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DA-36-039 SC-75055

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ILLINOIS STATE WATER SURVEY
METEOROLOGIC LABORATORY
at the
University of Illinois
Urbana, Illinois

STUDY ON INTENSITY OF SURFACE PRECIPITATION USING RADAR INSTRUMENTATION

FINAL REPORT

1 April 1958 - 30 September 1961

Sponsored by
U. S. ARMY SIGNAL RESEARCH and DEVELOPMENT LABORATORY
Fort Monmouth, New Jersey

CONTRACT NO. DA-36-039 SC-75055
DA Task 3A99-07-001-01

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Signal Corps Contracts DA-36-039 SC-75055

DA Task 3A99-07-001-01

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

Prepared by

R. M. Johnson
Meteorologist

E. A. Mueller
Project Engineer

G. E. Stout
Project Director

William C. Ackermann, Chief
Illinois State Water Survey

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PURPOSE

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

ABSTRACT

The progress and results of the research accomplished during the year ending September 30, 1961, is presented. An evaluation of the streak camera as a raindrop sizing device is presented. Results of separating the raindrop data according to upper air stability are reviewed. The operations of the cameras at Island Beach, New Jersey; Franklin, North Carolina; and Mt. Withington, New Mexico, are summarized. One of the New Mexico storms which produced hail is examined in detail.

PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

Mr. E. A. Mueller installed and operated a raindrop camera at Mt. Withington, New Mexico, during July and August. The camera was dismantled and returned to Illinois on September 6, 1961.

Six papers were prepared during this period for publication. Three of these have been submitted for concurrence in printing?

Research Report No. 8 entitled "Raindrop Size Distributions with Rainfall Types and Weather Conditions" by Miyuki Fujiwara; Research Report No. 9B entitled "Raindrop Distributions from Miami, Florida"; and Technical Note No. 1 on "An IBM-650 Computer Program for Determining the Positive Area Stability Index, Precipitable Water, Freezing Level and Temperature and Height of the Condensation Level."

Three papers were prepared for publication in the Proceedings and for presentation at the Ninth Weather Radar Conference at Kansas City, Kansas. The titles of these were: "Attractive Forces Between Charged Drops and Their Effect on the Coalescence Process" by Miyuki Fujiwara and Eugene A. Mueller; "Uncertainty in Rainfall Measurements Due to Drop Size Distributions" by E. A. Mueller; and "Effects of Stability on Drop Size Distributions" by Robert M. Johnson.

Other papers prepared on this contract are; "Climatic Variations in Raindrop Distribution", E. A. Mueller, Seventh Weather Radar Conference; "Recent Observations of Unusual Echoes," E. A. Mueller, Seventh Weather Radar Conference; "Drop Size Distribution in Florida," E. A. Mueller and D. M. A. Jones, Eighth Weather Radar Conference; "Z-R Relationships from Drop Size Data," D. M. A. Jones and E„ A. Mueller, Eighth Weather Radar Conference; "An Analytical Investigation of the Variability of Size Distributions of Raindrop in Convective Storms," M„ Fujiwara, Eighth Weather Radar Conference; and "Drop Size Distributions in Oregon," E. A. Mueller and G. E. Stout.

INTRODUCTION

This final report will be restricted to work that has been accomplished on this contract since September 30, 1960. The Tenth Quarterly Technical Report, which was prepared at that time, described in detail the research during the first two and one-half years of the contract,, The raindrop camera was discussed as well as data collection and procedures for reducing the data. The status of data collection and analyses for drop size distributions for Miami, Florida; Corvallis, Oregon; Majuro, Marshall Islands; Woody Island, Alaska; and Bogor, Indonesia, was presented.

The original intent of this research was to determine how the effects of varying drop size distributions could be accounted for in the measurement of rainfall amounts by radar means. It now appears that an estimate of rainfall amounts from radar can be reduced to a reasonable level of accuracy provided that measurements of radar reflectivity can be made sufficiently accurately. This is to say that the uncertainty in estimates of rainfall amounts due to variations in the drop size spectra can now be reduced to less than 15 percent. These results have been reported at the Ninth Weather Radar Conference and the papers are included as appendices to this report.

Some effort has been expended in developing an automatic drop sizing technique referred to as a streak camera. This device, when proven satisfactory, would allow much larger samples of drop size data to be drawn and analyzed economically.

Due to the unsatisfactory results obtained with reflected light, and because water drops are known to transmit approximately 85 percent of all incident light, the principle of using transmitted light to illuminate the drops was conceived. This principle requires that the drop be located between the camera lens and the light source, and that the only light which should reach the camera lens is that light which passes through the drop,,

The light source of the resulting design consists of six 400-watt mercury vapor lamps mounted in a semi-circular reflector with the sampling zone located near the reflector'S center. There are three transformers, each operating on a different phase and each operating a pair of lamps. The three pairs consist of bulbs 1-2, 3-4, and 5-6 as shown in Figure 1.

The streaks are recorded on 35-mm film by a Bausch & Lomb 50-mm lens mounted on a strip camera that is on loan from the Air Force. Both the film advance and the shutter are operated by an electric drive motor linked through a variable speed reducer which will allow the film advance to be varied from 82 up to 230 frames per minute.

During the design stages, it was shown theoretically, by means of constructing light ray diagrams, that the illuminated portion of the drop would appear to be in the shape of a quarter moon. Figure 2 is a sketch showing this moon-shaped band and the portion of the band that is illuminated by the various lights.

To perform a meaningful evaluation of various types of films, it was necessary to artificially produce raindrops of a relatively constant size and to be able to release them in such a way that they approached their terminal velocity at the time they were photographed. Velocity was of great importance because the amount of light exposure the film receives is directly proportional to the velocity of the drop as it passes through the field of vision of the camera lens.

A device for producing drops having a diameter of approximately 2-mm was designed and constructed. The device consisted of a row of 27-gage hypodermic needles connected to a tank so that distilled water could be forced out of the needles under pressure. This device was mounted on top of an enclosed tower giving a total free-fall distance of 9 feet. It was calculated that a free-fall of 9 feet would allow a 2-mm drop time enough to reach 85 percent of its terminal velocity. The entire tower was then mounted over the sampling zone by means of guy wires.

Figure 3a is a picture of the streaks produced by the drop tower. It should be noted that the contrast is quite adequate for automatic reading using flying scanner.

Various films and processing techniques were evaluated. The best compromise for resolution with adequate contrast appears to be Tri-X Pan film developed as recommended by Eastman.

Figure 3b is a sample of streak camera data obtained in moderate rainfall. This sample was selected for the extremes that it represents. This record was obtained under gusty conditions, and it can be noted that during the time of exposure of just one frame, droplets can be seen traveling on different trajectories. Under less gusty conditions the streaks tend to be more nearly parallel so that the stretching effect due to nonvertical fall could be corrected in the analysis. The greatest angle from the vertical is about 30° which would mean an error of about 16 percent in measurement if no correction were applied.

Evidences of drop oscillation are also notable in Figure 3b, particularly in frames 1 and 4 numbering from the top. The frequency of the oscillation of the droplet in the top frame is greater than 100 cycles per second, while the droplet on frame 4 represents a frequency of nearly 10 cps.

Frame 5 is probably an example of a drop which impinged on the edges of the slit and broke into many quite small droplets. The area surrounding the intake slit is covered with fine copper mesh to reduce the effects of splashing as much as possible.

The streak camera is now installed alongside the raindrop camera and comparisons between drop size spectra will be made by simultaneous measurements.

RAINDROP CAMERA LOCATIONS

Island Beach, New Jersey

A raindrop camera was installed at Island Beach during the latter part of October 1960. After a few minor malfunctions, the camera operated satisfactorily. However, very little data were received during the first few months of operation due to the nonavailability of the operator. His primary duties were such that little time remained for the routine servicing of the cameras.

He suggested that another operator be found to replace him and in May, Mr. Warren Carlson of Point Pleasant, Hew Jersey, took over the routine service and maintenance of the camera. Since that time the camera has been operating satisfactorily and data have been arriving at regular intervals. Since the first part of June, 27 rolls of 70-mm film have been received. A total of 33 rolls has been collected at Island Beach thus far.

In the spring of 1961, a transmissometer was installed to obtain visibility measurements for the area. A malfunctioning of the receiving head resulted in its return to Chicago for repairs. This involved considerable delay and the operation of the transmissometer on a routine basis did not begin until the middle of July. Since then six rolls of visibility data have been received.

After the Island Beach data have been measured, an attempt will be made to correlate the visibility during periods of rain with the drop size distributions. In addition, the theoretical visibility will be compared with the actual visibility measurements.

Franklin, North Carolina

In November 1960 a raindrop camera was installed at Coweeta Hydrologic Laboratory in Franklin, North Carolina. Since no electricity was available in this mountainous area, it was necessary to employ a gasoline driven generator as a source of power. Considerable trouble was experienced with this generator, especially during the winter months, resulting in the intermittent collection of data. In June a factory representative visited the site to repair and adjust the generator. Since that time, it appears to be operating satisfactorily.

During periods of high humidity, considerable fogging of the 30-inch mirror occurred. Although the unit was equipped with a dehumidifier, it was not activated until the motor generator was started by the tipping bucket rain switch. Therefore, the first part of some of the rolls of film were unuseable. In order to expedite the clearing of the mirror a blower was installed and directed at the mirror.

In May an anemograph was installed to record the wind field in the immediate vicinity of the drop camera. The effects of wind speed and direction on the sorting of drop size distributions will be attempted after the data have been measured and analyzed.

Since installation, 73 rolls of film have been received from North Carolina. The majority of these were exposed during the spring and summer months. Since many samples during the winter months were missed, a six-month extension on the present contract was suggested. This would extend the operating period through March 1962.

The New Jersey and North Carolina sites are shown in Figure 4.

Mt. Withington, New Mexico

A raindrop camera was installed, see Figure 4c, on the summit of Mt. Withington, New Mexico, during July and August of 1961. The primary purpose of the installation was to gain information on the drop size distribution as a function of the life history of a storm. Horizontal motion of the storm elements is practically nonexistent.

Personnel from Arthur D. Little, New Mexico Institute of Mining and Technology, and other organizations were also present on Mt. Withington. and operated equipment to measure the development and growth of mountain top cumulus clouds. The summer was disappointing in the number of rain situations which occurred. There were, however, several days in which interesting data were obtained.

Figure 5 is an example of the drop size distribution obtained in a consecutive 12-minute period. This storm was an intense thunderstorm with lightning actually striking the Cornell Aeronautical Laboratory's radar trailer that was about 50 yards north of the drop camera. This 12-minute section of storm is chosen as an example because as far as is known it represents on the drop size-data sequence that brackets falling hail. Hail was observed from the Arthur D. Littie observatory trailer, which was 150 yards north of the camera, between 1301 and 1308. The 12 minutes of storm produced 4.5 mm of rain calculated from the drop size data and 5.0 mm according to the raingage. The storm occurred with low winds. The highest rainfall rate recorded during the 12 minutes was 55 mm/hr at 1309, after most of the hail had occurred.

The striking feature of the series of drop size spectra is that the appearance of the second mode is not spontaneous but seems to move out from the rain mode. All of the hail that was noted on the ground was of the classical cone shape with rounded cap. Some rough sizing was performed by individual measurement of the hail by a ruler. The largest measured 1 cm. The photograph from the drop camera showed the largest stone to be 7 mm.

The question of the orientation of these cones is not clearly answered by the drop camera. The appearance of the hailstones as a shadowgraph seldom shows the cone shape. This can be interpreted as the apex of the cone pointing into or away from the camera. An attempt to define the angle of departure of the apex from the vertical failed in most cases because of this difficulty. Of the remaining stones for which an apex could be determined, the apex showed no preference of direction. Of course, the sample in the drop camera had already experienced some local turbulence which could have destroyed any original order that the stones may have had.

In general, hail may be separated from rain drops on the drop camera film by the absence or existence of a transmitted light high light located within the drop image. However, for some very clear hail, it has been recently noted that a high light does appear. This complicated the decision as to hail stone or rain drop somewhat; nonetheless, it appears that for this series all of the drops larger than 3.5 mm are hail and that a large percentage of those larger than 3.0 mm are hail.

At 1300 and 1301 a very common rain type distribution is shown. The first hail definitely noted on the drop camera occurred in the 1304 sample. The samples at 1302 and 1304 are somewhat unusual and represent lower rainfall rates. The observer logged start of hail at 1301, so that 1302 and 1303 samples were taken at onset of the hail but with a low density of stones. The 1304 sample shows a strong second mode centered at 2.7 mm. A large part of this second mode Is undoubtedly ice, although the particles may be partly ice and partly water. Hail is still apparent on the drop camera through 1309, but at 1310, the sample returns to a normal rain type distribution.

Because of the limited amount of data obtained during 1961, it is suggested that further work in this area be pursued.

DATA ANALYSIS

The method of reducing the raindrop data was reported fully in the Tenth Quarterly Technical Report. Since that time a number of modifications have been made. The computer program has been rewritten to produce the median volume diameter, median scattering diameter, and the median rainfall rate diameter. The last two variables are defined in a manner similar to the median volume diameter except that the reflectivity and the rainfall rate are used in place of the liquid water content. The positive area stability index has been added to the summary cards as well as the volume diameters.

During the contract period, a total of 481 rolls of 70-mm film was received from the various drop camera locations. Some 55 rolls were unmeasurable because of bad focus, camera misalignment, very low rainfall rates, false triggering of rain switch, etc. Of the 426 rolls of good data 310 have been measured and 114 remain to be measured. Table 1 presents the status of the data film to date.

It can be seen from the table that the measurements of Miami, Oregon, Majuro, and Alaska films have been completed. It may be noted also that the measurements of Indonesia and New Mexico data are nearly completed. After these two locations are completed, emphasis will be placed on the measurement of data from North Carolina and New Jersey.

TABLE 1

STATUS OP RAINDROP DATA MEASUREMENTS

Location	Received	Measured	To Be Measured	On Projector
Illinois	7	0	0	0
Miami	65	61	0	0
Oregon	98	68	0	0
Majuro	57	54	0	0
Alaska	72	72	0	0
Indonesia	59	41	1	2
New Jersey	35	0	33	0
North Carolina	73	1	70	0
New Mexico	15	13	2	0

STABILITY AND DROP SIZE DISTRIBUTIONS

The grouping of drop size distributions into rain types and synoptic types succeeded in reducing the variance from that found with the ungrouped data. However, it was felt that a further reduction might be attained if a different classification were employed. Since strong vertical motions would tend to suspend water droplets longer and thus increase the probability of collision and

CONCLUSIONS AND RECOMMENDATIONS

The analyses of drop size distributions show promise in reducing the variations in radar measurements of rainfall due to drop size variations. Various schemes of choosing a radar reflectivity versus rainfall rate regression line have been examined, the most successful scheme being one based on the upper air stability as determined from a radiosonde. Other methods, such as those based on synoptic type or rain type, do reduce the variations experienced but not to the degree shown by the stability index method. Work should continue in evaluating this scheme for the other climatic areas where drop size distributions have been collected.

The data collected at Mt. Withington during the summer of 1961, though insufficient in quantity, suggest that the life histories of drop size spectra can be studied in this location. Knowledge of the history of the spectra can be used to eliminate or strengthen the various processes proposed for the transformation of cloud droplets to raindrops. In this respect the value of a radar set in measuring rainfall at the ground due to variations of drop size spectras aloft must be analyzed before the full utility of a radar set in quantitative work can be assesed. It is recommended that further work in the theoretical evaluation of droplet coalescence be pursued and that data be obtained on droplet size spectra aloft. An instrument called the disdrometer developed by Cornell Aeronautical Laboratories is available for obtaining cloud droplet size spectra from an airplane.

Efforts to deduce the physical causes of the climatic differences noted in drop size spectra should be continued. The streak camera should be further evaluated and, if proven successful, an automatic reader for the film should be built. Future data should then be collected using this type device.

PERSONNEL

The following professional personnel were instrumental in the performance of this contract:

Glenn E. Stout
Project Director

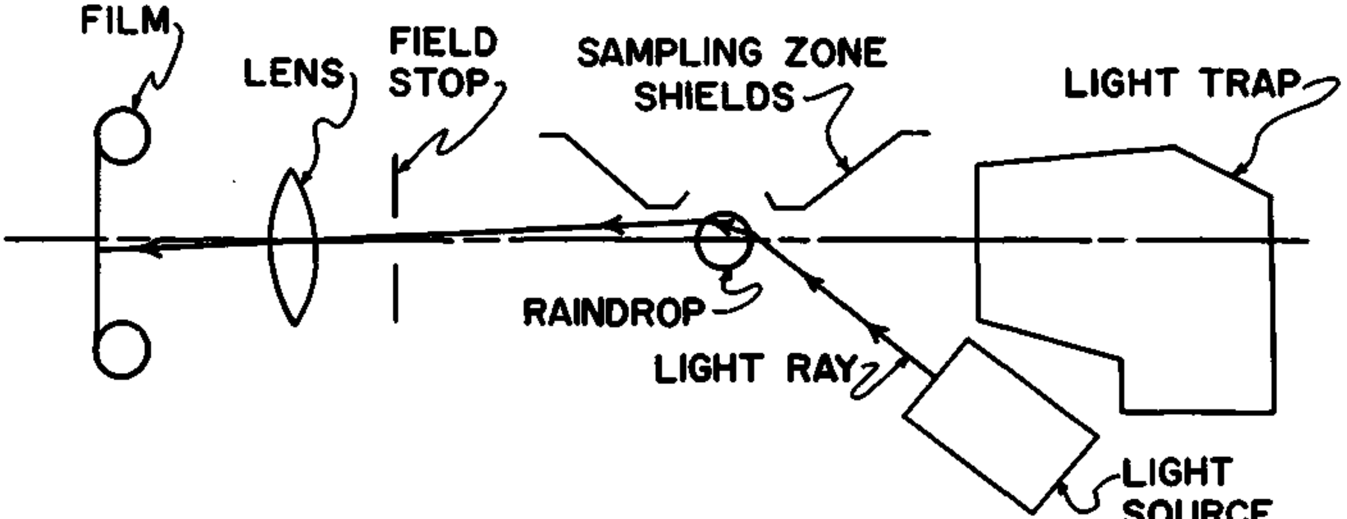
Eugene A. Mueller
Project Engineer

Robert M. Johnson
Meteorologist

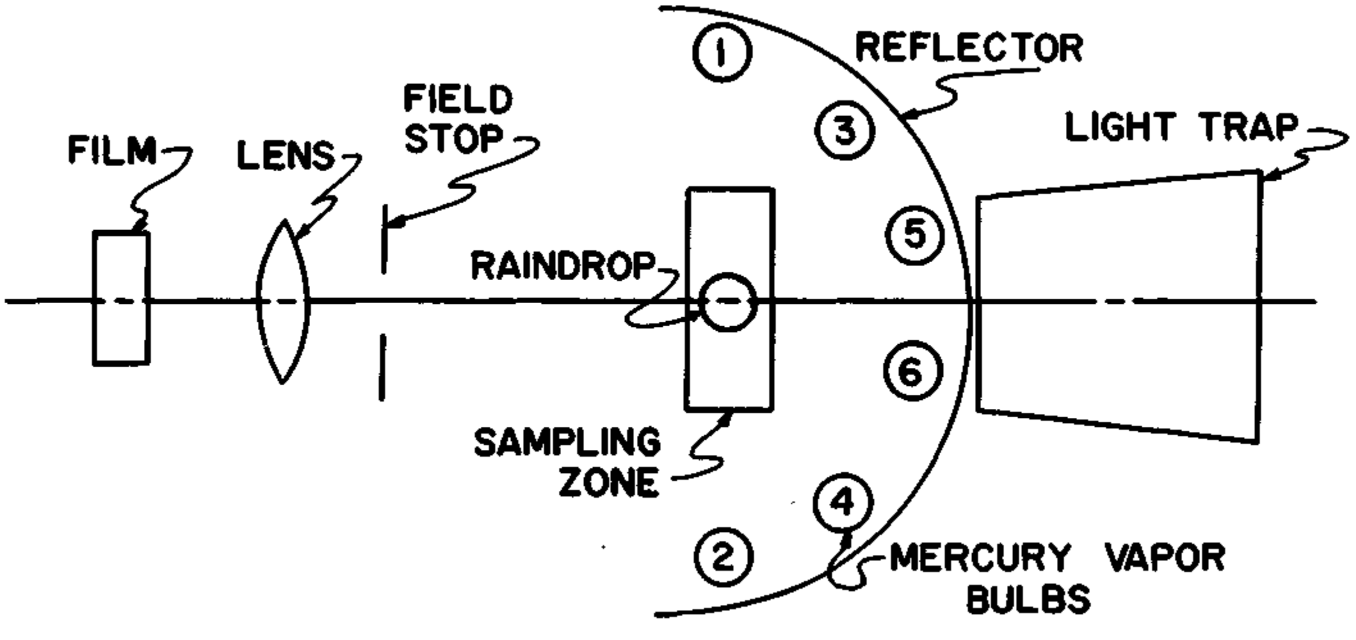
Miyuki Fujiwara
Meteorologist

Douglas M. A. Jones
Meteorologist

There were a number of meteorological aides and student assistants who were employed under this contract. The quarterly technical reports contain detailed reports on these assistants.



SIDE VIEW



TOP VIEW

FIG. I SCHEMATIC DIAGRAM OF STREAK CAMERA

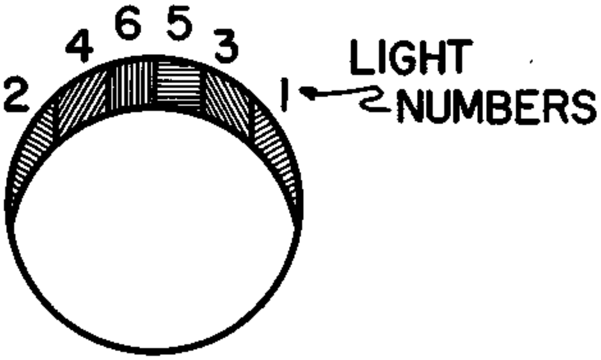
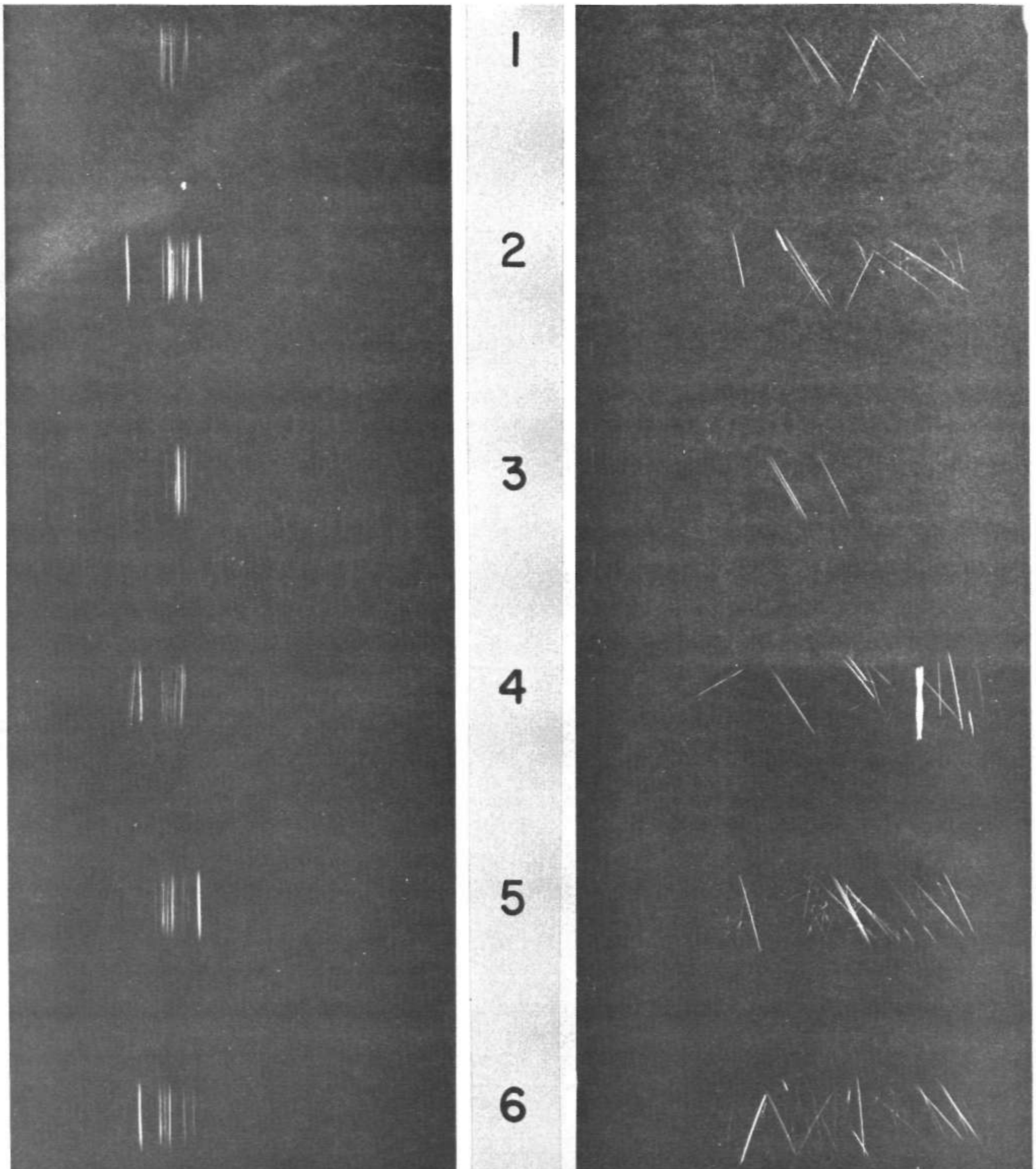


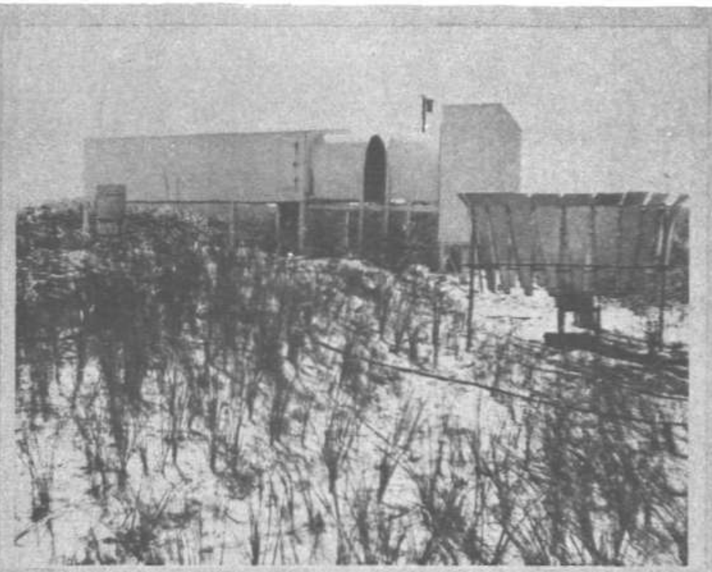
FIG. 2 BAND OF ILLUMINATION VIEWED FROM POSITION OF CAMERA LENS



a. TEST DROPS

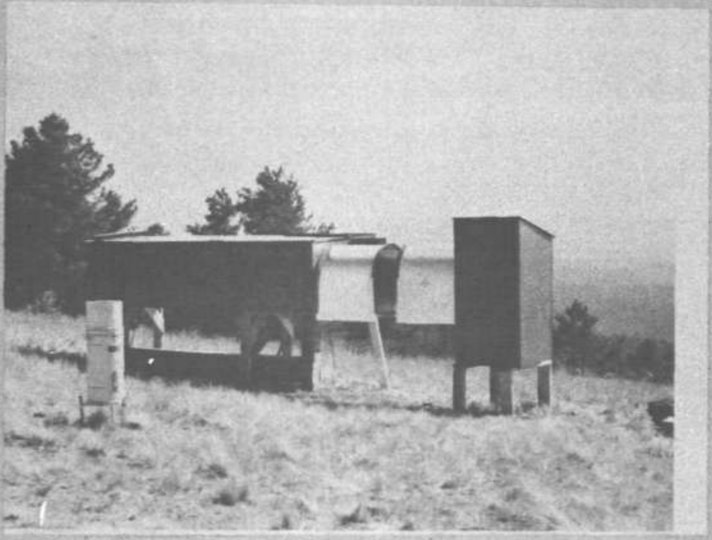
b. NATURAL RAINFALL

FIG. 3 EXAMPLES OF DATA FILM FROM STREAK CAMERA



a. ISLAND BEACH, NEW JERSEY

b. MOONEY GAP, NORTH CAROLINA



c. MT. WITHINGTON, NEW MEXICO

FIG. 4 RAINDROP CAMERA SITES - 1961

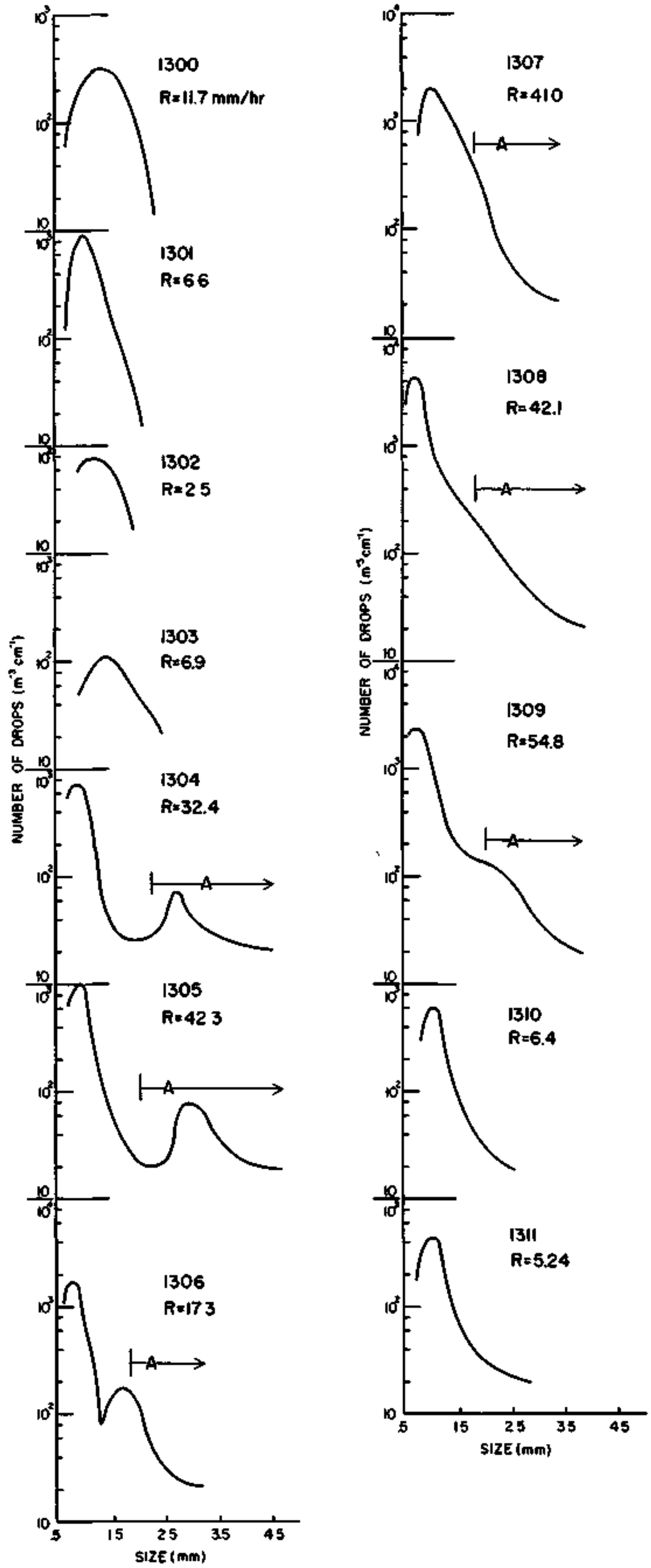


FIG. 5 SAMPLE DROP SIZE DISTRIBUTIONS WITH HAIL FROM MT WITHINGTON, NEW MEXICO

ATTRACTIVE PORCSS BETWEEN TWo CHARGED DROPS AND THEIR EFFECT ON THE COALESCENCE PROCESS*

M. Fujiwara and E. A. Mueller
Illinois State Water Survey

ABSTRACT

As a basis for calculation of the collision coefficient, the electrostatic forces between charged drops were numerically computed by means of the electronic digital computer at the University of Illinois. The results show that strong attractive forces appear when the drops come close together even if the charges on both drops have the same signs. This tendency is very remarkable when the smaller drop has a larger charge than the large drop and when the ratio of the radius of the large drop to the radius of the small drop is large. The quantitative results are shown by figures.

I. INTRODUCTION

Recently, the importance of electrostatic forces for the coalescence of drops has been emphasized by Sartor[1] and Vonnegut[2]. Also, R. Semonin and N. Lindblad of the Illinois State Water Survey have studied the behavior of small drops in experiments in which certain electrostatic forces were applied to the small drops. The authors of this paper have attempted an evaluation of the modification of raindrop size distributions caused by the coalescence process. Since the effect of electrostatic forces on the coalescence of drops seems to be very important, the electrostatic forces between two charged drops were calculated for the data as a basis for further research (presently underway) on the calculation of the collision coefficient.

The method used here is the well-known image method. Although electrostatic forces between two spheres have long been investigated (see Jeans, *Mathematical Theory of Electricity and Magnetism*[3]. calculations for the case of fixed charges throughout the various conditions have not yet been made. The tedious work of calculation was lightened by using a high speed digital computer.

2. EQUATIONS FOR CALCULATION OF THE ATTRACTIVE FORCES

The equations for the calculation were reduced to the following expressions based on the theory of image charges. The resultant force, F, between charged spheres, A and B, is given by

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*This research is being supported by the U. S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey, under Contract DA-36-039 SC-75055.

where

$$R = \sum_m b_0 \; a_1 \; b_2 \; \cdots\cdots\cdots \; a_{2m-1} ,$$
$$S = \sum_m a_0 \; b_1 \; a_2 \; \cdots\cdots\cdots \; a_{2m-2} , \qquad (7)$$
$$T = \sum_m a_0 \; b_1 \; a_2 \; \cdots\cdots\cdots \; b_{2m-1} ,$$
$$U = \sum_m b_0 \; a_1 \; b_2 \; \cdots\cdots\cdots \; b_{2m-2} ,$$

and q_o q_o are the initially given charges on spheres A and B, respectively.

To obtain a good convergence for this series, 107 images were placed on each sphere. In addition, the program was written to avoid the accumulation of any rounding errors.

3. RESULTANT FORCE BETWEEN SPHERES

The various conditions for which calculations were obtained are listed below:

1. The radius b of the larger sphere B is constant.
2. The ratio of the radii of smaller sphere A and larger sphere B,

$$a/b \;\; (= u_i) \; = 2^{-i} , \; i = 0,1,2, \; . \; . \; . \; ,9.$$

3. The separation between the surfaces of the spheres

$$d_j = b.2^{-j} x \; 10, \qquad j = 0,1,2, \; . \; . \; . \; ,9.$$

4. The ratio of the charges $,q_o/q_o$ ($= x_k$), on the two spheres

$$X_k = 2^{3-k}, \;\; \text{when} \;\; k = 0,1, \; ... \; ,4 \; ,$$
$$X_k = (-1) \; 2^{8-k}, \;\; \text{when} \;\; k = 5,6, \; . \; . \; . \; ,9.$$

Figure 1 shows two examples calculated in terms of the non-dimensional quantity $F = F.(b^2/q_o^2)$, where F is the force in dynes, and where b is the radius of the larger sphere B in cm, and q_o is the electric charge on the smaller sphere A in e. s. u.

Figure 2 shows examples of the contours of J defined by the following equations on the coordinates of parameters i and j for each k.

$$J \; = \; 2^{-j+k-4} \; . \; 10^3 . \; F' , \qquad \text{when } k \; = 0,1,2,3,4,$$
$$= \; -2^{-j+k-9} . \; 10^3 . \; F' , \qquad \text{when } k \; = 5,6,7,8,9.$$

These results indicate that attractive forces usually exist even if the charges on the two spheres have the same signs. As the interval d. decreases, the value F' increases asympatically. The region of the attractive force by charges of same signs is larger with smaller a and also with the larger charge on A (cf. Figs, la and lb).

4. CONCLUDING REMARKS

Because there are strong attractive forces between charged drops when they come close enough to each other, regardless of the signs of charges, coalescence will occur more readily between charged drops than it will between non-charged drops. Thus, not only will the effective cross-section of sweep by the larger drop increase, but also the larger drop will more effectively "capture" the small droplets when they collide.

Because cloud physicists have suspected that some effects of surface tension might cause bounce off when drops collide, they have hesitated to apply the collision coefficient as a coalescence coefficient. The results of the calculations in this paper suggest that the tendency of the skin effect to cause drops to bounce after contact will be easily overcome by the strong attractive forces, since most of the droplets found in the natural cloud have a certain amount of charge.

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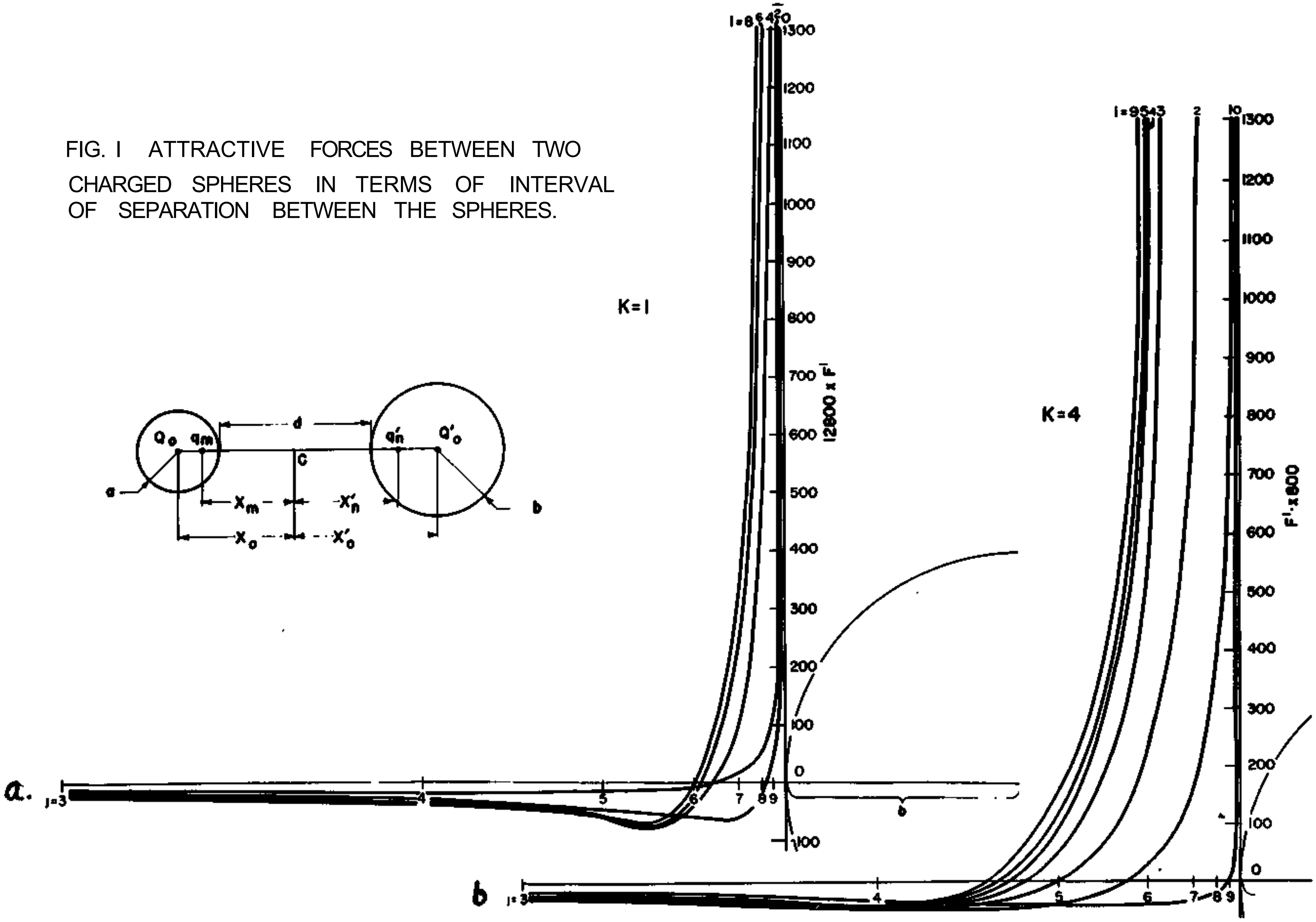
FIG. I ATTRACTIVE FORCES BETWEEN TWO CHARGED SPHERES IN TERMS OF INTERVAL OF SEPARATION BETWEEN THE SPHERES.



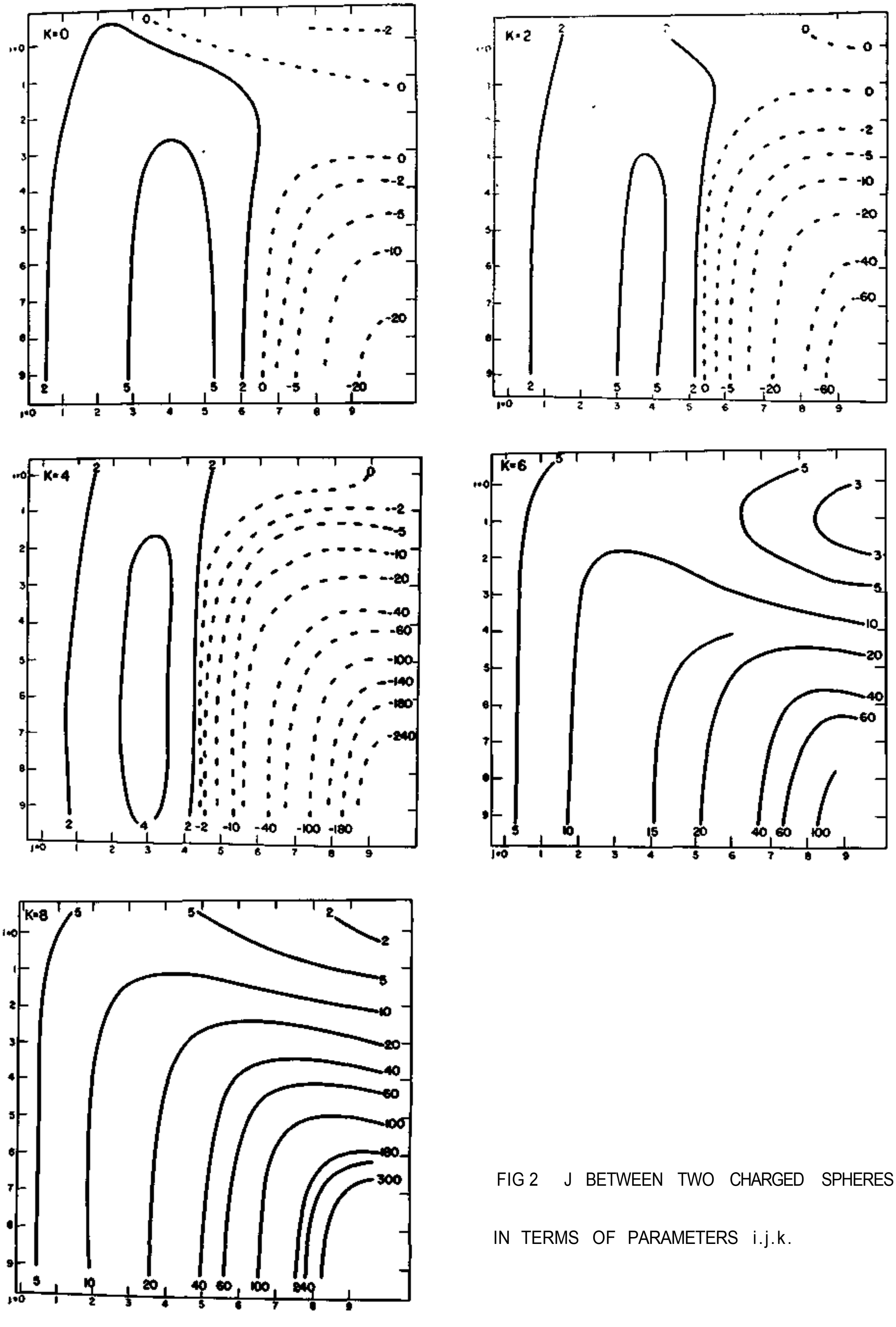


FIG 2 J BETWEEN TWO CHARGED SPHERES IN TERMS OF PARAMETERS i.j.k.

UNCERTAINTY IN RAINFALL MEASUREMENTS DUE TO DROP SIZE DISTRIBUTIONS*

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ABSTRACT

Raindrop size distributions obtained by the raindrop camera located at the University of Miami were analyzed to determine the amount of error In rainfall estimate caused by variations in drop size distributions.

The individual storms were divided into groups according to synoptic types. The relationships between rainfall rate and radar back scattering cross section were then determined for each group according to two fitting criteria. The usual log R- log Z least square fit was obtained, and the sum of the products of the absolute deviations and the rainfall rate was minimized. The latter method appears superior in minimizing the quantity error in the total rainfall amount,

1. INTRODUCTION

The question as to how accurately rainfall amounts may be measured by a radar set has been frequently asked the radar meteorologist in the past. One of the limiting factors in determining rainfall by radar is the variability of the drop size distributions for a particular rainfall rate. Using the data that was gathered with the raindrop camera located at the University of Miami, an answer to the question of the accuracy of the rainfall estimate, as influenced by the drop size variability, has been obtained.

The following basic assumptions are made: firstly, the drop size distributions obtained from the 1-cubic meter sample is considered representative of the drop size distribution of the entire radar volume; secondly, the terminal velocities as measured by Gunn and Kinzer are effective throughout the radar volume; thirdly, the radar measurements of the radar reflectivity contain no error. Of these assumptions the first is probably the most serious as there is considerable doubt that a 1-cubic meter volume is sufficiently large, when a radar volume at 30 miles might be as large as 108 cubic meters. If it is assumed that the variability of the distribution is due just to sampling error, application of Student's "T" distribution to the average of the number of drops in each of

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was then estimated from the rainfall rate frequency and used to compare with the rainfall amount as determined from the radar reflectivity frequency curve and one of two relationships between rainfall rate and radar reflectivity.

The usual logarithmic least squares relationship between radar reflectivity and rainfall rate was determined. Since this procedure tends to place equal weight on all points and since it was felt that the higher rate contributed more to the total rainfall amount, a second procedure which weighted the larger amounts was sought. The procedure adopted consisted of determining a relationship in the form of

$$R^* = AZ^b \tag{1}$$

such that the function

$$K = \sum_i \left| R_i (R_i - R_i^*) \right| \tag{2}$$

Where R_i is the true rate for sample i and R_i^* is the rate which would be determined by Equation 1 and the true Z_i for sample i. This procedure weights the large values of R more than the small values of R. The functional form of Equation 1 was adopted for convenience and for easy comparison with the standard relationship. The calculation of the coefficients of Equation 1 were performed by means of digital computer, ILLIAC, at the University of Illinois. One group of data was calculated by hand using a more sophisticated three-parameter form for Equation 1 of the form

$$\log R^* = A + b \log Z + c (\log Z)^2$$

It did not produce sufficiently less error in the final estimates to warrant the added complexity of its calculation.

3. RESULTS

Table 2 indicates the final equation determined by both methods. It can be noted that in general, the weighting of the higher rainfall rate produces larger exponents and lower coefficients than the least square procedure. This weighting may be considered to be analogous to weighting the samples with the large drops more than the samples with small drops, as the large drops tend to increase the exponent also. Further analysis in this direction leads one to suspect that certainly a three-parameter fitting form would be more appropriate, but as mentioned above, the scatter in the data does not justify this refinement.

Table 3 reveals the average errors of the total rainfall amount from the storm of 100-minutes duration. It can be noted that the average total error under the assumption previously made does not exceed 7% for the second procedure of rate estimation. It is felt that this is extremely close considering the calibration

TABLE 2

REGRESSIONS AND NUMBER OP CUBIC METERS OP SAMPLE

	Synoptic Type					
	Air Mass	Pre-Cold Frontal	Cold Front	Post Cold Occlusion	Warm Front	Easterly Wave
Squares	$323R^{1.42}$	$281R^{1.49}$	$296R^{1.35}$	$302R^{1.36}$	$403R^{1.24}$	$296R^{1.35}$
Min $\sum R_i/[R_i - f(Z_i)]/$	$155R^{1.47}$	$181R^{1.60}$	$205R^{1.42}$	$214R^{1.44}$	$230R^{1.44}$	$205R^{1.42}$

uncertainty in radar measurement. The log least squares appear nearly as good as the weighted relationship and in fact might be argued to be better since it underestimates and overestimateS where the rated curve tends to overestimate on the average.

TABLE 3

AVERAGE % ERROR IN RAINFALL AMOUNTS DUE TO DROP SIZE VARIATION ALONE (+ indicates over estimate)

	Synoptic Type					
Computed From	Air Mass	Pre-Cold Frontal	Cold Front	Post Cold Occlusion	Warm Front	Easterly Wave
Log least Squares	-12.1	+3.7	+2.5	-8.0	-4.6	-2.5
Min of $\sum R_i/[R_i - f(Z_i)]$	+ 6.3	+6.6	+5.5	-2.4	+1.0	+5.5
Total Rainfall Amount in Model Storm (inches)	2.64.	1.20	1.66	1.40	1.49	1.79

4. CONCLUSIONS

In general, it appears that drop size variations that were found at Miami, Florida, can be minimized sufficiently to allow reasonable estimates of rainfall amounts provided that sufficiently accurate measurements of the radar can be made, and providing that synoptic information to separate classes is available. The equation for each synoptic type varies also with climatic regions. Examination of the variations in the exponents and coefficients presented in Table 1 indicates that separation of the data into synoptic types is necessary to obtain this amount of accuracy.

THE EFFECTS OF STABILITY ON DROP SIZE DISTRIBUTIONS*

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ABSTRACT

An attempt to reduce the variance occurring in rainfall rate-radar reflectivity relationships was investigated using stability as a criterion. A preliminary investigation employing drop size data and upper air soundings during thirty storms at Miami, Florida, indicated that the positive area generated using the parcel method may be significant in classifying drop size distributions. An IBM 650 computer program was written to obtain the positive area stability index for a large number of soundings. Punched cards of radiosonde observations for Miami, covering the period August 20, 1957, to August 15, 1958, were processed through the IBM 650. Soundings were grouped into varying degrees of stability and compared with drop size distributions. Rainfall rate-radar reflectivity relationships were computed and the results are discussed. Highest values were found among conditions of moderate stability while lowest values occurred under stable conditions. A three per cent reduction in the standard error of estimate over rain type and synoptic type classifications was obtained.

I. INTRODUCTION

Jones described the method for determining drop size distributions.[1] Mueller and Jones[2] described 2403 cubic meter drop size samples obtained by this method at Miami, Florida. A sample consisted of one cubic meter collected at one-minute intervals. Z-R relationships computed from these data were grouped into rainfall types and discussed by Jones and Mueller.3 Further classification by synoptic types has been completed by Mueller and Jones, but the results have not been published.

II. DISCUSSION

Although grouping the samples into rain types and synoptic types succeeded in reducing the variance, it was felt that a further reduction might be obtained if a different classification were applied. Upper air parameters and their possible influence on drop size distributions were examined. Since strong vertical motions tend to suspend water droplets longer, and thus increase the probability of collision and coalescence among the drops, a stability classification seemed an appropriate measure. A preliminary study was undertaken in which different stability indices and their relationships, if any, to drop size distributions were investigated.

This research is supported by the U. S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey, under contract DA-36-039 SC-75055.

$$T_h = T_s \left[\frac{6.11\,(1 + K)}{P_s\,K}\right]^{R/C_p} \left[e^{\frac{4.938\,(Th - 273.6)}{Th - 35.7}}\right] \quad (3)$$

$$\text{where } K = \frac{W_s}{.622}$$

Once the point, T_h, P_h, has been determined, the entropy constant for the moist adiabat passing through this point may be calculated from the approximation used by Rossby

$$C_p \ln T_h - R\ln\,(P_h - e_s) + \frac{wL}{T_h} = \text{Constant} \quad (4)$$

where L = latent heat of vaporization

The temperature values at 50 mb intervals along this moist adiabat are calculated by means of interpolation from standard values stored in the computer.

The energy expended or liberated by a parcel of air rising adiabatically through an environment may be given by the equation:

$$dW = -R(T_\gamma - T)\ d\ln P \quad (5)$$

where $T_\&$ = temperature of rising air at pressure, P

T = temperature of the environment at pressure, P

Integrating, setting $\Delta_p = 50$ and clearing the equation, the relative PASI used in this analysis may be expressed as

$$\text{PASI} = \sum_{i = P_s}^{100\text{ mb}} \frac{T_\gamma - T}{P} \quad (6)$$

Positive Area Stability Indices were computed for each radiosonde observation during the period of raindrop camera operation. The one-minute samples obtained from the drop camera were grouped into varying degrees of stability. Samples obtained in the time interval commencing at the time of the sounding to twelve hours thereafter were assigned the PASI computed for that sounding.

III. RESULTS

The results for the PASI classifications for 80 storm days, along with values obtained for rain type and synoptic type classifications by Jones and Mueller, are shown in Table I. The Z-R regression lines for selected stability classes are shown in Figure 2. Classes 2, 3, 6, 7, and 9 are not shown due to space limitations, since the regression lines for these classes all fell between lines 5 and 8 in the figure.

With the exception of class 5, the coefficients generally increase to a maximum value of 420 found with class 4 and then gradually diminish thereafter. The exponents also gradually increase to a value of 1.41 at class 4. and then remain relatively constant. It appears, therefore, that at Miami the highest Z values for a given rainfall rate will be found for conditions of moderate instability

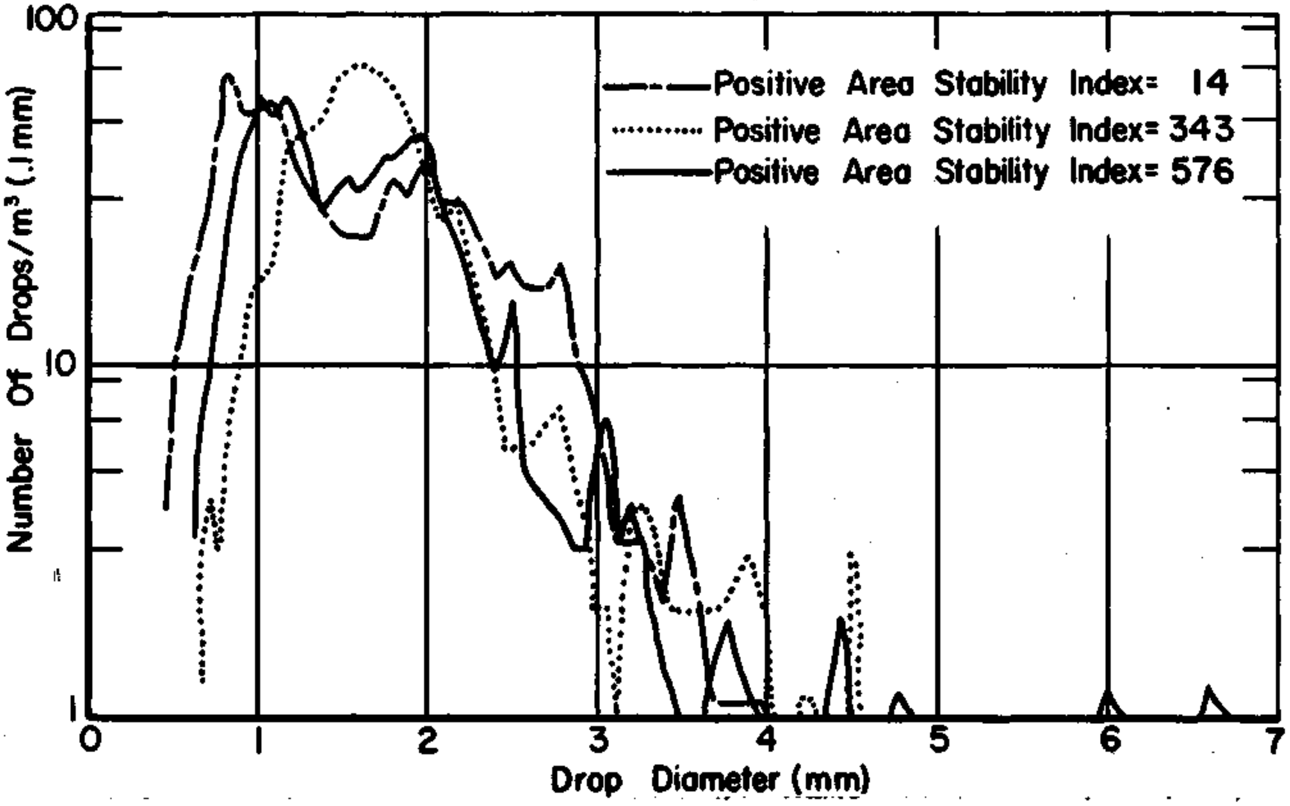

Fig. 1 DROP SIZE DISTRIBUTIONS WITH DIFFERENT POSITIVE AREA STABILITY INDICES
Rainfall Rate In All Curves Is 70 mm/hr.

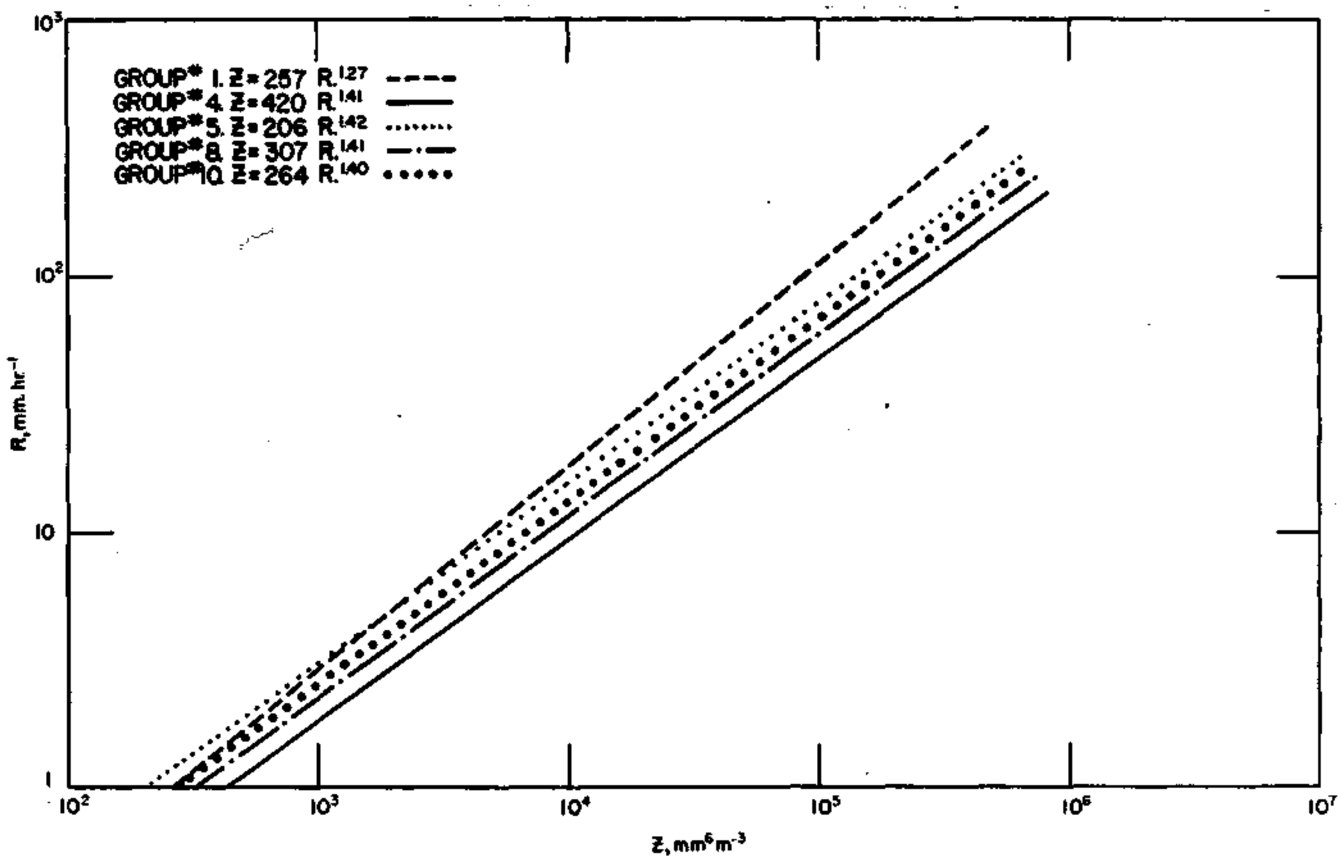

Fig. 2 Z-R RELATIONSHIPS FOR FIVE STABILITY GROUPS AT MIAMI

might be better suited unless computer facilities were readily available. A further reduction in the standard errors might be possible if instantaneous values of instability for each sample were available. The assumption that the instability will not change considerably in the twelve hour period following the radiosonde observation is not a good one for rapidly changing synoptic conditions.

One factor which may prove the stability classification a better means of estimating rainfall rate is the possibility that Z-R relationships, when classified by stability, may not change significantly for different climatic zones. Future studies will involve classifying samples obtained from other areas and comparing the computed Z-R relationships with the ones obtained from Miami.

IV. CONCLUSIONS

At Miami, for a constant rainfall rate, the highest Z values occurred with moderate instability. Lowest Z values were associated with the most stable conditions. Classification of the Z-R relationships observed at Miami according to varying degrees of stability succeeded in reducing the standard error of estimate by a small amount. The standard error could possibly be reduced even further if the twelve-hour time differential between radiosonde observations could be shortened. The stability classification may prove to be of greater value if the Z-R relationships obtained in other climatic areas compare favorably when classified according to degrees of stability.

V. ACKNOWLEDGMENTS

The author wishes to thank Mr. E. A. Mueller for his great assistance in writing the IBM 650 computer program for the determination of the Positive Area Stability Index.

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