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

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

Interim Report No. 1
1 October 1964 - 31 March 1965

Sponsored by
U. S. Army Electronics Command
Port Monmouth, New Jersey

CONTRACT NO. DA-28-043 AMC-00032(E)
DA Project No. 1V0-14501-B-53A-07

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MINERAL CONTENT OF
PUBLIC GROUNDWATER
SUPPLIES IN ILLINOIS.

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The general purpose of this contract is to determine the correlation between the amount and rate of precipitation and the intensity of the radar signal returned from the rain clouds. Detailed studies of correlations between radar signal, the amount of precipitation, and the drop spectra are being used to improve the accuracy and determine the reliability of radar-measured precipitation amounts for Army requirements.

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PURPOSE

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In addition and more specifically, the objectives of this research are:

1. To develop new techniques or to modify existing techniques that will reflect the latest results in radar research activities.

2. These techniques will include the accuracy and stability of the radar parameters necessary to achieve the desired accuracy of rainfall measurements for Army applications. Accuracy as a function of range will be stated.

3. Preliminary study to determine rainfall rates for short periods of time that cause attenuation of the 3-cm radar signal will be made with data available from raindrop spectrometers and the East Central Illinois raingage network. Rainfall rates are to be considered in measured inches or millimeters for 5-minute periods.

4. Determination of the requirements for a weather radar network within a Field Army area, based on the currently available knowledge, will also be studied. This determination will include

the number of radar sets and the spacing of the sets within an area of 150 miles by 300 miles (the smaller figure being the forward edge of the battle area), the frequency to be utilized, and the operating range of the sets.

ABSTRACT

The parameters of the log normal distribution are used to show the contributions to the rainfall rate of the number of drops, the width of the distribution, and the mode of the distribution.

The progress of a statistical study of short period rainfall rates is reported.

Drop break-up is investigated as an explanation for the large increase in the number of small drops for high rainfall rates in Miami. It is found to be an inadequate explanation.

Some preliminary results of a study to determine an adequate sample size for drop-size studies are reported.

PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

A talk was presented at the meeting of the East Central Illinois Chapter of the American Meteorological Society on the subject of drop-size studies on February 10, 1965, by E. A. Mueller and A. L. Sims.

A visit by Dr. H. Weickmann to the contractor's facilities planned for February 5 was cancelled because of adverse weather conditions.

On November 17, 1964, G. E. Stout and E. A. Mueller visited USAEL, Belmar, New Jersey, and conferred with J. R. Walsh and Dr. H. Weickmann. Research objectives on the present contract were discussed.

RADAR OPERATIONS

No routine radar operations were performed during the period. Routine maintenance for the CPS-9 radar included installing a new elevation drive motor and cleaning and recalibrating the test waveguide. Some difficulties have occurred again in the azimuth rotating Joint. At present, only one lead is bad, and this has been rerouted on another slip ring.

The azimuth data presentation system of the M-33 radar has been modified to permit remoting of the PPI scope into the radar room. This modification will be installed during the coming data collection period.

DATA ANALYSIS

Log Normal Distributions

As was discussed in the final report on SC-87280, the log normal distribution is believed to be the best fitting equation for raindrop-size distributions. This has held true for the average distributions that have now been analyzed for all of the data for Miami rainshowers, thunderstorms, continuous rain, as well as data from Majuro, Oregon, North Carolina, and New Jersey. In an effort to determine how the variables of the log normal distributions vary in nature with rainfall rate, the variables are examined individually.

The log normal distribution equation is

$$N_D = \frac{N_t}{D\sqrt{2\pi}\,\sigma'}\left[\exp -\frac{1}{2}\left(\frac{\ln D/D_G}{\sigma'}\right)\right]$$

and the parameters of this function are N_t, σ', D_G, which will be discussed in the following paragraphs.

First, the value of the total concentration per cubic meter, which has been named N_t, is self-explanatory in that it gives, as its name implies, the total number of drops per cubic meter. N_t is proportional to the height of the drop-size distribution. This parameter varies with rainfall rate as indicated in figure 1c for Miami thunderstorms. It can be noticed that the Miami thunderstorm concentration tends to be curved, or if it is considered as two straight lines, to have a break in it around 30-50 mm/hr. This does not occur so strongly, if at all, in the continuous rain. Figure 2j indicates that most of the increase in number for the Miami thunderstorms occurs in the small-drop interval. Figure 2j is a plot of the number of drops in the size class of 1.0 mm, whereas figure 2k is the number of drops in the 2.0-mm class, and figure 2l is the number in the 3.0-mm class for Miami thunderstorms. Figure 2 also shows similar data for Miami continuous rain, Oregon, and Majuro.

The logarithmic standard deviation parameter, σ', corresponds roughly to the width of the drop-size distributions. It does not precisely define the width for a log normal distribution since it is more appropriate to the width of the distribution when the diameter of the drops (abscissa) is plotted on a logarithmic scale.

Likewise, the D_G or geometric mean diameter does not properly represent the mode of a log normal distribution, but represents more properly the mode on a logarithmic plot of the diameters of the drops. With these considerations in mind, it still is approximately true that the σ' measures the width of the spectrum and D_G is a measure of the location of the spectra relative to the drop size. In the Miami thunderstorm case, the width of the spectrum tends to increase at the very high rainfall rates; that is, the σ' began to increase at a rainfall rate of about 30 mm/hr. At the same time that the width of the spectrum is increasing, the mode in general has been decreasing. This effect is due to a large increase in the concentration of small drops. The increase in small drops is not due entirely to drop break-up as discussed in another section. A similar set of curves has been plotted for other locations and for the other conditions at Miami. With the aid of these curves and derived equations for the rainfall rate from a log normal distribution, which can be obtained by assuming a terminal velocity that is proportional to the square root of diameter, the rainfall rate can be expressed as an integral,

$$R = K\int_0^\infty N_D \frac{\pi}{6} D^{3\frac{1}{2}}\, dD \,.$$

where K includes a unit adjusting parameter and the constant of proportionality of terminal velocity. This equation may be differentiated to obtain

$$R = 8.46 \cdot 10^{-3}\ N_t\ \exp \tfrac{1}{2} \left[\frac{49(\sigma')^2}{4} + 7\ D_G \right]$$

which upon normalizing by R becomes

$$\frac{\Delta R}{R} = \Delta N_t' + 12.25\, \sigma' \Delta \sigma' + 3.5\, \Delta D_G'$$

Then, in the last equation the first term of the right-hand side represents the fractional increase in the rainfall rate due to the change in concentration; the second term, the increase due to the change in width and, finally, the third term represents the increase in rate due to the change in geometric mode. Data from the aforementioned plots of the variables for the log normal distribution were inserted into the equation to determine the values in table 1. In this table, the values represent the percentage of increase in rainfall rate that is attributable to each of the variables in question. It is interesting to note that there are appreciable differences between different types of rainfall. In some cases, the total percentage changes do not add up to 100 percent, and this must be attributed to inaccuracies in choosing line fits for the data.

The surprising fact in table 1 is that at some locations increases in rate are accompanied by decrease in the mode of the distribution. A physical basis for this shift has been suggested by Dr. H. Weickmann, in that the shift might be due to more rapid activation of condensation nuclei without a sufficiently long growth period to allow the drops to become large. This suggestion will be pursued in detail during the next period.

TABLE 1

CONTRIBUTIONS TO PERCENTAGE RAINFALL INCREASES
ATTRIBUTABLE TO THE LOG NORMAL PARAMETERS

Location and Rain Type	Percent Fractional Rate Increase								
	Low Rate			Med. Rate			High Rate		
	N_t	D_G	σ'	N_t	D_G		N_t	D_G	σ'
Florida Thunderstorms	54	51	0	93	15	0	93	-45	58
		R < 14			14 < R < 50			R > 50	
Florida Rainshowers				65	30	0			
				All rates					
Florida Continuous Rain	81	20	0				71	28	0
		R < 20						R > 20	
Oregon (All rain types)	51	48	0				141	-40	0
		R < 10						R > 10	
North Carolina (All rain types)	59	40	0				111	-10	0
		R < 30						R > 30	
Majuro (All rain types)	64	37	0				64	2	32
		R < 20						R > 20	

Rainfall Rate Statistics

A number of problems have been encountered recently which require knowledge of the statistics of instantaneous rainfall rates. One of these is the problem of attenuation by rainfall of both radar signals and communication signals. Instantaneous rainfall rate is a paradox because, when carried to very small area and time considerations, there is either a very high rate (a raindrop is contacting) or a rainfall rate of zero (no raindrop is contacting). Obviously, these extremes cannot be profitably used. In the past, some rainfall studies at the Illinois State Water Survey have used 1-minute rainfall amounts or rates. However, the gages are subject to inaccuracies in amount recording, in the clock drives, and in the reading of the charts, particularly with regard to the time scale. These inaccuracies, while negligible for many purposes, are greatly accentuated for periods as short as one minute. Also, since the clock errors are not linear with time and are not the same on all gages, the 1-minute rate determined from one gage may not be relatable to the surrounding gages. It has been decided, therefore, to use time periods of 5 minutes for this study, all rainfall rates are being calculated on the basis of 5-minute amounts.

Since the attenuation of a radio signal varies with the path length through the rainfall as well as the rate of rainfall, the statistic of $\int R \cdot ds$, where R is the rainfall rate and s is the horizontal distance through the rainfall, is being investigated. It is desired to process rainfall rate data to determine the frequency distribution of $\int R \cdot ds$, and to examine these frequencies for a possible relationship to the rainfall rate frequencies for a single gage in the same area.

In the data analyses, raingage charts are read on a Benson-Lehner chart reader. This chart reader semi-automatically reads the curvilinear raingage charts and produces an output of the raingage amounts and the times of significant rate changes. These cards are processed by a computer to provide 5-minute rainfall amounts to hundredths of an inch. These amounts serve as input data to the frequency analysis programs.

The source of data for network studies of $\int R \cdot ds$ is the East Central Illinois (ECI) Network, a 7 x 7 array of gages on a nearly square grid with 3 miles between gages, from which 5-minute rainfall rates can be determined. Inquiries have been made for available 5-minute rate readings from other networks.

Currently, the progress consists of two programs which perform the initial frequency calculations on rainfall data. One program is operating which calculates the frequency of rainfall rate at a single point, or the mean frequency of several gages simultaneously. This program has been used to process data from: a) a single gage at Miami, Florida, for the period August 1957 to August 1958, and b) the ECI Network for June 3-13, 1964. The results with the Miami data are plotted in figure 3. The ECI Network data was processed primarily for program testing purposes and to obtain data for comparison with the $\int R \cdot ds$ frequencies calculated from the same data.

A second program to calculate the frequency of $\int R \cdot ds$ is currently being developed. The near-square grid pattern of the ECI Network yields almost straight line paths over 4 or more gages in eight azimuthal directions: 22°, 48°, 67°, 82°, 111°, 137°, 156°, and 173°. The spacing between gages in a line has been considered equal. Program changes are being made to correct for the small spacing Inequalities. Occasionally, because of gage malfunctions, data from a gage In a line are missing. Calculations thus far have assumed these missing points to have no rain. This assumption Is, of course, unrealistic, and further program revisions are being written to properly correct for the missing data points.

Once the rainfall data has been satisfactorily reduced to frequency tables, two other programs will be written to analyze the results. One will be a program to test the significance of variation of radial direction on frequency, and possible to predict an azimuthal direction along which the frequency of high $\int R \cdot ds$ values is greatest. The second will be a program to test the relation of line frequency against point frequency.

<u>Drop Break-up</u>

In order to investigate the Increase in the number of small drops at higher rainfall rates at some locations, a study of the effects of drop break-up was performed. Since in a drop break-up the total mass is conserved, transformation of the log normal diameter distribution to an equivalent log normal mass distribution is convenient. The necessary transformation is

$$N_M = N_D \frac{dD}{dM}$$

and

$$M = \frac{\pi}{6} D^3$$

This transformation results in the following:

$$N_M = \frac{N_t}{M\sqrt{2\pi}\,\sigma'_M} \exp -\frac{1}{2}\left(\frac{M' - M'_G}{\sigma'_M}\right)^2$$

where

$M_G = \frac{\pi}{6} D_G^3$ = **geometric mean mass**

$\sigma'_M = 3\sigma'_G$ = **geometric standard deviation**

M = mass of a drop in milligrams

N_M = number of drops per cubic meter milligram

and the prime (') indicates natural logarithm.

As an example, the average curve for Miami thunderstorms for a rainfall rate of 100 mm/hr is transformed to an N_M curve. The original fitting equation is:

$$N_D = \frac{1133}{D\sqrt{2\pi}\,(.4645)} \exp -\frac{1}{2}\left(\frac{D' - .3314}{.4645}\right)^2$$

After transformation it is:

$$N_M = \frac{1133}{M\sqrt{2\pi}\,(1.394)} \exp -\frac{1}{2}\left(\frac{M' - .4022}{1.394}\right)^2$$

This equation is plotted in figure 4. To consider the effects of drop break-up, some law of break-up must be assumed. From work by Magarvey and Taylor[1], and by Blanchard[2], a reasonable drop break-up law might be stated as; After break-up, 75 percent of the water will be in 3 equal size drops and 25 percent of the water in about 20 smaller drops. Using this law and directing attention only to the number of 1.0 mm drops (M = .524 mg), there are 288 additional drops to be supplied by break-up. This assumes that the number of natural drops of this size can be obtained by extrapolating on figure 2j to a rainfall rate of 100 mm/hr. The extrapolated number must be transformed, which results in 64 natural drops. If the total increase in number was due to the larger broken drops, an additional 96 drops of mass 2.1 mb (1.6-mm diameter) would be required. Drops this size are reasonably stable so that the additional number of 1.0-mm drops cannot be considered to be due to the larger drops in the break-up process. Consider now the smaller drops in the break-up process. The mass of the drop being broken up must be 80 times the mass of the resulting drop or a mass of 41.92 mg (4.3 mm). Furthermore, there must have been about 14 more drops of 41.92 mg mass per cubic meter than actually observed. At any height, this concentration is unlikely. Extrapolation of larger drops with rainfall rate does not show a reduction due to break-up. Furthermore, extrapolated concentrations are not this high.

It is concluded that in all probability the drop break-up does not provide for all of the large increases in the small drops as shown in figure 2j.

Sample Size Studies

During the summer of 1964, data were collected for a study to determine what sample size is sufficient to represent the rain in the radar volume. For this purpose, two drop cameras were operated approximately 100 feet apart at their maximum sampling rates. They were synchronized so that both cameras exposed frames at the same time, and 28 photographs were taken by each camera per minute. Since each frame photographs approximately 1/7 cubic meter of space, the total sample obtained per minute was 8 cubic meters recorded on 56 frames of film, 28 of these from each camera. The drop measurements from each frame are entered on a separately coded group of cards. The measuring of these data from the synchronized cameras is very near completion.

Concurrently, work has progressed on the development of techniques and computer programs for the analysis of the data, A basic program computes the equivalent sperical diameter of each drop and tabulates these diameters into a frequency distribution form. This is done on a frame-by-frame basis. These one-frame distributions are then used to calculate rainfall rate, radar reflectivity, liquid water content, and total number of drops for each frame. A table of one of these parameters is being used as the input to a statistical analysis sub-program, which is still under development. At this time, it begins by computing a least-squares linear regression for rainfall rate versus time, with time as the independent variable. This is done for the data from each camera for one minute (28 frames). Each rainfall-rate measurement is then divided by the value from the regression equation for the corresponding time. This gives a normalized set of data that has a mean of approximately one and has the one-minute average trend of the data removed. These 56 normalized measurements of the rate

(28 from each camera) are then considered as measurements of the same parameter, the variations in these measurements being measurement error and short period fluctuations in the rate. Unfortunately, it is not possible to separate the two causes of variations.

The variance and mean deviation for the 1-minute set of normalized 1-frame rates are then calculated. These calculations are repeated for averages of 2-frame groups of rates, then 4-frame groups and 8-frame groups. It is planned to extend this to groups of up to 28 frames. Similar calculations can be repeated for any of the other parameters. It is expected that other computations may need to be added to the program, based on experience with this version.

It was originally anticipated that examination of the manner in which the variance of the variables reduced as a function of the number of frames in the sample would yield the number of frames required to reduce the standard error to an acceptable level. It was also anticipated that the frequency distribution of the single frame observation would be approximately normal and centered on the 56-frame average value. On the basis of one storm of July 25, 1964, the second hypothesis was proven unacceptable. In fact, the frequency distribution is almost completely random. This has complicated the analysis procedures greatly. Upon noting the nature of the frequency distribution of the 1-frame samples, attention was directed toward the statistic of the mean deviation of the samples from the sample mean. This statistic is more easily interpreted for these distributions but still does not immediately yield easily interpretable results.

In general, if two samples from a population are chosen, averaged, and considered as a single sample, the resulting frequency distribution from these amalgamated samples will have smaller variances and mean deviations. As this process of increasing sample size is continued, the resultant frequency distributions should tend rapidly towards normal distributions. This is a direct result of application of the Central Limit Theory of statistics. At present, insufficient data have been processed to evaluate the number which must be added together to yield a satisfactory normal fit, but this will be investigated. Provided eight frames are nearing normal distributions, figure 5 indicates that the variance is on the order of 0.02 to 0.04. This means that the standard deviation is on the order of 0.14 to 0.20. This can be interpreted to mean that 68 percent of the time a sample of 8/7 cubic meter will estimate the value of rainfall rate to within 20 percent of the true mean.

Still remaining are two problems for which some decisions will have to be made. First, is it statistically proper to remove the rainfall-rate trend by normalizing the data with respect to the linear regression calculated from one minute of data? One obvious case of invalidity is where the derivative of the rainfall rate changes during the minute. This will occasionally occur and probably cannot always be noticed by routine data inspection. The second difficulty concerns whether the inhomogeniety of rainfall spatially is related simply to the inhomogeniety in time. In other words, can samples from the two cameras taken at the same time be considered samples of the same parent population as are samples taken by one camera at two different times? To some extent, data from the cameras can be used to help determine how serious the assumption of equality in space and time is.

Future work with this data will allow placing uncertainty limits on the R-Z points used In obtaining the uncertainty in the radar-rainfall equation. This will allow better estimates of the reliability of quantitative radar data.

SUMMARY AND CONCLUSIONS

The log normal distribution has been found useful in examining the contributions of height, width, and mode of the drop size distribution to rainfall rate.

The short period rainfall statistics study Is progressing. The principal results of this study are yet to be obtained.

Natural free-fall break-up of drops is not considered adequate to explain the large numbers of small drops observed at high rainfall rates in Miami thunderstorms.

Very tentative preliminary results of the drop-size sample-size study indicate that an 8/7 cubic meter sample will estimate the value of rainfall rate to within 20 percent of the true mean about 68 percent of the time.

PROGRAM FOR NEXT INTERVAL

During the next interval, work will continue on these projects;

1. The study of short-period rainfall statistics.
2. The study of sample-size using the 1964 data.
3. The analysis of the drop data from the remote locations, including further examination of the changes in the distributions with changes in rainfall rate.

Also, some drop-size data will be collected in Illinois on the two synchronized drop cameras.

REFERENCES

1. Magarvey, R. H., and B. W. Taylor, 1956: Free-fall Break-up of Large Drops. J. of Applied Physics. Vol. 27, No. 10.

2. Blanchard, D. C, 1951: Experiments with Water Drops and the Interaction Between Them at Terminal Velocity in Air. Final Report Project Cirrus, Contract No, W-36-039-SC-38141, General Electric Research Laboratory, Schenectady, N. Y., pp. 102-130.

PERSONNEL

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

Name and Title	Starting Date	Hours Worked	Terminated
G. E. Stout Project Director	10/1/64	102	
Eugene A, Mueller Electronic Engineer	10/1/64	510	
Arthur L. Sims Research Assistant	10/1/64	1020	
Stanley G. Peery Electronics Technician II	10/1/64	1020	
Ronald K. Tibbetts Electronics Technician II	3/1/65	170	
Marian E. Adair Meteorological Aide I	11/1/64	850	
Edna M. Anderson Meteorological Aide I	10/1/64	1020	
Mitchell S. Budniak Research Assistant	1/27/65	163	
David E. Burns Laboratory Assistant	12/28/64	156	
John H. Dickerson Laboratory Assistant	12/21/64	268	
William W. Lowe Laboratory Assistant	10/1/64	178	1/15/65

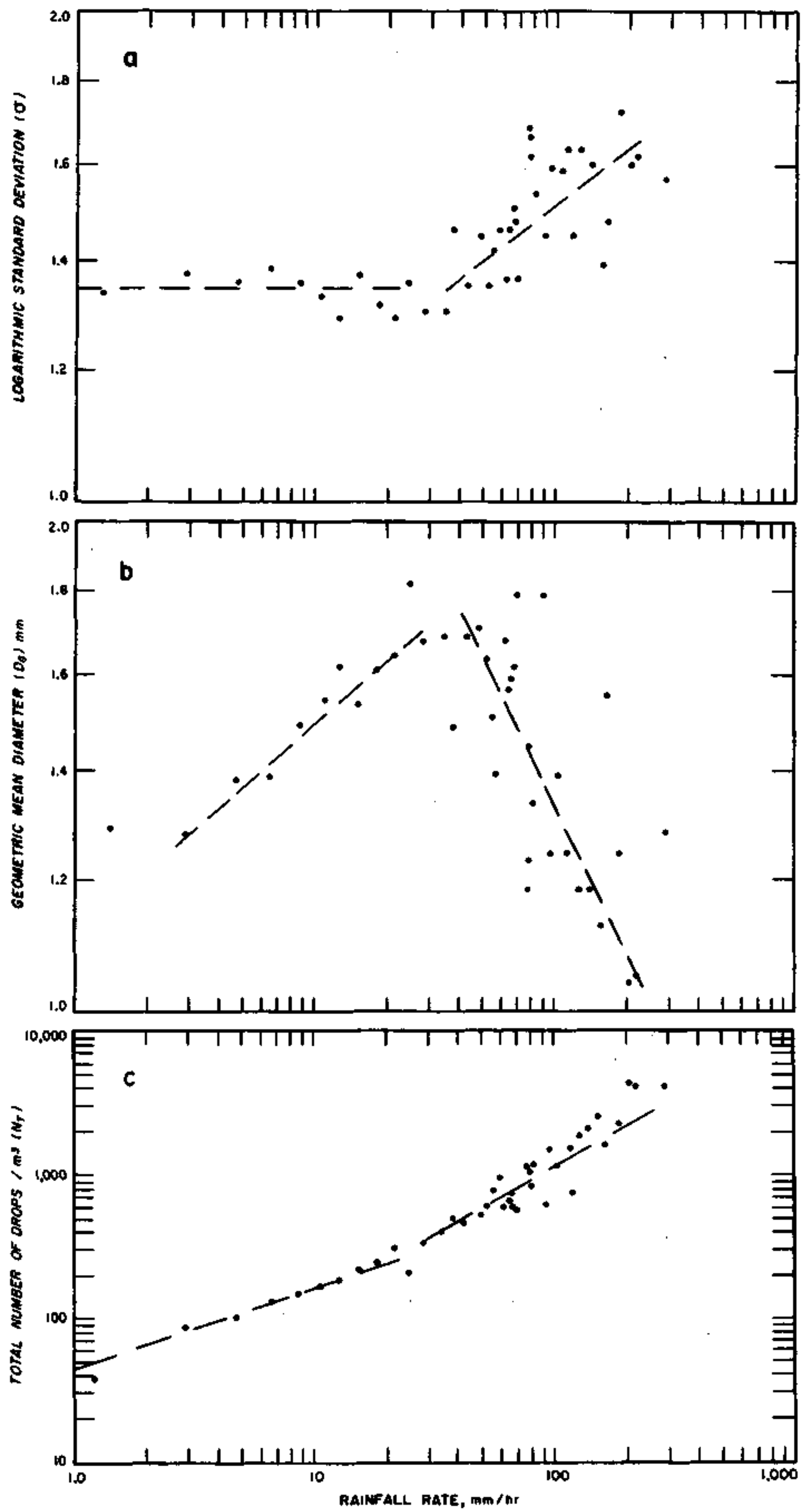

Figure 1. EXAMPLE OF DEPENDENCE OF THE LOG NORMAL COEFFICIENTS ON RAINFALL RATE FOR MIAMI THUNDERSTORMS

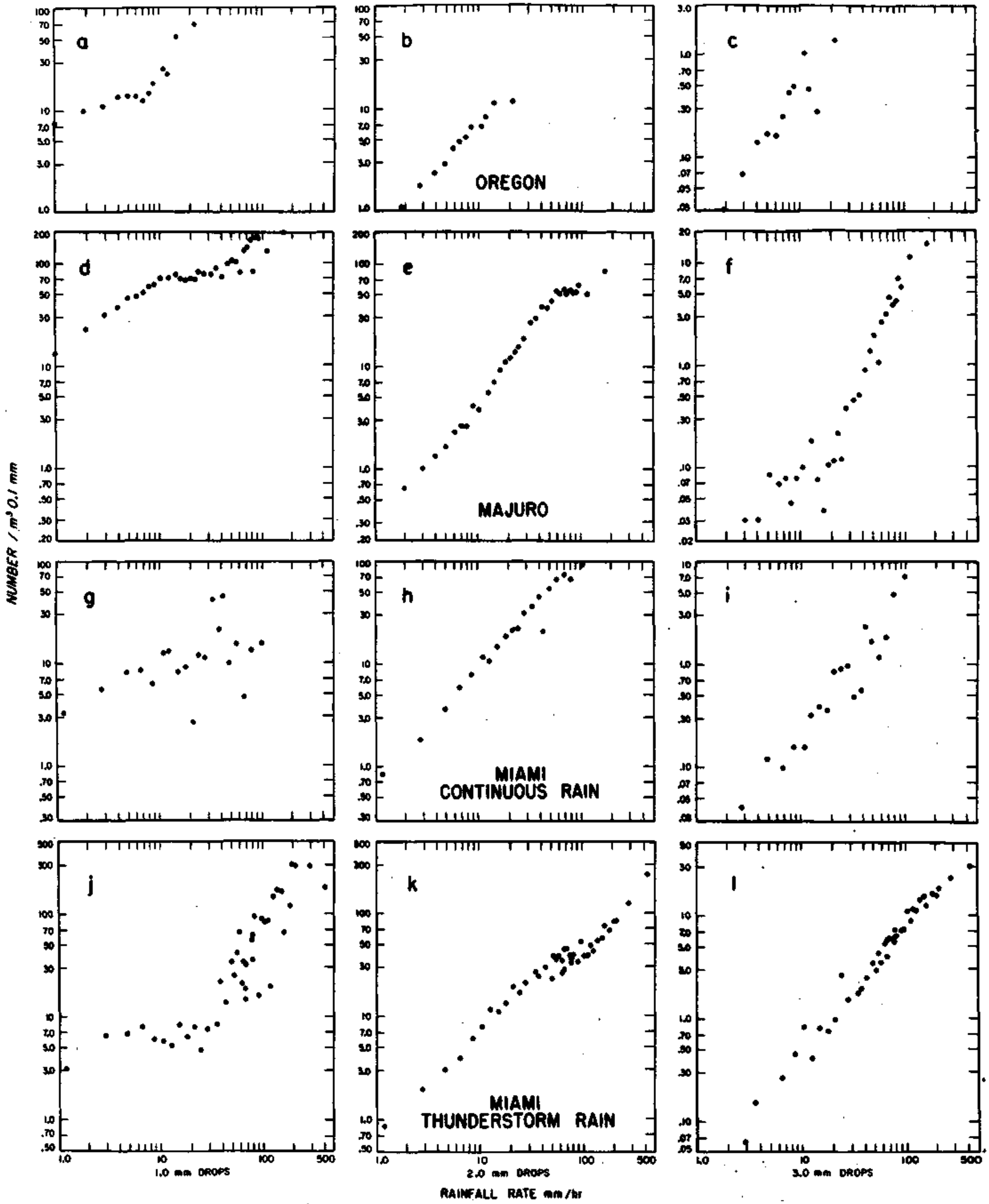

Figure 2. COMPARISON OF THE VARIATION OF DROP CONCENTRATION WITH RAINFALL RATE FOR DROP SIZES OF I.O, 2.0, AND 3.0 mm

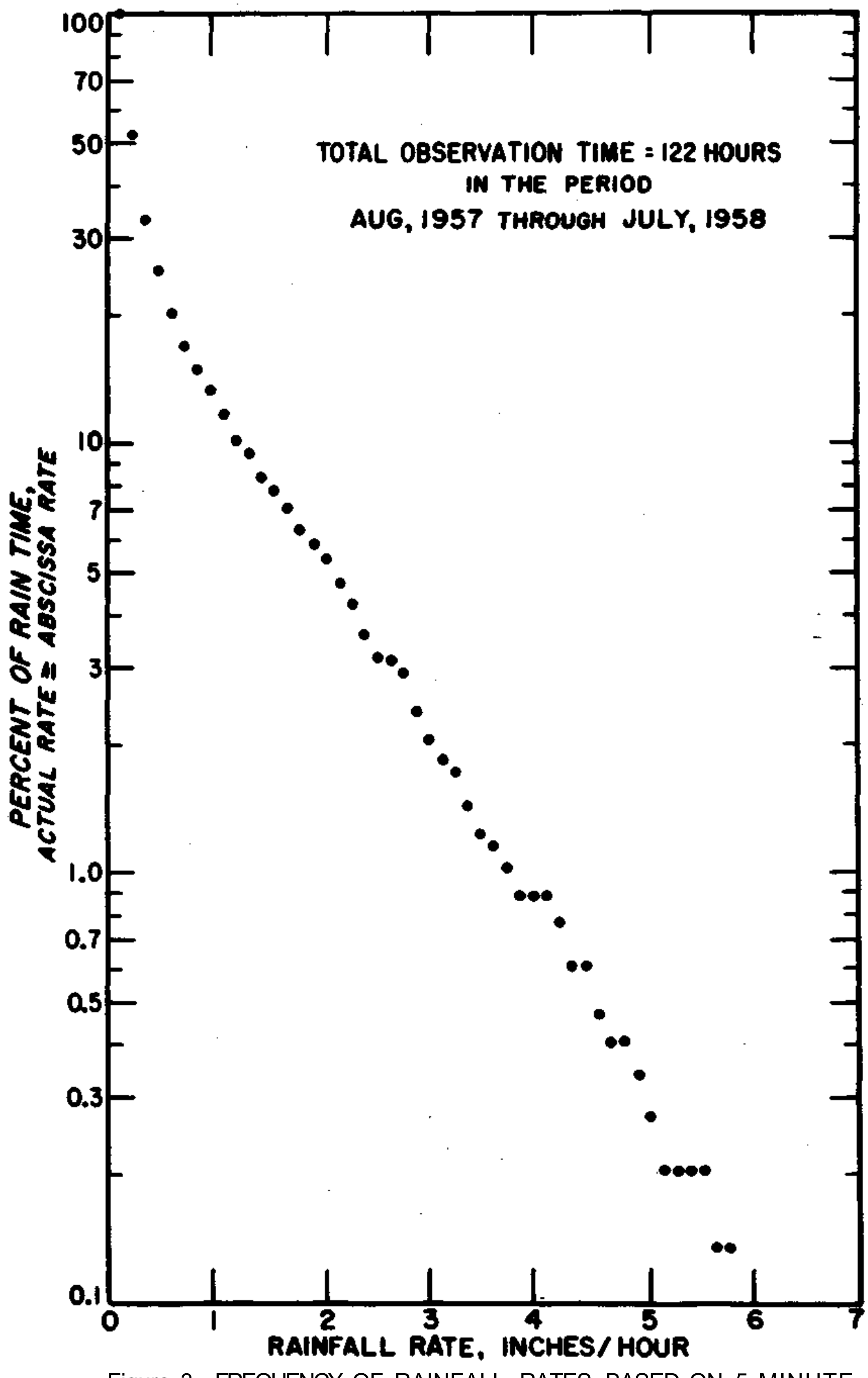

Figure 3. FREQUENCY OF RAINFALL RATES BASED ON 5-MINUTE AMOUNTS FROM MIAMI, FLORIDA

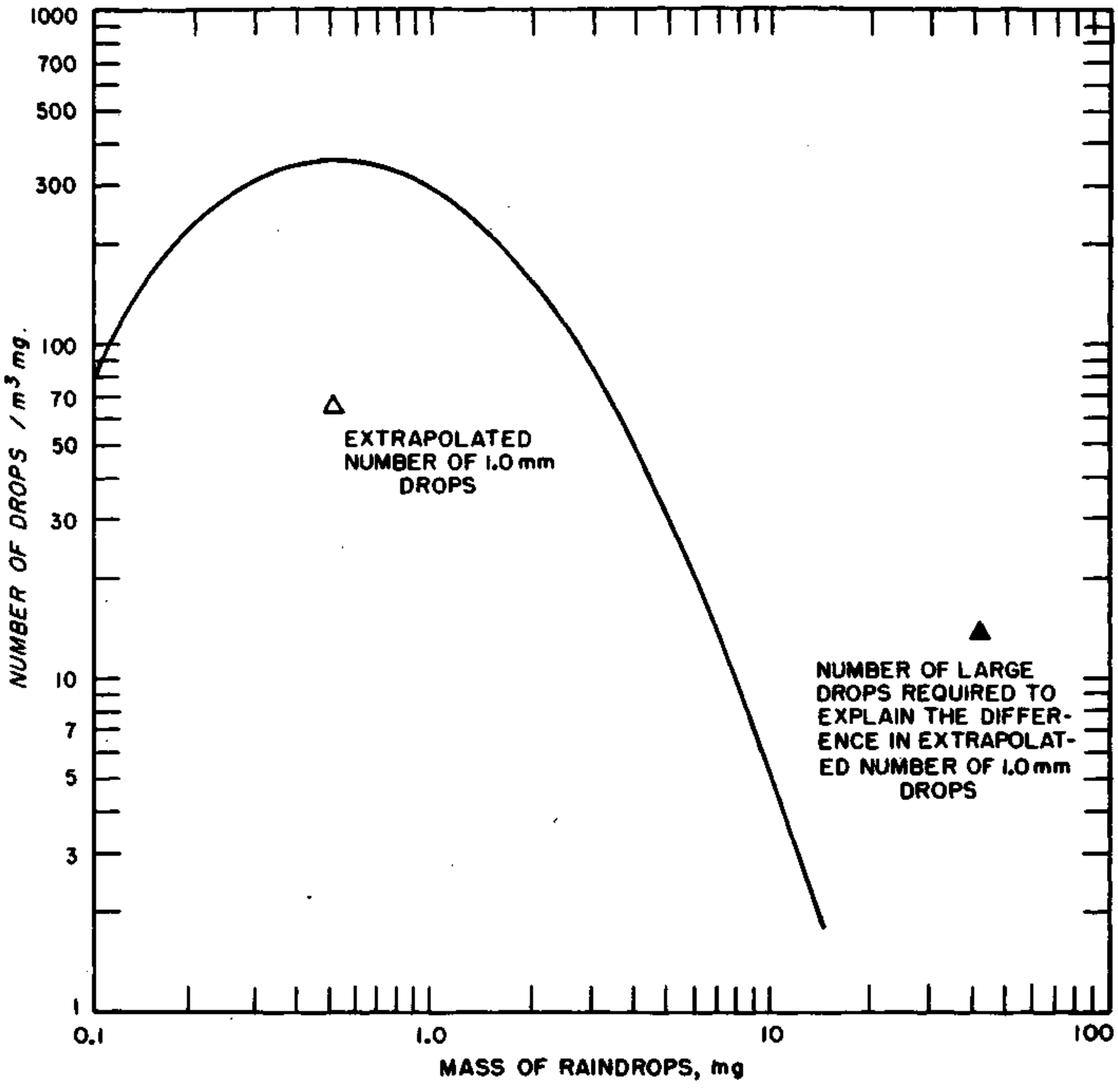

Figure 4. MASS DISTRIBUTION OF RAINDROPS FROM MIAMI THUNDERSTORMS WITH RAINFALL RATE OF 100 mm/hr

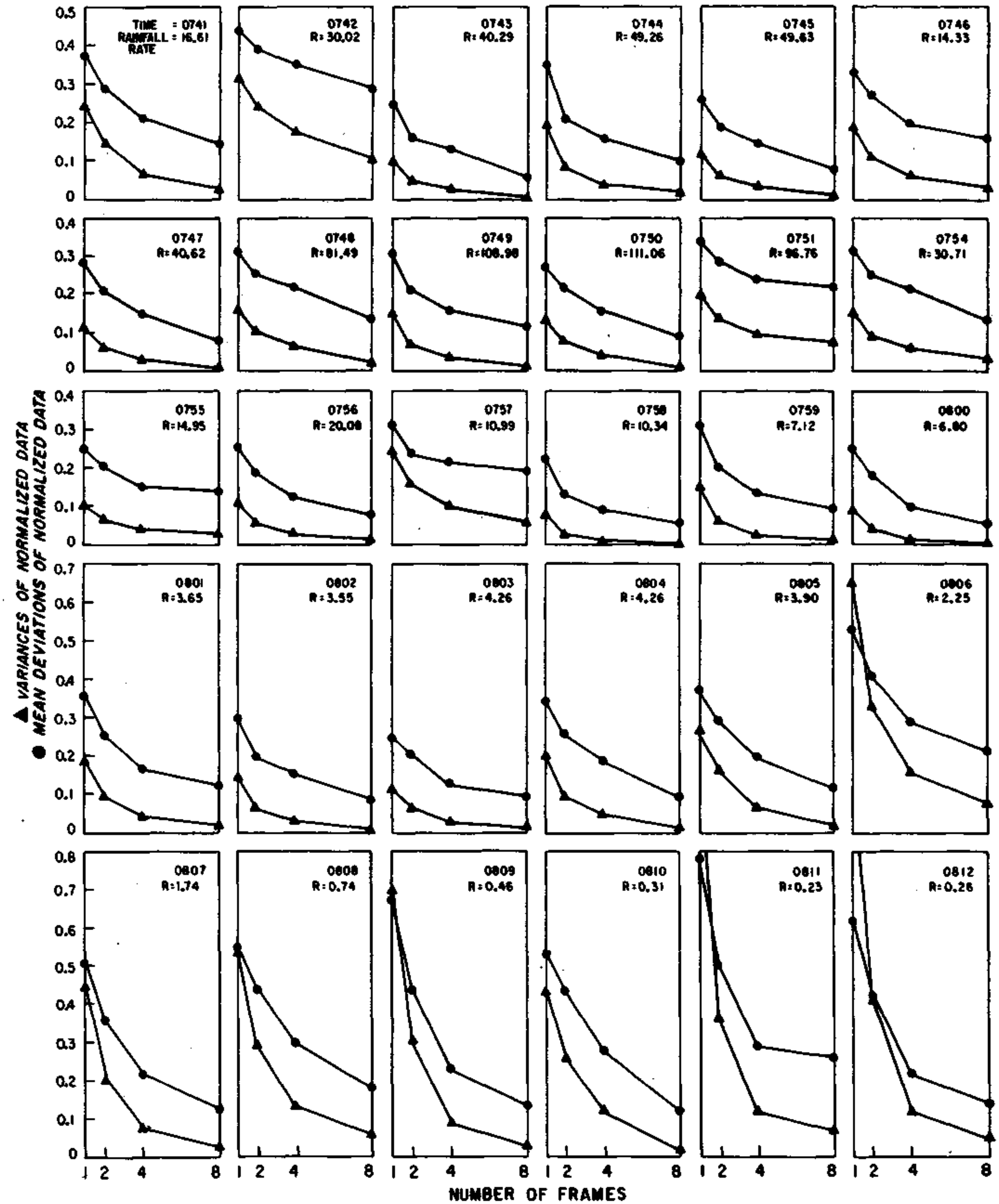

Figure 5. VARIANCE AND MEAN DEVIATION FOR DROP SIZE-SAMPLE SIZE STUDY

25 JULY 1964

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13. ABSTRACT

The parameters of the log normal distribution are used to shov the contributions to the rainfall rate of the number of drops, the width of the distribution, and the mode of the distribution.

The progress of a statistical study of short period rainfall rates is reported.

Drop break-up is investigated as an explanation for the large increase in the number of small drops for high rainfall rates in Miami. It is found to be an inadequate explanation.

Some preliminary results of a study to determine an adequate sample size for drop-size studies are reported.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Weather Research Meteorology Rainfall rate Size Distribution						

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