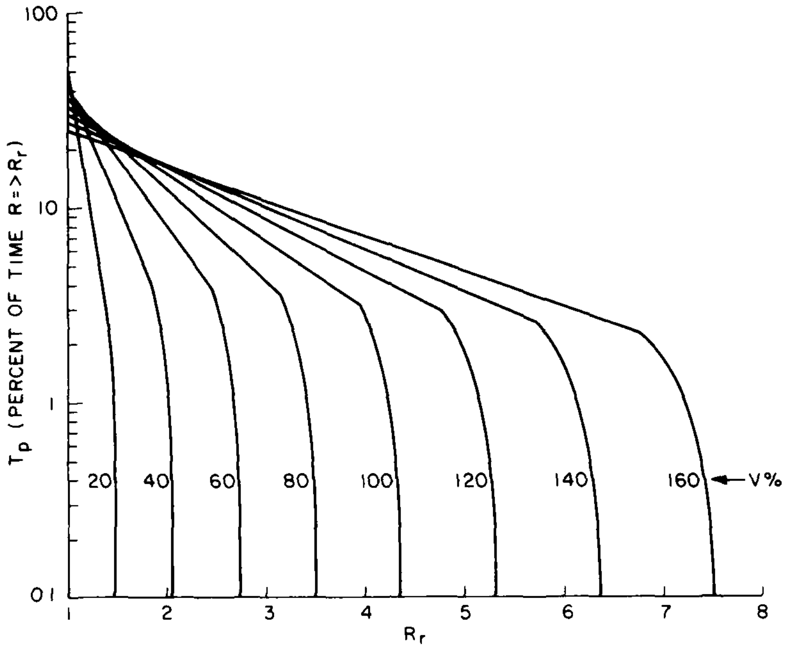


Figure 21. Estimated Percentages of Time That Rain Rates are Equal to or Larger Than Specific Relative Intensity Levels for Various Coefficients of Variation