A Model 10-Inch Rainstorm

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ABSTRACT

On 16–17 August 1959, a severe rainstorm in which amounts exceeded 10 inches in 16 hours occurred in southern Illinois and bordering states. A dense raingage network was located on the major axis of this storm, and one of the heaviest rainfall centers along the axis was enclosed by the network. This network provided data on storm characteristics rarely available in such storms. Rainfall amounts in the network storm center exceeded the 100-year frequencies in this area. A study of this storm has been made utilizing the dense raingage network data, synoptic weather data, radar observations, U. S. Weather Bureau rainfall data, and 200 field survey measurements of rainfall. A statistical model of severe rainstorms is derived and information on the life cycle is presented.

1. Introduction

On 16–17 August 1959 a severe rainstorm occurred in southern Illinois and bordering states in which amounts exceeded 10 inches within 16 hours. Fortunately, from a scientific basis, the major axis of this storm passed through a raingage network consisting of 54 gages in 550 square miles in southern Illinois.

Review of recent meteorological literature reveals only a few papers concerning severe rainstorms, knowledge of which is extremely pertinent in the design of hydraulic structures in the United States. Furthermore, no papers have been found which included observations of a rainstorm of this magnitude in the United States with the detail presented here through use of the 54-gage network. Property damage resulting from such rainstorms in Illinois normally exceeds $100,000 and thus these storms attain a severity equivalent to many tornadoes and other severe local storms. Many farmers in the core of the August 1959 storm had a complete loss of crops due to flooding.

Data employed in this study include the dense raingage network data, synoptic weather data, radar observations, U. S. Weather Bureau rainfall data, and 200 field survey measurements of rainfall (Changnon, 1958). Major emphasis has been placed upon analysis of the dense network data. Fig. 1 shows the storm isohyetal pattern. The outline of the concentrated raingage network of 54 gages, known as the Little Egypt Network, is shown in the center of the storm. Amounts exceeding six inches were recorded over 2000 square miles and amounts in excess of four inches over a 5000-square mile area. Detailed analyses of the major flood-producing storms in Illinois, such as the one described in this paper, are being made in an effort to obtain a more reliable definition of the time and space distribution of heavy rainstorms in the state (Huff and Semonin, 1960). The detailed findings from this storm were combined with those from other previous storms to derive a statistical rainstorm model and to describe a method of formation, sustenance, and dissipation of these storms.

2. Area-depth-duration relations

Area-depth-duration data are basic to the design of hydraulic structures, such as dams, drainage facilities, and water-supply facilities. Furthermore, these relationships provide a useful method of numerically defining the areal and temporal distribution of rainfall. For example, the slope of the area-depth curve appearing on a graph is a measure of the rainfall variability in a storm.[1]

Table 1 shows area-depth relations in the portion of the storm over the Little Egypt Network for various increments of time. Table 2 shows area-depth relations for the entire storm zone for the 12-hr period of maximum rainfall in the storm of 16–17 August 1959 along with comparable data for other outstanding storms centered in Illinois during recent years. The several rainfall centers in the storm of 16–17 August (Fig. 1) were combined in determination of the area-depth relations of Table 2. The relative magnitude of the storms in Table 2 is revealed by comparison of their depths with those in Table 3, which shows the average frequency distribution of point rainfall in southern Illinois for 12-hr periods.

Fig. 2 illustrates the relative magnitude and intensity of the storm on the Little Egypt Network. In this figure,

[1] Huff, F. A., and J. C. Neill, 1957: Rainfall relations on small areas in Illinois. Urbana, Ill., *State Water Survey Bulletin 44*, p. 61.

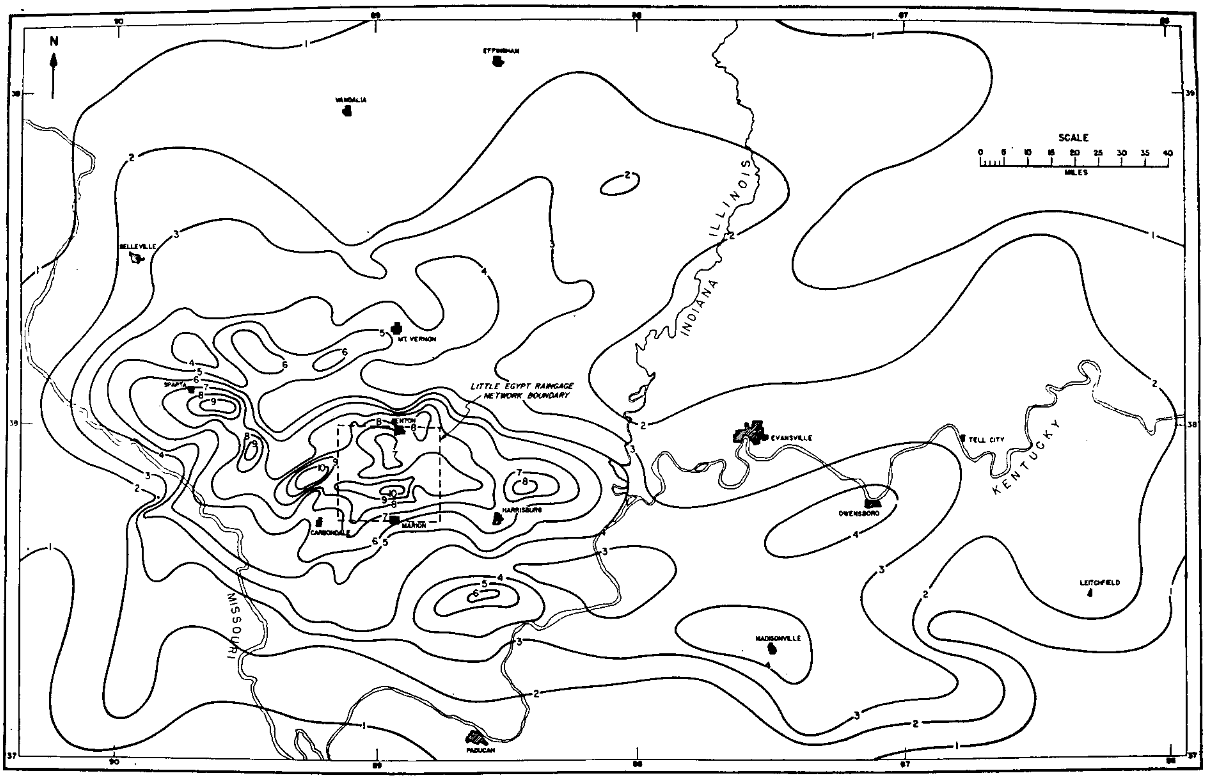

FIG. 1. Total storm rainfall for 16–17 August 1959.

TABLE 1. Area-depth-duration data 16–17 August 1959 on Little Egypt Network.

Storm period (hours)	Average depth (in.) for given area (sq mi) 10	50	100	200	550
1	2.71	2.33	2.04	1.67	0.92
2	4.08	3.65	3.30	2.85	1.77
3	4.25	3.96	3.72	3.37	2.36
6	4.80	4.52	4.34	4.08	3.61
12	9.28	8.60	8.15	7.52	6.28
24	10.40	9.85	9.40	8.90	7.83

TABLE 2. Area-depth-duration data 12-hr periods, outstanding storms, 1950–59.

Date	Average depth (in.) for given area (sq mi) 50	100	500	1000	5000
7/ 8/51	11.3	10.6	8.8	7.8	5.6
7/18/52	8.8	7.9	5.4	—	—
10/ 9/54	7.2	7.0	6.3	5.9	4.2
5/26/56	8.5	7.6	4.8	3.5	—
5/21/57	7.1	6.8	5.9	5.3	3.6
6/14/57	15.7	14.7	12.0	10.4	6.1
6/27/57	11.5	10.9	9.3	8.4	5.9
7/12/57	11.0	10.7	9.5	8.7	5.9
7/14/58	8.5	8.2	7.0	6.2	3.9
8/16/59	10.1	9.8	8.8	8.2	5.9

TABLE 3. Average point rainfall frequency for storm period of 12 hours.

Recurrence interval (yr)	Rainfall depth (in.)	Recurrence interval (yr)	Rainfall depth (in.)
2	2.3	25	4.8
5	3.1	50	5.8
10	3.7	100	7.0

selected isohyets have been drawn for the 12-hr period of maximum rainfall and labeled in terms of recurrence interval of point rainfall. Thus, through the central area of the network of 550 sq mi an area of approximately 100 sq mi experienced 12-hr amounts which exceed the 100-yr expectancy.[2]

3. Synoptic weather conditions

The surface synoptic map for 1800 CST on 16 August, near the start of the storm, showed a strong flow of moist maritime tropical air over southern Illinois (Fig. 3). The isobaric pattern indicated a relatively steep gradient, with a weak ridge through the storm

[2] Huff, F. A., and J. C. Neill, 1959: Frequency relations for storm rainfall in Illinois. Urbana, Ill., *State Water Survey Bulletin 46*, p. 58.

region and a trough over the Ozarks to the southwest. Dew points were 70–72F and air temperature in the upper 70's. The nearest front to the storm area was located approximately 400 miles to the west. Radar and

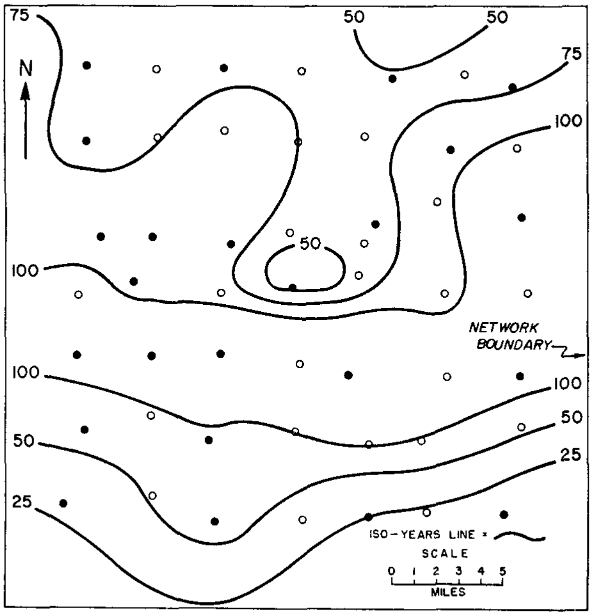

Fig. 2. Average recurrence interval of maximum 12-hr rainfall on Little Egypt network, 16–17 August 1959.

weather station observations indicated widespread thunderstorm activity over central and southern Illinois and adjoining states throughout the afternoon.

West-southwest flow at 35 knots over the southern portion of Illinois was indicated on the 850-mb chart for 1800 CST, 16 August. A weak trough in the contour pattern was oriented from north-northwest to south-southeast through the storm region. A flat dew-point gradient existed over Illinois and bordering states at this level.

The 700-mb chart for 1800 CST, 16 August showed west-southwesterly flow at about 30 knots over southern Illinois (Fig. 4a). A slight trough oriented from north-northwest to south-southeast was evident in this area. Furthermore, the contour pattern indicated that contrasting mP and mT air masses were meeting over southern Illinois. A ridge in the dew point pattern was oriented from northeast to southwest through the storm zone. Upper air analysis was aided considerably by supplementary radiosonde data from mobile stations at Scott Field, Illinois, South Bend, Indiana, and Waterloo, Iowa.

The 500-mb chart at 1800 CST showed westerly flow at approximately 25 knots over southern Illinois (Fig. 4b). A slight trough in the contour pattern was indicated over the state, and similar to the 700-mb chart, a dew-point ridge extended northeast-southwest through the storm region. The 300-mb chart indicated west-north-

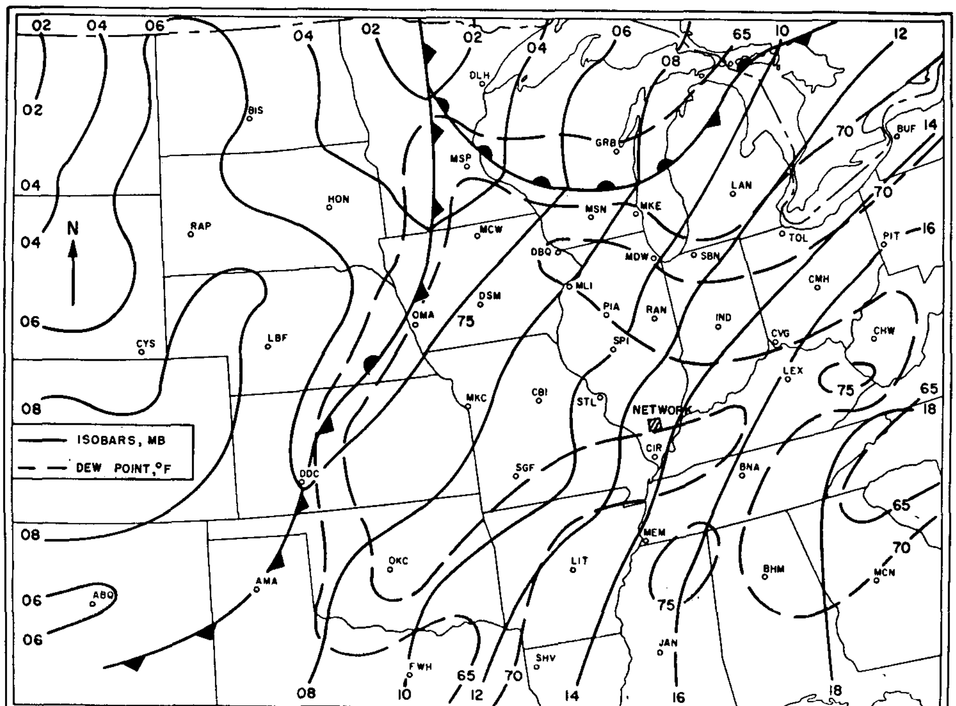

Fig. 3. Surface map at 1800 CST on 16 August 1959.

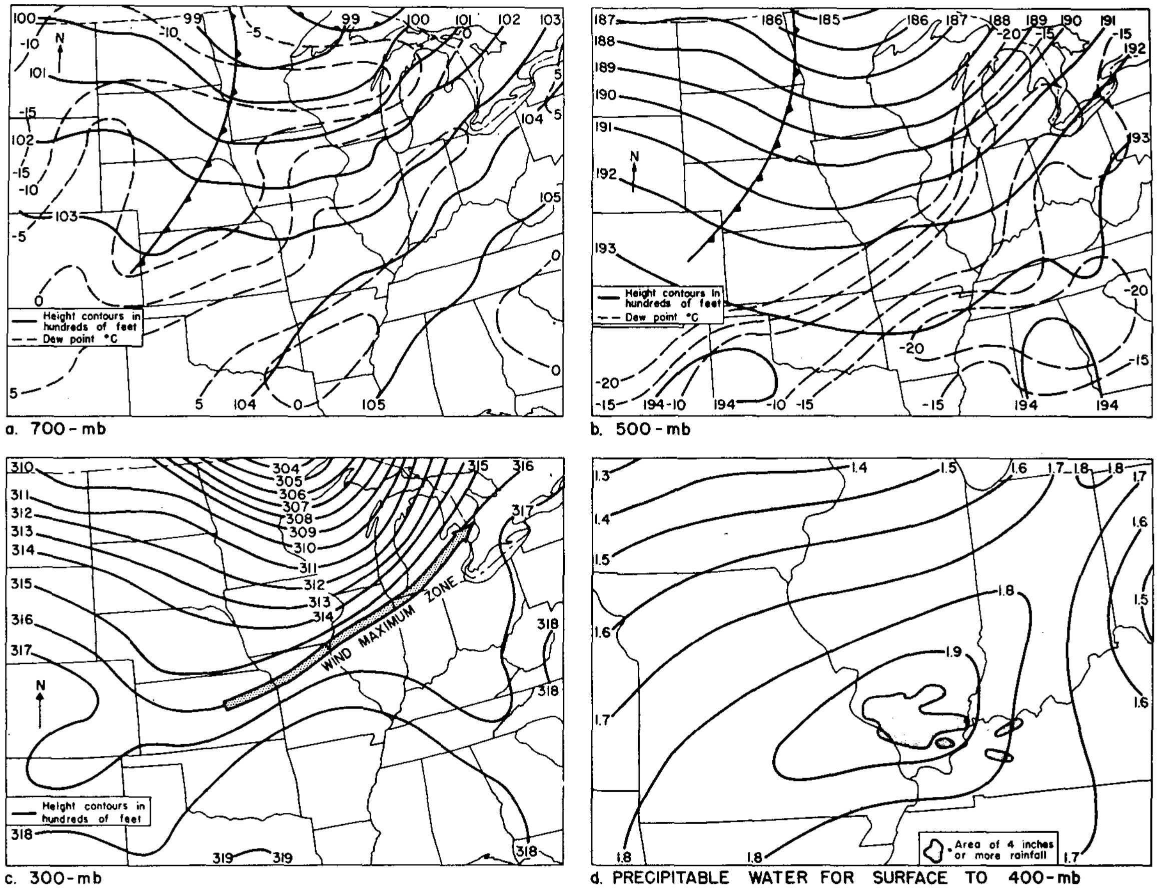

FIG. 4. Upper air and precipitable water maps at 1800 CST, 16 August 1959.

westerly flow through the storm region with a wind maximum of 50–70 knots extending northeastward from western to northeastern Illinois about 200 miles northwest of the rainstorm center (Fig. 4c). The contour pattern indicated divergence in and north of the storm zone.

The precipitable water map for the surface to 400 mb at 1800 CST (Fig. 4d) showed a maximum zone with values near two inches extending southwestward from Michigan through southern Illinois to Oklahoma. Radiosonde data indicated the core of the zone of maximum precipitable water extended through the storm zone of southern Illinois. Scott Field, located near the northern edge of the heavy rainfall zone, had a precipitable water content of 1.93 inches for the layer, surface to 400 mb at the start of the storm. This amount is about 35 per cent above normal for August, based upon Illinois Water Survey studies. This abnormality was due to excessive amounts of moisture above 850 mb, the surface to 850-mb level having a near normal amount. The Showalter stability index of +2 at 1800 CST was not indicative of a highly unstable atmosphere in the storm zone.

4. Radar observations

Radar observations with a 3-cm CPS-9 set were made during a portion of the storm. The radar set was turned off at 1930 CST on 16 August during the early part of the storm and turned on again at 0700 CST on 17 August, near the end of the storm period. However, sufficient observations were made to reveal some interesting features of the storm, particularly when combined with the macro-scale features of the storm revealed by radar reports from the U. S. Weather Bureau Network and when supplemented by the raingage network data.

Fig. 5 shows the CPS-9 portrayal of precipitation within range of the radar set at selected times. Shading of the radar echoes has been employed to identify separate convection systems. At 1230 CST, four separate areas of rainstorms are indicated by the shading of the radar echoes (Fig. 5a). All lines were moving in a general eastward to southeastward direction, except the echo area on the Ohio River (EVV) which remained relatively stationary. The number and extent of the squall zones shown by the radar at this time indicates that conditions were favorable for thunderstorm de-

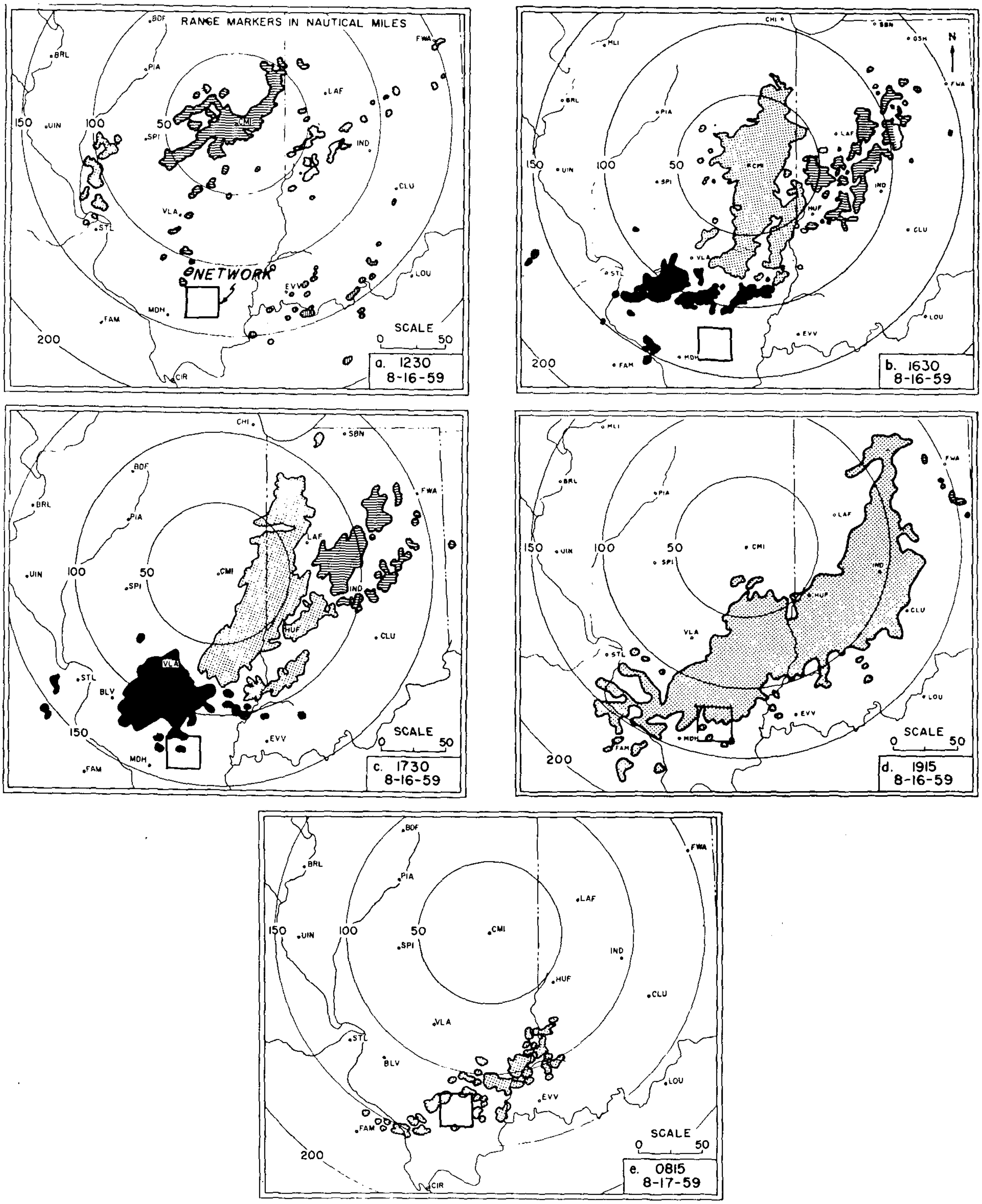

Fig. 5. CPS-9 radar echoes on 16–17 August 1959.

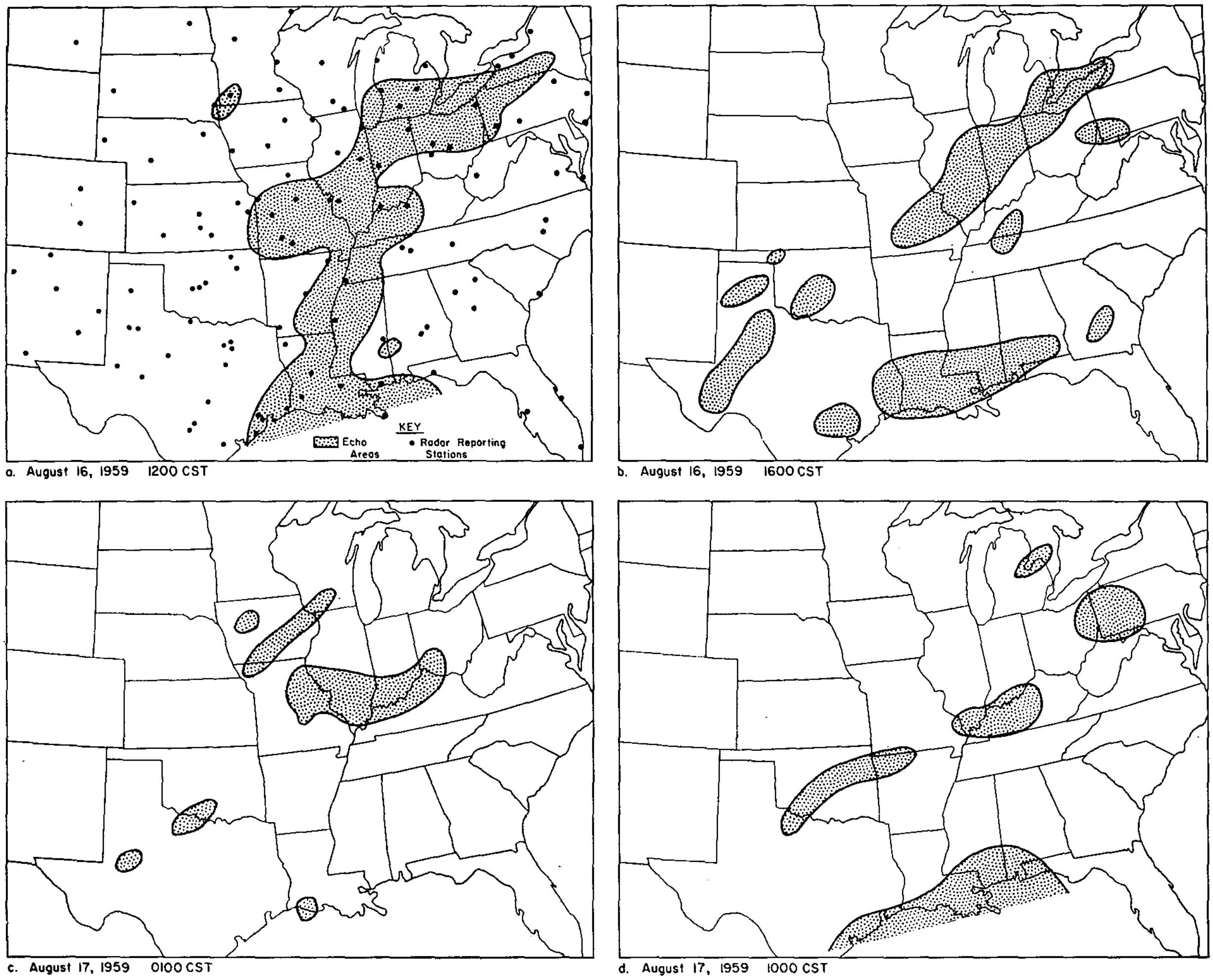

FIG. 6. Echo areas indicated by radar network.

velopment and sustainment over a wide area in Illinois and Indiana. The squall line shown over southern Illinois produced light rainfall as it moved across southern Illinois where the severe rainstorm developed later.

Fig. 6 shows regions within which echoes were reported by the U. S. Weather Bureau radar network at selected times. The stippled areas represent envelopes of areas in which echoes were widespread but not necessarily contiguous. In most cases, over 50 per cent of the stippled areas were occupied by echoes. At 1200 CST, a band of convective activity extended northward into the central United States from the Gulf. The hill regions in southern Illinois appeared to be augmenting the convective activity at this time.

Three separate squall zone areas are indicated by the CPS-9 at 1630 CST (Fig. 5b). The west-east line extending through southern Illinois was first detected about 1500 CST when it developed slightly south of the position shown at 1630 CST. This development was in the region in which the southern extremity of the squall line to the north had passed earlier (Fig. 5a). This line apparently resulted from intensification of northward-moving cells formed in the hill country to the south and southwest in Illinois and Missouri as they reached an area of increased evaporation, which was produced as clearing followed the passage of the earlier squall line. This west-east squall line is oriented approximately parallel to the southern Illinois storm zone which developed later, and probably represents the initial phase of development of the zone.

As observed in a majority of the 10-inch storms studied in Illinois, this development took place over the boundary separating a hot, mostly sunny, humid region from a partly cloudy to cloudy, rainy area with somewhat cooler temperatures. Maximum temperatures on 16 August exceeded 90F in the storm region compared to 75–80F in northern Illinois, with generally clear conditions except during brief shower periods in the region south of the storm zone.

At 1730 CST (Fig. 5c) the CPS-9 shows the southern

Illinois squall line merging with the line to the north, while the line to the north is about to merge with the line east of it over central Indiana. With the merging of these three squall lines, the heavy storm was underway. The CPS-9 presentation at 1915 CST (Fig. 5d) shows that the merger had been completed by that time. The southern portion of the squall line was drifting very slowly southward while the northern portion was moving eastward at a considerably greater speed.

By 1600 CST (Fig. 6b), the Mississippi Valley area of rainstorms had largely dissipated as the peak of diurnal heating passed. However, a large area of convection still existed from western New York southwestward through Illinois.

By 0100 CST (Fig. 6c), the precipitation areas were restricted primarily to southern Illinois and adjacent states. A weak squall line was indicated through Iowa, probably initiated by the cold front to the west, and this line dissipated upon entering Illinois.

The last CPS-9 illustration in Fig. 5 shows the radar portrayal at 0815 CST on 17 August. The last heavy rainfall burst was occurring in the storm zone at this time, after which the whole system moved southward at a speed of 10 mph. Fig. 6d for 1000 CST shows the southward drift of the large-scale system associated with the Illinois storm earlier. Note the redevelopment of the Gulf activity at this time as diurnal heating increases.

5. Storm characteristics

Using data from 18 recording gages in southern Illinois and southeastern Missouri in conjunction with the Little Egypt data, an effort was made to determine the movement of squall lines through the storm region and surrounding area to obtain information on the origins of these lines and to gain a better understanding of the storm characteristics. Newton and Katz (1958) have demonstrated the feasibility of using the hydroclimatic network for this purpose. This approach was dictated by the lack of detailed radar data during a large portion of the storm.

Results of this analysis indicated that nine lines passed through or near the storm center during the storm period. Most of these lines were detected first in the surface rainfall pattern 75–100 miles northwest of the storm center. Using rainfall data, hourly sequence data from nearby Weather Bureau stations, and upper air maps, it appears that these lines formed on the south side of and approximately parallel to a wind maximum found at the 300-mb level. These lines moved toward the rainstorm center at calculated speeds of 12 to 42 mph, with a median value of 27 mph. Most of the lines appeared to move from the north-northwest. The line speeds decreased greatly in moving through the rainstorm core. The median speed was 10 mph for the six lines which passed through the storm center. These lines appeared to dissipate or increase considerably in speed upon leaving the storm center.

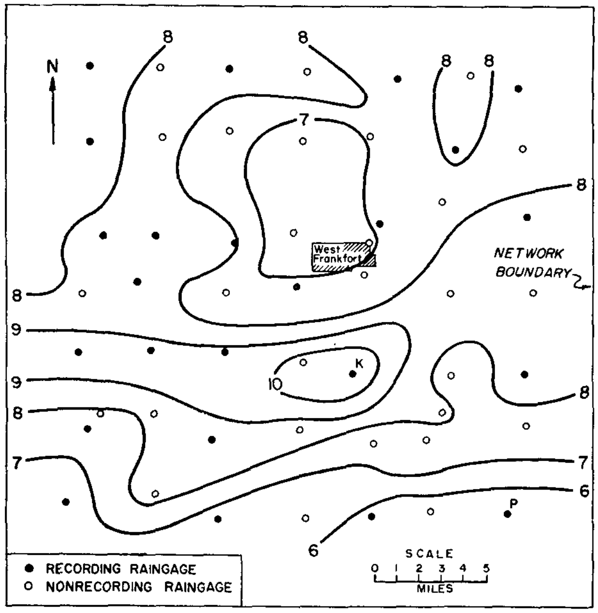

FIG. 7. Total storm rainfall, Little Egypt network, 16–17 August 1959.

Analysis of synoptic data suggests that after forming near the wind maximum, the squall lines developed vertically as they moved toward the rainstorm center through the 300-mb divergence area (Fig. 4c). As a line approached the rainstorm center, the moisture inflow was increased appreciably upon entering the zone of maximum precipitable water content (Fig. 4d) and the precipitation process maximized in this region. With vertical development of the lines as they approached the rainstorm zone, the motion of individual thunderstorms in the line, and consequently the line itself, became increasingly influenced by higher level winds. As a result, the lines frequently assumed an east-northeast–west-southwest orientation by the time they entered the storm zone, and the majority of the individual storms within a line moved nearly parallel to the rainstorm axis, which was oriented from 280 to 100 degrees (Fig. 1).

This change in orientation of lines as they entered the storm zone probably accounts for the rapid reduction in line movement. As the lines left the rainstorm zone they moved out of the maximum precipitable water region and the 300-mb divergence area, and became less intense and more under the influence of the lower level winds again. With veering of winds and the advent of drier air, the rainstorm zone decreased in intensity and moved southward during the forenoon of 17 August (Fig. 6d).

6. Network rainfall

As shown in Fig. 1, much of the heaviest rainfall of the storm occurred in the Little Egypt Network. A larger scale presentation of the network rainfall pattern as depicted by the 54 raingages is shown in Fig. 7. The network gages are arranged in a nearly square grid pattern with approximately 3.3 miles between gages on a network area of 550 square miles. Extreme variability with distance occurred with the lowest network value of 5.58 inches at gage P, nine miles southeast of the highest value, 10.58 inches, at gage K. The major east-west core across the network was a result of the maximization of several individual rainstorms in this general area.

In Fig. 8a-e, maps of the maximum 1-, 2-, 3-, 6- and 12-hr rainfall periods are presented. The 1-, 2- and 3-hr periods of maximum rainfall started at 0000 CST, the 6-hr period at 2300 CST, and the 12-hr period at 2100 CST. Approximately 80 per cent of the total storm rainfall occurred in the maximum 12-hr period.

The analysis of data from each recording gage indicated that six squall lines crossed the network. The orientation, speed and direction of movement of these lines are depicted in Fig. 9. The line speeds varied from 8 to 25 mph with a median value of 10 mph. In Fig. 9c the simultaneous occurrence of two lines on the network is shown. The third line, enhanced by its interaction with the fourth, produced the 3-hr period of heaviest rainfall on the network, 2400-0300 CST.

The rainfall patterns for each hour from 1500 CST 16 August to 1200 CST 17 August are shown in Figs. 10 and 11. Examination of the heavier individual rainstorms, those in which the hourly rainfall exceeded 0.3 inch, provided an estimate of their direction and speed of movement. The 19 individual rainstorms detected in this 21-hr period were assigned, for identification purposes, lower case letters on the hourly rainfall maps.

Within the Little Egypt Network, the storm speeds varied from 7 to 25 mph, and the direction of movement from 240 to 330 deg. Part of the variation in motion, at least, is due to development of new cells on the right flank of a line, as pointed out by Newton and Katz (1958), which causes the surface rainstorms to move to the right of the mean upper wind flow, the amount depending upon the rapidity of development on the flank. Other factors which may be an influence are differences in vertical development and meso-scale convergence in the storm zone.

The median speed of the individual storms in the rainstorm core was 13 mph with the majority between 10 and 15 mph. The median direction was 280 deg with the majority between 270 and 290 deg. The mean wind from 2000 to 30,000 ft at 1800 CST was 250 deg at 35 mph. From mean values obtained by Newton and Katz (1958), individual rainstorms would be expected to move at 275 deg, 27 mph. The median direction of 280 deg on the Little Egypt Network compares favorably with these mean values, but the median speed of 13 mph is only about one-half of the expected value. It is believed that the large reduction in speed of individual rainstorms in the storm core may have been due to blocking action on the wind flow by the convection system which was well-developed vertically up to a distance of 90 miles to the west, upwind of the speed reduction.

The deceleration of the individual storms and lines within the storm core is partially responsible for the heavy amounts recorded. However, strong intensification is indicated also in the storm core, since approximately 5-inch amounts would have occurred without any decrease in speed through the core with the rainfall intensities experienced.

7. Comparison with other severe rainstorms

Applying radar data in conjunction with recording raingage and synoptic weather data, a study has been made of the characteristics of the 10 most severe rainstorms in Illinois during the 10-yr period, 1950–59 (Table 2). In Table 4, the characteristics of these storms have been briefly summarized in the form of a statistical model for the 12-hr period of maximum rainfall in each storm. The model is based upon mean and median values of the various parameters. Similar parameters are listed for the 16–17 August storm for comparison purposes. In most respects the August storm was strikingly similar to the statistical model derived from the 10 storms and it may be considered as a typical model of a severe rainstorm. Removal of the August storm

TABLE 4. Statistical model of 12-hr severe rainstorm and comparison with 16–17 August storm.

	Model	16–17 Aug.
Squall line orientation in rainstorm zone, degrees	255–75	255–75
Orientation of surface rainfall pattern, degrees	265–85	280–100
Squall line speed in storm zone, mph	9	10
Squall line speed outside storm zone, mph	22	27
Number of distinct bursts or storms	5	5
Average interval between bursts, hours	2.4	2.4
850-mb wind	245°, 30 knots	250°, 35 knots
700-mb wind	255°, 30 knots	260°, 30 knots
500-mb wind	270°, 30 knots	270°, 25 knots
Surface dew point, departure from normal, deg F	+9	+9
Precipitable water, surface 400-mb departure from normal, per cent	+50	+61
Starting time of storm, CST	1900	1700
Maximization of storm, CST	2130–0330	2300–0500
Maximum point rainfall, inches	9.4	10.6
5000 sq mi mean rainfall, inches	4.5	5.9

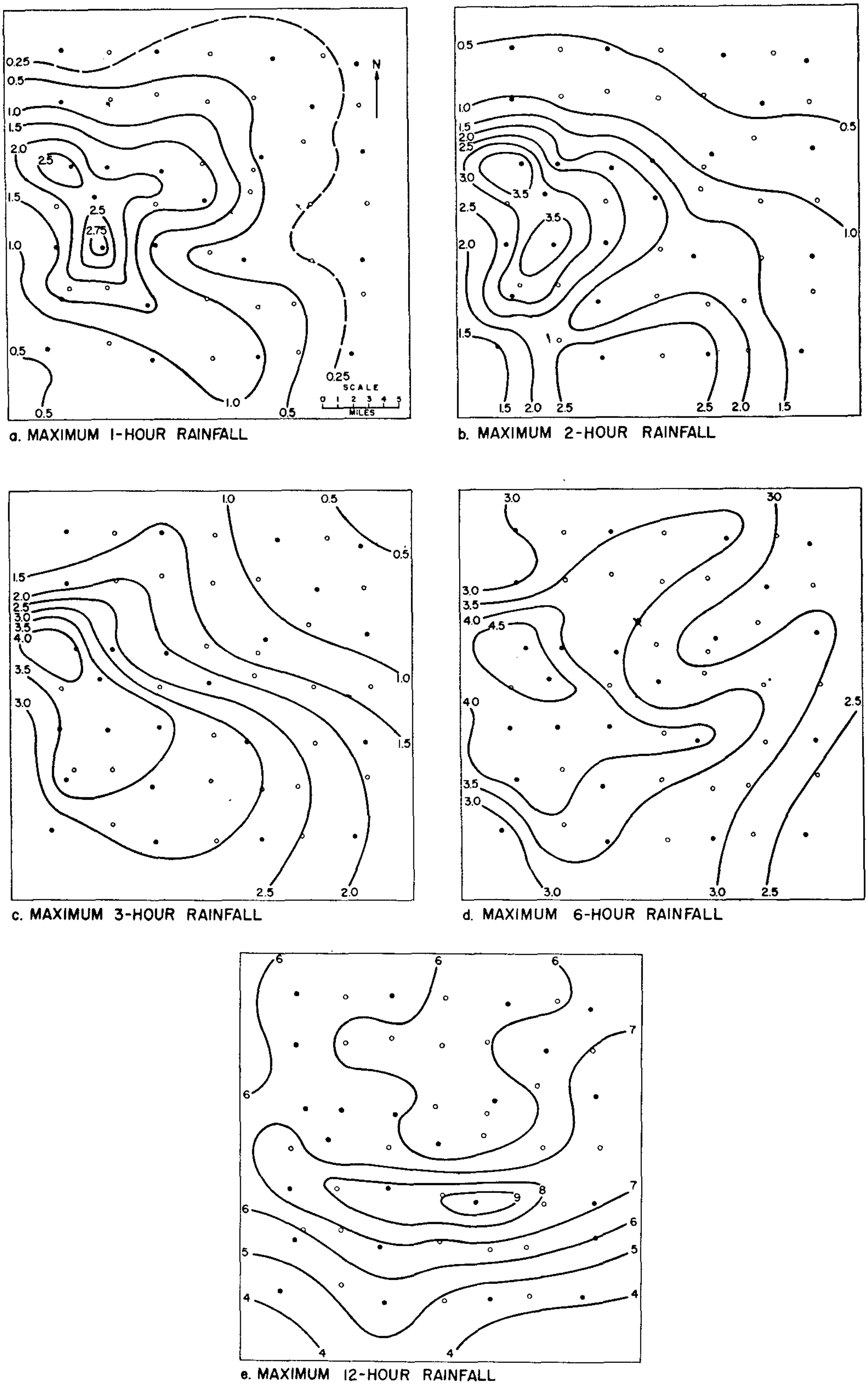

Fig. 8. Maximum rainfall periods on Little Egypt network, 16–17 August 1959.

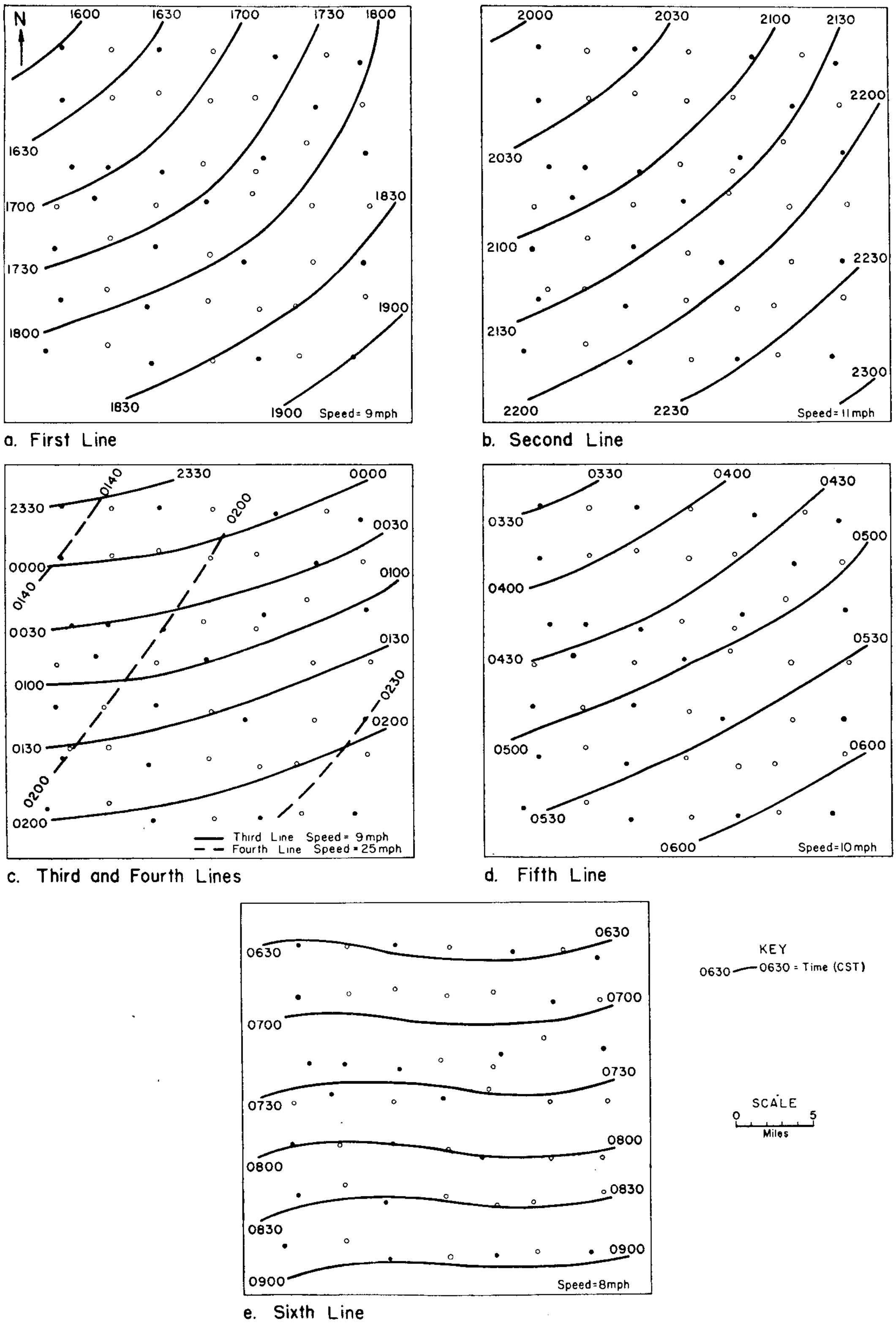

FIG. 9. Squall line movement across Little Egypt network, 16–17 August 1959.

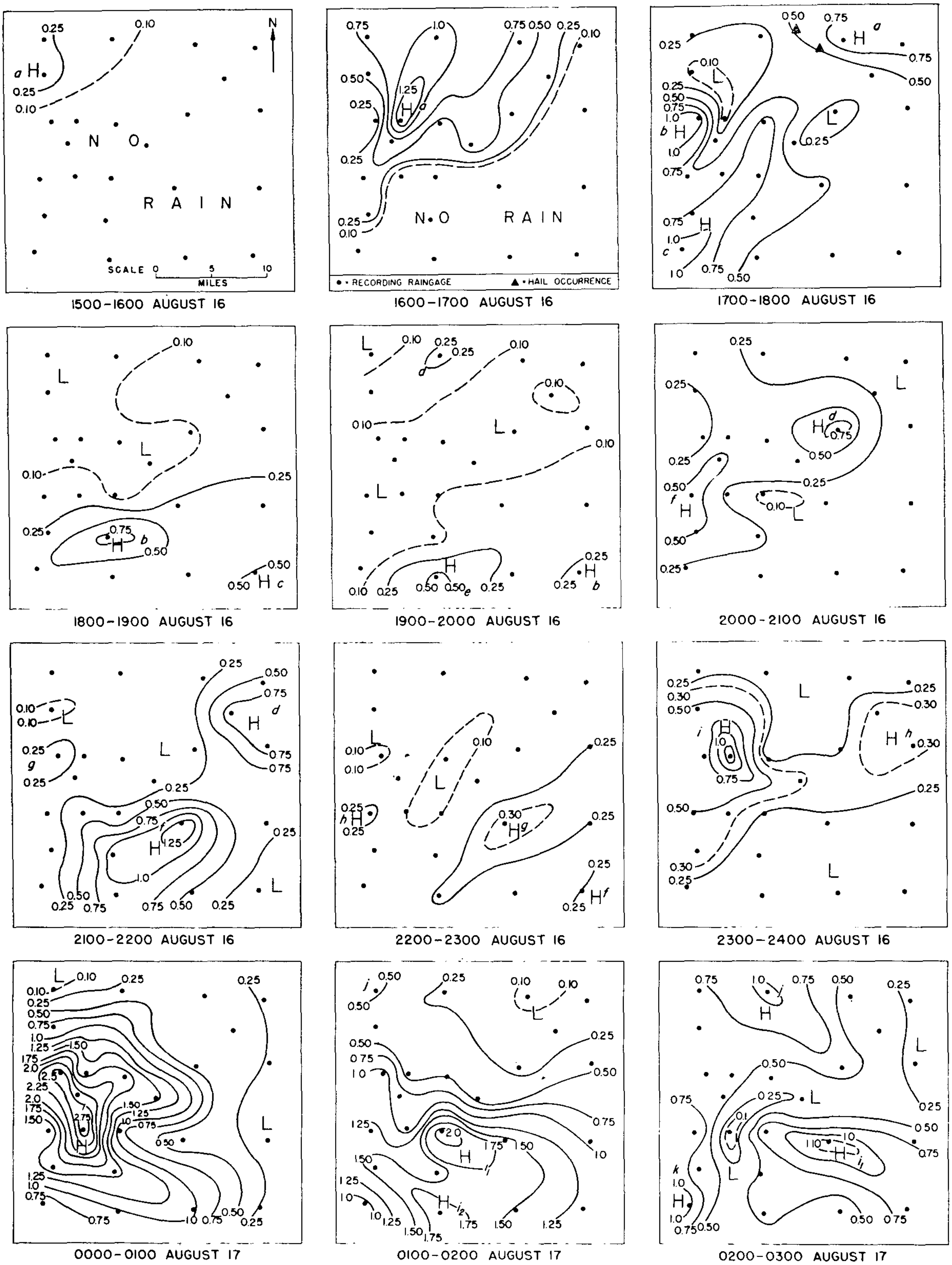

Fig. 10. Hourly rainfall maps for 16–17 August 1959.

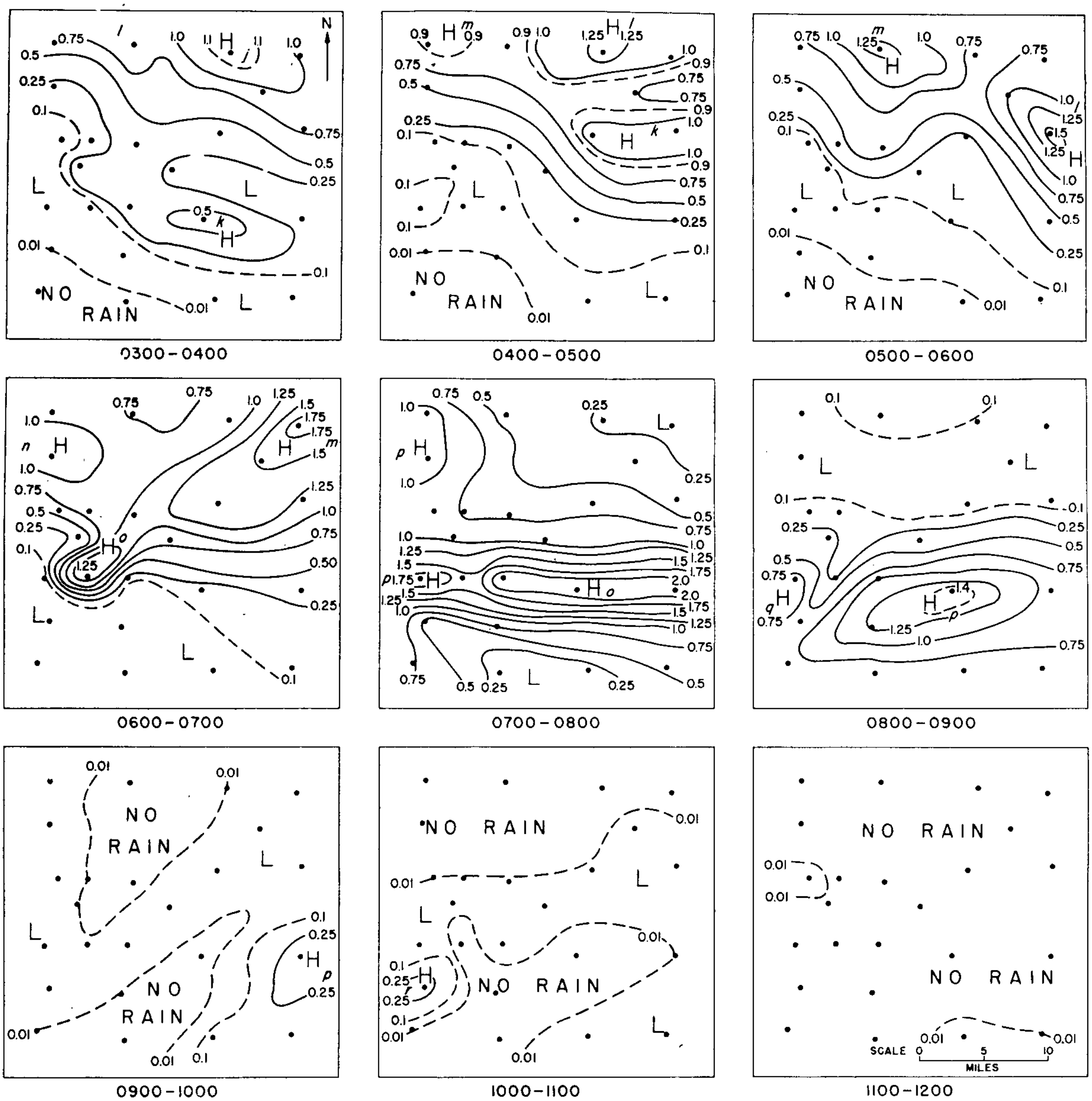

FIG. 11. Hourly rainfall maps for 17 August 1959.

from the 10-storm model only slightly modifies the model.

Analysis of radar and recording raingage data has revealed other interesting features of the 10 severe rainstorms (Huff, 1960). All occurred with quasi-stationary squall zones through which several lines or groups of thunderstorms passed. Intersecting and/or merging squall lines were observed in the heavy rainfall zone with five of the storms, and these mergers appeared to be associated with the initiation of the heavy rainfall at the start of three storms and with the occurrence of the heaviest rainfall burst in the other two cases.

In several cases, distinct waves were indicated on the squall lines and in other cases appreciable rotation of lines was noted. On 8 of the 10 storm days, squall lines with orientations differing by 45 deg or more were observed within 200 mi of the radar station depicted on Fig. 5. These lines displayed converging motion, with generally west-east oriented lines moving in a northerly or southerly direction, while other lines with north-south to northeast-southwest orientations moved in an easterly direction. These observations indicate the presence of relatively strong convergence on a meso-scale on days with severe rainstorms. This situation was found to be common also on days with heavy rainfall on which intensities exceeded one inch per hour but which did not result in the type of severe rainstorms discussed in this paper (Huff, 1960). Therefore, the use of such radar observations should be useful in short-range forecasts of heavy rainfall.

Other frequently observed characteristics of the severe rainstorms include: presence of minor troughs aloft, most frequently observed at the 700-mb level but often detectable from the 850-mb level to the 500-mb level, as in the 16–17 August storm (Fig. 4); Showalter stability indices of +2 or lower; development of the rainstorm near the boundary of a cloudy, rainy zone and a partly cloudy, humid zone with little or no rainfall in the previous 12 hours; development of the rainfall zone in late afternoon or early evening, maximizing of rainfall intensity during the night, and dissipation in early forenoon shortly after sunrise; and, the presence of a widespread area of humid, relatively unstable air over the midwest, built up over a period of several days.

8. Summary and conclusions

A severe rainstorm in which amounts exceeded 10 inches in 16 hr occurred in southern Illinois and bordering states on 16–17 August 1959. A raingage network consisting of 54 gages in 550 square miles was located on the major axis of this storm. Rainfall amounts in the storm center within the network exceeded the 100-yr frequencies in this area.

Radar observations indicate that this severe rainstorm was initiated over southern Illinois when a squall line, oriented east-west in extreme southern Illinois and moving slowly northward, merged with a squall line moving southeastward from central Illinois. Merging and subsequent intensification took place in the region of maximum precipitable water content at that time. The storm was sustained by a series of squall lines which moved into the storm zone during the 16-hr period following the initial merger.

Six lines of rainfall swept across the storm core and a total of nine lines occurred within or surrounding the storm region. Most of these lines were detected first in the surface rainfall pattern 75 to 100 mi northwest of the storm center. The supporting lines formed south of and approximately parallel with a 300-mb wind maximum located about 200 mi northwest of the storm core.

The rain cells developed vertically as they moved southeastward toward the storm region and through an area of divergence at the 300-mb level. As the squall lines approached the storm zone, they entered the region of maximum precipitable water and strong uplift which resulted in maximization of the precipitation process within the storm zone, a zone of wind convergence and cyclonic shear. As the lines entered the storm zone, their speed decreased greatly as they became oriented approximately parallel to the mean upper wind flow. Furthermore, the speed of individual rainstorms within the lines decreased greatly in the storm center, associated with blocking action on the winds from the well-developed portion of the convection system upwind from the surface storm core. As the lines moved southeastward out of the storm zone, they left the region of maximum precipitable water content and the upper level divergence field, and gradually dissipated. The storm ended when the zone of maximum moisture content drifted slowly southward, the upper winds veered to a more northerly direction, and drier air moved into southern Illinois during the forenoon of 17 August.

Comparison of the results of this storm analysis with other detailed storm analyses of severe rainstorms in Illinois indicates that the method of formation, sustenance, and dissipation described in the foregoing paragraphs is typical of most storms of this severity. The exceptionally detailed information obtained from the raingage network data for the 16–17 August case has aided in establishing a better understanding of the meso-scale structure and movements of such storms. The resulting characteristics of these flood-producing rainstorms are defined by the statistical model presented in Table 4. Furthermore, the storm characteristics revealed by the analysis of the Illinois storm data should be representative of those in rainstorms which occur in regions of similar climate and topography.

Studies of these severe rainstorms stresses the necessity of meso-scale observations of hydrometeors to supplement macro-scale synoptic data, if such storm formations are to be recognized and predictions made of the downstream flood potential. The use of 10-cm radar equipment, such as the WSR-57, offers a means of obtaining much of the meso-scale data necessary to permit short-range forecasting of these severe storm events.

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