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RESEARCH CONCERNING ANALYSIS OP SEVERE THUNDERSTORMS

K. E. Wilk

Illinois State Water Survey-
Meteorology Laboratory
at the
University of Illinois
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PINAL REPORT

Contract No. AF 19(604)-4940

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PROJECT 6672

TASK 667203

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GEOPHYSICS RESEARCH DIRECTORATE
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ABSTRACT

This report describes the scales of severe thunderstorm phenomena in the Midwest and discusses the time and space resolution of observational data used in the investigation of severe local storms in Illinois. A detailed analysis of radar, TIROS I, and synoptic data acquired for the specific storm of 16 May 1960 shows the complete storm system contains several distinct thunderstorm complexes. Radar echo composites, which were constructed for 4 standard pressure levels for this storm system, disclosed that only one or two major thunderstorms within a complex were responsible for the observed severe weather. Approximately 10 percent of the thunderstorms on the severe storm day reached sufficient magnitude to be classified as severe.

Analysis of climatological upper air data for a four-year period indicated that advective stability changes were not the predominant cause of storm intensification in the Midwest. Sixty-nine percent of the data obtained on 25 severe storm days from 1954 through 1957 showed advective change in stability of less than $0.3^{\circ}C.hr^{-1}$ at any level. Also, calculations of potential energy, using the parcel method, indicated that over 70 percent of the severe hailstorm air masses had energy values less than 144 joules gm^{-1}.

Calculations of potential energy were also made for a particular storm by adjusting the surface temperature and relative humidity values of a single radiosonde run to those observed at

numerous locations in Illinois. These calculations showed that the region of maximum potential energy delineated the area of most frequent hail occurrences and therefore suggested that the local temperature and moisture effect is of major importance in thunderstorm intensification.

Radar intensity values acquired from hailstorms in Illinois during 1959 and 1960 indicated that the highest Z value observed most frequently was between 1 and 9 x 10^5 mm^6 m^{-3}. When grouped by 5000-foot intervals, 61 percent of the hailstorms sampled showed reflectivity maximums at one specific 5000-foot height interval which was at least a factor of 10 higher than the reflectivity at any other height interval. The height interval of 15,000 to 19,000 feet had the greatest frequency of Z maxima. Comparison of the frequency of maximum Z values between 1 and 9 x 10^5 $mm^6 m^{-3}$ for hail and rainstorms indicated a significant difference in the frequency distribution of Z with height. The height interval showing the greatest difference between rain and hail was the interval from 15,000 to 19,000 feet. The frequency of various hailstone sizes for maximum Z values for 8 height intervals showed a corresponding increase in hailstone size with the height of the maximum Z value. The Z values acquired from severe wind storms without hail showed little difference from those acquired from thunderstorms with rain only.

The duration of hail production from severe thunderstorms in Illinois ranges from 30 minutes to 2 hours, and the high radar reflectivity values measured in these storms are first apparent approximately 10 minutes before the hail reaches the ground.

A detailed case analysis of the cell structure and reflectivity gradient within a severe thunderstorm indicated that vertical transfer of momentum existed within the storm and that the environmental wind velocity and upper echo velocity may be related to the surface outflow velocity.

ACKNOWLEDGEMENTS

This report was written under the direction of William C. Ackermann, Chief of the Illinois State Water Survey. Research was accomplished under the general guidance of the Project Director, Glenn E. Stout, Head, Meteorology Section,,

The author wishes to express appreciation to Irene Koch for assistance in data processing and analyses, and the final preparation of this report. Special credit is due George R. Boyd for preparation of the illustrations in this report.

Credit is due also to the many cooperative weather observers who have volunteered their services to the project. These observers were contacted through the Agricultural Extension service at the University of Illinois. The crop insurance data were provided by the Crop-Hail Insurance Actuarial Association, Chicago, Illinois.

INTRODUCTION

This report summarizes the severe thunderstorm research program conducted in central Illinois by the Illinois State Water Survey from 15 October 1958 to 15 November 1961. The purpose of the investigation was to collect and analyze radar, synoptic, and special surface observations of severe thunderstorms, to explore the interrelationship of these observations, and to provide meso-scale techniques for severe storm identification.

The investigation was divided into three principal areas of study. These areas included: 1) the determination of the characteristics of air masses in which severe thunderstorms develop and propagate; 2) the collection and analysis of a large quantity of hail and wind observations in order to better describe the extent and magnitude of severe thunderstorm occurrences; 3) the collection and analysis of 3-cm radar data in order to compare the magnitude of radar reflectivity values with the magnitude of severe thunderstorm occurrences.

The format of the investigation closely paralleled that accomplished by Donaldson[1] in New England, and later by Inman[2] in Texas. The techniques employed in these investigations have been based upon measurements of the vertical radar reflectivity (Z) structure of thunderstorms. The principle difference between the investigation conducted in central Illinois, and the work done elsewhere is that of the radar sampling technique employed. Both

Donaldson and Inman used CPS-9 radars of the operational type which are capable of both PPI and RHI measurements. The CPS-9 radar used in Illinois is an experimental model without the RHI capability. Therefore, the Illinois study did not include concurrent measurements of echo tops.

The Illinois radar was scanned by means of a pseudo-CAPPI technique whereby the antenna was tilted through a series of 5 tilt angles with 8 receiver sensitivity settings used at each tilt angle.[3] Attempts were made to sample the thunderstorms at levels corresponding to the standard pressure levels of 1000, 850, 700, 500, and 300 mb. During 1960, an additional scan was added at the 400-mb level, after the analysis of the data collected during 1959 showed that the maximum radar reflectivity of severe storms generally occurred between the 500- and 300-mb levels. The various photographic techniques employed to record these data are described in detail in Scientific Report No. 1.

SPATIAL AND TEMPORAL CHARACTERISTICS OF SEVERE THUNDERSTORMS IN ILLINOIS

The success in each of the 3 areas of the Illinois study was greatly influenced by the temporal and spatial scale of the thunderstorm activity which was investigated. Thunderstorm activity in the Midwest is usually classified in accordance with general weather system theory; i.e., frontal thunderstorms, air mass thunderstorms, and squall line thunderstorms.

When examined by a high-powered 3-cm radar set, such as the CPS-9, these weather systems show great variability in time and space. Both lines and clusters of convective echoes, as well as isolated echoes, have been observed with each of the synoptic types.

Radar has also indicated that the development of a severe thunderstorm is generally preceded by the growth of a group, or cluster, of convective showers having a cross-sectional area of approximately 15,000 to 20,000 square miles. These clusters, which shall be referred to in this report as "complexes," contain a variable number of individual thunderstorms depending upon the stage of development of the complex. The average complex has a lifetime of 6 hours and follows a life cycle analogous to the individual thunderstorm; i.e., containing 1 to 5 individual cells (in this case thunderstorms) which grow, mature, and dissipate.

The majority of intense, convective complexes originate in cyclone warm sectors in the proximity of the cold front and propagate through the warm air mass. Occasionally, a small but intense complex may originate well ahead of the cold front, usually in an area favorable for orographic lifting. For example, several warm sector complex formations which later matured in Illinois and resulted in numerous severe weather occurrences have been noted to have developed over the Ozark Plateau region of southern Missouri. The specific characteristics of a particular series of complexes will be discussed later in the report.

The individual thunderstorms within a complex have average lifetimes of 30 minutes to 2 hours, while the cells within the thunderstorms have durations of 10 to 20 minutes. Thunderstorm spacing, like cell spacing, varies considerably. Generally, however, thunderstorm spacing appears to be inversely related to intensity — the more intense the thunderstorm, the greater the affected volume in the environment and the greater the distance between thunderstorms.

The size and spacing of cells, thunderstorms, and complexes, must be considered when evaluating the analyses of synoptic and radar data. In the case of the Illinois severe storm research program, where the emphasis was placed on the determination of radar echo characteristics, the very nature of the target studied was dependent upon; the azimuth and range resolution of the radar; the frequency of radar observations; and the time and space distribution of radiosonde data, First-Order station observations, and various special data collection networks. The complete data source used in the Illinois program and the accepted time and space resolution for each type of observation are graphically described in Figure 1, A comparison of the scale of thunderstorm complex, thunderstorm, and thunderstorm cell phenomena with the scale of resolution of control data quickly points out the tremendous problem encountered in resolving physical characteristics of severe storms. Obviously, the determination of radar echo characteristics for severe storm detection and identification can be ascertained only when the control data can adequately describe the time, location, and magnitude of the severe storm.

The use of routine upper air observations in severe storm studies is restricted to determining characteristics of air masses in which complexes or systems of complexes develop. First-Order station observations also lack the necessary reporting density to reliably describe thunderstorm complexes on an operational basis. However, in post analyses used in research, station records can be used to construct time and space cross-sections which are completely adequate for the study of complexes.[4]

The analysis of individual thunderstorms required a special reporting network of volunteer observers (Fig. 1) to provide a sufficient number of observations to define storm intensity. Approximately 1200 observers were organized as part of the Illinois project to provide such observations. Details of this network are described in Scientific Report No. 1.[3]

The investigation of thunderstorm cells was restricted to a heavily instrumented raingage network located 20 miles from the research radar site. Hail indicators described previously were

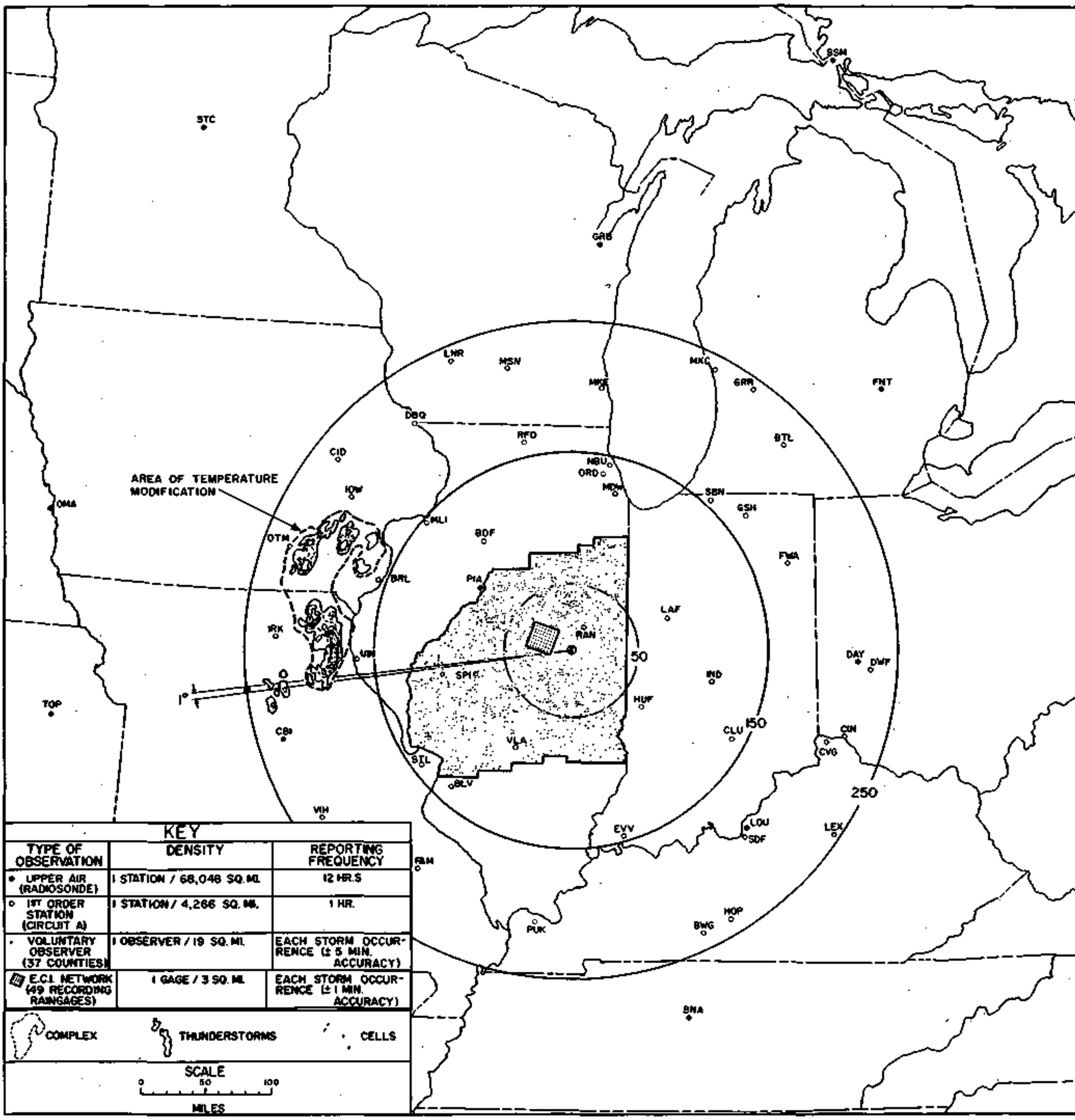


FIG. 1 SEVERE STORM DATA COLLECTION NETWORKS

used In conjunction with raingage records to determine hailstorm severity. Special ground and aerial surveys were made after particularly severe storms which occurred in the region of the special network.

The beam resolution of the radar (CPS-9) used in this investigation was adequate for the study of complexes and individual thunderstorms for range intervals of 20 to 200 and 20 to 100 miles, respectively. The study of thunderstorm cells, however, was restricted to a range less than 50 miles.

SYNOPTIC CHARACTERISTICS OF SEVERE HAILSTORMS

An analysis was made of the 26 most severe hailstorms (1953-1957) to determine the synoptic patterns associated with the storms based upon Weather Bureau data. To be considered severe the storm had to produce greater than 1/2-inch diameter hail. This five-year sample showed a nearly random distribution of storms with synoptic types consisting of 8 cold fronts, 6 warm fronts, 5 frontal waves, and 7 air mass showers. Investigations of hail climatology in Illinois by Huff,[5] and Changnon,[6] based on more than 20-year records, indicate the greatest frequency of hailstorms is with cold fronts in the summer and warm fronts in the spring. This seasonal transition appears to be in accord with potential air mass instability trends since it might be assumed that the predominant factor in the spring is abnormal low level warm air advection, whereas in the summer the cause of instability is more dependent upon cold air advection aloft.

In order to evaluate the importance of temperature advection upon severe storm generation, a study was made using upper air data for 25 hailstorm days between 1954 and 1957. This period was used because the upper air data were readily available on IBM punch cards as part of an earlier study.

Calculations of temperature advection were made for the 850-, 700-, 500-, and 300-mb levels from observations made ats Peoria or Rantoul, Illinois; Nashville, Tennessee; Columbia, Missouri; St. Cloud, Minnesota; and Green Bay, Wisconsin. Rates of temperature change were computed for 6 specific triangles formed by these stations using the approximation:

$$A = V_x\left(\frac{\Delta t}{\Delta x}\right) + V_y\left(\frac{\Delta t}{\Delta y}\right)$$

where:

A is the temperature advection

V_x is the east-west wind velocity component

$\frac{\Delta t}{\Delta x}$ is the east-west temperature change component

V_y is the north-south wind velocity component

$\frac{\Delta t}{\Delta y}$ is the north-south temperature change component

The frequency distributions of the temperature advection values which were obtained are shown in Figure 2. Only 50 percent of the total cases examined showed advection values exceeding $0.04^{\circ}C.hr^{-1}$ at any one level. Figure 2 also shows the advection values sorted according to the direction of storm movement. The median values at the 850- and 700-mb levels are positive which indicate general warming in the lower layers. The 500- and 300-mb temperature changes are negative and indicative of cold air advection aloft. Both the northwest and west storms show stronger advection at the higher levels, while the southwest storms show predominantly warm air advection in the lower layers. The strongest advection is associated with the northwest storms at the 300-mb level.

The net differences in advection values between 850 and 700, 700 and 500, and 500 and 300 mb were also calculated to determine the rate of change in stability. The frequencies of these net

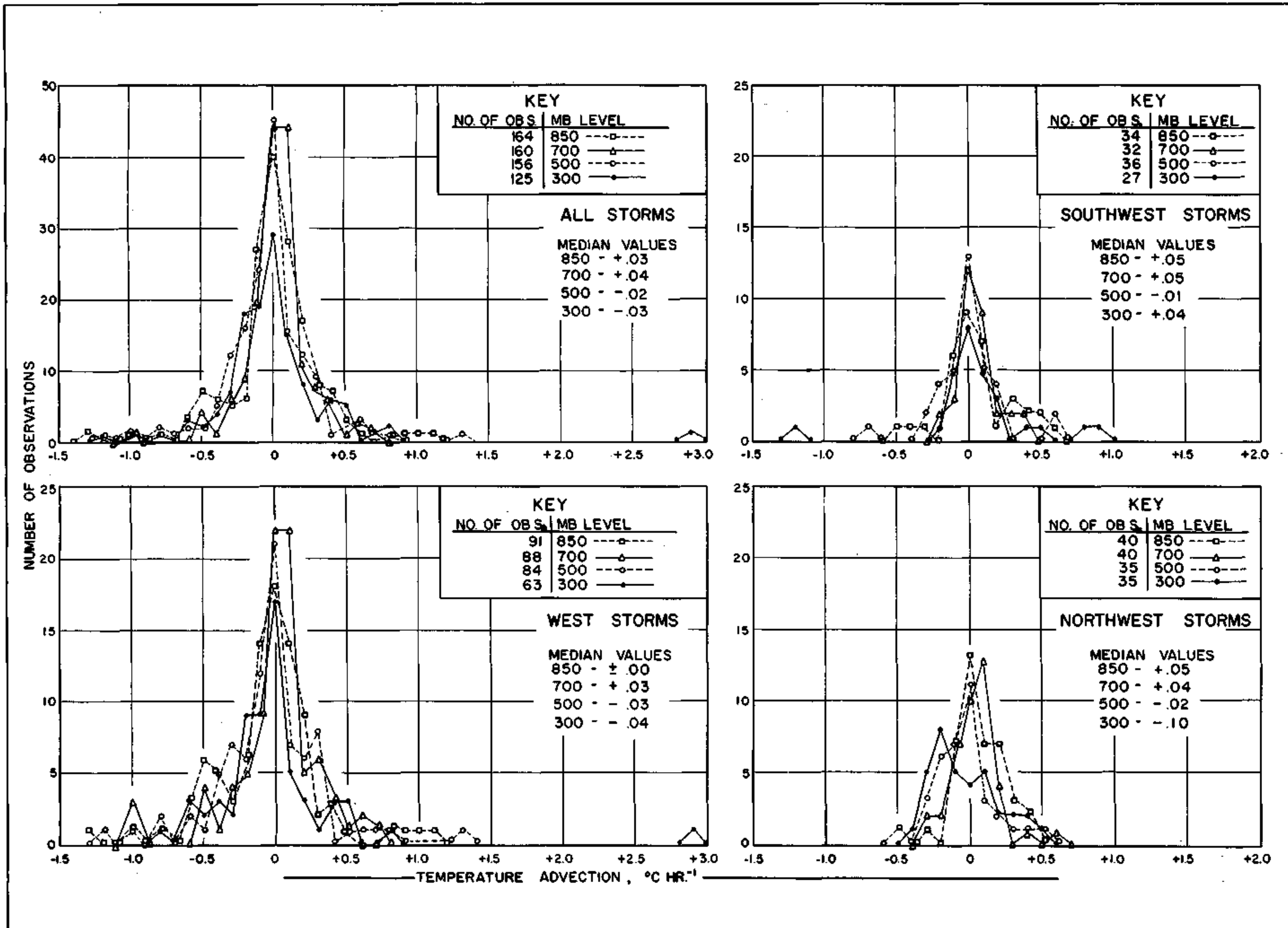


FIG. 2 FREQUENCY DISTRIBUTIONS OF TEMPERATURE ADVECTION, HAILSTORM DAYS, 1953-1957

differences are shown in Figure 3. Positive values indicate changes toward stability. Sixty-nine percent of the cases showed a change in stability of less than 0.3°C.hr^{-1} at any level. The remaining 31 percent appear to be distributed normally out to a limit of approximately plus or minus 1.5°C.hr^{-1} . Figure 3 also shows the stability change associated with storms which moved from the southwest, west, and northwest. It is obvious from these frequency distributions that a large percentage of the cases show no rapid change in stability in any of the pressure intervals. However, it is interesting to note that the median values in all intervals for all 3 directions are negative, indicating a continuing decrease in stability throughout the troposphere. In all 3 classes of storm movement the fastest rate of stability change is between the 700- and 500-mb levels.

Another study of air mass stability was made in addition to the preceding advection calculations. Upper air observations at 50-mb intervals were available for Columbia, Missouri; Peoria, Illinois; and Rantoul, Illinois, for 126 spring and summer storm days, 1953-1957. The soundings taken when a thunderstorm with hail was observed within 100 miles and 3 hours of the time of the observation were used to obtain frequency distributions of temperature, relative humidity, and wind speed. These distributions for the four standard reporting levels are shown in Figures 4. 5, and 6.

The temperature distribution at the 850-mb level shows a maximum frequency at 14 to 16°C. Fifty percent of the observations

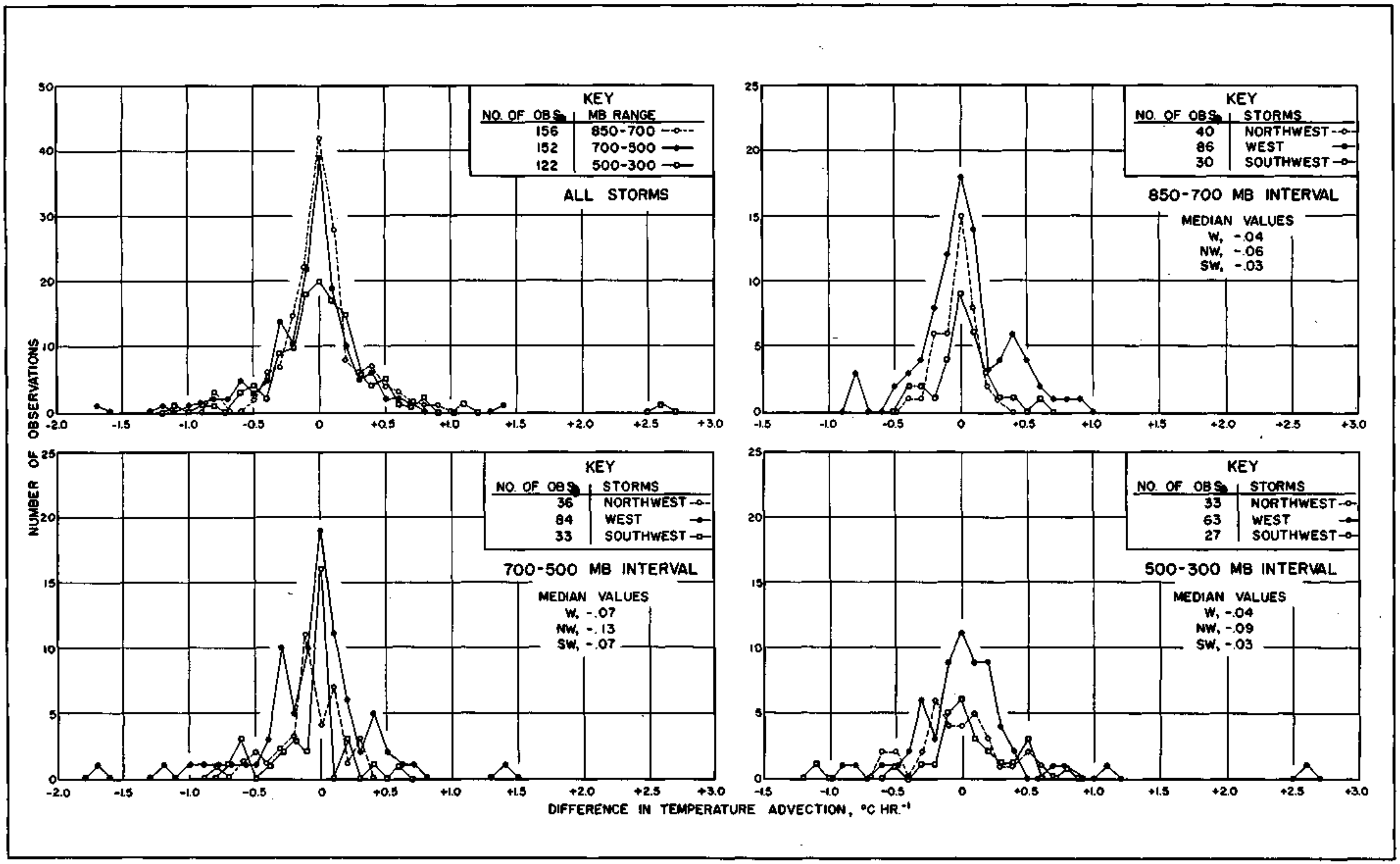


FIG. 3 FREQUENCY DISTRIBUTIONS OF NET DIFFERENCES IN TEMPERATURE ADVECTION

were In the temperature range of 11 to 19°C. with the median value being 14°C. At the 700-mb level, the peak frequency occurs at 7°C. and the median value is 4°C. Fifty percent of the observations are between 2 and 8°C. The peak frequency at the 500-mb level occurred at -8°C. At this level, the median value is -12°C. Fifty percent of the values were between -7 and -13°C. The data for the highest level considered (400-mb) had a maximum frequency at -18°C. with a median temperature of -23°C. At this level, 50 percent of the values were between -17 and -24°C.

The frequency distributions of relative humidity at the standard levels are shown in Figure 5. There were no strong maxima at any of the 4 levels. At the 850-mb level, 50 percent of the values ranged from 6l to 89 percent relative humidity. The median values ranged from 72 percent at 850 mb to 20 percent at 400 mb.

The frequency spectra of wind speed are shown in Figure 6. At the 850-mb level, the peak frequency is 7 to 9 meters per second (mps), the median speed is 11 mps, and 50 percent of the speeds are between 6 and 13 mps. The wind speed at the 700-mb level has a maximum frequency value of 16 mps. The median speed was 14 mps and 50 percent of the values were between 9 and 18 mps. At the 500-mb level, the spectrum begins to broaden with maxima occurring from 13 to 24 mps, with the median being 19 mps, and with 50 percent of the observations falling between 12 and 24 mps. The data at the 300-mb level show the influence of the jet stream with the peak frequency occurring at 35 mps. The median value was 27 mps and 50 percent of the observations were between 19 and 36 mps.

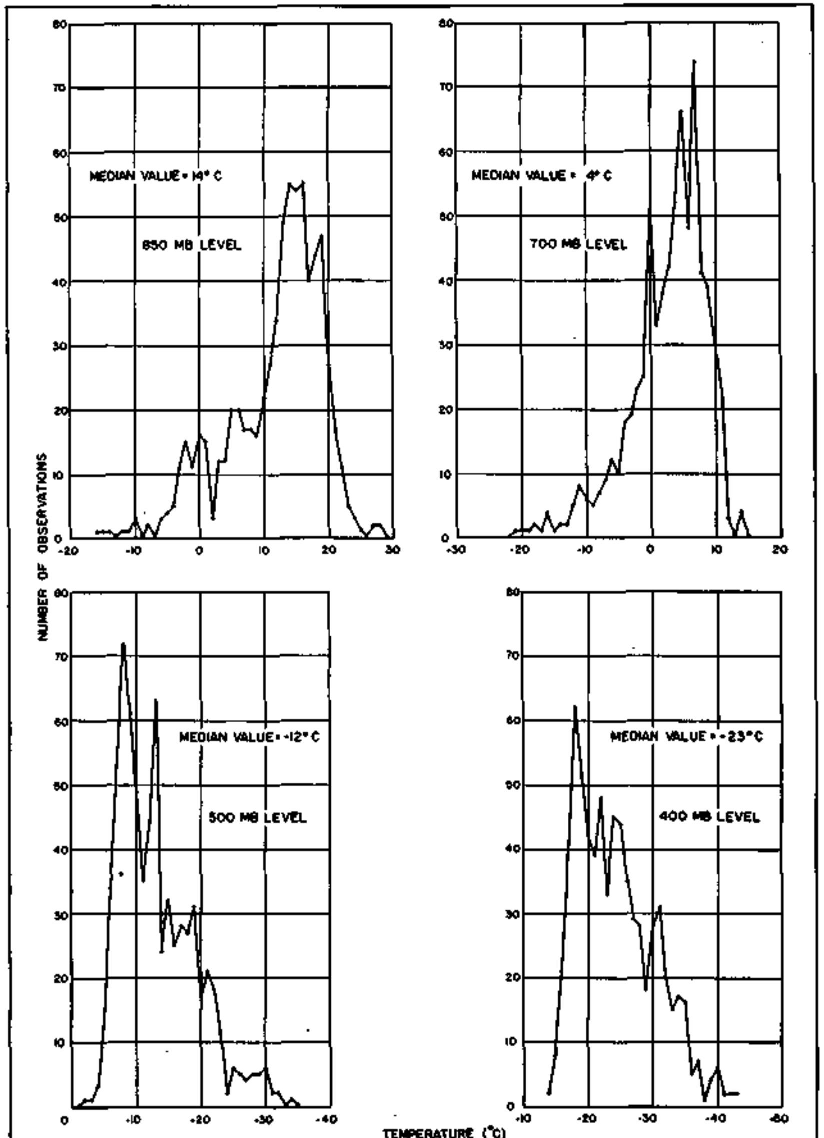


FIG. 4 FREQUENCY DISTRIBUTIONS OF TEMPERATURE, HAILSTORM DAYS, 1953-1957

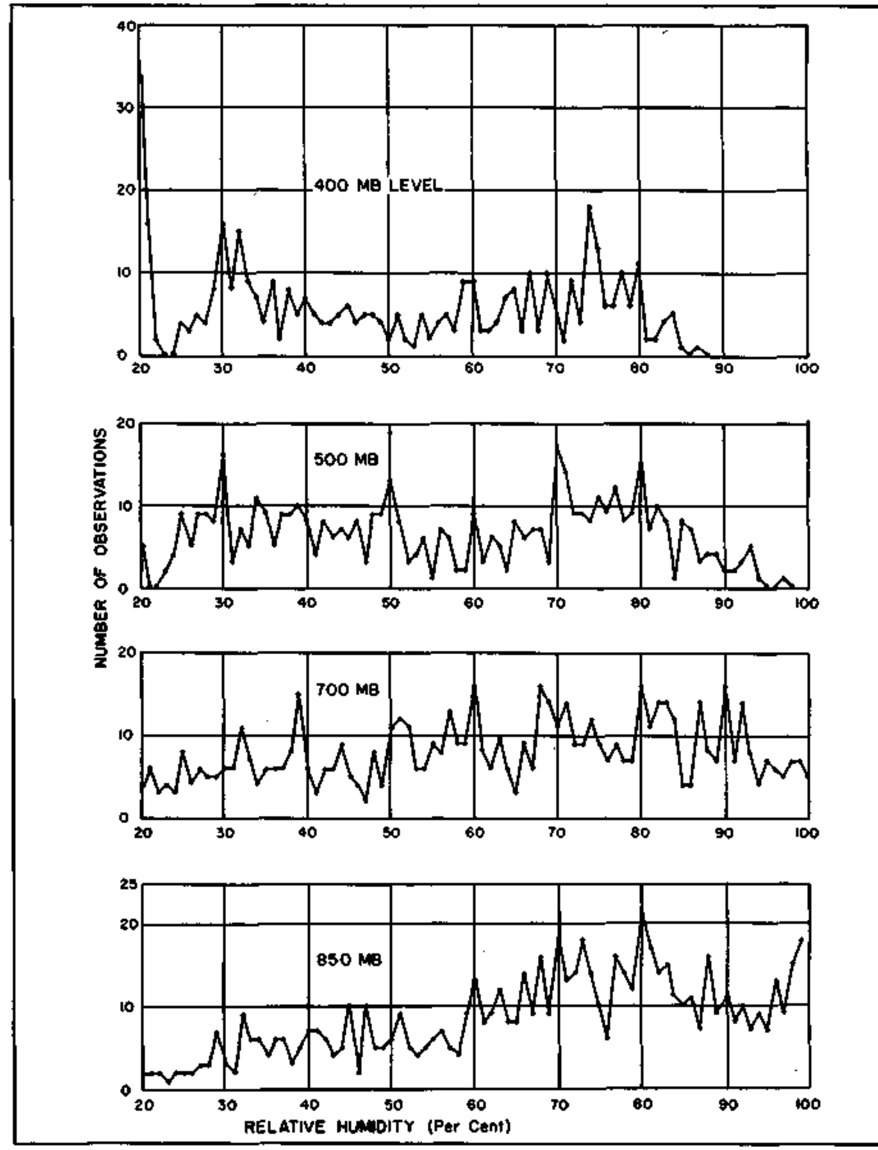


FIG. 5 FREQUENCY DISTRIBUTIONS OF RELATIVE HUMIDITY, HAILSTORM DAYS, 1953-1957

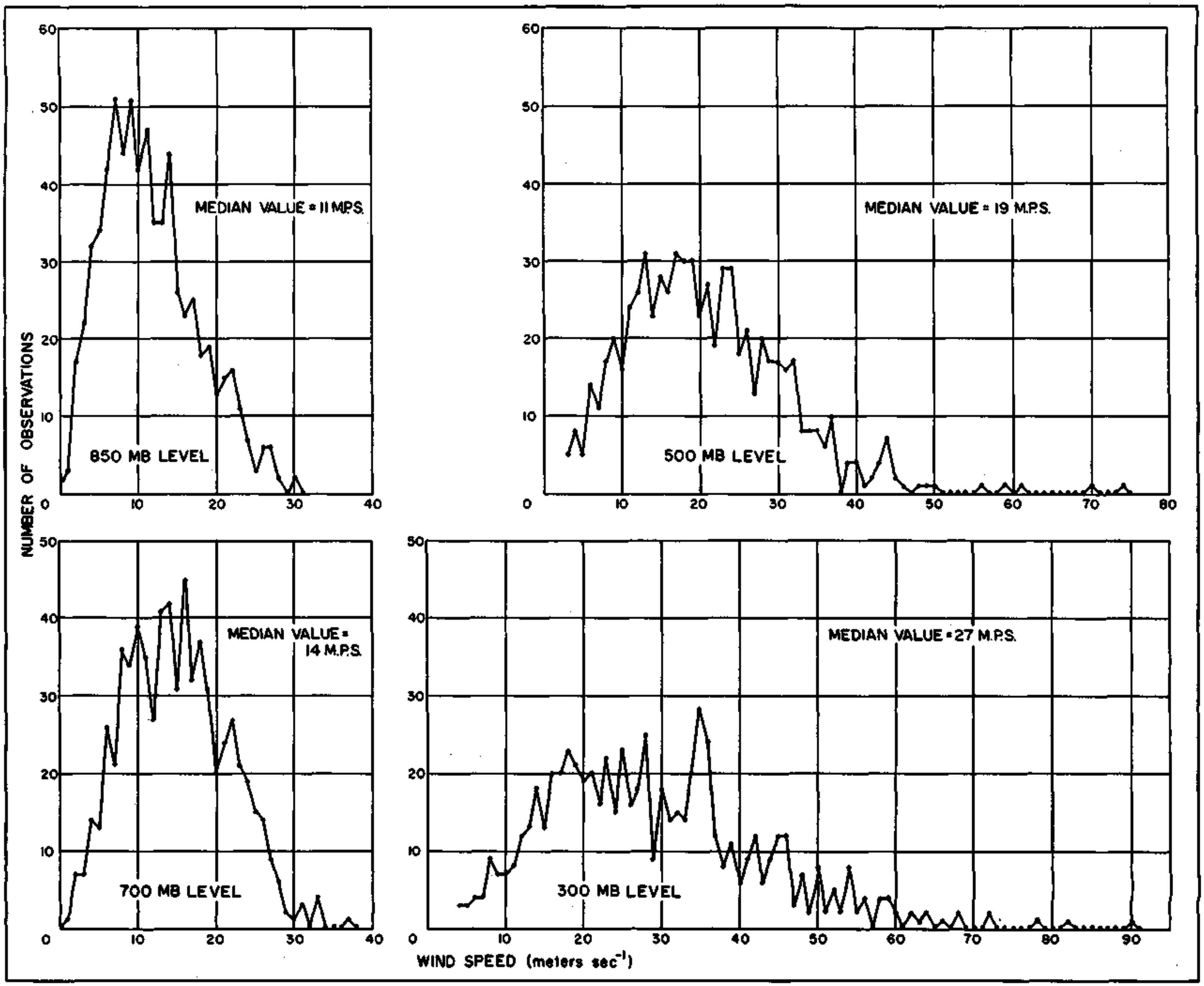


FIG. 6 FREQUENCY DISTRIBUTIONS OF WIND SPEED, HAILSTORM DAYS, 1953-1957

The radiosonde data were also used to compute total precipitable water and positive area values for the hailstorm days. The frequency distributions of these 2 parameters are shown in Figure 7. The most common precipitable water value observed was 1.25 inches. The spectrum is quite broad with 40 percent of the observations below and 60 percent above 1.25 Inches.

The calculation of total net positive area was made using a technique devised for sorting raindrop size distributions. The distribution of these net area values, also shown in Figure 7, shows a surprisingly narrow spectrum with 46 percent of the values ranging from 0 through 0.49 units (0 to 0.7 joules gm). It is also surprising that over 70 percent of the air masses considered had potential energy values less than 144 joules gm^{-1}.

The analysis of air mass conditions associated with hail-producing thunderstorms strengthens the argument that localized convection is extremely important in severe storm generation. Local variations in potential energy will be discussed later in conjunction with a particular storm development.

Hall Production Characteristics

Probably the most useful data currently available in Illinois to best describe the areal extent of hail are the reports of crop damage as tabulated by the Crop-Hail Insurance Actuarial Association. One obvious restriction of these data, however, is that it is available only during the crop-growing season, from late May to early September. If one is willing to accept this restriction, that is.

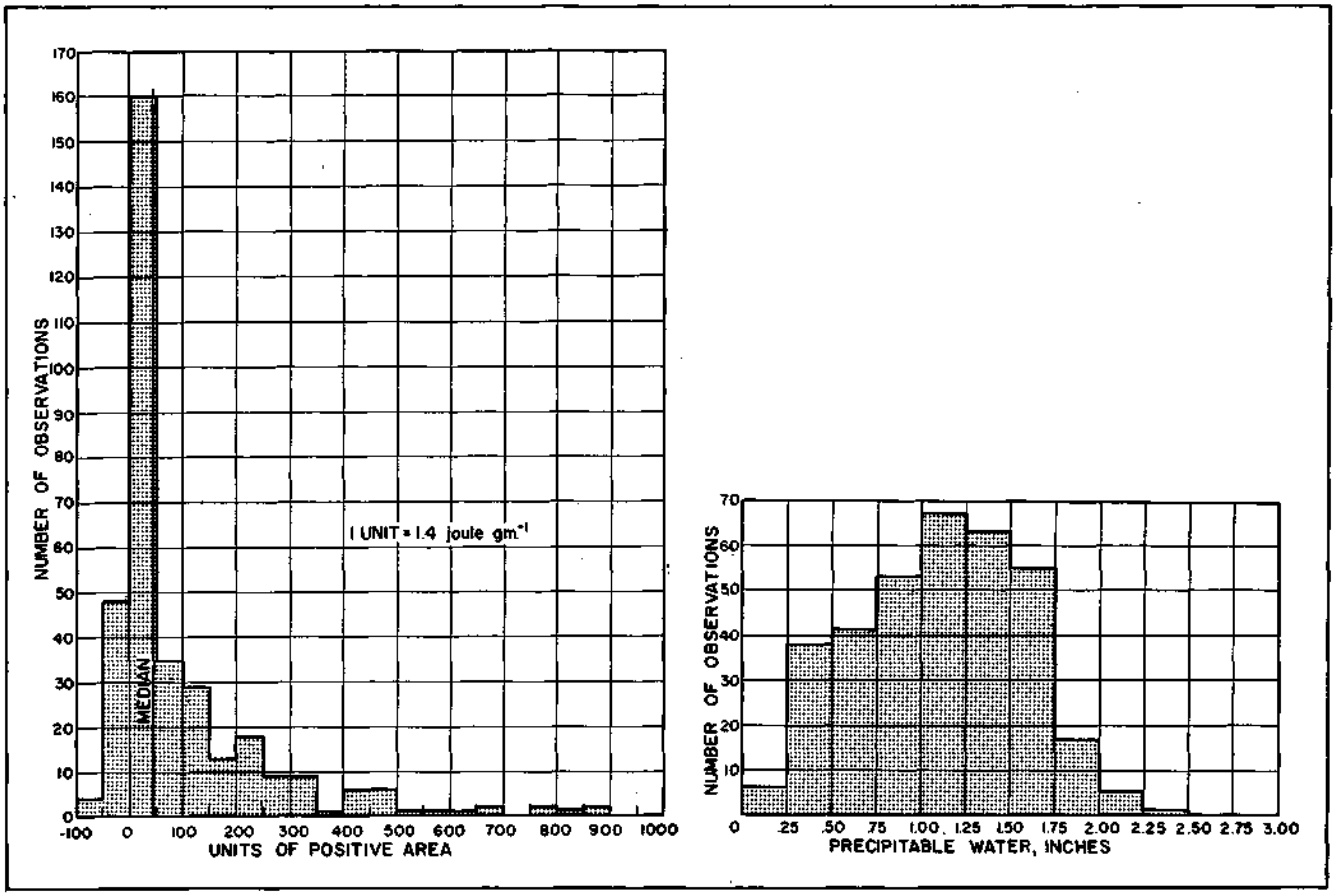


FIG. 7 FREQUENCY DISTRIBUTIONS OF PRECIPITABLE WATER AND POSITIVE AREA, HAILSTORM DAYS, 1953-1957

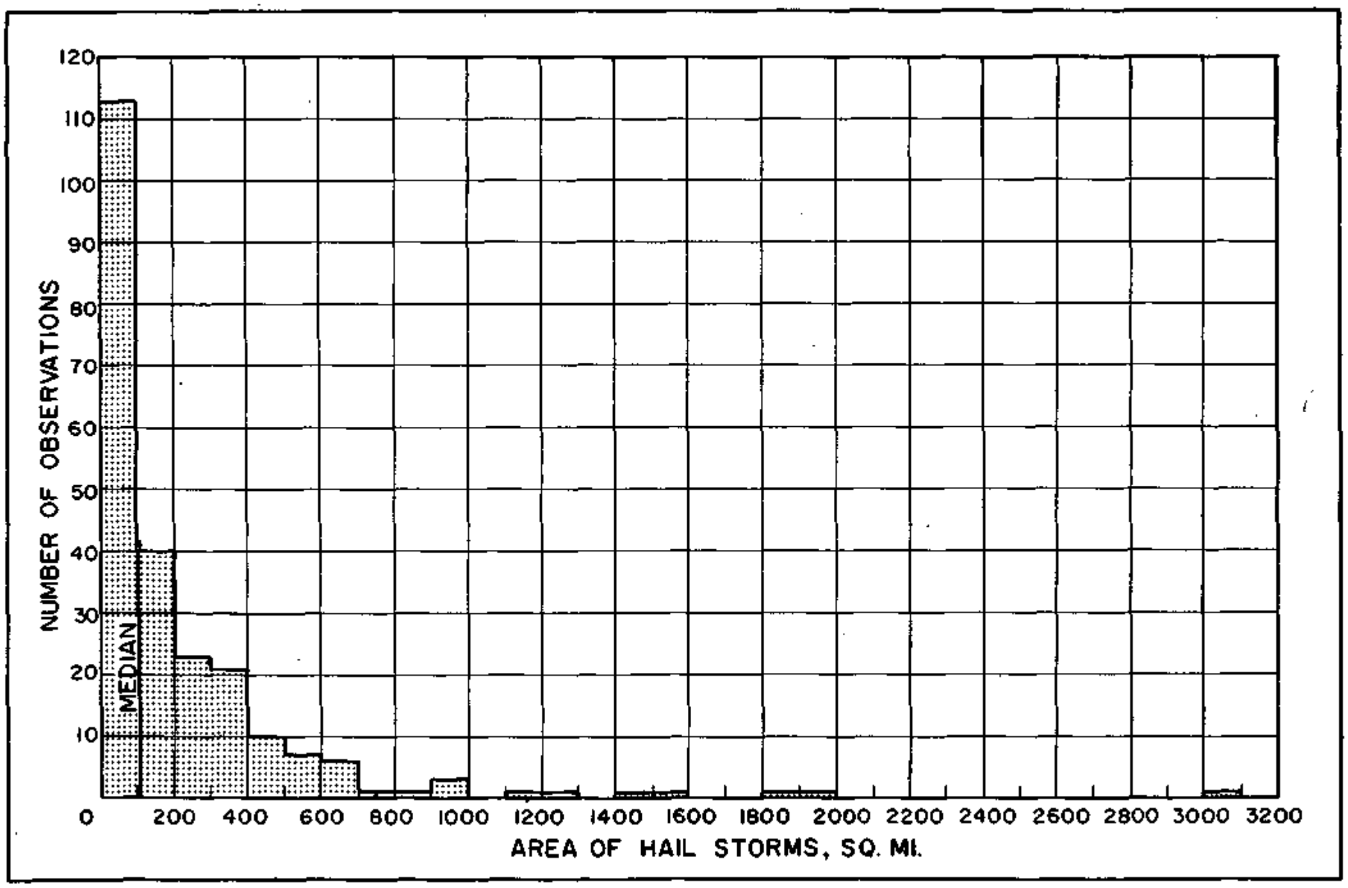


FIG. 8 FREQUENCY DISTRIBUTION OF SIZE OF HAILSTORM AREAS, 1953-1959

to limit the data to primarily summer storms, it is possible to obtain a comprehensive sample of the frequency distribution of the size of hailstorm areas. Figure 8 shows this distribution for the Illinois severe storm reporting network for the period 1953-1959. The median size of the area covered by damaging hail per thunderstorm complex is between 100 and 200 square miles. The median length to width ratio of the area was 4.

Attempts to quantitize the crop-damage data in terms of hailstone size or concentration have met with little or no success. However, it is the author's opinion, after conducting several storm surveys, that the predominance of heavy crop damage results from high concentrations of hail ranging from 1/4- to 3/4-inch in diameter.

The most reliable data for the determination of the distribution Of hail size was acquired from the volunteer observer reports. Pour years of operation of the Illinois severe storm reporting network provided over 600 detailed observations of the size of hail. The distributions of hail size and concentration from the observer reports by year are shown in Table 1. Ninety-five percent of the maximum hail size observed was 1-inch or smaller in diameter. Also, 90 percent of the average hail size was l/2-inch or less in diameter. Approximately one-half of the observations showed hail concentrations equal to or less than 10 stones per square foot.

A sample of the distribution of hail size within individual thunderstorm cells was obtained for 4 thunderstorms during 196l.

TABLE 1

HAIL OBSERVATIONS IN THE SEVERE STORM NETWORK

Distribution of Hailstone Size (inches)

Maximum Hail Size

Year	1/4	%	1/2	%	3/4	%	1	%	>1	%	Total
1961	68	34	62	32	24	12	30	15	14	7	198
1960	93	35	86	32	57	22	17	6	12	5	265
1959	35	49	22	31	8	11	5	7	2	3	72
1958	43	29	45	31	34	23	18	12	6	4	146
Total	239	35	215	32	123	18	70	10	34	5	681

Average Hail Size

Year	1/4	%	1/2	%	3/4	%	1	%	>1	%	Total
1961	107	60	46	26	19	11	4	2	2	1	178
1960	164	67	63	26	11	4	7	3	1	-	246
1959	52	74	13	19	4	6	1	1	0	-	70
1958	80	57	44	31	13	9	3	2	0	-	140
Total	403	64	166	26	47	7	15	2	3	1	634

Distribution of Hailstone Concentration

No. of Hailstones Per Square Foot

Year	≤10	20	30	40	50	60	70	80	90	100	150	200	250
1961	69	31	10	6	3	3	2	1	0	3	5	2	0
1960	70	40	12	10	11	1	1	5	0	5	8	1	1
1959	13	6	2	2	3	0	0	2	1	1	5	3	0
1958	73	18	0	4	3	0	0	1	0	0	0	0	0
Total	225	95	24	22	20	4	3	9	1	9	18	6	1
Percent of Total	51	22	6	5	5	1	1	2	-	2	4	1	-

The data were collected using metal foil hail indicators[2] which were located at 2-mile intervals throughout the East Central Illinois Raingage Network. The total sample distribution is shown in Figure 9. The mode and median of the hail distribution were 0.13 inch (3.3 mm) and 0.15 inch (3.8 mm), respectively. This distribution is similar to that detected in raindrop data by Mueller[8] shown in the upper right corner of this figure.

Computed Radar Reflectivities

A selected sample of 127 observer reports obtained during 1958, 1959, and 1960 were Judged to have a high reliability in estimates of hail size, concentration, and duration. These observations were used to calculate radar refleotivity values using the relation:

$$Z = \frac{N A_d f_s (D/\lambda, m)}{\frac{\pi^5}{\lambda^4} (K)^2}$$

where:

A_d is the cross-seotion area of the hail

f_s $(D/\lambda,m)$ is the back soatter cross-section

λ is the wavelength

$(K)^2$ is the complex index of refraotion

N is the number of stones per nr

The f_s values were obtained from theoretical values by Ryde,[9] and the $(K)^2$ value was assumed to be 0.93. The computed "climatological" Z values are shown in Table 2.

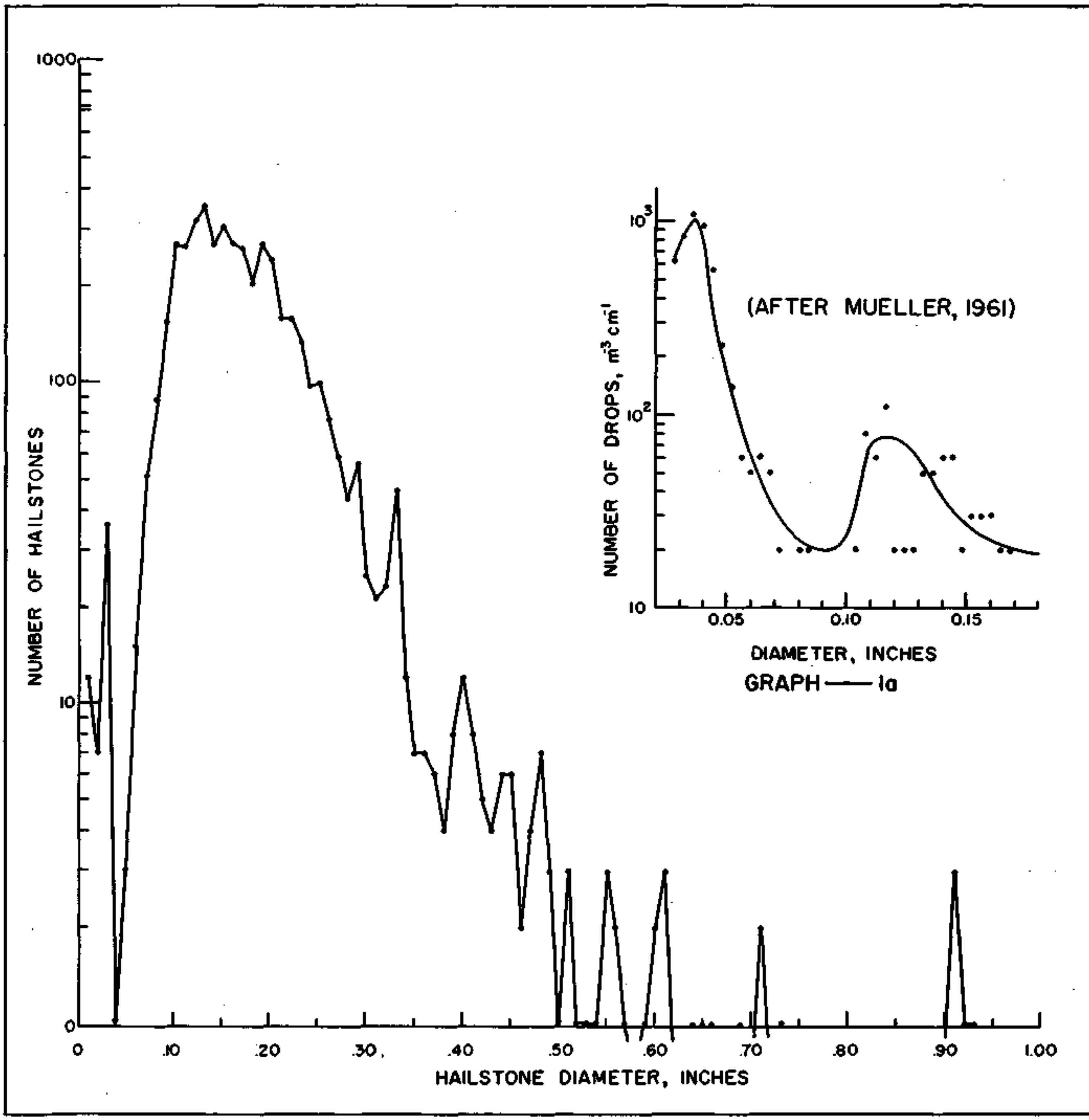


FIG. 9 HAILSTONE SIZE DISTRIBUTION, 1961

TABLE 2

COMPUTED RADAR REFLECTIVITY VALUES
FOR SELECTED HAIL OBSERVATIONS

Reported Hail Diameter (in.)	Number of Observations	Radar Reflectivity Factor (Z) mm^6m^{-3}
0.25	84	1×10^3
0.50	36	9×10^3
0.75	5	1×10^4
1.00	2	2×10^5

Except for the 1-inch diameter hail, the calculated Z values were approximately a factor of 10 lower than the corresponding radar measured values. Of course, part of the difference is due to the contribution of the accompanying rain. A probable explanation of the remaining difference is the higher stone concentration aloft in the cloud where the maximum radar reflectivities were observed.

As mentioned earlier, the technique used to measure the radar reflectivity factor values consisted of a series of radar receiver gain reductions to determine the threshold level of echo extinction. Each receiver gain setting was routinely calibrated using a signal generator. The Z values were calculated using the relationship:

$$Z = \frac{P_r}{P_t} \frac{R^2}{C}$$

where:

P_r is the power returned

P_t is the power transmitted

R is the range in nautical miles

C is the radar constant

The characteristics of the two radars used in this investigation were as follows:

Radar	TPS-10	CPS-9
Type of scan	RHI	PPI
Scan rate	$22° \sec^{-1}$	6 RPM
Beam width (H,V)	1.8°, 0.8°	1.0°
Transmitted power	65 KW	250 KW
Wavelength	3.3 cm	3.2 cm
Pulse length	1.0 μsec	5 μsec
Antenna gain	39 db	42 db

RADAR ECHO CHARACTERISTICS OP ILLINOIS THUNDERSTORMS

The three basic parameters used to describe radar return from thunderstorm complexes, thunderstorms, and thunderstorm cells are configuration (shape, area, or volume), velocity, and intensity. These parameters may be analyzed qualitatively, for integration with synoptic analyses or, quantitatively, for digital correlation with other weather parameters. Both types of analyses were used in this investigation, especially with respect to radar echo intensities.

There have been numerous investigations[1,2,10] showing a relationship between high radar reflectivities aloft and the existence of hail in thunderstorms. Experiences with this relationship in Illinois have shown its chief limitation in operational use to be that it has little prognostic value. The high intensity is first detected at, or a few minutes prior to, the onset of hail at the surface. Since most high intensity thunderstorm cells exist for a maximum of 20 minutes, the prognostic value to the forecaster of hail identification constitutes a warning to watch adjoining cells in the same complex, or adjacent complexes, for intensification.

The logical sequence of events in severe weather detection, identification, and prognosis by weather radar involvess the detection and delineation of thunderstorm complexes; the detection and identification of high intensity thunderstorms; and the determination of the velocities of both. For large areas which include several complexes, continual monitoring and verification of existing conditions using First Order station observations is necessary to compensate for the lack of accurate reflectivity measurements. Thus, an investigation of thunderstorm complexes represents an integration of macroscale and mesoscale radar and synoptic features.

These features were the subject of several case studies of complete weather systems made as part of this research program. One such case occurred on 16 May 1960 when 4 damaging thunderstorm complexes (squall lines and/or mesosystems) developed in the Midwest and within an 18-hour period produced tornadoes, hail, and damaging winds in Missouri, Illinois, and Indiana. The investigation of the thunderstorm complexes on this storm day represented an attempt to integrate the macroscale and mesoscale radar and synoptic features of midwestern squall lines. The detailed structure of this complete storm system is included in the next section of this report to clarify certain aspects of storm development and movement.

<u>16 May 1960 - Distribution of Precipitation and Severe Weather</u>

On 16 May 1960, the Weather Bureau reported that there were 11 confirmed tornadoes, 5 severe thunderstorms, 4 funnels aloft, and 2 occurrences of lightning damage within the area investigated. There were 30 reports of damaging hail received from the Crop-Hail Insurance Actuarial Association. This is a relatively large number of reports of hail damage considering the limited amount of crops susceptible to damage in May. Figure 10 shows the

distribution of these phenomena over a 5-state area, Also shown are: the area which experienced any measurable precipitation during the day (light gray); the areas which experienced at least 0.30-inch in any one hour (gray); and the areas which experienced at least 0.50-inch during any one hour (dark gray).

The configuration of the precipitation pattern and the distribution of severe weather occurrences suggest that a primary storm track extended northeast from Kansas across northern Missouri and into central Illinois, while secondary systems occurred from central Missouri across south-central Illinois and into north-central Indiana. A more comprehensive illustration of the thunderstorm complexes responsible for the distribution of the precipitation and severe weather occurrences is shown in Figure 11. This composite, constructed for 1500 CST, shows the TIROS I data, the synoptic analysis, and the radar data for the Midwest. The TIROS I data is shown in the 2-step gray scale of light gray and gray, with the radar echo depicted in dark gray. The majority of these TIROS I data were interpreted as being middle and high cloud generated by the convective systems. It is apparent that at 1500 CST 3 major thunderstorm complexes existed in the 3-state area. All 3 complexes were contained within the warm sector of the frontal system which extended from the deepening low-pressure system centered in northeastern Iowa. As will be shown later, the complex in Indiana was a mature system with the associated middle and high cloud very extensive, reaching into south-central Michigan and west-central Ohio. The life history of these 3

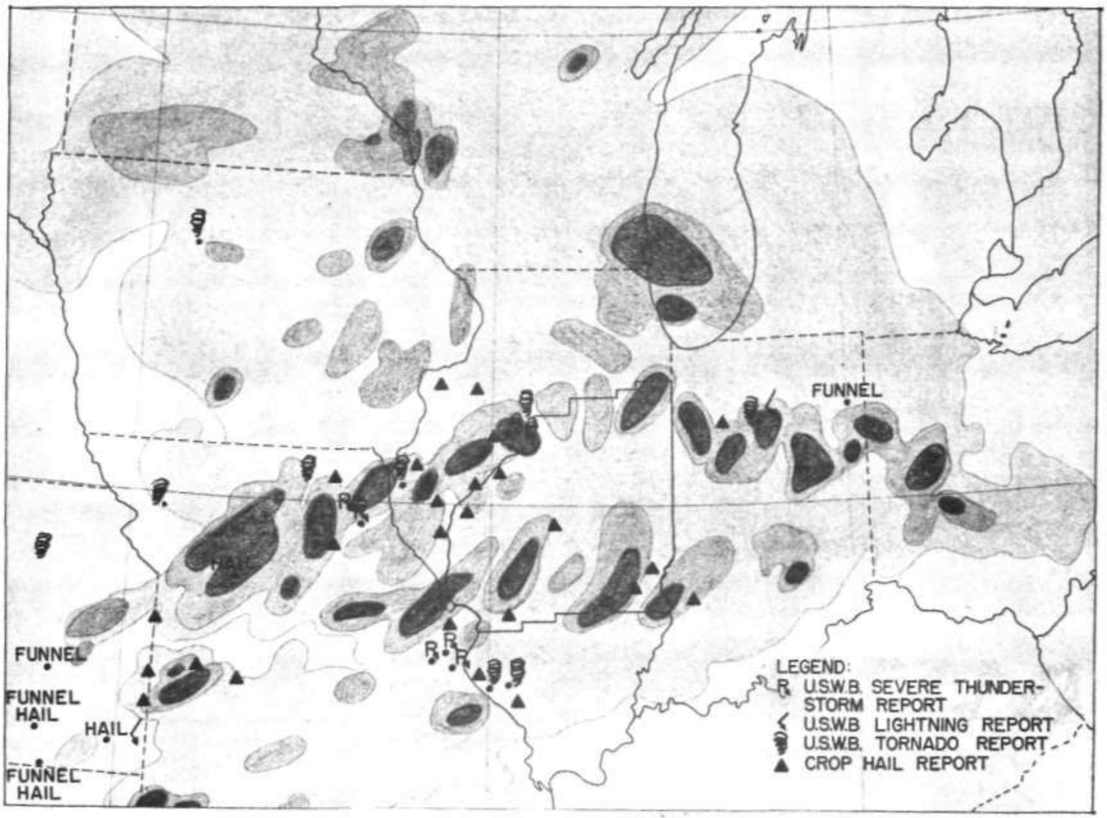
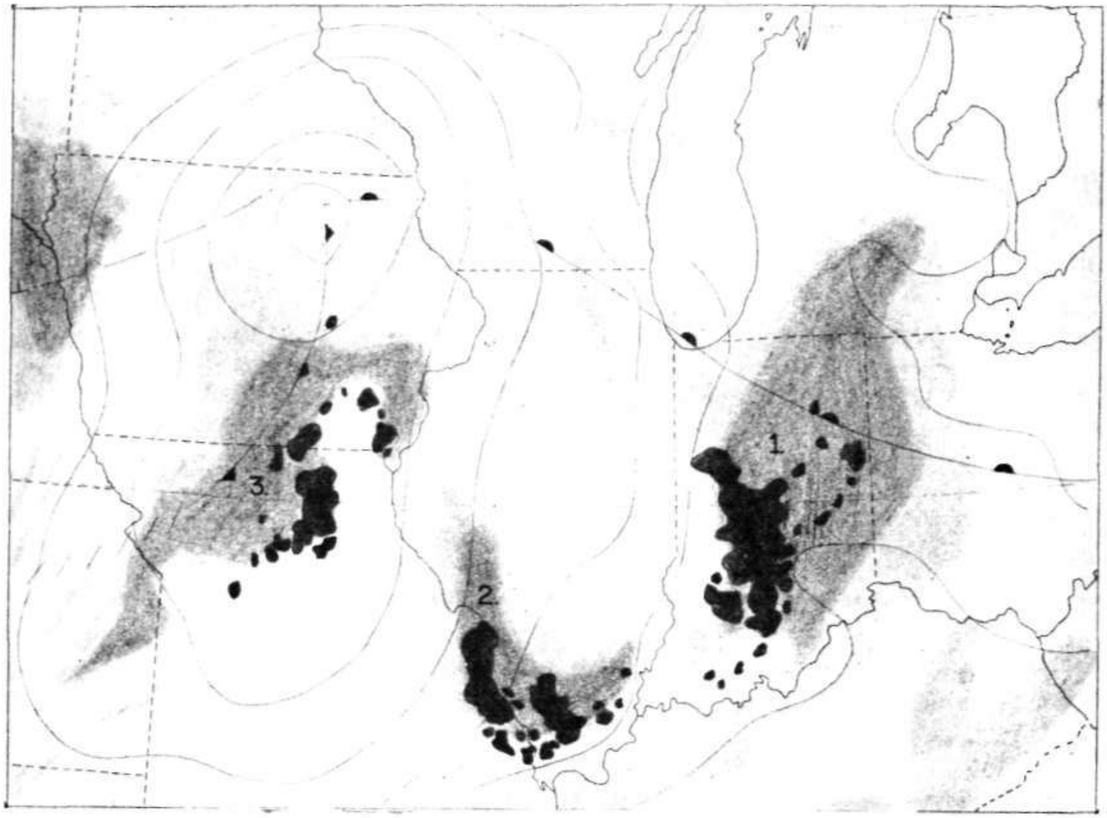


FIG. 10 PRECIPITATION AND SEVERE WEATHER, 16 MAY 1960



FIG, 11 RADAR AND TIROS I DATA 1500 CST, 16 MAY 1960

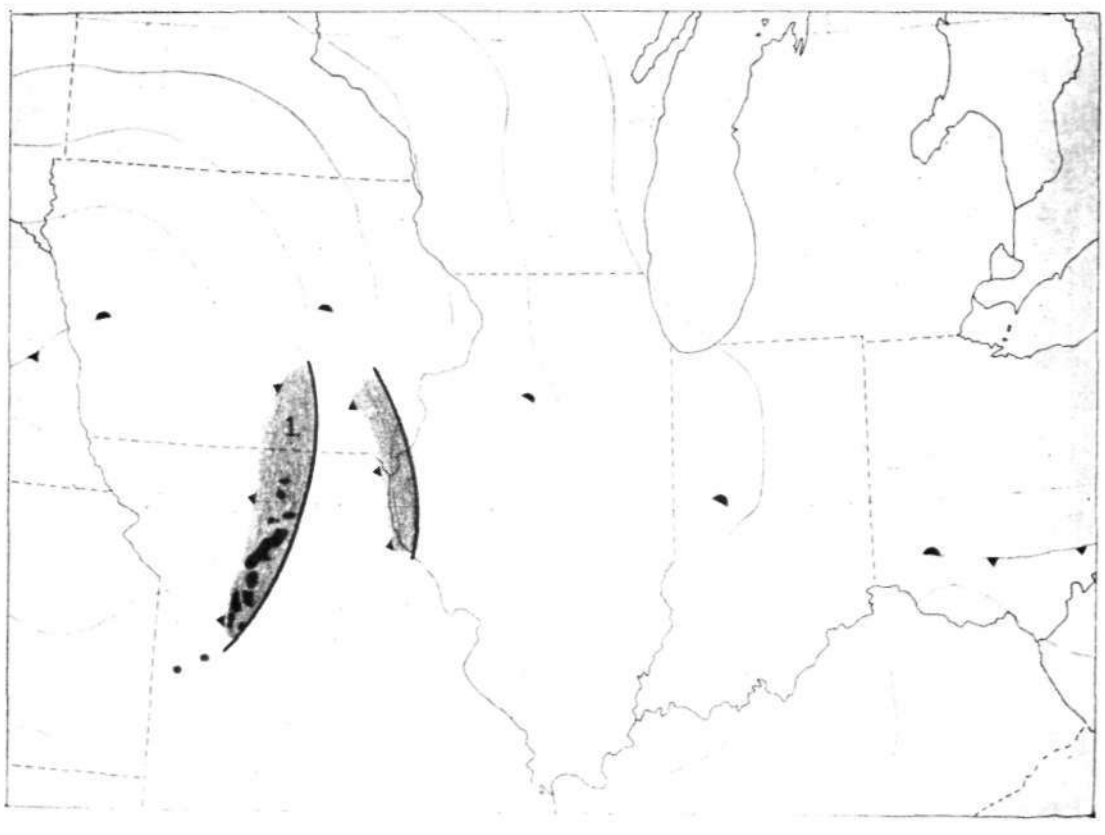


FIG. 12 RADAR SYNOPTIC COMPOSITE 0600 CST, 16 MAY 1960

thunderstorm complexes can be reviewed by examining the 3-hourly composite maps from 0600 to 2400 CST. In order to avoid confusion, the first 3 complexes depicted in Figure 11 will be referred to as complex 1, complex 2, and complex 3 as shown.

16 May 1960 - Synoptic Radar Patterns

At 0600 CST, the low pressure system was centered over southwestern Iowa and complex 1, already a mature system, was located over north-central Missouri and moving eastward at approximately 34 mph. The limited radar data shown in Figure 12 was obtained from observations at Columbia, Missouri, (CBI); however, no radar intensity values were available. A Fujita-type[4] analysis, using a space section constructed from time sections of pressure, temperature, wind, and weather observations at all available stations, was used to determine the location and areal extent of the squall line. A summary of the synoptic and radar data for 0600 CST is shown in Figure 12. In Figures 12 through 18, the leading edges mark the wind-shift lines, the black areas delineate the radar echoes, and the shaded areas mark the modified temperature regions. As shown in Figure 12, there were actually 2 squall lines in existence at 0600 CST. However, the eastern one contained only light shower activity with no severe weather occurrences reported and consequently was not numbered as a separate complex. The primary squall line, shown with the radar echoes, was associated with hail and damaging wind occurrences shortly after midnight near Kansas City, Missouri, (MKC), and at 0600 CST with a tornado at Kirksville, Missouri, (IRK).

By 0900 CST, the mature squall line, as shown in Figure 13, had moved eastward into Illinois. The first radar data from the Illinois CPS-9 were obtained at this time. The echo depicted in Figure 13 was obtained at 0° antenna tilt and maximum receiver gain. The strongest echo cells and their equivalent radar reflectivity (Z) values are shown for the most intense portions of the squall line. These values were also obtained at 0° antenna tilt. The intensities of cells with Z values lower than 1×10^3 mm^6m^{-3} are not indicated. The western line was still the predominant system with the maximum Z value near the surface reaching 4×10^5 mm^6m^{-3} near the center of the line. This cell was associated with damaging hail reports between 0900 and 1000 CST. The area encompassed by this squall line as it moved across northern Missouri experienced a temperature drop of 8^oF. which established a pseudo-cold front across south-central Missouri, separating the modified air from the warm air of the warm sector. This boundary is indicated in Figure 13 by the dots extending westward from the primary squall line. Actually, the western extremity of this pseudo-front was a pseudo-warm front, since the moderate southerly air flow in the warm sector had recovered and at this time was returning the warm moist air northward into western Missouri. At this time, the primary squall line in western Illinois was approximately 8 hours old and was passing from a mature stage to the dissipation stage. The period with the greatest number of severe weather occurrences was from 0600 to 0800 CST when the primary squall line was located between Kirksville, Missouri, and the

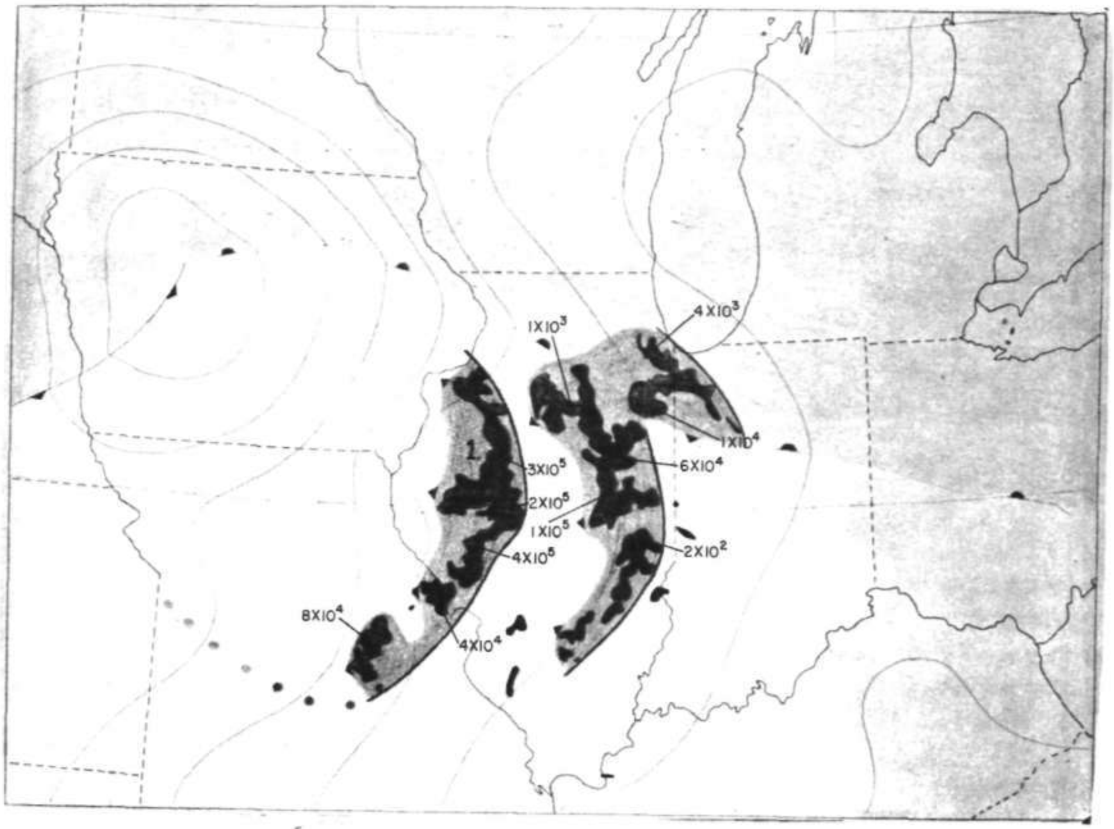


FIG. 13 RADAR SYNOPTIC COMPOSITE 0900 CST, 16 MAY 1960

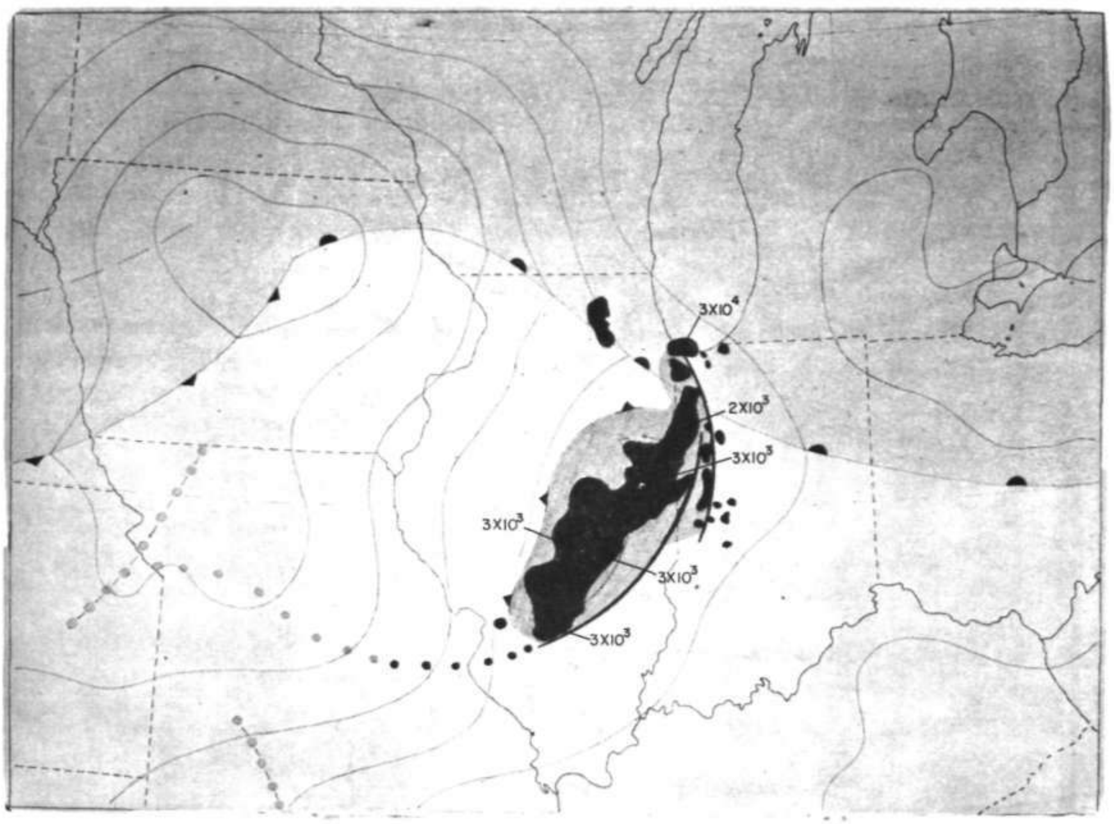


FIG. 14 RADAR SYNOPTIC COMPOSITE 1200 CST, 16 MAY 1960

Mississippi River. The low pressure center was located in west-central Iowa at 0900 CST as it continued to move steadily north-eastward, while the warm front remained almost stationary across eastern Illinois, Indiana, and Ohio.

By 1200 CST, thunderstorm complex 1, as shown in Figure 14, had moved to eastern Illinois and extended from Chicago, Illinois, (MDW), southwestward to St. Louis, Missouri, (STL). The primary and secondary lines of complex 1 had merged and were dissipating. The Z values were fairly uniform throughout the line, averaging 2 to 3×10^3 mm^6m^{-3} with the exception of a single observation in excess of 3×10^4 mm^6m^{-3} near Chicago. The pseudo-front established by the modified air was well marked by the temperature gradient through central Missouri by this time. The warm air had returned steadily northward into western Missouri after 0900 CST, and a temperature contrast of 6 to 10°F. was well established between northern and southern Missouri. Also at this time, a new line of towering cumulus was forming along the western extremities of the return warm air flow. Another line was developing concurrently in south-central Missouri. The low pressure system in northeastern Iowa was deepening with a central pressure of approximately 1001 mb. The cold front associated with the low pressure system had accelerated and reached the northwestern corner of Missouri by 1200 CST.

Analysis of the 1500 CST data, summarized in Figure 15, showed the existence of 3 definite thunderstorm complexes. The northern portion of complex 1 had continued to weaken but the southerly portion remained moderately strong over south-central Indiana, The Z values of this system averaged 3 x 10^3 mm^6m^{-3}, with the maximum value reaching 2 x 10^4 mm^6m^{-3}. The 2 new complexes which developed shortly after 1200 CST had moved east-northeastward to the Mississippi River.

The southernmost complex, referred to as complex 2, developed rapidly in the Ozark Plateau region which is the principal physiographic section of southern Missouri. The relative position of this complex suggests that its principal cause of development was the orographic influence of southern Missouri. Development of thunderstorm complexes in warm sectors has been observed in this area on several occasions in the past. Radar reflectivity values of the cells in complex 2 were moderate to strong, ranging from 7 x 10^3 to 7 x 10^5 mm^6m^{-3}. The maximum Z value was measured from cells associated with hail occurrences south of St. Louis, while an echo area with a measured Z value of 5 x 10^4 m^6mm^{-3} was associated with 2 tornado occurrences across the Mississippi River in Illinoiso It is of interest to note that complex 2 reached maturity in the warm air mass which was unmodified by complex 1. Complex 2 weakened considerably as it moved northward across the pseudo-frontal system established by complex 1.

The complex in northeastern Missouri, designated as complex 3 in Figure 15, was still in the growth stage at 1200 CST. Radar reflectivity values of the 5 major cells ranged from 1 x 10^4 to 1 x 10^5 mm^6m^{-3}. This complex developed in the major trough from the low pressure system centered at this time in northeastern

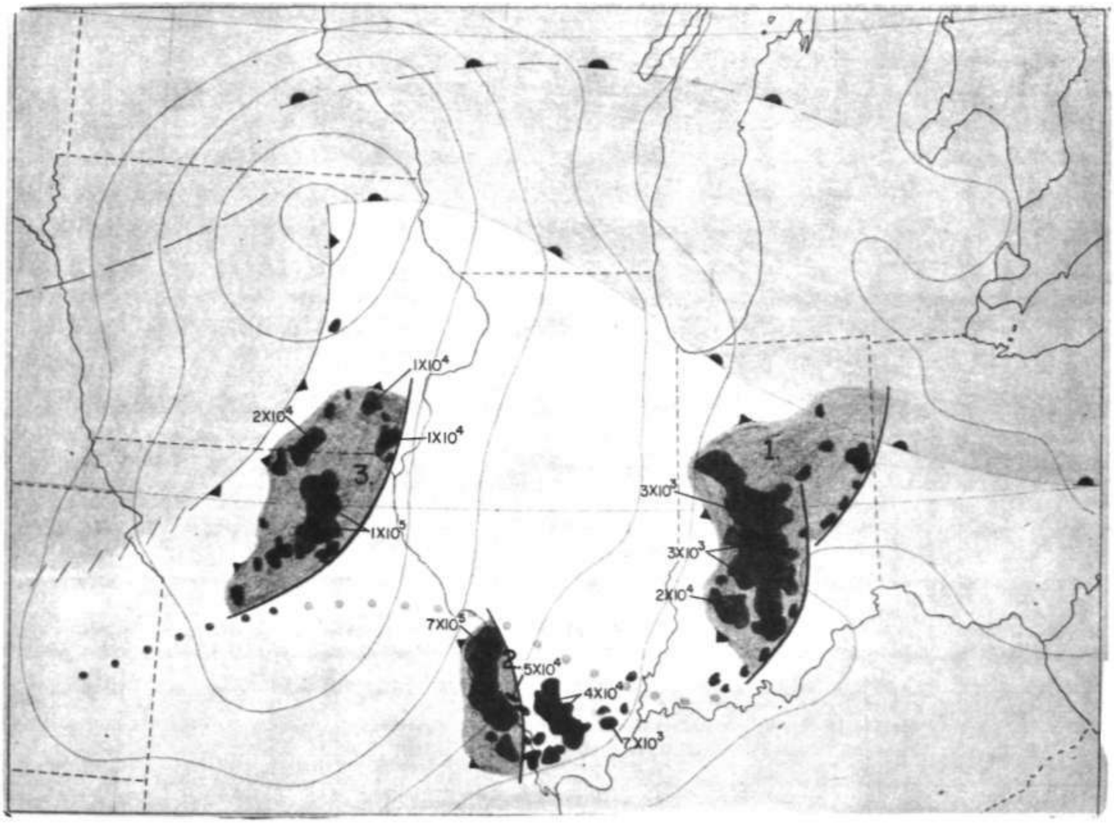


FIG. 15 RADAR SYNOPTIC COMPOSITE 1500 CST, 16 MAY 1960

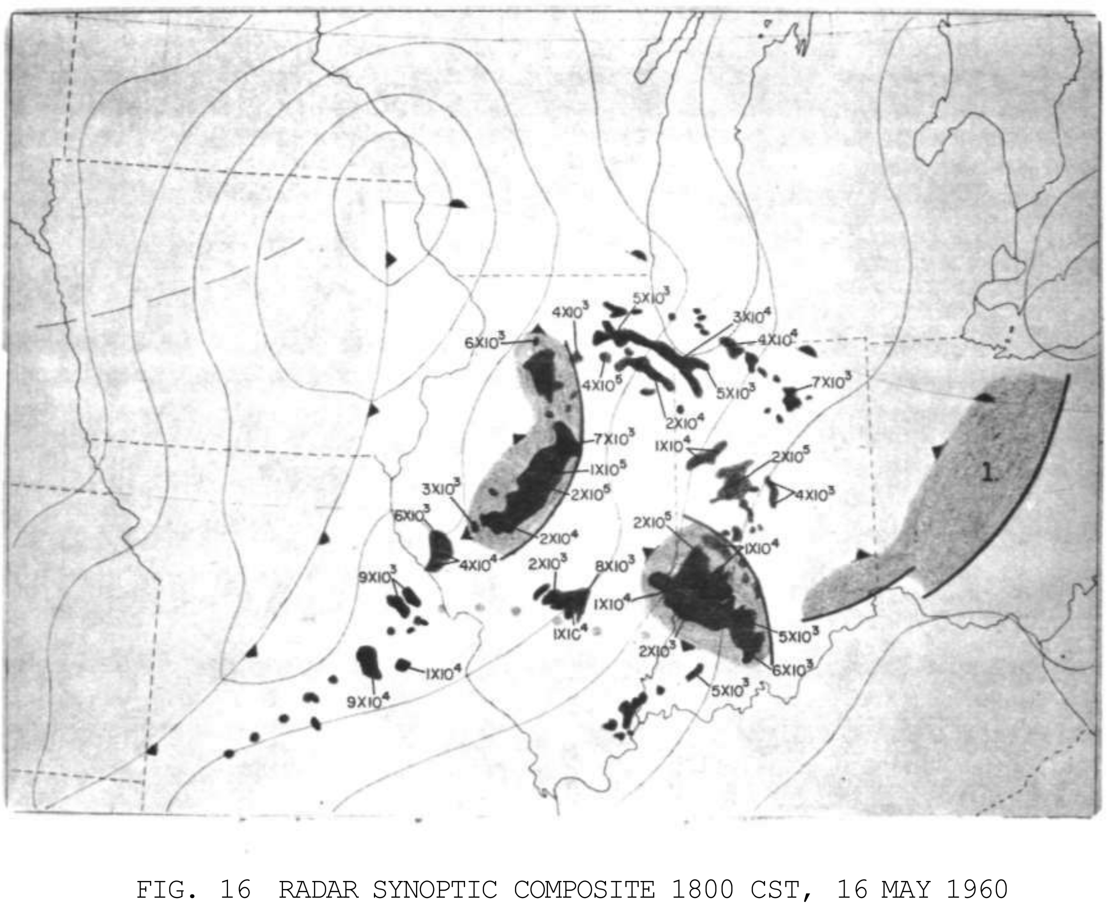


FIG. 16 RADAR SYNOPTIC COMPOSITE 1800 CST, 16 MAY 1960

Iowa. The cold front had accelerated from 12 to 34 mph and was moving rapidly southeastward into central Missouri. The south-western extremity of the cold front was dissipating as the pseudo-cold front, established by the modified air from complex 3, created the strongest temperature and wind shift contrast further south.

The position and relative intensities of the 3 complexes at 1800 CST are shown in Figure 16. Complex 1 was still evident from the surface observations in central Ohio; however, the complex was too weak and the radar range too great for detection at this time. No severe weather was reported from this complex in Ohio. Complex 2, which weakened as it crossed the pseudo-frontal system resulting from complex 1, appeared to strengthen between 1700 and 1800 CST while in the Indiana Wabash River Valley. A Z value of 2×10^5 mm^6m^{-3} was measured at the northern end of the complex in eastern Illinois and was associated with 3/4-inch hail. A significant increase in the number of air mass showers in the warm sector can be noted between 1500 and 1800 CST.

Complex 3 had reached the mature stage by 1800 CST with the center of the system showing Z values of 2×10^5 mm^6m^{-3}. The majority of the severe weather occurrences associated with complex 3 occurred just prior to 1800 CST. The cold front, which had a mean speed of 31 mph between 1500 and 1800 CST, had now moved into the major trough of the low pressure system. A pseudo-cold front established by complex 3 in eastern Missouri was marked by a line of scattered echoes which suggested the development of new squall line activity in advance of the cold front in southeastern Missouri.

The radar synoptic composite at 2100 CST, Figure 17, shows that a rapid change had occurred in all 3 complexes since 1800 CST, Complexes 1 and 2 had dissipated completely by 2100 CST, while a new complex designated complex 4, had been generated by the cold front as it crossed the Mississippi River. Complex 4 reached maturity shortly after 2100 CST with a maximum Z value of 2×10^5 mm^6m^{-3} measured near the center of the complex in central Illinois. Complex 3 was still evident in central Indiana; however, the measured Z values of all echoes were below 1×10^3 mm^6m^{-3}. The broken line of echoes oriented north-south in south-central Illinois is the line which developed at 1800 CST on the pseudo-cold front. This pseudo-cold front created by complex 3 was still evident across southern Indiana and southern Illinois; however, diurnal cooling had lowered the temperature contrast to 3 to 5^0F_0 An extension of complex 4 had developed ahead of the cold front over southwestern Illinois. One cell in this secondary complex had a significant Z value of 7×10^4 mm^6m^{-3}. By 2400 CST, the secondary complex (labeled complex 5 in Figure 18), had become the predominant system remaining in the warm sector. Reflectivity values in this complex ranged from 2×10^3 to 3×10^5 mm^6m^{-3}. Complex 4, located in extreme northeastern Illinois, had reached the dissipation stage with the exception of the echo in its southern extremity where a Z value of 9×10^4 mm^6m^{-3} was measured.

Analysis of the seven 3-hourly sectional, radar, and synoptic

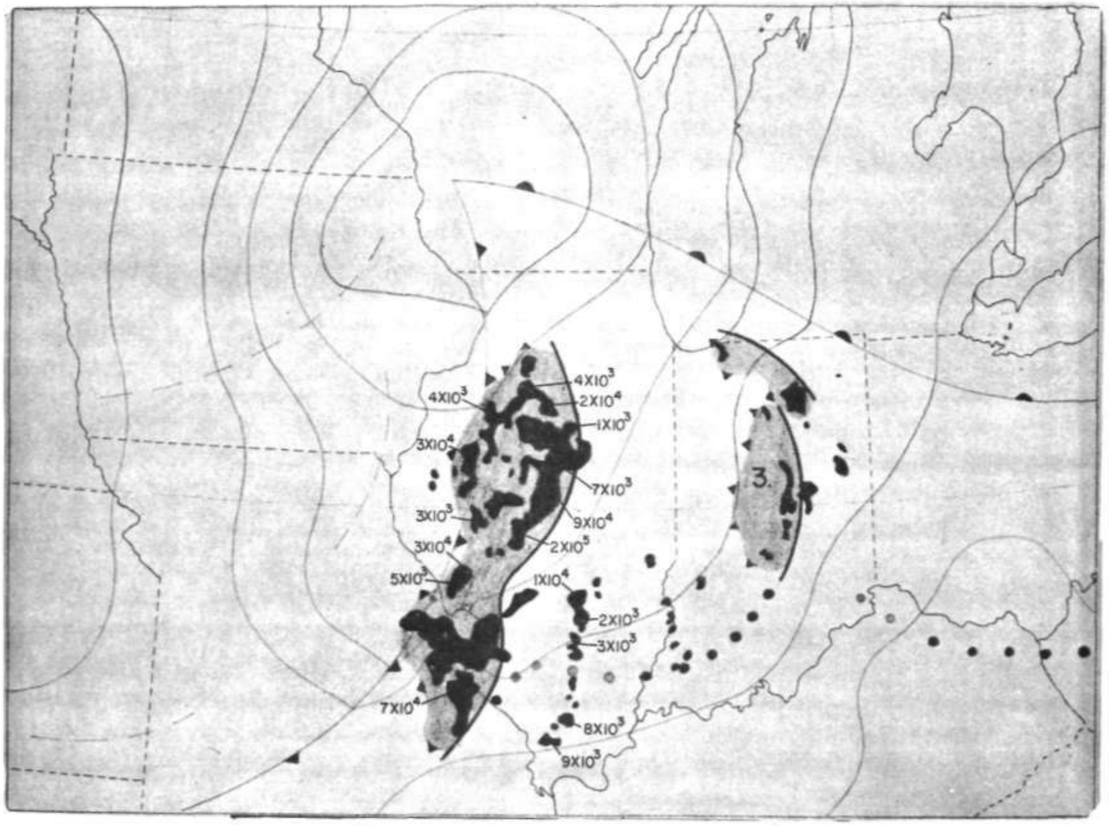


FIG. 17 RADAR SYNOPTIC COMPOSITE 2100 CST, 16 MAY 1960

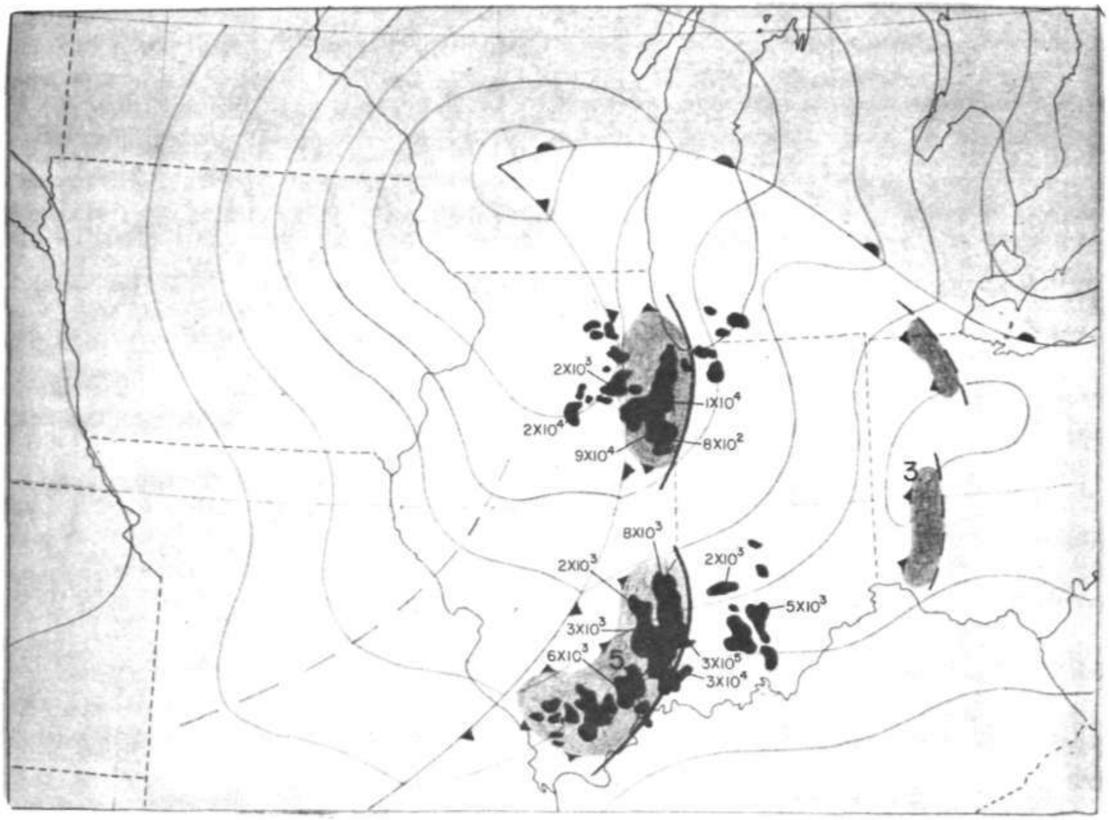


FIG. 18 RADAR SYNOPTIC COMPOSITE 2400 CST, 16 MAY 1960

maps has shown the existence of 5 distinct thunderstorm complexes on 16 May 1960. The first 4 of these complexes are known to have been associated with some form of severe weather,,

An attempt was made to investigate the characteristics of each of the 4 thunderstorm complexes by constructing time sections of First Order station data. Figures 19 and 20 show the pressure, temperature, dew point traces, and the observed weather at stations located along the track of the individual complexes.

Of course, the Individual station records primarily reflect the characteristics of a particular cell within the complex rather than the average characteristics of the entire complex. However, the stations shown in the time sections were located near the center of the complexes and, thus, are accepted as being representative of the average cell characteristics within the complex. The 3-hourly synoptic analyses of complex 1 indicated a complex was in existence for at least 12 hours, moving from Kirksville, Missouri, at 0600 CST to Columbus, Ohio, (CMH), by 1800 CST. The thunderstorm high registered by the microbarograph at Kirksville indicated a maximum excess pressure of nearly 4 mb, a wind shift from SSE to SW, and measured wind gusts to 28 mph. Obviously, the complex was In the mature stage at that time. Complex 1 began dissipating soon after crossing the Mississippi River and the associated pressure trace broadened considerably on the microbarographs at Quincy, (UIF), and Springfield, Illinois, (SPI). The excess pressure was 1 to 2 mb at this time and both stations experienced a 3°F. temperature change. Quincy had a peak wind

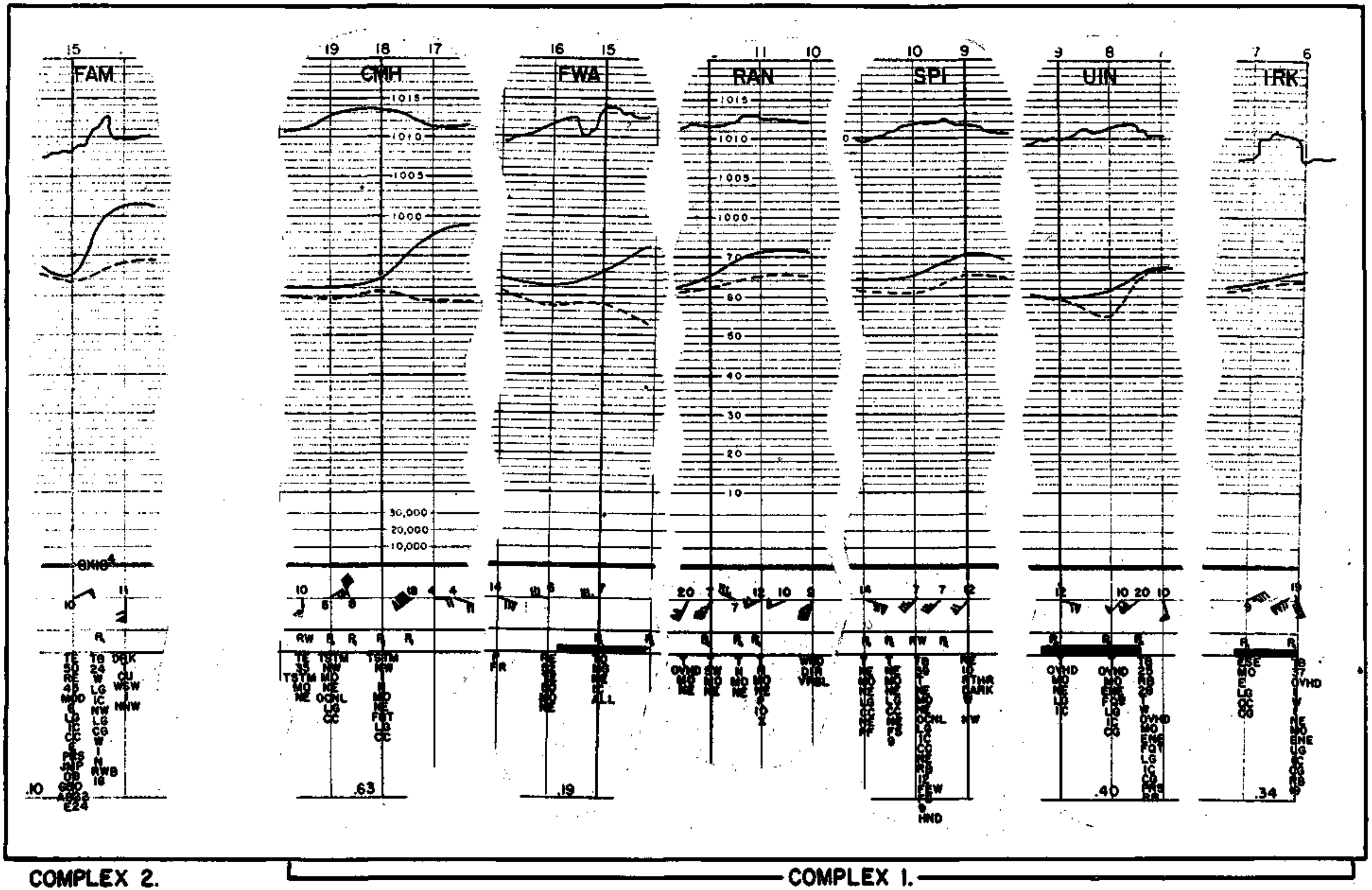


FIG. 19 THUNDERSTORM TIME SECTIONS

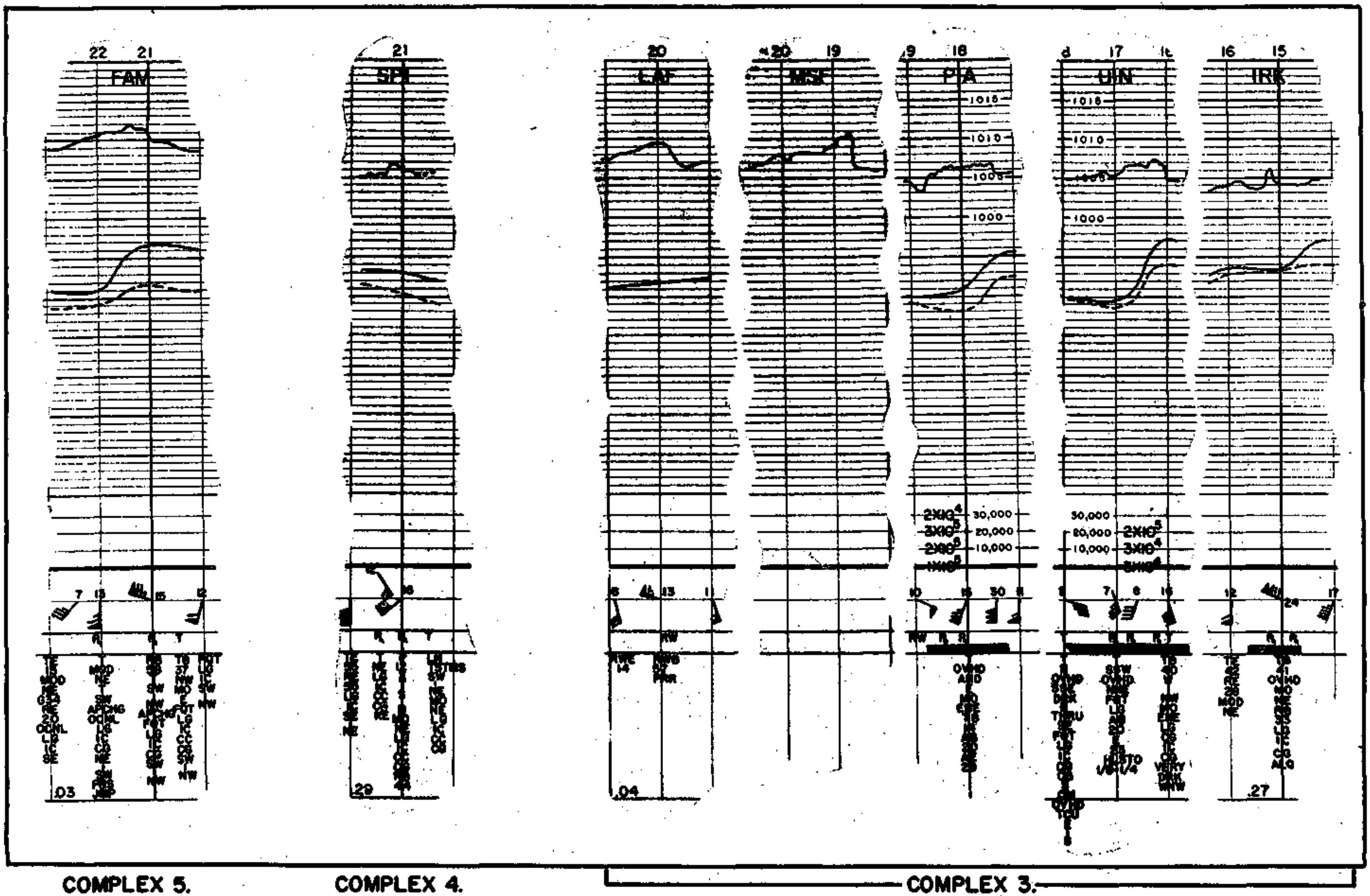


FIG. 20 THUNDERSTORM TIME SECTIONS

gust of 22 mph, while at Springfield, 16 mph was the maximum recorded. As the complex passed Rantoul, Illinois," (RAN), the microbarograph indicated a continual flattening of the thunderstorm high, although a moderate temperature drop of 4°F. was still being experienced across the complex at this time. Rantoul recorded a maximum wind gust of 14 mph with the passage. After moving eastward Into Indiana, complex 1 suddenly strengthened. This renewed activity was probably a consequence of surface heating and enhancement of conditional instability. The Port Wayne, Indiana, (FWA), pressure trace shows the regeneration of the thunderstorm high in addition to the first evidence of a wake depression. The first tornado activity since 0600 CST was observed with the complex in central Indiana just prior to 1500 CST. It is interesting to note that, as in the case of Kirksville, the high excess pressure was associated with a relatively low precipitation value. Only 0.19 inch of precipitation was recorded at Port Wayne. By 1800 CST, complex 1, now in the vicinity of Columbus, Ohio, was again dissipating with an excess pressure of approximately 2 mb. Total precipitation at Columbus, as at Quincy, was again relatively high. The average Z value measured from complex 1 was 8×10^4 mm^6m^{-3}.

Complex 2, also shown in Figure 19, had a short life history and directly affected only one First Order station. Parmington, Missouri, (FAM), experienced passage of complex 2 as it reached Its mature stage. Farmington's pressure trace indicated a sharp thunderstorm high with an excess pressure of almost 4 mb and a temperature drop of 9°F. A wind gust of 58 mph and hail were observed at Farmington at approximately 1420 CST. The measured Z value of this complex was 8×10^4 mm^6m^{-3}. The total precipitation reported was 0.10 inch.

Complex 3, shown in Figure 20, originated near Kirksville, Missouri, at 1500 CST, and had moved eastward to Lafayette, Indiana, (LAP), by 2000 CST. A narrow thunderstorm high with an excess pressure of 2 mb was evident on the Kirksville record shortly after 1500 CST. A sharp wind shift with maximum gusts to 29 mph was noted as the complex moved eastward from Kirksville across the Mississippi River. Complex 3 was still in the growth stage as it passed Quincy at approximately 1620 CST, with 1/8- to 1/4-inch hail observed at the station. The measured Z values near the surface, at 10,000 feet, and at 20,000 feet, were 3×10^4, 3.x 10 , and 2×10^5 mm^6m^{-3}, respectively. There were 3 tornado occurrences near Peoria, Illinois, (PIA), between 1700 and 1800 CST when complex 3 presumably reached maturity. The Peoria observation in Figure 20 shows an unusual pressure trace for a complex in the growth stage. The excess pressure was relatively low with numerous minor pressure fluctuations across the thunderstorm high. A wake depression, generally characteristic of a mature system, can be noted just before 1900 CST. A maximum wind gust of 35 mph was recorded at Peoria. Hail occurred at approximately 1720 CST. The associated Z values near the surface, 10,000 feet, 20,000 feet, and 30,000 feet, were 1×10^5, 2×10^5, 3×10^5, and 2×10^4 mm^6m^{-3}, respectively. A field microbarograph station (MSF) in the Illinois Severe Local Storm Reporting Network recorded the pressure configuration of complex 3 as it moved through central Illinois. This trace showed the characteristic mature pattern of a thunderstorm high and a small wake depression with a maximum excess pressure of approximately 3 mb. Unfortunately, no other observations were available from this location. Complex 3 was in the dissipation stage as it moved into Indiana. The observations at Lafayette, Indiana, showed an excess pressure of approximately 2 mb, a wind gust of 13 mph, and a total precipitation measurement of 0.04 inch.

Complex 4, which originated after the cold front had crossed the Mississippi River, could be labeled as pre-frontal precipitation since it remained in the proximity of the front during its development and dissipation. Figure 20 shows the characteristic weather of this complex as it passed Springfield, Illinois at approximately 2100 CST. The microbarograph indicated an excess pressure of 1 mb and the maximum wind gust recorded was 18 mph. Complex 5, which was an extension southward of complex 4, was equally unimpressive in its severity. The excess pressure of complex 5 was slightly higher than that shown in complex 4. A temperature drop of approximately 6°P. was registered at Farmington, Missouri. Observations at Parmington also showed a maximum wind gust of 39 mph and a precipitation total of 0.03 inch.

Each of the 4 thunderstorm complexes resolved from synoptic analysis of the 3-hourly data has shown identifiable characteristics at individual stations that suggest the stage of development of the complex as well as the magnitude of weather change in terms of pressure, temperature, and wind speed. The hail reported in complex 2 and complex 3 occurred during the growth stage of the systems. Three tornado occurrences associated with complex 3 were accompanied by a fluctuating pressure trace recorded at Peoria, Illinois, at 1800 CST. Radar reflectivity values acquired from the cells which were associated with the hail and tornado observations showed maximum Z values at 20,000 feet in excess of 5 x 10^5 mm^6m^{-3}.

16 May 1960 - Meso-Structure of the Radar Echoes

Passage of the first 4 complexes through the severe local storm reporting network in central Illinois provided a more detailed look at the variation of echo intensity within a complex. Also, the change of scale from macro to meso allowed a better comparison of severe weather occurrences with a particular cell within a complex. Figure 21 shows the network with the observations of hail, rain, lightning, and damaging winds. The grid of numbers on the base map in the center of the network represents the East Central Illinois Raingage Network which contained 25 hail indicators, 6 microbarographs, 2 recording anemometers, and 49 recording raingages. This special network provided only thunderstorm data for the complexes since no severe weather occurred in that particular area. As can be seen in Figure 21, the occurrences of hail were confined principally to the southeast, north, and extreme western sections of the severe local storm reporting network. Hail size ranged from 1/4- to 1-inch in diameter, with

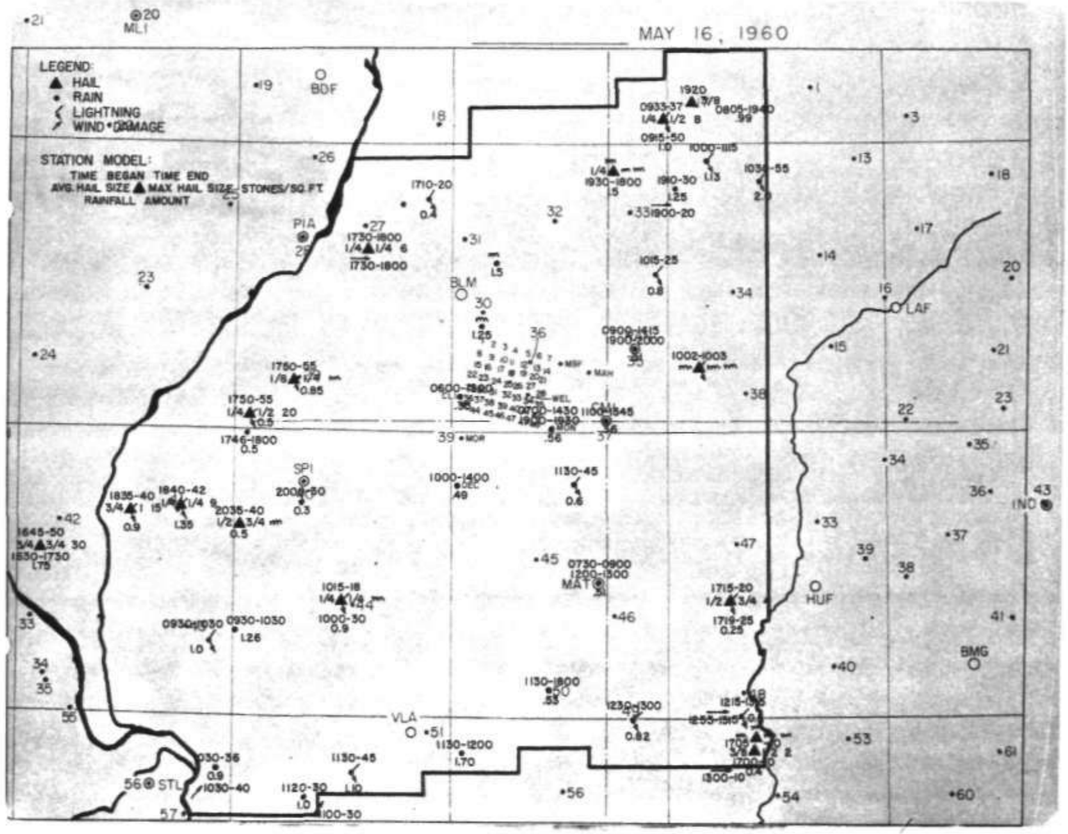


FIG. 21 PRECIPITATION AMD SEVERE WEATHER, 16 MAY 1960

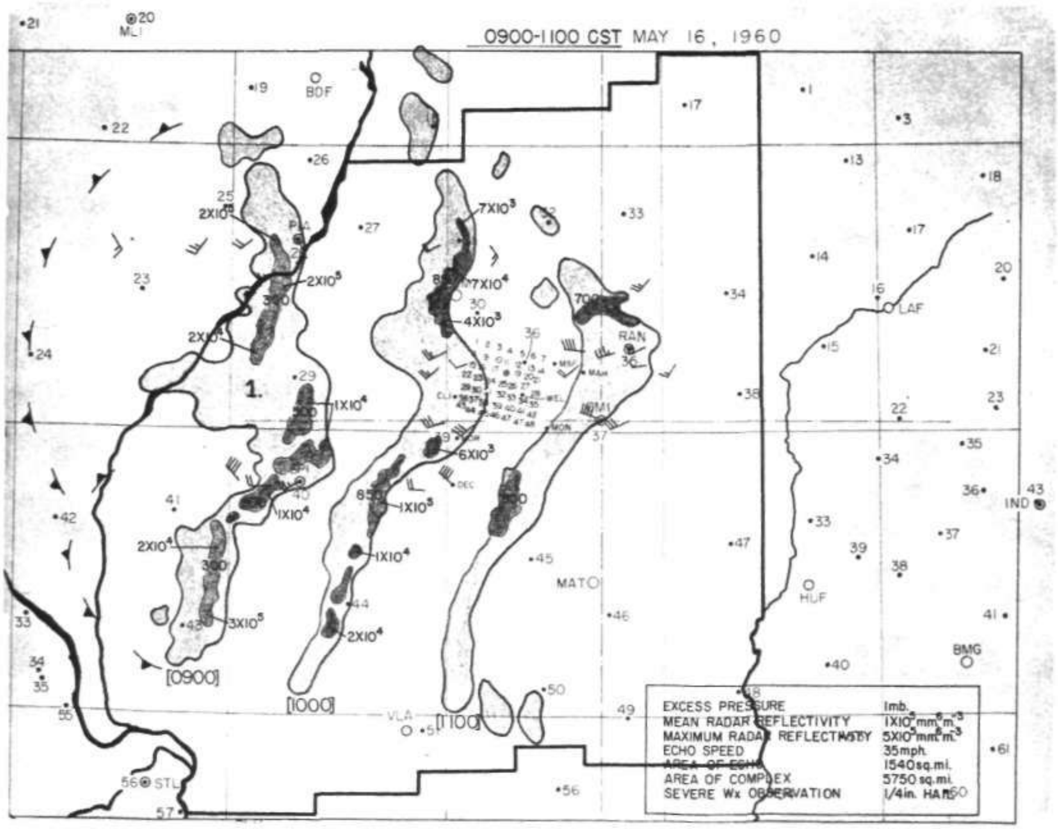


FIG. 22 RADAR ECHO COMPOSITES, 16 MAY 1960

the largest and heaviest concentration of hail occurring west of Springfield in an area of high hail incidence.[5]

A review of the 2-hour history of complex 1 from 0900 to 1100 CST, shown in Figure 22, confirms the dissipation of the complex as it moved into the severe local storm reporting network. Figure 22 shows the echo composite at 0900, 1000, and 1100 CST acquired at 0° antenna tilt and maximum receiver gain sensitivity. The cells within the echo composites were sampled at the height of the standard pressure levels as indicated. The maximum Z values at these levels are also indicated. The wind velocities are shown for various stations within the complexes. Using the individual temperature traces for the First Order stations, an approximation was made of the boundary of the cold air outflow from the complex at 0900 CST. This boundary is shown in Figure 22 by the cold front symbols. The characteristics of complex 1 between 0900 and 1100 CST are shown in the table in the lower right corner of Figure 22. The excess pressure value of 1 mb was the mean maximum excess pressure for the First Order stations which experienced passage of complex 1. The mean Z value for all cells beyond 20-mile range was 1×10^5 mm^6m^{-3}. The maximum radar reflectivity measured during the 2-hour period was 5×10^5 mm^6m^{-3}. This value was measured from the cell located at the extreme south end of the complex at 0900 CST. A point rainfall measurement of 1.26 inches was made from this echo area between 0930 and 1030 CST. Dissipation of this portion of the complex began shortly thereafter. The average echo speed during the 2-hour period was 35 mph. The echo area, measured at the start of dissipation at 0900 CST, was 1540 square miles. The area of the complex at 0900 CST, measured from the leading edge of the 0° tilt, step 1 echo, to the western boundary of the cold air outflow, was 5750 square miles. The severe weather associated with this complex between 0900 and 1100 CST was 1 to 2 inches of rainfall and 1/4-inch hail.

Complex 2, which developed in southern Missouri over the Ozark Plateau, is shown in the bottom of Figure 23. As stated in the earlier discussion of this complex, the most severe weather occurred south of St. Louis as the complex moved into Illinois. A brief intensification of the system occurred as it moved across the southeastern corner of the severe local storm reporting network between 1600 and 1800 CST as shown in Figure 23. One cell in this complex at 1700 CST provided the maximum Z value measured for all complexes of 1 x 10^6 mm^6m^{-3}. The corresponding surface observation from the cell at approximately 1715 CST confirmed the presence of 3/4-inch hail. Analysis of the Belleville, Illinois, (BLV), data showed that complex 2 had a maximum excess pressure of 3 mb. The mean Z value was 2 x 10^5 mm^6m^{-3}. The echo speed from 1600 to 1800 CST averaged 45 mph.

Complex 3, shown in the upper portion of Figure 23, was the second complex to be generated by the cold fronti This complex reached maturity in the western part of the network and was associated with tornadic winds and 1/4-inch hail. The mean maximum excess pressure between 1700 and 1900 CST was 3 mb. The mean Z value was 1 x 10^5 mm^6m^{-3} while the maximum Z value was 6 x 10^5 mm^6m^{-3}.

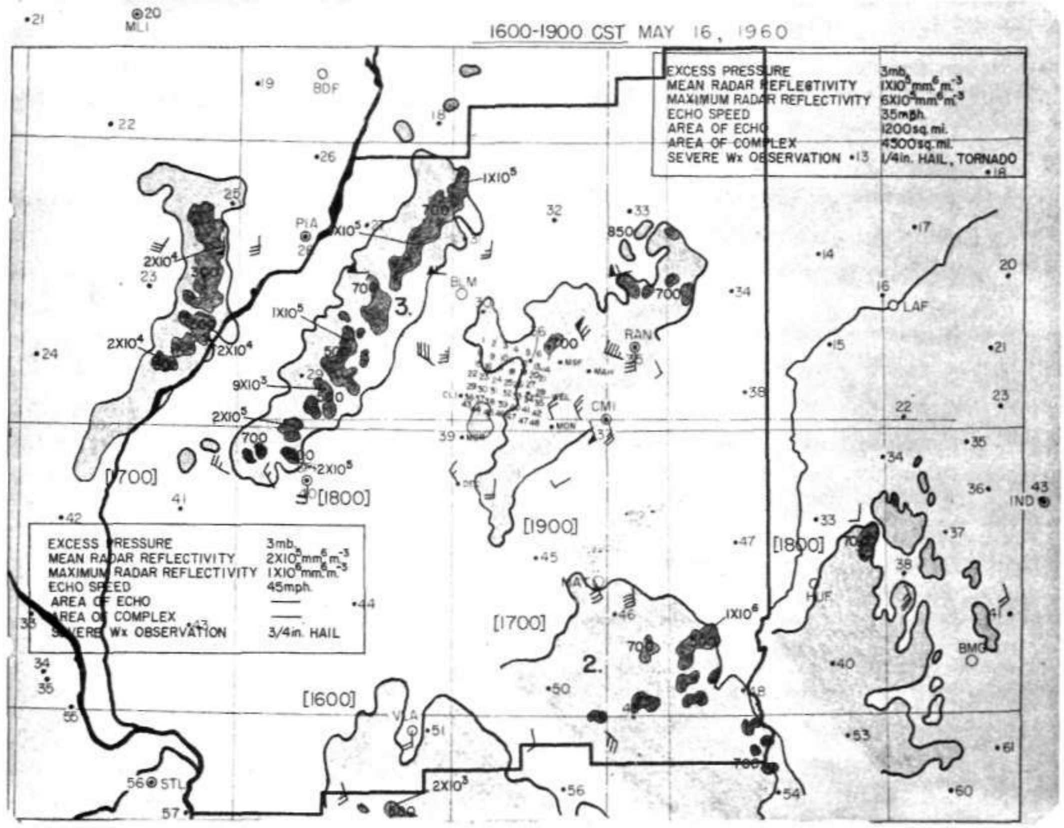


FIG. 23 RADAR ECHO COMPOSITES, 16 MAY 1960

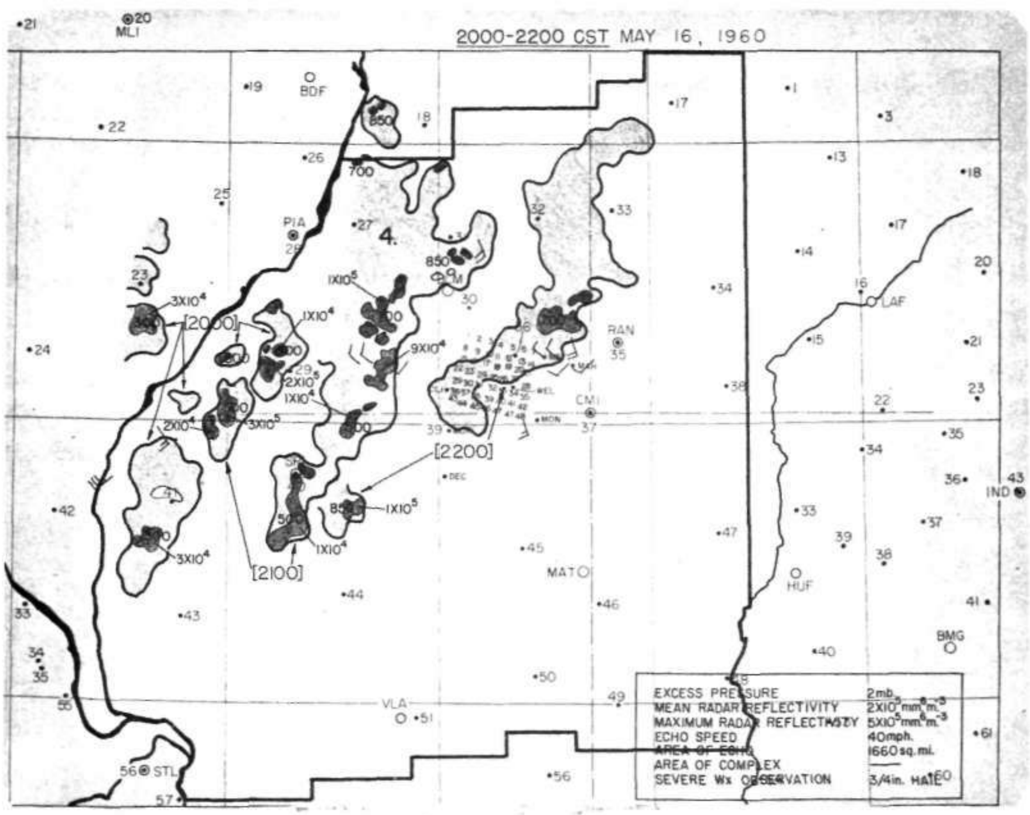


FIG. 24 RADAR ECHO COMPOSITES, 16 MAY 1960

This maximum value occurred at approximately 1720 CST near Peoria, Illinois. The cell responsible for the high Z value was associated with reports of 3 tornado occurrences a few miles south of Peoria. A sharp wind shift line preceded complex 3 as it moved east to east-southeast across central Illinois. The average echo speed was 35 mph. The area of the echo was approximately 1200 square miles and the area of the entire complex was approximately 4500 square miles. All of the moderate to high intensity cells which were apparent at 1800 CST dissipated prior to entering the East Central Illinois Raingage Network. However, by 1900 CST new activity was developing in extreme western Illinois in the proximity of the approaching cold front. An isolated cell developed west-southwest of Springfield at 1815 CST and was associated with 1/4- to 1-inch hail occurrences at 1835 to 1842 CST, as shown in Figure 21. Although complex 3 was causing an unknown amount of attenuation at this time, a Z value of 2×10^4 mm^6m^{-3} was measured at 1839 CST from the Isolated hail-producing cell.

The generation of complex 4 began at approximately 1900 CST. The complex reached maturity between 2000 and 2100 CST and produced 3/4-inch hail southwest of Springfield at 2035 CST. The relative positions of the cells in this complex are shown in Figure 24. The known hail-producing cell is shown at the south end of the echo configuration at 2000 CST. The Z value at this time at the 300-mb level was 3×10^4 mm^6m^{-3}. This cell Intensified and had a measured Z value of 5×10^5 mm^6m^{-3} when it reached the vicinity of the

3/4-inch hail observation (Pig. 21). Two other Z values at 2000 CST exceeded 1 x 10^5 mm^6m^{-3} at the 500-mb level, although no confirmation of hail occurrence was found for this area. The mean maximum excess pressure of this complex was 2 mb and the mean Z value was 2 x 10^5 mm^6m^{-3}. The average echo speed from 2000 to 2200 CST was 40 mph. The area of the echo was 1660 square miles.

In summary,the duration of the 5 thunderstorm complexes ranged from 3 to 15 hours with the mean duration being approximately 6 hours. The average Z values of the thunderstorms within the complexes ranged from 3 to 9 x 10^4 mm^6m^{-3}. The radar composites, which were constructed for 4 standard pressure levels, disclosed that 1 or 2 major thunderstorms within a complex were responsible for the severe weather occurrence.

FREQUENCY DISTRIBUTION OF THUNDERSTORM RADAR REFLECTIVITY VALUES

Single case analyses such as the 16 May storm are quite informative for establishing analysis techniques and for interpreting synoptic and radar data. However, in order to test the reliability of radar reflectivity values as indicators of thunderstorm severity, it was much more efficient and meaningful to make a statistical study of the radar and surface observations collected during the entire 3-year program.

Approximately 4500 surface and concurrent radar observations were acquired during 1959 and 1960 from thunderstorms known to have been associated with severe weather. The analysis of these observations was accomplished by calculating the Z value for the strongest portion of the storm, determining the altitude of this value, and storing these parameters -- as well as the surface observations of hail, wind, and rain -- on IBM cards.

The vast majority of the surface observations were obtained from the volunteer observer network. In general, the reports received from these observers were excellent, with the reliability of individual measurements being quite compatible with the time and space resolution of the radar measurements. The time resolution of the radar was 10 minutes, which was the time required to complete a tilt-gain reduction cycle, and the space resolution of the radar measurements was approximately 5 miles on 100-mile range. Considering both the radar resolution and the observer reliability, it was concluded that the time of the severe weather phenomena was known within plus or minus 5 minutes, and that the corresponding radar measurement represented a period of 10 minutes. Therefore, the radar and surface data were categorized into 10-mlnute observations. The radar data were separated Into 3 groups consisting of the 10 minutes prior to scan, the 10 minutes during scan, and the 10 minute scan after the hail or wind occurrence. Comparisons were then made of the Z values and the frequency with which they occurred at various altitudes.

The resolution of the intensity measurements was determined primarily by the separation of the gain steps in the receiver sensitivity reductions. The stability of the radar and the resolution of the film used in photographing the PPI scope permitted a resolution of approximately 4 db. Therefore, the separation of gain steps was maintained at approximately 4 to 6 db. On an operational basis, it is probable that a 10-db echo intensity resolution would be more realistic; thus, 10 db was accepted as the intensity resolution of the Illinois radar reflectivity measurements for this study.

An initial sort of the radar reflectivity data was made to separate the observations of hail, wind, and rain. The calculated Z values associated with each of the phenomena were then tabulated to determine the frequency distribution of Z from 1 x 10 to 1 x 10 ram^{6}m^{-3} for 9 height intervals from 0 to 45,000 feet. The Z values also were sorted to determine the cases where the maximum value was at least a factor of 10 higher than that measured at other height intervals. These 2 distributions of radar reflectivity values for various height intervals associated with hail observations during 1959 and 1960 are shown in Tables 3, 4, and 5. The 3 tables represent the scan 10 minutes prior to hail occurrence, the scan during the hail occurrence, and the scan 10-minutes after hail occurrence. The first characteristic noted from Table 3 is that over 90 percent of the observations are in the Z interval from 1×10^3 to 9×10^5 mm^6m^{-3}. Another equally apparent feature is the predominance of the 10^3 and 10^4 mm^6m^{-3} observations in the height interval from 0 to 4000 feet. The maximum frequency of Z values between 10^5 and 10^6 mm^6m^{-3} occurred aloft in the height Interval of 15,000 to 19,000 feet for the before hail and during hail scans. However, the highest frequency for the after hail scan for Z values of 10^5 to 10^6 mm^6m^{-3} remained at 0 to 4000 feet. Secondary maximums are suggested in the after hail scan at height intervals of 10,000 to 14,000 and 20,000 to 24,000 feet.

A study was made of the cases In the during-hail scan to determine if there was a relationship between the altitude of the maximum Z and the reported hailstone size. Since the reflectivity interval of 1 to. 9×10^5 mm^6m^{-3} had the highest frequency of Z maximums, the distribution of various hailstone sizes was sorted for this intensity interval. This frequency distribution, shown In Table 6, indicated that the greatest frequency of hail larger than 3/4-inch is associated with Z maximums above 20,000 feet. The greatest frequency of hail less than 3/4-inch in diameter occurs with Z maximums from 15,000 to 19,000 feet. The 3 observations of hail greater than 1-inch in diameter were associated with Z maximums from 25,000 to 35,000 feet.

TABLE 3

DISTRIBUTION OF Z VALUES FOR THUNDERSTORMS
WITH HAIL 1959-1960
(Before Scan)

Height Ft x 10^3	$Z(mm^6 m^{-3})$ 10^1	10^2	10^3	10^4	10^5	10^6
0-4	1	4	14	90	53	2
5-9			5	39	55	2
10-14		1	2	45	46	4
15-19			4	33	59	2
20-24			6	36	43	1
25-29		1	3	34	21	
30-34		2	6	20	6	
35-39			2	13	3	
40-45			3	2	2	

Distribution of Z Maximums

Height Ft x 10^3	10^1	10^2	10^3	10^4	10^5	10^6
0-4					4	
5-9				4	3	
10-14				3	6	
15-19				4	16	2
20-24				6	14	
25-29				4	5	
30-34				3	3	
35-39				3	2	
40-45			1	1		
Total Max. Z			1	28	53	2

58% of the cases had Z maximums

TABLE 4

DISTRIBUTION OP Z VALUES FOR THUNDERSTORMS
WITH HAIL 1959-196.0
(During Scan)

$Z(mm^6m^{-3})$

Height Ft x 10^3	10^1	10^2	10^3	10^4	10^5	10^6
0-4	4	3	20	80	55	7
5-9			8	40	43	7
10-14	1		3	37	53	6
15-19		2	1	34	57	1
20-24		1	3	39	47	1
25-29			7	27	28	
30-34		1	6	23	7	
35-39			3	20	4	
40-45			5	4	4	

Distribution of Z Maximums

Height Ft x 10^3	10^1	10^2	10^3	10^4	10^5	10^6
0-4		1	1	2	5	
5-9				1	3	1
10-14					11	2
15-19				8	14	
20-24				7	13	
25-29				5	4	
30-34				4	4	
35-39				2	1	
40-45				3		
Total Max. Z		1	1	32	55	3

61% of the cases had Z maximums

TABLE 5

DISTRIBUTION OP Z VALUES FOR THUNDERSTORMS
WITH HAIL 1959-1960
(After Scan)

$Z(mm^6m^{-3})$

Height, Ft x 10^3	10^1	10^2	10^3	10^4	10^5	10^6
0-4	4	1	11	71	61	5
5-9	1		3	31	47	1
10-14		1	4	30	54	9
15-19		1	4	33	36	6
20-24			2	26	50	1
25-29			7	26	25	2
30-34		1	6	19	10	
35-39			1	24	3	
40-45			2	3	4	

Distribution of Z Maximums

Height, Ft x 10^3	10^1	10^2	10^3	10^4	10^5	10^6
0-4			1	3	6	
5-9				2	1	
10-14		1			14	1
15-19				5	10	2
20-24				4	15	
25-29				6	6	2
30-34					2	
35-39					1	
40-45				2		
Total Max. Z		1	1	22	55	5

58% of the cases had Z maximums

Until 1960, the observers were instructed to report only severe weather events; thus, very little non-hail, or rain only, data were collected. However, during 1960, the volunteer observers were requested to report on all thunderstorms. A sufficient sample of rain only data was collected for analysis. The distribution of Z's for thunderstorms with rain only is listed in Table 7. There were no observations in excess of 9×10^5 mm^6m^{-3}. The Z distribution for rain showed a maximum for all three Z categories in the initial interval from 0 to 4000 feet. Also all three Z categories showed a secondary frequency maximum in the height interval from 10,000 to 14,000 feet. It is suspected that this secondary maximum aloft was caused by small hail melting as it passed through the freezing level within the cloud. When the hail is completely melted, the resulting large drops are dynamically unstable and break up, thus causing a decrease in reflectivity.

In order to show the differences between the rain distribution and the frequency distribution of hail, hail-rain ratios (H/R) were calculated for each of the corresponding layers of Z frequencies. The rain data were first normalized to make the total number of observations in each height interval for all Z intervals the same as that measured with hail. Normalized rain frequency, hail frequency, and H/R distributions for the three Z intervals from 1×10^3 to 1×10^6 mm^6m^{-3} are shown in Table 8. For Z values between 1 and 9×10^3 mm^6m^{-3}, the frequency of rain observations greatly exceeds those of hail at all levels. The low H/R values support the conclusion that Z values of less than 9×10^3 mm^6m^{-3} are

TABLE 6

DISTRIBUTION OP HAIL SIZES AND HEIGHT
OP Z MAXIMUMS FOR Z INTERVAL 1 to 9 x 10^5 mm^6m^{-3}
(1959-1960)

Height Ft x 10^3	Maximum Hail Diameter, inches 1/4	1/2	3/4	1	≥1
0-4	3	1	1		
5-9	2	1			
10-14	3	6	2		
15-19	8	4	2		
20-24	5	2	5	1	
25-29	1		2		1
30-34			2		2
35-39			1		

TABLE 7

DISTRIBUTION OP Z VALUES FOR THUNDERSTORMS
WITH RAIN ONLY
(1960)

Height Ft x 10^3	10^2	10^3	10^4	10^5
0-4	3	15	20	16
5-9		6	7	8
10-14		9	15	12
15-19		5	6	6
20-24		6	6	6
25-29		2	5	
30-34			3	2
35-39			1	

TABLE 8

COMPARISON OP NORMALIZED RAIN FREQUENCY AND
HAIL FREQUENCY DISTRIBUTIONS

	$Z(mm^6 m^{-3})$								
	10^3			10^4			10^5		
Height, Ft x 10^3	Rain R	Hail H	Ratio H/R	Rain R	Hail H	Ratio H/R	Rain R	Hail H	Ratio H/R
Before Scan									
0-4	45	14	0.3	60	90	1.5	48	53	1.1
5-9	28	5	0.2	33	39	1.2	38	55	1.5
10-14	23	2	0.1	38	45	1.2	30	46	1.5
15-19	28	4	0.1	34	33	1.0	34	59	1.7
20-24	28	6	0.2	28	36	1.3	28	43	1.5
25-29	10	3	0.3	26	34	1.3	--	--	---
During Scan									
0-4	45	20	0.4	60	80	1.3	48	55	1.2
5-9	26	8	0.3	30	40	1.3	34	43	1.3
10-14	23	3	0.1	38	37	1.0	30	53	1.8
15-19	27	1	0.0	32	34	1.1	32	57	1.8
20-24	29	3	0.1	29	39	1.3	29	47	1.6
25-29	10	7	0.7	24	27	1.1	--	--	---
After Scan									
0-4	42	11	0.3	56	71	1.3	45	61	1.4
5-9	23	3	0.1	27	31	1.2	30	47	1.6
10-14	22	4	0.2	36	30	0.8	29	54	1.9
15-19	21	4	0.2	25	33	1.3	25	36	1.4
20-24	26	2	0.1	26	26	1.0	26	50	1.9
25-29	9	7	0.8	24	26	1.1	--	--	---

usually associated with rain only. The distribution of Z values between 1 and 9 x 10^4 mm^6m^{-3} shows little significant difference except in the initial height interval from 0 to 4000 feet. The predominance of hail observations with this Z value measured near the surface can be attributed to the fact that observations were acquired in every case for the interval 0 to 4000 feet, while, because of the pseudo-CAPPI system, the 5 observations above the initial interval were distributed over 7 height intervals from 5000 to 39,000 feet. Another probable cause of this maximum frequency in the first interval was the inclusion of ground targets. Differentiation of coherent and noncoherent targets on 100-mile range was extremely difficult when anomalous propagation occurred. Therefore, conclusions concerning the variations between frequencies of Z values between rain and hail should be restricted to height intervals above 4000 feet. The relatively low H/R values for Z values between 1 and 9 x 10^4 mm^6m^{-3} from 5000 to 29,000 feet indicated the similarity of the rain and hail distributions. A significant difference between the rain and hail frequencies can be noted in the third Z category, 1 to 9 x 10^5 mm^6m^{-3}. The H/R value in this category suggested that the interval of 15,000 to 19,000 feet was the most significant one for the before and during scans; however, the after scan showed maximum differences at height intervals of 10,000 to 14,000 and 20,000 to 24,000 feet.

A comparison of data similar to those just described was made for rain and wind observations obtained during 1960, The wind observations pertained to damage to trees, property, or crops as

TABLE 9

COMPARISON OP NORMALIZED RAIN FREQUENCY AND WIND FREQUENCY DISTRIBUTIONS

Before Scan

$Z(mm^6m^{-3})$

	10^3			10^4			10^5		
Height, Ft x 10^3	Rain R	Wind W	Ratio W/R	Rain R	Wind W	Ratio W/R	Rain R	Wind W	Ratio W/R
0-4	20	18	0.9	26	34	1.3	21	17	0.8
5-9	12	8	0.7	14	23	1.6	16	12	0.8
10-14	8	10	1.3	14	9	0.6	11	16	1.5
15-19	11	2	0.2	13	18	1.4	13	18	1.4
20-24	11	4	0.4	11	16	1.5	11	13	1.2
25-29	2	2	1.0	5	5	1.0	--	--	---
30-34	--	--	---	5	13	2.6	--	--	---

During Scan

0-4	21	18	0.9	28	40	1.4	22	17	0.8
5-9	13	8	0.6	15	25	1.7	17	12	0.7
10-14	10	9	0.9	17	14	0.8	13	18	1.4
15-19	11	3	0.3	13	21	1.6	13	13	1.0
20-24	12	5	0.4	12	16	1.3	12	15	1.3
25-29	3	3	1.0	8	8	1.0	--	--	---
30-34	--	--	---	5	11	2.2	--	--	---

reported by the volunteer observers. No observations with both wind and hail were included. Table 9 shows the comparison of normalized rain frequencies, wind frequencies, and ratios (W/R). An inspection of the frequencies for the 6-height intervals and the computed W/R values shows few, if any, anomalies. The only possible separation of wind and rain is In the Z interval of from 1 to 9 x 10^4 mm^6m^{-3}, where a surprisingly high frequency exists in the height interval from 30,000 to 34,000 feet. If such a high secondary maximum were representative of a wind distribution, one might speculate that this measurement was due to hail which was occurring at a higher altitude than usual as the result of exceptionally strong updrafts. Compensating downdrafts or outflow from such thunderstorms would naturally increase the likelihood of wind damage at the surface.

Comparison of Z Frequencies in New England, Texas, and Illinois

Probably the best means of comparing New England, Texas, and Illinois data is with the median Z values for various height intervals. A review of Donaldson[1] and Inman's[2] data for thunderstorms with hail showed a maximum median Z value occurred from 15,000 to 20,000 feet. This maximum Z value was between 10^5 and 10^6 mm^6m^{-3} which, referring again to Tables 3 and 4, Is also the maximum median Z value for this height interval In hail producing thunderstorms in Illinois. The major differences between New England, Texas, and Illinois thunderstorm median Z profiles appeared when comparisons were made of the rain and wind phenomena cases. The median Z rain profile acquired by Donaldson in New England showed a range of Z from 1 to 5 x 10^4 mm^6m^{-3} up to 20,000 feet, while Inman in Texas measured corresponding median Z values which were higher by a factor of 5. A review of Table 7 indicated that the median Z value for thunderstorms with rain only in Illinois equalled or exceeded the Texas values; over 30 percent of the Illinois measurements equalled or exceeded 1 x 10^5 mm^6m^{-3}. Obviously, the higher Z values for rain in Illinois make the problem of hail differentiation more difficult. Another major difference between New England, Texas, and Illinois data was that of the median Z profiles obtained from thunderstorms which produced severe wind. Eleven tornado eases in New England showed a maximum median Z value of 8 x 10^6 mm^6m^{-3} with median Z values exceeding 1 x 10^5 mm^6m^{-3} up to 30,000 feet. Texas data for severe wind storms also showed a relatively high median Z value with all values up to 25,000 feet exceeding those measured for hail or rain. In contrast, the Illinois data shown in Table 9 indicate that Illinois wind storms have a maximum medium Z value between 1 and 9 x 10^4 mm^6m^{-3} for all height intervals, except 10,000 to 14,000 feet. This value is not significantly different from that measured in rainstorms at the same height interval. However, it should be stated that no major tornadoes were included in Illinois data.

Summary of Thunderstorm Intensity Measurements

Radar intensity values acquired from hailstorms in Illinois during 1959 and 1960 indicate that the highest Z value observed most frequently was between 1 and 9 x 10^5 mm^6m^{-3}. This range of Z was observed most frequently from 15,000 to 19,000 feet.

Sixty-one percent of the hailstorms sampled showed reflectivity maximums at one 5000-foot height interval which was at least a factor of 10 higher than the reflectivity at any other height interval. The height Interval of 15,000 to 19,000 feet had the greatest frequency of Z maxima. These Z maxima were between 1 and 9 x 10^5 mm^6m^{-3}. Comparison of the frequency of Z values between 1 and 9 x 10^5 mm^6m^{-3} for hail and rainstorms indicates a significant difference in the frequency distribution of Z with height. The height interval below 25,000 feet which showed the greatest difference between rain and hail was the interval from 15,000 to 19,000 feet. The frequency of various hailstone sizes for Z values between 1 and 9 x 10^5 mm^6m^{-3} for 8 height intervals showed a corresponding increase in hailstone size with the height of the maximum Z value. The Z values acquired from severe wind storms showed little difference from those acquired from thunderstorms with rain only.

UTILIZATION OP RADAR DATA

The full utilization of the capability of 3-cm radar to provide detection and identification of hail-producing thunderstorms requires a highly flexible data collection and analysis program. The initial development and movement of thunderstorm complexes can be adequately described by hourly reports of the general shape, velocity, age, and number of thunderstorms. This provides 3 observations for a radar summary which can be integrated with the 3-hourly synoptic data. Radar reflectivity values for several of the discernible thunderstorms are valuable as an indicator of the age, or growth stage, of a complex. However, there are two serious limitations to radar reflectivity measurements on the complex scale. First, in order to track and maintain continuity on high intensity echoes, observations are required at least every 10 to 20 minutes, or within the lifetimes of the intense cells. Second, the limitations of azimuth and height resolution of the radar suggest that detailed intensity measurements are possible only at ranges less than 150 miles, or in less than 40 percent of the total area scanned by the radar. Therefore, the use of 60 percent of the echo information from a single radar is restricted to the delineation of complexes.

However, within the 31,400-square-mile area which is within 100-mile range of the radar, hail-producing thunderstorms can be identified routinely by monitoring the radar reflectivity values at 15,000 to 19,000 feet. It should be noted, however, that monitoring on the thunderstorm scale requires that observations be made at approximately 10-minute intervals. The duration of hail production from a severe thunderstorm ranges from 30 minutes to 2 hours, and the high radar reflectivity values are first apparent approximately 10 minutes before the hail reaches the ground; therefore, the identification of the severe thunderstorm is applicable as a terminal forecast from first occurrence time plus 10 minutes to first occurrence time plus 2 hours. If a 10-minute radar scan time is used, the lead time is eliminated and identification and tracking are basically a terminal warning and not a forecast. The implication of this use of the radar is that time does not allow observations and forecasts to be shuttled between a forecast central and a regional station. In fact, the identification of the storms with durations approaching 30 minutes may be of questionable value because of the necessary delay time in forwarding the information to the user.

Another radar data problem, in addition to time, is the sorting and memorizing of all moderate to high radar reflectivity values which are detected. As stated earlier, most of the radar information from a thunderstorm complex can be integrated with hourly synoptic data in pattern analyses. When it becomes necessary to accurately monitor the intensities of all individual thunderstorms, possibly at more than one altitude, and at the rate of 6 observations per hour, it may be more advantageous to completely quantitize the PPI display. Several investigators[11,12] have suggested referencing the radar reflectivity values to a grid composed of 5 x 5 nautical mile squares.

A test analysis of this type of data was made for a complete Illinois storm in 1960.[3] Radar information for that particular study was extracted by tabulating the frequency of echo occurrence within each 6 x 6 statute mile square. The limitations of this technique were that the data resolution was too coarse and the analysis could not be adjusted to the size of a particular thunderstorm. Recently, a second grid study was made with a more flexible program which permitted the grid square size to be varied. The polar coordinates of the centers of all echoes recorded on 8 gain settings through 6 antenna tilt angles were used in this analysis of the storm of 22 June 1960. An IBM 650 computer was used to transform the echo locations to rectangular coordinates and to tabulate the 10-minute and total radar reflectivity distributions. The storm damage pattern and observer reports resulting from the 22 June 1960 storm are shown in Figure 25. Also shown, are the 6 x 6, 4 x 4, and 2 x 2 mile squares which were used in the analysis. Approximately 14,000 echo intensity measurements were made during the 12-hour storm period. The thunderstorms which produced the most damaging hail were concentrated in the 2 storm tracks located in the central and southern parts of the network. The largest hail occurred in an area north of the radar, where, suprisingly enough, no crop damage was reported.

The frequency distribution based on a grid of 6 x 6 mile squares for 3 levels of radar reflectivity were plotted against range as shown in Figure 26. Also shown in the same figure is the range distribution of the hail damage. The best agreement

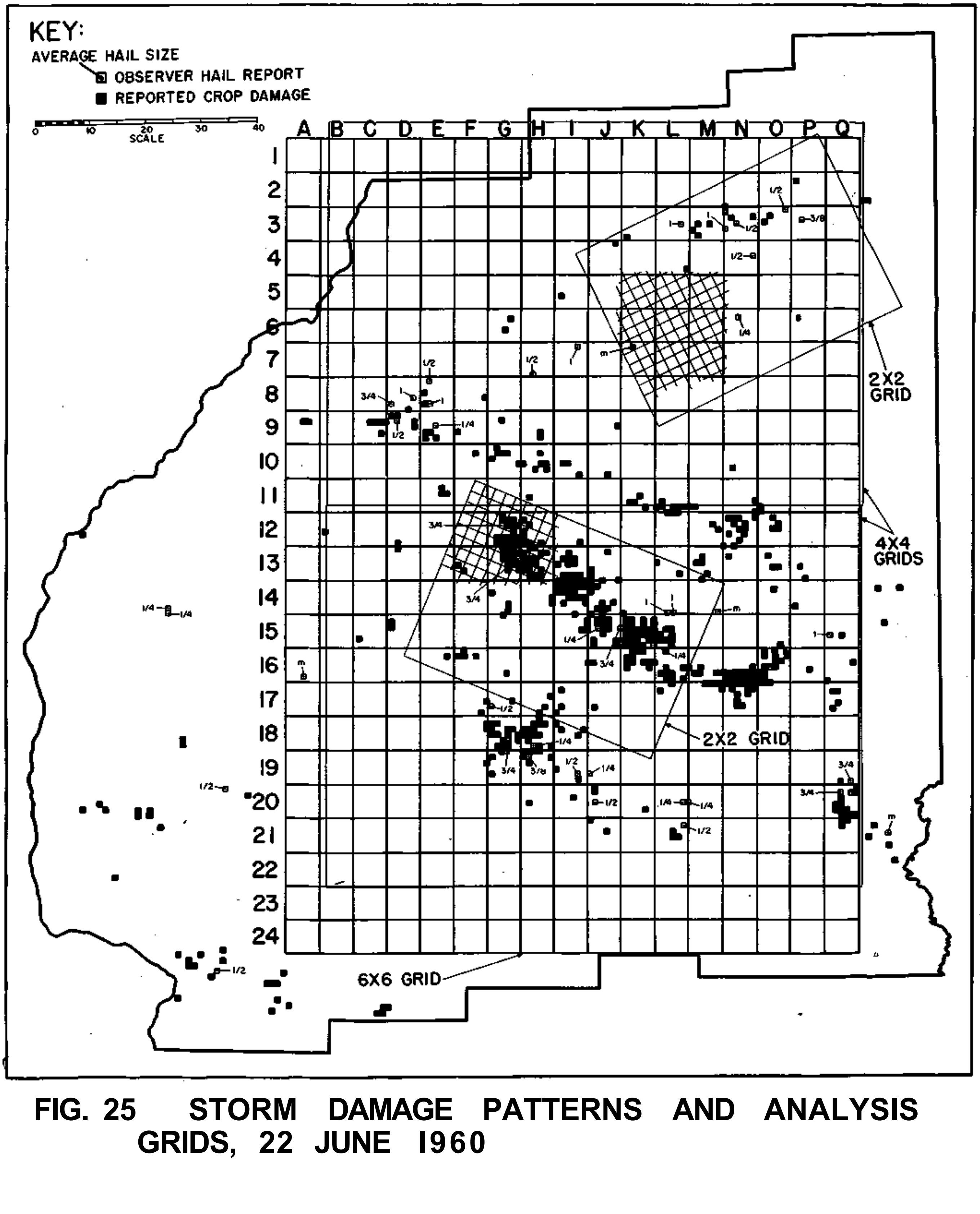


FIG. 25 STORM DAMAGE PATTERNS AND ANALYSIS GRIDS, 22 JUNE 1960

between radar reflectivity and damage is in the interval 1 to 9 x 10^5 mm^6m^{-3}.

An analysis was made of radar reflectivity distributions based upon grids of 6 x 6, 4 x 4, and *2x2* mile squares for *2* specific thunderstorms which occurred in the 6 x 6 mile squares centered at G12, and L6 in Figure *25*. Nine 6 x 6 mile (324 square miles) squares which enclosed 2 of the severe thunderstorms were analyzed using resolutions of 3 different square sizes. In the case of the 6 x 6 mile squares, the high intensity echoes are effectively point targets since they never cover the entire 36-square-mile area. The echoes become area and not point targets, however, when the square size is reduced to the point that it is comparable to the echo area. The effect of grid square size on percent of area assumed covered by echo at various altitudes is shown in Figure 27. The values for the percent of area assumed covered were obtained from the ratio of the total area of squares with Z values equal to or greater than 3 x 10^4 mm^6m^{-3} to the total 324-square-mile area included in the nine 6 x 6 squares. Nine out of 10 of the radar reflectivity observations based on 6 x 6 mile square resolution suggest areal coverages of 30 to 60 percent. Reducing the square size to 4 x 4 miles increases the resolution and reduces the percent of area assumed to be covered to approximately 10 to 30 percent. A further increase in resolution to 2 x 2 mile squares reduces the percent of area assumed covered to less than 15 percent. Therefore, in this particular case, the application of radar reflectivity values equal to or greater than

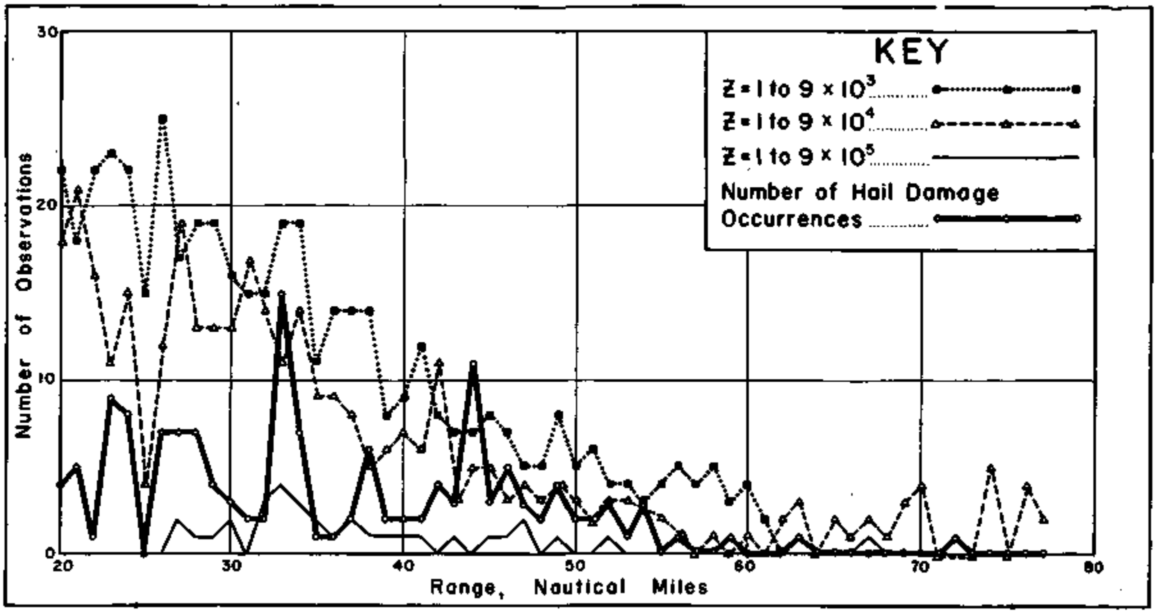


FIG. 26 FREQUENCY DISTRIBUTION OF RADAR REFLECTIVITY BY RANGE, 22 JUNE 1960

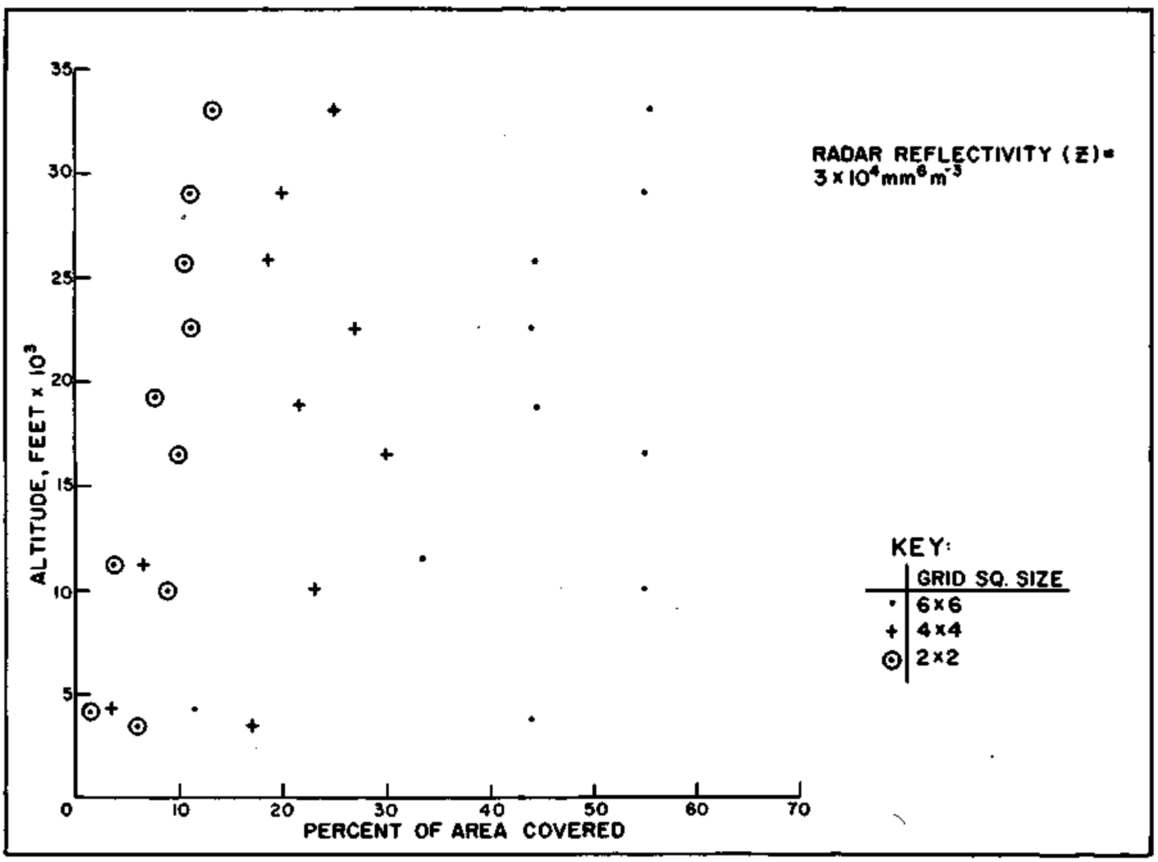


FIG. 27 PERCENT OF AREA ASSUMED COVERED AS A FUNCTION OF GRID SQUARE SIZE, 22 JUNE 1960

3×10^4 mm^6m^{-3} to the entire 6 x 6 mile squares caused an areal forecast which was an overestimate by at least a factor of 5.

Another problem in using a grid of 6 x 6 mile squares Is in the error of convective echo velocity measurements. Two 10-mlnute observations of an echo which is one mile in diameter could have a speed ambiguity of 2 to 72 miles hr . Using 2 x 2 mile squares the speed ambiguity reduces to 2 to 24 miles hr-1.

However, it should not be assumed that the choice of the optimum size is always on the order of 2 x 2 mile squares. It certainly is not practical to process such an enormous amount of data for large areas. Also, stratified activity might even require a much coarser grid system than 6 x 6 mile squares. The most Important point to consider Is that a successful grid system for describing radar reflectivities in convective shower conditions must be highly flexible if it is to use the full capability of the radar in terminal forecasting.

A side light which arose from the study of digitizing intensity measurements was a rather successful attempt at extrapolating a single radiosonde observation for application over a large area. The climatological study of positive area values and advective stability for the major hailstorms has indicated that local effect may be of great importance In causing a thunderstorm to reach severe proportions. In order to test this hypothesis, the maximum dry bulb temperatures and associated dew point temperatures recorded at the First Order stations were substituted for the surface data In the Peoria or Columbia radiosonde observations.

The soundings were taken approximately 2 hours prior to the first reported hail occurrence and the maximum temperature values occurred approximately 5 hours prior to hail occurrence. The net positive area and total precipitable water were calculated and analyzed for comparison with the hail reports. The results are shown in Figure 28. The positive area pattern is remarkably similar to the hail occurrence area shown In Figure 25, with the highest values located near Springfield, Illinois. The area of maximum precipitable water occurred north of Springfield and a few miles upwind of the start of the major hail damage track. This net positive area parameter can also be derived from substation reports which would further increase the resolution. However, since these data are not available on an operational basis, no evaluation was attempted on this scale.

8 September 1960 - A Three-Dimensional Analysis of Thunderstorm Cell Structure

Thus far, this report has discussed characteristics of complexes and thunderstorms and the associated air mass conditions. The systematic data collection procedures followed during the 3-year period provided practically no observations suitable for individual thunderstorm cell analysis. The time resolution of the radar data was maintained at 10 minutes for almost all of the severe storm occurrences. The observer reports were assumed to have approximately the same time resolution as the radar program, that is, an accuracy of plus or minus 5 minutes. Since thunder-

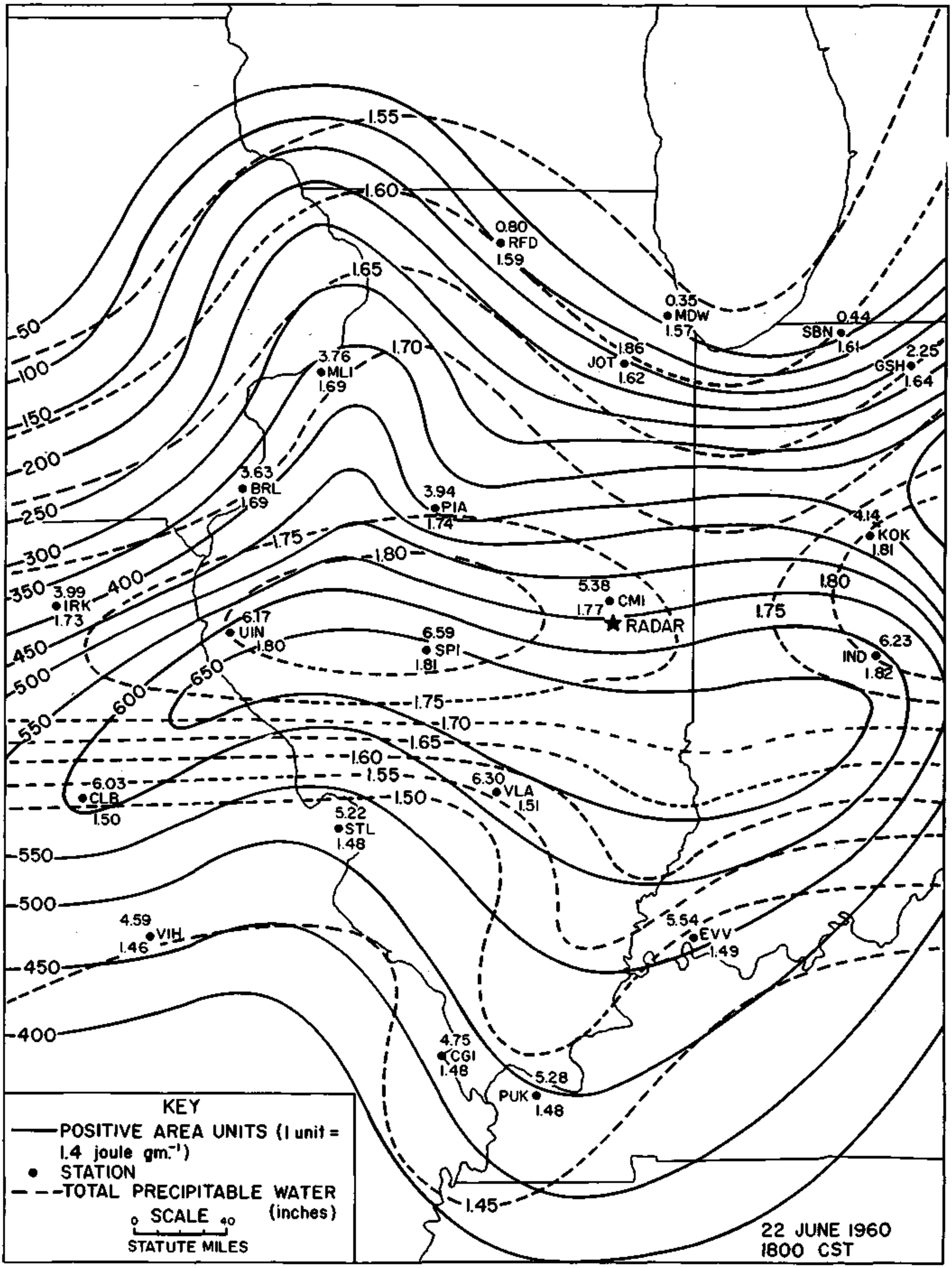


FIG. 28 DISTRIBUTION OF NET POSITIVE AREA AND TOTAL PRECIPITABLE WATER, 22 JUNE 1960

storm cell life Is probably on the order of 10 minutes, the analysis of cells requires timely and detailed radar observations followed by a comprehensive survey of surface effects. Also, a great deal of patience is necessary to obtain adequate data from severe thunderstorm cells since the probability of occurrence within a small area (at the optimum range of the radar) is quite low.

The best documented thunderstorm suitable for the analysis of cell structure in this investigation occurred on 8 September 1960, 15 to 29 miles northwest of the research radar site. On this date, a cold front accompanied by a wide zone of conditional instability moved across Iowa, Illinois, and Indiana between noon and midnight. The associated macroscale frontal analysis, hail, lightning, and wind occurrences are shown in Figure 29. Also shown in this Illustration is the echo structure at the time of intensification of the specific thunderstorm near the radar site.

A stable wave development, which was evident in the line echo near Springfield, Illinois, was assumed to be the primary cause of the thunderstorm Intensification. An expanded, three-dimensional view of the convective activity near this wave Is shown in Figure 30. This echo composite was constructed from observations acquired with a TPS-10, RHI radar which was being operated In conjunction with the CPS-9 radar. A vertical scan display of the TPS-10 data is shown in the upper left corner of the figure. The wave echo complex was composed of three short lines, or groups,of thunderstorms. The west group contained the highest echoes with 3 of the tops reaching above 40,000 feet. The tops of the center group were

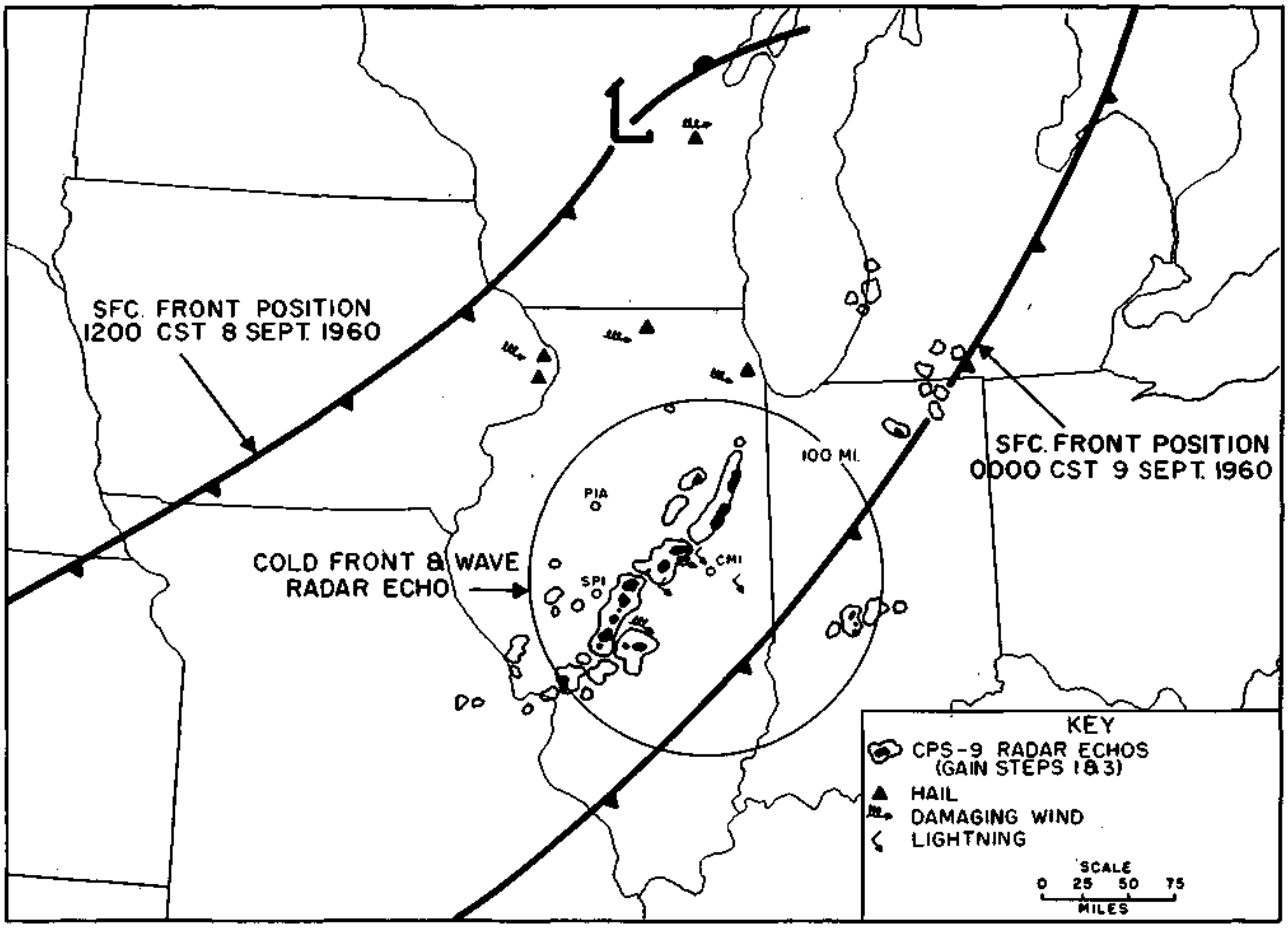


FIG. 29 SYNOPTIC AND RADAR PATTERN, 8 SEPTEMBER 1960

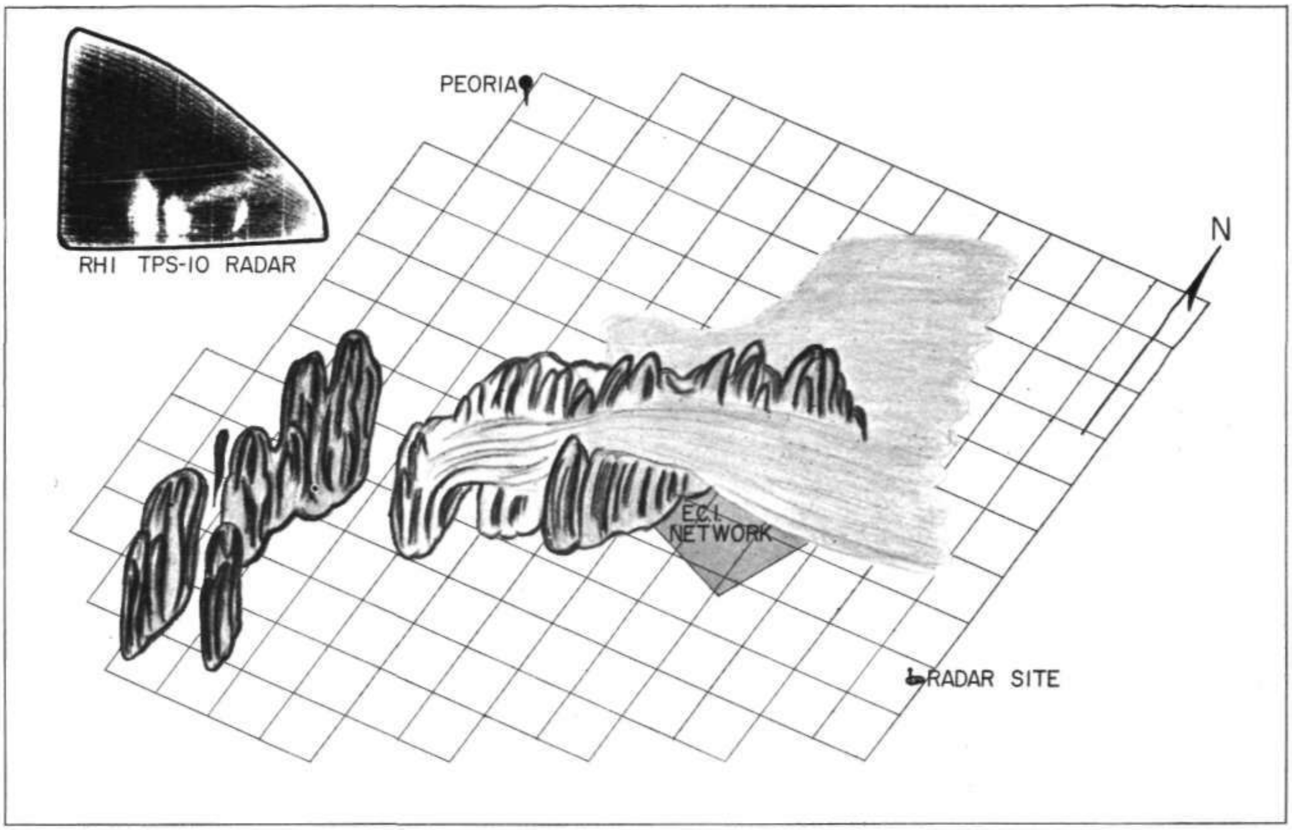


FIG. 30 RADAR ECHOES ASSOCIATED WITH FRONTAL WAVE,
2035 CST, 8 SEPTEMBER 1960

significantly lower at 30,000 feet. An extraordinary feature of these shorter thunderstorms was their apparent association with a very dense, cirrus plume which extended to the northeast. Since it was difficult to imagine a wind field which would result in such a selective ice-crystal blow-off, it was originally thought that the cirrus was the remnants of previous thunderstorm activity. Unfortunately, there was no radar data prior to 2000 GST to determine if previous thunderstorm activity had occurred. A thorough check of the substation rainfall data showed no evidence of earlier precipitation to the west. The severe thunderstorm developed originally in the forward portion of the complex, and intensified while over the East Central Illinois Raingage Network. It is suspected that the natural seeding from the cirrus plume contributed to the initial growth of this thunderstorm. However, there is equally strong evidence that the growth of hail was suppressed by the over-abundance of ice crystals. The thunderstorm reached maximum intensity one hour after initial development at a point 20 miles to the northeast where severe damage to crops and property was caused by strong outflow. The maximum hail size was less than 1/2-inch and accounted for less than 25 percent of the dollar loss.

Approximately 1000 tracings of photographs of PPI and RHI displays were used to construct three-dimensional composites of the severe thunderstorm. The composites were drawn for 3 levels of radar reflectivity and for five 10-minute time intervals during the storm's development and decay.

The first echo composite (Fig. 31) was constructed for the first 10-minute radar sequence prior to the arrival of the damaging outflow. The surface area shown is a 1300-square mile section of the volunteer observer network that includes the eastern half of the East Central Illinois (ECI) Raingage Network. The area is predominantly level farmland with no pronounced changes in relief. Although the. storm occurred late in the crop-growing season, the majority of the corn crop had not yet been harvested and was still susceptible to damage. The dotted areas in Figure 31 denote the reports of crop damage. The isohyetal pattern in the raingage network is delineated by the light and dark diagonal shading. The severe thunderstorm responsible for the surface damage occurrences developed, as described previously, in the raingage network and moved northeastward toward the small community of Mahomet, Illinois. There were 2 "bursts" of hail and damaging outflow as indicated by the damage reports. The first damage was recorded in the raingage network a few minutes after the initial development of the thunderstorm. The second and most damaging "burst" came at the mature stage of the thunderstorm a few miles north of Mahomet. An aerial damage survey was made of the area of heaviest damage by photographing the surface from an altitude of 700 feet while flying a series of radial tracks from the Mahomet water tower. The tower is a prominent radar ground target and served as ah excellent reference point for echo analysis. The blow-up of the damage area is shown in the right of Figure 31. The arrows denote the direction of the damaging wind and the letters B, C, and T denote the

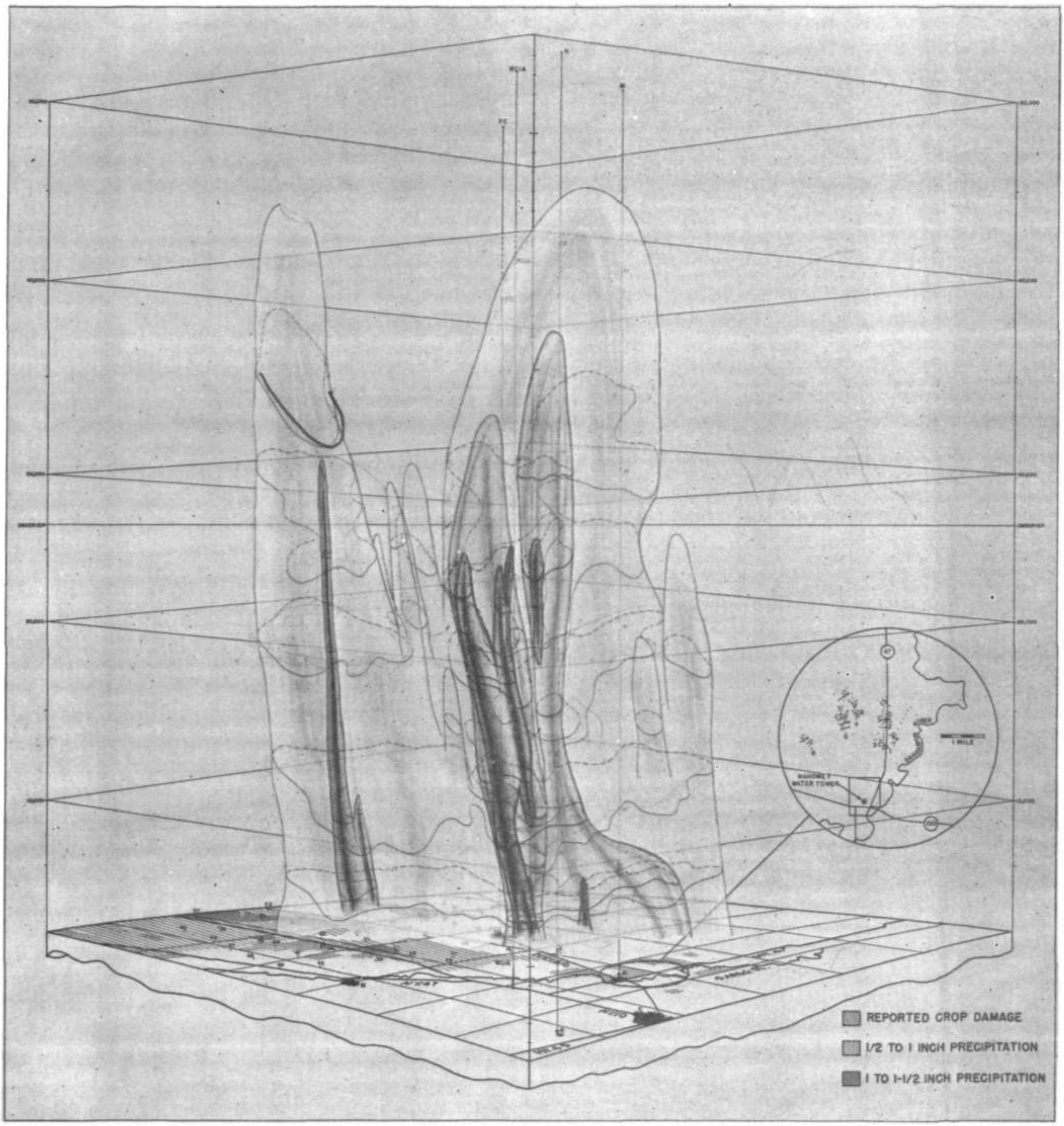


FIG. 31 RAEAR ECHO COMPOSITE 2100 CST, 8 SEPTEMBER 1960

locations of damage to buildings, crops, and trees, respectively. It is interesting to note that the severe wind damage occurred with basically two wind directions -- southwest and northwest.

The 3 gray levels shown in the echo composite in Figure 31 represent radar reflectivity values of 80, 8×10^3, and 5×10^4 mm^6m^{-3}, respectively. There were 2 thunderstorms apparent at the first Z level in this sequence -- the primary, or severe, storm and a secondary thunderstorm which followed a more northerly track west of Farmer City, (F.C.), Illinois. The primary thunderstorm contained 2 cells with equivalent Z values of 8×10^3 mm^6m^{-3}, both of which were located toward the rear of the thunderstorm. The forwardmost cell appeared to be in the growth stage and contained one high Z core of 5×10^4 mm^6m^{-3} which was suspended between 20,000 and 25,000 feet. The second 8×10^3 mm^6m^{-3} cell appeared to be in the mature stage and contained three Z cores of 5×10^4 mm^6m^{-3}, one of which reached the ground.

Figure 32 shows the thunderstorm cell configuration 10 minutes later. The secondary storm caused very little damage and therefore was eliminated in subsequent composites. In the primary storm the position of the Z core near the start of the surface damage track indicated that the mature stage had been reached at this time. Three 8×10^3 mm^6m^{-3} cells were apparent. The center and largest of these cells contained at least 4 cells equal to or greater than 5×10^4 mm^6m^{-3}. The 4 cells, which were distinctly separated above 20,000 feet, merged below 20,000 feet and became a single cell from 10,000 feet to the surface. The high Z axis had moved forward and

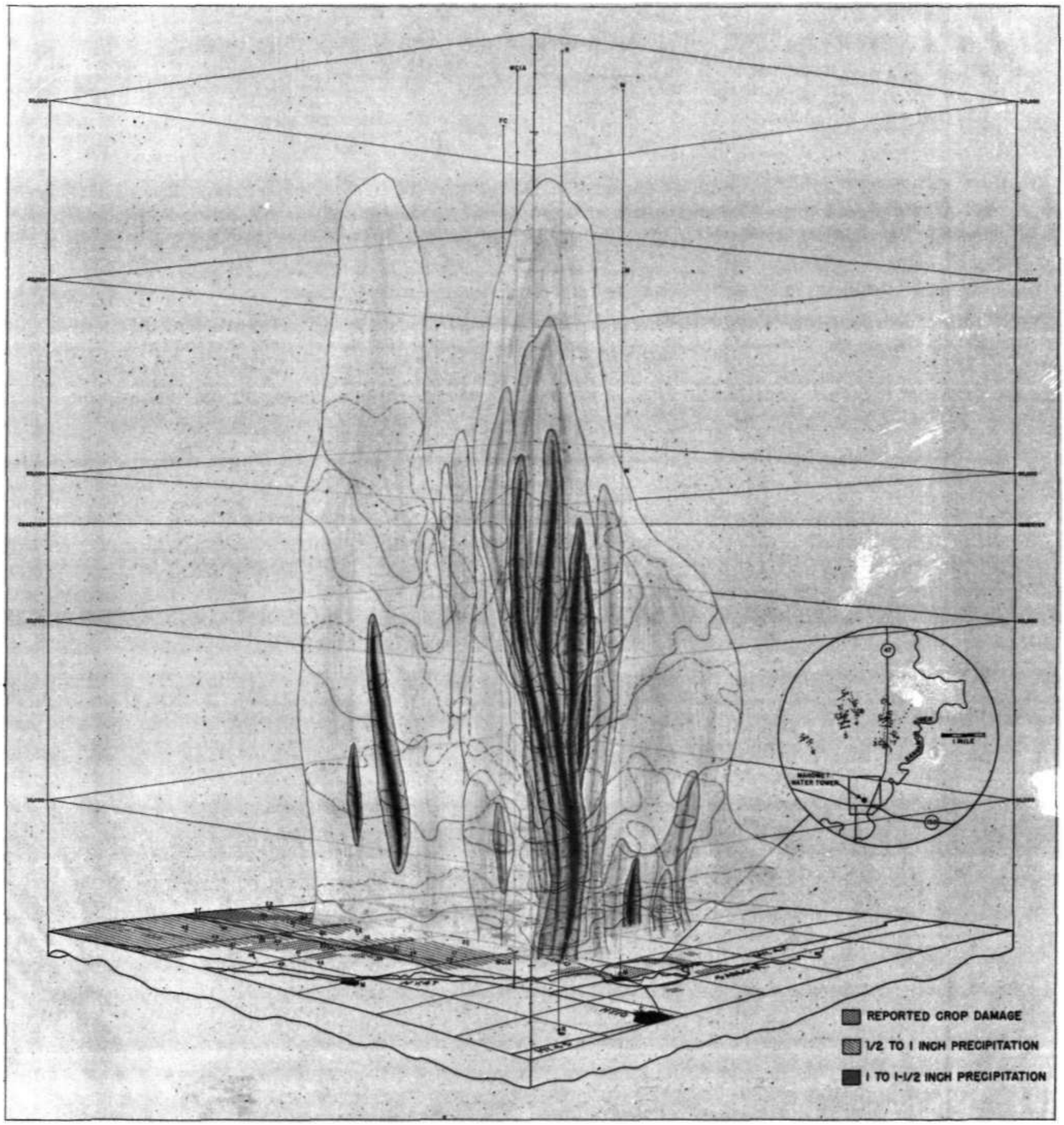


FIG. 32 RADAR ECHO COMPOSITE 2110 CST, 8 SEPTEMBER 1960

was approaching the geometric center of the thunderstorm.

The third composite, Figure 33, shows conditions 10 minutes later, or 20 minutes after the first composite. There were by this time 2 main 8 x 10^3 mm^6m^{-3} cells and 5 high Z cores. There was an appreciable increase in the cross-sectional area below 15,000 feet as the downdraft and precipitation began to maximize in the heavy damage area. Since the surface damage was known in great detail, attempts were made to establish the 10-minute change in the individual high Z cores. However, it was impossible to maintain continuity of growth or dissipation or to make positive identification of any of these cores even with the reduced gain RHI data, which was available at 3-minute intervals. It was concluded that the status quo condition, e.g., the growth, maturity, or dissipation stage, of a Z cell in excess of 5 x 10^4 mm^6m^{-3} has an existence of less than 3 minutes.

The fourth and last composite, Figure 34, shows the cell structure as the thunderstorm reached the dissipation stage. There were five 8 x 10^3 mm^6m^{-3} cells and at least 13 small cores exceeding 5 x 10^4 mm^6m^{-3}. The main core which showed vertical continuity had moved into the forward position of the thunderstorm. There was apparently complete disorganization of cell structure at this stage. The damage survey indicated that the thunderstorm would not be classified as severe after this time.

Echo Movement

The echo velocities shown in the first composite in Figure 31

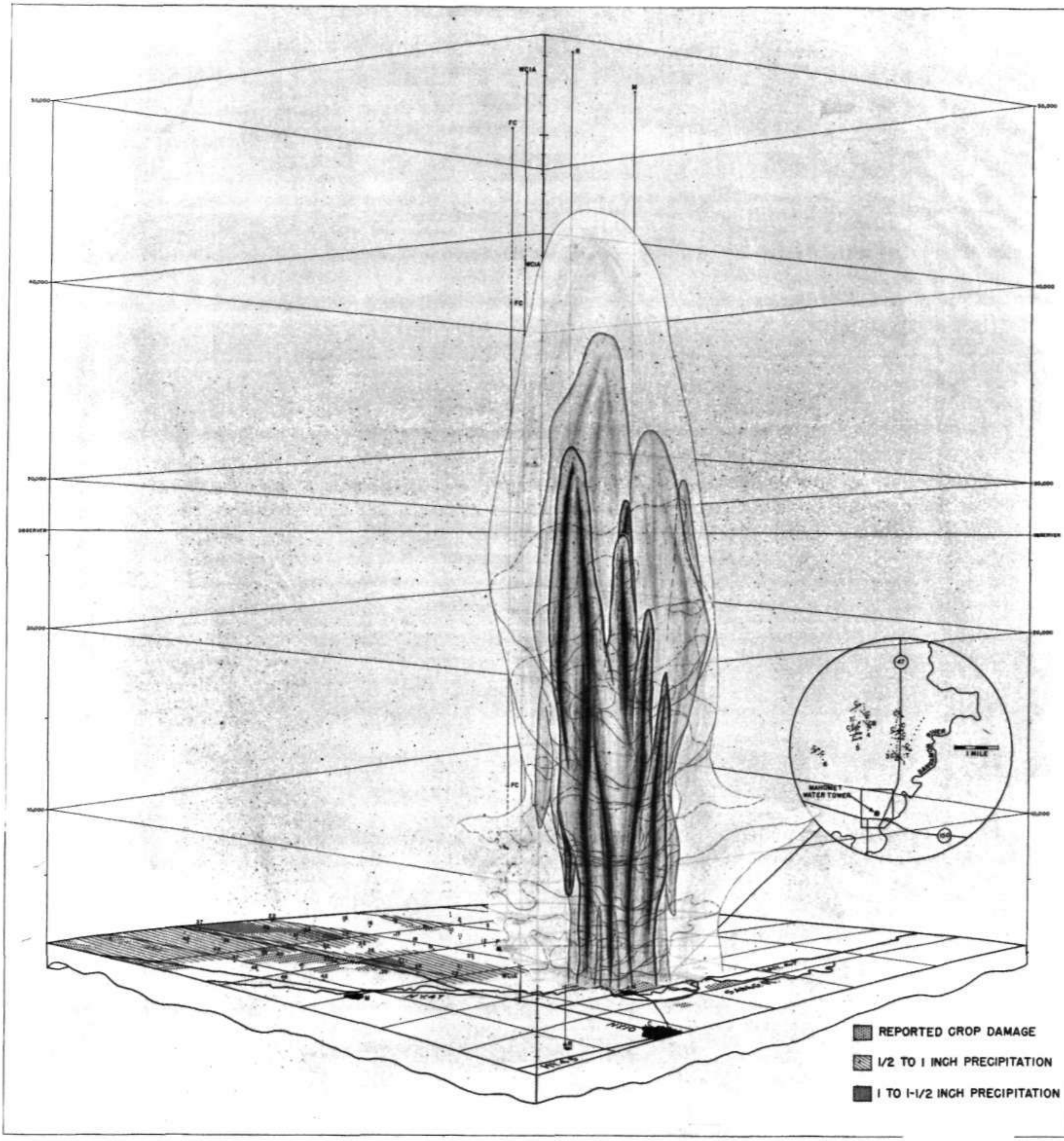


FIG. 33 RADAR ECHO COMPOSITE 2120 CST, 8 SEPTEMBER 1960

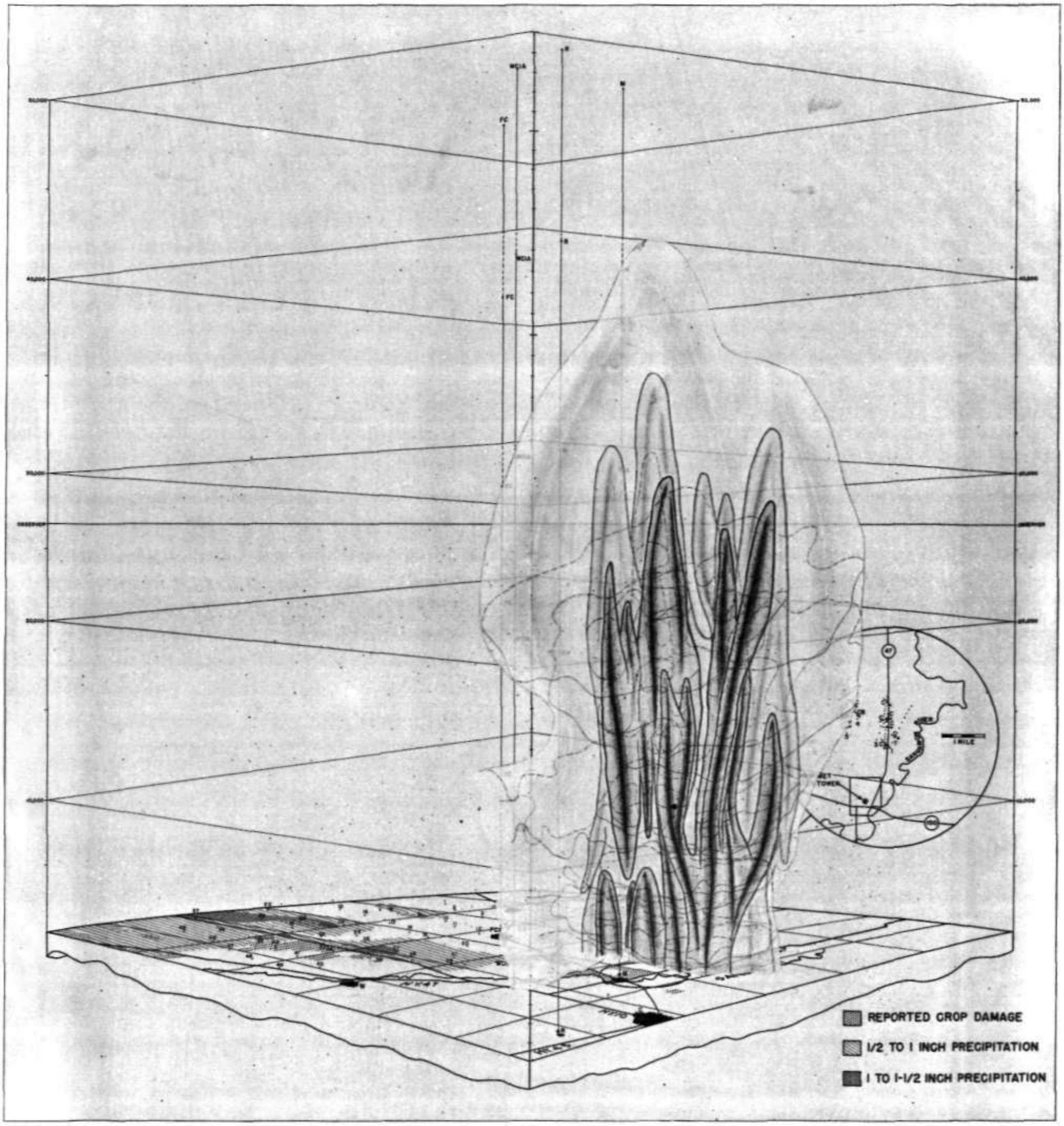


FIG. 34 RADAR ECHO COMPOSITE 2130 CST, 8 SEPTEMBER 1960

were measured from the leading and trailing edges of the PPI echoes obtained at 5 altitudes. The technique used to obtain the echo speeds was to planimeter the area enclosed by the leading edges of the echo for 2 different times. The echo speed in miles per hour was then determined from:

$$V = \frac{A}{d} \cdot \frac{60}{t} S$$

where:

A is the area enclosed by the leading edges and a pair of boundary lines drawn parallel to the direction of movement

d is the distance between the boundary lines

t is the time interval between the leading edge echo tracings

S is the scale conversion from the units of d to miles.

This technique was used to calculate the speeds of all echoes with Z values between 80 and 5×10^4 mm^6m^{-3} whenever continuity in echo identification could be maintained.

Reliable speed calculations were obtained for 10 cells between the first and second sequences, 7 cells between the second and third sequences, and 7 cells between the third and fourth sequences. Plots of these speed measurements by height between the sequences are shown in Figure 35. The pibal data recorded at Columbia, Missouri, 2 hours earlier are also shown with the speed data for the first and second sequences.

The leading edge speeds were 5 to 7 miles per hour higher than the trailing edge speeds. Apparently, this was a reflection of the growth stage of the thunderstorm. There was an amazingly close agreement between the trailing edge speeds and the environmental wind speeds. This shear in the medium to high Z regions was surprising because the RHI maximum sensitivity profiles showed relatively little tilt to the echo.

Cell speeds obtained from the second and third radar sequences, Figure 35, showed considerable change, especially at the echo extremities. Speeds of trailing edges above 18,000 feet had decreased while leading and trailing edge speeds below 10,000 feet had increased by approximately 10 miles per hour. The leading edge speed aloft had approached the environmental speed. The trailing edge had a speed approximately 10 miles per hour slower than the environment, possible due to propagation in the upwind direction. However, propagation cannot account for the general decrease of both leading and trailing edge speeds. This deceleration became apparent in the speeds measured from the third and fourth sequences shown in Figure 35. The trailing edge speeds were higher than the leading edge speeds which apparently signified the decay of cells above 5000 feet. It is interesting to note that the leading edge speed remains relatively high at 3000 feet. The average horizontal component at the surface was apparently 28 to 30 miles per hour, or approximately a factor of 3 greater than the environment. An equivalent environmental wind speed existed between 16,000 and 20,000 feet. A comparison of the 3 sequences of cell speeds might

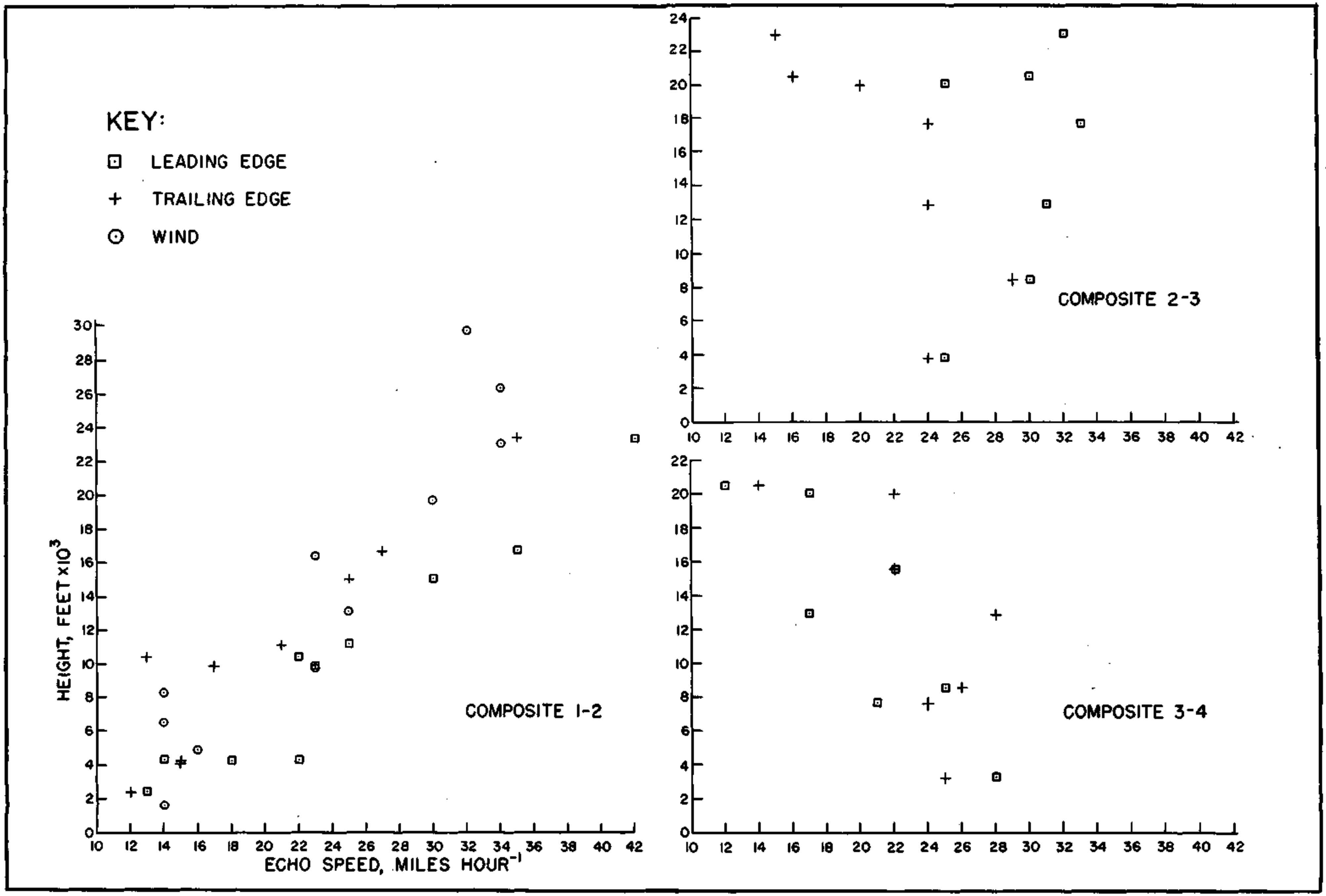


FIG. 35 VERTICAL DISTRIBUTIONS OF RADAR ECHO SPEEDS, 8 SEPTEMBER 1960

lead to the speculation that a transfer of momentum had occurred within the thunderstorm. However, as stated earlier, cell continuity is not maintained sufficiently for 10-minute sampling and, therefore, speed measurements obtained at any one level during the 3 sequences probably involve more than one cell.

It is obvious from this study that complete examination of individual cell structure and velocity in time and space requires a highly detailed and very rapid radar sampling program. Such a program is currently beyond the scope of most operational radars.

CONCLUSIONS AND RECOMMENDATIONS

An attempt has been made in this report to discuss and generally describe the characteristics of 3 scales of thunderstorm phenomena that occur in the Midwest.

The unit of study for which the radar program was specifically designed and used in this investigation was the thunderstorm. The conclusions that were reached concerning the mean radar reflectivity profiles of approximately 500 severe thunderstorms represent the principal findings of this investigation and should receive the the greatest emphasis in application to operational radar echo interpretation,

Case studies were used in the investigation of thunderstorm cells to better define their time and space distribution as a radar target and to suggest future methods of investigating the interaction of the severe thunderstorm with its environment.

As a consequence of this investigation, the following recommendations are made for future radar study:

1. A complete investigation of the velocity of radar echoes at various heights in thunderstorms to determine the echo level which best indicates the average outflow velocity and to investigate the magnitude of vertical transfer of momentum;
2. The investigation of the vertical and horizontal distribution of liquid water content in thunderstorms and its relation to the radar reflectivity maximum aloft;

3. A comparison of the variations in raindrop size distributions, hail size distributions, and radar reflectivity-distributions within individual thunderstorm cells.

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