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PROGRAM IN ATMOSPHERIC ELECTRICITY AND CLOUD MODIFICATION FLAGSTAFF - 1966

FINAL REPORT

edited by

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Project Director
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June 15, 1967

ECOM

ATMOSPHERIC SCIENCES LABORATORY
UNITED STATES ARMY ELECTRONICS COMMAND- FORT MONMOUTH, N.J.
Contract DA-28-043 AMC-02376(E)

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

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ABSTRACT

This report summarizes the data collection and preliminary analyses of various activities under Army support which were carried out in the Flagstaff area in the summer of 1966. A number of investigators have provided reports of their activities which have been combined into one volume.

Basic studies were undertaken to study the raindrop-size distribution, radar echo climatology, and chloride particle concentrations by the Water Survey. Infra-red measurements, electrical measurements of clouds, and chaff seeding were carried on by the Army. The Atmospheric Sciences Research Center of the State University of New York carried on studies concerning the airflow in the region, and condensation nuclei activities.

The results of the field program provided additional information concerning meteorological conditions pertinent to precipitation of the Flagstaff area as well as additional support that chaff seeding influences the electrical fields of growing cumulus clouds. The resulting drop-size measurements suggested a different distribution of raindrops on several days which are either due to silver iodide seeding by another group in the area or from the evaporation of the falling drops.

INTRODUCTION

In 1966 as in several previous years*, the Atmospheric Science Laboratory of Fort Monmouth, USAECOM has used the area near the San Francisco Peaks north of Flagstaff, Arizona, as a laboratory for the study of certain characteristics of thunderstorms. In 1966 the program involved not only personnel USAECOM, but scientists from the Environmental Science Services Administration (ESSA) and contracted organizations. The Illinois State Water Survey was one of the contracted organizations.

The Illinois State Water Survey was instructed:

1. To participate and to observe the Atmospheric Electricity and Weather Modification Program in the Flagstaff, Arizona, area in July and August in the calendar year of 1966.

2. To participate, to observe, in the technical critiques held weekly to discuss the results of the past week and plans for the coming period. Meteorology Research, Inc., and other contractors working on contracts with the Bureau of Reclamation frequently participate in these weekly critiques.

3. To prepare with the joint assistance of ESSA and USAECOM, a final report on the atmospheric electricity and weather modification program conducted at Flagstaff. This is that report.

4. To attend and to participate in technical conferences in atmospheric electricity, cloud physics, and weather modification which are held during the course of this contract.

The first experiments were performed on 10 July with the infrared scanner installed in the C-47 aircraft. The experiments were supported by an Army Meteorological Team from USAECOM making 2 atmospheric soundings each operational day with GMD-1 equipment. Autographic equipment for the recording of pressure, temperature, relative humidity, precipitation, and wind speed and direction was also serviced by the Team. The Team was based at the Navajo Ordnance Depot 9 nautical miles west-northwest of the City of Flagstaff. The records collected by the Team are filed at the Illinois State Water Survey in Champaign, Illinois. In addition to the Meteorological Team, personnel from USAECOM operated M-33 radar equipment to track the project aircraft and to advise the aircraft operators of the location of precipitation echoes either for avoidance or study.

The reports of the investigators are included herein in the form in which they were received at the close of the project. Research had not been completed at that time in all cases. Some of the figures appearing in the reports have been redrafted for clarity, but most of them have been reproduced as they were submitted.

* Project Report of 1965 Operations

REPORTS OF THE INVESTIGATORS

The following report on instruments under development and evaluation by the Atmospheric Science Laboratory of USAECOM and is a preliminary report giving the program of testing during the 1966 project and is not intended as an evaluation of the performance of the instruments; that report will be published after the reduction of the detailed data from the instruments by USAECOM and the National Bureau of Standards.

Infrared Scanning Radiometer, Humidity Probe, and CO2 Temperature Sensor - A. R. Tebo

A. Ground temperature measurements with the Infrared Scanning Radiometer

1. The Infrared Scanning Radiometer was installed in Army C-47 Aircraft #39103 during the week of 4 July 1966 at Flagstaff.

2. Ground tests were performed on 10 July 66 and calibrations were made using an ice bath as a fixed temperature source.

3. Operational flights to obtain thermal imagery on film were made on the dates listed below, over the paths listed. The ice bath was a plastic pool filled with melting ice (and water). The cattle watering tank was a large metal tank filled with water, with a regulated inlet flow. Its temperature was measured at several points at the surface, with mercury thermometers, both before and after flight. The "CIRCUIT" consisted of a flight from the airport, over Lake Mary, over Sunset Crater, over desert area north of San Francisco Peaks, over Rogers Lake, and back to the airport. Flights were made at different altitudes to check both the resolution of the equipment and the effect of the intervening atmosphere.

Date (1966)	MST Time	Path	Altitude, Ft. above ground
10 Jul	1533	Tank - Pool	300, 500, 1000, 2000, 5000
10 Jul	1616	Circuit	4000
10 Jul	1959	Tank - Pool	500
10 Jul	2007	Circuit	1000
10 Jul	2029	Tank - Pool	500
11 Jul	0456	Tank - Pool	500
11 Jul	0503	Circuit	1000
11 Jul	0528	Tank - Pool	500
11 Jul	1134	Tank - Pool	300, 500, 1000, 2000, 5000
11 Jul	1210	Circuit	1000
11 Jul	1244	Tank - Pool	500
11 Jul	1522	Tank - Pool	300, 500, 1000, 2000, 5000
11 Jul	1554	Circuit	1000
11 Jul	1622	Tank - Pool	500
11 Jul	2020	Tank - Pool	500
11 Jul	2032	Circuit	1000
11 Jul	2100	Tank - Pool	500
12 Jul	0455	Tank - Pool	500
12 Jul	0500	Circuit	1000
12 Jul	0527	Tank - Pool	500

B. Air temperature measurements

4. Flights were made thru clouds during the week of 12 July 1966 to make measurements of: (a) humidity with the barium fluoride thin film hygrometer; (b) temperature with the infrared atmospheric thermometer, and with the vortex thermistor thermometer; and (c) aerosol counts with the portable nuclei counter.

5. The thermistor of the vortex thermometer broke shortly after takeoff on the first flight. So no data were recorded at all. The nuclei counter was not used on flights after 15 July 1966. Beginning with the flight of 19 July, both the radiometer temperatures and the thin film humidities were recorded simultaneously on the temperature recorder and on the humidity recorder, to enable convenient correlation of data. This should be especially useful when entering and leaving a cloud, where sharp changes of both parameters occur.

No particular geographical pattern was followed on these flights. the routes were chosen only to pass thru several types of clouds, in order to enable a study of the temperatures and humidities encountered.

6. A summary of the flights is given below.

Date (1966)	MST Time	Instruments
14 Jul	1708	Radiation Thermometer, Thin Film Hygrometer, Nuclei Counter
15 Jul	1055	Radiation Thermometer, Thin Film Hygrometer, Nuclei Counter
15 Jul	1400	Radiation Thermometer, Thin Film Hygrometer, Nuclei Counter
19 Jul	1413	Radiation Thermometer, Thin Film Hygrometer
20 Jul	1119	Radiation Thermometer, Thin Film Hygrometer
20 Jul	1445	Radiation Thermometer, Thin Film Hygrometer
21 Jul	1519	Radiation Thermometer, Thin Film Hygrometer

C. Results

7. Imagery was obtained on the infrared scanning radiometer flights which should enable an analysis of optimum settings of calibration scale, bias, and gain. Reduction of values to actual temperatures will be a long process, using a manual microdensitometer. It appears that an a.c. noise level, from the 400 hertz power source, is so large that it will prevent the attainment of desirable target resolution and temperature resolution. It is hoped that the use of the ice bath in the pool and the water bath in the cattle tank will provide reliable calibration spots for temperature reference on the film. When the technique is perfected, these ground references can be dispensed with.

8. The flights with infrared atmospheric thermometer and the thin film barium fluoride hygrometer were successful. The thermometer verified our conclusion on previous flights that the temperature inside some types of clouds can be colder than the temperature of the air outside the cloud.

A cursory look at the data disclosed that the temperature and humidity incurred rapid changes at the same time, when entering and leaving clouds.

9. A thorough analysis of the temperature-humidity relationship will necessitate coordination with the National Bureau of Standards, because Frank Jones of that organization holds the primary data on humidity, while the primary data on temperature are held at Fort Monmouth.

Modification of Electric Fields in Thunderstorms - H. W. Kasemir

The U. S. Army Electronics Command has supported as in-house research for several years and as joint enterprise with the Atmospheric Physics and Chemistry Laboratory, ESSA, Boulder, Colorado, in 1966, a research program, to study the feasibility of lightning suppression by chaff seeding. Results of the previous years have been reported at the last Interagency conference on weather modification 1965. The achievements of this year's work will be given below.

Before the test flights at Flagstaff, Arizona in July and August 1966 were undertaken, three essential improvements of equipment and laboratory tests on chaff needles were carried out. The improvement of the equipment involved the design of a new chaff dispenser and a corona discharge indicator. The new chaff dispenser contains the chaff not as needles cut to a certain length and pressed a million apiece in little packages, but the chaff is a long strand of conductive fibers wound up on a reel. Ten reels constitute one dispenser unit housed in one wing tank. During operation the ten strands are forced out through ten guide holes at great speed, and before leaving the tank completely are chopped by a helical chopper into needles of a preset length. This design has several features which are crucial for lightning suppression. (1) The chaff is emitted continuously. Bird nesting, i.e., bunching together in clumps of several 100 or 1,000 needles, is completely eliminated. (2) The chaff is distributed more evenly behind the airplane because a continuous stream of needles and not individual packages emerge from the airplane. (3) It is possible to experiment with different lengths of needles, the needle length depends on the speed of the chopper, which is easily adjustable.

The new chaff dispenser was developed and tested. It performed during the tests and the Flagstaff operation satisfactorily. Minor improvements such as push button control from the operator's place will be installed for next year's test.

A new instrument, a corona indicator installed in the airplane, was tested and operated during part of the Flagstaff period. The instrument is supposed to indicate the corona discharge on the chaff needles, as soon as they emerge from the chaff dispenser. The range should be limited to 50 to 100 meters and the indication selective to corona discharge on the chaff only, i.e., corona discharge on the airplane itself should not be indicated. The last point is difficult to establish and needs a more detailed study. Otherwise the instrument seems to be working properly. One essential point has already been confirmed, namely that corona discharge occurs on the chaff needles if the electric field in the atmosphere surpasses a threshold value of about 25 kv/m, which is in agreement with the laboratory tests.

An extensive laboratory investigation of the onset of corona discharge on chaff needles of different type and length has been carried out in the last year. This investigation confirmed the theoretical calculations on which the feasibility of lightning suppression by chaff seeding was based. The threshold value of the field for the onset of corona discharge is about 25 to 30 kv/m for needles of 10 to 15 cm length. The corona current increases roughly with the square of the field and is about 1μ A at 40 kv/m and 10μ A at 70 kv/m. 100,000 chaff needles in an electric field of 100 kv/m will produce about 5 amp corona current, which should be sufficient to conteract the field enhancing effect of the thunderstorm current. An electric field of 100 kv/m is still far below the threshold field necessary to ignite lightning discharges.

For the field test the C-47 airplane was equipped with the following instruments:

(1) Two field mills measuring the three components, of the electric field.

(2) Two chaff dispensers.

(3) One corona discharge indicator.

(4) Sensors for different meteorological and airplane parameters including strip chart and tape recorders.

The field tests in Flagstaff, Arizona, 1966, were handicapped by the limitation that the airplane was required to stay below the clouds and outside heavy precipitation. Therefore the birthplaces of lightning discharges, which are inside the cloud and at higher altitudes, could not be penetrated and seeded. Nevertheless two essential facts could be established by flights below the cloud: (1) Corona discharge is generated, if chaff is dispersed in areas with electric fields higher than 30 kv/m. (2) A rapid decay of stronger fields (200 kv/m and above) is caused or accelerated by chaff seeding.

The following flight procedure has been worked out. The airplane would fly below developing thunderstorms or shower clouds and would hunt for areas with electric fields above 30 kv/m. If such an area was found and the field pattern had been established by several passes through this area, chaff would be ejected on two to four runs and corona discharge and the electric field were recorded by continuous passes back and forth through the seeded area until either corona discharge or the strong electric field disappeared. Fig. 1 and 2 are typical examples of such flight records.

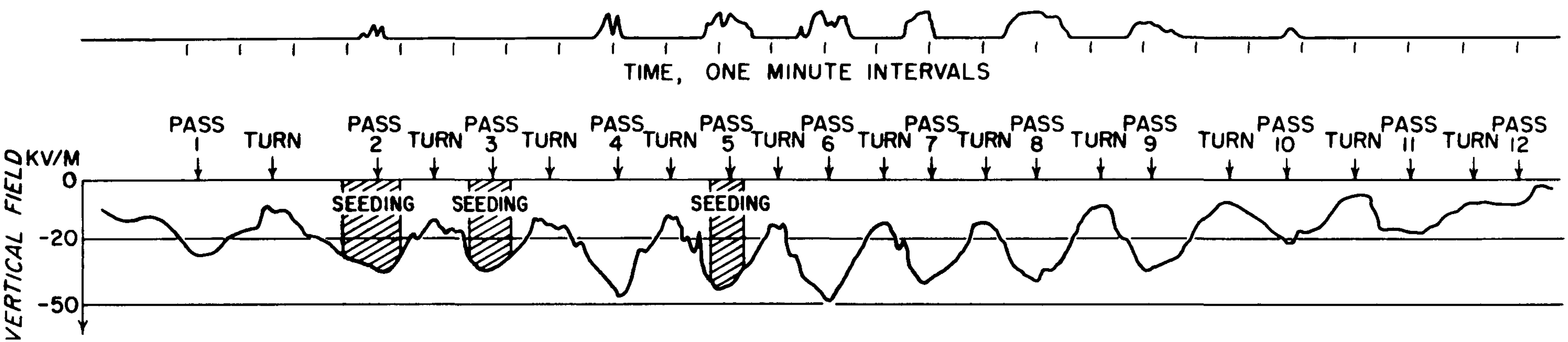

FIG.1. CORONA DISCHARGE GENERATED BY CHAFF SEEDING 2 AUGUST 1966

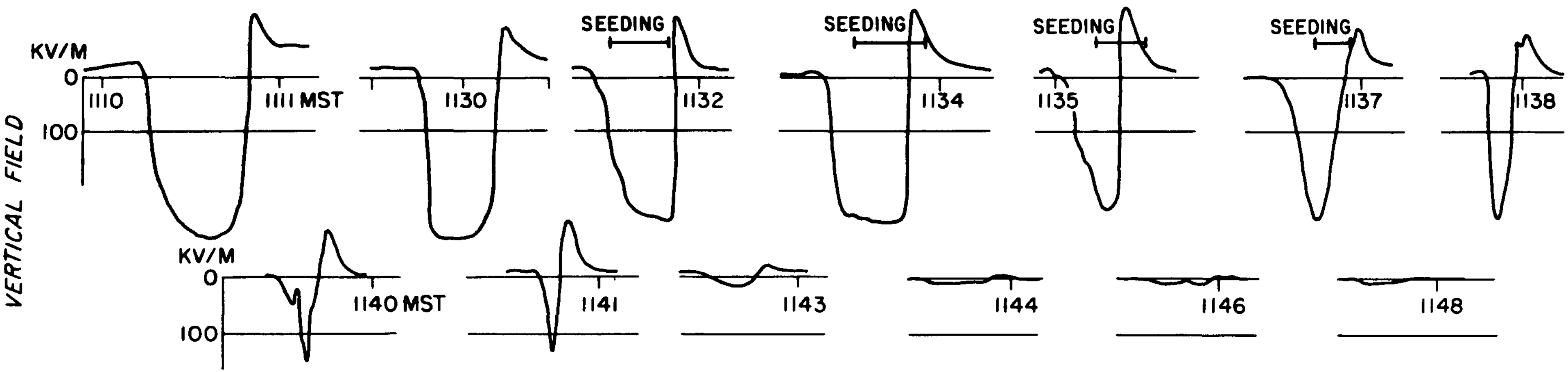

FIG. 2. FIELD DECAY AFTER CHAFF SEEDING 1 AUGUST 1966

Fig. 1 shows the corona discharge on the upper trace and the vertical field component on the lower trace. Seeding and the seeded area are marked as such. Eleven passes have been made below the storm. On the second, third, and fifth pass chaff was dispersed. On the second and fourth pass corona discharge is small and irregular. At the third pass the plane missed the previous seeded area completely and no corona discharge was recorded. But it seems that the chaff needles spread out very rapidly and after five to ten minutes the whole area is solidly filled with corona discharge until the fields drop below 20 kv/m.

Fig. 2 shows the decay of a strong electric field after chaff seeding. It may be pointed out that between the first and the second pass more than 20 minutes elapsed due to the fact that the area was lost and could not be re-located earlier. This proved to be fortunate, because it shows that during this time the field remained at it's high value of about 300 kv/m. After the area was found again chaff seeding began at the third and following passes. The decay of the field can be recognized already three minutes after chaff seeding started. Ten minutes thereafter the field was completely collapsed.

The Flagstaff experiments of 1966 have established that corona discharge is generated if chaff needles of 15 cm length are dispersed in the electric field of thunderstorms exceeding values of 30 kv/m.

It seems highly probable that the decay of strong electric fields is caused or accelerated by corona current produced by the chaff needles.

To study the effect of lightning suppression by chaff seeding an airplane is required, which is capable of penetrating the storm and locating the birthplaces of lightnings. The airplane used in the reported tests was limited to areas below the storm and outside heavier precipitation and turbulence.

Future work:

About four successful flights have been accomplished during the Flagstaff field tests 1966, showing either a rapid field decay of strong fields or corona discharge after chaff seeding. It is planned to back up these results by at least 10 but not more than 20 test flights of the same type and with the same airplane. One surprising result of the 1966 test flights was the location of a small area below the storm with relative high electric fields in the order of several 100 kv/m. Only light precipitation is found in this area without any remarkable meteorological conditions (absence of turbulence, strong up or down drafts, icing, and so on). A thorough investigation of this area even without chaff seeding is highly desirable.

The next step in the lightning suppression program is to equip an airplane capable of penetrating a thunderstorm at higher altitudes with the same instrumentation as installed in the C-47. Tentatively the ESSA plane DC-6 (Douglas) is proposed for this task. The flight procedure would be similar to that worked out in the previous test flights with the C-47. The objective would be to locate the places of origin of lightning discharges inside the cloud (areas with highest electric fields) and to observe the result of chaff seeding in these areas. It is expected that the effect of chaff seeding here is much more pronounced then in the areas below the cloud.

Two mobile ground stations have been equipped with lightning recording and direction finding instruments. The final goal is to develop a system which automatically plots the location of the lightning flashes occurring inside an area of about 30 miles diameter, and records simultaneously the electric field of each lightning in sufficient detail, to determine the characteristic parameter of the flash. The purpose of the ground station is to establish the influence of chaff seeding on the life history of lightning discharges of the individual storm.

The field recorder is developed to its final stage and works reliably in the desired frequency range.

The direction finding equipment is incomplete. Several methods have been tested but none of them work satisfactorily at the present time. It is planned to improve the instrumentation during 1966 and 1967 at the APCL in Boulder, Colorado and have it in proper working condition for the planned Flagstaff expedition 1967.

Table 2.1. Electric Field Measurements and Chaff Seeding under Thunderstorms in Flagstaff 1966

Date	Time	Fz	Fx	Fy	Corona	Tape	Seeding
22.7.66	-	X	X	X			
23.7.66,FL	-	X	X	X			
23.7.66,2FL	1509- 1551	X	X	X			
25.7.66,1FL	0957- 1104	X	X	X			
25.7.66,2FL	1446- 1539	X	X	X			
26.7.66,1FL	0851- 0945	X	X	X			
26.7.66,2FL	1603 1745	X	X	X			
27.7.66		X	X	X			

Date	Time	Fz	Fx	Fy	Corona	Tape	Seeding
28.7.66,1FL	1038- 1135	X	X	X			
28.7.66,2FL		X	X	X			
28.7.66,3FL	1655- 1751	X	X	X		X	
29.7.66,1FL	1116- 1303	X	X	X		X	
29.7.66,2FL	1357 1621	X	X	X	X	X	
30.7.66,1FL	1000- 1153	X	X	X	X	X	X
30.7.66,2FL	1411- 1611	X	X	X	X	X	X
1.8.66,1FL	1017- 1259	X	X	X	X	X	X
1.8.66,2FL	1500- 1619	X	X	X	X	X	X
2.8.66,1FL	-	X	X	X	X	X	
2.8.66,2FL	1430- 1615	X	X	X	X	X	X
3.8.66	-	X	X	X	X	X	
4.8.66	-	X	X	X	X	X	
5.8.66	-	X	X	X	X	X	
6.8.66	1106- 1208	X					

Fz: Field component vertical (Back-Belly)

Fx: Field component horizontal (Wing-Wing)

Fy: Field component horizontal (Head-Tail)

Corona: Recording of corona - discharge with Litton Corona Meter

Tape: Field components, corona, and voice recorded on tape recorder

Seeding: Chaff seeding

Raindrop Spectrometer - A. M. Nathan

This report has been edited from a letter from Nathan in which he described the operation of the raindrop spectrometer during the 1966 project.

The New York University automatic raindrop spectrometer was transported to Flagstaff for field trials during early July 1966. Unfortunately, it arrived in an inoperable condition from rough treatment during shipment. Consequently, a good part of the month of July was spent in restoring it to working order.

By the end of July, it was operating in reasonable fashion and efforts were made to calibrate the device on site (roof of Fleischman Hall, Museum of Northern Arizona). This site was within approximately 50 yards of the Illinois Drop Camera with which it was hoped to compare data.

The calibration procedure proved to be difficult in the field; and, although 3 days' worth of data were obtained (August 6, 7, and 8), the data were not self-consistent. Post-test diagnosis suggests that optical alignment was imperfect and calibration somewhat uncertain.

Once the machine had been repaired, its operation under both test and natural conditions was entirely satisfactory even though the data recorded are of doubtful value because of the misalignment. It is believed that the techniques utilized by the instrument are basically practicable, but that improved alignment methods must be incorporated.

Comparison of the data accumulated on August 6, 7, and 8 with simultaneously obtained data of the Illinois camera should be carried out to complete an evaluation of the instrument's performance.

Raindrop Spectra - E. A. Mueller

A raindrop camera developed under previous Army sponsorship was operated at the Northern Arizona Museum research site north of Flagstaff. One of the prime intents was to evaluate the raindrop spectrometer developed by New York University. Concurrent data was obtained on August 8, but it is understood by personal communication with A. Nathan that the spectrometer was not operating properly. Operation of the raindrop camera was successful and data were obtained on 10 days during the period. Two of these days had very little rain and have been discarded from the analysis. There were 485 minutes of data on the remaining eight days.

There are several interesting results from this data which are reported in the following sections.

Radar-Reflectivity Relationships for Flagstaff

Table 4.1 shows the regression coefficients between rainfall rate and radar reflectivity. The calculations have been performed considering the radar reflectivity as the independent variable. In addition to the regression for individual days, there are grouped data for the high concentration days and for the low concentration days. This distinction will be discussed further in a following section. The coefficient for these regressions is much higher than is usual. This is especially true for the days in August and in the low concentration group. For all of this data, it is apparent that there is a paucity of small drops. When the coefficient of the regressions is high, it is an indication that the low rainfall rates have large raindrops which contribute strongly to the reflectivity. Only one other storm day at any of the 8 other locations sampled by a drop camera had a coefficient as high as the individual August storms or the low concentration group.

Overall, these relationships show that the raindrops in Flagstaff are relatively large. This general tendency has been noted but not published by other investigators. Foote of the Arizona Institute for Atmospheric Physics gave a relationship of $Z = 520\ R^{1.81}$. This relationship does have a high coefficient although not as high as the low concentration cases. The exponent is much larger than that of the Flagstaff data. This larger exponent indicates the larger importance of large drops at the higher rainfall rates. Hardy (1962) reports a relationship of $Z = 460\ R^{1.41}$ for 31 July 1961 from Flagstaff. Thus, it appears that all drop size investigations in this area tend to have large coefficients. The drop size spectra given by Hardy show more 0.5 mm drops than were measured using the drop camera, but, apparently, there was an insufficient number to influence the R-Z relationship. Hardy attributes the high coefficient primarily to evaporation, which may indeed be quite effective in this area. However, as is shown later, this does not explain the differences of the high and low concentration cases. Hardy's regression assumes that Z is a function of R.

The relationships from the Flagstaff data do not scatter about the regression line as much as the data from other locations. The standard error of estimate is a good measure of this scatter despite the failure of the data to be normally distributed. As can be noted from Table 4.1 , the standard error of estimate varies from 0.09 to 0.158 for this data. Most of the values are near 0.13. This is contrasted to Miami data, where the standard error of estimate is around 0.17 on the average, with values of 0.2 not uncommon. From this it may be argued that there is more consistent relationship in these data than elsewhere; a statement which seems to be supported by the lack of as much short time variability of rainfall rates as predicted from drop size data. Thus, it would seem that this supports the validity of the one-cubic-meter sample as being more nearly adequate in the Flagstaff rain than elsewhere.

The relationships predict a greater amount of radar return at Flagstaff for the same rainfall rate than the other locations for which drop size spectra are available. This seems somewhat paradoxical, since it has been observed that the non-precipitating clouds are less likely to be seen by radar in this area than central Illinois (Jones, et al., 1967). As discussed elsewhere, the lack of scattering from the clouds may be due in part to extremely high concentrations of small cloud droplets although the concentration of raindrops at ground level appears to be abnormally low.

It may be noted that when the high and low concentration data are combined, the resulting relationship has a larger standard error of estimate. This is to be expected, of course. The exponent from this relationship is larger or equal to any of the individual exponents and is approaching the value from Foote's data. All of the regressions have been determined considering the reflectivity as the independent variable. If the rainfall rate had been considered as the independent variable, the coefficients would be higher and the exponents lower.

Table 4.1. Radar Reflectivity-Rainfall Rate Relationships from Flagstaff

Date or Group	$Z = AR^b$ A	b	Correlation Coefficient	Standard Error of Estimate	No. of cubic meters in sample
7/18	577	1.58	0.981	0.120	20
7/21	439	1.44	0.984	0.103	101
7/25	569	1.54	0.891	0.132	21
7/27	493	1.42	0.990	0.093	42
7/29	566	1.61	0.954	0.131	61
8/2	830	1.43	0.960	0.158	36
8/8	904	1.62	0.986	0.093	61
8/10	884	1.60	0.972	0.113	100
High Concentration	490	1.47	0.979	0.123	245
Low Concentration	889	1.55	0.974	0.128	197
All Data	593	1.61	0.969	0.153	442

Table 1.2. Comparisons of Rainfall Amounts from the Raingage and from the Raindrop Camera

Date	Amount of rain (mm) Raingage	Drop Camera	Percentage Error + indicates an excess of drop camera	Duration of rain (minutes)	Max. rate drop camera mm/hr
8/8/66	2.8	2.88	+ 3	19	37.1
8/10/66	2.8	2.96	+ 6	31	51.7
7/27/66	6.3	5.10	-14	44	49.3
7/21/66	8.6	9.20	+ 7	92	76.6

During preliminary data analysis, two different regimes of rainfall were noticed. Before speculating on the reasons for these differences, some of these differences will be examined.

Differences in Concentration

The total number of raindrops per cubic meter of air space will be referred to as the concentration. Figure 4.1 shows concentration versus rainfall rate for 4 days. It should be noted that the two graphs on the top of the page have higher concentrations than the two on the bottom. All of the Flagstaff data tend to separate easily into these two groups which will be called the high and low concentration groups. The differences in concentration are sufficiently large to make it highly improbable that the differences are a result of sampling error or of any sorting effects of either the raindrop camera or of its immediate surroundings. There are a few points which overlap from one group to the other.

There were 5 days in which the concentrations were high. These dates were July 18, 21, 25, 27, and 29. There were three days, August 2, 8, and 10, in which there were low concentrations. If the high concentration cases are compared with data from other locales, it is found that the differences are not great. On an individual day basis, there were days at Miami which produced concentrations greater than the highest concentration but, after examining the data, there were no cases of concentrations as low as found on August 8 and 10.

It was conjectured that perhaps the raindrop camera in some way was faulty. One possible difficulty would have been that the focusing was incorrect so that the volume sampled was incorrectly judged. That is to say that, if the point of best focus was inside one of the shelters, the drops which were measured were only those in a small volume near the shield in which the focus point was located. If this were true, the rainfall rates calculated from the drop camera would have been lower than actual. Table 4.2 has a comparison of the drop size data and the raingage data for these 4 days. The drop camera amount is obtained by integrating the calculated rainfall rates. Since the rates from the drop camera integrate to values of rainfall somewhat larger than determined by the raingage, the thesis that there is large instrumental error of this type is untenable and is rejected. For all but August 8, the drop camera was operated for 15 seconds of each one-minute period. On August 8, the camera was operated continuously during the minute. It may be fortuitous, but this may account for the better agreement on this day than others. In general, at other locations the drop camera amounts have tended to be less than raingage amounts by 10 to 15 percent. This has been attributed to either errors in the terminal velocities of the raindrops or to wind sorting effects of small drops in the vicinity of the raindrop camera shelters.

The drop data were separated into the two groups of low and high concentration, and average distributions calculated for each group. These average distributions, shown in figures 4.2 and 4.3, separated into rainfall

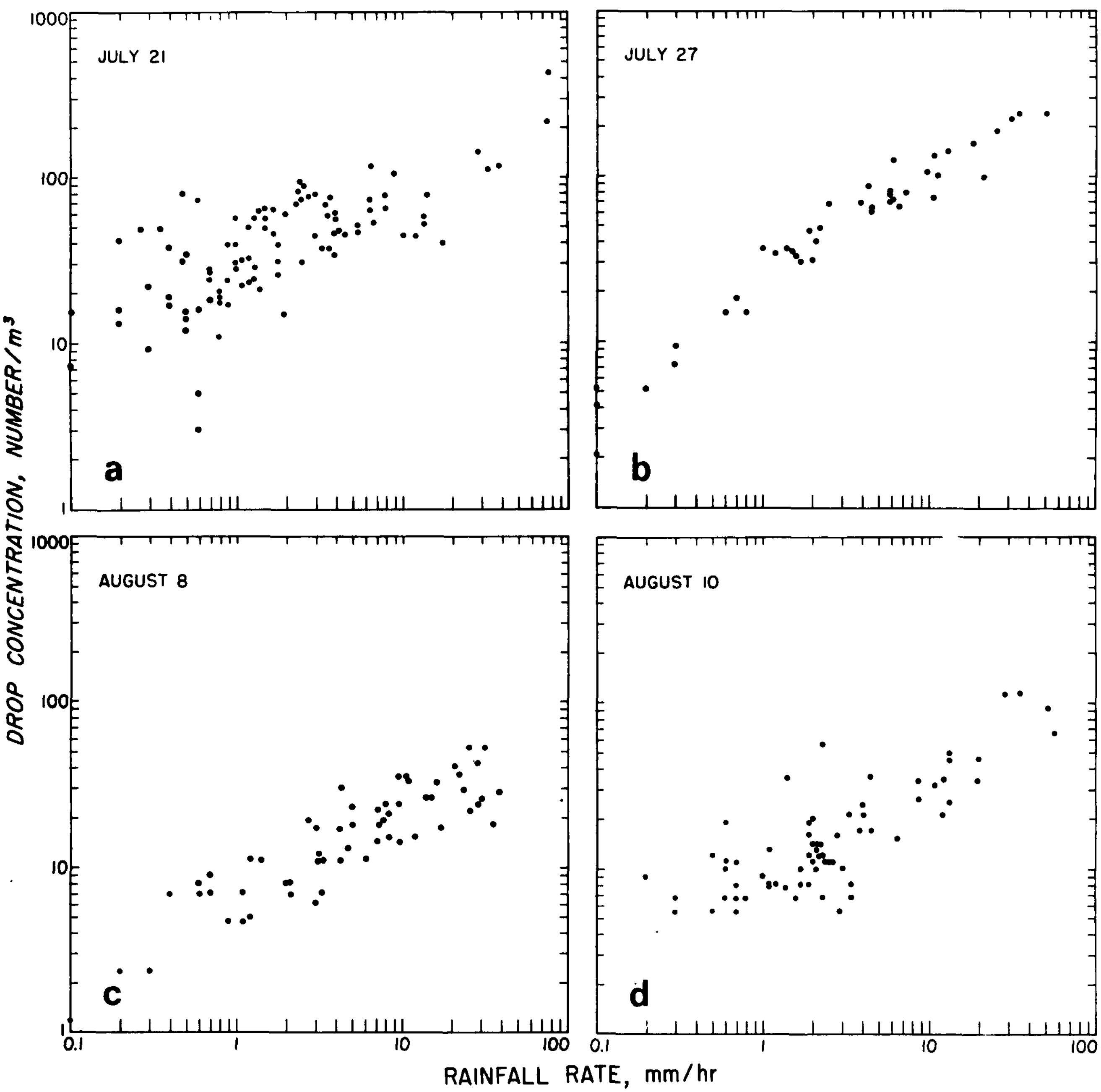

FIG. 4.1. DROP CONCENTRATION VS. RAINFALL RATE FOR FOUR DAYS AT FLAGSTAFF, ARIZONA

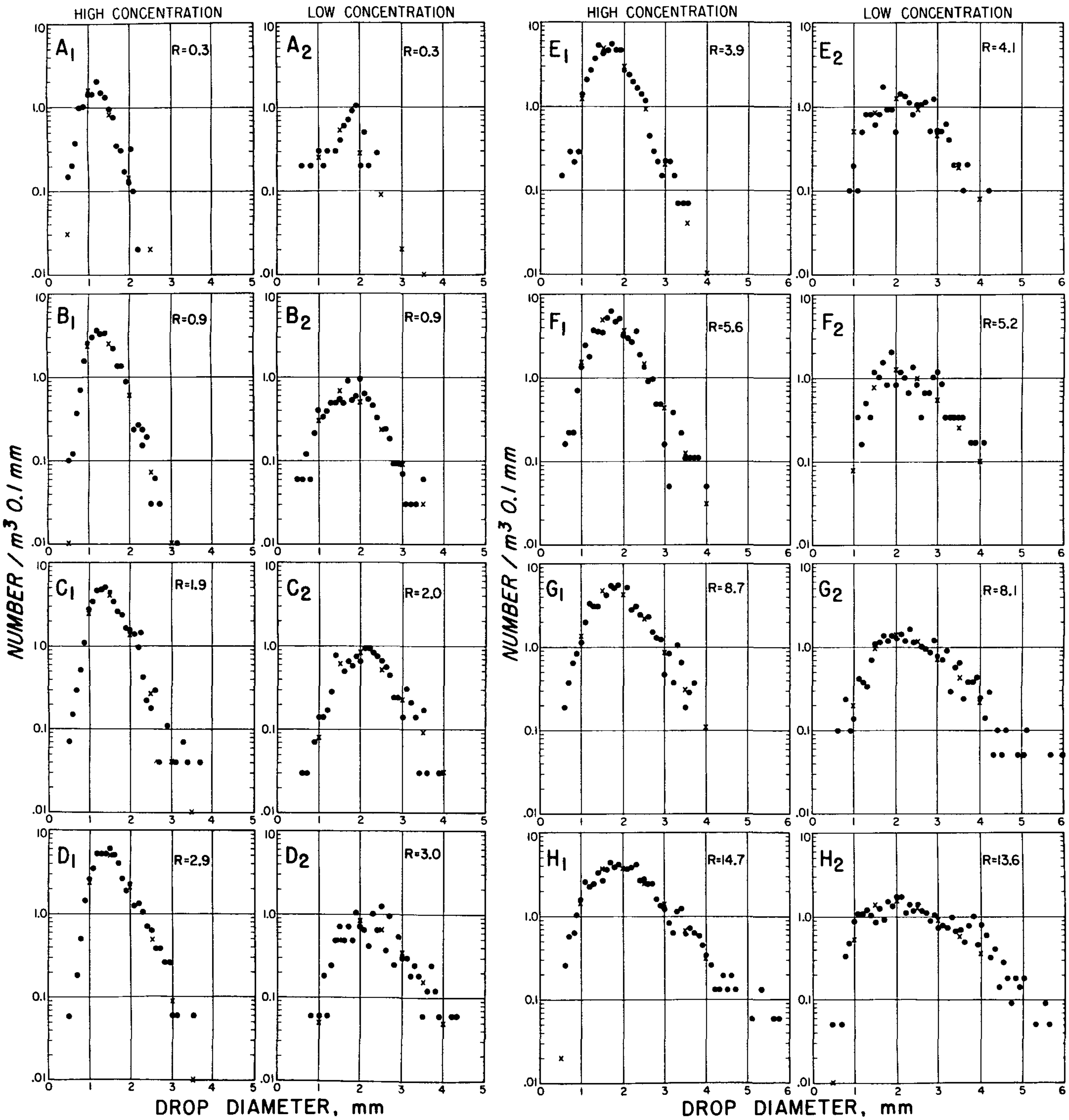

FIG. 4.2. AVERAGE DROP-SIZE DISTRIBUTION FOR THE LOW AND HIGH CONCENTRATION CASES

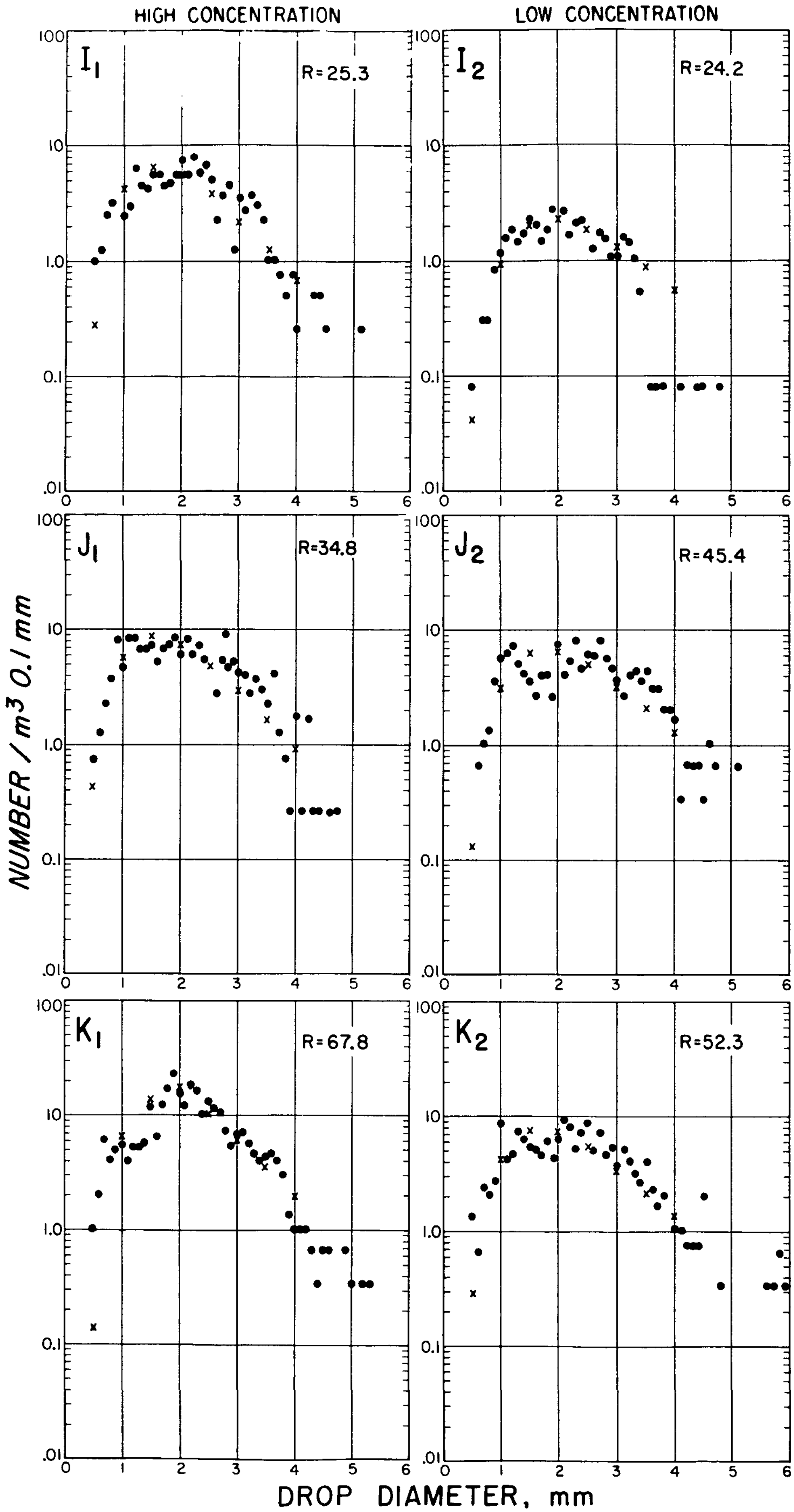

FIG. 4.3. AVERAGE DROP-SIZE DISTRIBUTION FOR THE LOW AND HIGH CONCENTRATION CASES

rate intervals and serve to reduce the sampling noise considerably. The resultant distributions, particularly in the high concentration group, appear to be reasonably smooth spectra. From previous work, it has been noted that logarithmic normal distribution is the best fitting equation for drop size spectra. Values from the log normal fitting curve are plotted as X's on multiples of 0.5 mm. At the very least, the log normal curve provides an excellent means of further smoothing the data. Thus, values of the modal diameter, width of the spectra, rainfall rate, and liquid water content can be calculated from the log normal parameters. In most cases the results of computing the rainfall rate from the average distribution directly compares favorably with the calculation from log normal coefficients. There are two notable exceptions. If the number of cubic meters in the average distribution is small and if there are a few large drops, there is a significant difference in the calculated rates. This is true because of the poor estimate of the average number of large drops due to small sample volume. This is the case in figure 4.3, where the distribution rate is 67.8 and the log normal rate is 87.28. In this case there is only 3 cubic meters of sample so that for any interval, a concentration less than $0.3/m^3$ cannot be measured. The other exception occurs with an obvious misfit of the log normal curve. Such cases are demonstrated by the lowest and highest rainfall rates of the low concentration case.

With these exceptions noted, the log normal parameters were used to calculate the diameter of the mode, D_m, the width of the spectrum at 1/2 number of the mode points, W, and the mean volume diameter, D_v. The mean volume diameter is defined as the size of drop whose volume multiplied by the concentration yields the liquid water content.

The three statistics, D_m, D_v, and W are plotted in figure 4.4 as a function of rainfall rate. The width remains nearly 0.5 mm larger for the low concentration case for all rates. In both cases the width increases with rainfall rate. It can be noted that these two groups of data do have much different characteristics.

There is a tendency for some of the curves to converge at the higher rainfall rates. This may indicate that whatever the mechanism which is producing these distinct groups, it may become less important at the higher rainfall rates. Unfortunately, this conclusion does not help much in eliminating possible reasons for these discrepancies since evaporation, cloud seeding, and drop generation mechanisms may all be less effective when the dynamics of the storm become the overwhelming force in producing rain.

As in previous data, the diameter of the mode of the distribution tends to pass through a maximum and decrease as the rainfall rate increases. In the low concentration case, this maximum is at 3 to 4 mm/hr. The high concentration case has its maximum at 10-15 mm/hr. Miami data has a peak of the mode at rainfall rates of 4-0-50 mm/hr. One explanation of these differences is the evaporation which takes place after the raindrops leave the cloud. Evaporation tends to produce the effect of increasing the

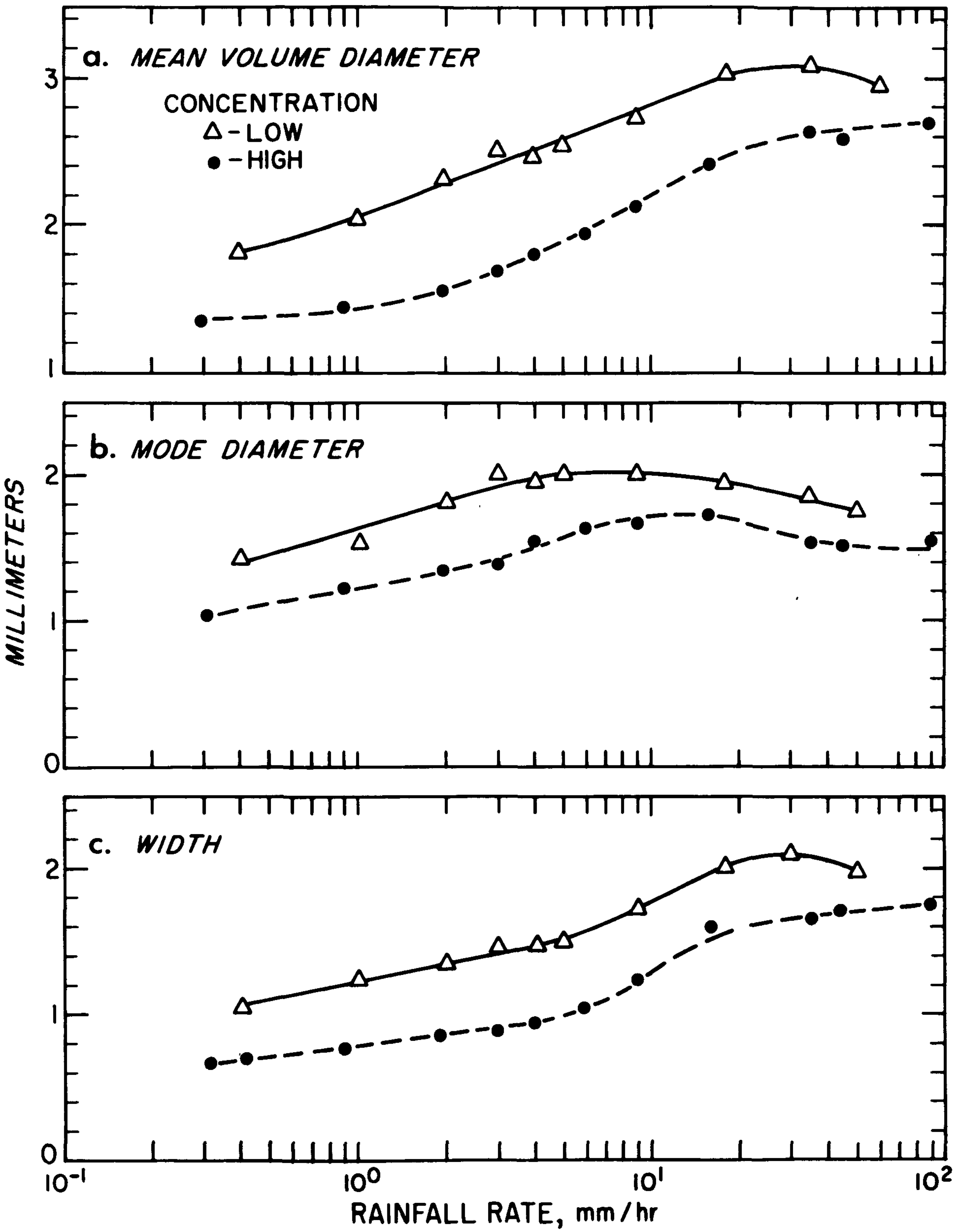

FIG. 4.4. COMPARISON OF RAINDROP SPECTRA PARAMETERS WITH RAINFALL RATE FOR LOW AND HIGH CONCENTRATION CASES

diameter of the mode. Further, it appears that at high rainfall rates evaporation becomes less important and the modes shift to lower values. Thus, if the low concentration is due to increased evaporation, it is reasonable to expect the maximum mode to occur at lower values of rainfall rate.

Differences in Spectra

There are a number of conditions which may have produced the differences in spectra. These are cloud modifications by silver iodide seeding, evaporation, droplet growth by sublimation or coalescence, and a sampling error by virtue of either wind or gravitational sorting. These will be discussed in the ensuing paragraphs, but at the onset it should be pointed out that the ability to reach a firm conclusion on the basis of this rather limited sample is impossible. Some of the hypotheses would seem more likely than others, but none can be completely eliminated.

Silver Iodide Seeding

Meteorology Research, Incorporated, under contract from the Bureau of Reclamation, was conducting an experiment in weather modification in the Flagstaff area concurrently with this investigation. This group seeded with silver iodide generators from both ground stations and from aircraft. A personal communication from D. M. Takeuchi of MRI indicated the days during which he felt that their seeding activities could have influenced the rainfall in the vicinity of the research center. This information, along with the analysis of the raindrop spectra, is shown in table 4.3.

Table 4.3. Comparisons of MRI Seeding Activities with Drop Size Spectra

Date	Influenced by seeding	Concentration class	Notes
7/18	Yes	High	
7/21	Yes	High	
7/25	No	?	Small sample and rates < 1 mm/hr
7/27	Yes	High	
7/29	Yes	High	
8/2	No	Low	
8/8	Yes	Low	
8/10	No	Low	

On 7/25, Takeuchi did not believe that the seeding would have affected the drop camera spectra. Notes taken at the MRI debriefing would indicate that there was considerable doubt as to the location of the silver iodide. There were only 14 spectra obtained on this day and the rates were all very low, but if a decision as to which group had to be made, this day would have to be considered as a high concentration day. The data on 8/8/66 are complete and there is no doubt that this is a low concentration day. There is some doubt as to whether the silver iodide was ingested by the rain cloud over the camera. Seeding was accomplished northwest of the San Francisco Peaks with light and variable winds. The radar echoes on this day did move from the northwest, but at relatively low speeds.

The agreement between high concentrations and silver iodide seeding is suggestive that the silver iodide is affecting the rainfall mechanism. Furthermore, such an effect is in the direction which would be expected from the physics of cloud seeding.

The high concentration group contains spectra which are similar to spectra from other locations. The concentration-versus-rate relationship is about the same as was obtained at Miami, Florida. It may be argued that evaporation effects and ice nuclei deficiencies are more prevalent in Flagstaff than in Miami, and seeding is required to bring the storm system to equivalent states.

If it is assumed that the silver iodide seeding was the prime reason for the spectra differences, there remains the necessity of explaining why the unseeded spectra are so different from those obtained elsewhere. The data from Foote do appear to be as closely related to the low concentration days as to the high, and thus it cannot be categorically stated that the low concentration days are not the normal situation.

Gravitational and Wind Sorting Effects

It is conceivable that on the edges of shower cells, a drop size spectrum may exhibit unusually large drops and thus a lower concentration for a given rainfall rate. It is common to experience large drops at the onset of rain at a point, and if it is assumed that for the entire rain period an observer was located on the edge, a biased estimate may well result. In an attempt to evaluate the possible occurrence of this bias, the data from the MPS-34 radar were examined. A brief summary of the radar observations for 4 days of good camera data follows.

On 7/27 between 1210M and 1300M, an echo formed just south of the drop camera. This echo intensified and moved slowly northward during the data collection. The echo developed an anvil which spread westward during the heavier rainfall periods. By 1240M, the core of the storm had passed just east of the drop camera and was located northeast of the site. The rainfall gradient was very sharp. By 1245M there remained only light echo over the site with rainfall rates from the drop camera of 0.1 to 0.3 mm/hr. It would appear that all parts of this storm were sampled sufficiently.

On 8/8/66, two echoes passed over the drop camera. The first data at 1310M was when the core of the first echo was east of the site. The echo moved southeastward and changed from a large (7-mile diameter) echo into a number of smaller and less intense echoes. At 1320M, a small cell was located west of the site. This second cell grew rapidly and passed directly over the drop camera. This second cell became more intense than the first echo, but did not grow to the same size. By 1340M, the second cell was the only echo remaining, and had passed beyond the drop camera. On this day, the data may have been biased somewhat by the first cell, but the second cell tracked directly over the site. It was, however, in a growing stage during its passage and this may have contributed to some bias.

On 7/21, the rain was from a very large echo which was centered southwest of the radar. This echo moved northward during the course of the observations. Within the large echo mass, several cells were included. The rain was quite general. It is not likely that any edge effect or growth phase was unduly biasing the drop camera results.

On 8/2/66 the rain began at the camera at 1403M falling from showers to the east of the site. The rain was too light at this time to be measured by the raingage with an over-sized receiver. By 1433M a developing cell southeast of the camera had moved and grown sufficiently to the northwest to have the camera near the center of the heaviest rain. The heaviest rain continued to fall over the camera until 1500M when the cell began to dissipate and move to the north. Thus, the camera photographed the raindrops from a shower which was over the camera during its maximum development and should not have an undue amount of edge or growth bias.

Unfortunately, no radar data are available for 8/10. The radar waveguide broke on 8/9, eliminating the possibility of observations on 8/10, the last day that data were taken. The results of the radar analysis are mostly negative in that no apparent biases due to locations of the echo or growth phases can be discerned.

Evaporation Effects

Evaporation effects on drop size distribution tend to be more effective on the small raindrops. Thus, qualitatively one might expect that if rain fell through a dry, warm layer, the large drops would become more important in the resulting distribution. As a result, one might expect lower concentrations. Since, indeed, the climate of Arizona is such that evaporation may be quite significant, and the shifts are in the direction observed, an investigation of evaporative effects was undertaken.

Radiosonde data provided by the U. S. Army meteorological team gives the environmental temperatures and humidities on the days for which drop size data are available. An abstract of this data is shown in table 4.4. No radiosonde data is available for 8/10. The data on 7/18 is extrapolated from an early morning sounding. On other days, it was usual to find very small changes in the moisture between the early morning sounding and the late morning sounding. It also was common for the temperatures between 700 mb and the surface to become nearly adiabatic between soundings. Thus, to estimate the surface temperature, humidity, and lifting condensation level, the adiabatic lapse rate from 700 mb temperature was used. There were no soundings on 7/19, but on the early morning sounding of 7/20, a considerable amount of moisture had entered the Flagstaff area. The surface mixing ratio changed from less than 5 g/kg on 7/18 to more than 12 g/kg on 7/20. Thus, it may be that the sounding on 7/18 is not representative of the rain time. The case of 7/18 is belabored, since it does not appear to fit with the rest of the data if evaporation is the cause of the concentration effects noted.

If the 7/18 is ignored, the two classes of high and low concentration are separable into two identical groups with respect to the humidity. The low concentration cases occur with surface humidities of 45 and 48%, while the high concentrations occur from 50 to 63%. The 7/27 case where the surface humidity is 50% is a marginally high concentration as mentioned elsewhere. The humidity differences are even more pronounced at the 700 mb level. Here, the low concentration cases are much drier. The differences in lifting condensation levels are also apparent in table 4.4,

In an attempt to make the evaporation arguments more quantitative, the evaporative effects on drop size distributions from the lifting condensation levels to the ground have been examined. Kinzer and Gunn experimentally derived tables of rate of evaporation. Their equation (29) is:

$$\frac{dM}{dt} = 4\,\pi\, aD\,(\rho_a - \rho_b)\,(1 + \frac{Fa}{s'})$$

where $\frac{dM}{dt}$ = mass rate of evaporation and the two factors

$$4\,\pi\, a(1 + \frac{Fa}{s'}) \quad \text{and} \quad D(\rho_a - \rho_b)$$

are empirically determined and listed in tabular form. For convenience, let the first factor be called A and the second B. Then:

$$\frac{dM}{dt} = AB$$

Since:

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

where D = diameter of the drop in cm and p = density of water

$$\frac{dM}{dt} = \frac{\rho \pi D^2}{2} \frac{dD}{dt}$$

and

$$\frac{dD}{dt} = \frac{2}{\pi \rho D^2} \frac{dM}{dt}$$

If the drop is falling at its terminal velocity V, then

$$\frac{dD}{dt} = \frac{dD}{dZ}\frac{dZ}{dt} = V\frac{dD}{dZ}$$

where Z = the height coordinate.

Combining and writing in differential form:

$$dD = \frac{2AB}{\pi\rho D^2 V} dZ$$

For convenience in interpolating values, the initial drop size distribution at the ground will be approximated by the logarithmic normal distribution. Let N(D) dD represent the distribution at ground level, and N(ξ) dξ the distribution which after undergoing evaporation yields N(D) dD at ground level.

Then:

$$D = \xi - \frac{2\ AB}{\pi\rho\xi^2 V} \Delta Z$$

Table 4.4. Environmental Conditions on Days of Drop Size Data

	Time	Ground		700 mb		Height
	MST	RH	Temp	RH	Temp	LCL (km MSL)
7/18	*	35	25	42	14	4.1
7/21	1055	55	22.1	74	11.0	3.3
7/25	1040	56	22	59	13.5	3.35
7/27	1030	50	24.3	56	14.2	3.57
7/29	1210	63	22	78	12.0	3.1
8/2	1030	45	26.2	38	13.0	3.72
8/8	1000	48	23.2	48	14	3.7

*Estimated from 0530 7/18 sounding.

Table 4.5 shows the magnitude of changes of the drop diameters for the environmental conditions on 7/29 and 8/2.

As the diameter of the drop changes, the terminal velocity of the drop changes. This leads to the so called "traffic problem". This can be compensated by considering the number of drops within a volume defined by unit area in the horizontal and height equal to the terminal velocity. As the evaporation process continues and provided the drops do not completely evaporate, the number of drops in a new volume defined by unit area and the new terminal velocity will be the same as before.

Thus

$$N(\xi)\, d\xi\, V_\xi = N(D) dD V_D$$

and

$$N(\xi) = N(D) \frac{V_D}{V_\xi} \frac{dD}{d\xi}$$

This latter equation was programmed for steps of 100 m from the surface

Table 4.5. Evaporation Effects on Drops for July 29 and August 2.

Diameter at ground level (mm)	Diameter at lifting condensation level (mm) 7/29	8/2
.5	0.85	1.17
1.0	1.23	1.44
1.5	1.65	1.81
2.0	2.11	2.24
2.5	2.60	2.71
3.0	3.09	3.20
3.5	3.59	3.70

to the lifting condensation level. These calculations were performed for each of the average distributions for the low and high concentration conditions. The nature of the problem is such that no information of the number of small drops aloft can be determined since these evaporate before reaching the ground. However if one examines only the concentration of drops larger than 2.0 mm, it can be seen that the evaporation does not make the two distributions similar although they are closer than initially. Table 4.6 shows the values for three of the lower rates for both concentrations. It can be noted that even after evaporation the number of drops in larger sizes is not comparable. Only the lower rates are considered since the evaporation is proportionally less for the higher rates. The rainfall rate calculated at the lifting condensation level (LCL) must be considered fictitious since the concentration of small drops is unknown. Thus this rate is only the rate from the larger drops which survive the fall to the ground. It may be noticed that the percentage increase in rainfall rates for the low concentration is always less than or equal to the percentage increase in the high concentration. That is to say the effect of the drier environment on the low concentration case is not sufficient to override the relatively large number of big drops.

Figure 4.5 shows 2 examples of the drop size spectra after evaporation has taken place. Again it would certainly seem that these two distributions are sufficiently different that evaporation cannot explain the differences noted between the high and low concentration cases.

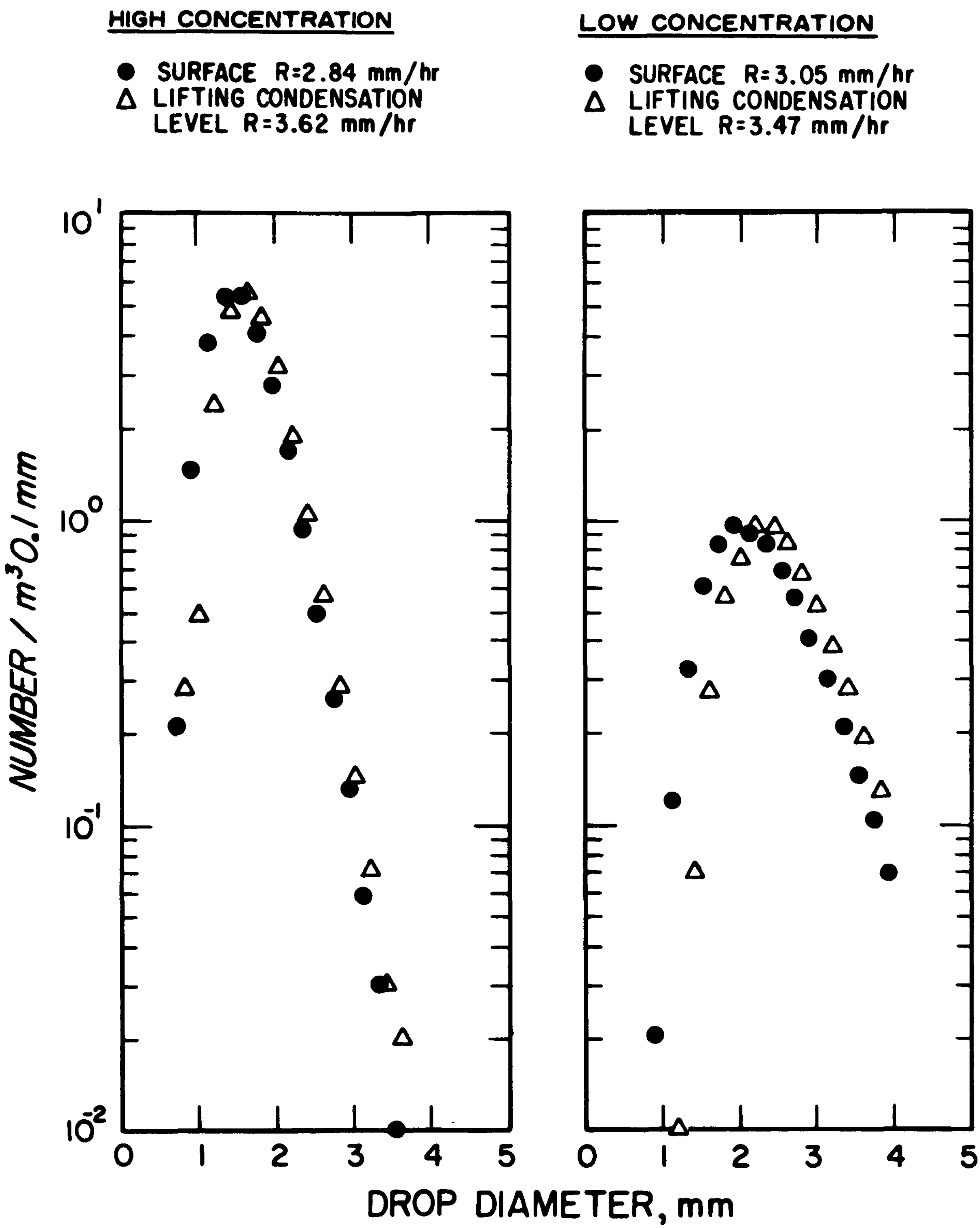

FIG. 4.5. DROP SIZE SPECTRA AFTER EVAPORATION

In summary evaporation apparently does explain qualitatively the high coefficient in the radar reflectivity rainfall rate relationship but does not explain quantitatively the differences between the different cases at Flagstaff.

Table 4.6. Numbers of Drops in 0.5 mm Intervals for Three of the Lower Rates for High and Low Concentration Cases

Rainfall rate at surface mm/hr	Rate aloft	Concentration type L = low H = high	Number of drops between 2.0 and 2.5	Number of drops between 2.5 and 3.0	Number of drops greater than 3.0 mm
1.06	1.41	L	2.91	1.41	.75
.93	1.23	H	2.64	.35	.03
3.05	3.47	L	4.70	4.21	2.76
2.84	3.62	H	9.76	2.18	.46
4.94	5.72	L	8.23	6.31	4.39
3.98	4.93	H	13.69	4.08	1.07

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Jones, D. M. A., R. E. Rinehart, E. A. Mueller, and D. W. Staggs, 1967. Evaluation of the maser-equipped radar set AN/MPS-34 and area precipitation measurement indicator. Illinois State Water Survey, Final Report on Contract No. AMC-01257(E).

Kinzer, G. D. and R. Gunn. The evaporation, temperature and thermal relaxation-time of freely falling waterdrops. Journal of Meteorology, Vol. 8, No. 2, April 1951.

Foote, G. B., A Z-R relation for mountain thunderstorms, Journal of Meteorology, Vol. 5, April 1966, pp. 229-231.

Raindrop Camera and Meso-Network Precipitation - D. M. A. Jones

It has long been recognized that the drop size-distribution will probably vary for any given time spatially along a chord through a rainstorm. Although it was realized before the installation of the equipment that a closely-spaced network of recording raingages would be necessary to delineate the chronological and spatial variations in intensity of the rainfall measured by the raindrop camera, neither the time nor the instrumentation was available for such a network. As a first approximation, an accelerated raingage recorder fitted with an expanded collector was installed within 15 ft of the camera and four inexpensive non-recording gages were placed on a one-half mile radius of the camera. The intention was to read these non-recording gages after each shower, but this was accomplished only once for lack of personnel and space between showers. Instead, all gages were serviced routinely once each 24 hours, usually near 0900 MST. The 24-hr rainfall from this meso-network are given in Table 5.1. A map of the gage locations is shown in figure 5.1.

Table 5.1 . Precipitation Around Raindrop Camera for Twenty-Four Hour Period Ending at 0900 MST of Date Shown

Date	RC	NW	NE	SE	SW
7-11-66	.00				
7-12	.00				
7-13	.00				
7-14	.00				
7-15	T				
7-16	.04				
7-17	.00				
7-18	.04				
7-19	.22				
7-20-66	.04	.01	.02	.02	.01
7-21	T	.00	.00	.00	.00
7-22	.91	.76	.99	.76	.80
7-23	T	.00	.00	.00	.00
7-24	.00	.00	.00	.00	.00
7-25	.13	.05	.17	.10	.11
7-26	.04	.03	.03	.01	.02
7-27	*	.20	.18	.29	.26
7-28	.36	.10	.10	.12	.10
7-29	.00	.00	.00	.00	.00
7-30-66	.17	.17	.20	.14	.22
7-31	.02	T	.03	.00	.00
8-01	.00	.00	.00	.00	.00
8-02	.00	.00	.00	.00	.00
8-03	.59	.38	.24	.48	.40
8-04	.00	.00	.00	.00	.00
8-05	.00	.00	.00	.00	.00
8-06	.00	.00	.00	.00	.00
8-07	.02	*	*	*	*
8-08	.01	.01	T	.05	.16
8-09	.12	.01	.19	.30	.03
8-10-66	.00	.00	.00	.00	.00
8-11	.11	.14	.39	.08	.09

* amount included in the next day's total

In general, the gage with the highest total rainfall for the period of operation was closest to the San Francisco Peaks.

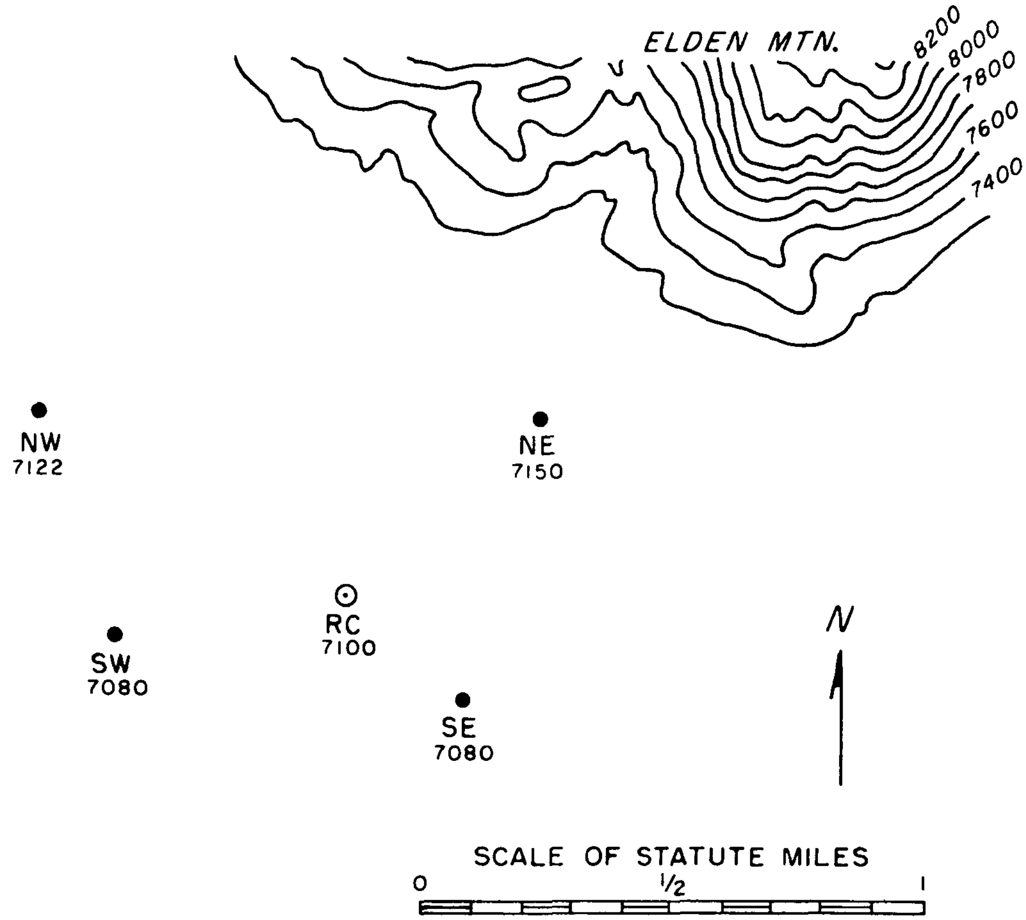

FIG. 5.1. MAP OF RAINDROP CAMERA AND NEARBY RAINGAGES

Condensation Nuclei - R. G. Semonin

The chloride particulate content of the Flagstaff, Arizona air was sampled during the period from July 26 through August 11 at the Navajo Depot. A ground-based sampling unit available from the Millipore Filter Corporation, Bedford, Massachusetts was used to obtain twice daily samples. Their 47 millimeter in diameter, type AA filters were used in the system. The sampling time was varied according to the operational work load imposed by the radar program. However, the flow rate through the sampler was constant at 10 liters per minute.

The samples were sealed and stored in plastic petri dishes and subsequently were sent to the Cloud Physics Laboratory of the Water Survey in Champaign for analysis. The techniques for analysis have been discussed by Semonin and McCrady (1961) and Semonin (1966).

The results obtained from the analysis of 22 samples are shown in Figure 6.1. The actual particle count on the slides was normalized by volume so that the results are presented as the number of particles per cubic meter. The number of chloride particles, as indicated in Figure 6.1, ranged from 424 to 2800 particles per cubic meter. The size of the individual particles ranged from 1.32 microns (limit of resolution) to 59.4 microns in diameter. In general, the width of the size spectrum increased with increasing total number of particles per unit volume.

The purpose of the data collection was to examine the relationship between the influx of chloride particles and the strength of the Arizona monsoon. The implicit assumption is made that the particles are of marine origin. The synoptic weather data required to obtain a measurement of the monsoon strength were not available for detailed comparison with the particle analysis. In addition the observational frequency was inadequate to allow a more detailed analysis of individual situations. For example, the interplay between the cumulus clouds and the nearly daily occurrence of cirrus could play an important role in the number of observed chloride particles. If the sub-cloud layer is quite dry, as is often the case in Arizona in the summer, then cumulus clouds penetrating the cirrus level could bring particles from aloft to the surface as evaporated droplets. The development of trajectories from synoptic studies would not indicate this type of transport mechanism.

A more comprehensive program should be developed for the collection of this type of data along with detailed notes on the synoptic weather during the program period in order that the full potentiality of the technique as an atmospheric tracer can be realized.

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Semonin, R. G., 1966: "Observations of giant chloride particles in the Midwest," J. de Recherches Atmospheriques, 2, 251-260.

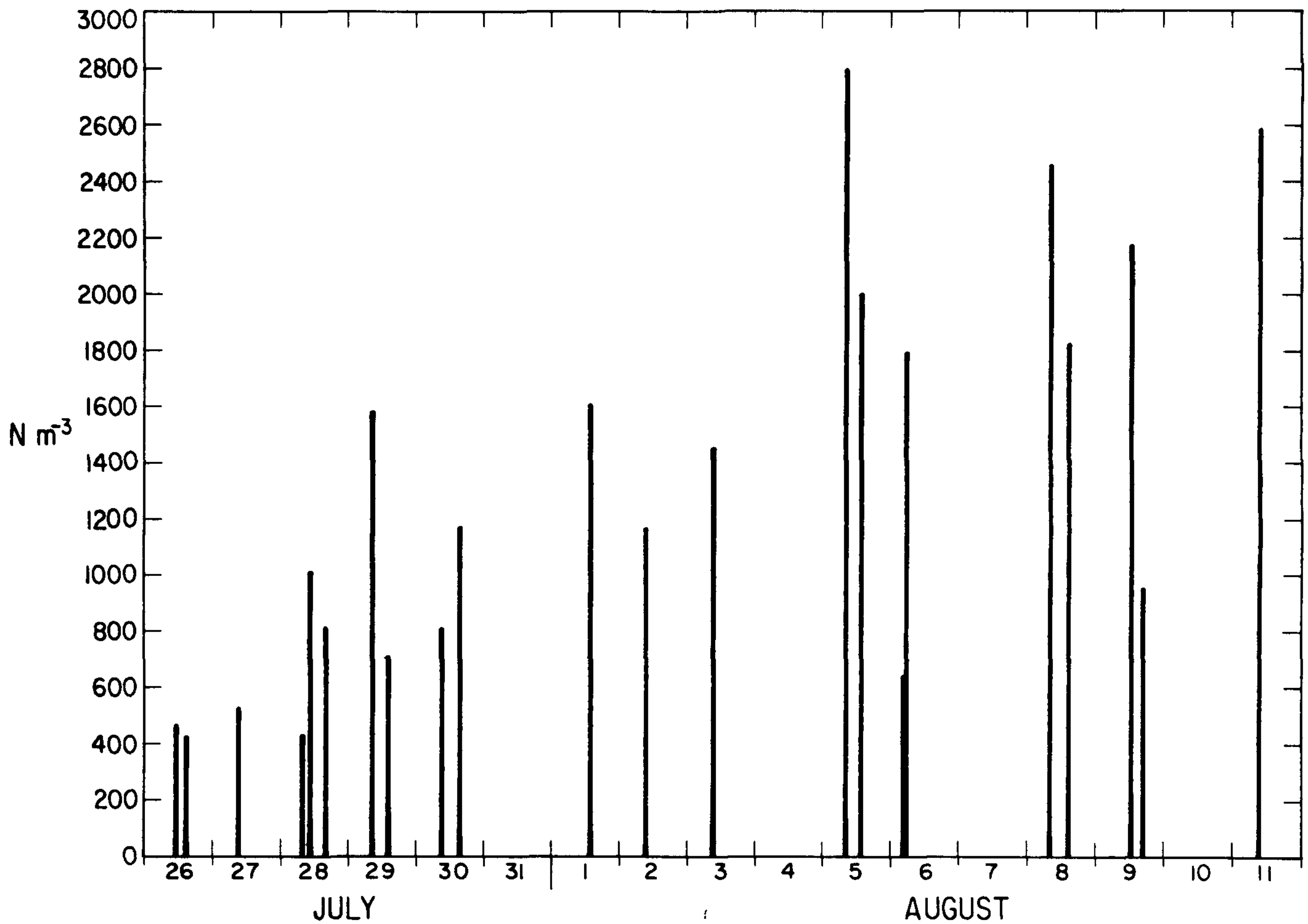


FIG. 6.1. NUMBER OF CHLORIDE PARTICLES PER CUBIC METER

Time-Lapse Cloud Photographs - D. M. A. Jones

A 16-mm Bell and Howell automatic time-lapse camera was borrowed from ESSA by the Illinois State Water Survey to photograph the development of clouds during the 1966 Cloud Physics Project. This camera had been modified by the addition of a rotary solenoid driven by an intervalometer at either 2- or 4-sec intervals. Unfortunately, no provision was made for recording either the time or the date on the film. Hence, the identification of the film was accomplished by holding a tablet with the time, date, and Roll Number written on it in front of the camera at appropriate intervals - the beginning and end of each collection period and at the beginning of each new roll of film. The intervalometer was always set for the 4-sec interval so that the time of any individual frame could be found by counting the seconds from the last identification exposure.

The first day of operation was 21 July 1966 and operation continued through 9 August 1966. The camera was not operated on Sundays. The schedule of the dates and times of operation may be found at the end of this report.

No analysis has been performed on the photographs although some information on cloud growths and movements from them has been used in the analysis of raindrop data. In general, the camera was aimed to photograph the clouds forming over the San Francisco Peaks. Since the Peaks were 10 n. mi. from the camera and only the standard 20 mm objective lens was furnished with the camera, the angle of view with the camera was insufficient to prevent the tops of the clouds of interest from going off the top of the camera, frame.

The films have been combined into four 400-ft reels and copies made for USAECOM.

TIME-LAPSE CLOUD CAMERA LOG

Reel #1

7-22-66
- 1100 MST Begins on 2 sec mode
- 1210 MST Changed film and used 4 sec mode
- 1330 MST End of data for the day

7-23-66
- 0754 MST Beginning of the day on 4 sec mode
- 1019 MST Changed film
- 1050 MST End of data for the day

7-25-66
- 0742 MST Beginning of the day on 4 sec mode
- 0921 MST Changed film
- 1056 MST End of data for the day

7-26-66
- 0736 MST Beginning of the day on 4 sec mode
- 0844 MST Changed film
- 1100 MST Changed film
- 1321 MST Changed film
- 1535 MST End of data for the day

Reel #2

7-27-66

0844 MST Beginning of the day on 4 sec mode
1104 MST Changed film; camera directed toward Saddle
1325 MST End of data for the day as it starts to rain

7-29-66

0851 MST Beginning of the day on 4 sec mode
1113 MST Changed film
1120 MST Camera pointed West
1157 MST End of data for the day

7-30-66

0810 MST Beginning of the day on 4 sec mode
0945 MST Changed film

8-1-66

1109 MST Beginning of the day on 4 sec mode
1337 MST Changed film
1600 MST End of data for the day

8-2-66

0909 MST Beginning of the day on 4 sec mode
1100 MST Camera failed
1342 MST Camera back on

Reel #3

8-2-66

1430 MST End of data for the day

8-3-66

0835 MST Beginning of the day on 4 sec mode
Camera operation intermittent until
1018 MST Camera operation continuous
1035 MST Film Change
1240 MST Film Change
1340 MST Film Change
1545 MST End of data for the day

8-4-66

0810 MST Beginning of the day on 4 sec mode
0940 MST Film change
1236 MST Film change; camera pointed East
1252 MST Camera pointed north-northeast
1330 MST Film change
1545 MST End of data for the day

8-5-66

0830 MST Beginning of the day on 4 sec mode
1201 MST Film change
1355 MST Camera pointed Southeast
1408 MST End of data for the day

Reel #4

8-6-66

0445 MST	Beginning of the day on 4 sec mode - sunrise Camera pointing East
0704 MST	Film change; camera pointed toward San Francisco Peaks
0800 MST	End of data for the day

8-8-66

0817 MST	Beginning of the day on 4 sec mode
0937 MST	Film change
1153 MST	Film change; camera pointing East
1413 MST	Film change
1630 MST	End of data for the day

8-9-66

0823 MST	Beginning of the day on 4 sec mode
1030 MST	Camera turned off to use tripod elsewhere
1047 MST	Camera turned on again
1110 MST	Film change; camera reset for Kodachrome II
1231 MST	End of cloud data collection at Flagstaff

AN/MPS-34 Maser-Equipped Radar - D. M. A. Jones

The AN/MPS-34 radar was based at the Navajo Ordnance Depot west of Flagstaff from 21 July thru 9 August, 1966, for two purposes. Primarily, the radar was being evaluated as a meteorological tool under ECOM Contract Number AMC-01257(E). Secondarily, the radar lent valuable support to the Army's program in cloud physics research at Flagstaff in 1966. The two purposes were compatible permitting the radar to be evaluated while the unique sensitivity of the radar receiver suggested a number of experiments which would be of benefit to the cloud physics investigation. One such desirable experiment was the detection and measurement of the vertical growth of cumulus clouds.

The AN/MPS-34 radar operates at a 3-cm wavelength focussed into a 1-deg conical beam. Both PPI and RHI modes are available although the PPI mode was the only mode routinely photographed. Normal operation while in the Flagstaff area was with 9 levels of stepped-gain at 9 stepped-tilt angles. This program permitted the construction of 3-dimensional models of the echoes detected by the radar with a completed series every 16 minutes. The following is a tabulation of the radar data recorded on 35-mm film:

Table 8.1

TABULATION OF RADAR DATA

MST

Date	Camera On	Camera Off	Remarks
7/21/66	1233	1338	No maser operation
	1346	1358	No maser operation
7/26/66	1005	1051	Maser operation
	1100	1250	Maser operation
	1315	1518	Maser operation
	1520	1556	Maser operation
7/27/66	1047	1159	Maser operation
	1201	1305	Maser operation
	1310	1330	Maser operation
	1526	1555	Maser operation
	1613	1624	Maser operation
7/28/66	1505	1519	Maser operation
	1522	1605	Maser operation
7/29/66	0946	1517	Maser operation
	1559	1650	Maser operation
7/30/66	1022	1144	No maser operation
	1210	1324	No maser operation
	1333	1344	No maser operation
	1352	1710	No maser operation
8/1/66	1047	1103	No maser operation
	1208	1527	No maser operation
8/2/66	0858	1632	No maser operation
8/4/66	1145	1249	Maser operation
8/4/66	1302	1328	Maser operation
	1329	1333	No maser operation
	1345	1502	Maser operation
	1532	1631	Maser operation
8/6/66	0539	0757	Maser operation
8/8/66	1127	1633	Maser operation
8/9/66	1022	1109	Maser operating but not tuned
	1118	1224	Maser operation
8/9/66	1240	1327	Maser operation
	1410	1542	Maser operation

It will be noted that the radar was operated routinely throughout the normal work week, but, as with the rest of the Cloud Physics Project, it was not normally operated on Saturdays and Sundays. It will also be noted that there were times when the radar was operated without the maser-amplifier. The maser was not available on those days due to lack of liquid helium, which had to be shipped from Torrance, California.

The AN/MPS-34 radar was found to be most useful in providing information on the position of rain echoes with respect to the raindrop camera and on the location of longer-range echoes not detected by the Army's M-33 radar at the Flagstaff airport. The AN/MPS-34 radar was the only radar equipped with continuous photographic recording available to the Army project. On several occasions during the evaluation of the chaff suppression of thunderstorm electrical fields, the AN/MPS-34 radar operator was asked to act as control for the flight personnel in the project aircraft, since this radar was the only one available with sufficient range to view the large area being flown by the project aircraft. On occasion, communication between the project aircraft and the radar van was lost, leaving the flight personnel without radar guidance. This occurred when the aircraft was at low altitude and beyond approximately 50 miles range from the radar. The radar with its maser-amplifier was capable of detecting low and middle level clouds to approximately 16 miles, whereas precipitating clouds were detected to the maximum range permitted by the height of the clouds and the curvature of the earth.

On two days, echoes isolated from the main convective activity were noted on the film record and their growth rates measured. Since these were isolated echoes and remained isolated throughout their life history, these storms were not actively self-propagating and probably little precipitation was realized from them. Table 8.2 lists the level of first detection, growth, and decay rates. The freezing level on both of these days was about 16,500 feet msl.

Table 8.2

CHARACTERISTICS OF THREE ISOLATED ECHOES

	Echo 1	Echo 2	Echo 3
Date	7/26/66	7/26/66	7/29/66
First Detection Time	1347MST	1347MST	1303MST
Height (feet, msl)	19,000	15,500	19,000
Top Increase (feet per minute)	------	230	------
Top Decrease (feet per minute)	710 a 170 b	1,150	90
Base Decrease (feet per minute)	1,300	1,300	285
Base Increase (feet per minute)	225	------	170

a - 1347MST-1357MST
b - 1357MST-1407MST

Some difficulty was experienced in the determination of growth rates from the radar since the usual interval between samples was 16 minutes. Much growth and other change may occur to a cumulus cloud within this period.

The radar did detect the presence of fair weather cumulus clouds forming over the San Francisco peaks, approximately 10 miles from the radar. The vertical growth of these clouds was limited, and no attempt has been made to calculate their growth rates. The presence of the clouds was determined from the film records as an augmentation of the persistent echo from the Peaks themselves.

The radar on occasion indicated that much of the water condensed in the cloud was not realized as rainfall at the ground. This could be determined from the sequence of stepped-tilt and gain photographs upon which there was more areal coverage of echo at the higher tilt angles than there was at the tilt angles skimming the ground. This is a normally observed phenomenon in all regions since it is expected that there should be more water aloft than there is falling to the ground. However, the Flagstaff observations often indicated that, although there seemed to be an abundance of water aloft as evidenced by the amount of radar echo, there was little or no echo near the ground. This lack of echo near the ground may have been caused by the blocking of the radar signal by ground objects. This will be quantitatively investigated further.

METEOROLOGICAL REVIEW, JULY AND AUGUST 1966

E. M. Frisby

INTRODUCTION

Two programs were conducted simultaneously in the Flagstaff, Arizona, area during the summer of 1966. The U. S. Army - Environmental Science Services Administration (ESSA) Cloud Physics Program was concerned principally with the field-testing of items of meteorological measuring equipment that had been in process of laboratory development over considerable periods of time. Its function was observational, with the single exception of chaff dispensing, which was undertaken on only three individual days. On the other hand, the Meteorology Research, Inc., program was avowedly operational. Ground and airborne generators, as well as pyrotechnics, were used to seed clouds with both dry ice and silver iodide.

This difference in function must be recognized at the outset.

Those interested in watching the natural onset of the monsoon in Arizona were fortunate in that the transition period was completed before the Meteorology Research, Inc., cloud-seeding program began.

DISCUSSION

Variability in the Summer Monsoon Season

In the Flagstaff area, although the summer monsoon sets in each year with sufficient regularity to allow cloud physics programs to be scheduled ahead of time with a fair degree of accuracy, there is considerable variation from year to year, not only in the time of onset of the rains, but in their amount.

It is recognized that in an area experiencing principally thunderstorm rain, no one station record will provide a completely representative picture of the area as a whole. Nevertheless, a long-enough record at an individual station will give an idea of the degree of variability that can be expected from place to place and month to month.

The rainfall record for Flagstaff Airport over the past ten years is as follows:

Year	June	July	August
1957	1.59	1.57	1.65
1958	.70	.75	3.02
1959	.77	2.93	4.96
1960	.39	.96	3.28
1961	.37	2.03	3.37
1962	.52	2.36	.26
1963	(trace)	.32	4.96
1964	.17	5.23	1.32
1965	.30	2.34	1.01
1966	.21	1.59	(incomplete)

From such information it might be deduced that in some years, e.g., 1957, June would be as interesting a month for study as July, since the rains arrived early; while in others, e.g., 1963, August would be the most useful study month, since the rains arrived late. Whether these deductions are valid or not, it is evident that July is the most variable of the three summer months.

Variability in Northern Hemisphere Weather Patterns

Variations in the timing and intensity of Arizona's summer monsoon rains are reflections of differences in the overall hemispheric circulation pattern. Essentially three flow patterns affect the Southwest of the United States in the summer time:

1. In some years, the Azores high-pressure system maintains a strong cell over southeastern states. Flow around the under side of this high ensures a constant moisture stream from the Gulf of Mexico across the state of Arizona throughout the summer months (Fig. 1).

2. In other years, a typical winter pattern, the salient feature of which is a low pressure trough in the eastern Pacific, persists into early summer (Fig. 2). Under this regime, southwesterly winds blow across Arizona, bringing intermittent incursions of moist air from the Pacific. However, since this weather type is usually associated with very strong winds at jet stream levels, it is not conducive to high convective cloud development, and rainfall from this direction is small in amount compared with that experienced under flow pattern 1.

3. A third flow pattern occurs when the Azores high moves east of its "average" summer position, leaving Arizona in a weak ridge of high pressure, subject to influxes of tropical and equatorial air from the south. Such a contingency arises when small westward-moving depressions or waves, associated with the intertropical convergence zone (in the latitude

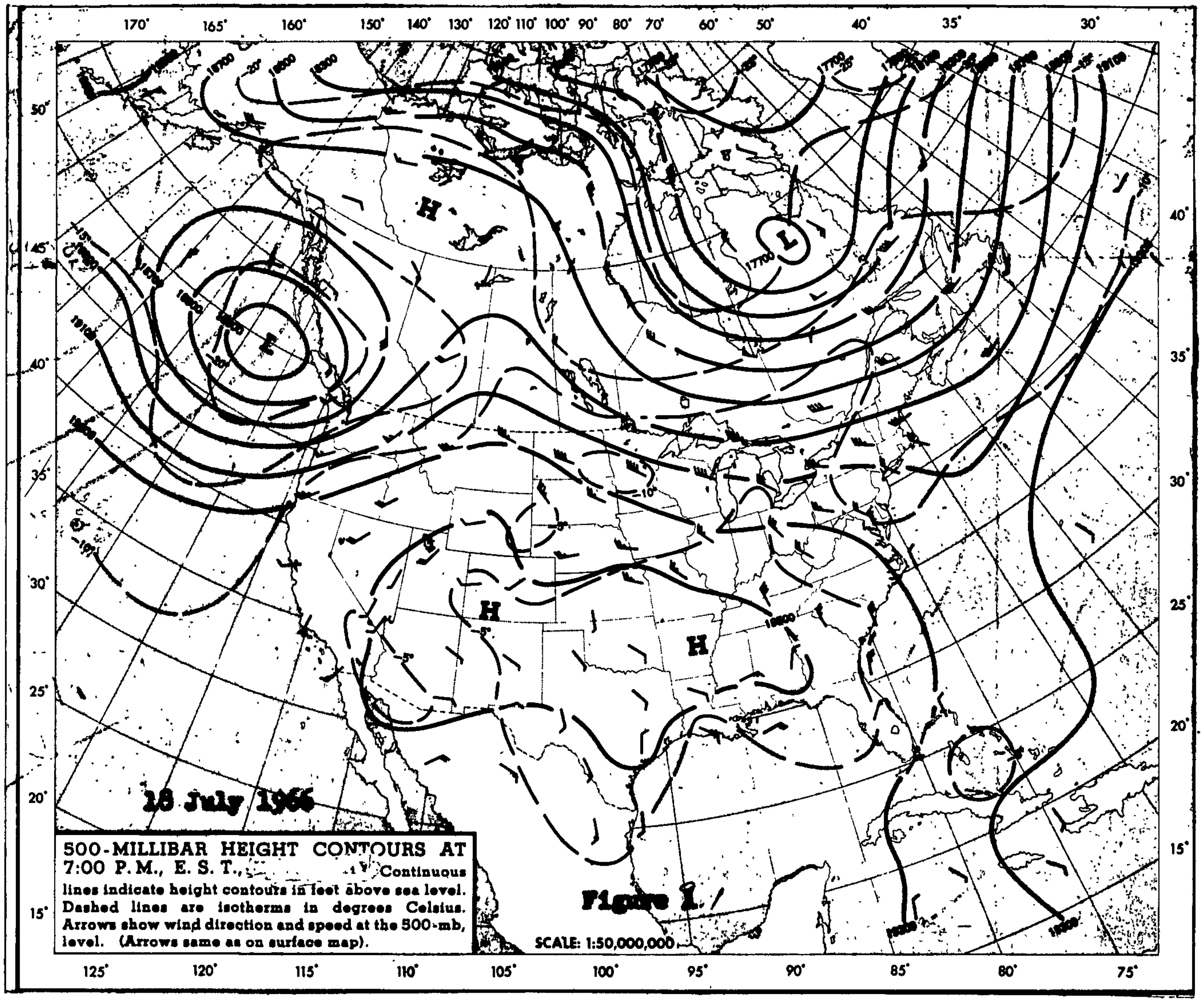

18 July 1966
500-MILLIBAR HEIGHT CONTOURS AT 7:00 P.M., E.S.T., Continuous lines indicate height contours in feet above sea level. Dashed lines are isotherms in degrees Celsius. Arrows show wind direction and speed at the 500-mb, level. (Arrows same as on surface map).
SCALE: 1:50,000,000
H
H
H
L
L

Figure 1

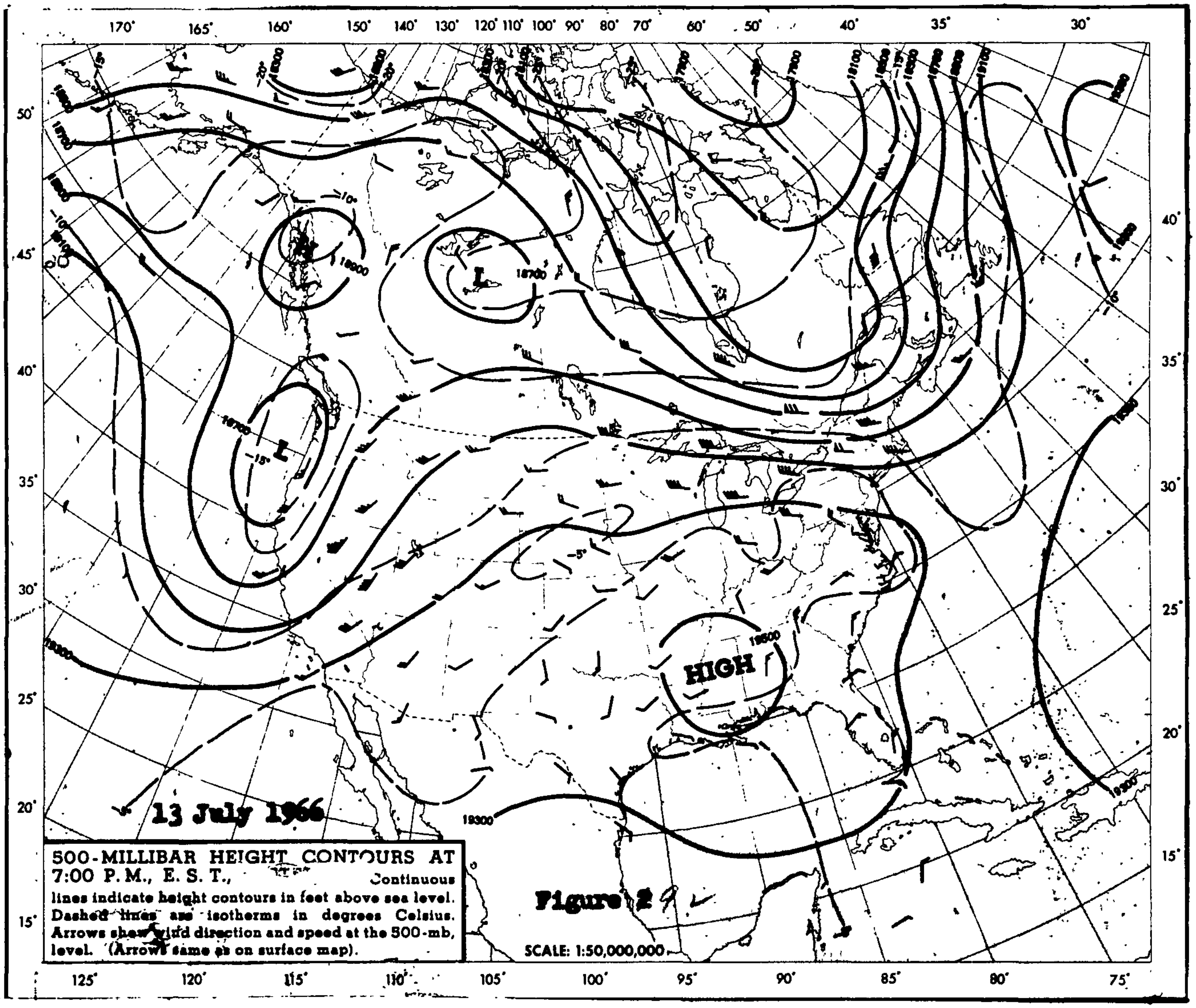

13 July 1966
500-MILLIBAR HEIGHT CONTOURS AT 7:00 P.M., E.S.T., Continuous lines indicate height contours in feet above sea level. Dashed lines are isotherms in degrees Celsius. Arrows show wind direction and speed at the 500-mb, level. (Arrows same as on surface map).
HIGH
SCALE: 1:50,000,000

Figure 2

of northern Mexico in the summer time), kick up saturated air in their wake. This air floods southern Arizona first and reaches northern sections of the state in two or three days' time (Fig. 3)*.

In summary, northern Arizona in the summer time is under the influence of air masses arriving from the southeast, southwest, and south. All three are potential rain bearers, especially those from the south and southeast. All three are modified by their passage over high and complex terrain.

Summer Monsoon, Flagstaff, Arizona, 1966. Transition Season

The interesting transition from the dry heat of late spring to the moist warmth of early summer was experienced almost in its entirety this year by those members of the research party who arrived in Flagstaff by 3 July. In Table 1 an attempt was made to assemble some of the key parameters of the changeover in such a way that they can be followed individually or in relationship to each other. Of the items shown, dewpoint temperatures and precipitation values are those recorded in the Flagstaff Airport log; 500 mb winds and precipitable water values are those taken from the 0530 MST radiosonde ascent at the Navajo Army Depot.

Surface dewpoints for an individual place and for an area provide an excellent picture of the pulsing effect of the onset of the monsoon. Flagstaff dewpoints show an increase in value to the 40's by 5 July, and a subsequent retreat and upsurge into the 40's again by the ninth. A further drop into the 20's on 13 July was followed by a resurge to the 50's by the 16th. After this date they ceased to be of forecast interest as they remained uniformly high. Figure 4 gives similar information for Arizona as a whole.

Thus in 1966, at least, the monsoon process took place over a period of several weeks and was synoptically forecastable by reason of its pulsing gradualism.

Monsoon Proper

The monsoon season may be regarded as fully set in when dewpoint temperatures exceed 50 every day. There is enough atmospheric moisture at this stage to ensure active convection every afternoon as long as cloudiness does not prevent maximum temperatures from reaching the low 80's.

Diurnal recycling of moisture is a marked feature of the monsoon period par excellence. But the pulsing effect, noted in the transition phase,

*Figures 1, 2, and 3 are taken from "Daily Weather Map, " U. S. Department of Commerce.

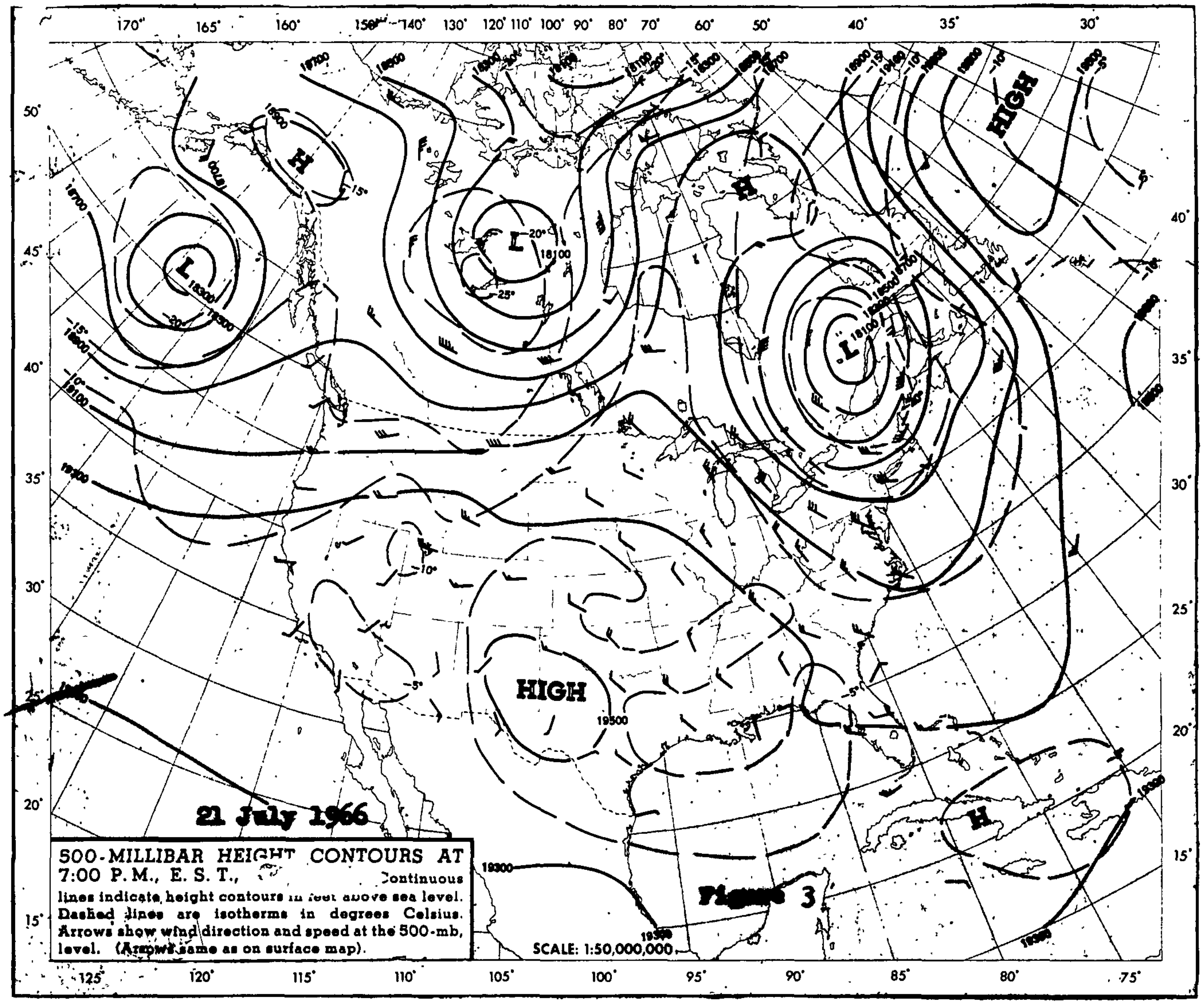

21 July 1966
500-MILLIBAR HEIGHT CONTOURS AT
7:00 P.M., E. S. T., Continuous
lines indicate height contours in feet above sea level.
Dashed lines are isotherms in degrees Celsius.
Arrows show wind direction and speed at the 500-mb,
level. (Arrows same as on surface map).
HIGH
L
H
SCALE: 1:50,000,000

Figure 3

TABLE I

FLAGSTAFF WEATHER JULY 1966

	F 1	S 2	S 3	M 4	T 5	W 6	TH 7	F 8	S 9	S 10	M 11	T 12	W 13	TH 14	F 15	S 16	S 17	M 18	T 19	W 20	TH 21	F 22	S 23	S 24	M 25	T 26	W 27	TH 28	F 29	S 30	S 31		
Dewpoint Temp °F 0600M.	44	44	39	39	42	20	32	38	43	48	47	43	29	28	39	53	54	47	51	55	52	54	51	53	53	52	53	58	58	53	52		
Precip. ins.									T	T					.02	04	07	.10	.10	T	.65		.01	.01	02		.23	.02	T	.32			
Wind Direction 500 mb (NAD sounding)								SW	SE		SW	SW	SW	SW	SSE			SE		E	SW	SE	SW			SW	SE	E	E	S	S		
Precipitable Water (NAD sounding)								.42	.74		.66	68	67	.48	.70			.77		.99	.96	1.09	.83		85	.77	.74	1.15	.96	.81			
Condensation Level								18,700	14,600		10,400	14,000	15,800	17,500	13,800			14,000		12,000	11,200	13,400	12,750		14,500	12,700	12,750	12,500	10,100	14,500		13,500	11,700
Freezing Level								16,000	14,800		14,900	15,000	14,600	14,500	14,500			15,000		13,790	14,800	15,600	15,000		15,300	16,200	15,000	15,300	15,800	16,000		15,600	15,600

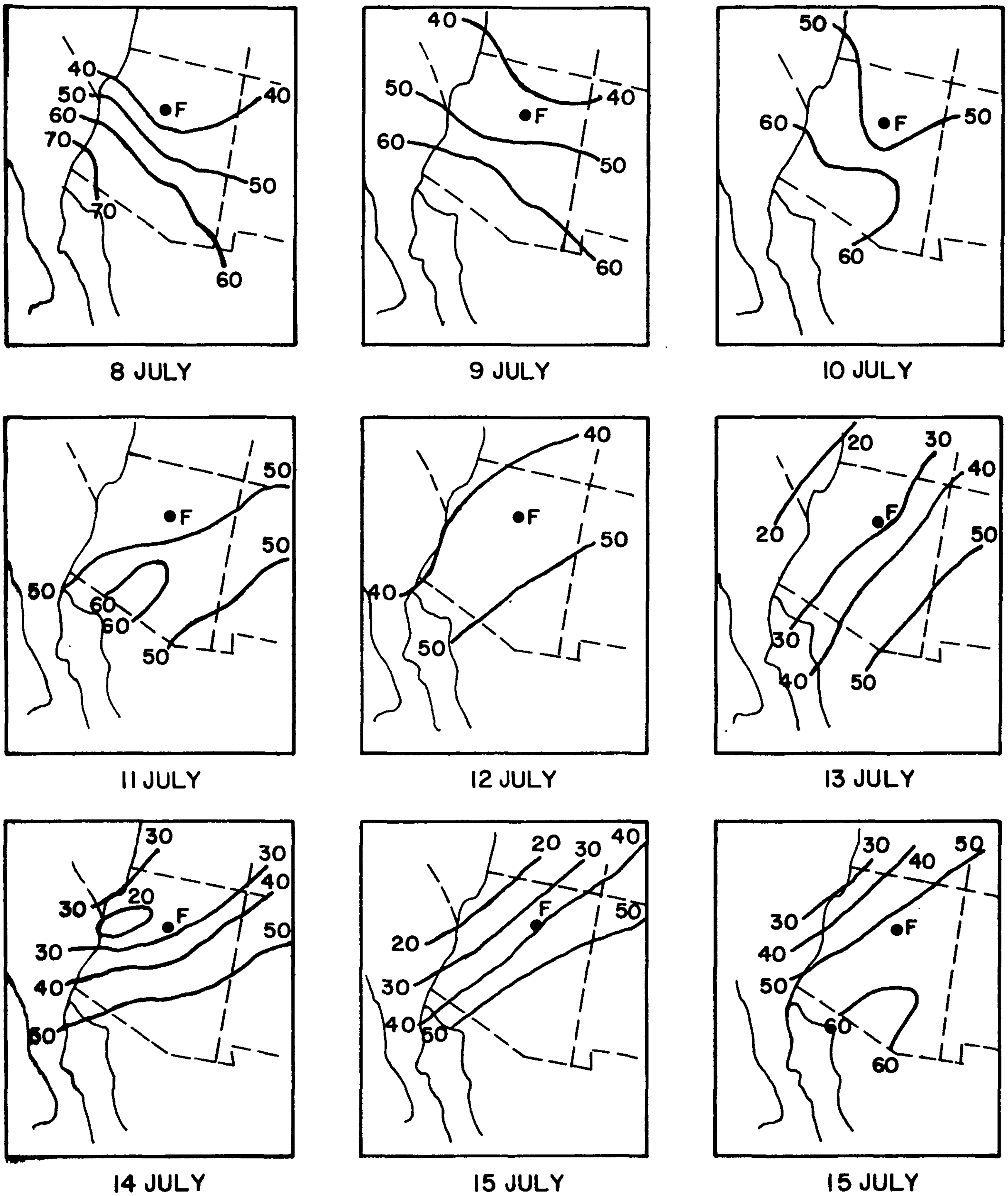


FIG. 4 ARIZONA DEWPOINT DISTRIBUTION (°F) 0600 MST

F = FLAGSTAFF ARIZONA

continues at the mature stage, as shifts in synoptic pattern result in changes in wind direction and moisture source. The increase in dewpoints with a change to southeasterly flow on 27 July is a case in point.

Of special interest are changes in upper air ascents, not only from day to day but within a few hours. For example, Fig. 5 shows a typical sounding for a hot, dry lenticular day. Figure 6 shows the sounding taken the following morning when moisture had seeped into lower levels as the result of a change to southeasterly flow.

Still more striking is the contrast between Figs. 7 and 8, taken within five hours of each other. Humidity increased rapidly during the morning as winds became gradually more firmly southeasterly to the 400 mb level.

Figure 9 is included as a contrast to Fig. 5; the latter a sample of pre-monsoon conditions, the former of monsoon conditions par excellence.

Daily Weather Forecasts

Weather was reviewed at each morning meeting and forecasts made by 0800 hours each day from 5 July to 2 August 1966. Each forecast covered later morning and afternoon hours of the same day.

Early in July the most important single item in the review was the estimated proximity of a moist air mass to the Flagstaff area. Once moisture had arrived in northern Arizona and was available for daily recycling, interest tended to focus on the predicted time of day for shower activity to begin. Weather forecasting in northern Arizona in the summer time involves essentially three parameters:

1. The amount and height of atmospheric moisture, coupled with the presence or absence of inversions at the surface and aloft.

2. The degree of surface heating.

3. The interaction of earth and atmosphere in a complex zone of mountain and desert terrain.

Every facility of the Meteorological Office at the Flagstaff Airport was used in the determination of all three, by courtesy of Mr. P. Sorensen, Chief. Upper-air ascents for Winslow, Tucson, and Yuma were kept under constant surveillance for changes in wind direction as well as atmospheric temperature and humidity structure. Information from these and surface sources was further supplemented by a radiosonde ascent made twice daily by an Army meteorological team at the nearby Navajo Army Depot.

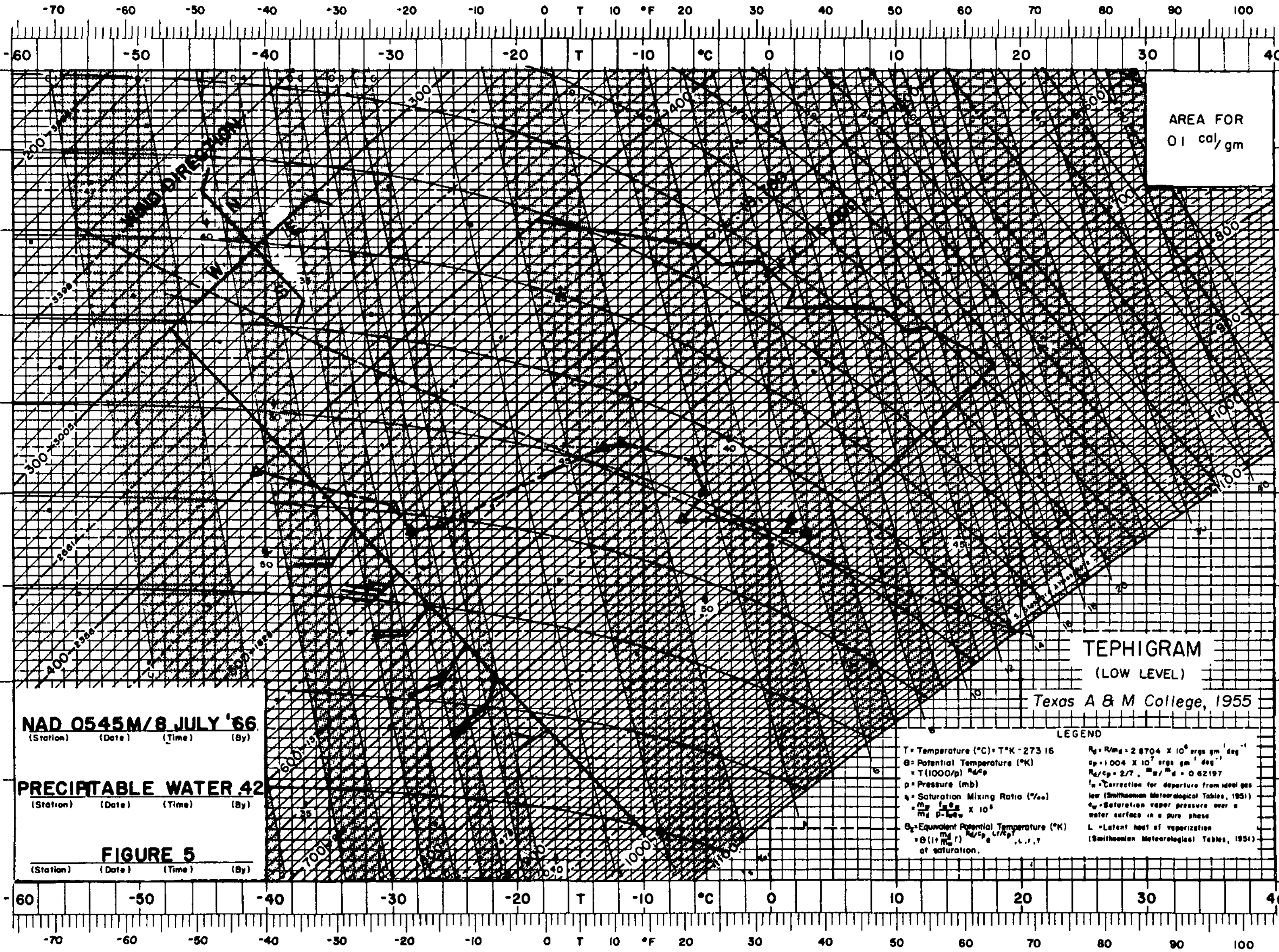
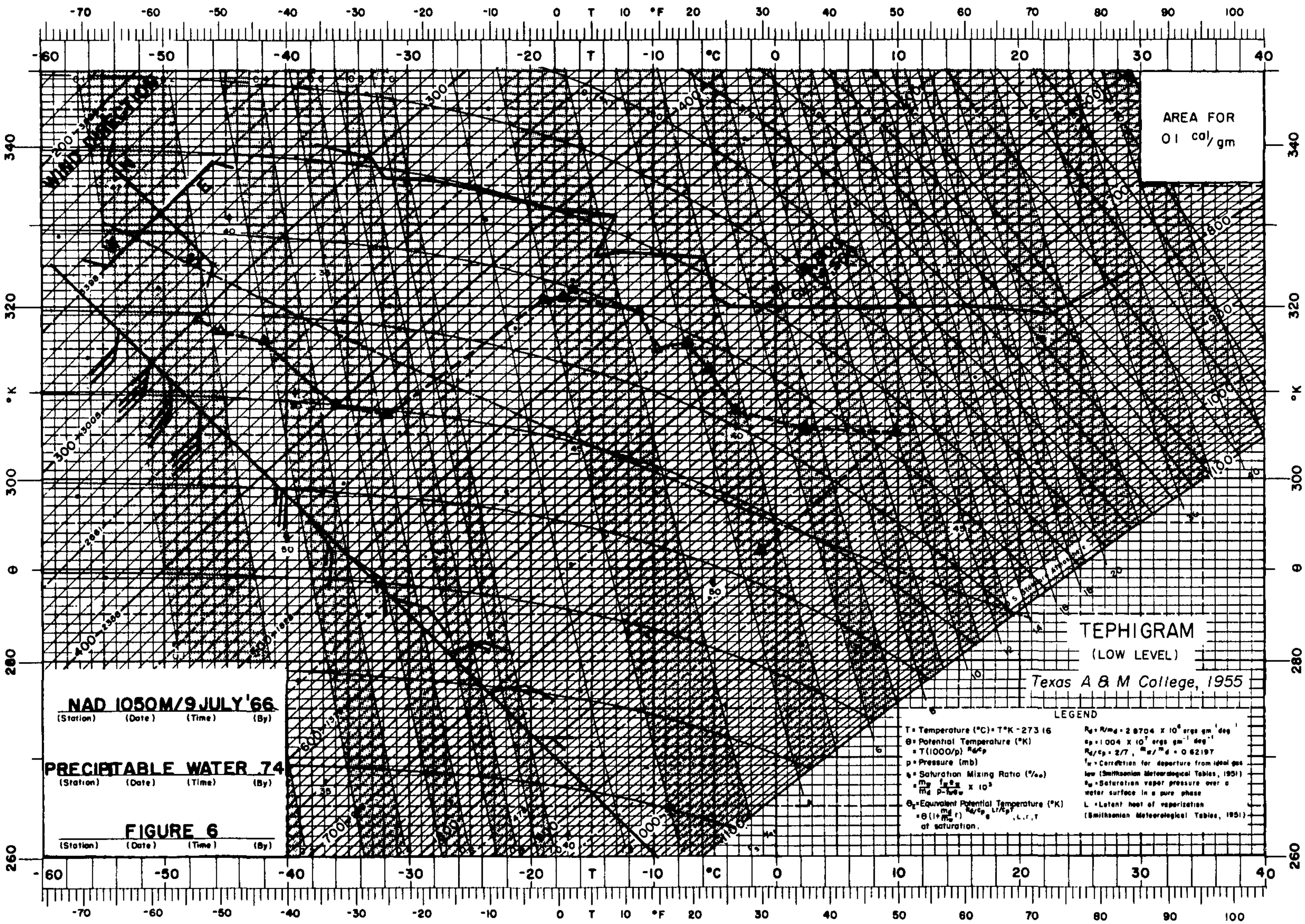
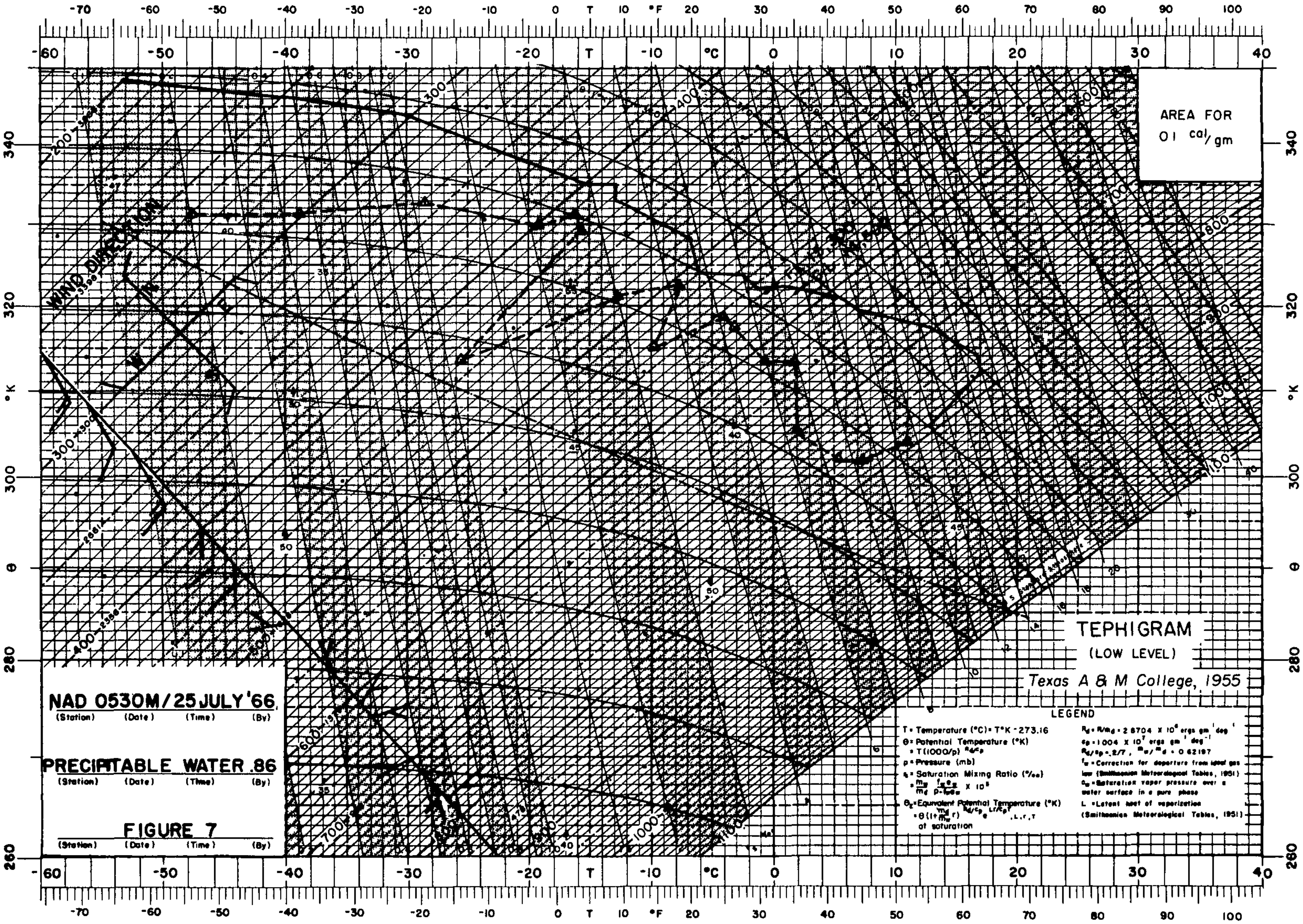
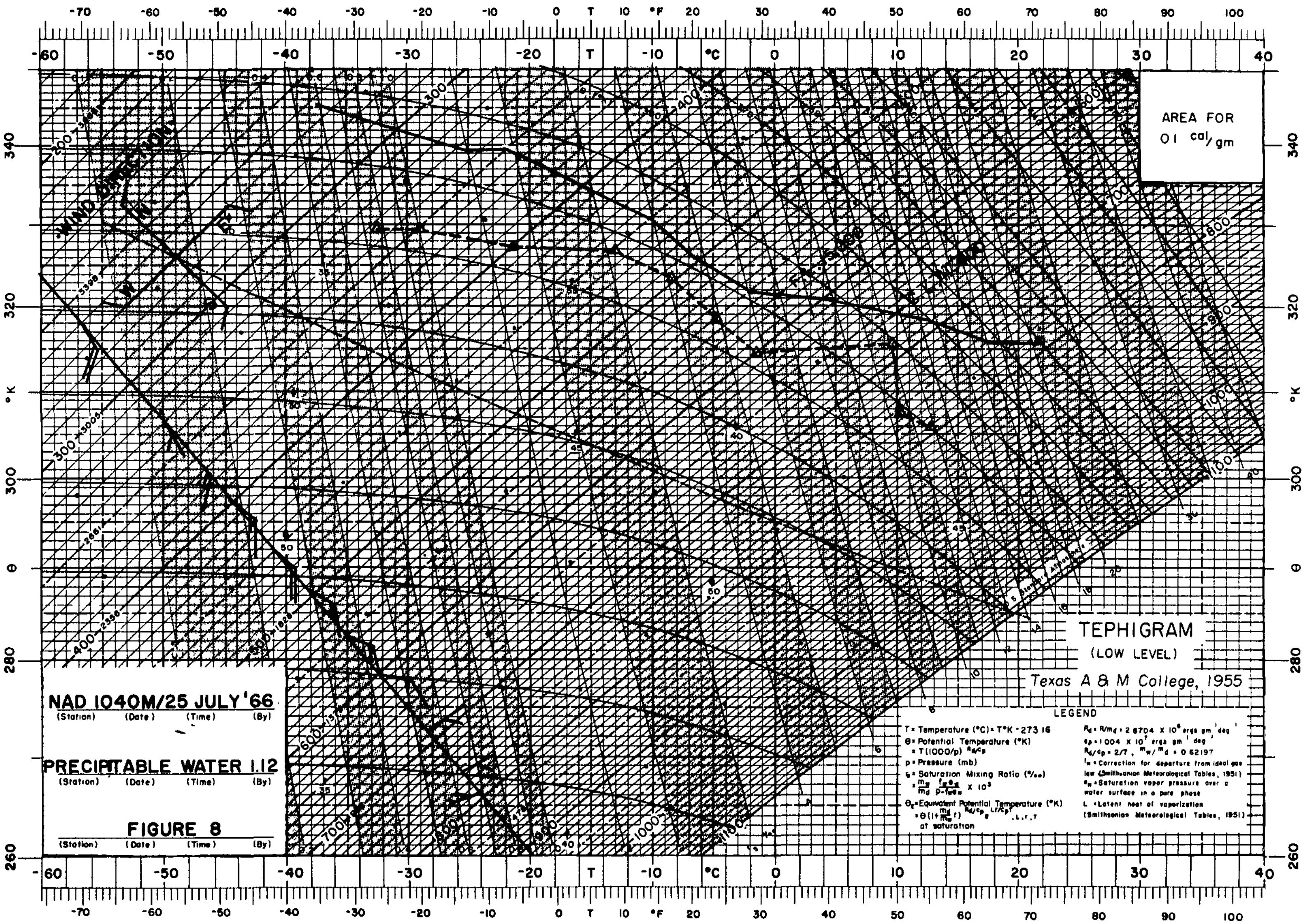
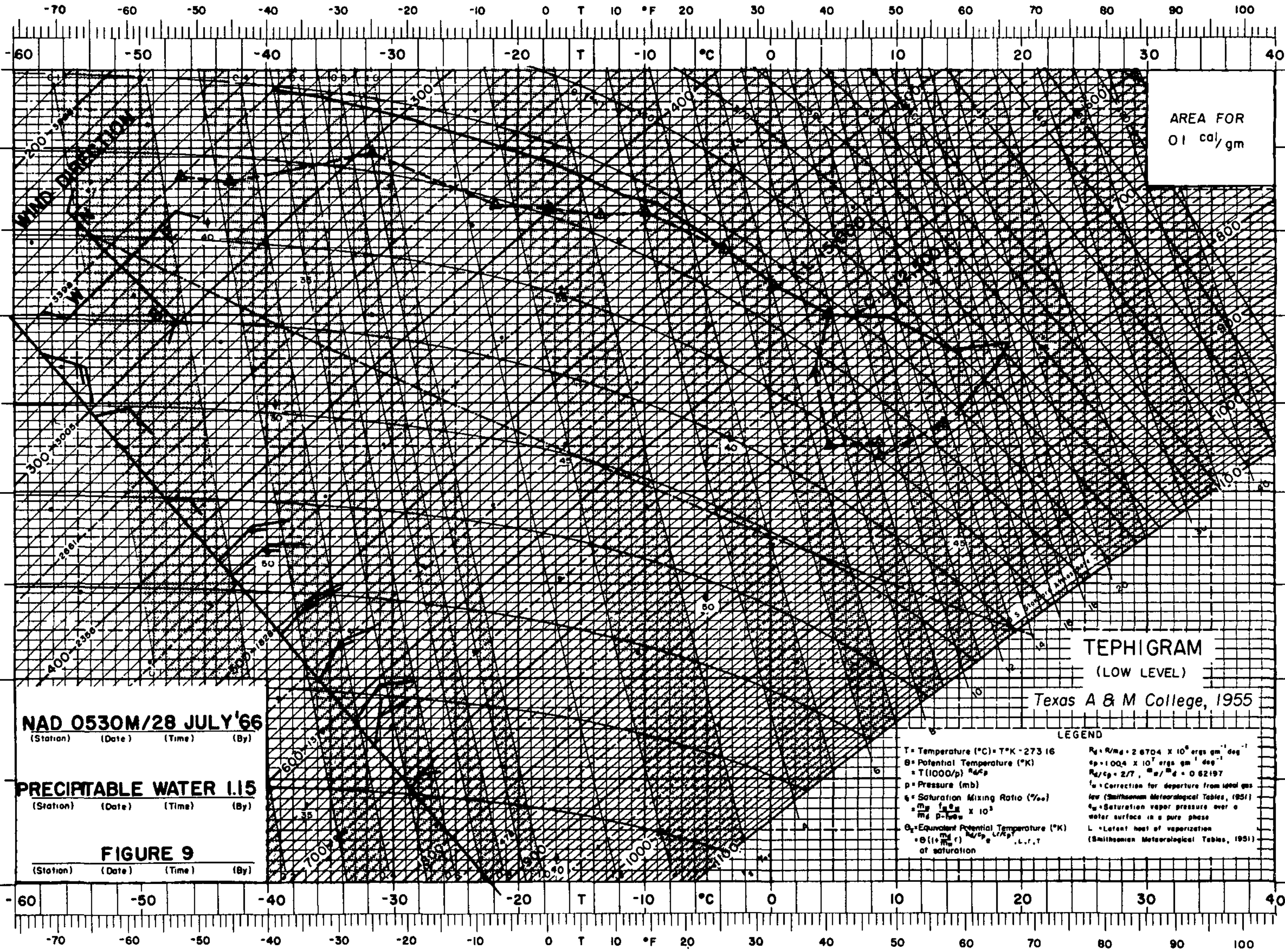

AREA FOR 0.1 cal/gm
WIND DIRECTION
TEPHIGRAM
(LOW LEVEL)
Texas A & M College, 1955
LEGEND
T = Temperature (°C) = T°K - 273.16
θ = Potential Temperature (°K)
p = Pressure (mb)
Saturation Mixing Ratio (‰)
Equivalent Potential Temperature (°K)
at saturation.
NAD 0545M/8 JULY '66
(Station) (Date) (Time) (By)
PRECIPITABLE WATER .42
(Station) (Date) (Time) (By)
(Station) (Date) (Time) (By)

FIGURE 5


AREA FOR 0.1 cal/gm
TEPHIGRAM
(LOW LEVEL)
Texas A & M College, 1955
LEGEND
WIND DIRECTION
NAD 1050M/9 JULY '66
(Station) (Date) (Time) (By)
PRECIPITABLE WATER .74
(Station) (Date) (Time) (By)
FIGURE 6
(Station) (Date) (Time) (By)
°C
°F
°K
θ


AREA FOR
0.1 cal/gm
WIND DIRECTION
TEPHIGRAM
(LOW LEVEL)
Texas A & M College, 1955
NAD 0530M/25 JULY '66
(Station) (Date) (Time) (By)
PRECIPITABLE WATER .86
(Station) (Date) (Time) (By)
FIGURE 7
(Station) (Date) (Time) (By)
LEGEND
T = Temperature (°C) = T°K - 273.16
θ = Potential Temperature (°K)
p = Pressure (mb)
θE = Equivalent Potential Temperature (°K) of saturation
L = Latent heat of vaporization (Smithsonian Meteorological Tables, 1951)
°C
°F
°K
θ


AREA FOR
0.1 cal/gm
WIND DIRECTION
TEPHIGRAM
(LOW LEVEL)
Texas A & M College, 1955
NAD 1040M/25 JULY '66
(Station) (Date) (Time) (By)
PRECIPITABLE WATER 1.12
(Station) (Date) (Time) (By)
FIGURE 8
(Station) (Date) (Time) (By)
LEGEND
T = Temperature (°C) = T°K - 273.16
θ = Potential Temperature (°K)
p = Pressure (mb)
θ_E = Equivalent Potential Temperature (°K) at saturation
L = Latent heat of vaporization (Smithsonian Meteorological Tables, 1951)
°C
°F
°K
θ


AREA FOR
01 cal/gm
WIND DIRECTION
TEPHIGRAM
(LOW LEVEL)
Texas A & M College, 1955
LEGEND
T = Temperature (°C) = T°K - 273.16
θ = Potential Temperature (°K)
p = Pressure (mb)
L = Latent heat of vaporization
(Smithsonian Meteorological Tables, 1951)
NAD 0530M/28 JULY '66
(Station) (Date) (Time) (By)
PRECIPITABLE WATER 1.15
(Station) (Date) (Time) (By)
FIGURE 9
(Station) (Date) (Time) (By)

Just how sensitive the balance is between parameters 1 and 2, above, may be realized from the fact that it is not enough to get breaks in the cloud in the early morning; the breaks must be in the path of the sun if enough heating is to get to the ground to set up active convection before noon.

From this discussion it may be deduced that precipitable water and the total amount of lifting energy in the atmosphere from the surface to the 400-mb level are the two most vital elements in a forecast of:

1. No rain
2. Rainshowers
3. Thunderstorms
4. Thunderstorms with hail.

A forecast technique incorporating these ideas is in the process of devel opment.

Each weather briefing included a general inference, special information relating to the day's operation (where this was known), and items gleaned from local soundings such as freezing and condensation levels. The essentials of each forecast have been tabulated with their evaluation in terms of storm intensity, following the four categories listed above. In cases where two categories are shown, the second in parenthesis, the implication is that the first weather type is widespread; the second, occasional, e.g., 2(3) general rainshowers, occasional thunderstorms.

Forecasts made prior to Meteorology Research, Inc., cloud-seeding program:

Date	Day	Type	Additional notes	Evaluation
5 July	T	1	Break in drought by weekend	Correct
6 "	W	1		"
7 "	TH	1	Increasing clouds	"
8 "	F	2	Moisture seeping in from Pacific and Gulf	"
9 "	S	2(3)	Thunderstorms late	"
10 "	S	2(3)		
11 "	M	2	Showers along rim	"
12 "	T	1	Further influx of moisture by Thursday	"
13 "	W	1		
14 "	TH	1(2)	Day of transition	
15 "	F	2(3)		
16 "	S	3	Widespread in afternoon	Hit Flagstaff at 1800
17 "	S	3(4)		Correct

Forecasts made during Meteorology Research, Inc., cloud-seeding program

Date	Day	Type	Additional notes	Evaluation
18 July	M	2(3)		Should have been 3
19 "	T	2(3)		Correct, but rain occurred also at night
20 "	W	2(3)		Incorrect; many towering cumulus without rain or thunder
21 "	TH	2(3)		Mainly heavy rain; few thunderstorms
22 "	F	1(2)		Correct
23 "	S	2(3)		Correct
24 "	S	2(3)		3(4) at night
25 "	M	2(3)		Should have been 3 (4)
26 "	T	1(2)		Correct
27 "	W	2(3)	Activity P.M.	Rain started A.M.
28 "	TH	1(2)		Correct
29 "	F	2(3)		Correct
30 "	S	2(3)		Correct
31 "	S	1(2)		Correct
1 Aug	M	3	Most activity to east and south	Correct
2 "	T	3	Most activity to north	Correct

CONCLUSIONS AND RECOMMENDATIONS

It is difficult and unjustifiable to draw firm conclusions from a small sample of data and from one season's operation, but the evidence of the 1966 Flagstaff program suggests that it is possible to forecast the onset of the monsoon by synoptic means.

Deterioration in forecast accuracy on and after 18 July (when the Meteorology Research, Inc., cloud-seeding program started) suggests that either weather became naturally more difficult to forecast during the second half of July, or cloud-seeding operations made it more difficult to forecast.

Finally, although not mentioned in the "Forecasts" section of this report, two experimental attempts were made at forecasting the outcome of cloud-seeding operations, the details of which had been ascertained early in the day. Both attempts were signally successful. Thus, for the first time at Flagstaff, in 1966, forecasting was attempted experimentally on the "artificial" as well as on the "natural" level.

Recommendations must depend entirely on the further program envisaged. If cloud seeding is the goal, then the following meteorological and climatological research should be undertaken:

1. A study of storms of past years to determine natural distributions of precipitation.

2. A study of precipitation amounts and intensities to determine maximum and minimum values that can be experienced in synoptically similar storms under natural conditions.

3. Analysis of data that will allow the feasibility of cloud seeding in specific conditions to be determined.

4. A study to determine the frequency of occurrence of feasible conditions for cloud seeding operation, based on the little that is known from experimental work.

5. A continuation of the 1966 forecast experiment to increase the number of samples of forecasts based on artificial, superimposed on natural, conditions.

RECOMMENDATIONS FOR ARMY-ESSA CLOUD PHYSICS RESEARCH IN 1967*

INTRODUCTION

The 1966 Flagstaff Field Project of USAECOM in cooperation with the Atmospheric Physics and Chemistry Laboratory of ESSA was a successful program in advancing our knowledge of certain cloud physics problems and the state of the art of some instruments for cloud physics research. The project was a success in spite of the fact that the project was in the midst of a transition of major proportions in scientific personnel.

The operational period was from 10 July through 12 August during the peak of the southeast-monsoonal thunderstorm season in the Flagstaff, Arizona, area. Although it was stated that this was a unique year in the type of weather observed, thunderstorms were in the area on almost every day and their abundance was a factor in the successful completion of the 1966 project.

In 1966 the major project in cloud physics studied was the idea of suppressing atmospheric electric fields through the dispensing from an aircraft of 15 cm metallized chaff into the electric fields to induce corona discharge. Thus, the fields would be held at the corona potential and could not build to the level required for lightning discharge. The 1966 experiments "established that corona discharge is generated if chaff needles of 15 cm length are dispersed in the electric field of thunderstorms exceeding values of 30 kv/m. It seems highly probable that the decay of strong electric fields is caused or accelerated by corona current produced by the chaff needles".

In addition to the atmospheric electricity experiments, the development of additional instruments for the study of cloud physics was continued in field trials. These instruments included an infrared scanner for the mapping of surface temperatures, a detector of the radiation temperature of atmospheric carbon dioxide, a sensitive, high response humidity element, and a raindrop spectrometer.

The infrared scanner was found to operate satisfactorily and should prove an important tool in cloud dynamics studies. The same may be said of the carbon dioxide thermometer.

The fast-response humidity element under development by the National Bureau of Standards was found to perform as expected, but because it responds much faster than any previously developed instrument and there exists no standard by which its performance may be evaluated; additional testing is required before the instrument's reading may be considered definitive.

The New York University raindrop spectrometer was operated for only one storm of any significance. The results from this storm have not been determined at this writing.

*Prepared on November 17, 1966

In addition to the above instruments, a high-sensitivity 3-cm radar operated by the Illinois State Water Survey was used to survey and record the detectable clouds within the operational area. The reduction of the recorded data from this instrument is in process of analysis. A raindrop camera was also operated by this group for the comparison of its analyzed data with the NYU spectrometer. Although much of the rain photographed by this camera was of low intensity, the data are available for analysis should this be desirable. The heavier rains are being reduced from the film records including the storm recorded by the NYU spectrometer and will be correlated with the records from the 3-cm radar.

Membrane filter samples of atmospheric aerosols from the Flagstaff area were collected by the Illinois group. Their identification and sizing has been completed for inclusion in the final report of the project.

RECOMMENDATIONS

Emphasis for the summer data-collection season for the combined Army-ESSA cloud physics project should be placed upon the completion of the attempts to suppress electric fields in clouds with the hope that an operational program may be worked out of the research phase of the investigation. From Dr. Heinz Kasemir's report on the 1966 results, he would like to conduct between 10 and 20 additional successful flights to verify the earlier observations and his theory. By successful is meant a flight in which all essential instrumentation is operational and the tracking of the electric fields of interest is reasonable. Dr. Kasemir would like to investigate further the unexpected area of strong fields found underneath the storm where relatively little turbulence or precipitation were observed at the same time as the fields.

Dr. Kasemir would like to not only have the Army C-47, but an additional airplane, likely the ESSA DC-6, instrumented for chaff dispensing and field measurements. We recommend that USAECOM not only furnish the C-47, but an additional airplane capable of thunderstorm penetration and instrumented for chaff dispensing and field measurements in order to smoothly perform the transition from direction by Dr. Kasemir to USAECOM direction in future work. It is not anticipated that the electric field modification research will be completed in 1967.

It is strongly recommended that an area other than Flagstaff be considered for future field projects in cloud physics since the desirable weather conditions are limited in time and there is an operation (Bureau of Reclamation) already in the area with interests which are not always compatible with cloud physics research. There is a strong possibility that the two projects can contaminate each other and it is not likely that satisfactory cooperation can be maintained between the two. It is suggested that two other sites having similar weather conditions be considered. The Langmuir Laboratory at Socorro, New Mexico, is involved in cloud physics research of a similar nature to the Army and should be willing to give cooperation with all of its facilities which are more complete than are available in the Flagstaff area. In addition there is the Missoula, Montana area with excellent facilities and personnel who are likely to be anxious to cooperate. The question of aircraft operation is no more severe for these areas than is the Flagstaff area although the Socorro area may be less restrictive in air space.

The AFCRL has expressed an interest in cooperating in the USAECOM atmospheric electricity project with its C-130 aircraft. An invitation to AFCRL to participate in 1967 is recommended after preliminary plans are completed for the 1967 project.

It is to be expected that there will continue to be the marked lack of coordination between the several individuals who are actively engaged in research which they have initiated in the cooperative program between the Army and ESSA. This is deplorable, but probably unavoidable. What steps that may be possible should be taken to see that coordination be maintained between surface observers and the aircraft so that the maximum amount of information may be obtained from the flights that are made. The aircraft should be kept under tracking surveillance of ground-based radar and, in-so-far as possible, over a surface network of observing instruments. One person to act with authority as the coordinator of operations would be very desirable. This was the position assumed by Dr. Helmut Weickmann in past projects and it would be desirable to have him maintain this position in 1967 if he will remain in the project area for the duration of the field phase. This is probably a vain hope.

It is strongly recommended that the NBS humidity element with integral temperature sensor be pushed to completion; not because USAECOM has an immediate need for such an instrument, but because it is an instrument which has the capability of being a very powerful tool in cloud physics research. As an illustration capable of implementation in the 1967 program, the humidity sensor and the carbon dioxide temperature sensor should be flown on the same flights to resolve the question of the lower humidity readings observed in clouds during the 1966 project. The discovery that in cloud humidities are less than 100 percent would be a major confusing contribution to an understanding of the physics of clouds.

Because the NYU spectrometer is not designed for field use, it is not recommended that this instrument be included in the 1967 project.

The infrared scanning spectrometer holds great promise in a number of problems in cloud physics. One that comes to mind is the question of unequal surface heating and its effect upon the subsequent genesis and growth of cumulus. This is thought to be the reason for its inclusion in previous field projects. Such questions are not limited to the monsoon season in the southwestern United States, however. Once this instrument is ready for operational use, it will be found useful in determining the radiative properties of warm fogs, for example.

It is suggested that a third raob each operational day, a sounding made after completion of the day's flights, would be sufficiently informative to warrant its expense. This sounding should be designed to tie down any question of the effect that the day's operations may have had upon the atmosphere and what changes may have occurred due to natural processes.

RESEARCH SUPPORT OF 1966 FLAGSTAFF FIELD OPERATIONS*

INTRODUCTION - V. J. Schaefer

Atmospheric sciences research studies, centered about the area including the San Francisco Peaks north of Flagstaff, Arizona, were carried out during the period June 19 - August 15, 1966 by participants of the Arizona Unit of the Natural Sciences Institute (NSI) in cooperation with the United States Army Electronics Research and Development Laboratories (USAERDL) under Contract No. DA-043-AMC-02435(E). Nine college students under the supervision of Dr. Vincent J. Schaefer were available to help in the field projects. Four of these NSI students spent nearly full time in assisting USAERDL scientists during their field operations, then they continued working on the data obtained and prepared the summaries included as appendices to this final report. (Original and 4 copies of final report submitted to the U. S. Army Command, Attn. Mr. William C. Barr, Atmospheric Sciences Laboratory. Appendices of the original final report include a set of copies of the full texts of the students' summaries. The students' summaries are in abstract form in copies of the final report.)

The Arizona Unit of the NSI was one of seven units operating under sponsorship of the Atmospheric Sciences Research Center (ASRC) of the State University of New York at Albany (SUNYA) under primary support of the Charles F. Kettering Foundation. As at Flagstaff, where partial support of the program was provided by USAERDL, all of the other programs were also assisted in one way or another by the institutions cosponsoring the local units.

This was the fifth year in which the USAERDL cooperated with NSI-ASRC-SUNYA. This activity has mutual advantages. Scientists working on the USAERDL program outline their interests and objectives to the NSI students helping them. The students in turn help the scientists operate scientific equipment and analyze data. They thus obtain a first-hand experience of the manner in which scientific field research is conducted and in a number of instances decide to make a career of atmospheric science.

* Final Report under Contract No. DA-043-AMC-02435(E) - Natural Sciences Institute Arizona Unit, Atmospheric Sciences Research Center, State University of New York on August 28, 1966

RESEARCH ACTIVITIES

USAERDL-ESSA FIELD STATIONS

At the start of the NSI program, Norbert Ensslin and Steven Simmons, with the help of Alan Miller of MRI, set up a comparison study of two potential gradient meters. When Dr. Heinz Kasemir arrived, these two NSI students assisted in the installation and operation of his two USAERDL/ESSA field stations located at the Flagstaff airport and the Navajo Ordnance Depot. These stations were equipped with Kasemir field mills, SPARSA units, lightning observation grids, and the portable potential gradient meters. Subsequently Ensslin and Simmons helped evaluate the data obtained with the detection units. They summarized their activities in their report entitled "The Army-ESSA Project."

WAKE EFFECT STUDIES

As in preceding years, portable anemometers of the Lambrecht-type and MRI-type were deployed in the area north of the San Francisco Peaks to obtain additional data on the airflow patterns related to storms, including the Convective Wake. The instruments were placed in about the same locations as in the preceding two years. The weather patterns occurring during the USAERDL flight operations did not fit into the general pattern of preceding years, consequently the locations of the wind instruments were not suitable for providing much supporting information. The data obtained will eventually be analyzed by the MRI group. A copy of the recorded data will be filed at NSI headquarters in the Max C. Fleischmann Hall at the Research Center of the Museum of Northern Arizona and will be available for flight evaluation.

PREPARATION OF DAILY FORECASTS

An important feature of the USAERDL/ESSA program was the preparation of a daily forecast presented at the 0800 briefing each operational day. As in preceding years, this forecast was prepared by Dr. E. M. Frisby, using radiosonde flights from Winslow and from the Navajo Ordnance Depot where special runs were made for the project. Assisting Miss Frisby was Eric Schwartz of our group. To be helpful, the evaluation of data necessitated getting to the airport early in the morning, plotting the radiosonde data, and then working out the general and local forecasts. Eric attempted to classify the weather patterns that produced the various types of weather in the Flagstaff area, including moist air sources and other significant features. His analysis showed that the monsoon-type weather pattern reached the Flagstaff area July 16, but subsequently a shift in the general circulation brought in moisture from the central California coast. This Pacific air dominated the moisture regime during much of the thunderstorm season in 1966, producing cloud patterns east of the Peaks on a number of occasions.

DIURNAL AIR FLOW PATTERN AT ROGERS LAKE

An aspect of the USAERDL flight program involved infra-red radiation characteristics of the terrain surrounding the San Francisco Peaks. Three years ago we made a detailed study of a temperature anomaly at the Bonito Lava Flow and discovered that the cold spot effect of the lava flow was caused by the entrapment of cold air in the deep cracks that permeate the flow in all directions. The cold air from nighttime outgoing radiation flows into the crevices displacing any warm air that may have developed during the daytime. This residual cold air is one of the causes of the durable ice caves of the area.

Although we do not have information on the temperature pattern at Rogers Lake, it was possible to establish on very short notice a group of three recording anemometers around Rogers Lake. These were placed symmetrically (N, SW, SE) and showed a very fine diurnal flow pattern of air near the ground. The detailed information is included in a report prepared by NSI student Larry Proctor with the active help of John Lindl, Assistant Field Director of the Arizona NSI Unit. The analysis shows that the normal gradient wind dominates the airflow pattern at the edge of the Rogers Lake open area from 0800 to 1800. Rogers Lake, approximately 1.5 - 1.8 miles in diameter and surrounded by a Ponderosa pine forest, is essentially a "dry" lake, primarily a swampy, nearly circular "park" covered with thick grass. As the sun goes down and outgoing radiation begins to cool the open grassy swale, the air stagnates, a temperature inversion develops, and air begins to flow toward the center of the lake from all sides. This continues until 0800 at which time insolation from the sun causes a dispersal of the cold air inversion so that by 0900 the gradient wind again dominates the airflow of the area. Details of the study are described in the special report prepared by Larry Proctor entitled "Wind Flow Patterns Around Rogers Lake."

CONDENSATION NUCLEI STUDIES

Although the USAERDL flight research program did not involve condensation nuclei seeding as was the case two summers ago, we made nuclei concentration studies in a number of locations. The. majority of readings were made at the Research Center 2 1/2 miles NNW of town and at S. P. Crater 15 miles N. of the Peaks. This latter location is as free from local air pollution as it is possible to get near ground level in northern Arizona.

As with all our readings, the Gardner Counter is operated at low, high and intermediate levels of supersaturation by controlling the amount of vacuum in the expansion section of the instrument. When a 2-inch level of mercury is used, the instrument indicates the approximate concentration of condensation nuclei that will form cloud droplets. When the 22-inch level is used, all particles, including the submicroscopic, are forced to accept moisture due to the high degree (about 300 percent) of supersaturation produced.

The values this year were higher than last year on the average. The lowest values at the Research Center were about the same as in preceding years, running from 150 to 300/ccm. The higher values were rarely below 3000 and occasionally exceeded 10,000. This reflects the increased amount of air pollution which, unfortunately, is beginning to appear over the city of Flagstaff.

This is a localized phenomenon as indicated by the lower values found throughout the day and night at S. P. Crater. Although the low supersaturation values were about the same as at the Research Center — ranging from 150 - 200 — the high supersaturation values were from a half to a full order of magnitude lower. Values at maximum supersaturation were often less than 800 and rarely above 1250. Consequently, it is safe to conclude, I believe, that these values are the background level, higher values reflecting either air pollution from the Flagstaff city area, the highways, or the effect of prescribed forest fires. These latter were mostly to the east and south with little chance of reaching the S. P. Crater area. On one occasion measurements were made on the rim and in the canyon at Grand Falls on the Little Colorado when the river was dry. Values the same as at S. P. Crater were found: low supersaturation 150 - 200 particles per cubic centimeter; highest supersaturation 1200 - 1500 per ccm.

Two visits were made to Government Cave approximately 15 miles northwest of the Research Center. As in preceding occasions, values at maximum supersaturation were under 300 per ccm. Also, as in preceding years, there was a slight drift of air out of the cave. Since this cave has a volume estimated at 150,000 cubic meters, it would be a good location to conduct semi-quantitative nuclei reaction studies. The drift of cold air from the cavern mouth of 1/2 to 1 meter per second would flush out any reaction materials. The purity of the air of Government Cave is thought to be due to the filtering action of the lava bed above it through which the "make-up" air must pass.

All of the measurements of nuclei were made by Mr. Larry Proctor, the NSI student who also measured the airflow pattern at Rogers Lake.

FIELD OBSERVATIONS

Every operational day during the period of the flight operations of the USAERDL aircraft, I (V. J. Schaefer) tried to get as close as possible on the ground to the most active part of the first storm and its precipitation zone. At such locations I made local observations of lightning strikes and the general development and behavior of the storm. In a number of instances I observed the USAERDL aircraft as it probed the cloud base of the active storm. Salient developments and the time and location of observed lightning were reported the following morning at the briefing held at 0800 in the Science Building of the University. Field notes on lightning occurrences were given to Norbert Ensslin, who was evaluating the lightning data from the two field stations.

At the morning briefings I also made it a point to ascertain from Mr. Barr how we could be of additional help to his program of operations.

ADDITIONAL SUPPORT TO USAERDL PROJECTS

Two additional operations involved in the 1966 Field Project were assisted by us at the Research Center. The Raindrop Camera developed at the Illinois State Water Survey for USAERDL was located in a clearing adjacent to our Southwestern Field Station, the Max C. Fleischmann Hall. Power to operate the electrical equipment was provided by us. Several years ago our students operated the unit, but this year Dr. Eugene A. Mueller and Mr. Douglas Jones, in charge of the unit, had adequate manpower.

A Raindrop Spectrophotometer, developed at New York University by Mr. Alan Nathan, was located on our observation platform on top of Fleischmann Hall. Power and other facilities were made available by us to Mr. Nathan during his work at Flagstaff. Telephone, lights, storage space and other facilities were available as needed.

LOCATION OF REPORTS, NOTEBOOKS AND RAW DATA

A collated set of the 1964, 1965 and 1966 Research Project Reports of all Arizona Unit NSI students has been placed on file in the Library of the Research Center of the Museum of Northern Arizona at Flagstaff. The original reports are in my office at R. D. 3, Schenectady. The Field Notebooks and other raw data are in the Director's files in Max C. Fleischmann Hall of the Research Center. The raw data from the wind recorders are filed with Meteorology Research, Inc. at Altadena, California, where the data will be analyzed.

ACKNOWLEDGEMENTS

Sincere thanks are extended to the Atmospheric Physics Section of the U. S. Army Electronics Research and Development Laboratories whose field force at Flagstaff this year was headed by Mr. William C. Barr. He was of much help to us in the initial preparation of plans, the continuing loan of the three Lambrecht wind instruments, and the transportation during the program. Special thanks are also offered to members of his staff who helped our NSI students whenever needed.

Our thanks also go to Drs. Helmut Weichmann, Heinz Kasemir, and E. M. Frisby associated with the Environmental Science Services Administration organization at Boulder, Colorado, and their staff, especially H. J. Wells and J. Kelly.

THE ARMY-E.S.S.A. PROJECT

by

Norbert Ensslin and Carver Simmons

THE NATURAL SCIENCES INSTITUTE

ATMOSPHERIC SCIENCES RESEARCH CENTER

STATE UNIVERSITY OF NEW YORK

Supported by

CHARLES F. KETTERING FOUNDATION

Max C. Fleischmann Hall

Research Center, Museum of Northern Arizona

Flagstaff, Arizona

August 9, 1966

THE ARMY-E.S.S.A. PROJECT

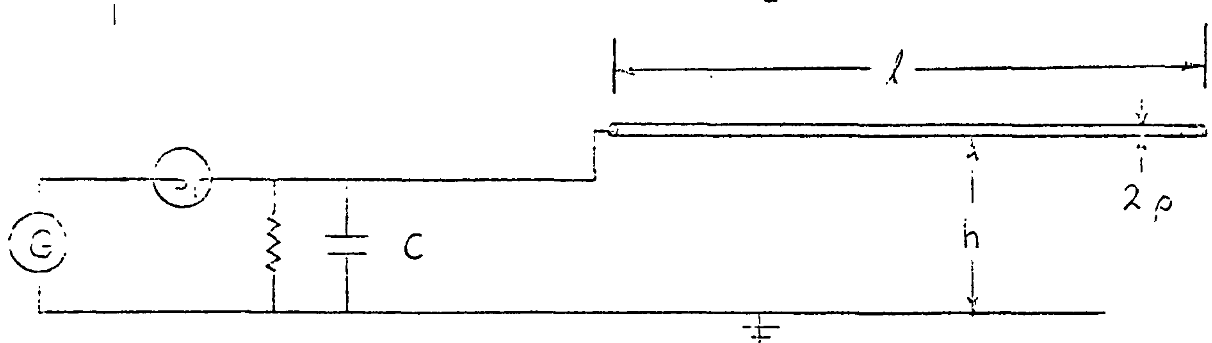
ABSTRACT

During the summer of 1966 Dr. Kasemir continued his lightning triangulation studies at Flagstaff. We assisted with the operation of the two ground stations, and we carried out preliminary reduction of data. The immediate result of this work is an insight into the improvements needed in technique and equipment.

Dr. Kasemir's study of thunderstorm fields and lightning was conducted as part of a joint Army-ESSA project. He was interested in measuring thunderstorm fields from the air with field mills attached to an airplane and in modifying these fields by dispensing chaff into the air beneath the cloud. Two mobile vans were supplied by the Army in order to make it possible to triangulate strokes and correlate them with strokes observed from the air by Dr. Kasemir.

One van was located at the Flagstaff Airport and the other at the Navajo Ordinance Depot, providing a base line roughly ten miles long. The former was equipped with an eight channel Sanborn recorder and a Sargent recorder, and the latter with a six channel Sanborn recorder. The Sanborn recorders provided a wide range of speeds and amplifications and they were used to record field components from a variety of instruments.

At each station one channel of the Sanborn was used to record the vertical component of the electric field, as determined by a long wire suspended horizontally above the ground. According to Dr. Kasemir, the wire couples to the air with a capacitance $C_a = 2\pi\varepsilon_0 \, l/\ln(l/\rho)$.



If C is the larger measured capacitance between the wire and the ground, and U_a the potential of the wire, the potential before amplification is

$$U_o = U_a C_a/(C + C_a) \approx U_a C_a/C$$

and, after amplification by a factor K,

$$U = K C_a U_a/C.$$

Then

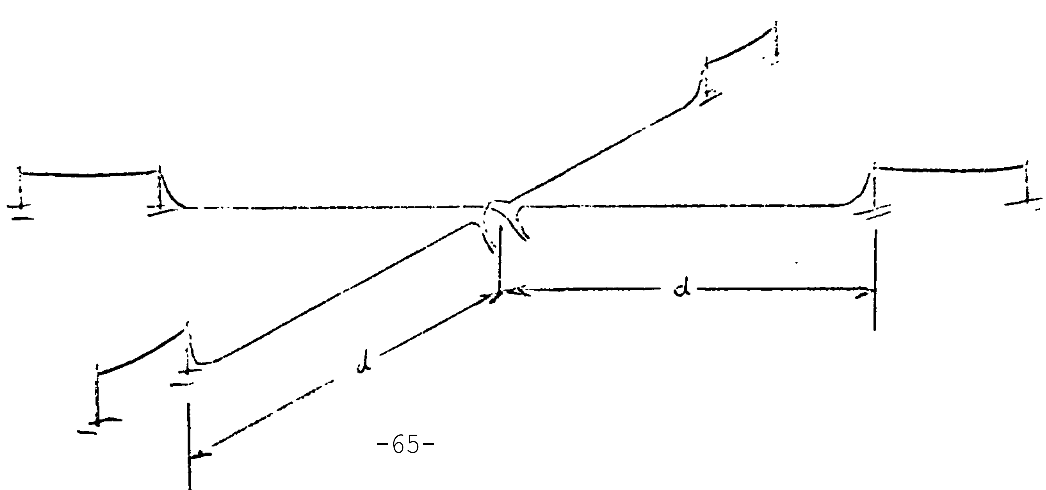
$$E = U_a/h = \frac{U}{hK}\left(\frac{C}{C_a}\right) ,$$

where U is the potential read from the Sanborn recorder.

Two channels of each recorder were used for the East-West and North-South horizontal field components, which were measured by field mills mounted on 30 foot masts. These cylindrical mills, designed by Dr. Kasemir, measure the potential between two semi-circular plates. They rotate at high speed and are thereby able to measure both horizontal components from a single stroke, which determines its direction. The field mills were first "calibrated" by shooting charged teflon mounted on arrows past them in order to determine their orientation. This orientation is the same as that for cloud (negative potential) strokes; for ground (positive potential) strokes the compass directions given by the mill must be reversed.

Another direction-finding instrument available at each ground station was the "Sparsa," built by Dr. Douglas Kohl of Litton Industries. According to Dr. Kohl the instrument consists of three mutually perpendicular ferrite cores which are rotated at 2 r.p.s. These cores respond to the magnetic component of 500kc radiation emitted by lightning, but only if the voltages induced in them are in a certain ratio is a "T-pulse" produced, which is superimposed on a sine wave trace on the Sanborn recorder. This technique gives the instrument a very narrow "acceptance angle," so that in principle its precision is limited primarily by the crookedness of the lightning channel.

The remaining two channels of the Sanborn recorder at the Navajo ground station recorded the East-West and North-South horizontal field changes as measured by a set of antennas, "crossed" as illustrated, with "d" about 75 meters.



Each of these four antennas measures the vertical field in the same manner as the field antenna discussed above. Opposing antennas, however, are coupled by balanced capacitors so that each pair measures the horizontal change of this vertical component over 150 meters.

The determination of these field changes is not obviously feasible, since the field strength is perhaps far larger than the field change over 150 meters. According to Dr. Kasemir, however, fields due to near strokes decrease as the inverse cube of the distance, if the action of the stroke may be interpreted as the change in a vertical dipole. This is borne out by the following calculation: the field of a dipole is given by

$$\vec{E} = \frac{1}{4\pi\varepsilon_o} \left[\frac{3(\vec{p}\cdot\vec{r}) - \vec{p}r^2}{r^5} + \frac{3(\dot{\vec{p}}\cdot\vec{r})\vec{r} - r^2\dot{\vec{p}}}{r^4 c} + \frac{(\ddot{\vec{p}}\cdot\vec{r})\vec{r} - \ddot{\vec{p}}\, r^2}{r^3\, c^2} \right]$$

Here $\vec{p}(t) = q(t)$ times (some)$\vec{h}$ is perpendicular to $\vec{r}$, and

$$E \;\alpha\; \frac{q}{r^3} + \frac{1}{r^2 c}\frac{dq}{dt} + \frac{1}{rc^2}\frac{d^2q}{dt^2}\,.$$

A change in the field will be caused by changes of roughly $q = 20$ coul, $dq/dt = 20{,}000$ amps, and $d^2q/dt^2 =$ (20,000 amps)/(1/2 of 100 μsec stroke duration) $= 4 \times 10^3$ coul/sec^2.

At 10 kilometers,

$$E \;\alpha\; 2.0 \times 10^{-11} + 6.7 \times 10^{-13} + 4.4 \times 10^{-13}\,.$$

Thus the field does decrease roughly as the inverse cube of the distance, and since

$$\vec{E} = (1/4\pi\varepsilon_o)\, p/r^3\,,$$

$$dE = \frac{p}{4\pi\varepsilon_o}\left(\frac{-3r^2 dr}{r^c}\right) \quad \text{and} \quad \frac{\Delta E}{E} = -\frac{3\Delta r}{r}\,.$$

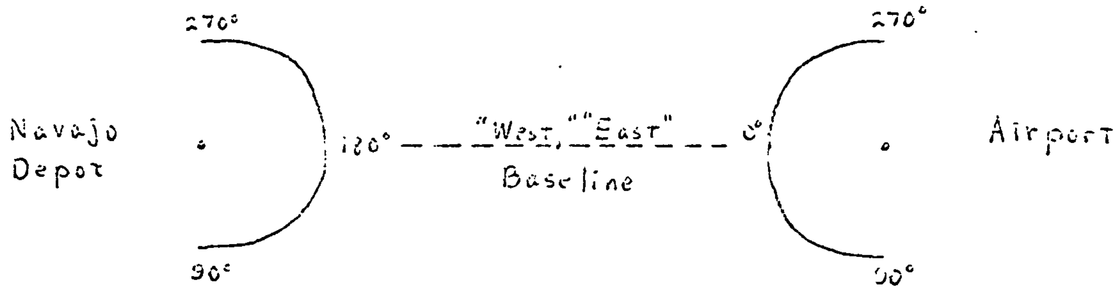
For $\Delta r = 150$ m, $\Delta E/E = .045$ at 10 kilometers.

According to Dr. Kasemir, the resistors and balanced capacitors of the cross-antenna system are accurate to 1 in 1000. Then each pair may be accurate to within about .045 = .002. This 4% error is doubled when the ratio of the measurements in the two pairs is used to calculate the direction of the stroke. Increasing the separation of the antennas or installing more accurate circuit elements will reduce this 8% error. At 10 km., however, the induction and radiation fields-as calculated above-seem to introduce a further error of roughly 5%.

At the Airport van one of the extra channels of the Sanborn recorder displayed the second derivative of the field with respect to time. This was measured by a small instrument constructed by Dr. Kohl and attached to a horizontal field antenna. The instrument responds to positive values of the second derivative by producing sharp pulses. The airport van also contained a Sargent recorder, which keeps a very sensitive record of lightning strokes by producing pulses varying with the magnitude and polarity of the stroke. These records were used to compare the relative number of negative and positive polarity strokes.

Samples of the Sanborn records produced by the aforementioned instruments are given in figures (1) to (7) for the Airport recorder and figure (8) for the Navajo recorder.

In addition to the instruments in the vans there were facilities for visual observation of strokes.



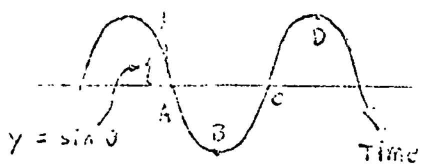
A "kindergarten," a semicircle of labelled stakes set at five degree intervals and having a radius of curvature of about 40 feet, was located at each ground station. The directions of the semicircles, as well as the directions of the field mills, Sparsa units, and cross-antennas, were all defined with respect to the baseline between the stations. An observer standing at the center of curvature called out visual strokes to the person monitoring the recorder, and the latter then wrote down the stroke number, time, and azimuth. Contact by intercom between the two stations made it possible to keep the numbering of strokes identical even if both stations did not see them.

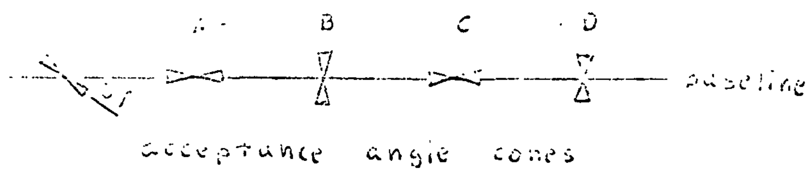
In the late afternoon the records were removed from the vans for analysis. The field change due to each stroke revealed its polarity. Then it was possible to assign the correct direction to the corresponding deflections on the East-West and North-South field mill and cross-antenna channels. The ratios of the deflections yielded the tangent of the angle. For the field mills, the magnitude of the deflection is given, according to Dr. Kasemir, by the distance "d." The field deflection due to the

"pre-discharge" is thereby neglected. For the cross-antennas as well, it

is the height of the capacitative decay curve which must be measured.

The trace of the Sparsa yielded the sine of the angle. A knowledge of the orientation of the Sparsa made it possible to determine the angle





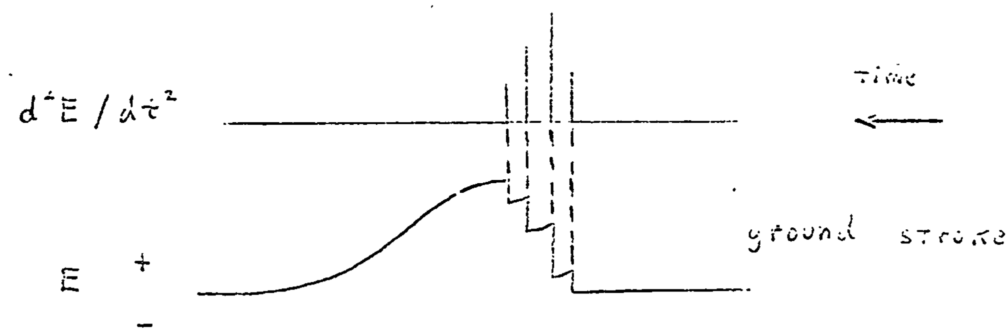
rapidly, although the visual sighting was necessary to eliminate the 180 degree ambiguity. By assigning 100 units to the amplitude of the wave, the sine could be read directly from the finely subdivided Sanborn chart. A slide rule or log. tables then yielded the angle with more precision than the trace warranted. This method was the most rapid and the most precise for the relatively slow (10 mm/sec.) chart speed used.

Table I summarizes the data obtained in this way at the Airport and Navajo stations. From those strokes seen at both stations it is possible to compute the position of the stroke by trigonometry.

Not all of the apparatus worked correctly. At Navajo the field mill was not properly "damped," or not properly balanced. Moderate to heavy strokes produced oscillatory patterns which could not be analyzed (fig. 8). The cross antennas were also not properly balanced: computed angles are consistently too far south (table I). At the Airport the field mill functioned properly, but the discrepancies with the visual sightings are often large (table I).

The Sparsa records were often difficult to interpret. Brief strokes were often missed, but some multiple strokes had no records as well. More often, however, there were a number of pulses for each stroke - more than might be expected from the fact that the Sparsa should record a long stroke every 180 degrees or every 1/4 second. As in the past, the pulse which most nearly agreed with the visual sighting was accepted, on the theory that the Sparsa sees more than the human eye. Nevertheless, the correlation of visual and Sparsa angles was worse than in previous years: about 10 degrees mean error at Navajo, and more at the Airport. Figure 9 compares the field mill and the Sparsa at the Airport, figure 10 compares visual and Sparsa at the Airport, and figure 11 compares visual and Sparsa at Navajo. In part, these poor results are due to the fact that strokes which appeared as hazy blurs were counted and their azimuths were estimated, but the fact that they were hazy was not recorded.

Interesting records were obtained from the trace of the second derivative of the field with time. An MRI potential gradient meter was connected to another extra channel of the Airport Sanborn so that the field and its second derivative could be displayed side by side (figures 2-7). A comparison of the number of jumps in d^2E/dt^2 with the curve of the electric field reveals that the largest jumps in d^2E/dt^2 occur at the time of the most rapid changes in the field. Also, the number of deflections in d^2E/dt^2 correspond to the step changes in the electric field produced by multiple return stroke current surges. The average lightning stroke has about four main return strokes, which implies four jumps in the record of d^2E/dt^2. The average stroke record would appear as in the diagram below.



The amplitude of d^2E/dt^2 is representative of the surge in each return stroke. Figure 7 shows a series of single surge ground strokes. Figure 6 is a rather unusual example of an extremely rapid recovery between multiple strokes. The initial negative deflection in figure 6 suggests the possibility that this ground stroke consisted partly of an internal cloud discharge. If the Sanborn recorder is run at its maximum speed, then the record of d^2E/dt^2 is dispersed; and it becomes possible to determine directly the duration of the larger return stroke surges. This result can be seen in figures 2 through 5. In these recordings the strokes are 0.02 to 0.4 seconds long. Following each series of main strokes there is usually a group of small fast changes in the d^2E/dt^2 that do not disturb greatly the existing form of the electric field. Such small variations perhaps indicate a continuing current flow in the ionized region of the stroke. Also, deflections of d^2E/dt^2 appear to have the greatest magnitude for positive field changes. Finally, small jumps in d^2E/dt^2begin to appear in the early stages of thunder cloud growth - usually before any detectable changes in electric field or dE/dt occur. (See multiple stroke data, figures 12 to 13.)

The Sargent recorder at the Airport yielded results on the relative number of cloud and ground strokes. Often the storms began with more cloud strokes than ground strokes (figures 14 to 18). This supports Dr. Kasemir's idea that ground strokes do not appear until rain begins.

The records are not conclusive, however. The counting technique favored the larger ground strokes. Also, cloud strokes will appear as positive (ground) strokes if the storm is closer than about six kilometers. Thus in reality cloud strokes might have been pre-eminent at the beginning of each of the storms recorded.

The primary result of the work on direction finding is an appraisal of the improvements needed. Visual sighting techniques must be made more rigorous, and communications between the two ground stations should be improved. Some time must be spent in correcting the field mill at the Navajo station and in balancing the crossed antennas. Hopefully such changes will soon make it possible to assist the airplane studies from the ground.

ACKNOWLEDGEMENTS

We would like to thank Dr. Kasemir of E.S.S.A. and Dr. Kohl of Litton Industries for their advice and help during the past weeks. We are also grateful to the Army for their support and for the opportunity to work with their equipment, and to Dr. Schaefer for making it possible for us to participate in this program.

Tnble I

Data on Strokes

Navajo Station, July 27, 1966

no.	time	crossed antennas,angle			Sparsa,angle		visuol
1	094100	1.9S	2.4E	142			259
2	124830	.4S	2.2E	170	.18	190	196
3	125110	.4S	1.2E	162	.36	201	203
4	125310	1.0S	2.0E	153	-.12	173	188
5	125430	.5S	2.7E	170	.49	209	193
6	123610	2.0S	4.3E	155	.04	182	184
7	130000	.3S	1.2 E	166	.43	205	200
8	130200	1.1S	3.0 E	3.60	.42	205	205
9	130345	1.9S	4.7E	158			192
10	130510	1.4S	3.1E	154	.58	215	187
11	130731	.2S	1.0E	169	.58	215	200
12	130845	1.0S	2.5E	158	.76	229	175
13	131412	2.3S	5.3E	157	-.13	173	175
14	131810	S	1.7E		-.26	165	185
15	132125	S	E		-.06	177	173
16	13 50	26.0S	3.0E	97	.99	262	270
17	133700	.9S	5.8E	171	1.00	262	240
18	133910	1.7N	6.0E	196	.96	254	255

Navajo Station, July 29, 1966

no.	time	crossed antennas,angle			Sparsa,angle		visuol
1	112105	19.0S	4.4E	103			136
2	112210	5.4S	2.8E	117			140
3	112305	19.8S	11.5E	120	-.38	158	152
4	112515	5.3S	2.4E	114	-.82	125	129
5	112600	8.1S	3.9E	116	-.62	143	160
7	113200	7.2S	2.7E	111	-.82	125	115
8	1134 00	9.2S	4.6E	116	-.36	159	132
9	113600	8.2S	4.0E	116	-.99	98	130
10	133720	3.1S	1.6E	117	-.66	139	140
11	113830.	4.4S	2.3E	118	-.61	143	138
12	113900	20.6S	4.8E	103	-.92	113	115
13	114100	8.0S	3.5E	114			105
14	114330	11.8S	5.6E	115			140
15	115200	16.3S	2.3E	98	-.98	101	90
17	115630	10.8S	1.6E	99	-.95	108	103
19	115910	8.3S	1.5E	100	-.95	108	117

Navajo Station, July 30, 1966

no.	time	crossed antennas,angle			Sparsa,angle		visuol
1	121040						160
2	121715						170
3	122310	3.3S	2.2E		.07	184	192
4	122420	4.7S	3.7E		.28	196	190
5	122655	18.5S	8.5E		.04	182	200

Table I, Data on Strokes, continued

no.	time	crossed antennas		Sparsa,angle		visual
6	122810	4.4S	3.4E	-.18	170	195
7	123005	2.8S	2.6E	.21	192	189
8	123130	5.5S	4.0E			190
9	123440	8.5S	4.7E			195
10	125203	1.7S	.9E	.26	195	185
11	142935	29.0S	5.0E			110
12	143550	6.0S	.9E	-.99	98	95
13	143645	22.2S	2.5E	-1.00	90	90
14	143745	2.0S	.4E			100
15	144033	16.7S	1.7E	-.98	101	
16	144110	7.4S	1.1E	-.99	98	105
17	144315	3.3S	.8E	-.90	116	120
18	144405	4.0S	.6E	-.99	98	115
19	144440	18.1S	2.0E	-.88	118	120
20	144630	3.8S	.5E			115
21	144755	6.5S	.9E			115
22	144735	2.9S	.6E	-.74	132	120
23	144802	2.6S	.5E	-.93	112	110
24	144850	3.3S	.5E			150
25	144900	4.5S	1.4E	-.91	115	120
26	144930	5.7S	1.3E			115
27	145120	3.9S	.7E	-.98	101	115
28	145155	3.1S	1.1E			130
29	145235	19.0S	2.0E	-.96	106	90
30	145240	6.6S	1.8E	-.84	123	120
31	145330	7.0S	1.7E	-.89	117	120
33	145640	5.43	1.5E			130
24	145720	18.7S	5.2E	-.93	112	120
35	145740	8.6S	1.5E	-.89	117	130
36	145840	17.0S	7.0E	-.93	112	115
37	145850	7.9S	2.1E	-.73	133	135
38	145910	7.5S	1.7E	-.85	122	115
39	150009	21.0S	6.0E	-.88	118	117
40	150016	5.2S	1.1E	-.94	110	120
41	150035	8.9S	2.3E			130

Table I, Data on Strokes, continued

no.	time	Visual angle	Mill angle	Sparsa angle
Airport Station, July 27, 1966				
4	125300	-	342	-
5	125400	-	212	254
7	130000	-	284	246
8	132000	-	58	70
9	130400	-	329	348
10	130500	-	78	74
11	130700	-	135	90
12	130900	-	35	-
13	131400	-	140	159
14	131800	-	180	166
Airport Station, July 29, 1966				
3	112305	80	132	-
4	112512	85	75	-
5	1126	110	117	90
6	11	120	120	130
7	113200	-	-	90
10	113720	85	120	106
11	113830	90	79	90
13	114100	80	135	-
14	114330	80	146	175
Airport Station, July 30, 1966				
24	144850	85	129	-
30	145250	88	135	-
31	145330	79	-	-
34	145740	88	125	-
35	145800	97	107	-
36	145830	85	42	-
37	145855	95	170	-
46	150141	84	21	-
51	150345	87	96	-
59	150818	120	90	-
66	151134	95	90	-
67	151208	90	68	

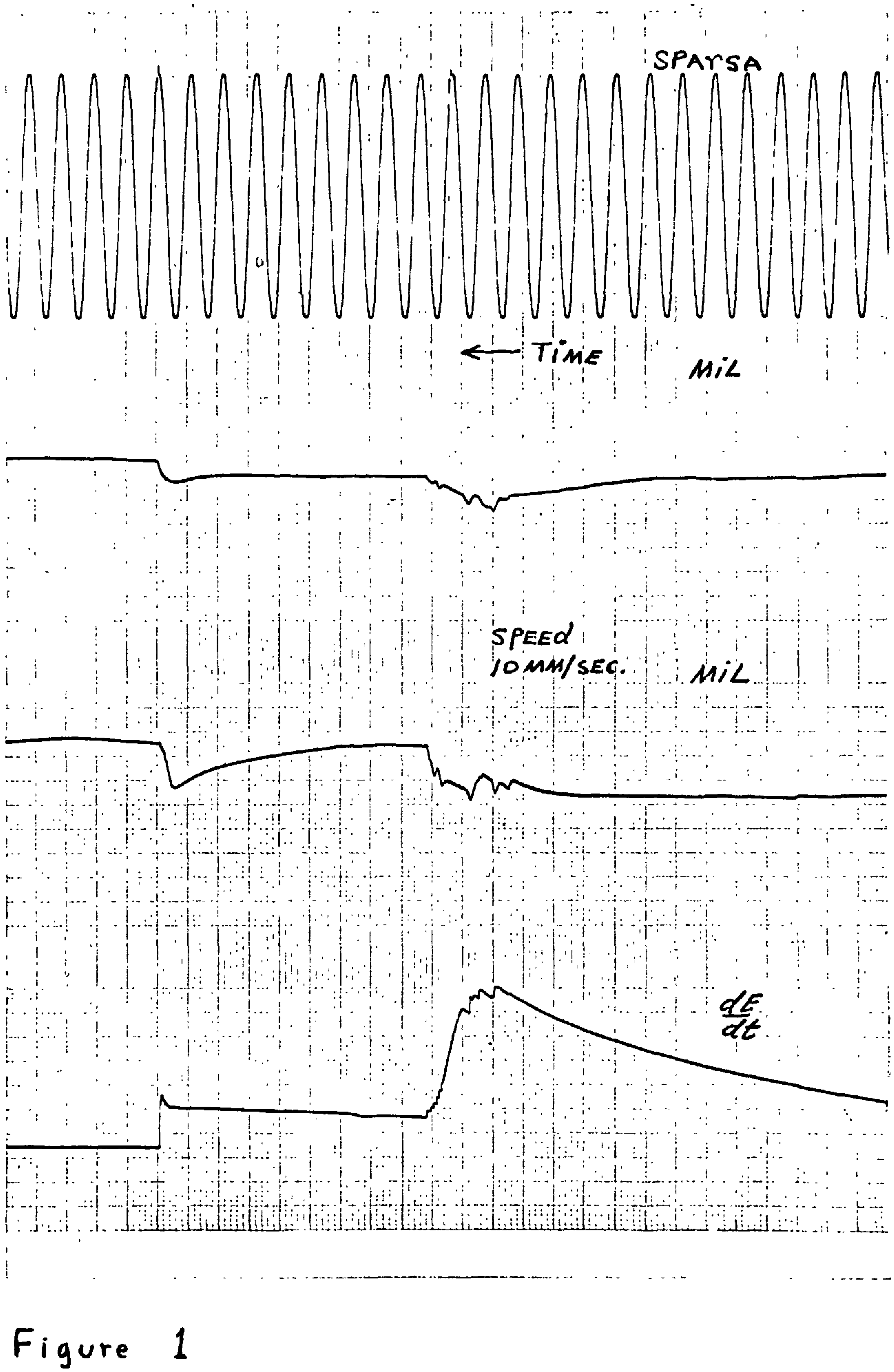


Figure 1

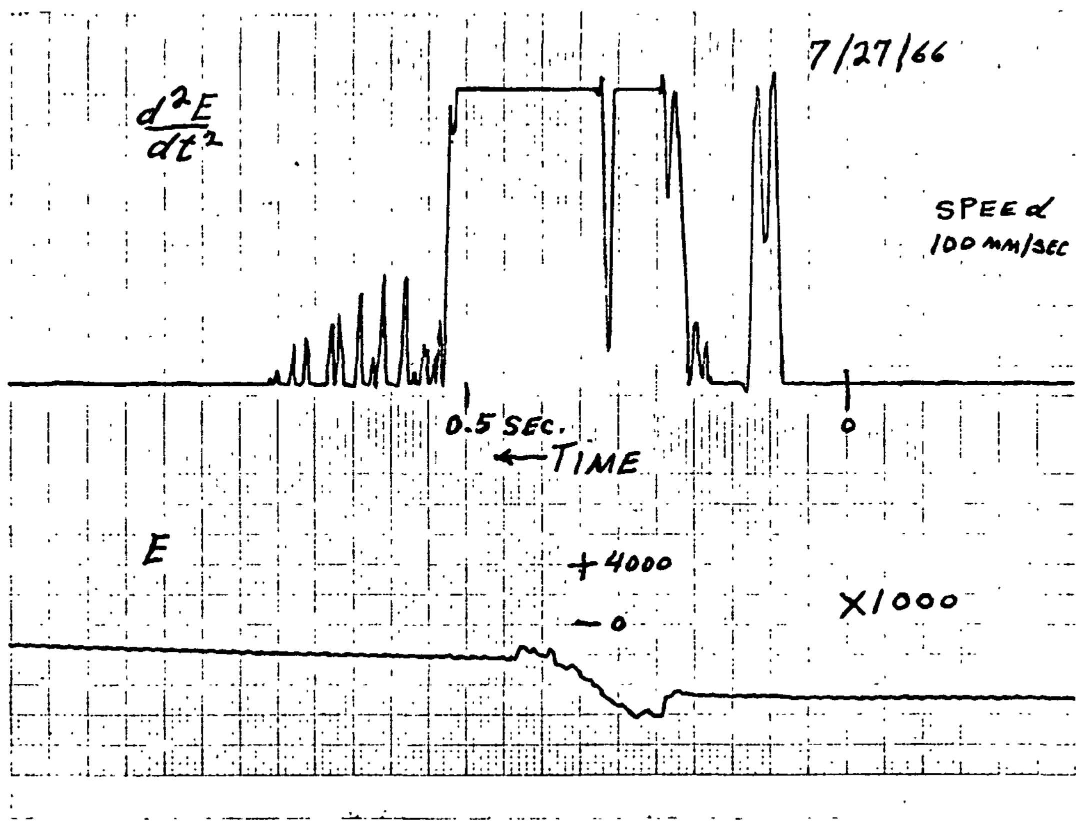


Figure 2

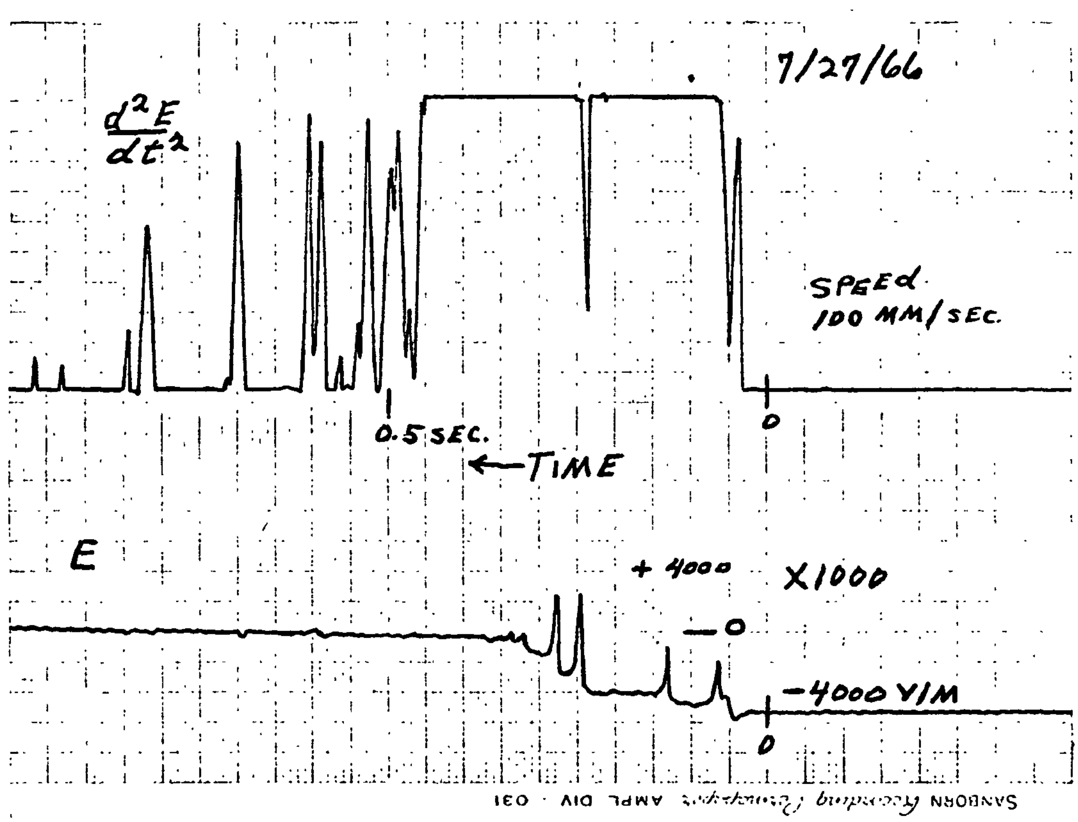


Figure 3

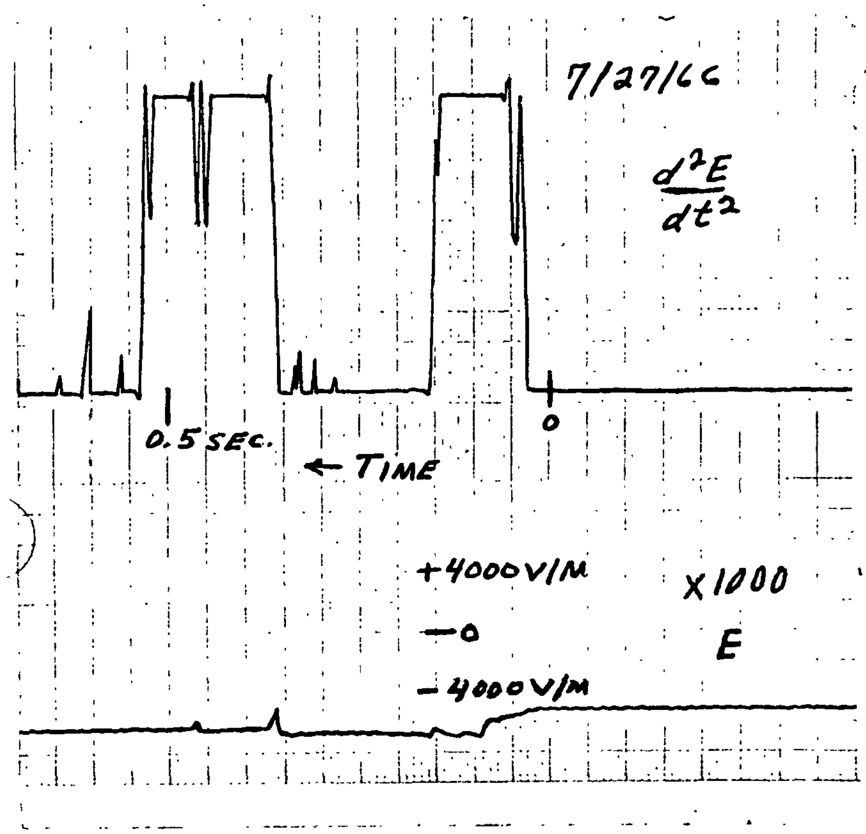


Figure 4

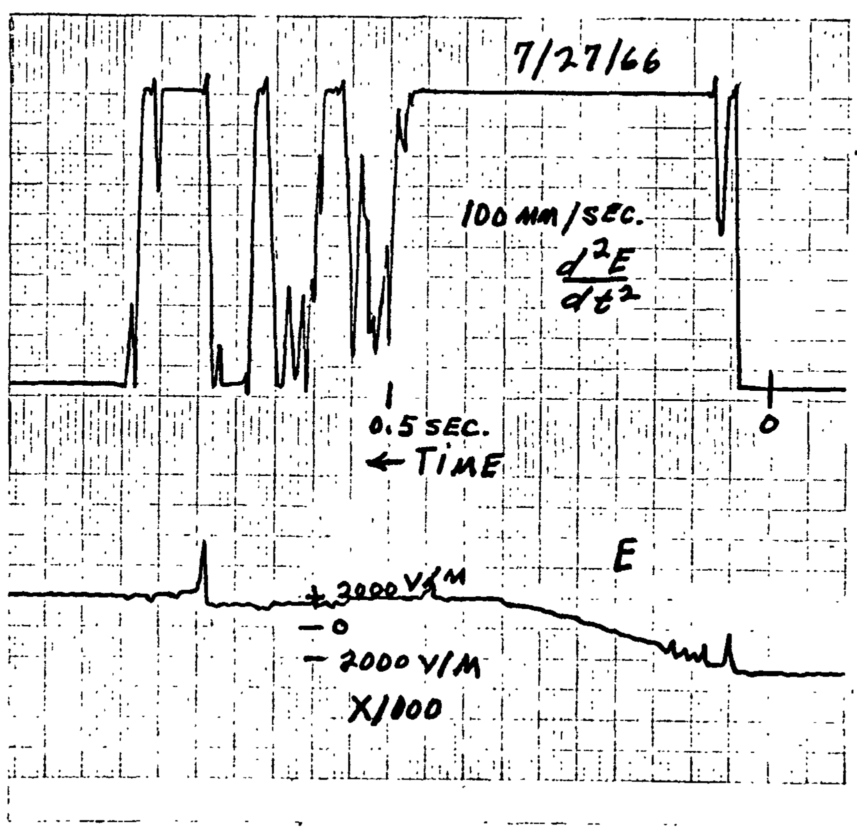


Figure 5

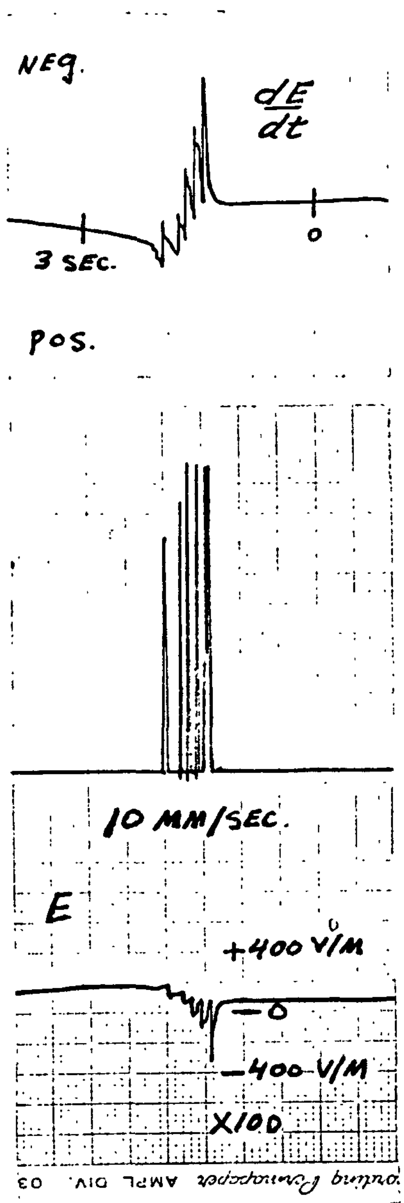


Figure 6

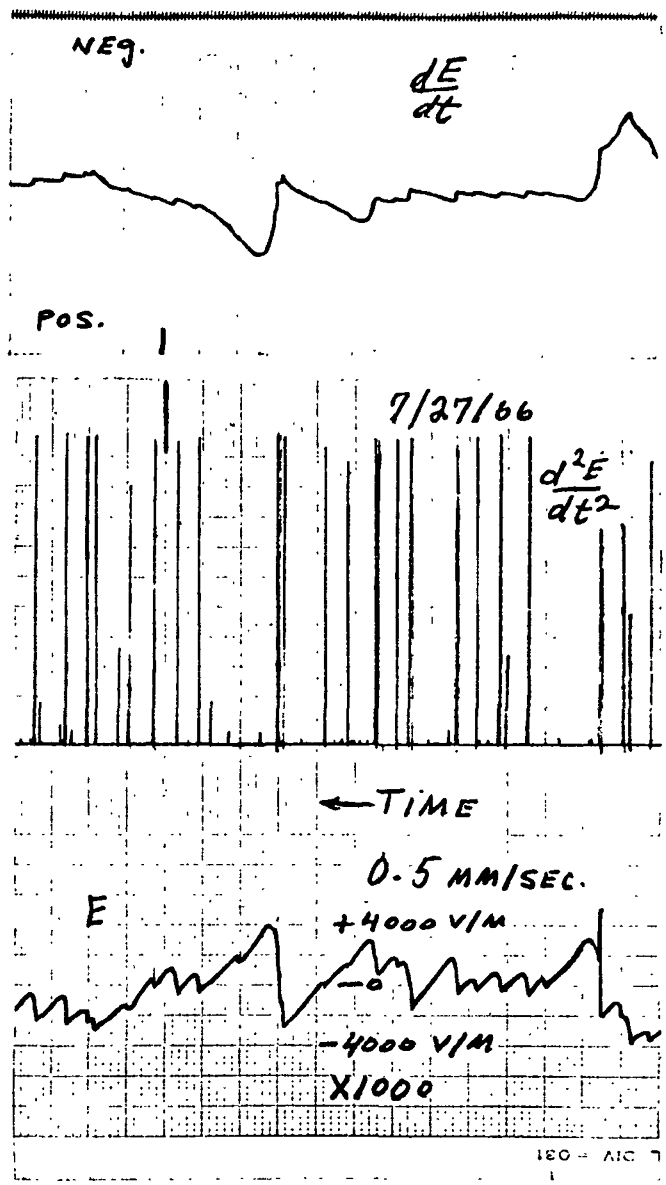


Figure 7

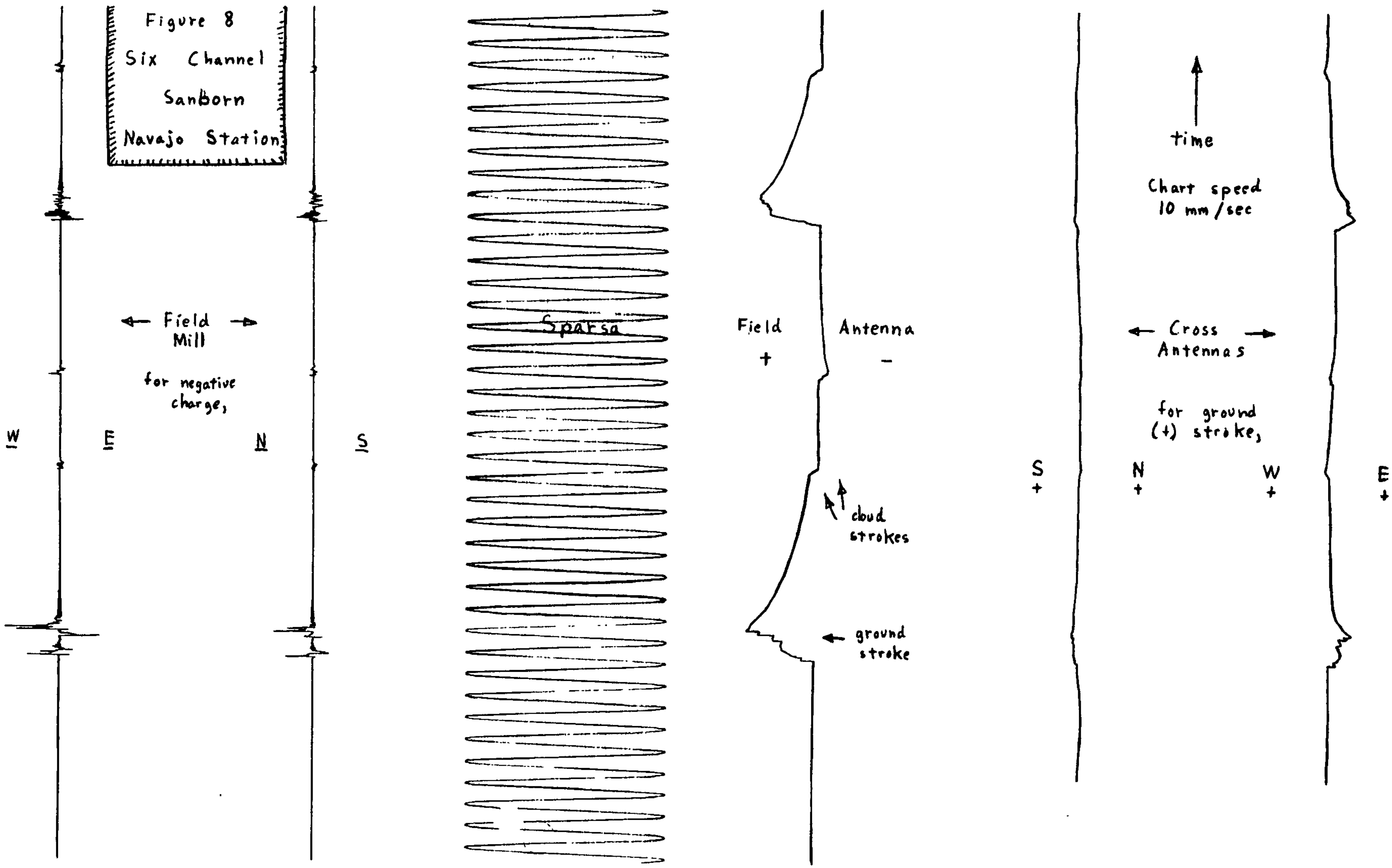


Figure 8
Six Channel
Sanborn
Navajo Station

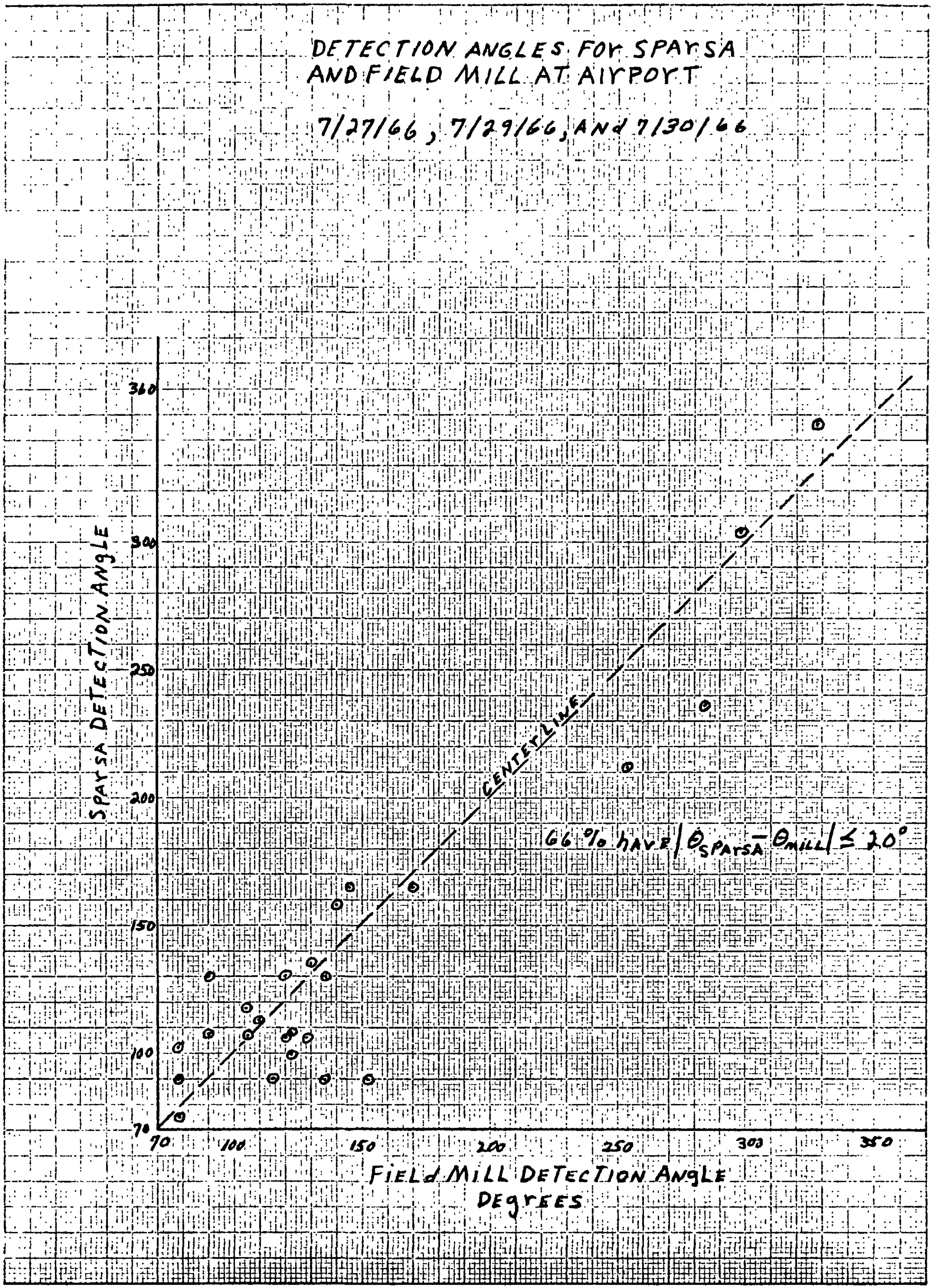

DETECTION ANGLES FOR SPARSA
AND FIELD MILL AT AIRPORT
7/27/66, 7/29/66, AND 7/30/66
SPARSA DETECTION ANGLE
FIELD MILL DETECTION ANGLE
DEGREES
CENTERLINE
66 % have |θSPARSA − θMILL| ≤ 20°
360
300
250
200
150
100
70
70
100
150
200
250
300
350
10 MILLIMETERS TO THE CENTIMETER • NO. 6-5554

Figure 9

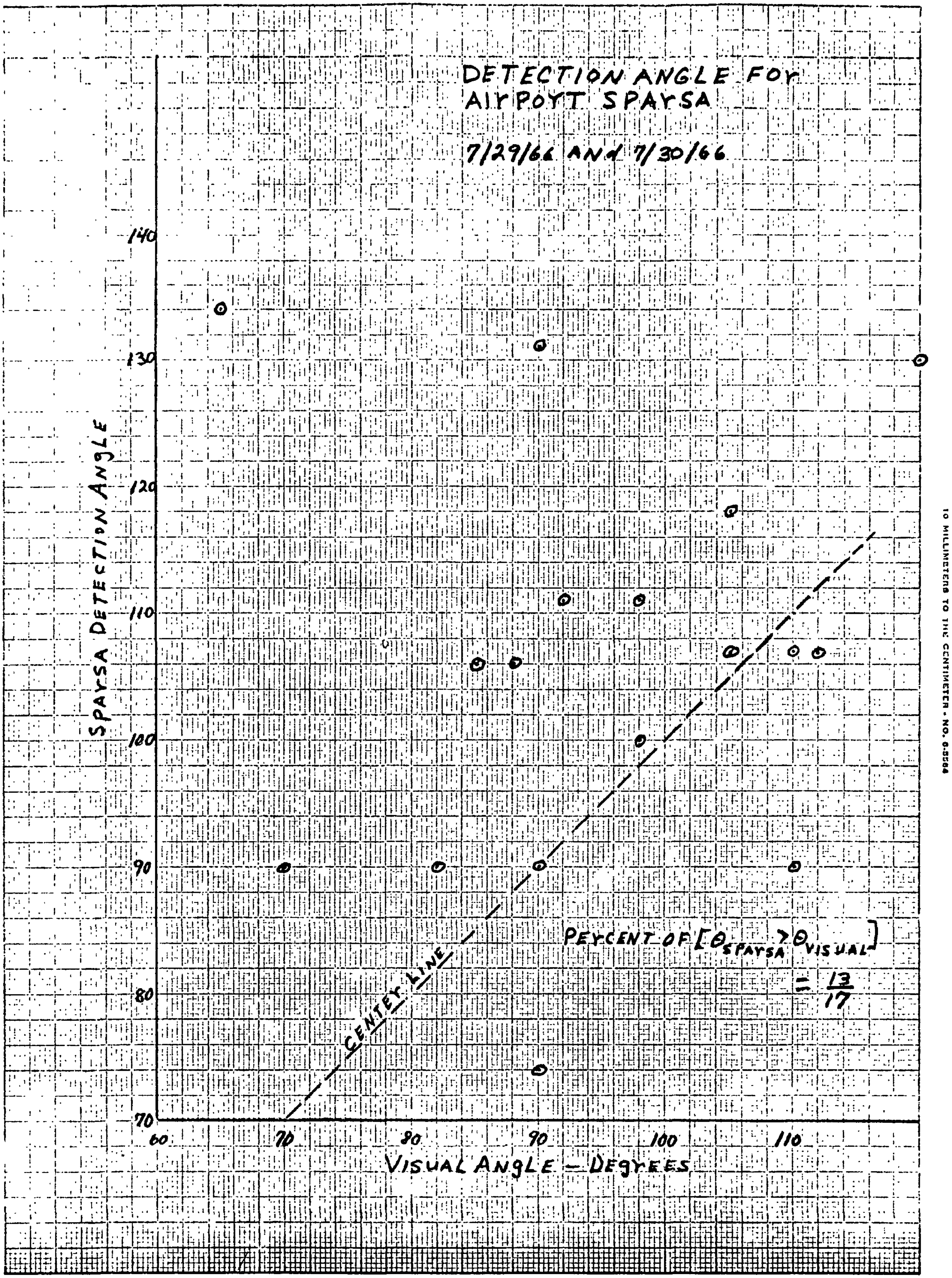

DETECTION ANGLE FOR AIRPORT SPARSA
7/29/66 AND 7/30/66
SPARSA DETECTION ANGLE
VISUAL ANGLE — DEGREES
CENTER LINE
PERCENT OF [θ SPARSA > θ VISUAL] = 13/17
10 MILLIMETERS TO THE CENTIMETER

Figure 10

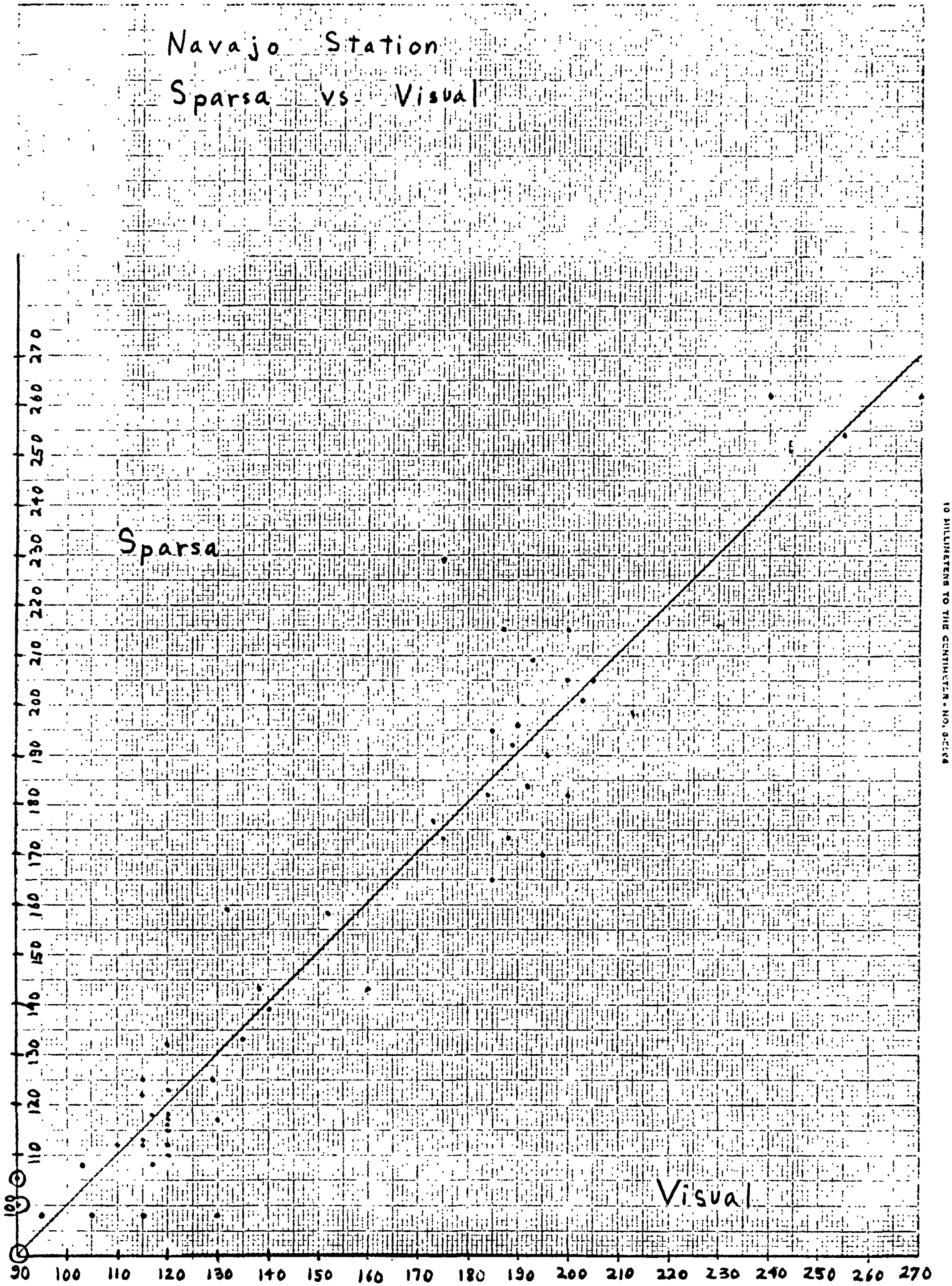

Navajo Station
Sparsa vs Visual
Sparsa
Visual
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
10 MILLIMETERS TO THE CENTIMETER

Figure 11

MULTIPLE STROKE DATA

7 STROKES OF 7/27/66

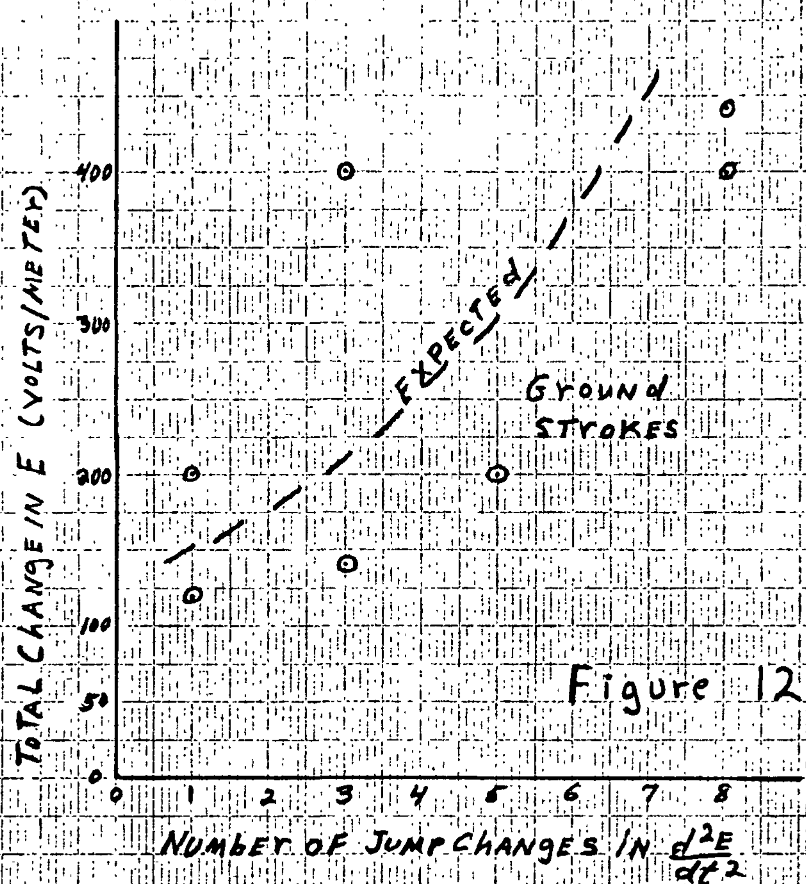


Figure 12

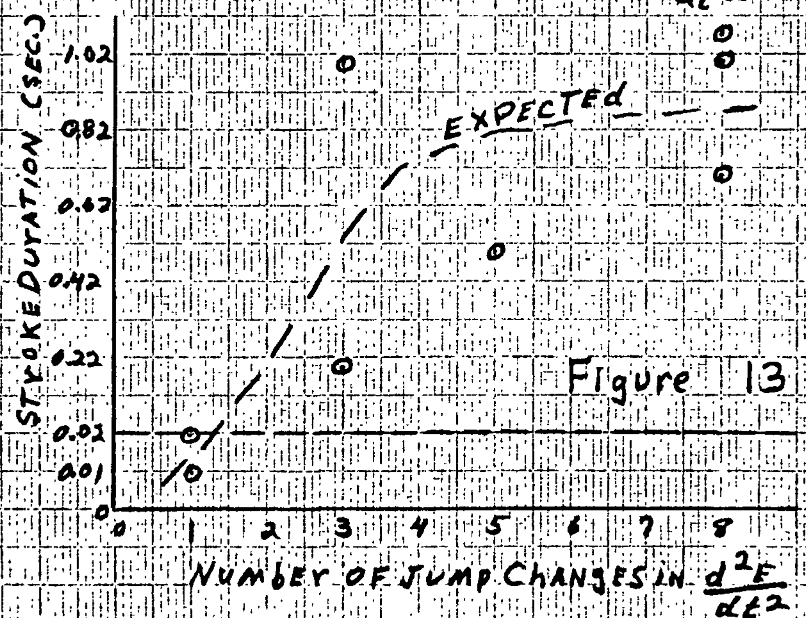


Figure 13

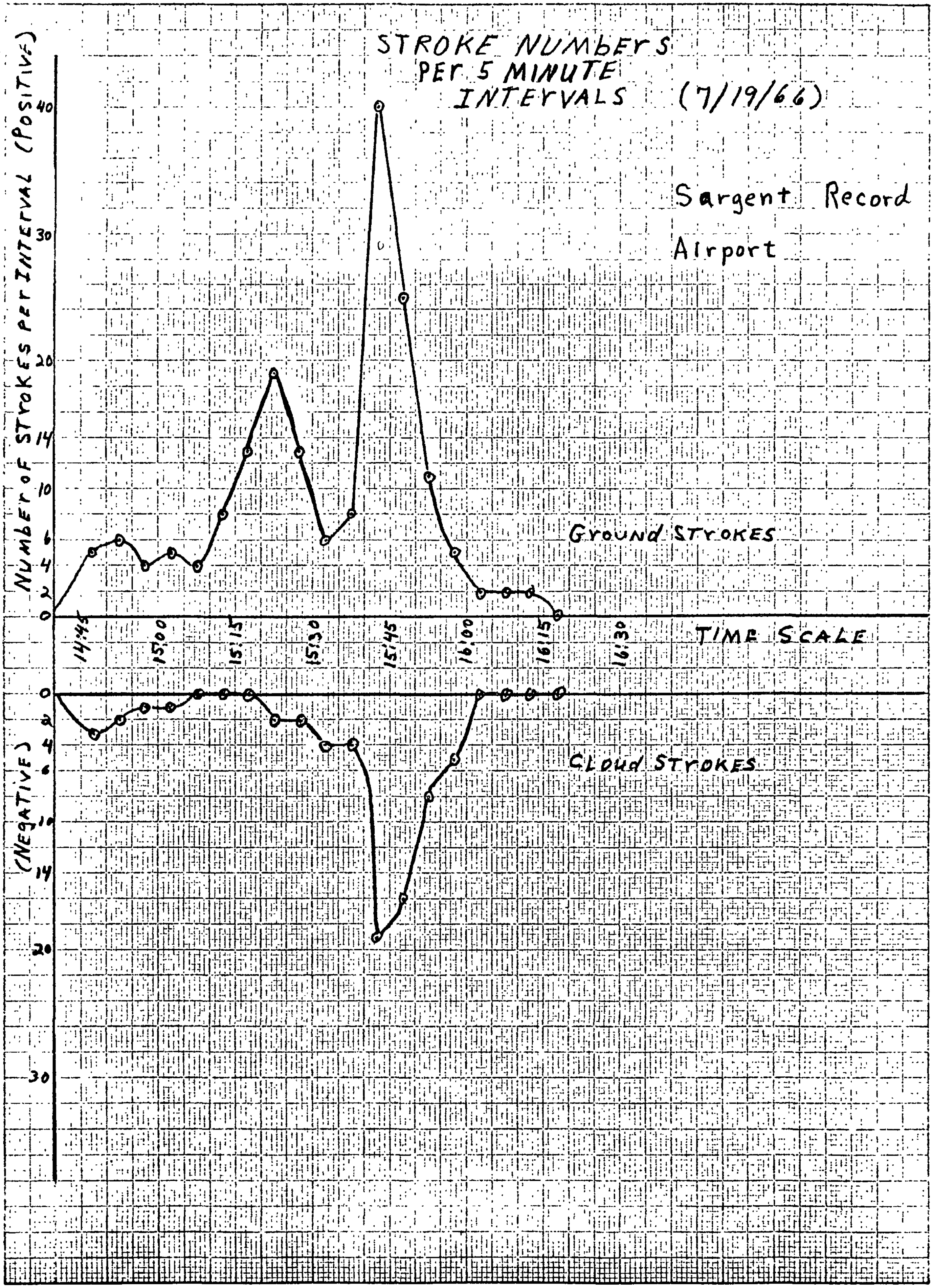

STROKE NUMBERS PER 5 MINUTE INTERVALS (7/19/66)
Sargent Record
Airport
Number of Strokes per Interval (Positive)
(Negative)
Ground Strokes
Cloud Strokes
Time Scale
14:45
15:00
15:15
15:30
15:45
16:00
16:15
16:30
40
30
20
14
10
6
4
2
0
0
2
4
6
10
14
20
30

Figure 14

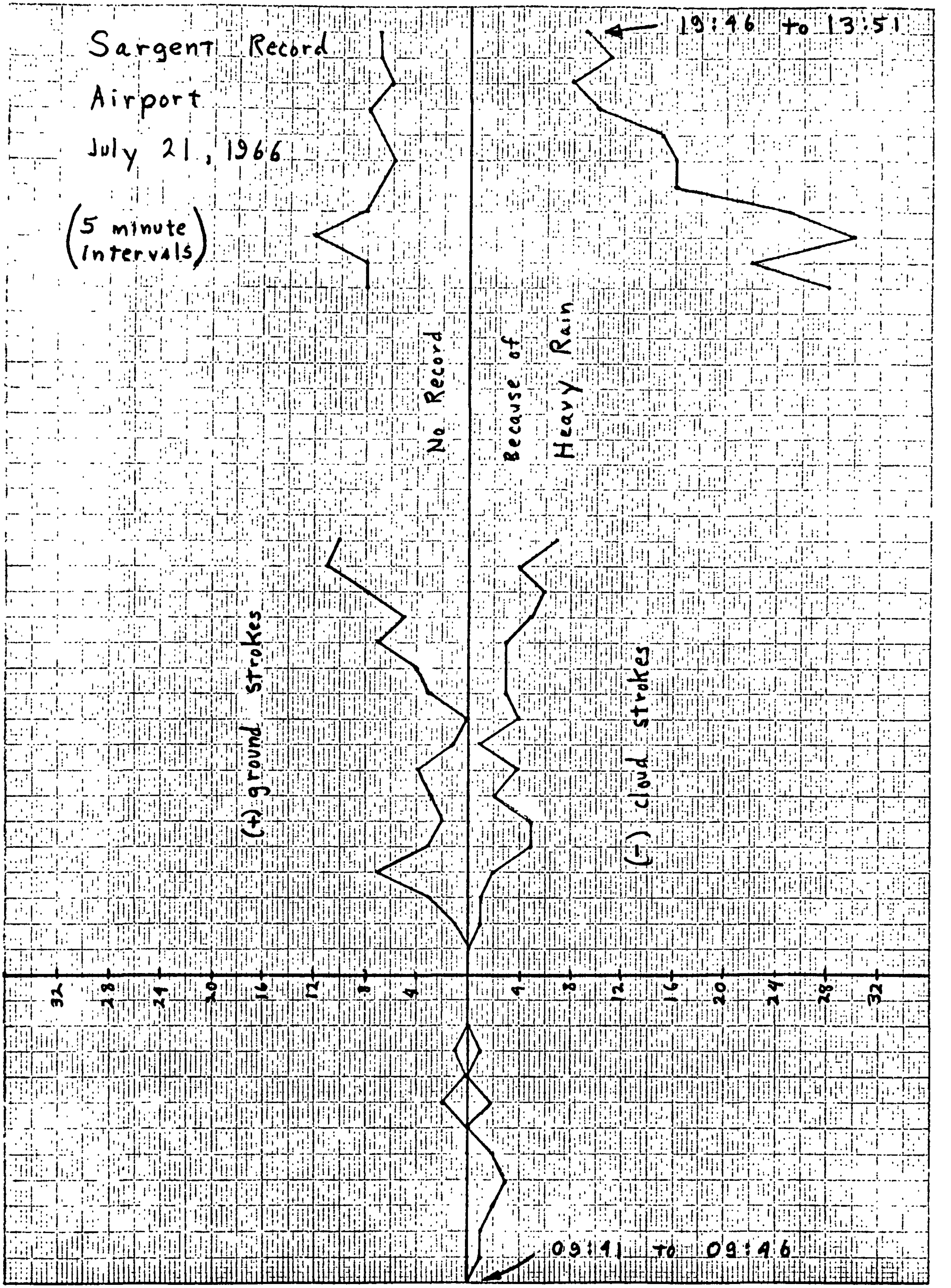
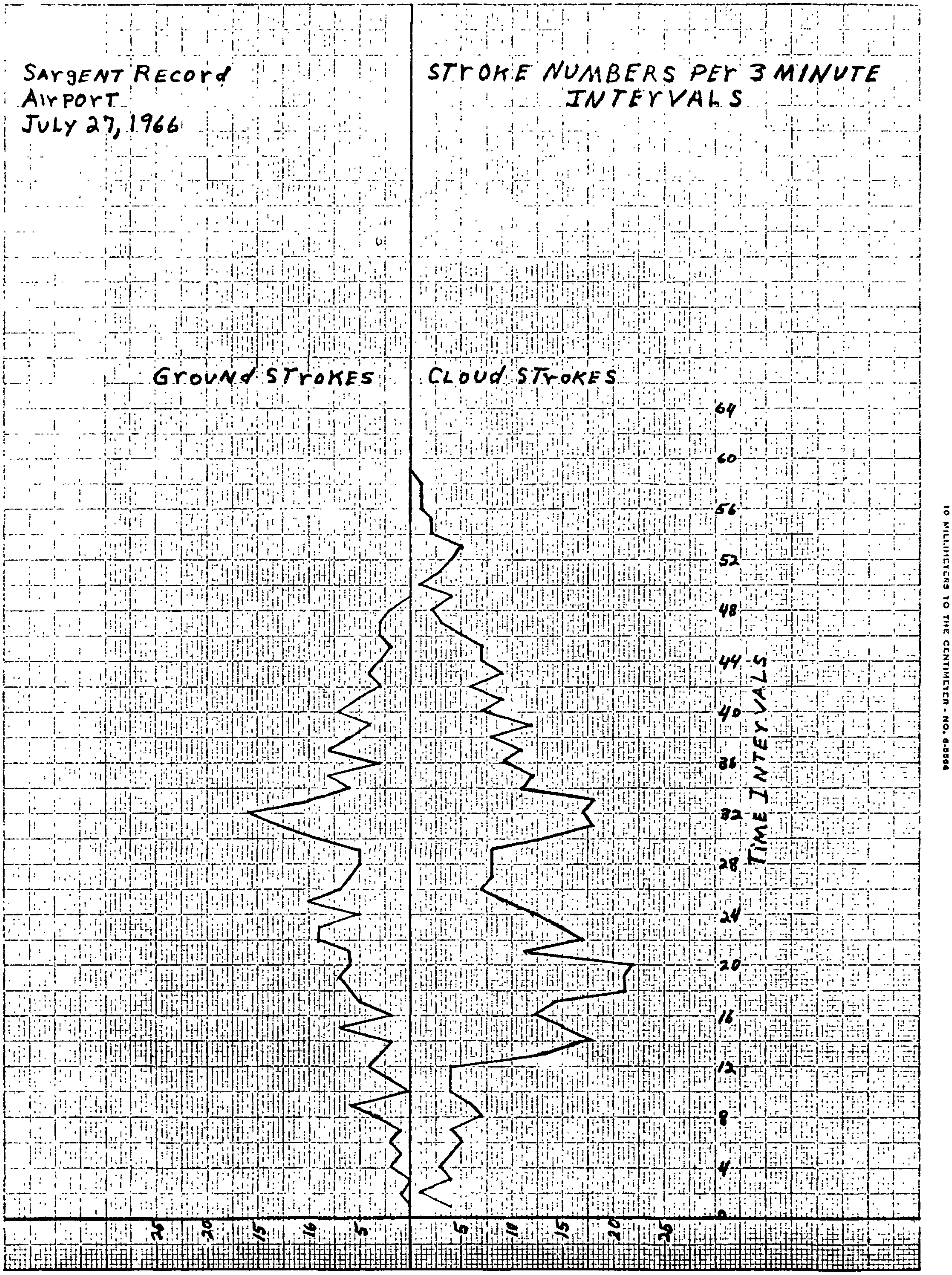
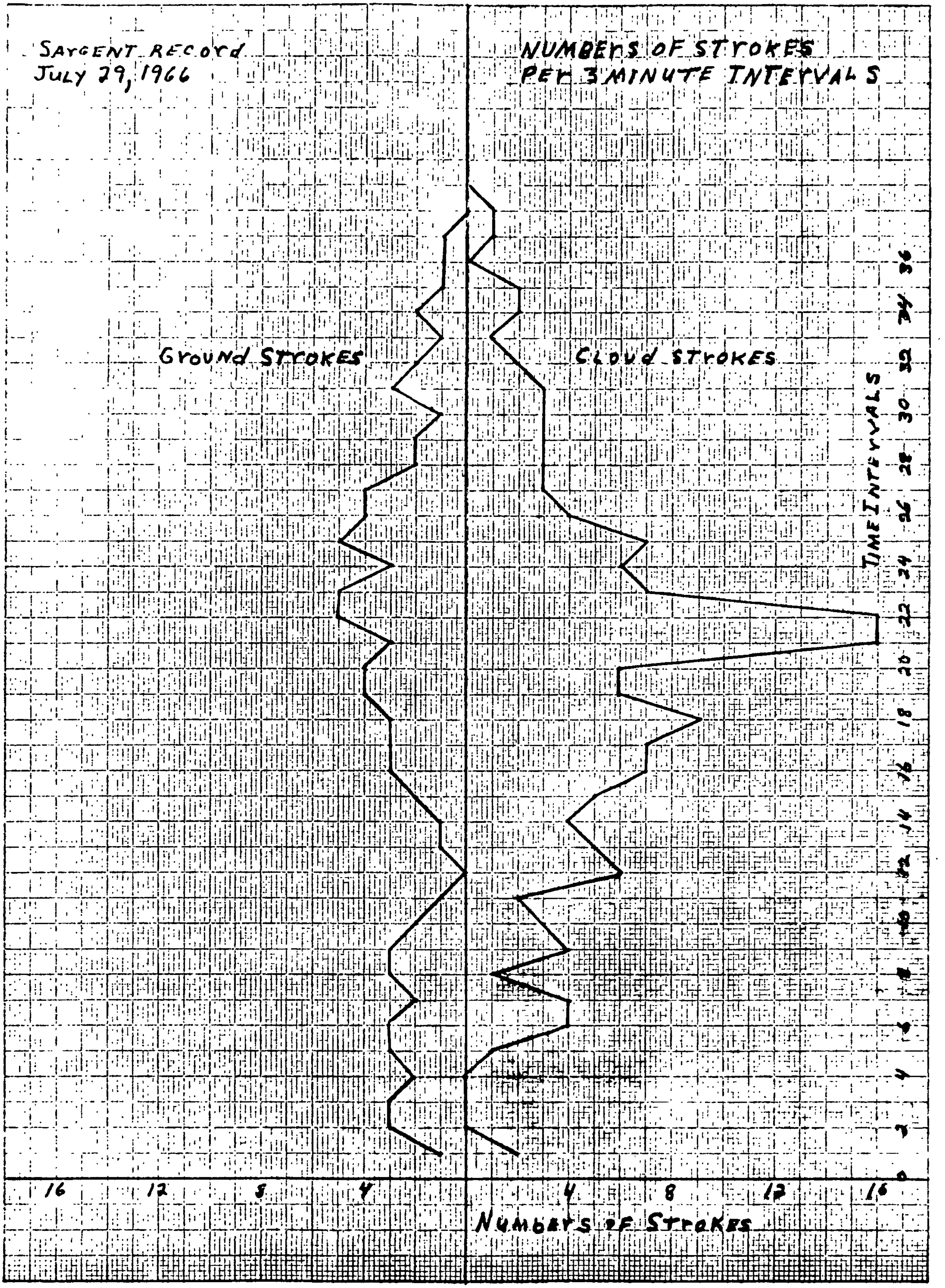

Sargent Record
Airport
July 21, 1966
(5 minute intervals)
19:46 to 13:51
No Record
Because of
Heavy Rain
(+) ground strokes
(-) cloud strokes
32
28
24
20
16
12
8
4
4
8
12
16
20
24
28
32
09:41 to 09:46
10 MILLIMETERS TO THE CENTIMETER - NO. 6-5564

Figure 15



SARGENT RECORD
AIRPORT
JULY 27, 1966
STROKE NUMBERS PER 3 MINUTE INTERVALS
GROUND STROKES
CLOUD STROKES
TIME INTERVALS
64
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
25
20
15
10
5
5
10
15
20
25
10 MILLIMETERS TO THE CENTIMETER - NO. 8-5584

Figure 16



SARGENT RECORD
JULY 29, 1966
NUMBERS OF STROKES
PER 3 MINUTE INTERVALS
GROUND STROKES
CLOUD STROKES
TIME INTERVALS
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
16
12
8
4
4
8
12
16
NUMBERS OF STROKES
10 MILLIMETERS TO THE CENTIMETER

Figure 17

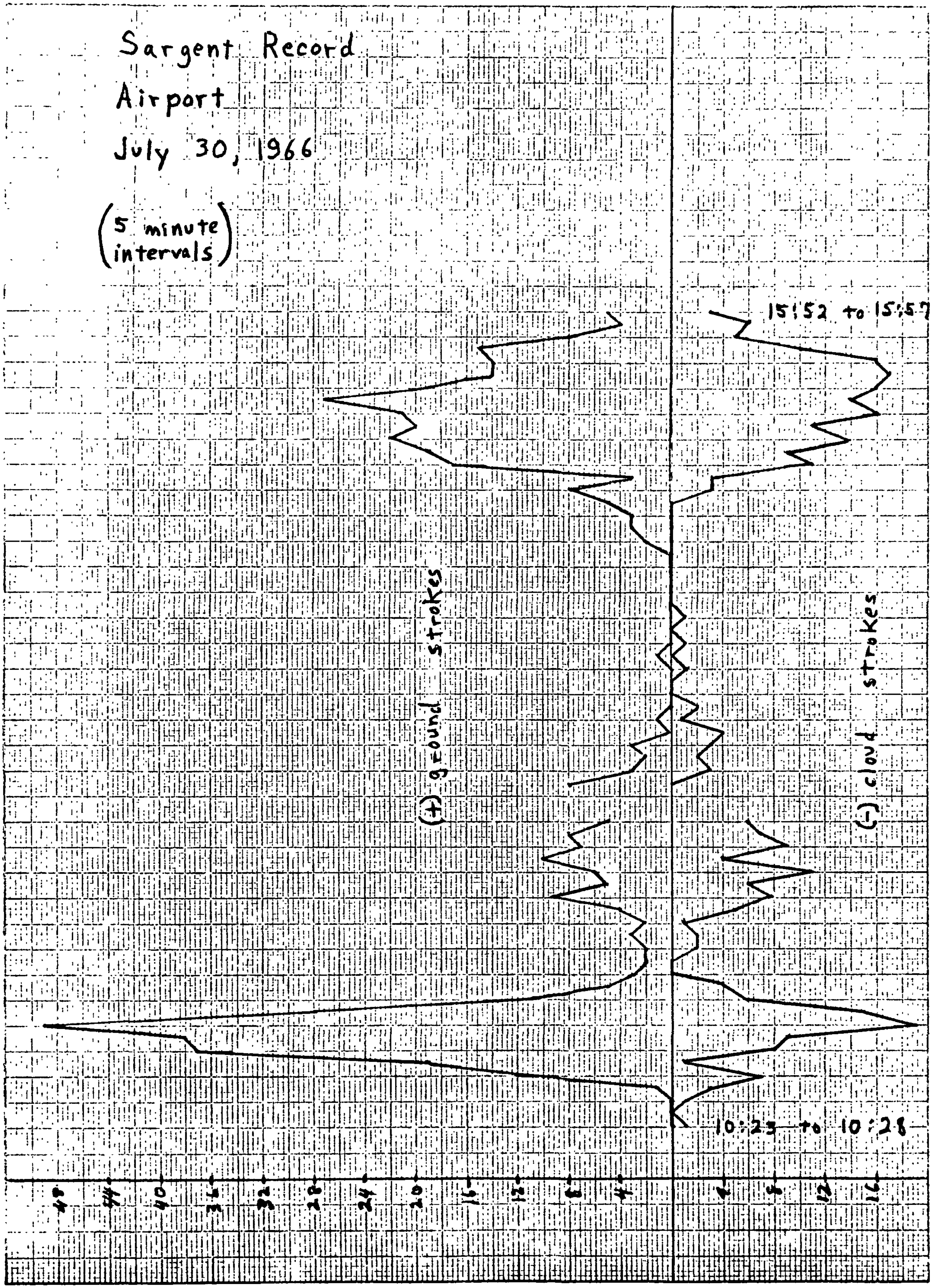

Sargent Record
Airport
July 30, 1966
(5 minute intervals)
15:52 to 15:57
(+) ground strokes
(-) cloud strokes
10:23 to 10:28
48
44
40
36
32
28
24
20
16
12
8
4
4
8
12
16

Figure 18

WIND FLOW PATTERNS
AROUND
ROGER'S LAKE

by

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supported by

Charles F. Kettering Foundation

Max C. Fleischmann Hall
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Flagstaff, Arizona

August 1966

WIND FLOW PATTERNS
AROUND
ROGER'S LAKE

ABSTRACT

Wind conditions around Roger's lake are discussed with emphasis on the nocturnal variations. An explanation of the wind flow is proposed and reasons for previously recorded radar observations over the lake are discussed.

INTRODUCTION

In the past, radar tracking devices have occasionally detected a vague mass rising over Roger's Lake. This curious phenomenon prompted the placement of mechanical weather stations on the fringes of the lake to determine if there is sufficient circulation to produce this effect.

DESCRIPTION

Roger's Lake is a shallow grassy lake about nine miles from Flagstaff, Arizona. It is approximately two miles west on U. S. 66 and seven miles southwest on a forest road 231. The maximum east-west diameter is about 1 3/4 miles and the maximum north-south diameter is 1 1/2 miles. The approximate area is 2 3/4 square miles and the perimeter is about seven miles, varying substantially with the season. The perimeter is surrounded by ponderosa pine forest and the lake is grazed by cattle in summer. Deer also graze the lake and a herd of approximately twenty were observed two out of the three days that the weather stations were maintained on the lake.

PROCEDURE

Three MRI mechanical weather stations were set up in three locations on a triangular plane around the fringe of the lake. One was placed on the north, one on the southwest and one on the southeast. Figure 1 shows the approximate location of the stations and the general shape of the lake itself. Readings were taken for three days but the stations were often overturned by the cattle.

Wind speed and direction were recorded and at least twenty-four hours were recorded at each station. The instrument on the southwest provided the most incomplete data because of being overturned and because winds from the southwest, the prevailing diurnal circulation, were somewhat erratic from passing through nearby trees. This difficulty was experienced only in the daytime and it made direction of the flow difficult to distinguish. The lighter nocturnal flow was steadier and direction indications were clear.

OBSERVATIONS

Solar caused instability produces a diurnal southwesterly flow around Roger's Lake that is typical throughout the area. During the day, the shallow water in the lake absorbs considerably more heat than the surrounding land and retains this heat longer after sundown. Nocturnal cooling (about 1900 hours) causes immediate stabilization of the air layers near the ground. The heat absorbed by the surrounding land is immediately expelled and the land is soon cooler than the water. The water in the lake takes longer to expell the heat and has more heat to get rid of. Calm wind conditions provide no circulation across the lake to remove warming air layers near the water surface. Therefore, these warm layers of air rise vertically drawing in cooler air from around the lake. This cooler air flows from all directions to the center of the lake, moving in horizontally under the rising warm air. As the cooler air moves in, it also is heated by the warmer water and the cycle is repeated. As the inward flow proceeds during the night, a constant vertical flow of warmer air is maintained over the lake. An inversion exists with the gradiation between the warmer and cooler areas.

This inward flow of air continues all night and is only negated by the diurnal instability which begins the daily cycle all over again (approximately 0700 - 0800).

GRAPHS AND ILLUSTRATION

Figure one is a reproduction of the lake area with pertinent location information. Figures two through four have wind speed plotted on them to show times of wind changes. Wind directions are given to facilitate recognition of inward flow. Figure five illustrates the directional flow of air with the circle representing the lake; the arrows showing wind direction, speed and location of the weather stations. The station indicator on the left at representative positions gives July 11 and 12 information while the indicator on the right represents July 13 and 14. The scale of wind speed is given, differing from standard notation because of slight wind variation that has to be accentuated by a more flexible scale.

CONCLUSION

A more extensive study of weather conditions and wind flow would make an interesting project and may provide more conclusive information than this

Fig. 1

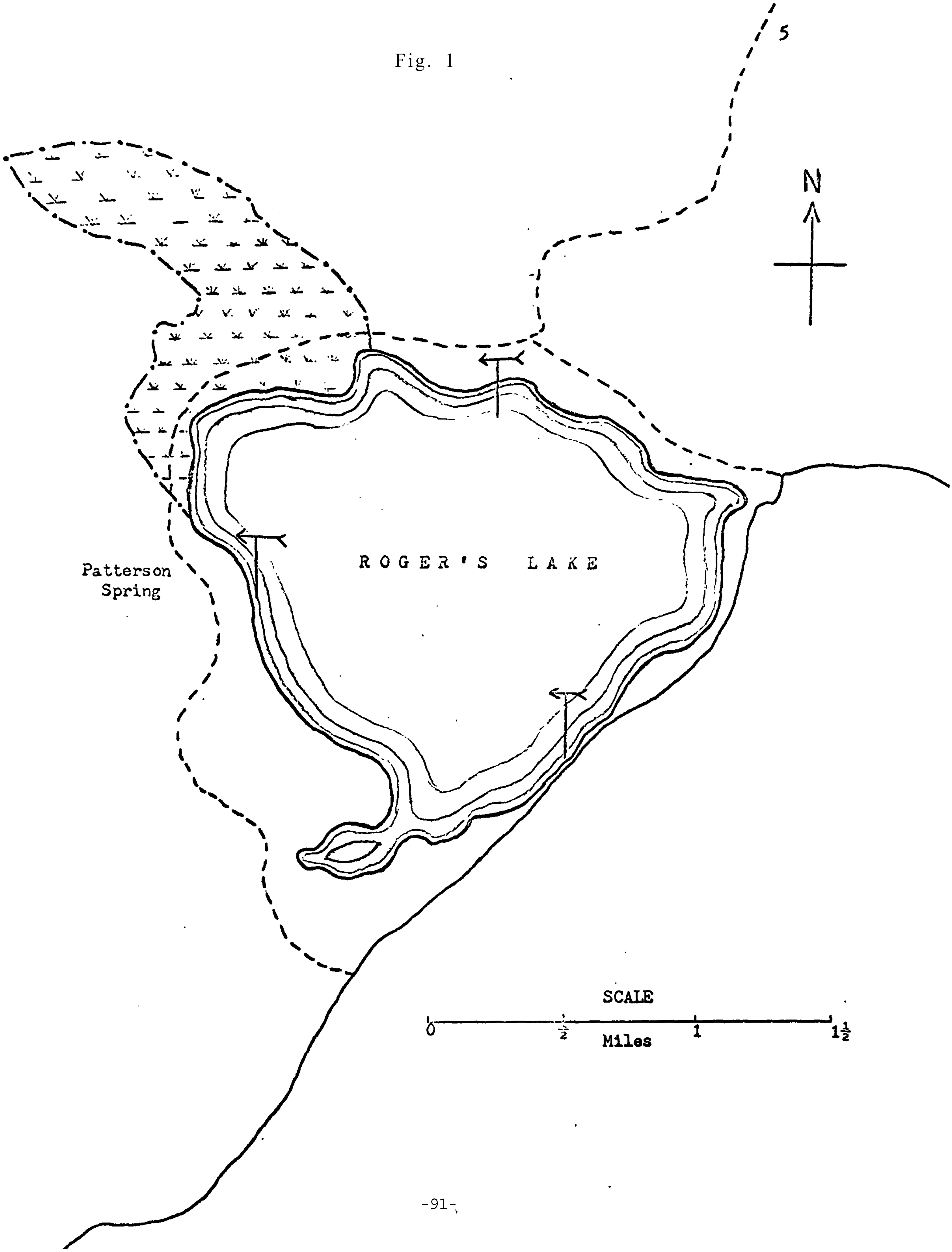


Fig. 2 - South-east Fringe of Roger's Lake

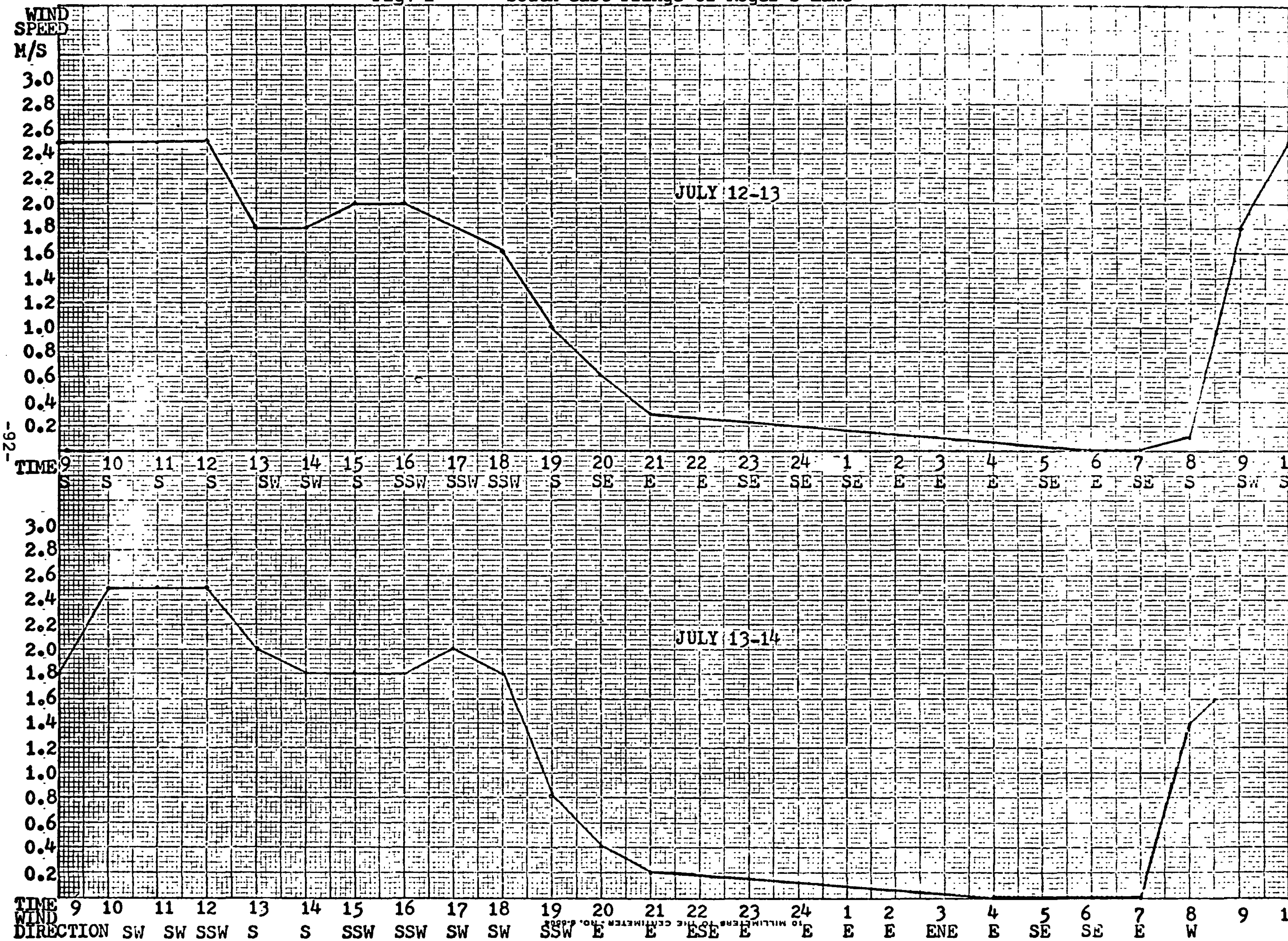


Fig. 3 - South-west Fringe of Roher's Lake

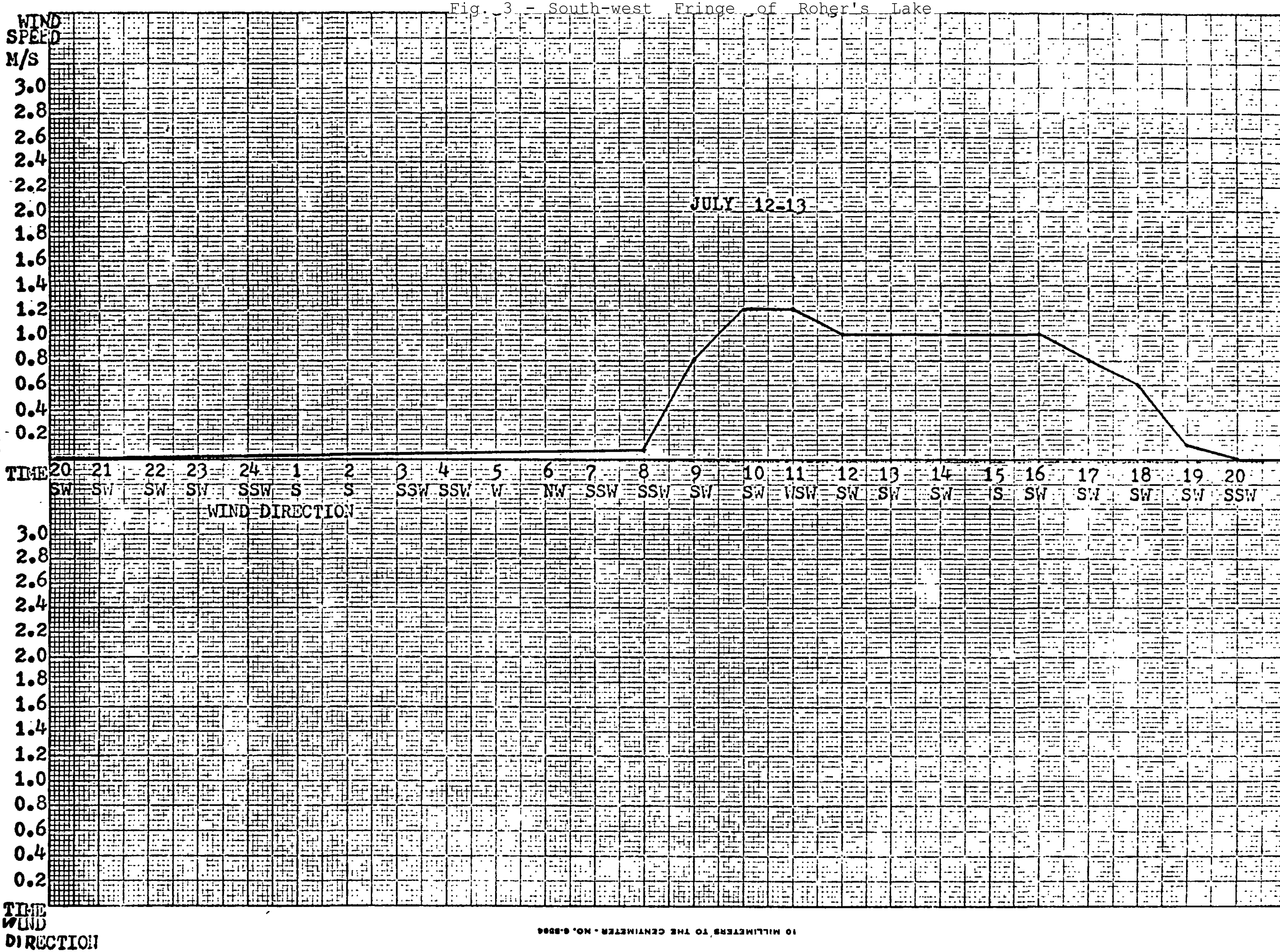


Fig. 4 - North Fringe of Roger's Lake

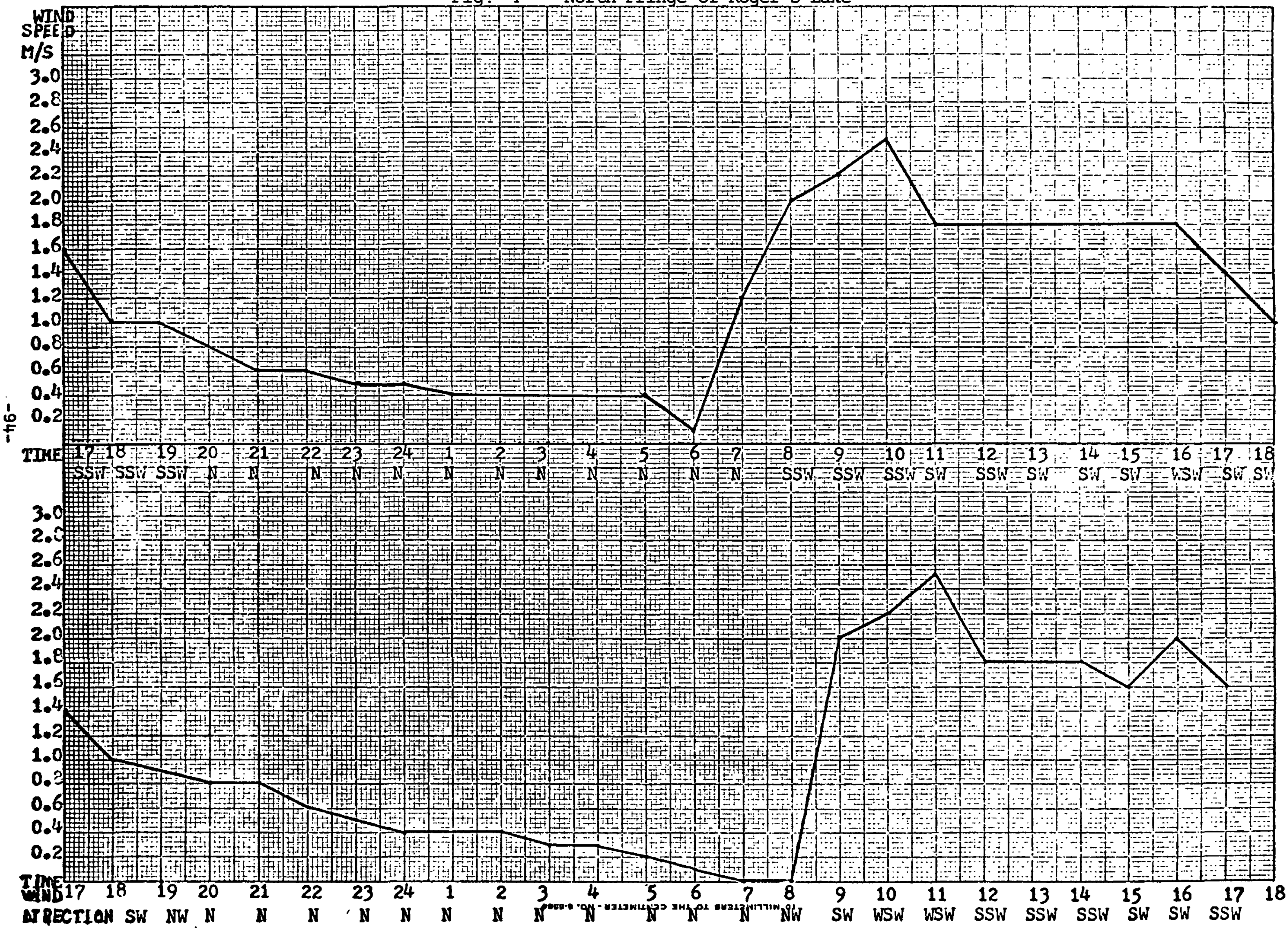
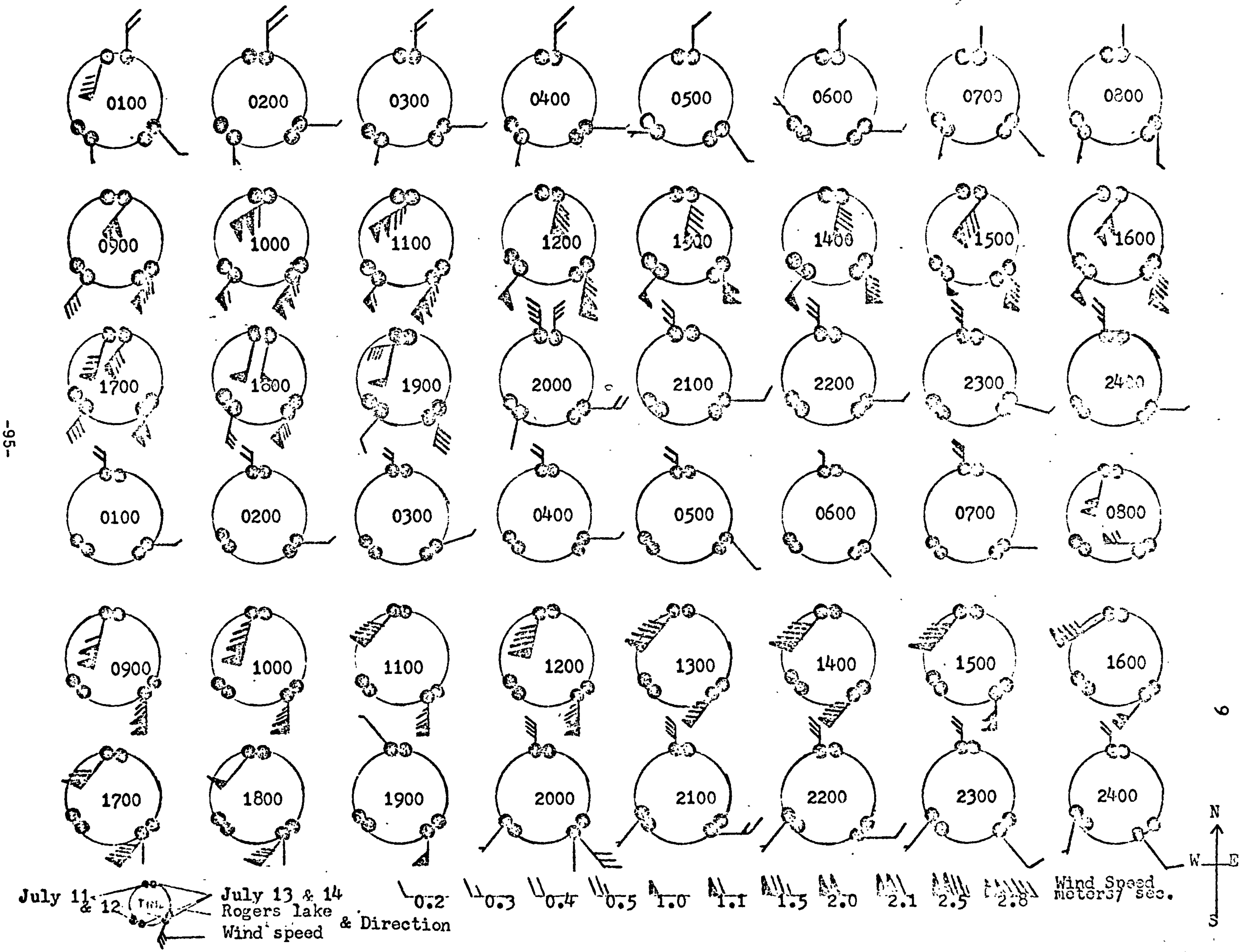


Fig. 5 WIND FLOW PATTERN AROUND ROGERS LAKE JULY 11-14 1966 Larry Proctor



-95-

9

short-term record but the data obtained from these three days was very good. The data upholds the theory that the flow of air upward causing circulation into the center of the lake from all directions is at times so pronounced and the inversion so distinct that it is feasible that it would be detected by radar instruments.

A C K N O W L E D G E M E N T S

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Dr. Vincent J. Schaefer	for his advice and explanation
John Lindl	for transportation and aid in setting up and checking the weather stations
Bill Barr and the Army-ESSA Meteorological group	for transportation and aid in setting up the weather stations
Charles F. Kettering Foundation and the State University of New York at Albany	for support and sponsorship of the NSI program

FLAGSTAFF WEATHER: JULY 1966

by

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Natural Sciences Institute

Atmospheric Sciences Research Center

of the

State University of New York

Supported by

Charles F. Kettering Foundation

Max C. Fleischmann Hall

Research Center, Museum of Northern Arizona

Flagstaff, Arizona

August 1966

FLAGSTAFF WEATHER: JULY 1966

ABSTRACT

Flagstaff weather was observed closely during the month of July. It was found that the Gulf of California was the moisture source for precipitation occurring in the first half of the month. The "monsoon" season was then triggered by moisture arriving from the Gulf of Mexico.

An intensive study of storms forming near Mormon Lake is recommended which could result in improved forecasting for the Flagstaff area.

Thunderstorms formed at an earlier time later in the month. An attempt to correlate time of thunderstorm activity with middle level clouds did not produce positive results.

During the month of July 1966 the author had the privilege of assisting Dr. E. M. Frisby in handling the daily meteorological data required by the joint Army-ESSA cloud physics project. This report is the result of work done in this period.

The weather at Flagstaff, elevation 7000 feet, is greatly influenced by the effects of the local terrain. To the south is the Mogollon Rim, the dividing line of mountains separating the low lying southern half of the state from the higher north. The San Francisco Peaks located just north of Flagstaff also provides lifting to incoming air. These and other centers of activity such as Mormon Lake are important factors in the Flagstaff weather.

Isobars were drawn daily on the type of map shown in Figure 1. These always showed a high pressure center near Flagstaff and a low pressure area somewhere to the south. Since air flows from high to low pressure the circulation pattern should be from north to south. However a glance at Table 5 will show there were no northerly winds during July, the prevailing direction being southerly.

The explanation of the discrepancy is to be found in the method of adjusting station pressure to sea level pressure used by the United States Weather Bureau. This is conclusively shown by a comparative study of the 400 mb surface for Tucson in southern Arizona and Flagstaff (Table 1).

The first method used to determine the true height of the 400 mb surface was the Bjerknes Construction. This is a graphical method which constructs a dry adiabatic atmosphere from the plotted radiosonde data. This method seemed to indicate the first flow of moisture into Flagstaff in July and the following cut-off. However this was done even better by other means which will be explained below.

The second method used was to obtain the height of the 400 mb surface from the pressure-altitude curves drawn by the Army Meteorological Team at the Navajo Army Depot and from the teletyped data from Tucson. This method showed virtually no difference in the height of the 400 mb surface between Tucson and Flagstaff. Thus there is no pressure differential blocking southerly flow.

The pressure figures in Table 1 were obtained by reading off the altitude-pressure from the standard atmosphere.

Dewpoint charts were drawn daily similar to those in Figure 1. These were used to show the different progressions of moisture into and out of the Flagstaff area. The progressions can be seen quite clearly from the changing position of the lines of equal dewpoints in Figure 1. Once the dewpoint at Flagstaff reached fifty though, the usefulness of this parameter as an indication of possible precipitation was ended. This can be seen from the listed dewpoints in Table 5. After July 16 the dewpoints remained in the fifties except for one day in the high forties.

The July 8 to July 9 period is extremely interesting. The slug of moist air which both the dewpoint charts and the 500 mb prevailing wind data showed to be coming from the southwest and thus the Gulf of California finally reached Flagstaff and resulted in the formation of thunderstorms in the area. The slow approach of this moisture had been followed for several days by use of the dewpoint charts and its arrival was forecast quite accurately by this means.

The effects of this influx of moisture can also be seen in the plotted radiosonde data for July 8 (Figure 2) and July 9 (Figure 3). The sounding for July 8 is dry with a high condensation level and the winds are from the southwest. Compare this with the sounding for July 9. Moisture has moved into the middle levels leaving only the surface and levels above 400 mb dry. The winds have shifted to the southeast and the condensation level has lowered considerably.

Dropping dewpoints followed the first influx of moisture (See Figure 1) but on July 11 the recycling of the residual moisture resulted in thunderstorms over the Rim and Peaks but left the Plateau area dry. This is an example of the importance of terrain to the weather in this area.

From the dewpoint patterns in the first days of July it appears that the moisture which fell on the last two days of June and gave Flagstaff its only measurable precipitation for the month also came from the southwest and the Gulf of California.

Many cloud research projects have been conducted at Flagstaff because of its "monsoon" season which is supposed to supply almost daily thunderstorms for study. But the variability of the weather during the summer months can be seen from the precipitation records for the last ten years shown in Table 2. It can be seen that each summer the weather is different.

The onset of the monsoon season began this year with the influx of moisture which arrived at Flagstaff on the 15th of July. This influx differed in several very important ways from that which occurred on July 9.

The influx on the 15th was the more permanent, maintaining high dew-points for the rest of the month. The prevailing wind direction at 500 mb given in Table 5 indicates that this wet period has winds from the south and southeast besides just from the southwest as during the drier period.

This second surge of moisture was triggered by air from the Gulf of Mexico. On 16 July a high level high over the central part of the country gave an easterly flow over the Flagstaff area which is necessary for moisture from the Gulf of Mexico to reach here. The flow from the Gulf of Mexico to Flagstaff could be followed on the upper level wind charts. It is the northerly migration of pressure patterns in the summer which is responsible for producing this easterly flow.

Thus the Gulf of California serves as the base supply of moisture for the area with the Gulf of Mexico moisture serving as the trigger for the onset of the "monsoon." The importance of the Gulf of California was brought out with the appearance on July 24 of a tropical low pressure system south of it on the nephigram from ESSA 1. July 28 produced the wettest sounding of the summer (See Figure 4) with saturation of the middle levels. This was the result of the tropical low carrying moisture from the Gulf of California into Arizona. However this system was too far south to be shown on any of the standard synoptic maps. This indicates the importance of having reports from Mexican stations. Yet the Weather Bureau does not carry these stations on its teletype lines at present. They did in the past and it is recommended that they do so in the future.

The normal feature which brings moisture from the Gulf of California is the presence of a thermal low over the Mexican mainland during the entire summer. The counterclockwise flow tends to kick up moisture from the Gulf of California to the north.

The flow of moisture from both Gulfs was cut-off several times during the month of July, most noticeably between July 10 and July 14 and at the end of the month. The soundings for these periods showed drying at the important middle levels. This was caused by high pressure systems over Northern Arizona forming a closed, landlocked circulation about the area.

A comparison was made of precipitation records (Tables 2 and 3 and Table 4) between the Flagstaff Airport south of town and the Research Center of the Museum of Northern Arizona north of town near the Peaks. The author drove several times from dry weather at the airport into rainshowers at the Research Center. It was thought that this was the effect of the Peaks. However the comparison shows that the amount of precipitation in past years is not consistently higher for the Research Center and that the difference in rainfall for July 1966 is not significant with the airport actually having a greater number of measurable rain days.

The comparison of maximum temperatures shows that the Research Center averaged over 3°F more than at the airport. No explanation for this difference was discovered.

The appearance of the jet stream over Flagstaff which occurred twice during July is a good indication of no thunderstorms. The high winds prevent cumulus clouds from developing to their full extent by blowing over their tops.

Another forecasting aid for this area is to plot the Tucson radiosonde sounding when there is southerly flow. An upper air inversion which appeared on July 14 at Tucson moved into the Flagstaff area on July 15 and persisted through the 16th. This limited activity in the area to rainshowers except for some lightning over the Peaks. With the surge of moisture in and the inversion breaking down, thunderstorms were accurately predicted for the next day.

The Mormon Lake area is worthy of intensive study because it is an area of great activity which brings precipitation to the Flagstaff area. From July 20 to July 24 large rainshowers or thunderstorms formed daily between Flagstaff and Winslow and then followed the same track onto the Peaks. For these days the Research Center received .93 inches of rain while the airport had only .67. If the conditions causing this storm were discovered and predictable and always followed the same track then a forecast would be able to pinpoint the areas of heavy precipitation instead of just predicting scattered showers and thunderstorms.

Figure 5 shows that the time of thunderstorm occurrence becomes earlier later in July. An attempt to correlate this with maximum temperature was unsuccessful. High cloud base might cause a delay in the start of thunderstorm activity. Thunderstorms on the 17th began at 1550 MST and the cloud base was lower than on the 16th when thunderstorms did not begin until 2045 MST.

It was thought likely that upper air inversions could delay thunderstorm growth. An attempt was made to correlate the prevalence of middle layer clouds which indicate these inversions with the time of thunderstorm activity but no positive results were obtained.

The 29th and 30th of July seem to present the simplest explanation of night thunderstorms. The cloud cover of the 29th apparently did prevent afternoon thunderstorms although there was good building during the day especially over the Peaks. At 1950 a thunderstorm began which gave heavy rains in the area from the Plaza shopping center to the Research Center. This evening storm was probably due to the decaying of the large cumulonimbus clouds which had formed over the Peaks earlier.

The next day dawned with a clear sky. Thunder was heard at 1048 MST. Development was unhindered by other cloud layers blocking surface heating or indicating inversion layers.

For more detailed information on Flagstaff weather for the summer of 1966 including the development of a forecasting technique refer to the report written by Dr. E. M. Frisby for the Army cloud physics project.

ACKNOWLEDGEMENTS

Many thanks go to Dr. E. M. Frisby for the time she gave to instruct and aid me during the course of this investigation. Thanks also go to Mr. Paul Sorenson of the Flagstaff Weather Bureau for the use of his office during the summer and other Weather Bureau facilities. Finally I thank the Charles F. Kettering Foundation which financed this research.

APPENDIX

TABLE 1

COMPARATIVE ALTITUDES (400 mb)

Date	Tucson	NAD	Difference	Comment
8 July	21,000' / 445 mb	24,000' / 390 mb	+55 mb	Bjerknes construction
9 July	21,100' / 440 mb	24,200' / 385 mb	+55 mb	" "
11 July	24,800' / 375 mb	27,100' / 345 mb	+30 mb	" "
12 July	23,900' / 395 mb	23,100' / 405 mb	-10 mb	" "
13 July	23,100' / 405 mb	21,800'/ 430 mb	-25 mb	" "
14 July	24,900' / 376 mb	24,900' / 376 mb	0 mb	" "
15 July	7,610GPM/ 376 mb	7,617GPtl/ 375 mb	+1 mb	**pressure-altitude curve**
16 July	7,630GPM/ 375 mb	7,640GPM/ 374 mb	+1 mb	Winslow **data, not** NAD
18 July	7,650GPM/ 373 mb	7,653GPM/ 373 mb	0 **mb**	
19 July	7,600GPM/ 376 mb	7,630GPM/ 375 mb	+1 **mb**	**Winslow data, not** NAD
20 July	7,590GPM/ 377 mb	7,574GPM/ 377 mb	0 mb	
21 July	7,600GPM/ 376 mb	7,615GPH/ 376 mb	0 mb	
22 July	7,610GPM/ 376 mb	7,663GPM/ 373 mb	+3 mb	
24 July	7,620GPM/ 375 mb	7,630GPM/ 375 mb	0 mb	**Winslow data, not** NAD
25 July	7,650GPM/ 373 mb	7,644GPM/ 374 mb	-1 mb	
26 July	7,650GPM/ 373 mb	7,653GPM/ 373 mb	0 mb	
27 July	7,630GPM/ 375 mb	7,643GPM/ 374 mb	+1 mb	
28 July	7,600GPM/ 376 mb	7,650GPM/ 373 **mb**	+3 mb	
29 July	7,620GPM/ 375 mb	7,650GPM/ 373 mb	+2 mb	**Winslow data, not** NAD
30 July	7,620GPM/ 375 mb	7,669GPM/ 373 mb	+2 mb	
31 July	7,640GPM/ 374 mb	7,660GPM/ 373 mb	+1 mb	**Winslow** data, **not** NAD
1 Aug	7,640GPM/ 374 mb	7,683GPM/ 372 mb	+2 mb	
2 Aug	7,660GPM/ 373 mb	7,691GPM/ 371 mb	+2 mb	

GPM: geopotential meters

mb: millibars

TABLE 2

SUMMARY OF PRECIPITATION (MONTHLY) FOR TEN PRIOR YEARS AT FLAGSTAFF AIRPORT

IN SUMMER

Year	June	July	August
1957	1.59	1.57	1.65
1958	.70	.75	3.02
1959	.77	2.93	4.96
1960	.39	.96	3.28
1961	.37	2.03	3.37
1962	.52	2.36	.26
1963	T	.32	4.96
1964	.17	5.23	1.32
1965	(6) .30	2.34	1.01
1966	(2) .21	(12) 1.62	

(x) measurable rain days
Precipitation is measured in inches.

TABLE 3

PRECIPITATION SUMMARY FOR THE RESEARCH CENTER OF MUSEUM OF NORTHERN ARIZONA

1961	.20	2.50	3.81
1962	.34	.78	.91
1963	0.0	1.21	3.38
1964	.10	4.90	1.94
1965	(6) .22	(10) 4.10	1.35
1966	(3) 1.09	(10) 1.66	

TABLE 4

Comparison of Rainfall and Maximum Temperatures for Flagstaff Airport and the Research Center for July 1966

Date	Rain (inches) FLG	Rain (inches) R.C.*	Max T (°F) FLG	Max T (°F) R.C.*	Difference
1			78	78	0
2			81	82	-1
3			84	86	-2
4			84	88	-4
5			86	90	-4
6			88	91	-3
7			82	87	-5
8			82	86	-4
9	T		85	90	-5
10	T	.04	81	84	-3
11			79	85	-6
12			83	86	-3
13			83	87	-4
14			33	88	-5
15	.02		86	92	-6
16	.04		88	92	-6
17	.07	.03	86	84	+2
18	.10	.19	84	86	-2
19	.10	.06	81	86	-5
20	T		75	78	-3
21	.65	.77	76	75	+1
22			82	81	+1
23	.01		83	86	-3
24	.01	.16	84	88	-4
25	.02	.03	77	80	-3
26			82	85	-3
27	.23	.26	82	84	-2
28	.02		77	88	-11
29	T	.12	76	80	-4
30	.32	T	74	78	-4
31		.04	81	82	-1
					-3.3

* Values for past 24 hrs taken at 0800 of following day.

TABLE 5

DAILY AMOUNTS OF RAIN, DEWPOINT, AND PREVAILING WIND (500 mb) FOE FLAGSTAFF AIRPORT IN JULY 1966

Date	Inches of Rain	°F 0600M Dewpoint	Wind	Date	Inches of Rain	°F 0600M Dewpoint	Wind
1	0	-	-	16	.04	53	SSE
2	0	-	-	17	.07	54	SW
3	0	39	-	18	.10	47	SW
4	0	39	-	19	.10	51	SE
5	0	42	SW	20	T	55	SE
6	0	20	SW	21	.65	52	SW SE
7	0	32	SW	22	0	54	SSE
8	0	38	SW	23	.01	51	SSE
9	T	43	SW SE	24	.01	52	SW E
10	T	48	S	25	.02	53	SSE
11	0	47	SW	26	0	52	SW
12	0	43	SW SE	27	.23	53	E
13	0	29	SW	28	.02	58	E
14	0	28	SSW	29	T	58	ESE
15	.02	39	SW	30	.32	53	S
				31	0	52	S

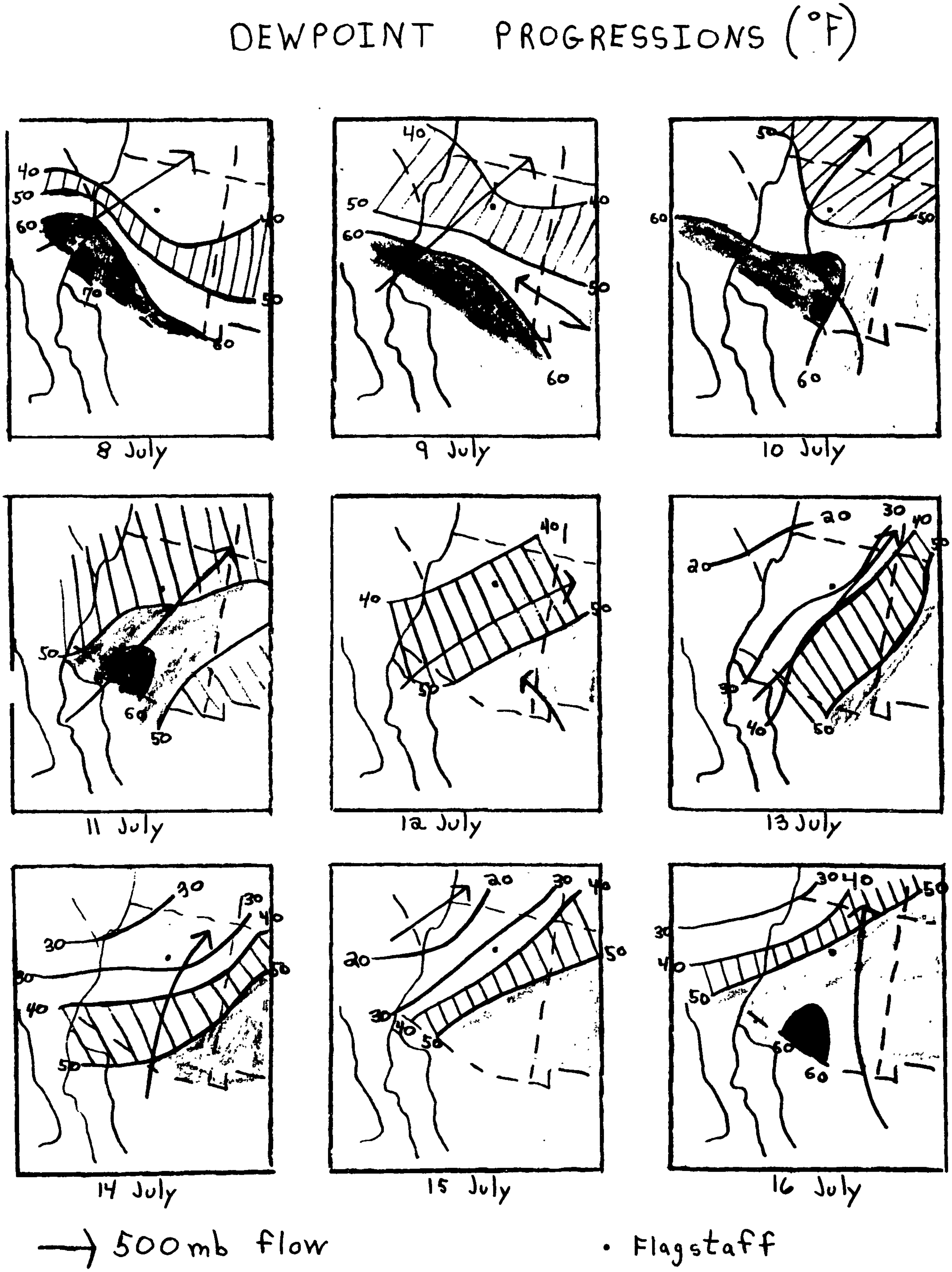
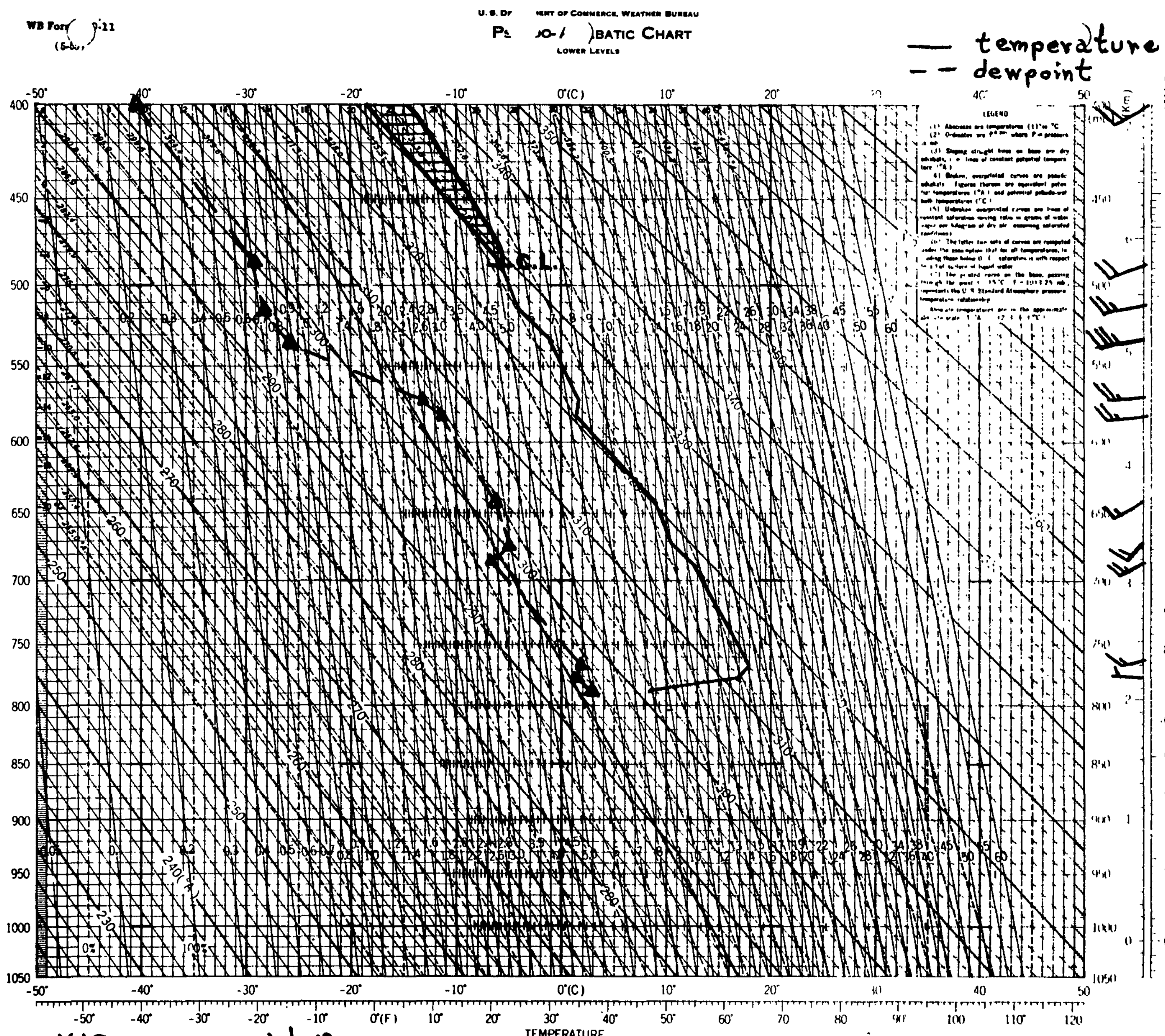

DEWPOINT PROGRESSIONS (°F)
8 July
9 July
10 July
11 July
12 July
13 July
14 July
15 July
16 July
500mb flow
Flagstaff

Figure 7



Station NAD Date (G.C.T.) 8 July 1966 Hour (G.C.T.) 0545M

Figure 2

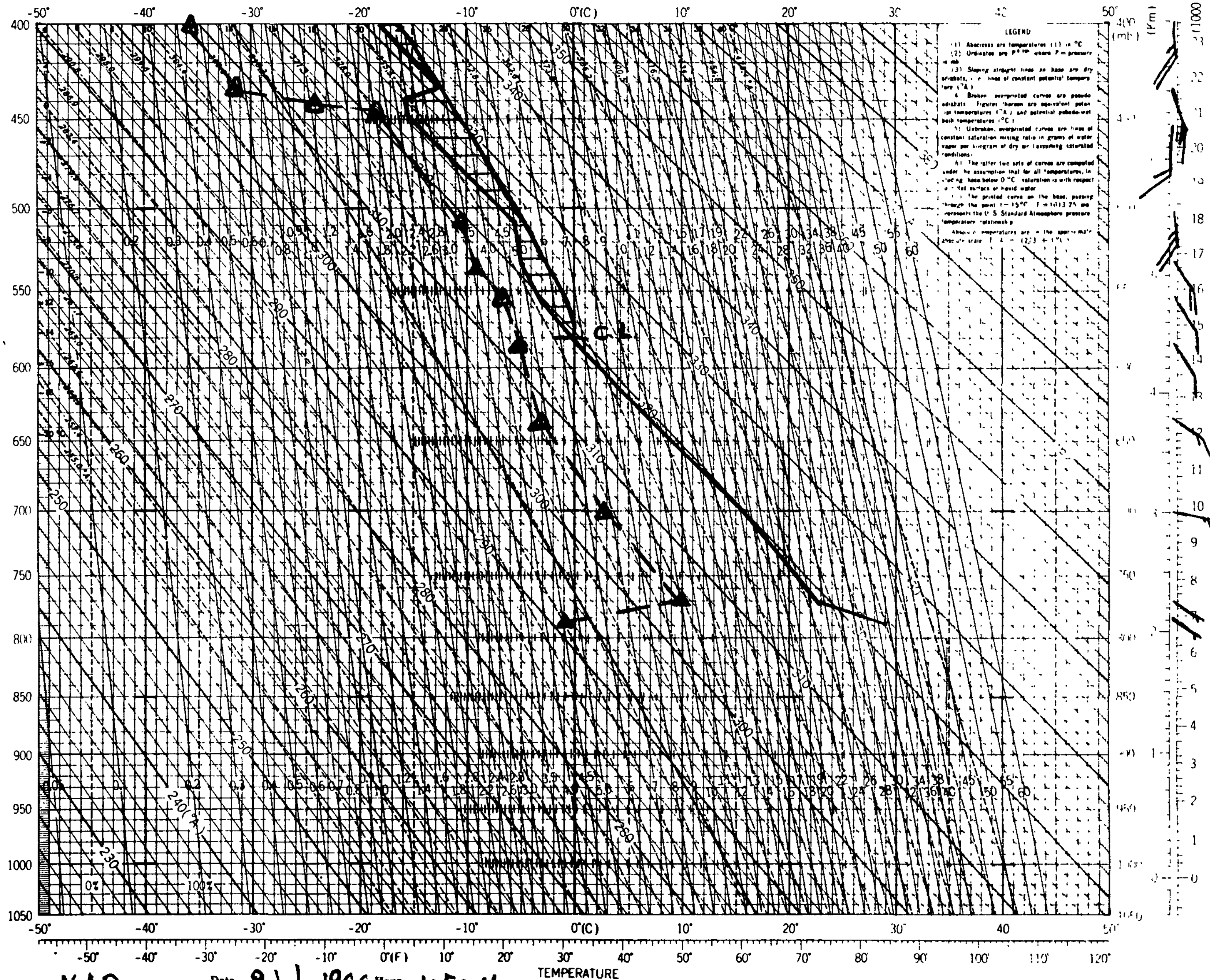
WB Form ( )-11
(5-5)

U S DEPARTMENT OF COMMERCE WEATHER BUREAU

PSEUD( )BATIC CHART

LOWER LEVELS

— temperatu
-- dewpoint



Station NAD Date (G.C.T.) 9 July 1966 Hour (G.C.T.) 1050M

Figure 3

USCOMM WB DC

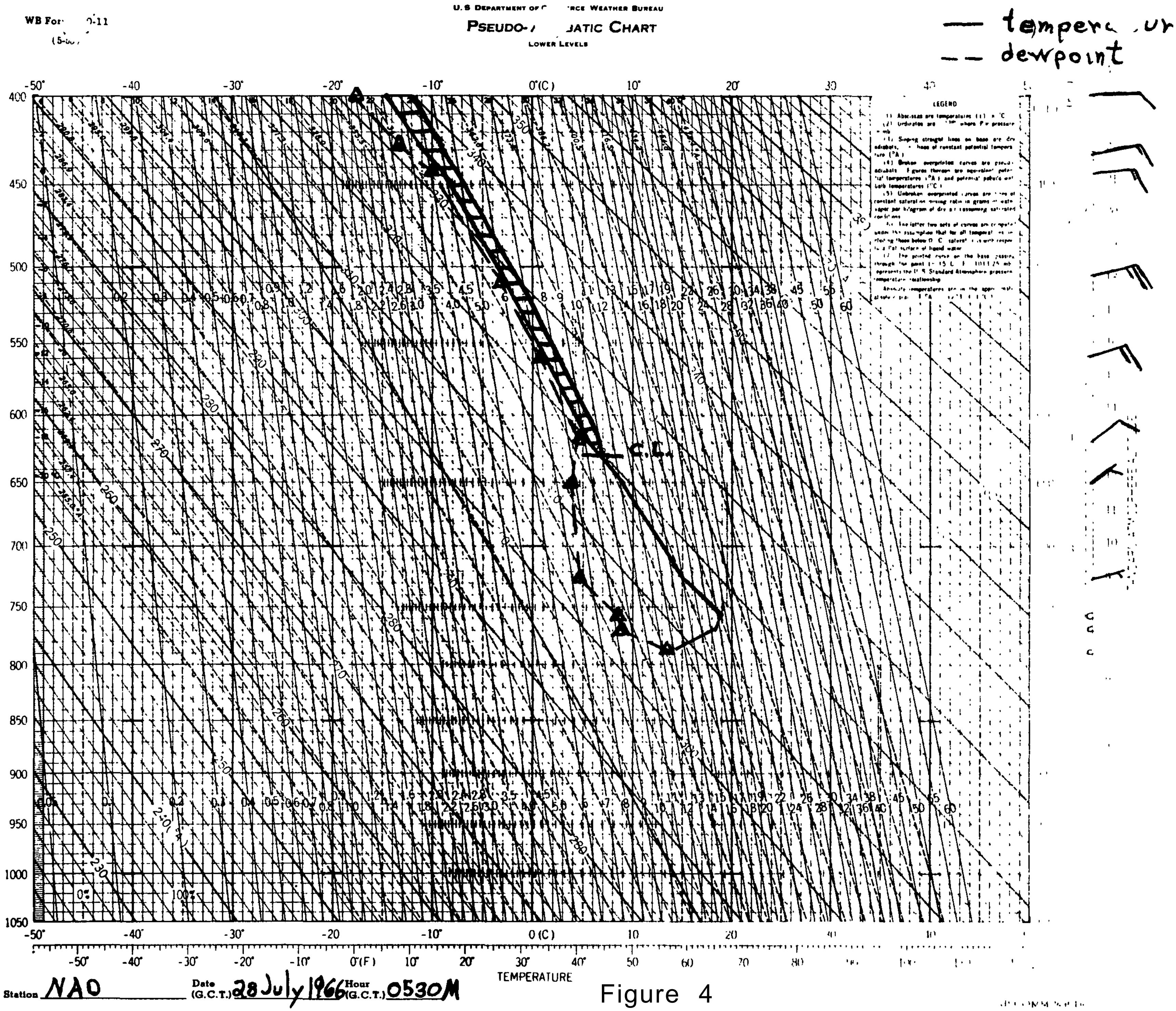
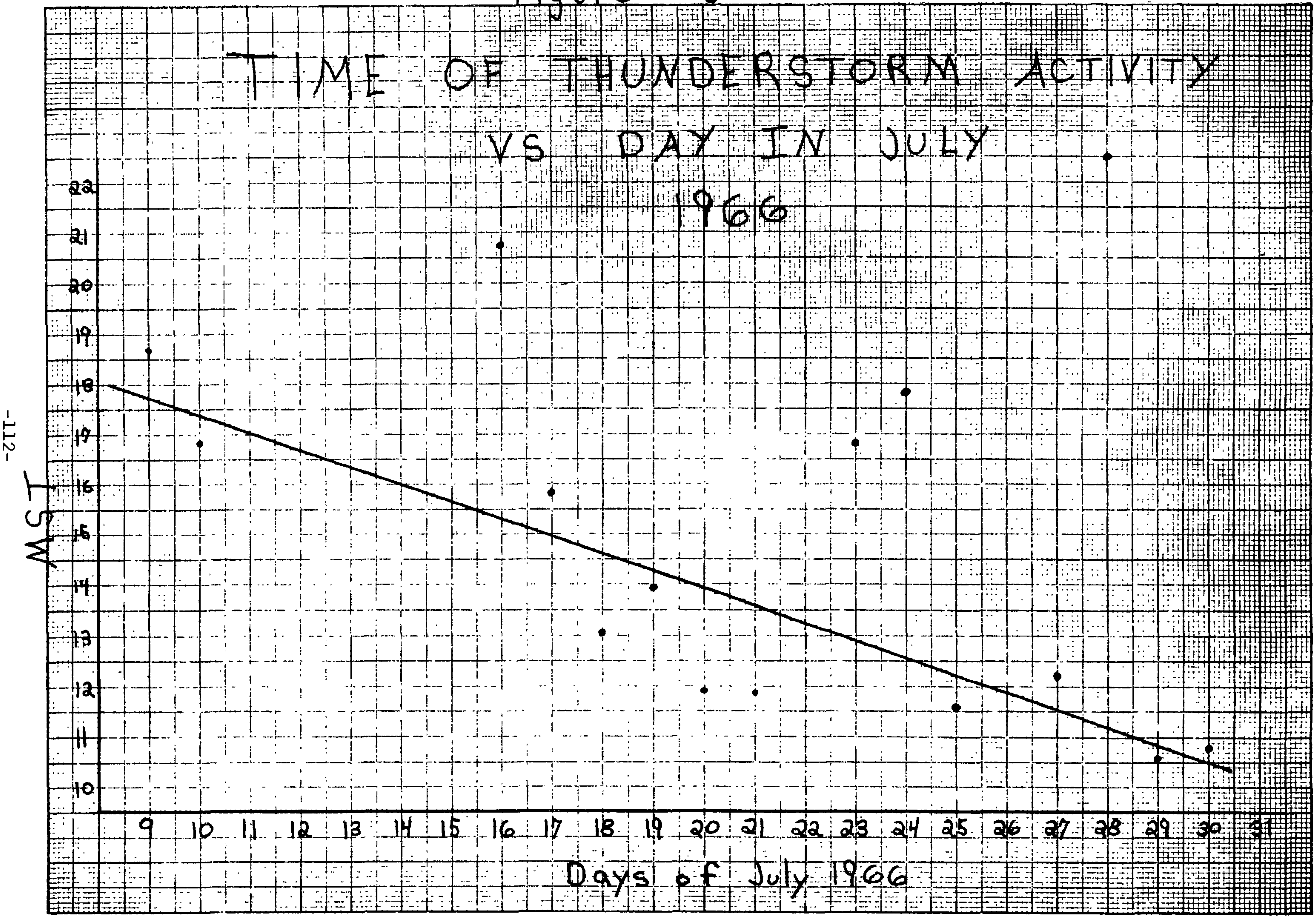

WB For 0-11
U. S. DEPARTMENT OF C RCE WEATHER BUREAU
PSEUDO-A BATIC CHART
LOWER LEVELS
— temperature
-- dewpoint
C.L.
TEMPERATURE
Station NAO
Date (G.C.T.) 28 July 1966
Hour (G.C.T.) 0530M

Figure 4

Figure 5



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