REPORT OF INVESTIGATION 66

ILLINOIS

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Heavy Rain, Hail, and Tornadoes on 15 May 1968

by STANLEY A. CHANGNON, JR., and JOHN W. WILSON

ILLINOIS STATE WATER SURVEY

URBANA

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Reference: Changnon, Stanley A., Jr., and John W. Wilson. Heavy Rain, Hail, and Tornadoes on 15 May 1968. Illinois State Water Survey, Urbana, Report of Investigation 66, **1971.**

Indexing Terms: Depth-area-duration analysis, design hailstorm, dimensional analysis (rain cells), excessive precipitation, hailstorms, Illinois, rainfall-runoff relationships, severe storms, storm damages, synoptic analysis, thunderstorms, tornadoes.

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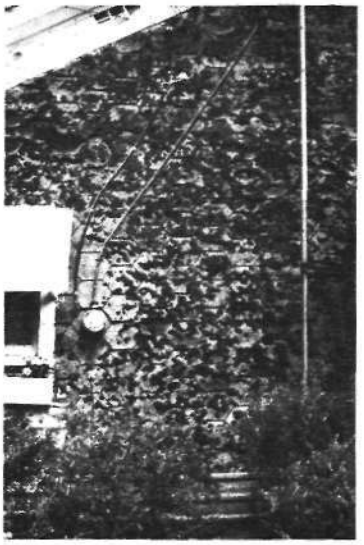
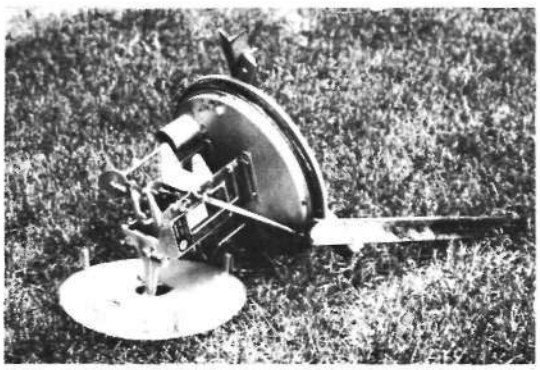
CONTENTS

Tornado-damaged house in Farmer City. Note the 4 x 8-foot plywood sheet driven endwise into the side of the house (Tornado D) .

Damaged house at network gage 111 east of Farmer City (Tornado D). Note 2 x Vs driven through roof.



Damage from a 32-minute hailfall (super hai1 - streak) west of Wapella. Asphalt siding on three sides was ruined and all windows broken.



Remnant of Water Survey recording raingage number 119 hit by Tornado D.

Farmstead 3 miles east of Wapella showing typical tornado damage to buildings and trees (the barn was totally flattened). A Water Survey raingage at the rear of the farmstead was blown away (Tornado C).

An illustration of multiple forms of severe weather. Excessive runoff down Salt Creek on the south side of Farmer City swept away bridge foundations, resulting in its collapse (l4 other rural bridges collapsed) and Tornado D caused the damage at the farm.

Excessive runoff southeast of Mansfield on Madden Creek, tributary of the Sangamon River, swept these two vehicles off route 150 and also swept away 280 feet of fill under the Penn Central R.R.

Power distribution tower, one of 78 such towers destroyed by Tornado C, in the area west of Wapella. These were constructed to withstand winds of 120 mph.

Example of ponding and minor tornado damage at farm west of Farmer City (Tornado D).

Figure 1. Photographs of various types of damage produced in the Central Illinois Network on 15 May 1968

Heavy Rain, Hail, and Tornadoes on 15 May 1968

by Stanley A. Changnon, Jr., and John W. Wilson

ABSTRACT

On 15 May 1968 a severe storm combining heavy rain, tornadoes, and extensive hail occurred and maximized over a 1765-square-mile dense raingage-hailpad and hail observer network in central Illinois. In a 14-hour period the network area had 4 major rain systems which included 19 thunderstorms (rain cells) and point rainfalls exceeding 10 inches, 113 hailstreaks with hail over 1664 square miles, and 6 tornadoes. Crop and property damages were extensive, estimated at over $10 million for the total storm; 4 persons were killed and 56 injured by the tornadoes.

One rain system was a gigantic steady-state storm that produced excessive rain rates, the tornadoes, and a "design" hailstreak which lasted 90 minutes with point durations up to 45 minutes, covered 788 square miles, and produced 2-inch hailstones. Rainfall rates for durations 'ranging from 15 minutes up to 6 hours easily exceeded 100-year point frequency values, and at its peak, the steady-state storm released 883 million cubic feet of water in one 15-minute period. The exhaustive analysis of the hailfalls revealed that the energy of some point hailfalls exceeded 25 foot-pounds per square foot, and the 113 hailstreaks were 42 percent of the network total in 1968.

Many synoptic weather conditions conducive to severe weather outbreaks existed in central Illinois on 15 May, but there was uniqueness about the fact that all four rain systems in Illinois maximized their rain, hail, and tornado production within a 1765-square-mile area. The afternoon steady-state storm developed, moved, and maximized where the first (morning) storm system occurred, strongly indicating that the conditions critical for severe weather formation had not altered their geographical position over a 6-hour period, a situation frequently necessary for the production of 10-inch or greater rainfalls in Illinois.

Certainly, the coincidence of severe weather, and especially a gigantic steady-state storm, over a large mesonetwork allowed study of the time-area surface structure of the storm systems over a larger area and in greater detail than heretofore possible.

INTRODUCTION

A major continuing goal of the Atmospheric Sciences Section of the Illinois State Water Survey is the thorough study of severe storms, particularly those producing heavy rainfall in short periods (6 inches or more in less than 24 hours). Several prior studies of such heavy rain conditions have used historical data[1,2,3] for climatic studies, whereas others have concerned field investigations of relatively recent severe rainstorms.[4,5,6,7]

A unique severe storm combining heavy rain, six tornadoes, and very extensive severe hail (figure 1) occurred in central Illinois in a 14-hour period on 15 May 1968. One phase of this storm consisted of a gigantic steady-state storm system. The complex storm, which was composed of four rain systems, occurred and maximized within the confines of a mesoscale measurement network operated by the Illinois State Water Survey. This network comprised 172 recording raingages, each modified to record time of hail, 96 passive hailpads, and 261 cooperative hail observers scattered throughout a 1765-square-mile area. This fortuitous coincidence of severe weather in a large mesonetwork provided an excellent opportunity to study the time-area surface structure of the storm's systems over a greater area and in greater detail than had been previously possible. An earlier heavy rainstorm had occurred in a Water Survey network in southern Illinois,[8] but the extent of that network (500 square miles) could not furnish the mesoscale information that was available for the May 1968 storm on the large Central Illinois Network.

Thorough study of this major storm system has been accomplished to present: 1) extensive time-area information on the storm rainfall for agricultural studies and for hydrologic systems design; 2) detailed analyses of many

hailstreaks from a "design" hail-producing system, extreme in both areal size and frequency of hail; 3) time-space studies of the simultaneous occurrence of hail and tornadoes with respect to rainfall; 4) dimensional data on rain cells in major rainstorm systems; and 5) information on the macroscale and mesoscale synoptic weather conditions that led to such a storm system.

This report consists of eight major sections, and the first treats the forms of data and analytical techniques that were employed. This is followed by a section on the synoptic weather conditions including surface and upper air analyses. The next section is a description of the storm morphology within Illinois as derived from radar, rainfall, and synoptic weather data.

The next four sections of the report deal with the four individual storm phases that occurred on the dense network. Those four phases, presented in chronological order, include the morning thunderstorm complex, the midafternoon steady-state storm, the late afternoon feeder storm system, and the evening squall line-cold front storms. Each of. these sections presents information on the temporal distribution of rain, hail, and tornadoes as well as on individual rain cells and hailstreaks and on the total rain and hail conditions. The final section of this report is a total storm analysis including the hydrologic information derived from the storm and the storm damages.

Acknowledgments

This report was prepared under the general supervision of Dr. William C. Ackermann, Chief of the Illinois State Water Survey, and under the partial supervision of Glenn E. Stout. Many people assisted in the compilation and analysis of the data relating to the 15 May storm. Ronald E. Rinehart and William L. Shipp of the Survey staff materially assisted the authors in the field surveys to collect the rain, hail, and tornado data. Mr. Shipp also compiled and analyzed much of the subsequent tornado data. Mrs. Edna Anderson and Daniel D. Watson performed much of the routine data analysis. Support for certain of the data collection and analysis came from the National Science Foundation (GA-482) and the Crop-Hail Insurance Actuarial Association.

Others of the Survey staff contributed materially. Mrs. J. Loreena Ivens reviewed the manuscript, and John W. Brother, Jr., and William Motherway, Jr., performed the drafting of the figures.

DATA AND ANALYSES

Rainfall Data

Much of the rainfall data used in this storm study came from recording raingages in a raingage network of the Illinois State Water Survey (figure 2). At the time of the storm, this Central Illinois Network was not quite complete since 24 raingages were yet to be installed in the southwest corner (figure 2). Thus, there were 172 gages installed in a uniform array with 3-mile spacing in a 1550-square-mile area. The planned network, completed by 28 May, consisted of 196 recording raingages in a 1765-square-mile area.

All of the 172 gages operating on 15 May were standard weighing bucket gages, and 168 had 24-hour clocks producing data that allow excellent resolution of 15-minute amounts. Detailed analysis of amounts was enhanced at 24 gages which had 12-inch diameter orifices; all other gages in the network had standard 8-inch diameter orifices. The temporal analyses of the rainfall data and all other meteorological and field survey data were based on Central Daylight Time since it was the local time.

From data and analytical considerations it was fortunate that the heaviest rains centered in the gaged portion of the planned Central Illinois Network rather than in the ungaged southwestern portion. However, useful rainfall data for this southwestern ungaged area were secured from 12 cooperative hail observers, arranged for by an on-going hail project,[9] who each had wedge-type raingages. Ten of these observers had emptied their gages after various rainfall periods during the storm, and thus were able to furnish data much more useful than just a daily total.

Further storm rainfall data for 26 locations in the area extending 20 miles east of the network and between Champaign and Gibson City (figure 2) were secured during the 4 days following the storm by field surveys. The final source of rainfall data used in the storm study was that from the nonrecording and recording raingage stations operated by ESSA at scattered locations throughout Illinois. These data helped define the total storm rainfall pattern as well as the morphology of the storm systems on 15 May.

Each of the charts from the 172 recording raingages for 15 May was analyzed to obtain 15-minute (clock hour) amounts, amounts for selected longer periods (rain cells and storm systems), and storm totals. These were analyzed after carefully correcting for 1) any time errors due to systematic clock speed variations (as noted on figure 3) or chart installation time errors, and 2) any errors in measurement of rain amount. Rainfall in the bucket of each gage was emptied into measuring tubes and stick measured. This "stick" total was compared with that amount shown on the chart at the removal time, and the chart values were linearly altered to match the stick

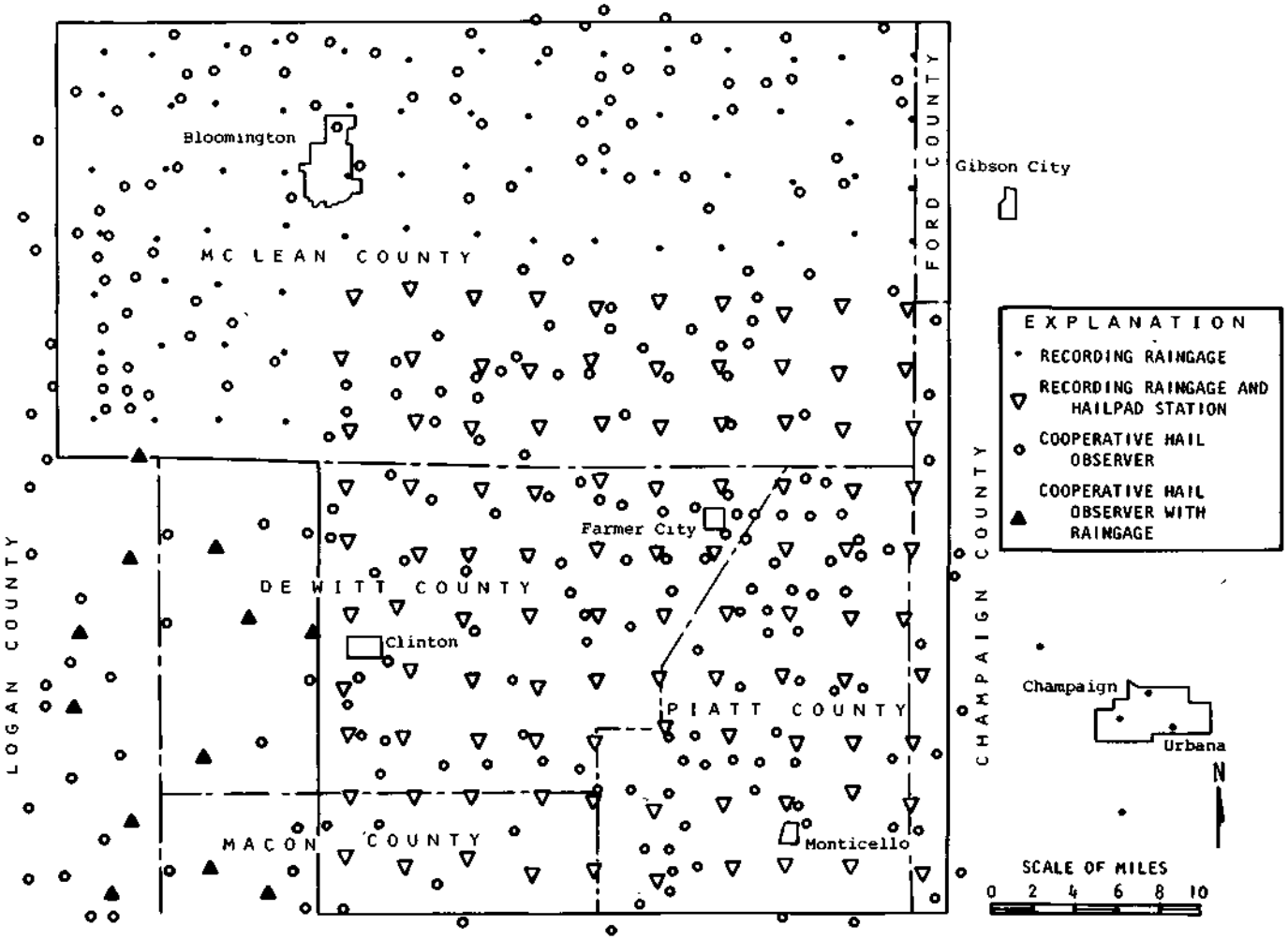


Figure 2. Central Illinois Network

measured amounts if a difference existed. For instance, the chart for gage 135 on figure 3 indicated 9.75 inches at its removal (off) time, whereas the "stick" amount was 9.80 inches. Thus, in the final analysis, 0.01 inch was added to each 2-inch amount indicated on the chart.

All but four raingages were serviced by Water Survey personnel within 2 days after the storm. Four gages had to be serviced 5 to 6 days after the storm because flood waters blocked access roads to these gages. Two other raingages were badly damaged by tornadoes. On one of these gages the chart was destroyed, but a storm total was obtained by measuring the water in the bucket. Most of the other gage (figure 1) was blown away, but the base with the clock and chart remained so that rainfall amounts that occurred prior to the tornado could be determined. This gage also furnished a good measure of the time of the tornado.

The 15-minute rainfall amounts, selected storm amounts, and the storm totals were analyzed in various ways to describe network rainfall depths and to develop isohyetal maps.

A part of the temporal analysis of the rainfall data included the mapping and study of the rainfall produced by individual rain cells, each of which was a thunderstorm on 15 May. Such an analysis for rain cells in a heavy rainstorm had not been possible in all previous studies of heavy rains because the earlier raingage networks had been too small (20 by 20 miles) to measure anything but a portion of the large rain cells that existed in such conditions.

A rain cell was determined by a time-space analysis of the point rainfall data within the network. In general, a rain cell at a point was considered to be either a period of rain separated from other rainfall by a 5-minute or longer period of no rain or by a distinctive change in rainfall rate. The rain cells defined at gages 107 and 135 are denoted in figure 3. When two cells converged at a point due to different speeds or directions, their values were determined on a basis of changes in rain rate and from a consideration of the cell speeds. The rain begin times, end times, and amounts for each rain cell at each raingage were plotted on a large base map to permit 1) preparation of isohyetal maps for each cell, and 2) identification of the individual cells on the 15-minute rainfall maps. On the 15-minute maps that contained two or more rain cells, boundaries between cells were drawn, but these sometimes were generalizations where the edges of adjacent cells had overlapped.

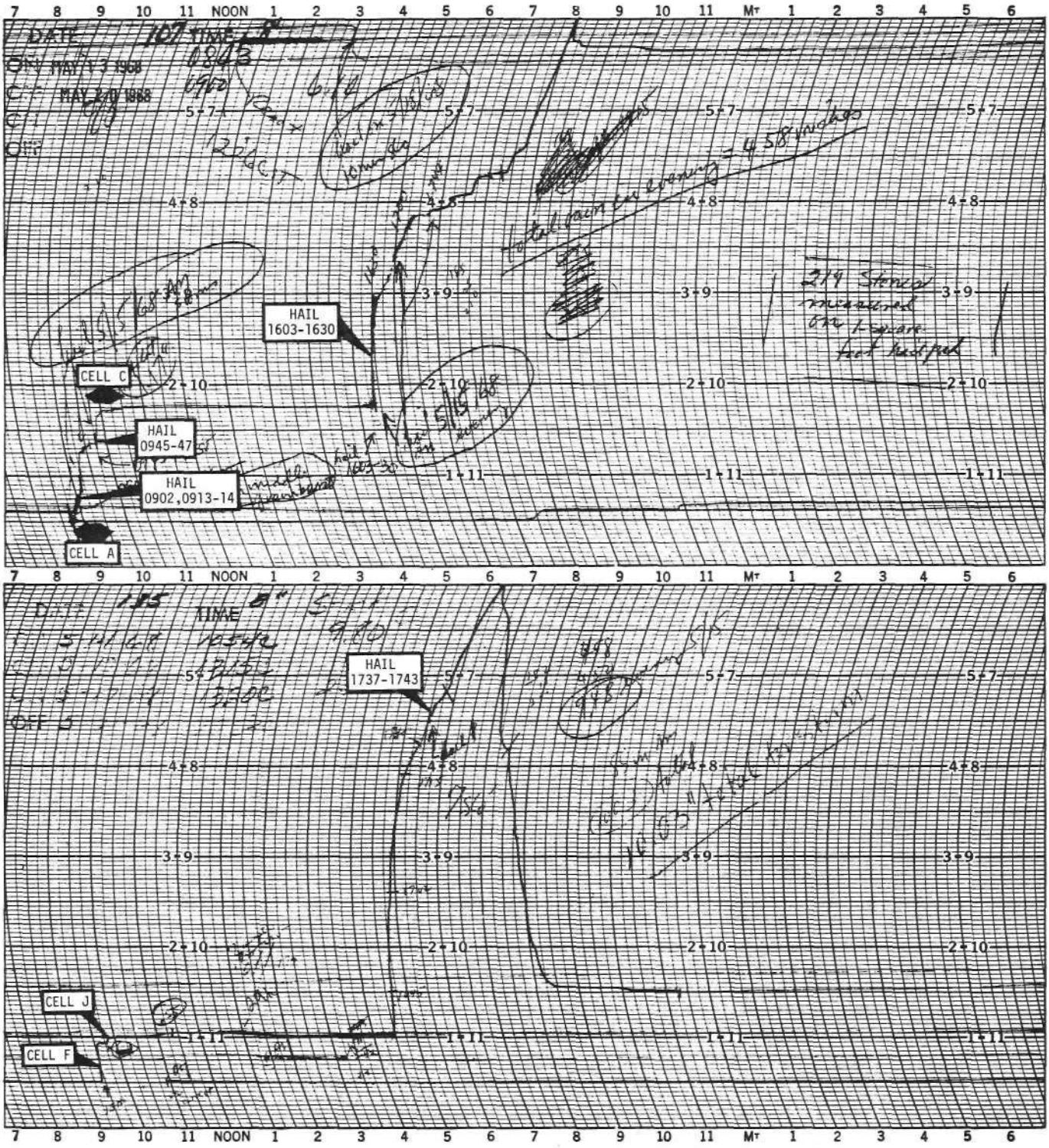


Figure 3. Charts for raingages 107 and 135 depicting high rainfall rales and hailfalls

Hail Data

Hail data were collected from five sources within the primary study area (figure 2), resulting in 461 point reports or measurements of hail for 15 May. All 172 raingages had been modified, by removing the evaporation funnels, to allow recording of any hail that fell into the bucket,[10] and 164 gages experienced one or more hailfalls on 15 May. Examples of the recorded hail "spikes" are shown on the charts of figure 3. Gage 107 had continuous hail from 1603 to 1630 GDT, a period when more than 1 inch of precipitation occurred. Several other lesser hail spikes are apparent in three different morning periods (0902, 0913-14, and 0945-47), and two others exist after 1700. Hail at gage 135 is indicated by spikes in the 1737-43 period.

Added hail data were obtained from 1-square-foot hailpads installed. near 96 of the raingages, at sites marked on figure' 2. The hailpads consist of styrofoam blocks, 1-inch thick and 12 x 12 inches, which are wrapped in 0.015-inch thick aluminum foil. These are placed on metal stands and supported at one foot above ground level. The hailstones leave dents in the foil that can be measured and translated into stone diameters and energy using a calibration procedure.[9] A total of 94 of the 96 hailpads experienced hail.

A third source of hail data consisted of 261 cooperative hail observers distributed throughout the network study area (figure 2). These observers were supplied with recording cards that allowed reporting of time of hail, the average and maximum stone sizes, number of stones per square foot, type of stone, associated hail damages, winds, lightning, and rainfall. Detailed hail reports for one or more hailstorms were received from 147 of these observers, and 88 others were contacted by telephone to confirm that their lack of report was due to an actual lack of hail occurrence at their sites.

The field surveys provided useful data on hailstone size and hail time at 19 other locations. All of the hail insurance companies with policies in and around the network area furnished copies of their detailed loss worksheets that had been used by adjusters to settle 176 paid claims, of which 131 were in the network area. The worksheets indicated the exact physical location of the field with loss and the type of crop.

In the initial phase of the hail analysis, all times (begin and end) of hail at all 330 points with such data were plotted on one large base map. This map data allowed 1) counting and analysis of the number of distinct hail falls per point (separated by 10 minutes or more), 2) the analysis of hailstreaks, or areas of hail that come from a single hail cell imbedded in a storm,[11] and 3) determination of the extent of the hailfall areas for each 15-minute period during the storm. Maps of hailfall energy were constructed from the hailpad data, and maps for the number of stones per square foot were developed from observer data and the hailpad data.

Tornado Data

Data on the tornadoes in the network study area were gathered largely from extensive field surveys conducted by Water Survey personnel during the 8 days following the storm. People in the network area were interviewed to gather information on times of storm occurrence, visual descriptions of the tornado clouds, and types of damage. Added information on the extent and nature of these storms was gathered by field mapping the location of damaged buildings, trees, and fences, and the types of patterns shown by the debris on the ground.

More than 200 persons were interviewed, and locations and types of damage were noted for 158 sites in the network. These data were used to reconstruct the temporal positions of the tornadoes as well as to define their areal extent and motion.

Radar Data

Unfortunately, the radars of the Water Survey were not operating on 15 May because of equipment problems. An FPS-77 located at Chanute Air Force Base in Rantoul, 12 miles east of the network, was operating during a short period on the morning of 15 May, and two RHI photographs of the storm echoes on the network were available and useful.

Most of the radar data available and used in the analysis of the 15 May storms were the PPI photographs from a WSR-57 radar operated by ESSA at St. Louis. Unfortunately, this set was too distant (100 to 130 nautical miles) from the various network storms to provide desired detailed echo data. At this range the beam of this radar has a considerable volume and at 0-degree elevation is centered at 12,000 feet above the terrain. However, PPI photographs, generally available once every 20 to 30 minutes during the day, were useful in analyzing the general storm-echo morphology. Selected echo height data recorded in the operational logs by the St. Louis radar operators were useful in obtaining information on the maximum vertical extent of the storm echoes over the network at selected times on 15 May.

Synoptic Weather Data

Extensive surface and upper air analyses were performed to examine the cause for and behavior of the storms which occurred on 15 May. The data used in these analyses were all taken by the U. S. Weather Bureau of ESSA, and were supplied to the Water Survey by that organization.

Facsimile maps were used as a guide to synoptic-scale patterns. Surface maps prepared at 3-hour intervals by the National Meteorological Center (NMC) were useful in determining the approximate time of events, and for

choosing periods for more intensive analysis. The data. for these maps were synoptic observations made at several hundred weather stations in North America. Such data include cloud heights and amounts, temperatures, dew points, winds, barometric pressures, and weather occurring at and prior to observation time.

Upper air facsimile data were composed of two general types of maps, constant pressure charts and charts of miscellaneous upper air data. Radiosonde balloons released twice daily from approximately 100 stations in North America gave temperatures, relative humidities, and winds from the surface to altitudes of over 20 miles. Maps of these data are plotted and analyzed by NMC for several constant pressure surfaces, and the analyses are used to determine upper air movement and conditions. The miscellaneous upper air charts contain such parameters as atmospheric stability, freezing level, tropopause height, upper air prognostic charts, and other maps useful to the forecaster. These maps are prepared by calculating the selected parameters from radiosonde data, and plotting the results of the computations.

When selected time periods had been chosen for intensive analysis, the facsimile maps were replaced by locally prepared maps analyzed in more detail. Surface maps were made using data taken at hourly rather than 3-hourly intervals. Teletype data in the airways reporting code were used as the data source for the maps. Only data from Illinois, Indiana, southern Wisconsin and Michigan, and eastern Iowa and Missouri were analyzed. Isobaric analyses at 2-millibar (mb) intervals were performed on hourly data for most of 15 May. From the same data, isotherm, streamline, and neph (cloud) analyses were also made.

The only re-analysis done for the upper air data involved constant pressure maps. The 850-, 700-, 500-, and 300-mb maps were analyzed for 0700 and 1900 CDT on 15 May in more detail than the NMC versions. These analyses showed small-scale features important in the overall analysis of the storms. Such features were not evident on the facsimile charts.

Results from the Peoria, Illinois, radiosonde released at 0700 CDT on the 15th were analyzed carefully for characteristics of the upper air. Since air over Peoria was involved in the generation of the storms, a careful analysis was necessary to ascertain its characteristics.

SYNOPTIC WEATHER CONDITIONS

Surface

The 15 May 1968 storms were in advance of an approaching cold front. Maps of surface weather features during the period of interest are shown in figure 4. A low pressure system formed in Oklahoma on the 14th, and by 0700 CDT on the 15th had moved northward into Nebraska.

During the morning the low moved into northwestern Iowa, and the weak E-W oriented cold front became a weak warm front and moved northward. The U. S. Weather Bureau analyzed the 1300 CDT Illinois weather to contain a squall line (figure 4), and the morning storm system was part of this line of thunderstorms.

The low deepened during the afternoon and moved little. The 1900 CDT map showed one squall line from Illinois into Ohio and another in southwestern Missouri. The afternoon steady-state thunderstorm had passed through the network by this time, and the feeder system was affecting the southern half of the network.

The fourth stage of the 15 May storms, the prefrontal squall line, passed through the network between 2000 and 2200 CDT. By 0100 CDT on the 16th, the cold front had begun to enter the network (figure 4), and all severe weather in Illinois had ended. The cold front dropped temperatures by 25 to 30 F (into the 50s) as it passed through the area.

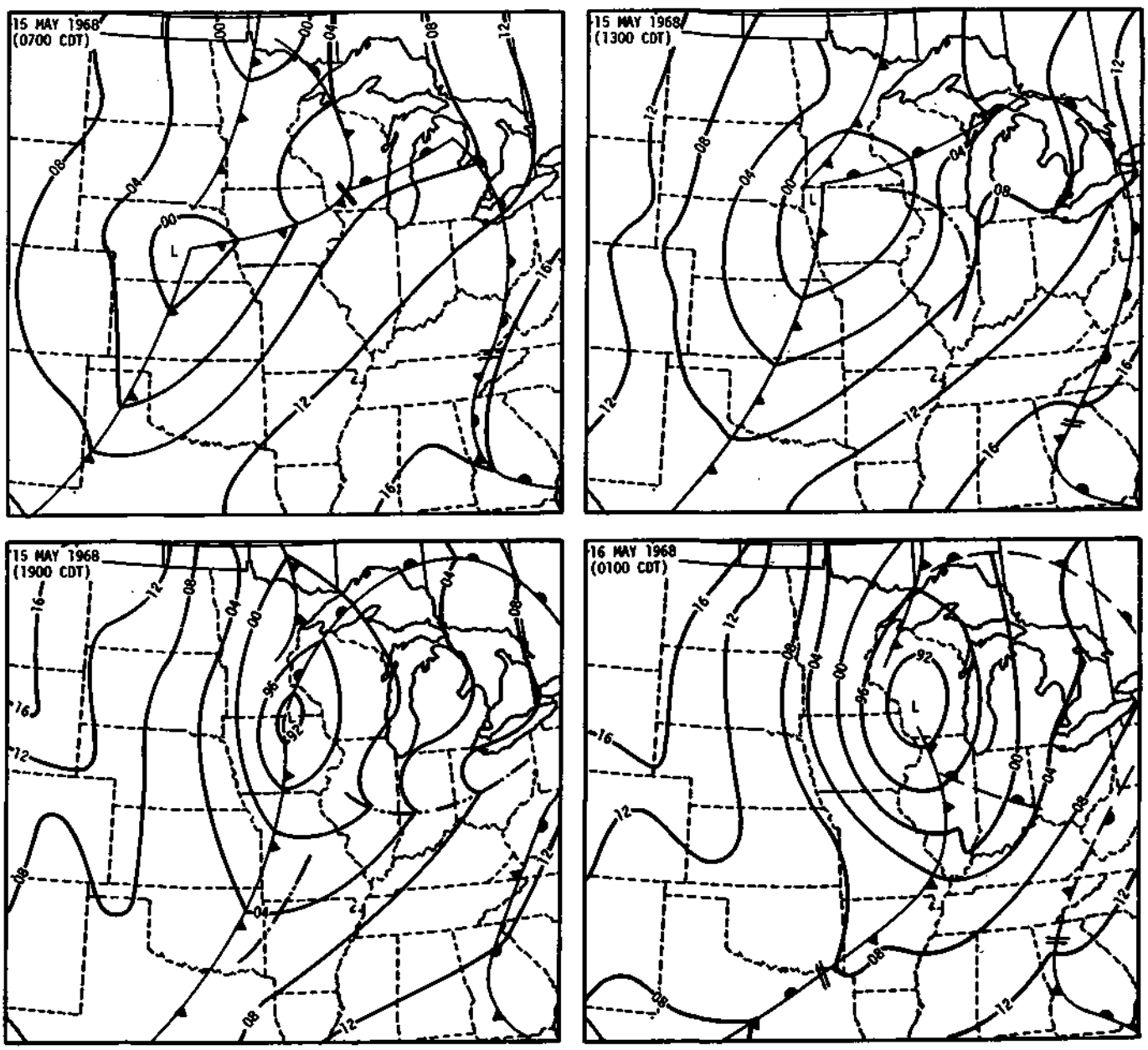


Figure 4. Surface weather maps at (elected times on 15 and 16 May

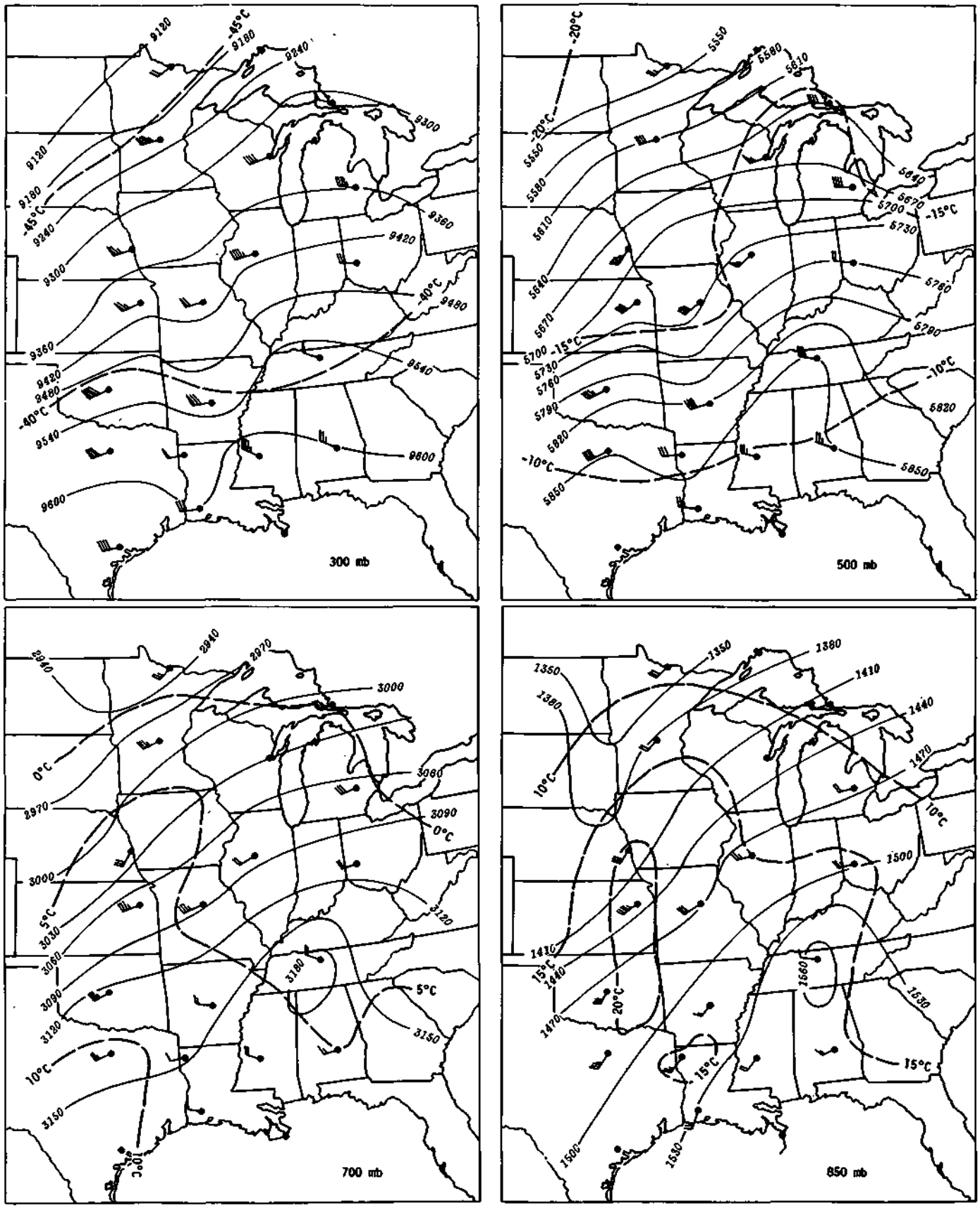


Figure 5. Upper air maps for 0700 CDT on 15 May

Considerable severe weather was prevalent in other states prior to passage of the cold front. Forty tornadoes were reported between 1100 CDT on 15 May and 0500 CDT on the 16th. Arkansas and Iowa received most of this activity, although tornadoes were also reported in Illinois, Indiana, and Missouri.[12]

Upper Air

Figure 5 depicts the upper air situation over the Midwest at 0700 CDT on 15 May. The flow was generally southwesterly, on the front side of a large trough which sloped to the west with height. A very small, almost vertically oriented trough in Iowa and Missouri seemed to strengthen with height up to 300 mb. This trough was not evident on the NMC analysis and, as will be shown later, was one of the prime factors affecting the afternoon severe storm. Columbia, Missouri, reported veering of the wind with height at 0700 CDT, although Peoria, Illinois, did not. Considerable warm air advection was present into and northeast of the Illinois area from the surface through 700 mb. This tended to destabilize the atmosphere, and forced the winds to veer with height later in the day.

The radiosonde sounding shown in figure 6 was made at Peoria at 0700 CDT on the 15th. This was analyzed by eliminating the inversion close to the surface, as the sun would do shortly after sunrise. Several interesting things could then be learned from this modified sounding.

The atmosphere was conditionally unstable, with the exception of a small, nearly isothermal layer near 23,000 feet at the top of a deck of cirrus clouds (probably the anvil from an early morning thunderstorm). The high degree of instability was evidenced by the Showalter index, -6.5 for the 850- to 500-mb layer. If the 830- to 500-mb layer is used instead (to be above the clouds at 850 mb), the index increases to zero. This is still fairly unstable.

The lifting condensation level (LCL) was 2500 feet above ground level, while the convective condensation level (CCL) and level of free convection (LFC) were both at 3800 feet or 850 mb. (The lifting condensation level is the height at which a parcel of moist air becomes saturated if lifted dry adiabatically, and the convective condensation level is the height at which the parcel becomes saturated if heated instead. The level of free convection is the height at which a parcel first becomes warmer than its environment.)

If the air is to rise to the CCL, the convective temperature of 84 F must be reached. If this temperature is unattainable, condensation at a height between the LCL and CCL could take place by a combination of convection and physical lifting of the air. Once a parcel of surface air reaches the LFC, it will continue to rise until it arrives at the equilibrium level (40,000 feet in this case).

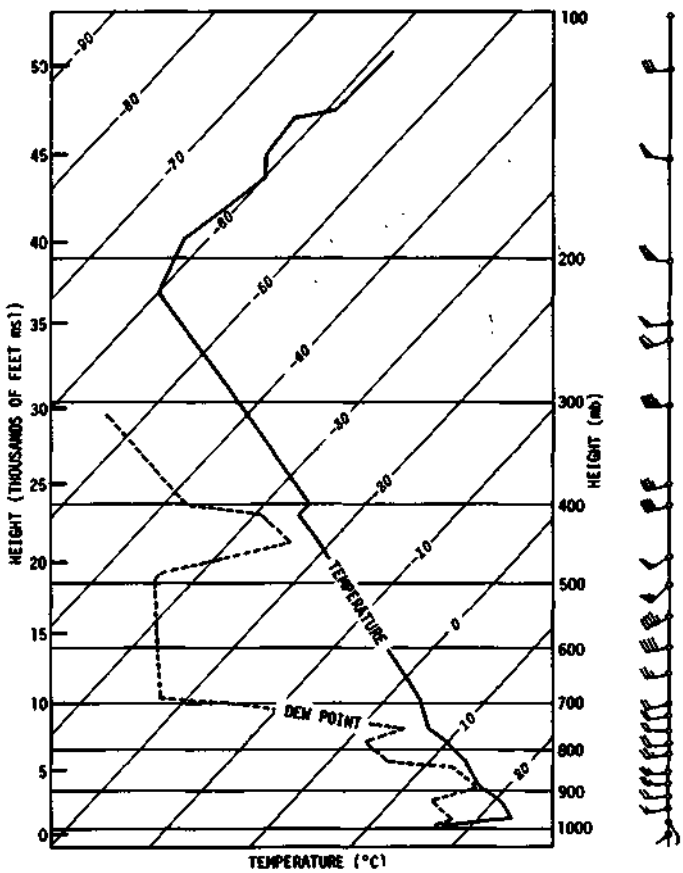


Figure 6. Sounding from the Peoria, Illinois, radiosonde released at 0700 CDT on 15 May

Air will continue to rise above this point only if it has sufficient momentum, since above the equilibrium level the parcel is cooler than its environment.

Moisture was adequate in the area. Precipitable water at Peoria amounted to 1.14 inches, of which 1.10 inches was below 700 mb. An extremely dry layer existed from 700 to 450 mb; average relative humidity dropped from 80 percent in the surface to 700-mb layer to 25 percent for the 700- to 500-mb layer.

Vertical windshear existed in the lower to middle troposphere, with wind speed increasing from 20 knots at 9000 feet to 54 knots at 18,000 feet. A second region of high winds was present from 35,000 to 45,000 feet with speeds greater than 50 knots prevalent. There was no veering with height at the time of the sounding, however.

Even though a nearby thunderstorm ended just prior to the release of the 0700 CDT radiosonde, the sounding was not affected markedly by the storm's proximity. This is evidenced by the instability at Columbia, Missouri, 175 miles southwest of Peoria. The Showalter index there was -6, the LCL was at 900 feet above ground level, and both the CCL and LFC were at 4800 feet. Moisture was present aloft, with precipitable water of 1.21 inches.

By 1900 CDT the entire upper air pattern had translated eastward, with the major low through Minnesota

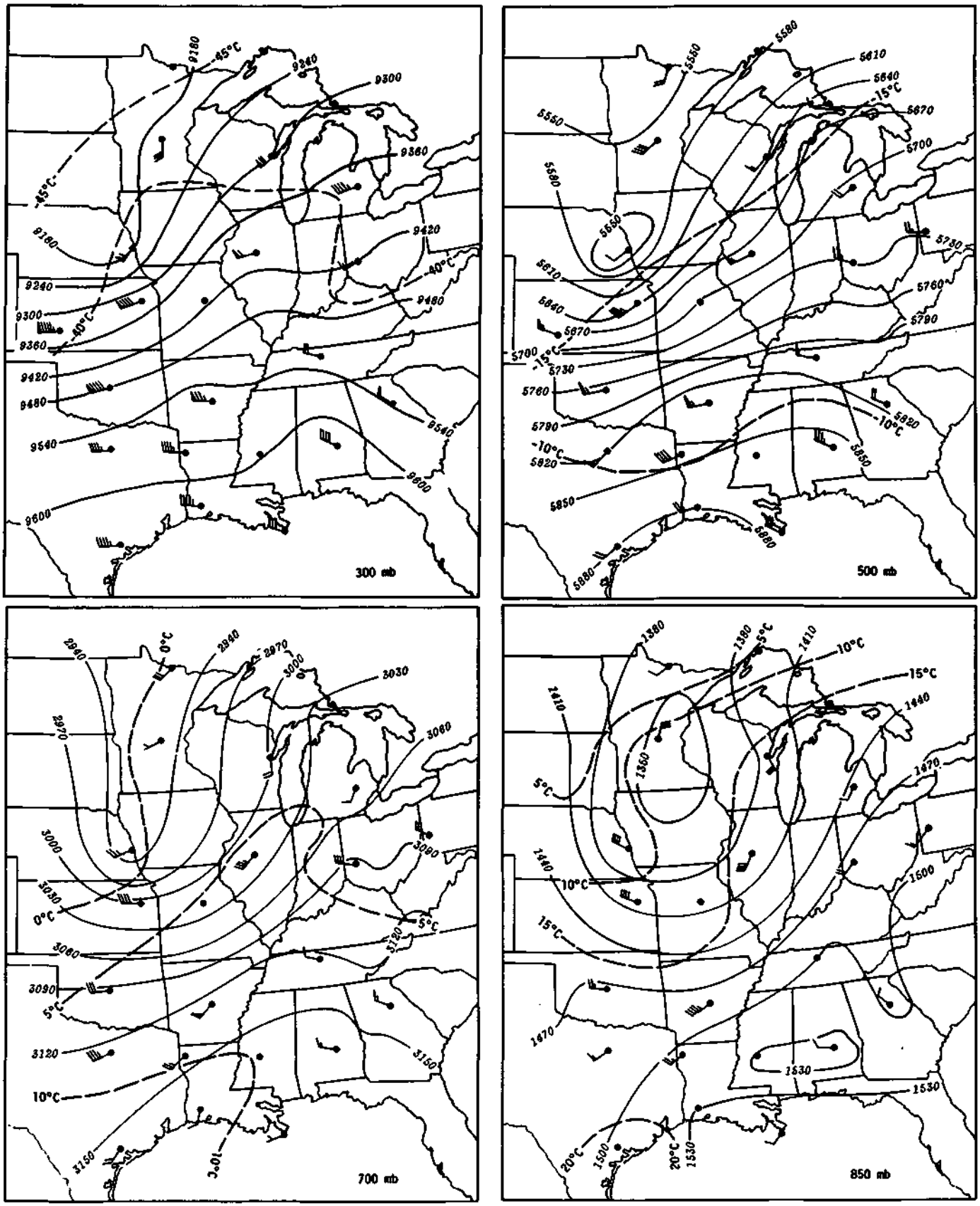


Figure 7. Upper air maps for 1900 CDT on 15 May

and Iowa (figure 7). The smaller trough had moved into Ohio and Kentucky, and it appears to have crossed central Illinois in the early afternoon. It is important to note that Dayton, Ohio, noted wind veering with height as the trough passed.

Since both Columbia and Dayton reported veering with height below 10,000 feet, it is valid to assume that the veering was present during the afternoon over Illinois. By plotting wind direction and speed profiles for Columbia and Dayton, a series of profiles was estimated to be midway between the two out-of-state values. These profiles were considered valid for midafternoon in central Illinois. The direction plot showed a secondary speed maximum of 35 knots present at 3000 feet, with higher level winds increasing to more than 50 knots. Lower tropospheric veering existed, with the direction changing from 235 degrees at 4000 feet to 275 degrees at 10,000 feet.

STORM MORPHOLOGY

The series of very severe storms in central Illinois on 15 May 1968 occurred largely within the dense raingage-hailpad and hail-observer network (figure 2). During the 14-hour period the 1765-square-mile network area had 19 major thunderstorms (rain cells), 113 hailstreaks, 6 tornadoes, and point rainfalls exceeding 10 inches.

The storm day in Illinois began with a minor thundershower that developed between 0500 and 0600 CDT (figure 8) west of Peoria and moved eastward. Just after 0800 CDT two thunderstorms developed just southwest of Peoria and subsequently joined (figure 8). Until this time the surface synoptic data had not depicted any unusual features that would have triggered these storms. The area was characterized by southerly winds, temperatures in the low 70s, and dew points of 65 F. A few small nocturnal thunderstorms had begun moving through central Illinois 3 hours earlier, and had undoubtedly modified the lower atmosphere. However, the specific triggering mechanism of the storms at 0800 is not known.

Once the storm's tops reached the LFC, they grew as they moved eastward across the state (figure 8). The direction of movement was approximately 10 degrees to the right of the mean 700-mb wind. Fed by warm air advecting into the area at heights above 700 mb, the storm system continued to grow. At 0952 CDT an FPS-77 radar located at Chanute AFB, 25 miles east of the storm system, indicated an echo top of 63,000 feet for a storm that produced 2-inch hailstones.

It is possible to estimate the vertical velocity at the equilibrium level of this storm, given the maximum cloud height. Vonnegut and Moore,[13] using the simplifying assumption of an isothermal stratosphere, found that a velocity of 10 knots was necessary for each kilometer of penetration. An upward motion of 70 knots at 40,000 feet can be calculated for 15 May. Since the cloud tops were probably higher than the echo tops, the 70-knot value is probably too low.

The system of maturing storms entered the network at 0900 CDT (figure 8), and by 1130 the 10 major thunderstorm cells had passed across the network. Most of these storms maximized as they crossed the network, with network rainfall amounts of 1.95 inches and damaging hail from some of the 48 hailstreaks that occurred. The size of the morning thunderstorm complex can be estimated from the ESSA 6 satellite picture in figure 9, taken at 1117 CDT. It shows the great extent of the anvil area, approximately 41,000 square miles, and the relatively clear area to the south of the complex.

Southern Illinois skies during the late morning were characterized by scattered to broken middle clouds (10,000-15,000 feet) with scattered cirroform clouds above, and although not totally free of clouds, this area was relatively clear. This is in contrast to the low or middle broken to overcast conditions beneath the anvil shield in northern Illinois. A temperature difference between southern and central Illinois was thereby partially caused by the dif-

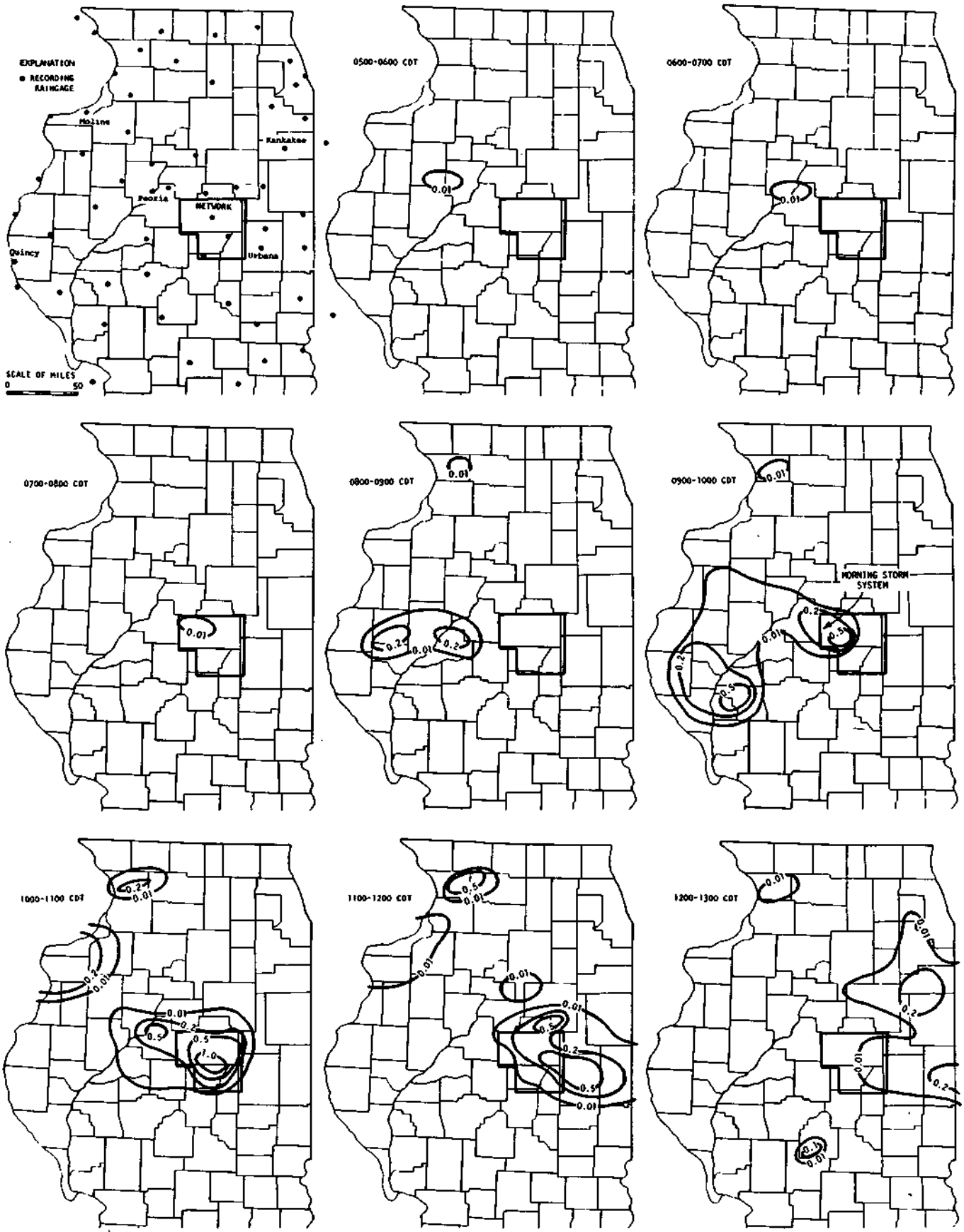


Figure 8. Hourly isohyetal maps for 0500-1300 CDT on 15 May

ferential insolation of the two areas. The cool outflow air in central Illinois from the thunderstorm system accentuated this difference, and between 1000 and 1100 CDT a mesoscale stationary front was formed in central Illinois and Indiana.

By 1400 CDT the surface weather pattern in the Midwest had several interesting mesoscale features (figure 10). The stationary front that separated the warm moist air in southern Illinois from the cooler thunderstorm outflow air to the north is quite evident. The inverted trough north of the front is nearly coincident with the northern boundary of the morning thunderstorm echoes.

At this time the first echoes of what would become a huge steady-state severe thunderstorm appeared on the St. Louis radar. Figure 10 also depicts how and where they were born. Warm air from southern Illinois moved northward at 10 to 20 knots, transporting moisture as it moved. Upon reaching the cold dome still present from the earlier storms, the air was forced to converge along the mesostationary front. The combination of the convergence and the already rising warm air accelerated the vertical motions, and it was only a short time until the air reached the level of free convection, 2500 feet above ground level. The area where the two early afternoon echoes first appeared (figure 10) was almost coincident with the origin of the morning storm system.

From this point the storm continued to build since the upper air requirements for explosive vertical and horizontal growth were already present. The two large nearby echoes at 1400 CDT had merged by 1500 CDT (figure 11) to form the giant storm, and the forward edge of the upper echo had moved much more rapidly eastward. This union of two thunderstorms between 1400 and 1500 produced a storm with a large horizontal dimension,

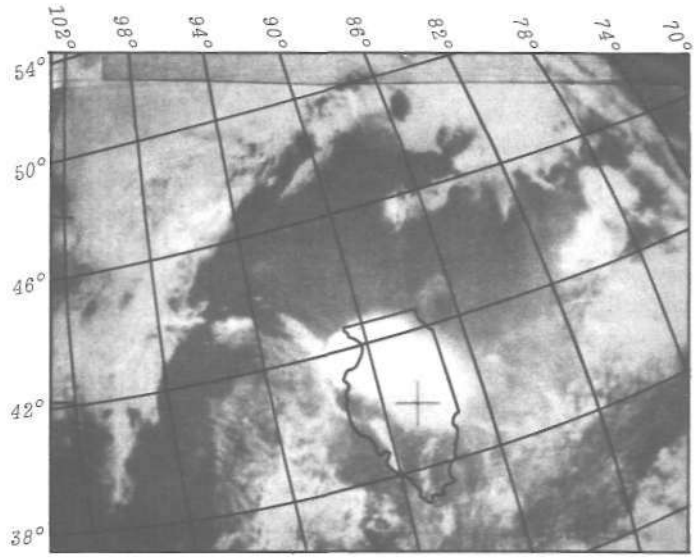


Figure 9. ESSA 6 satellite photograph over Illinois at 1117 CDT on 15 May

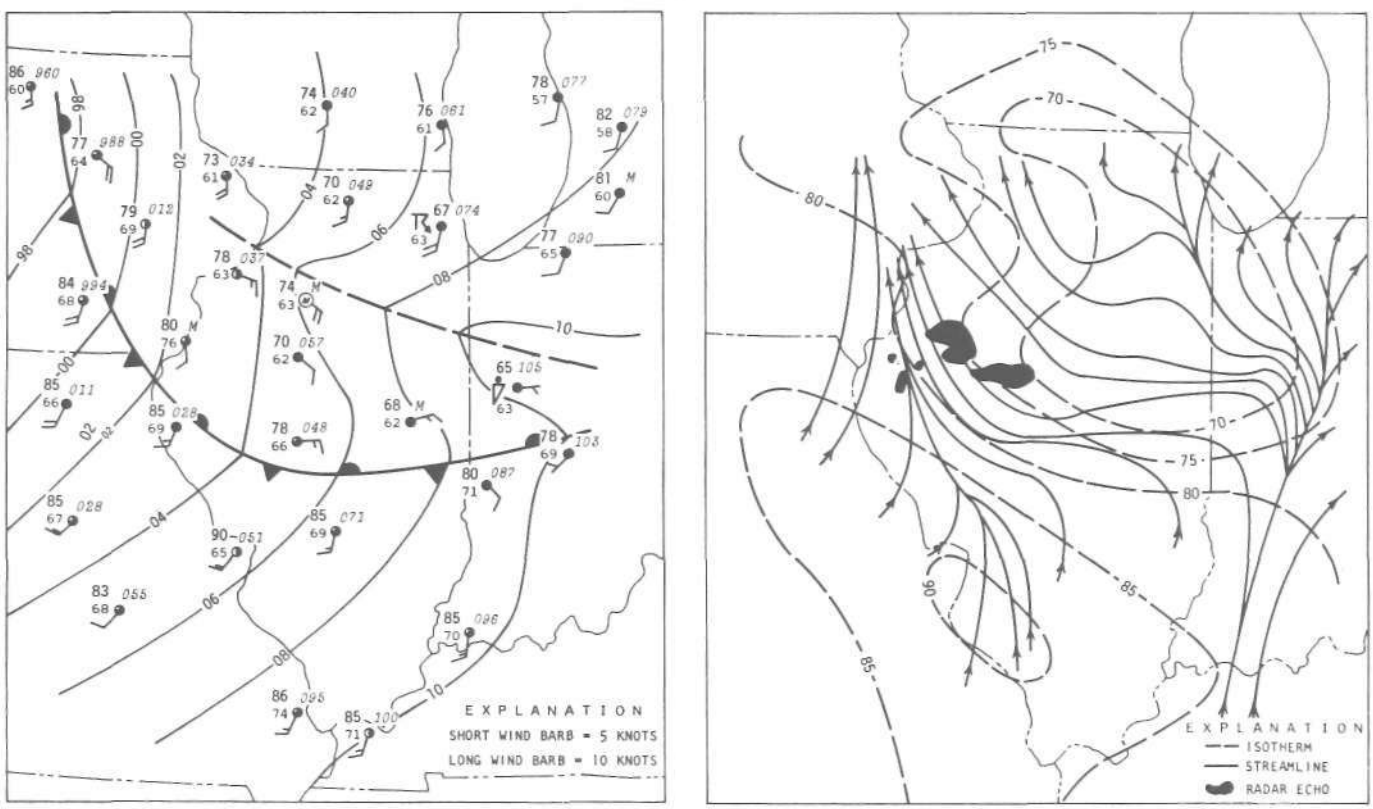


Figure 10. Mesoscale surface weather conditions at 1400 CDT on 15 May

which is a necessity for the growth of a storm to great elevations.[14]

The radar-indicated maximum storm top grew from 43,000 feet at 1500 CDT to 48,000 feet at 1600 and on to 50,000 feet by 1700 CDT (figure 11). Data from widely scattered ESSA recording raingages west of the network indicated that the storm produced at least 1.46 inches at one point between 1500 and 1600 (figure 12). The huge thunderstorm became imbedded in the short-wave trough over central Illinois, and the trough moved eastward at a speed sufficient to carry the storm with it. Most of the storm remained in the cool region north of the mesostationary front, with its right flank occasionally crossing the boundary into the warm air. Thus, the upslope of the cold dome was used to accelerate air upward and into new cells,[15] and excessive evaporation from the earlier heavy rains provided some of the moisture needed to sustain the storm's life.

The storm system moved from the west during its lifetime, developing and passing directly over the area where the morning storm system had moved. The storm had attained a steady state, and all of the conditions noted in previous steady-state storms[10] were present. These include 1) marked vertical shear with height, 2) divergence at 500 mb, 3) warm, moist low-level air to feed the storm on its right front flank, 4) a dome of cold air to aid massive penetrative convection, 5) no nearby storms to compete for the moist air, 6) a very unstable moist air mass, and 7) considerable veering of wind with height.

By 1600 CDT the St. Louis radar (figure 11) showed that as the storm entered the network, it had assumed a reverse C-shape which was generally evident until after 1800. This shape may indicate mid-troposphere backside feeding of dry air, which would help produce the volume of cold air needed to sustain the updraft, and may have resulted from differential motions between the central portion of the storm and the left and right flank portions. The very close agreement between the positions and shapes of the rear edge of the surface rain pattern (figure 12) and those of the radar echo at 1800, which at this range was a volume centered at 12,000 feet, indicates that the storm had a sharply defined, quite vertical backside wall.

By 1900 CDT the central and left flank portions of the storm were dissipating and had separated from the right flank feeder section, having moved faster than the continually developing right flank portion. Repeated growth of new cores on the right-rear flank of the steady-state storm likely blocked the westerly steering-level winds. This caused the eastward motion of the mature feeder cells to be slower than the central storm,[8] and also led to greater point rainfalls in the network than produced

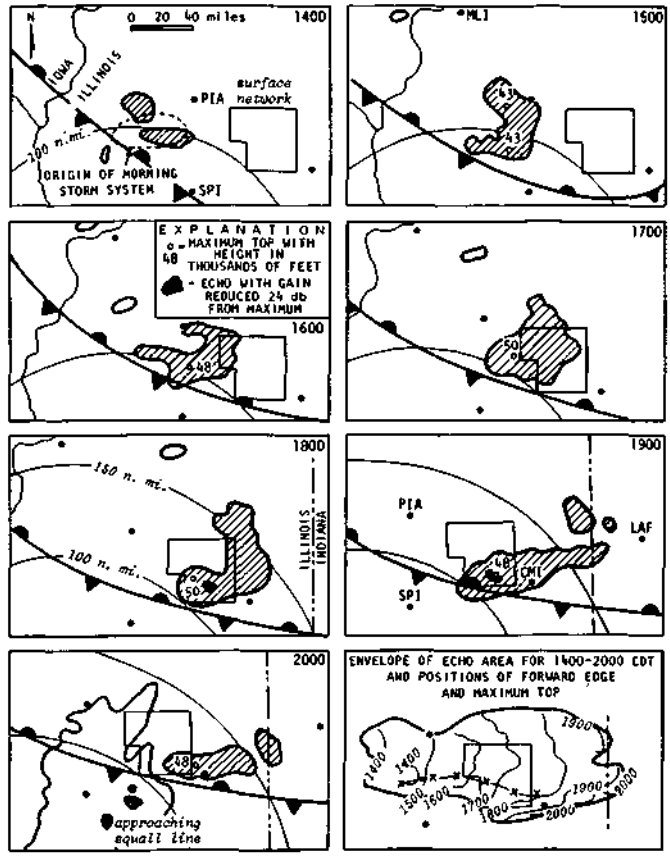


Figure 11. Radar echo maps at selected limes on 15 May

by the steady-state storm. The speed-produced separation of the steady-state storm from its low-level feeder portion led to the rapid dissipation of the storm in the 1830-1930 period, although the feeder system persisted until 2030 CDT when a rapidly moving squall line (figure 12) enveloped it in its dissipation phase on the network. The change in storm system shape is apparent at 1800 in the two 1-hour rain maps for 1700-1800 and 1800-1900 (figure 12). The approach of the cold front and its subsequent squall line is shown in figure 12, and the meshed line and feeder system in Illinois is apparent by 2200.

The steady-state storm realized 5.1 inches of rainfall during 2.1 hours along its right flank (in the network) although amounts in the central portion were less because of the more rapid movement there. A large hailstreak dominated the central section of the storm pattern, and six tornadoes occurred along the right flank of the storm.

The steady-state storm's feeder system (figure 12) also produced 5-inch rainfall amounts in 2.5 hours, and the squall line produced 2.5-inch amounts. The total storm rainfall exceeded 10 inches in the Clinton area where all four storm stages maximized (figure 13). The extremely heavy point amounts including the 5 inches in 2 hours, 7.5 inches in 4.5 hours (from the steady-state storm and

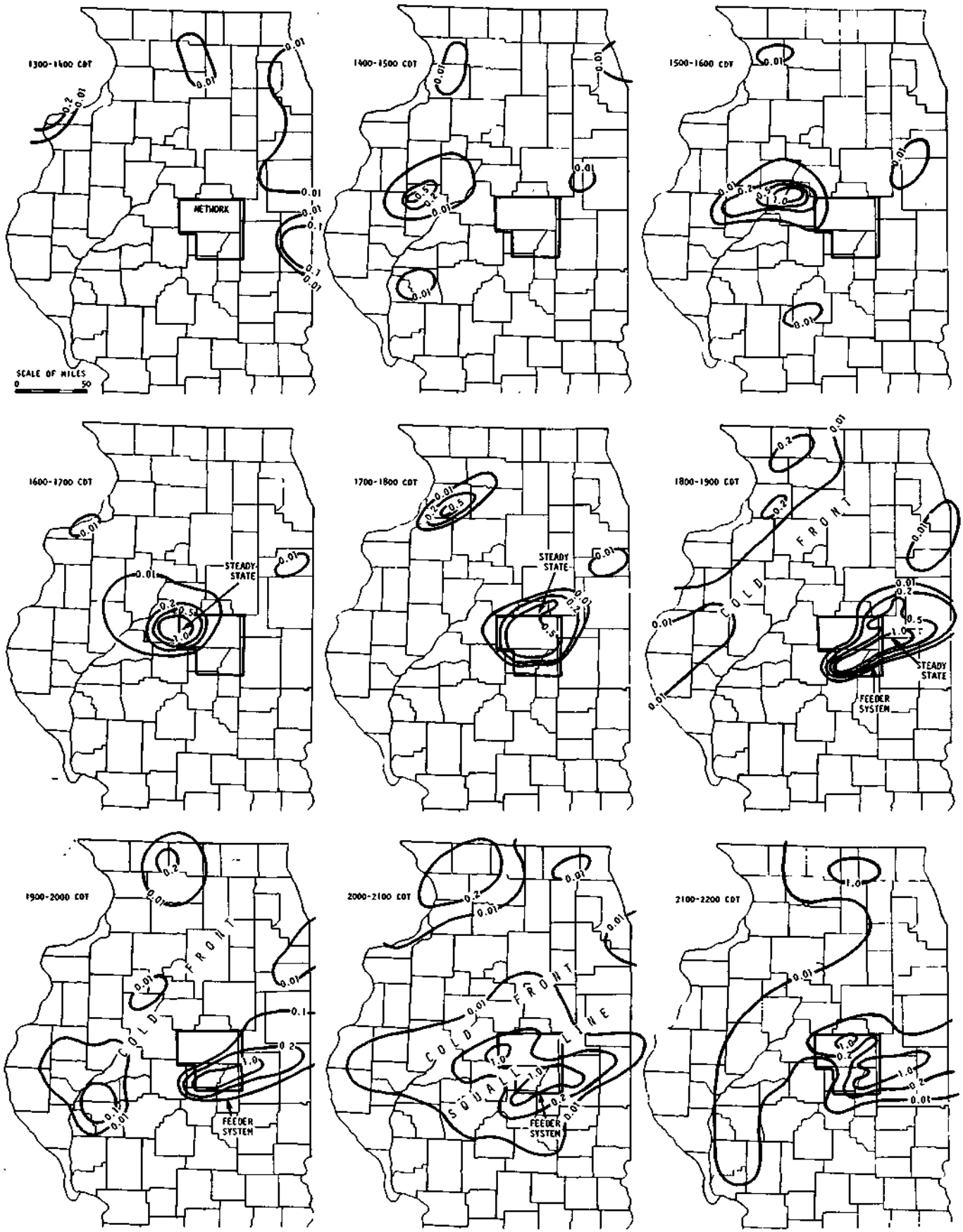


Figure 12. Hourly isohyetal maps for 1301-2200 CDT

its feeder system), and 10.2-inch maxima for 14 hours have a frequency of occurrence well beyond the once-in-500-year recurrence interval, as extrapolated from 2- to 100-year frequencies.[17]

The hourly rainfall data in figures 8 and 12 were used to construct envelopes of the morning rain system and the afternoon rain systems (steady-state plus the feeder system), as portrayed in figure 13. The amazing similarity in the envelopes of these two mesoscale rain systems is not considered to be coincidental. The same general meteorological conditions that favored the morning storms obviously continued into the afternoon, as reflected by the formation areas. The figure further indicates the probable enhancement of the afternoon rain system by the moisture available from the evaporation of morning rainfall.

To measure the maximization of the rainfall of the three storm systems on 15 May, the two points of their greatest rainfall anywhere in Illinois were established on the basis that the points had to be at least 20 miles apart. These two maximum rainfall points for each system are indicated on figure 13, and all occurred in the dense network. Of course, the greater sampling density (1 gage per 9 square miles) concentrated in this area favors detecting higher rainfall amounts there as opposed to elsewhere in Illinois where the gage density is about 1 per 225 square miles. Nevertheless, the unique combination of 1) two major storm systems developing and moving along the same path, and 2) maximization of these and two other rain systems in a 1765-square-mile area led to a design storm with a concentration of heavy rain and severe weather during a short period in a restricted area of Illinois.

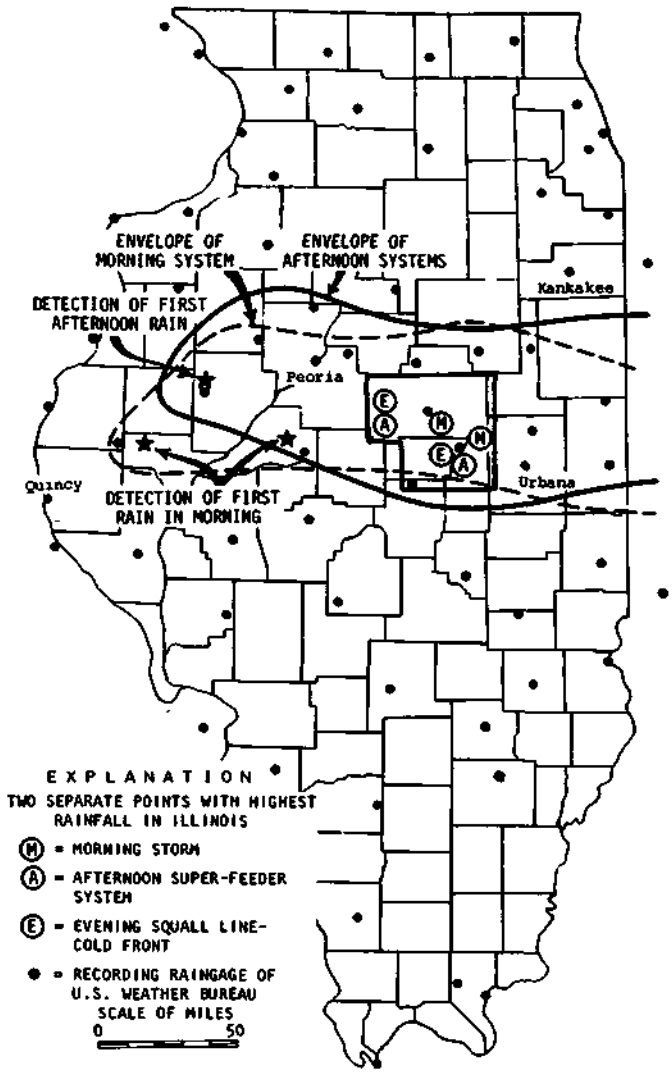


Figure 13. Rain system envelopes and locations of maximum point rainfalls from the four rain systems in Illinois

Temporal Distribution of Rain and Hail

The first rain in the network was at gage 57 (figure 14a) at 0919 CDT. The first complete clock-hour 15-minute period with rain was 0931-0945 CDT (figure 14a), and two rain cells, A and B, are shown. Six hailfall areas existed within cell A during this period, and the maximum point rainfall was 0.21 inch at gage 104.

The rapidly changing nature and complexity of the morning storm system is revealed in the next period, 0946-1000 CDT. Four rain cells now existed in the network; point rainfalls were above 0.3 inch in three cells; and eight hailfall areas were present during all or portions of this 15-minute period. Damaging hail (stones of 1.5-inch diameter) was occurring north of gage 106, and hail there and at gage 90 fell for the entire 15 minutes (figure 14b). The large hailfall area in cell A was related to two hailstreaks *(see hailstreaks 6 and 10 on figure 18a)* that had developed and merged at 0954. The hail area encompassing gages 104 through 106 had been present in the last 6 minutes of the previous period at gages 104 and 105, and was to persist in the core of cell A until 1045 CDT, or 62 minutes. This was the first of several very large and long-lived hailstreaks on 15 May 1968.

The pattern for the 1001-1015 CDT period (figure 14c) shows that two more rain cells (E and F) entered the network area, and that cell D was dissipating. Cells A and B were still maturing with several hail areas and point amounts in excess of 0.5 inch in both. The extensive hailfall area around gage 91 was a continuation of a slow moving (8 mph) hailstreak that began at gage 90 at 0942 (figure 14a) when it was on the front left flank of the rain core. By 1015 it was on the left rear flank of this core. Conversely, the large hailfall area extending eastward from gage 106 almost to gage 108 (figure 14c) was moving forward relatively rapidly (16 mph). When it initiated at 0939, it was in the front center of the rain core of cell A and was still there at 1015 indicating it was moving with the rain core and was likely a hail-producing volume directly associated with the heavy rain-producing center of this cell. Another hailfall area near the front of the cell had begun at gage 109 at 1007.

In the next period (1016-1030 CDT, figure 14d) cell A maintained its shape and amount of rain production, but added another hailfall area on its extreme left rear. The other four hailfall areas maintained their speed and juxtaposition to the core that existed prior to 1016. Cell B slowed from 20 to 8 mph but continued its movement to the ENE with little change in rainfall or hail production. Cell C slowed its forward motion to 20 mph and had begun to increase its rainfall production with 0.26 inch at gage 75 and a large hailfall area in its rain core. Hail was falling in the front edge of cell E. Cell F, moving rapidly to the ESE along the right flank of cell A, was intensifying its rain production and had hailfall areas in its extreme right front flank where a subcell was centered at gage 164. Two new cells, G and H, had entered the network. Cell H was in a mature stage with a point amount of 0.42 inch at gage 15 and a hailfall area on its left front flank. The hailfall area in the ungaged portion (figure 14d) was assumed to be produced by cell J which entered the network from that direction after 1030 CDT.

In the 1031-1045 CDT period (figure 15a) cell A continued to yield 0.5-inch point amounts and gained three new small hailfall areas along its front edge. The large hailfall area *(hailstreak 6, see figure 18a)* still persisted along its right flank. Cell B also maintained its rain production rate (0.4 inch), and had two new hailfall areas in its front edge. Cell C further slowed, enlarged, and intensified greatly with a point amount of 0.96 inch at gage 63. This represents a recurrence interval of at least once in 9 years.[18] Cell C produced three hailfall areas, two of which had existed during the previous period. The light rain remnants of cell D had almost disappeared from the network. Cell E had begun to intensify and was still producing a hailfall area in the front portion of its core. Cell F had slowed to 36 mph, and the maximum point rainfall value became 0.34 inch. The two hailfall areas numbered 19 and 20 that had existed in the previous 15-minute period were now located on the right flank rather than on the front right flank since their motions were slower than the rain core. Two additional hailfall areas had appeared in the right rear of cell F and one in the right front flank. Cell G produced only light rain and no hail, but cell H continued its production of moderately heavy rain (more than 0.3 inch). Two more new cells, I and J, appeared in the 1031-1045 CDT period, bringing the network cell total to 10. Cell I had developed (first rain) at gages 162 and 176 (figure 15a) at 1032 CDT, shortly after the passage of cell F over gage 162, and along the right flank of cell F. Cell I moved southeastward at 50 mph, as had cell F, and its development on the right flank of cell F was typical of that expected for large storms. Cell I produced 0.4-inch amounts and two hailfall areas in its first 13 minutes. Cell J had entered the network to the rear of cell F and also had a hailfall area.

The succeeding period, 1046-1100 CDT (figure 15b), was one of intensification of rainfall. The 15-minute area-depth curves *(see figure 16)* reveal this was the peak rain period in the morning system. Cell A, which had existed on the network since 0919 CDT, increased its maximum 15-minute point rainfalls from the 0.5-inch level to 1.02 inches at gage 111, a once-in-10-year amount. However, its production of hail on the network had diminished. Cell B also reached its maximum point rainfall with 0.65 inch at gage 48, and cell C sustained its heaviest rain yield with 0.98 inch at gage 92. Cells E and F also produced their maximum 15-minute amounts in this period with

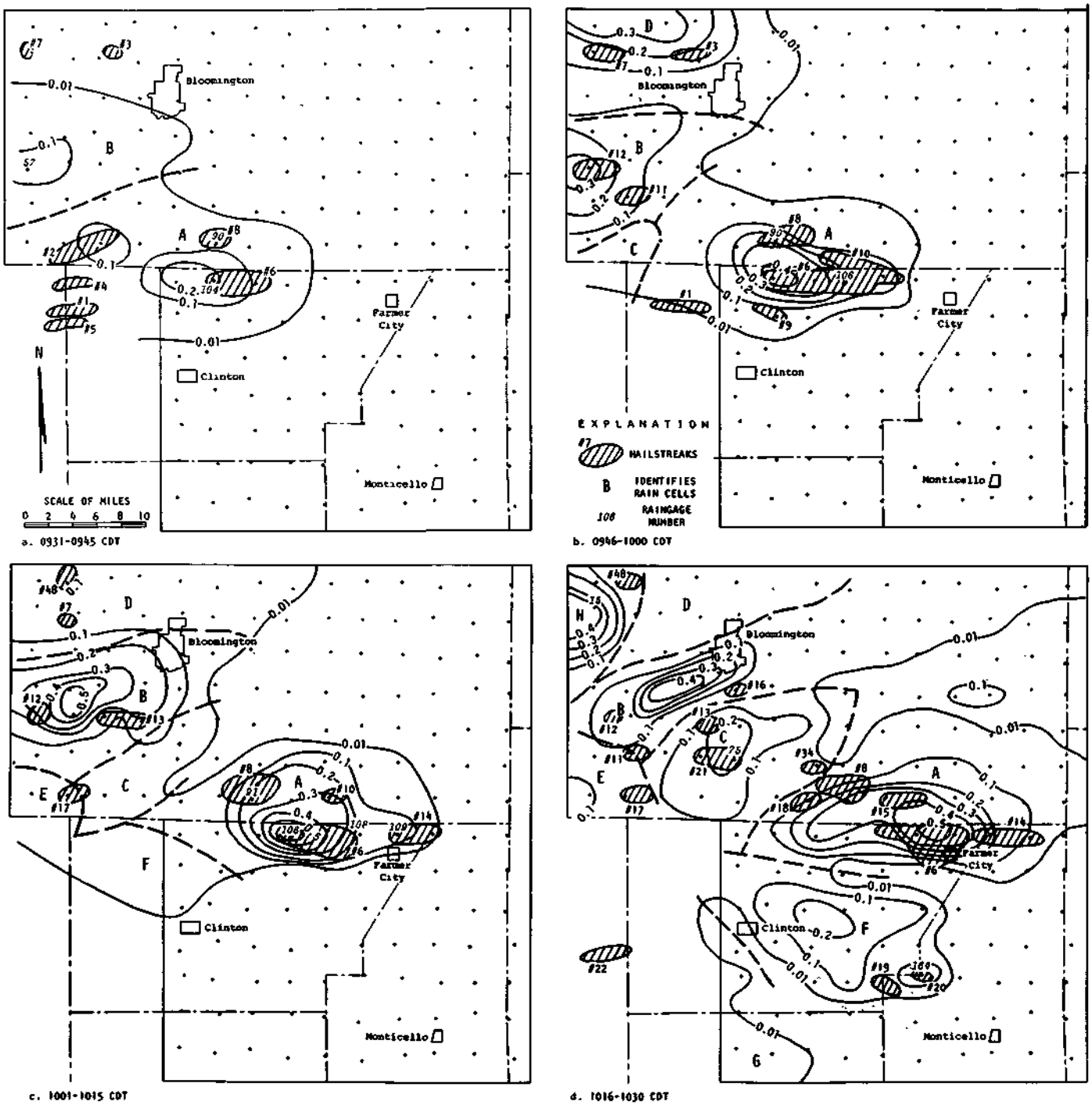


Figure 14. Isohyetal maps for 15-minute periods, 0931-1030 CDT

0.62 inch at gage 76 and 0.73 inch at gage 162, respectively. Cell G had dissipated, but cell H also maximized with 0.65 inch at gage 1. Cell I had almost disappeared from the network, but cell J reached its lifetime peak in the 1046-1100 period with 0.23 inch at gage 134. Thus, seven of the 10 major rain cells in the morning system maximized their 15-minute rain production in this period. However, hail production in all cells except cell F had diminished markedly in this period. Cell F had nine hailfall areas in the 1046-1100 period, and six were newly produced in this period. Interestingly, these nine areas were scattered throughout the cell, being on all sides of the rain core. The two large areas north (left) of the core were the start of two large hailstreaks *(see figure 18c).*

Rainfall production was still high in several cells in the next 15-minute period, 1101-1115 CDT (figure 15c). Heavy point amounts appear in the cores of cells A, B, C, F, and H. However, cell E had almost dissipated, cell J had dissipated, and the rear edge of the rain system, which was oriented WNW-ESE, had appeared in the network. Hailfall areas were still existing in the forward edge of cell B and in the rear portion of cell F.

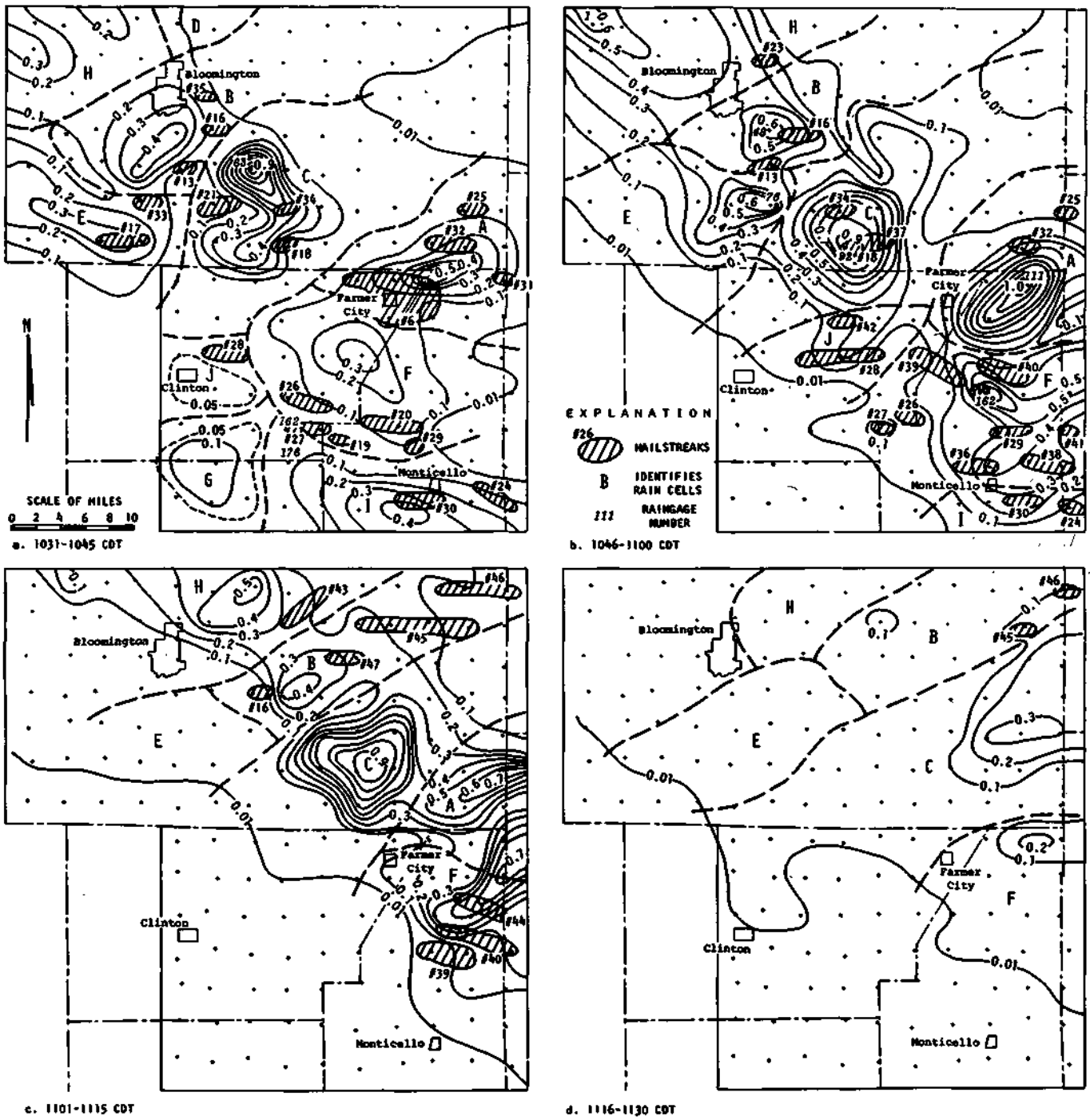


Figure 15. Isohyetal maps for 15-minute periods, 1031-1130 CDT

In the final 15-minute period portrayed (figure 15d), the rear of the cores of cells B, C, and F are shown, and in the 15-minute period thereafter, 1131-1145, no point amounts exceeded 0.09 inch and no hail fell. The final measurable rain in the network from the morning rain system occurred at 1235 CDT as the rear of the system exited along the eastern edge of the network. Thus, this rain system persisted on the network for 3 hours and 16 minutes, but most of the rain fell in 2 hours.

The areal-temporal distribution of the morning rainfall by 15-minute periods is shown in table 1, and these data were used to prepare area-depth curves (figure 16). These curves show the rapid increase in rainfall volume over the network in the first three periods with the fourth period (1001-1015) showing no marked increase except in maximum rainfall. The volume of rain above 0.2 inch in the fifth 15-minute period also represented little change, but the volume increased because of widespread rain in the 0.01-0.2-inch class. The sixth period, 1031-1045 CDT, had a marked increase in rain volume with rain covering the entire recording gage network (1550 square miles) and a point maximum of 0.96 inch. The peak period of rain volume came immediately thereafter when more than 600 square miles had 0.2 inch or more and

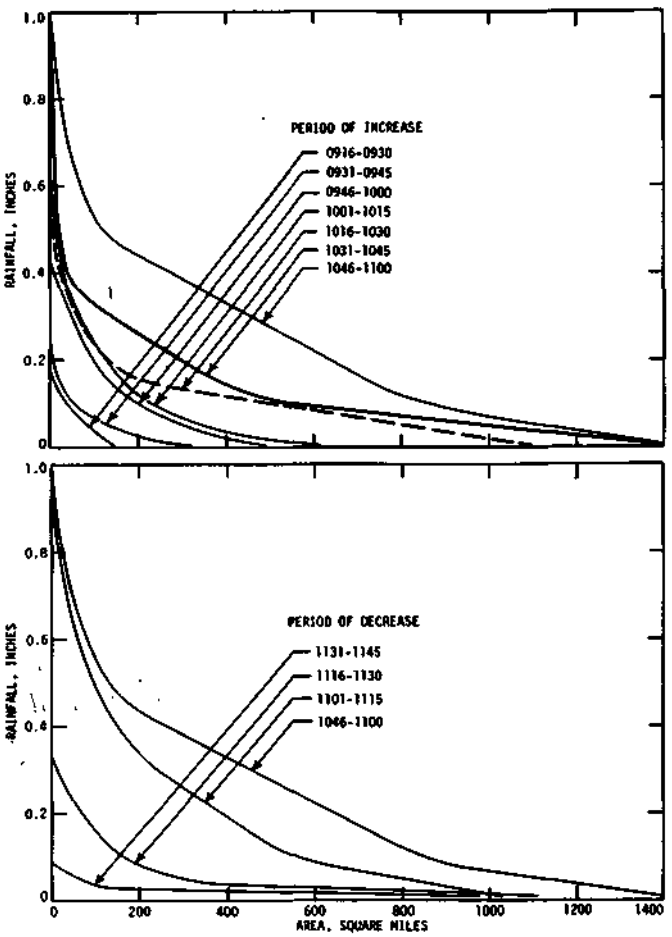


Figure 16. Area-depth curves for 15-minute periods for network area and morning storm system

68 miles had 0.6 inch or more. The decline in network rainfall after the 1046-1100 period was much more rapid than the increase had been, but the light rains normally found behind such thunderstorms extended the area of rain of 0.05 inch or less farther than this had been in the 15-minute periods of heavier rain prior to 1016 CDT.

The peak in the network hail activity, as measured by

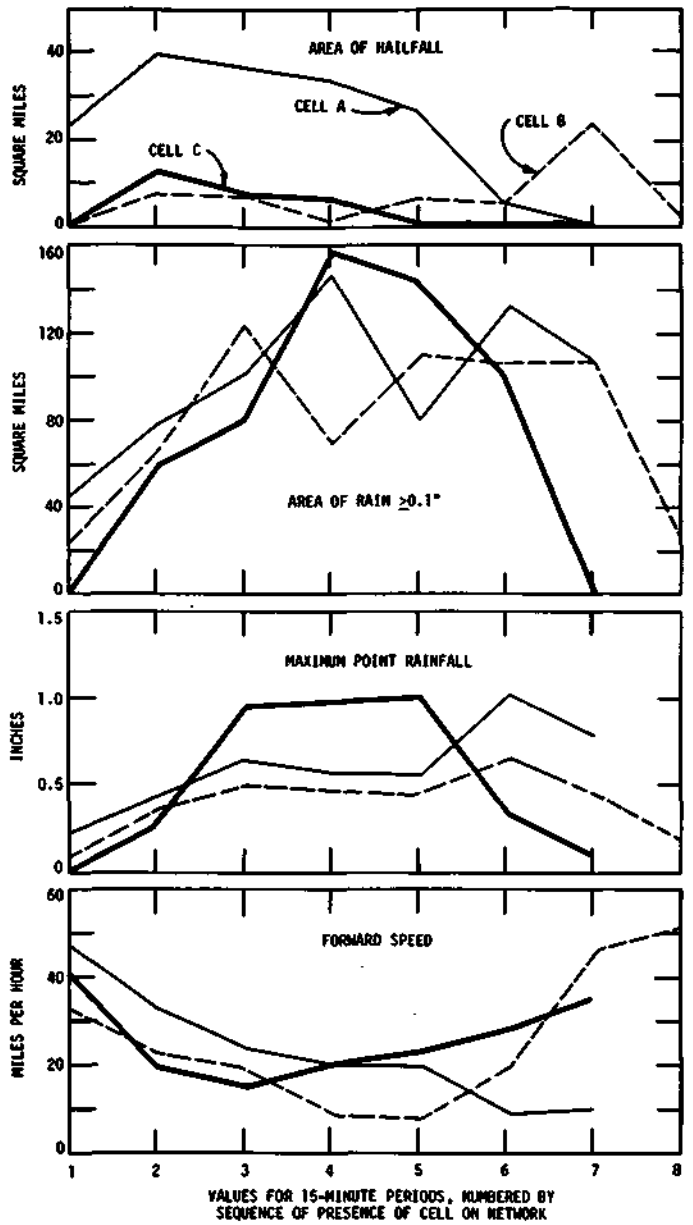


Figure 17. Temporal variations in rain and hail for rain cells in morning rain system

Table I. Network Area-Depth Values and Hail Values for 15-Minute Periods in Morning Storm System

Rainfall equalled or exceeded (in)	Rain area (aq mi) for given time periods. CDT										
	0916-0930	0931-0946	0946-1000	1001-1016	1016-1030	1031-1046	1046-1100	1101-1130	1116-1146	1131-1146	1146-1200
0.01	149	318	492	616	1097	1550	1550	1027	1129	979	785
0.05	86	128	303	343	797	1008	1118	804	304	61	0
0.1	40	55	205	226	508	522	856	561	161	0	0
0.2	0	10	100	132	123	2%	644	388	72	0	0
0.3	0	0	49	69	62	142	453	234	10	0	0
0.4	0	0	4	25	25	36	268	148	0	0	0
0.5	0	0	0	10	2	11	124	91	0	0	0
0.6	0	0	0	2	0	7	68	55	0	0	0
0.7	0	0	0	0	0	4	38	30	0	0	0
0.8	0	0	0	0	0	2	22	16	0	0	0
0.9	0	0	0	0	0	1	9	5	0	0	0
1.0	0	0	0	0	0	0	2	0	0	0	0
Maximum rain (in)	0.18	0.23	0.43	0.64	0.53	0.96	1.02	0.93	0.31	0.09	0.05
Average rain (in)	0	0.01	0.03	0.03	0.07	0.11	0.19	0.14	0.03	0.02	0.01
Number of hailfall areas	0	6	8	7	15	22	20	8	2	0	0
Areal extent of hail (sq mi)	0	23	53	46	55	70	59	45	3	0	0

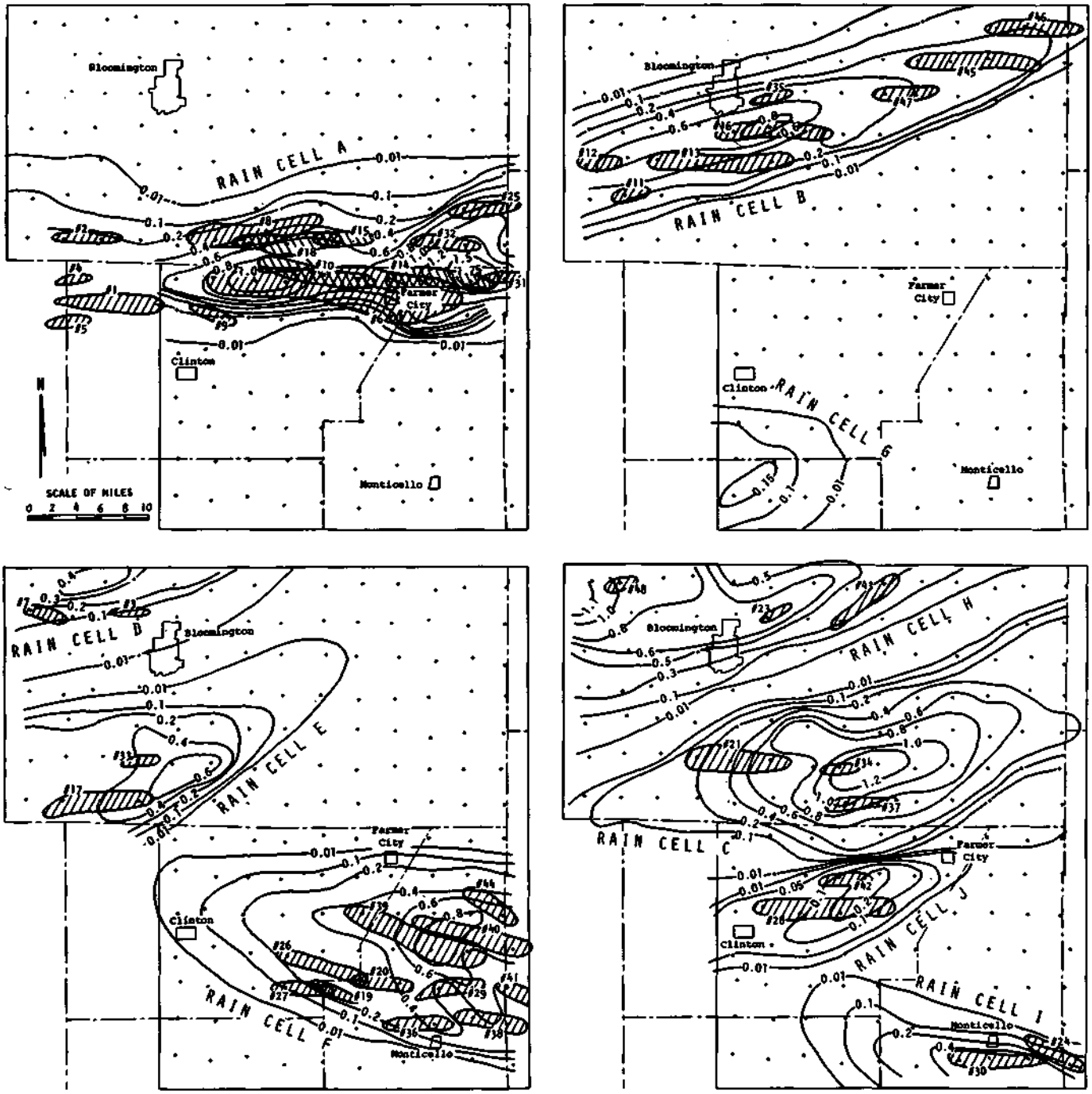


Figure 18. Isohyetal maps of rain cells in morning rain system

the frequency of hailfall areas and by the areal extent of hail, occurred in the 1031-1045 period (table 1). Although the number of hailstreaks was not large in the three preceding periods, the areal extent of hail was considerable after 0945.

Each cell was analyzed for its 15-minute values for speed of its rain core, maximum point rainfall, areal extent of its area of 0.1 inch or more, number of hailfall areas, and the areal extent of hail. The results for the three well-defined cells with long durations and lengths (cells A, B, and C) are presented in figure 17. Since these cells did not initiate on the network at the same time, their 15-minute values were not plotted against real time but according to their network sequence in order to compare results.

Rain production, as defined by the extent of the 0.1-inch area, was greatest in all cells during their third and fourth periods after their network initiation, whereas the maximum point rain amounts came 15 to 30 minutes later (figure 17). All three cells were moving quite fast as they entered the network, but they slowed rapidly and the areal extent of rain was greatest as they reached their slowest speeds. Rain production decreased as cell speeds increased later in life. Hail production maximized before

Table 2. Network Rain Cell and Related Hailstreak Data for Morning Storm System

Cell	Average width (mi) At 0.01" line	Average width (mi) At 0.1" line	Total length (mi)	Areal extent of 0.01" or more (sa mi)	Stages* in network	Network duration (min)	Development** related to other cells	Average speed*** Avg	Average speed*** Max	Average speed*** Min	Direction of motion	Rain production (in) Point average	Rain production (in) Point maximum
A	14	10	43 +	366	Y,M	92	I	25	48	8	W-E	0.44	1.83
B	10	8	46 +	356	Y,M,D	140	I	26	52	8	WSW-ENE	0.32	0.88
C	14	11	46 +	440	Y,M,D	120	R	26	40	14	WSW-ENE	0.48	1.35
D	m	m	20+	62	M	57	I	37	52	32	WSW-ENE	0.26	0.50
E	8	7	32 +	181	M,D	105	R	23	32	16	WSW-ENE	0.21	0.62
F	13	10	32 +	332	Y,M	110	R	33	56	20	WNW-ESE	0.31	0.73
G	m	m	9 +	41	D	25	I	m	m	m	W-E	0.09	0.16
H	m	m	42 +	248	M,D	105	m	37	56	13	WSW-ENE.	0.46	1.12
I	m	m	24+	89	Y,M	26	R	m	m	m	WNW-ESE	0.21	0.51
J	7	5	23 +	37	M,D	24	L	m	m	m	WSW-ENE	0.10	0.23

	Number of hailstreaks	Damaging hail	Areal extent of hail (8Q mi)	Streak size (8q mi) Largest	Streak size (8q mi) Smallest	Number of stresiks in given areal sizes (sq mi) 0.1-4	4-8	8-12	12-16	Over 16
A	14	yes	163.4	61.7	2.3	3	5	2	2	2
B	8	yes	57.7	14.5	2.2	3	1	3	1	0
C	3	yes	21.9	15.2	1.6	1	1	0	1	0
D	2	no	11.7	7.7	4.0	1	1	0	0	0
E	2	no	13.9	11.6	2.3	1	0	1	0	0
F	11	yes	103.1	26.8	3.4	1	7	1	0	2
G	0									
H	3	no	16.3	12.4	1.1	2	0	0	1	0
I	2	no	18.4	9.3	9.1	0	0	2	0	0
J	3	no	27.6	20.5	2.9	1	1	0	0	1

*Y = *youth;* M = *mature;* D = *dissipation*
**I = independent *of other cells;* L — on *left flank;* R = on *right flank*
****Average speed is based on all 15-minute values; maximum and minimum are from any 15-minute period*
Note: m = missing data, not measurable on network

rain production maximized in cells A and C, but the hail maximum in cell B followed the period of greatest rainfall. Cells A and C had only one general cycle composed of a hail maximum followed by a rain maximum, whereas cell B appeared to have two such cycles.

A storm model based on these results and those of the other seven cells suggests that in their youthful stages, the morning rain cells produced much of their hail, but were moving fast and hence did not produce much rain at a point or over an area. As they reached maturity they slowed considerably and expanded. At the beginning of their dissipation stage, they produced their heaviest point amounts, and then their speed increased while the rain and hail decreased rapidly. In essence, although these morning rain cells were long-lived storms, their uniform isohyetal patterns (figure 18) and the lack of large rain and hail fluctuations with time both indicate that they were large but not exceptionally complex storms.

Interestingly, cells A, B, and C, the first three cells of this morning rain system and ones that had developed west of the network, continued to exist as heavy rain and hail producers throughout their lifetimes on the network, and lasted generally for much longer periods than did any of the other cells in the system. However, these results may be affected by the fact that a sizeable portion of some of the other large rain and hail producing cells such as F and H, which were on the edge of the network or developed in the network, were not defined adequately.

Rain Cells and Hailstreaks

The isohyetal patterns of the 10 rain cells and their associated hailstreaks are presented in figure 18. None of the cells were contained entirely within the 1550-square-mile network, and cells A, B, and C moved across the full 42-mile width of the network. Cells E, G, and J dissipated in the network; cells D and H passed along the northern edge; and cells F and I developed in the network and moved away before dissipating. The six cells (A, B, C, E, F, and J) whose edges were well-defined over a considerable distance, were all between 8 and 12 miles wide during their mature (heavy rain) stage, but were narrower in their youthful and dissipation stages.

Various statistics on the 10 main cells and their hailstreaks are summarized in tables 2 and 3. Their widths, as measured across their long axis at points every 4 miles for the 0.01- and 0.1-inch isohyets, were averaged for the duration of each rain cell to obtain the values shown in table 2. Values for four cells are not shown because one side of each cell was beyond the network edge. The mean of the six average widths for the 0.01-inch edge is 11 miles. Cell lengths in the network varied from 9+ to 46+ miles, the plus sign indicating that all lengths were longer than measured within the network. Unfortunately, the network was not large enough to obtain the actual length of any of these 10 cells.

The three stages of each cell were subjectively determined by examining the cell rainfall patterns shown in

Table 3. Characteristics of 48 Hailstreaks Produced by the Morning Rain System

Hail-streak number	Begin time, CDT	Duration (min)	Areal extent (sq mi)	Maximum length (mi)	Speed (mph)	Maximum stone size (in)	Average point duration of hail (min)	Hail location from rain core*	Maximum point rain in streak (in)	Average point difference in rain-hail start (min)
1	0915	30	10.4	8.5	42	1	15	C	0.60	m
2	0927	15	7.2	7.5	24	1	3	L	0.17	5
3	0930	5	2.0	2.5	m	0.5	1	m	m	m
4	0930	5	2.9	4.3	m	0.5	5	m	in	m
5	0930	m	4.1	5.8	m	0.5	1	m	m	m
6	0934	57	61.7	26.0	20	0.75	10	C	1.12	8
7	0935	11	6.7	5.0	24	0.75	5	R	0.16	5
8	0940	45	19.3	12.1	18	0.75	13	L	0.50	23
9	0945	m	3.4	4.8	m	m	1	R	0.15	3
10	0955	43	11.1	10.1	11	1.5	7	C	0.75	1
11	0958	m	3.3	3.6	m	m	1	R	0.23	5
12	0959	7	4.2	4.8	21	0.25	3	C	0.76	3
13	1002	25	14.5	13.2	22	m	2	R	0.51	5
14	1006	26	13.4	9.8	23	m	8	C	1.83	8
15	1011	8	5.4	5.5	25	m	1	L	0.72	17
16	1015	31	9.1	9.2	13	m	1	C	0.88	5
17	1019	21	11.6	10.1	17	m	2	C	0.58	0
18	1025	13	14.4	9.6	36	0.5	5	L	0.74	3
19	1025	m	3.4	4.2	m	m	6	R	0.25	0
20	1025	7	4.7	5.0	30	0.25	1	R	0.43	0
21	1027	16	15.2	10.1	36	0.5	4	C	0.75	0
22	1030	3	2.9	4.1	m	0.25	1	m	m	m
23	1045	m	1.4	3.0	m	m	1	C	0.75	0
24	1038	12	9.3	6.6	36	0.5	4	L	0.19	0
25	1038	12	4.7	5.3	23	m	3	L	0.92	5
26	1038	9	7.2	8.0	45	m	2	R	0.32	0
27	1039	7	6.1	5.2	30	m	2	R	0.25	0
28	1040	11	20.5	12.0	50	m	2	C	0.22	0
29	1040	19	6.7	7.0	18	1	2	R	0.59	5
30	1040	10	9.1	7.9	50	m	2	C	0.50	0
31	1040	m	2.3 +	m	m	m	1	C	1.31	1
32	1040	13	5.1	6.7	30	m	5	C	1.27	3
33	1041	m	2.3	3.3	m	m	1	L	0.39	0
34	1043	m	1.6	3.3	m	m	5	C	1.34	7
35	1044	m	2.2	3.5	m	m	1	L	0.55	5
36	1044	7	5.0	5.4	45	m	2	R	0.43	4
37	1045	7	5.1	5.9	45	m	3	R	1.04	1
38	1046	10	7.2	6.5	48	m	5	R	0.40	0
39	1047	15	26.8	11.9	38	0.5	7	C	0.91	13
40	1050	21	20.2	12.1	37	1	10	C	0.79	8
41	1053	m	8.9+	m	m	m	1	C	0.39	0
42	1056	m	4.2	5.0	m	m	3	L	0.12	0
43	1103	10	12.4	7.0	30	m	1	R	0.35	0
44	1105	7	6.9	6.0	30	0.5	2	L	0.69	10
45	1105	21	11.9	11.3	36	m	2	R	0.34	4
46	1110	10+	9.2 +	7.0+	52	m	2	R	0.20	1
47	1101	8	3.3	4.8	45	m	3	R	0.47	0
48	1029	5	1.1	2.0	20	0.25	1	L	0.23	4

*C = *center of rain core; R = on right flank;* L = *on left flank*
Note: m = missing data

figure 18 and their size-intensification changes with time (figures 14 and 15). Nine cells were considered to have been in their mature stage during a portion of their existence on the network. The cell durations on the network are underestimates of total cell duration. However, the values indicate that six lasted at least 90 minutes.

An effort was made to classify the development of each cell, based on the temporal results in figures 14 and 15, as being 1) "independent" or not directly related to any existing adjacent cell, 2) on the immediate fight flank of an existing cell, or 3) on the left flank of one. The results in table 2 indicate that four cells were independent, four were on the right flank, one was on the left, and one could not be ascertained with any reliability. The prevalence of right flank developments supports claims for this preferred location of new cell growths on large thunderstorms.[16]

The cell motion values in table 2 reveal that there were three different directions (from WNW, W. and WSW) among the 10 cells that were all relatively quite close in space and time. The two cells with WNW-ESE motion were fast moving and represented right flank developments. Average speeds could be determined for seven cells and ranged from a low of 23 mph to a high of 37 mph, yielding a mean cell speed of 30 mph. This agrees well with a radar climatological study of 103 hail-producing echoes

in Illinois which showed an average cell speed of 27 mph.[19] The maximum and minimum speeds for each cell were obtained from the speeds determined for each 15-minute period. These showed large extremes for most cells, with maximum values being two to four times greater than the slowest speeds of a given cell.

All cells produced point rainfalls of 0.5 inch or more except cells G and J, which apparently were dissipating as they entered the network. The isohyetal patterns of the cells (figure 18) were generally uncomplicated with an oblate shape. Cell A was the only cell that had more than one distinct rain center.

The hailstreak data in table 2 indicate that 9 of the 10 cells produced hail, and the 9 cells exhibited considerable variability in their frequency and amount, of hail. There was a total of 48 hailstreaks with hail falling over 434 square miles, or more than 25 percent of the hail data area. Cells A, B, and F were the major producers of widespread hail and also were the only ones to produce crop-damaging hail. Hailstreak sizes varied considerably, from a low of 1.1 to a high of 61.7 square miles (tables 2 and 3), but the average size of 9 square miles for the 48 hailstreaks is smaller than the normal size of 16 square miles.[11] However, the frequency of hailstreaks in the 15 May morning system was considerably greater than usual. The normal hail-producing system in this network produces only 9 hailstreaks, as opposed to 48. Also, the normal rain cell produces only 1 hailstreak,[11] whereas 9 of the rain cells in this system produced 2 or more hailstreaks.

Total Rain and Hail

A map based on the total rainfall derived from the 10 rain cells of the morning rain system is shown in figure 19. Although most of the cells had W-E or WSW-ENE motions, the total rainfall pattern had a NW-SE orientation. The difference in orientations relates to the fact that the cells in the northern portions of the network maximized farther west than did those in the central and southern portions'. This exemplifies how a total storm rainfall pattern could be misleading in attempting to describe the motion of its rain system or cells across a dense network.

The heavier rainfall amounts, greater than 1.75 inches, fell in two separate locations where cell A had passed. However, the westernmost high resulted from a combination of considerable rain from cell A and maximization of cell C in the same area. The rainfall pattern in the ungaged southwestern area was based on data from 10 cooperative observers. The low totals in this area indicate that cells G and J, which had moved through this area into the network, were light rain producers throughout their lifetimes. The average rainfall of the morning storm system across the 1550-square-mile area of recording gages was 0.70 inch. The highest amount was 1.88 inches, and the lowest value was 0.07 inch.

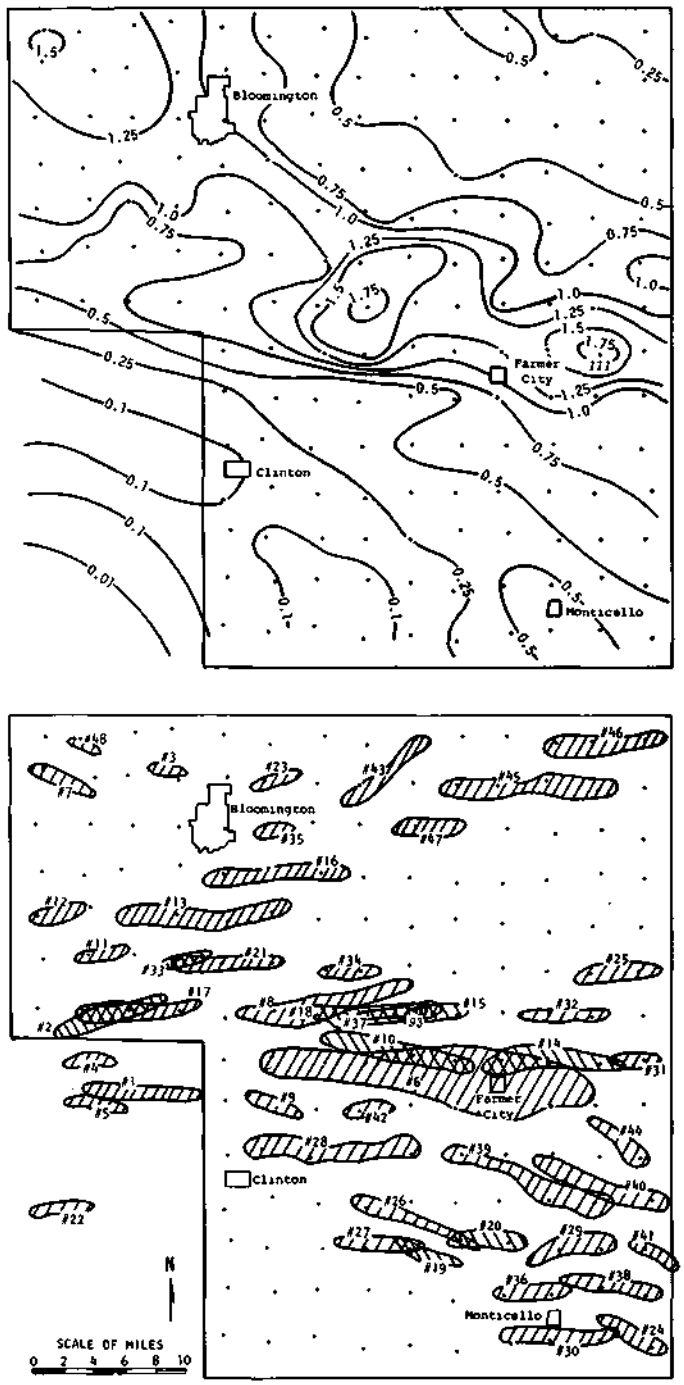


Figure 19. Patterns of total rainfall and hailstreaks in morning rain system

The composite of the 48 hailstreaks in the morning storm system is portrayed on figure 19. The actual area affected by hail was slightly less than the 434 square miles of hailfall listed in table 2 because portions of several hailstreaks overlapped. For instance, three hailstreaks occurred at gage 93. In general, the hailstreak distribution reveals they were most frequent in the NW-SE oriented area enclosed by the 0.5-inch or greater rain isohyet (figure 19).

Inspection of only the total storm rain and hail maps suggests that the heavy rain and hail were closely related, but the temporal results (figures 14, 15, and 17) showed that most hail in a given storm (cell) actually fell before the heaviest rain began. Thus, the degree of association between rain and hail varies depending upon the time-space scale used to study this relationship, and conclusions reached on analysis of daily rain-hail maps are suspect.[20]

Hail that damaged crops and property fell from hailstreak 10, and crop damages occurred with hailstreaks 6, 13, 26, 27, 34, and 37. Most of the hailstones in the morning system were 0.5-inch diameter or less, although a few 1.5-inch stones fell in hailstreak 10 and 0.75-inch stones fell in three hailstreaks (table 3).

AFTERNOON STEADY-STATE STORM SYSTEM

The single most important rain and severe weather producing storm on 15 May swept across the network during the midafternoon. The thorough study of this storm indicated that it was a classic example of the giant steady-state storms that have been identified by radar in Oklahoma[16] and England.[21] As shown in the storm morphology section (figures 11 and 12), the steady-state storm reached its mature stage as it entered the network's western edge, and the storm's production of heavy rain, widespread severe hail, and six tornadoes all occurred within the 1765-square-mile network. Thus, the resulting data furnished a unique opportunity to study in detail such a storm with heretofore unavailable dense surface rain and hail instrumentation.

Temporal Distribution of Rain, Hail, and Tornadoes

The forward edge of the rain from this storm system entered the network at 1540, and it swept eastward at 25 mph, reaching the middle of the network by 1645 (figure 20a). A small area of hail had occurred in the ungaged area between 1625 and 1628. The rain and hail patterns for 1631-1645 CDT portray the entry of a rain core labeled as A on figure 20a, and two large hailfall areas, both labeled as number 2. Hail from the northernmost hailfall area had developed at 1626 which was 90 minutes after the storm had developed. The more southern hailfall area had begun at 1635 CDT and expanded rapidly. Rain cores in this storm system were arbitrarily defined as areas on the 15-minute maps that were enclosed by isohyets of 0.9 inch.

In the succeeding 15-minute period (figure 20b) the backside of rain core A is defined, and the heavy rain area (greater than 0.5 inch) has expanded northward to the edge of the network. By 1650 CDT the large hailfall areas had merged to produce a "super" hailfall area of 132 square miles (table 4) and a "wall of ice" that was to sweep across the network during the next hour. Three tornadoes (A, B, and E) also appeared on the storm's right flank which was in the ungaged area of the network. The hail that had begun in the tornado area during this period persisted for 45 minutes at five locations (observers), and produced severe damages, as illustrated in figure 1.

In the following period (1701-1715, figure 20c) the rain area intensified and expanded with rain falling on nearly 700 square miles of the network and a maximum point amount of 1.2 inches at gage 74 (table 4). The 1700 CDT radar portrayal (figure 11) of the storm at the start of this rain period exhibits a storm pattern remarkably similar to that of the surface rainfall, and the highest echo top was at 50,000 feet, as high as any height measurement made of the steady-state storm. This helps to indicate that the storm had reached maturity. A second rain core (labeled B) appeared on the right front flank of the main storm system. The super hailfall area (2) had enlarged further, and with two new small hailfall areas (3 and 4), hail had fallen over 202 square miles (table 4). The length of the super hailfall area was 27 miles and its average width was 8 miles, extending from the forward edge of the rain area westward to the center of rain core A. Tornado B had dissipated by 1701; tornadoes A and E persisted into the 1701-1715 period; and three new tornadoes (C, D, and F) appeared in this period. Tornadoes A and D were directly associated with the new rain core B, and tornadoes A, C, and E were in the super hailfall area. This was the period of greatest tornado damage as evidenced by photographs in figure 1.

More of the expanding storm system was evident in the 1716-1730 CDT period (figure 20d). Two new rain cores, C and D, were evident along the left and right flanks, and 0.5 inch or more rain fell over 265 square miles of the network. The rainfall pattern assumed a general J shape. The area of 0.7 inch or more rain had a 28-mile N-S length, and throughout most of this very heavy rain area, hail also fell from the super hailstreak. The super hailfall area covered 324 square miles, and three new small hailfall areas (5, 6, and 8) had appeared along the storm's left flank. By 1730 the super hailstreak had existed for 64 minutes. Rain production in rain core B had increased to 1.16 inches, and associated tornadoes A and D had enlarged and persisted into this period. Tornado C, apparent in the ungaged area in the previous 15-minute period (figure 20c), also was shown to be directly associated with a heavy rain core, D.

The rain and hail production of the steady-state storm continued unabated during the next period (1731-1745, figure 20e), but only two tornadoes persisted into this

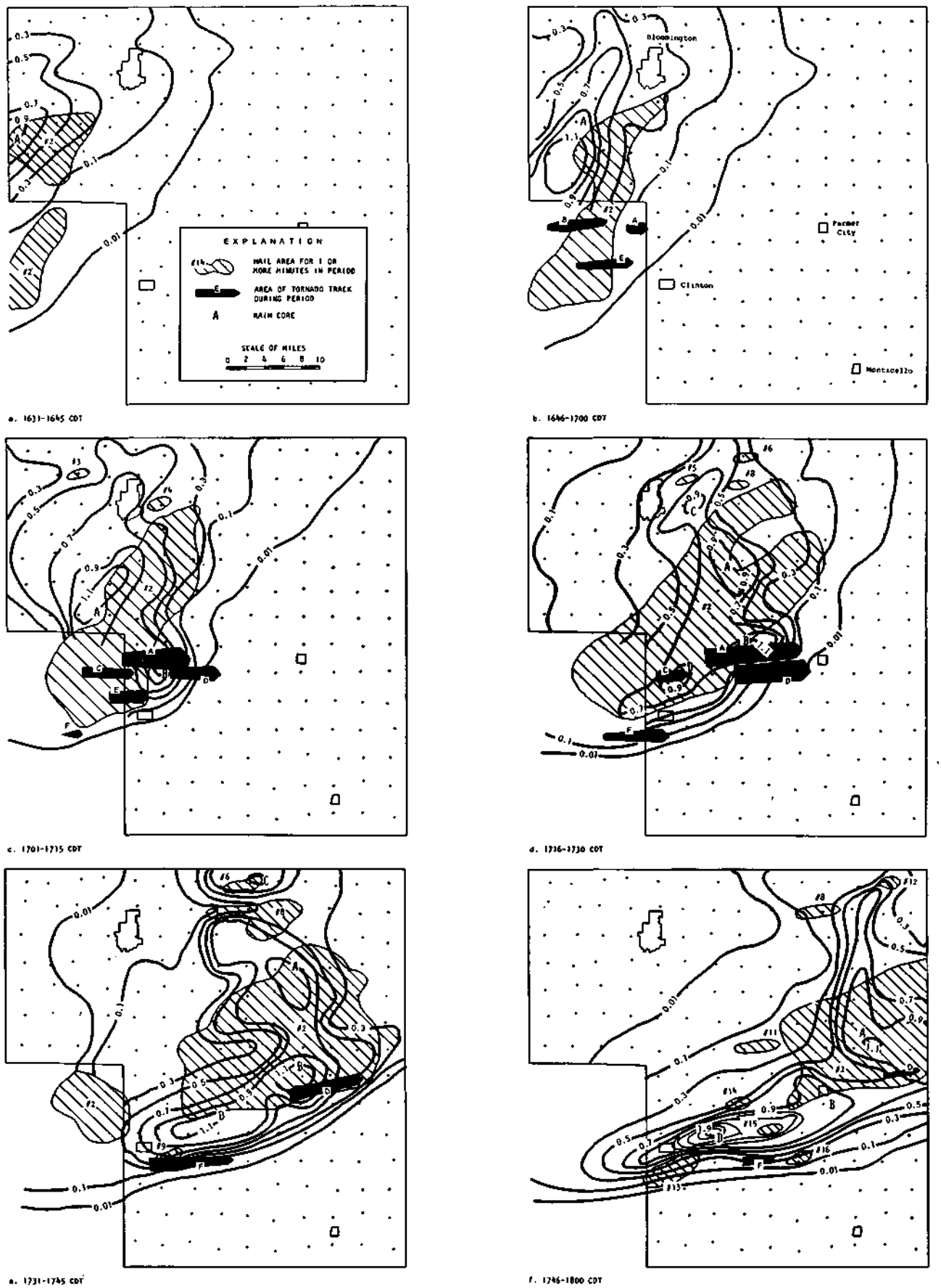


Figure 20. Isohyetal maps for 15-minute periods, 1631-1800 CDT

Table 4. Network Area-Depth Values and Hail Values for I5-Minute Periods In Afternoon Storm Systems

Rainfall equalled or exceeded (in)	Rain area *(sq mi)* for given time periods, CDT									
	1531-1545	1546-1600	1601-1615	1616-1630	1631-1645	1646-1700	1701-1715	1716-1730	1731-1745	1746-1800
0.01	19	83	159	340	442	572	699	934	885	807
0.1	0	0	33	162	275	378	513	711	685	609
0.3	0	0	0	26	109	244	430	424	503	422
0.5	0	0	0	5	55	125	277	265	334	312
0.7	0	0	0	0	19	74	155	148	226	210
0.9	0	0	0	0	5	48	50	23	89	107
1.1	0	0	0	0	0	18	14	6	17	37
1.3	0	0	0	0	0	0	0	0	0	20
1.5	0	0	0	0	0	0	0	0	0	9
1.7	0	0	0	0	0	0	0	0	0	4
1.9	0	0	0	0	0	0	0	0	0	2
Maximum rain *(in)*	0.03	0.05	0.20	0.60	0.92	1.20	1.28	1.16	1.20	1.94
Average rain *(in)*	0	0	0.01	0.03	0.06	0.11	0.16	0.18	0.23	0.25
Number of hailfall areas	0	0	0	2	2	1	3	4	5	7
Areal extent of hail *(sq mi)*	0	0	0	18	89	132	202	335	347	243

Rainfall equalled or exceeded *(in)*	1801-1815	1816-1830	1831-1845	1846-1900	1901-1915	1916-1930	1931-1945	1946-2000	2001-2015
0.01	680	604	576	572	692	762	792	667	586
0.1	470	346	327	388	482	455	402	335	341
0.3	299	205	192	240	385	254	175	121	153
0.5	188	106	88	147	153	135	49	23	59
0.7	96	44	10	54	88	37	10	4	21
0.9	39	14	1	15	22	14	0	0	3
1.1	11	3	0	5	0	0	0	0	0
1.3	4	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0
1.7	0	0	0	0	0	0	0	0	0
1.9	0	0	0	0	0	0	0	0	0
Maximum rain *(in)*	1.40	1.15	0.77	1.28	0.96	0.93	0.72	0.64	0.94
Average rain *(in)*	0.15	0.09	0.09	0.11	0.13	0.13	0.09	0.06	0.07
Number of hailfall areas	7	8	8	10	8	8	6	6	2
Areal extent of hail *(sq mi)*	51	33	57	24	32	26	19	25	4

period. The four rain cores still remained. Core D had intensified and core C had split from the 0.5-inch wall of rain that had extended from the network's northern edge to its south center section during the prior 45 minutes. The total rain area (table 4) in the network had decreased as the storm's rear edge appeared, but the heavy rain areas, those above 0.5 inch, had all increased. The hail area had reached its maximum, 347 square miles, as new hailfall area 9 appeared on the right flank. The super hailfall area had separated into two portions. The hail continued in the ungaged area. The major part of the super hailfall area was still occupying much of the heavy rain area. Tornado D was still in rain core B, and tornado F was along the right flank of core D. The changing internal mechanics and water load of this steady-state storm were obviously resulting in divergence in the heavy rain and a slowing. of the southernmost area.[22] Between 1730 and 1745, rain core C moved to the NE at 40 mph; rain core A to the ENE at 44 mph; core B to the east at 34 mph; and core D to the SE at 20 mph. Thus, a somewhat J-shaped 0.5-inch rain area resulted as did heavier rain in the slower moving cores, B and D.

This slowing in the southern portions persisted into the next period, 1746-1800 CDT (figure 20f). Rain core D remained centered at gage 133 and, as a result, produced 1.94 inches in 15 minutes, an amount in excess of that expected to occur at least once in 1000 years.[18] Core B had also slowed forming an elongated 0.9-inch area with core D. Core C was not evident because of either its dissipation or its departure from the network. Rain core A continued its motion to the ENE, although it also had slowed from 44 mph to 24 mph. Nevertheless, the J-shape of the rain area persisted. The very close agreement between the positions and shapes of the rear edge of the surface rain pattern (figure 20f) and those of the radar echo at 1800 (figure 11), which at this range was a volume centered at 12,000 feet, indicates that the storm had a sharply defined, quite vertical backside wall. The super hailfall area 2 was still quite large (182 square miles), but was diminishing. Four new hailfall areas appeared to the rear of the super hailfall area and in and around the very heavy rain core D, and tornadoes D and F persisted into this period.

Inspection of tables 1, 4, and 8 reveals that the areal extents of all rain classes of 0.9 inch and above were greater in the 1746-1800 period than in any other period on 15 May. Inspection of the radar, hail, rain, and tornado data indicated that this was about the end of the mature stage of the steady-state storm, and the maximization of the point rainfall appeared to be related more to the

slowing of the storm than to an increase in efficiency of the precipitation processes.

The sustainment of rapid forward motion in the center of the steady-state storm (rain core A) after 1730 led to its separation from the left flank portions (core C) by 1745 and a separation from the right flank portions (cores B and D) by 1800. Since all cores of the steady-state storm were relatively tall between 1700 and 1800, they all should have been similarly influenced by the steering-level winds. Thus, the slowing on the storm's right flank was apparently due either to internal storm mechanics or to the upwind blocking of the steering winds. This blocking could have been produced by rain core D and new rain cells developing to the west of the southern end of the storm. Rain core C probably separated because its motion .moved it away from core A and it lost its low-level source of indraft air. Radar data for 1900 (figure 11) and recorded rainfall data at Rantoul located east of the network indicate that core A and the center of the steady-state storm had dissipated by 1900 with only the slow moving right flank cores remaining. The remnants of the steady-state storm departed from the network by 1910 CDT *(see figure 25),* but not before a fifth rain core E and more hail fell.

The dissipation of the steady-state storm was finally induced by itself and occurred because 1) the four rain cores produced in the mature stage had divergent motions causing the storm to "spread out" and to separate; and 2) the growing cores on the right flank effectively blocked upwind steering forces which caused the cores to slow, separate from the storm center, and partially stop inflow to the center. This growth of new cells in the right flank is expected and explainable,[15] but the divergent motion of the cores in an apparently homogeneous heavy rainstorm is harder to explain. The efficiency of the storm in the core-developing period (1701-1730) was phenomenal with 754 million cubic feet of water in the 1731-1745 period. It is possible that the tremendous cold downdrafts associated with this downrush of rain may have reduced the indraft (particularly in the northern section of the storm) needed to sustain the heavy rainfall (and core C).

Total Rain

From 1646 through 1800 CDT the 0.5-inch unbroken wall of rain extended from the storm's left flank southward about 30 miles to cover an area not unlike that of the hailfall. This 0.5-inch wall of water in any one 15-minute period had from two to four cores of heavier (0.9-inch or greater) rainfall impregnated in it to match Newton's[13] typical large storm that has a "pulsating steady" updraft upon which are superimposed bursts of more intense convection.

The size and temporal continuity of the rainfall' wall, plus the size and continuity of the "super" hailstreak, are considered primary proofs that this was a giant steady-state storm. Its longevity, size, and persistent very high echo tops are also proof of its steady-state nature. Most atmospheric conditions noted in previous studies as present and necessary for steady-state storms existed. Of primary importance in the development, growth, and sustenance of the steady-state storm was its immediate juxtaposition to the morning storm system which furnished moisture and a cold air dome to set off massive penetrative convection.

The total rainfall map for the steady-state storm system appears in figure 21a. Although this system had several rain cores, it was a single rain cell by the terms of definition used in the morning rain system, and thus the total rain pattern of figure 21 is comparable to those in figure 18. The rainfall pattern did not have many small scale irregularities, and the network average was 1:47 inches. The area-depth values for this storm system or rain cell appear in table 5.

Table 5. Area-Depth Values for Steady-State Storm System

	Rainfall (fa) equalled or exceeded							
	0.01	0.25	1.0	1.6	2.0	3.0	4.0	5.0
Area (sq mi)	1272	1176	986	542	250	99	41	4

The maximum rainfall of 5.13 inches occurred at gage 133 where rain core D had centered. Rain was heaviest in the right flank area where rain cores B, D, and E developed and existed. Thus, this second rain system on 15 May maximized just a few miles south of where the morning system maximized.

Total Hail

The steady-state storm system produced 22 hailstreaks, including 21 small (typical) ones (figure 21c), and the super hailstreak (figure 21b). These are described in detail in table 6. The areal extent of hail from the 22 hailstreaks was 936 square miles, although because of hailstreak overlap, several parts of the network had two hailfalls from this system. There were repeated hailfalls and many hailstreaks in a small area, which is typical of a damage-producing hail situation in Illinois.[23, 24]

Reports from the hail observers west of the network indicated the steady-state storm did not begin hail production until it approached the network (90 minutes after storm inception). In and over the network, the steady-state storm produced 22 hailstreaks in a 2.7-hour period (see table 6). Most of these were small (less than 8 square miles), but the super hailstreak was a gigantic area of continuous hailfall having a maximum width of 19 miles, a maximum length of 51 miles, and a total area of 788 square miles.

This super hailstreak was formed by a wall of ice similar to that described for another steady-state storm.[25] This wall at times was 19 miles wide and 10 miles deep, was swept eastward at a nearly constant speed of 35 mph, was located within and in advance of the heavy rain "wall," and lasted

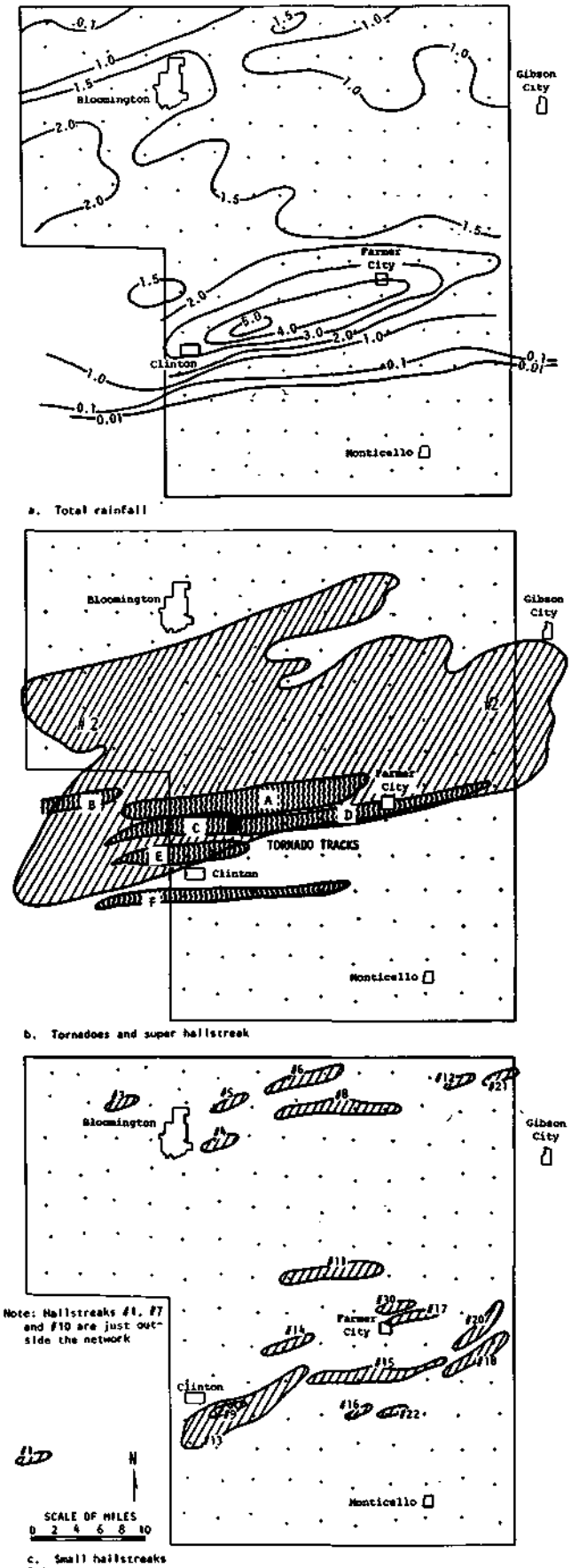


Figure 21. Patterns of total rainfall, hailstreaks, and tornadoes from steady-state storm

for 90 minutes. It produced hail at 69 raingage sites, including 45 with hailpads, and at 28 cooperative observer sites; and it caused crop damages ranging from 5 to 100 percent at 82 farms.

Certain aspects of the super hailstreak are depicted in figure 22. Point hailfall durations varied from 1 to 45 minutes with most of the lower section having hailfalls of 10 minutes or more. The map of the largest hailstones (figure 22b) shows that stones exceeding 1.5 inches in diameter fell over a large area; the largest stones were 2.25 inches in diameter. Frequency of stones per square foot (figure 22c) shows that large areas had more than 200 stones. The position of the area of longest durations and largest stones with respect to the storm rainfall patterns (figure 21a) is where Browning's[16] steady-state storm model would postulate them to be, and thus indicates that the major updraft went through a 270-degree cyclonic turn.

In that portion of the network where hailpads were located, a map based on the calculated energy values was developed (figure 22d). As expected, energies were highest (15 ft-lb/ft^2 or greater) in the south-central portion where stones were large and frequent, and hailfall durations were long. The maximum point energy value was 18.22 ft-lb/ft^2, and the area average energy was 6.18 ft-lb/ft^2. The worst hail as to size, energy, and duration came in the 1716-1730 CDT period (figure 20) when the hail area also was quite large (table 4).

The four maps on figure 22 combine to reveal a hailstreak that in 90 minutes produced 82,634,408 cubic feet of ice. The operation of the dense hail network in 1967 and 1968 allowed the detailed mapping of 434 hailstreaks in addition to the super hailstreak of 15 May.[11] The greatest measured values from these 434 hailstreaks, with the 15 May super hailstreak values in parentheses, were 62 square miles (788) for areal extent, 5.6 miles (19) for maximum width, 26 miles (51) for maximum length, 4.74 ft-lb/ft^2 (6.18) for area mean energy, and a duration of 26 minutes (90). The great differences in all these extreme values reveal the prodigious nature of the super hailstreak.

Tornado Summary

Discussion. The field surveys to collect tornado information revealed the existence of six separate tornadoes within the network, and all occurred during the steady-state storm. Accurate delineation of these was difficult because of their close proximity in space and time and because there generally were no distinct "damage-no damage" lines typical of most tornadoes. That is, funnels varying from 1/16 to 1/2 mile in diameter occurred at the surface, but the wind damage area for each was generally 1 to 2 miles across. Thus, it was impossible with available field data to define accurately the tracks of the funnels, but the areas (called envelopes) of wind damage related to each of the six tornadoes could be established accurately (figure 21b). No

Table 6. Characteristics of 49 Hailstreaks Produced by the Steady-State and Feeder Storm Systems

Hail-streak number	Begin time, CDT	Duration (min)	Areal extent (sq mi)	Maximum length (mi)	Speed (mph)	Maximum stone size (in)	Average point duration of hail (min)	Hail location from rain core*	Maximum point rain in streak (in)	Average point difference in rain-hail start (min)
					Steady-State Storm System					
1	1623	13	4	5	22	0.5	m	m	m	m
2	1627	90	788	51	38	2.3	13	C	3.6	6
3	1700	m	2	3	36	m	1	L	0.3	25
4	1703	8	2	3	28	0.4	1	L	1.6	20
5	1720	4	2	3	48	0.5	1	L	1.5	37
6	1727	18	4	5	45	m	1	L	1.5	46
7	1730	4	2	3	38	0.5	3	L	m	m
8	1730	36	14	14	21	0.6	2	L	1.0	45
9	1734	5	1	3	36	m	2	R	2.2	19
10	1740	11	3	4	38	0.5	7	L	m	m
11	1743	24	20	11	17	1.0	2	L	1.1	25
12	1745	3	1	3	36	m	1	L	1.0	34
13	1752	22	35	13	35	0.6	13	R	4.1	29
14	1753	6	3	4	25	m	2	L	3.2	28
15	1754	27	17	15	24	1.0	6	R	3.8	27
16	1754	6	3	4	36	m	5	R	0.4	8
17	1809	7	7	6	36	0.5	6	C	m	m
18	1809	8	9	7	30	0.8	3	R	1.4	22
20	1815	9	9	7	30	0.5	1	R	2.2	33
21	1820	5	3	4	36	m	1	L	0.9	5
22	1824	5	2	3	36	m	1	R	0.3	36
30	1845	6	5	5	30	0.5	4	L	1.2	7
					Feeder Storm System					
19	1815	13	8	8	35	0.5	5	C	4.4	1
23	1825	15	41	14	45	0.8	5	C	4.9	20
24	1830	51	6	7	9	0.5	10	C	4.4	34
25	1833	5	2	3	25	m	2	L	2.6	4
26	1836	54	19	13	16	1.0	4	C	4.4	40
27	1840	23	14	13	10	0.3	4	R	1.5	m
28	1840	11	5	5	m	0.5	7	L	m	m
29	1841	21	2	3	30	0.5	11	L	m	m
31	1845	5	3	3	36	0.3	5	R	1.7	13
32	1845	6	3	4	23	0.5	4	L	3.0	45
33	1850	7	2	3	m	0.8	6	C	m	m
34	1855	6	2	3	30	m	2	R	1.1	18
35	1858	9	2	3	36	m	8	R	1.0	19
36	1902	4	1	2	25	m	2	L	2.6	33
37	1903	48	11	8	15	0.2	11	R	0.5	4
38	1905	13	11	10	48	0.2	2	C	4.9	48
39	1907	5	2	4	25	m	1	R	2.1	32
40	1919	5	2	3	18	m	1	L	0.1	41
41	1925	18	14	11	32	0.5	5	R	1.6	53
44	1940	15	5	6	36	0.3	5	R	0.5	39
45	1943	9	6	6	25	m	3	C	4.4	86
46	1945	16	13	11	35	0.8	2	L	2.6	13
47	1952	19	11	10	30	m	6	R	1.7	81
48	1956	4	2	3	m	0.8	1	m	0.2	102
49	2010	21	7	7	21	0.2	10	C	4.9	112
50	2015	3	1	3	m	m	1	L	1.1	122
51	2017	9	14	10	45	0.3	9	R	2.3	98

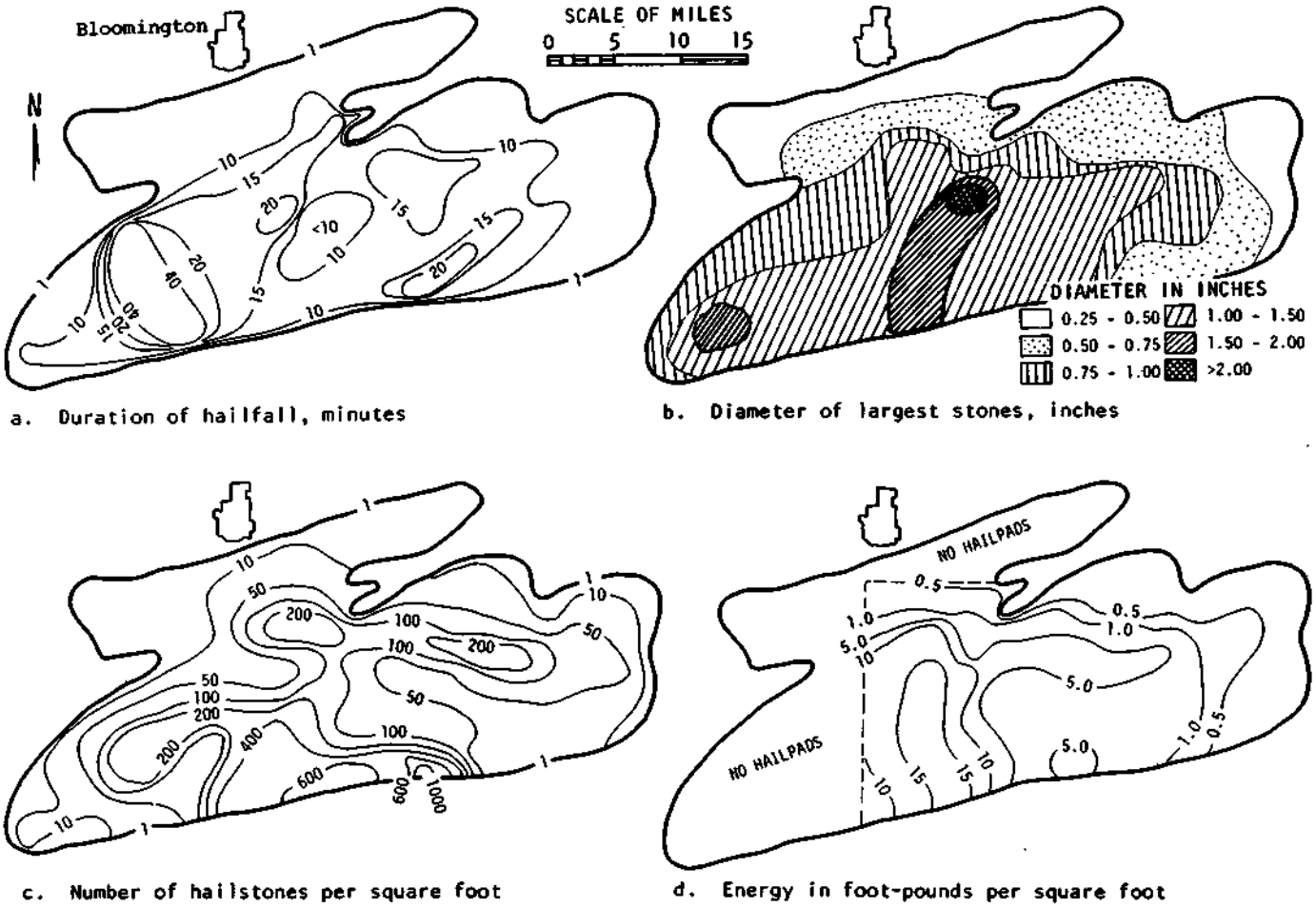
*C = *center of rain core; R — on right flank;* L = on *left flank*

Note: m = missing data

photographs of the tornadoes could be found, which is unfortunate since observer descriptions indicated a considerable variety of single and multi-funnel shapes and types. However, these funnel descriptions have been included.

The temporal analysis of the rain, hail, and tornado data (figure 20) revealed that three tornadoes formed in and remained with heavy rain cores, two were on the right flank of the storm and thus in light rain area, and the position with respect to rain could not be established for one tornado, B. Five of the tornadoes also were occurring in heavy hail areas.

The proximity of the five tornadoes (envelopes A, B,' C, D, and E) north of Clinton (figure 23) produced a nearly continuous damage area that was 4 to 6 miles wide and extended from Waynesville eastward to Farmer City, a distance of 26 miles. Almost every farm and town in this 100- to 150-square-mile area had some damage to



a. Duration of hailfall, minutes

b. Diameter of largest stones, inches

c. Number of hailstones per square foot

d. Energy in foot-pounds per square foot

Figure 22. Patterns of hailfall characteristics for the super hailstreak

buildings, fences, trees, and/or power lines. The major damage zone (figure 23) existed where tornado envelopes A, C, and D overlapped. Damage was extremely severe in the area extending eastward from 2 miles west of Wapella, through Wapella, and on to 8 miles east of Wapella. Two persons were killed in the Wapella area, and two others in nearby rural areas.

The complexity of this storm zone suggests a larger scale cyclone system such as the tornado cyclone,[26] where sudden pressure drops and high winds occur up to 5 miles distant

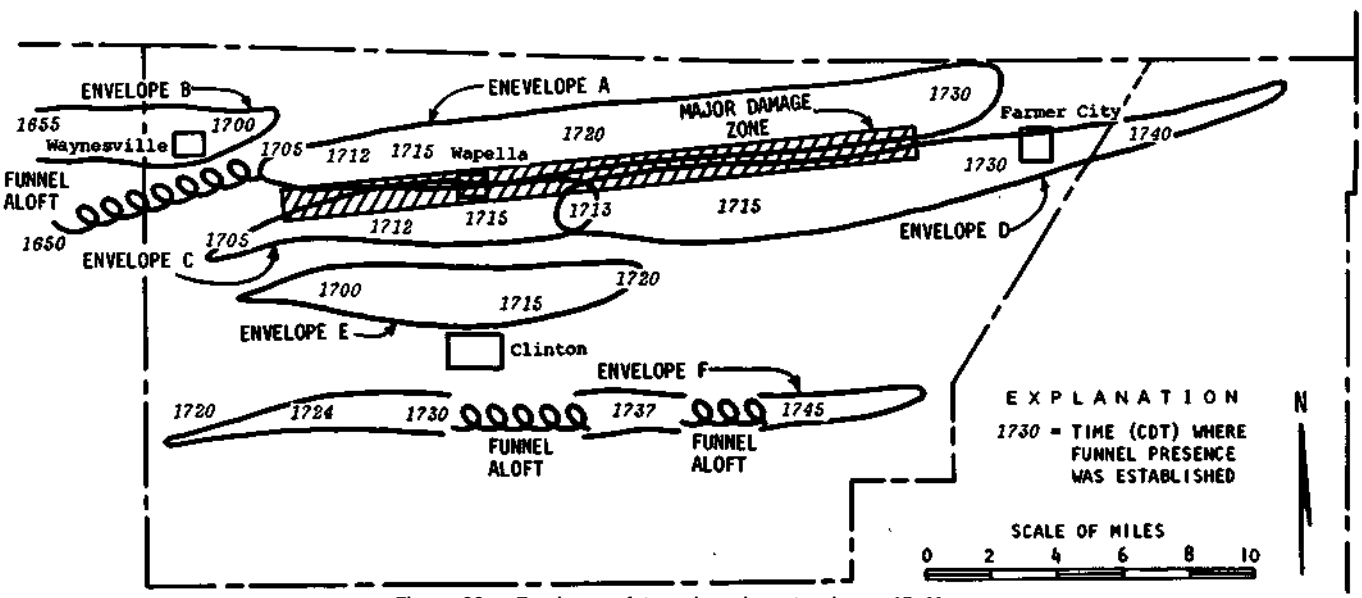


Figure 23. Envelopes of tornadoes in network on 15 May

from the tornado. The tornado cyclone is intermediate in size between the general parent low pressure system and the tornado funnel itself. With 40- to 50-mph winds out to 1 to 3 miles around the funnels there would be a tremendous contraction and a very large upward motion along with the release of great amounts of rainfall. Indeed, figure 20 reveals that very heavy rain fell in and immediately to the rear of these 15 May tornadoes.

Tornado Descriptions. Tornado A, as a funnel aloft, appeared as a grayish hook hanging from the cloud with its end flopping. It was observed to touch down at 1705 with the bottom spreading like a pillow of air on the ground when observed at 1712 CDT (figure 23). It was just NW of Wapella at 1715 when another tornado (C) coming from the WSW struck in Wapella. From the observations of damage patterns and observer reports, tornado A continued eastward until terminating just west of Farmer City at 1730 CDT.

The second funnel in the network area appeared at 1655 (tornado B), but it was first observed at 1645 when it was moving from WSW to ENE. Initially, the funnel appeared as a light streak against the black clouds behind it, and as the storm approached observers, there appeared to be a low-level fog moving ahead of it. Later, for several minutes near Waynesville, small funnels appeared around the large funnel, all moving to the ENE, and then about 1700 these were suddenly all drawn into one large funnel. Shortly thereafter, tornado B lifted.

Tornado C was first clearly observed at 1712 about 1.5 miles west of Wapella (figure 23). It had two funnels which appeared to converge immediately west of Wapella, where the tornado destroyed several steel power distribution towers (figure 1). This tornado also caused very heavy damage as it passed through Wapella. One observer on the SW side of Wapella stated that it looked like a "sheet of water" on the ground rolling toward him with rain falling on the water. He did not see the funnel but heard the typical tornado noise for about 30 seconds. The typical sequence of home damage in Wapella consisted of 1) windows breaking inward, 2) then the walls bursting outward, and 3) in some instances, a house being lifted and moved several yards. Another witness of tornado G located 2 miles SE of Wapella described it as a rectangular-shaped black box beneath the cloud base. Also, just west of this box-like tornado he saw a tremendous number of thin sandy-colored stringy formations extending toward the ground, with their tails flapping, and moving east very rapidly. Tornado C dissipated 4 miles east of Wapella, but produced very severe damage to farmsteads east of Wapella (figure 1).

Tornado D was first observed at 1713, 3 miles east of Wapella, and was described as a white V-shaped formation (50 feet wide at the ground) hanging from the base of the main cloud with clouds rolling into the center of the V. An observer on the east side of Wapella observed at 1710 the clouds above rotating counterclockwise with an associated roar, and this was apparently the formation of tornado D. This tornado raised briefly 5 miles west of Farmer City, but returned to the ground as it reached Farmer City (figure 1). It also destroyed a Water Survey raingage (figure 1).

The first observation of tornado E came at about 1710 from a site NE of Clinton (figure 23), but the damage patterns and times of occurrence west of that position indicate its formation WNW of Clinton at about 1700. One witness said the storm looked like white clouds of smoke rolling on the ground. Observers in the 1715-1720 period described the funnel as a long horizontal white streak having an elbow that hung toward the ground with the funnel wider near the surface. The witness was unable to tell if the funnel actually touched or not. This tornado dissipated after 1720.

The sixth tornado was labeled as F. The funnel at 1720 was narrow at the bottom and wide at the top. The damage pattern was intermittent and the tornado finally dissipated at 1745.

FEEDER STORM SYSTEM

The third rain system defined on the Central Illinois Network during 15 May closely followed the steady-state storm system in the late afternoon, and because of their close temporal-spatial relationships, it is considered to have been related to the mechanisms that produced the steady-state storm. This storm system consisted of four rain cores mat developed on the right rear flank of the remnants of the steady-state storm where feeder storms frequently occur, and hence it was labeled the feeder storm system. However, it was considered a separate system because its rainfall was separated from the steady-state storm's rainfall by a 5- to 15-minute no-rain period at most points in the network. Because of the temporal overlap in these two systems and the evening squall line, all 65 hailstreaks they produced were numbered consecutively, according to the times of their initiation.

Temporal Distribution of Rain and Hail

The first appearance of rain from this system occurred in the ungaged area at 1801-1815 CDT (figure 24a). Three observers in this area fortunately made a series of rain observations in the 1800-1900 period that provided detailed information on rainfall where this system developed. Rain core A, the first of this third system on 15 May, appeared

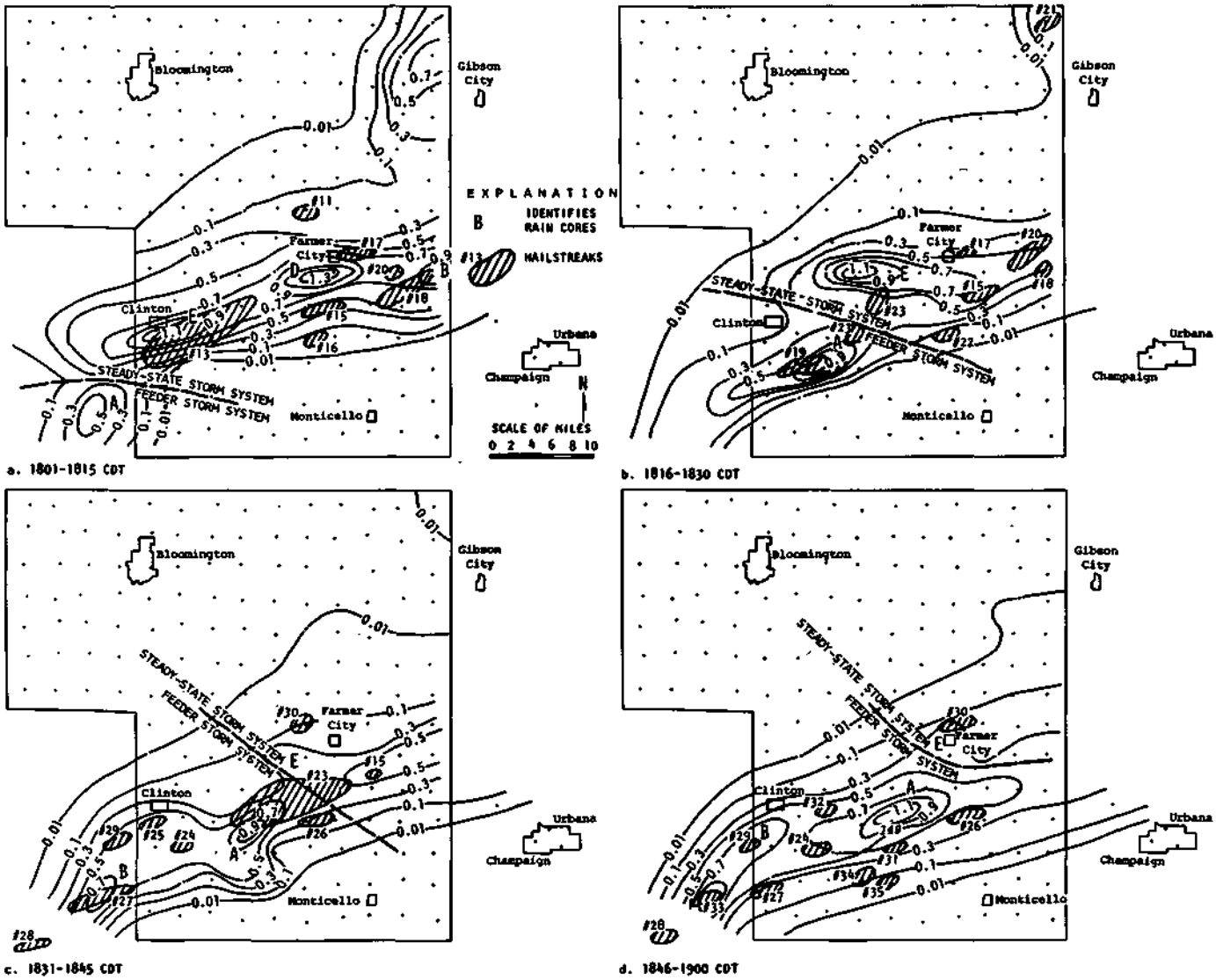


Figure 24. Isohyetal maps for 15-minute periods, 1801-1900 CDT

on the right flank of the fifth rain core (core E) of the steady-state storm system. Core E (figure 24a), as had core D of the steady-state system, produced quite heavy rain at gages located south and east of Clinton and moved along the same "track," or same area, as had rain cores B and D of the steady-state system. In the 1801-1815 period the steady-state system was still actively producing hail, having seven hailfall areas including those numbered 17, 18, and 20, and core E originated in this period.

The first hailfalls from the feeder storm system appeared 15 minutes later in the 1816-1830 period (figure 24b). Hailfall areas 19 and 23 were associated with rain core A which had enlarged, intensified, and moved rapidly (36 mph) to the ENE. A new hailfall area (22) appeared on the right front flank of core E of the steady-state system, and core E had four other areas persisting into this period. However, the production of hail on the network was decreasing as the areal coverage had decreased to 33 square miles in this period (table 4). The yield of rainfall from the growing feeder storm system also was not compensating for the diminishment of rain production from the steady-state storm system, as reflected by the decreases in areal extents of rainfall in all intensity classes and in the maximum point network values (table 4) during the 1801-1845 period.

In the next 15-minute period, 1831-1845, rain core E of the steady-state system rapidly decreased although a new hailfall area (30) appeared, the 22nd and final hailstreak of the steady-state storm. The rain and hail production in the feeder storm system was increasing with rain core B developing exactly where A had developed and including four new hailfall areas. Hailfall area 23 had expanded greatly, and became one of the larger ones of 15 May (table 6). Rain core A had slowed, now advancing at 25 mph as its point rainfall production increased.

In the succeeding period, 1846-1900 (figure 24d), rain core A slowed further, to 15 mph, and its point rainfall yield increased to 1.28 inches at gage 149. New hailfall areas (31, 32, and 35) also appeared within various portions of this core bringing the total to 10 as compared with 7 in

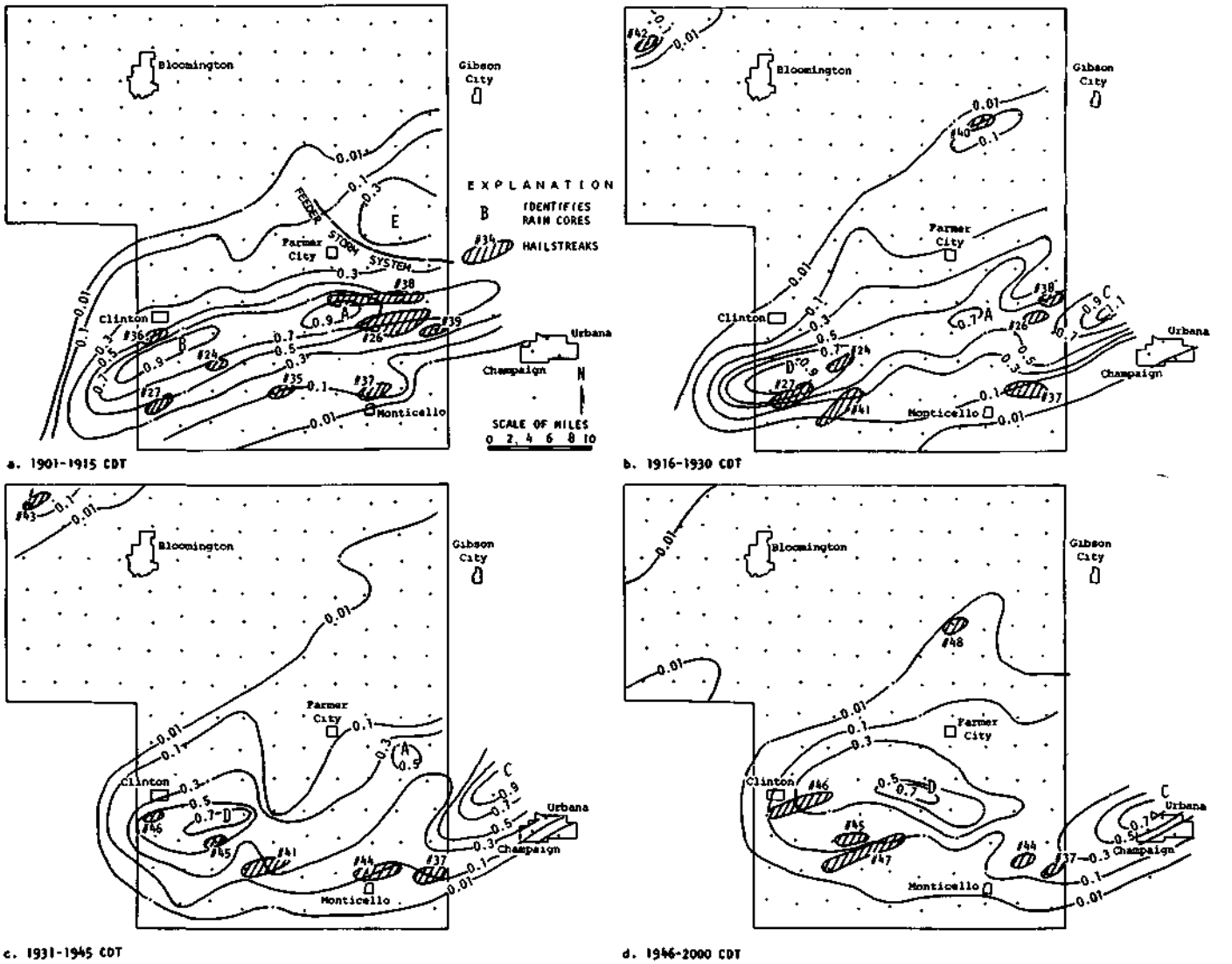


Figure 25. Isohyetal maps for 15-minuře periods, 1901-2000 COT

this system in the previous period. The forward edge (0.7-inch isohyet) of rain core B was moving into the gaged area of the network, but the point maximum (1.00 inch) was at the point (observer) where the core developed. An extensive area of 0.5 inch or more of rain extended along a WSW-ENE axis for 35 miles. The rear edge of the steady-state storm was still in the network.

The final appearance of the steady-state storm was in the 1901-1915 period (figure 25a). A portion of the feeder storm system was mapped east of the network using data from four Water Survey recording gages in the Champaign-Urbana area (figure 2). The network extent of the areas of most rain intensity classes increased in this period (table 4). Cell B had moved into the gaged portion of the network. New hailfall areas 37, 38, and 39 appeared with rain core A, keeping the system total to eight areas with hail falling over 32 square miles (table 4).

Rain core B totally dissipated in the next period (1916-1930), but rain core D developed along its right flank (figure 25b), producing 0.93 inch at gage 173. It was associated with a new hailfall area (41) and two continuing areas from the previous period (24 and 27). Another rain core, C, also appeared in this period, although it developed just beyond the network's eastern edge. Its point rainfall production was 1.15 inches. Hailfall area 42 appeared in the network's northwest corner along with the first rain element of the prefrontal squall line (figure 12) which entered the network at 1920. Another new hailfall area (40) appeared in a small light rain center on the distant left flank of the main system.

An interesting change in the feeder storm system began to be reflected in the overall rain pattern for the 1901-1915 period (figure 25a). In the previous 15-minute periods, the system, as outlined by the 0.3- and 0.5-inch isohyets, was quite uniform, and in the 1916-1930 period it began to become very irregular primarily because new cores developed along the right flank of the center axis formed originally by cores A and B.

This tendency toward a chaotic pattern was more evident in the next period, 1931-1945 (figure 25c) as the elongated 0.5-inch rain area that had existed since 1830 CDT separated into two small centers. Maximum point

rainfall amounts in cores A, C, and D also diminished, and the lessening production of rainfall is reflected in area-depth values in table 4. The rear edge of the feeder storm system was not apparent. Three new hailfall areas had appeared in the feeder system (44, 45, and 46), but they were small and hail production in the feeder system was diminishing, now down to 17 square miles (table 4) and only 5 hailfall areas. The squall line rain in the network's northwest corner persisted, now yielding another hailfall area, 43. Hailfall area 46, south of Clinton, was the third hailfall to occur at gage 146 in the 1835-1935 period, and hailstreak 44 was following part of the path where hailfall 37 had been 12 minutes earlier.

Rain core D continued its motion to the ENE at 32 mph in the 1946-2000 CDT period, but its rain production lessened in extent and point intensity. Core A, if still existent, was no longer on the network, and cell C had begun to move slowly to the ESE (figure 25d). The rear edge of the feeder storm system was now farther eastward. Two new hailfall areas (47 and 48) appeared, slightly increasing the area of hail production over that in the previous period.

The 15-minute rain-hail maps for the last 45 minutes that the feeder storm system persisted on the network appear in figure 27a-c. Rain core D reintensified briefly after 2000 as its motion slowed to 15 mph by 2015 CDT. Rain core C slowly (12 mph) moved to the ESE, and the last measure of significant rain from the feeder system was in the 2046-2100 CDT period (figure 27d) east of the network,

Total Rain

The feeder storm system, composed of four rain cores including three in the network, lasted 2.7 hours on the network, from 1800 to 2045 CDT. The resulting total rainfall pattern (figure 26a) is relatively uniform and represents a "rain cell," as defined previously. The narrow WSW-ENE axis of heavy rain (2 inches or more) resulted because three heavy rain cores of the rain cell system each originated in the same general area and each moved along the same path (figure 26c). The very heavy rainfall area (4 inches or more) resulted because cores A and D slowed as they moved across this area. The network area-depth values in table 7 reveal the restricted nature of the total rain area, but show larger areas for the classes of 2 inches or more than in the steady-state storm (table 5). The network average rainfall value was 1.55 inches.

Rain cores A, B, and D of this system and cores B, D, and E of the steady-state storm all moved along adjacent, nearly parallel tracks that overlapped in places (figure 26c). The three southernmost tracks of the steady-state storm cores revealed nearly W-E motion, whereas those of the feeder system were more WSW-ENE. However, four cores converged along the east-central portion of the network where the total storm rainfall was heaviest *(see figure 32).*

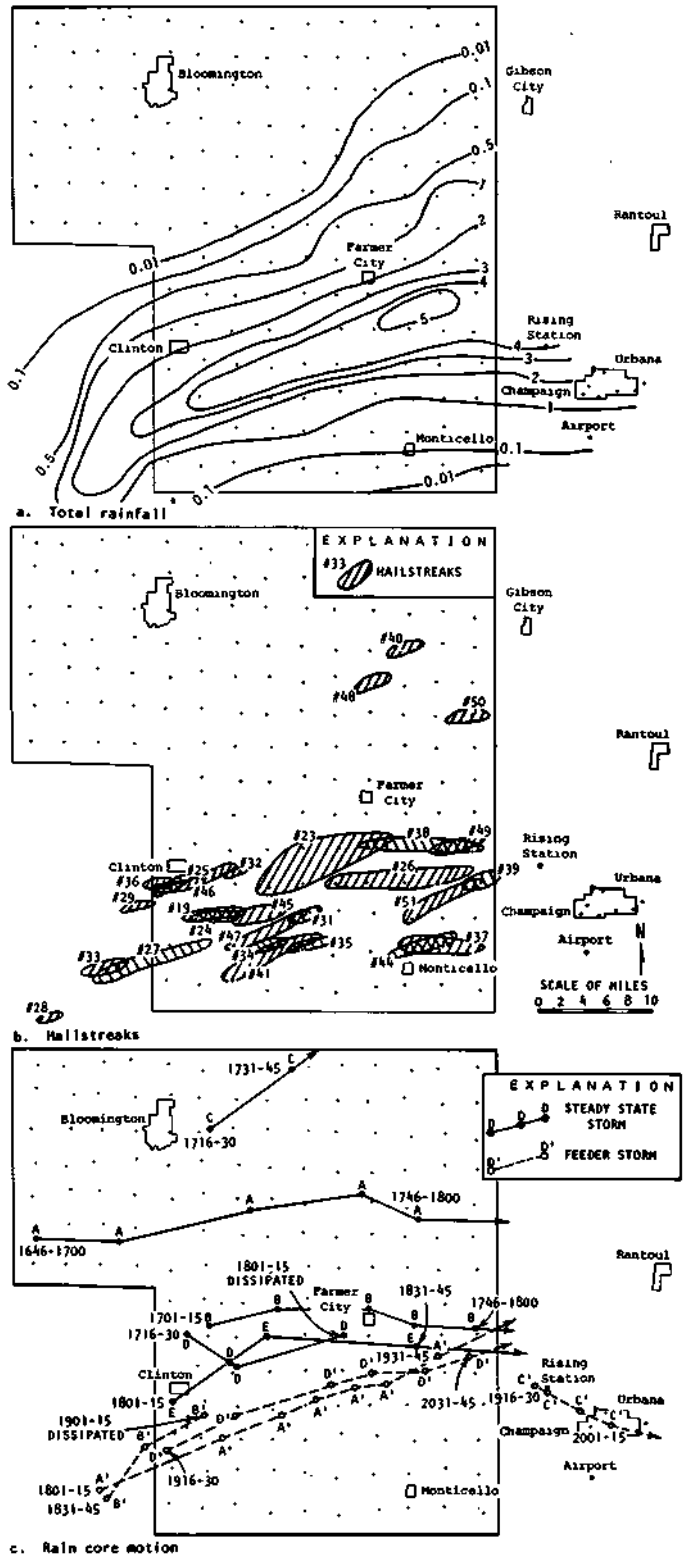


Figure 26. Patterns of total rainfall and hailstreaks for the feeder storm system and motions of rain core centers for afternoon rain systems

Table 7. Area-Depth Values for Feeder Storm System

	Rainfall *(in)* equalled or exceeded							
	0.01	0.1	0.5	1.0	2.0	3.0	4.0	6.0
Area *(sq mi)*	893	751	573	428	267	173	114	15

Inspection of the distances between centroid positions of most cores reveals that they initially were moving fast, then slowed, and then either dissipated or increased their speed. This proximity in space and time of heavy rain cores, each producing 15-minute amounts of 1 inch or more during portions of their durations, resulted in much of the exceptionally heavy point rainfall amounts on 15 May. The point amounts at gages between Clinton and Farmer City, such as gage 135 *(see figure 3)*, were between 6.3 and 6.7 inches during the 3-hour period beginning between 1715 and 1730 CDT. A 3-hour total of 6.7 inches represents an amount expected at least once every 760 years. The network average rainfall for both periods was 3.02 inches, a once-in-20-year 4-hour amount at a point.

Total Hail

The 2.7-hour feeder storm produced 27 hailstreaks, and their various characteristics are summarized in table 6. The combined areal extent of the 27 hailstreaks was 209 square miles, but because of some hailstreak overlap (figure 26b), the total areal extent of hail in the network was 178 square miles. As shown in figure 26b, the hailstreaks were concentrated along the rainfall axis of the storm. Most of the hailstreaks were small and short-lived, but hailstreak 23 was relatively large and 24 and 26 both lasted more than 50 minutes. Hailstreaks 25, 36, and 46 all partially overlapped south of Clinton, and streaks 19, 24, and 45 all hit gage 161.

Inspection of the hail-rain relations during the 15-minute periods and the positional data in table 6 revealed that the hailstreaks were evenly distributed in and around the rain cores. Ten were on the right flank, eight in the core center, and eight on the left flank.

Hail had fallen in the network continuously from 1623 through 2017 with most points in the 1765-square-mile network having experienced at least one hailfall. Hailstreak speeds in this system varied from 9 to 48 mph with an average of 28.6 mph.

SQUALL LINE—COLD FRONT SYSTEM

The fourth and final rain and hail system in the network on 15 May consisted of first a squall line and then its cold front. Although this system produced less rainfall and hail than did the three earlier precipitation systems, it had a few point rain amounts exceeding 2.5 inches and helped magnify the flooding already in progress.

Temporal Distribution of Rain and Hail

The first rain element of the squall line reached the network at 1920 CDT (figure 25b) and this rain cell also produced small hail between 1926 and 1940 (hailstreaks 42 and 43). Light rain associated with the squall line rain cells continued in the western parts of the network through 2015 CDT (figure 27a).

The first major heavy rain elements appeared in the network between 2016 and 2030 CDT (figure 27b). There were four identifiable rain cells (labeled A, B, C, and D) in the squall line, and hailfalls were associated with A, B, and D. Six hailfall areas totaling 33 square miles (table 8) existed, with three of these in the feeder storm system.

During the 2031-2045 period, rain covered 1365 square miles in the network (table 8), most of this being produced by the squall line elements. The fifth and sixth rain cells (E and F) had entered the network, and two hailfall areas were associated with E. The point production of rain in cell A had increased to 1.10 inches, and the five new hailfall areas (55, 58, 60, 61, and 62) had developed along the right flank of cells A and B. Hailfall areas 57 and 65 had appeared with rain cell C. The 11 hailfall areas during this 15-minute period represented the maximum number produced by the squall line in any period (table 8).

Table 8. Network Area-Depth Values and Hail Values for I5-Minute Periods in Evening Storm System

Rainfall equalled or exceeded (*in*)	Rain area (*eq mi*) for given time periods, CDT														
	2016-2030	2031-2046	2046-2100	2101-2116	2116-2130	2131-2145	2146-2200	2201-221S	2216-2230	2231-2245	2246-2300	2301-2316	2316-2330	2381-2346	2346-2400
0.01	981	1365	1510	1317	853	371	83	13	185	504	641	540	74	13	15
0.1	521	962	1203	982	364	75	8	0	0	29	83	39	32	0	0
0.3	247	457	537	534	140	0	0	0	0	0	11	6	0	0	0
0.5	120	225	247	326	61	0	0	0	0	0	4	0	0	0	0
0.7	34	86	106	193	23	0	0	0	0	0	0	0	0	0	0
0.9	0	28	32	60	0	0	0	0	0	0	0	0	0	0	0
1.1	0	3	5	5	0	0	0	0	0	0	0	0	0	0	0
Maximum rain *(in)*	0.81	1.10	1.10	0.94	0.77	0.30	0.19	0.01	0.04	0.25	0.65	0.30	0.29	0.01	0.02
Average rain *(in)*	0.14	0.21	0.26	0.27	0.11	0.02	0.01	0	0	0.01	0.03	0.02	0.01	0	0
Number of hailfall areas	6	11	5	1	0	0	0	0	0	0	0	0	0	0	0
Areal extent of hail *(sqmi)*	33	32	24	3	0	0	0	0	0	0	0	0	0	0	0

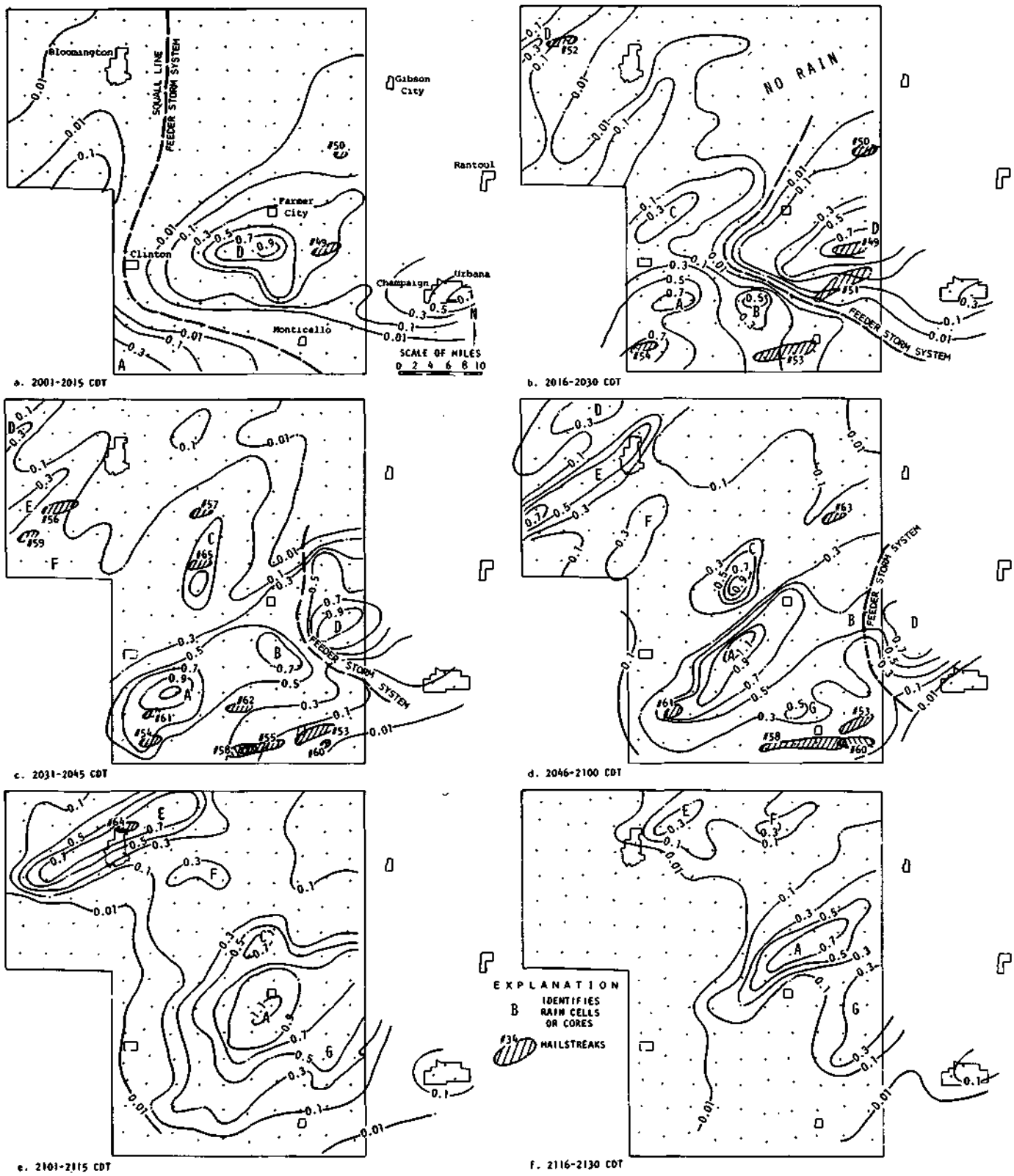


Figure 27. Isohyetal maps for 15-minute periods, 2001-2130 CDT

Rainfall continued to increase in the heavier intensity classes and in total areal extent in the next period, 2046-2100 CDT. The feeder system was still evident, but was now east of the network. Rain cell A had enlarged, and its center had moved 10 miles (40 mph) since the previous period. Four of the hailfall areas with rain cells A and B persisted, and hailfall area 63 was the only new one to appear. Cell C had intensified with a heavy rain rate (figure 3) at gage 107.

The most extensive heavy 15-minute rain amounts (0.5 inch or greater) in the squall line came in the 2101-2115 period (figure 27e). Rainfall of 0.7 inch or more covered

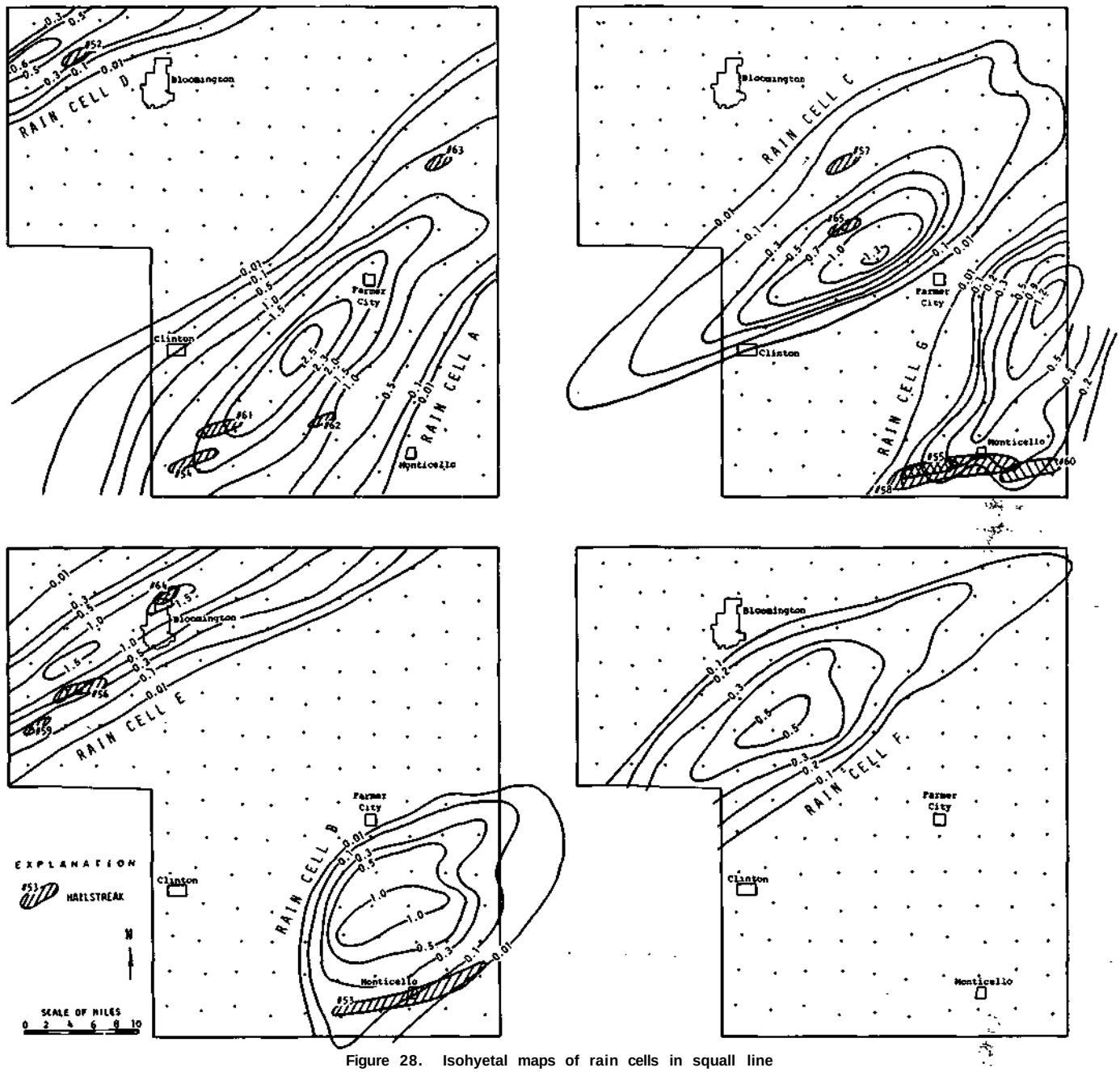


Figure 28. Isohyetal maps of rain cells in squall line

193 square miles (table 8). However, rain fell over only 1317 square miles as the rear edge of the squall line appeared in the west. Rain cells A and E were the major rain producers, and a final hailfall area (64) occurred in cell E. A seventh rain cell, G, developed along the right flank of cell A.

The final major rain period of the squall line occurred during the 2116-2130 period, although rain amounts were decreasing (figure 27f and table 8). As shown in table 8, the squall line rainfall in the network had practically terminated by 2200 CDT. Light rainshowers occurred along the cold front as it passed across the network in the 2200-2330 period, but they produced light rainfall amounts (table 8) and no hail.

Rain Cells and Hailstreaks

The isohyetal patterns of the seven rain cells and their associated hailstreaks are presented in figure 28. None of the rain cells were contained entirely in the network, but cells A, C, E, and F moved across large portions of the network. Except for cell C, the patterns reveal the rain core was centered in the cell with respect to narrow dimensions.

Various statistics relating to the seven rain cells and their associated hailstreaks are presented in table 9. Dimensions in length are all underestimates since all extended beyond the network. Width values based on the 0.01-inch lines averaged 14 miles and those for 0.1-inch lines averaged 11 miles. Areal extents varied from 623 to 72 square miles

Table 9. Rain Cell and Related Hailstreak Data for Evening Storms

Cell	Average width (mi) At 0.01" line	Average width (mi) At 0.1" line	Total length (mi)	Areal extent of 0.01" or more (sq mi)	Stages* in network	Network duration (min)	Development** related to other cells	Average speed*** Avg	Average speed*** Max	Average speed*** Min	Direction of motion	Rain production (in) Point average	Rain production (in) Point maximum
A	19	17	53 +	623	Y,M,D	120	I	34	45	24	SW-NE	1.09	2.59
B	15	11	28+	226	Y,M,D	45	R	32	35	30	SW-NE	0.46	1.08
C	12	9	53 +	336	Y,M,D	123	L	18	20	16	SW-NE	0.35	1.35
D	m	m	22 +	72	M,D	53	m	15	18	9	WSW-ENE	0.31	0.69
E	14	11	44+	322	M,D	127	R	40	48	32	WSW-ENE	0.56	1.62
F	11	10	46 +	375	M,D	65	R	36	46	28	SW-NE	0.24	0.56
G	14	10	33 +	217	Y,M	62	R	32	40	24	SSW-NNE	0.34	1.29

	Number of hailstreaks	Damaging hail	Areal extent of bail (89 mi)	Streak size (84 mi) Largest	Streak size (84 mi) Smallest	Number of streaks in given areal sizes (sq mi) 0.1-4	4-8	8-12	12-16	Over 16
A	6	yes	37	13	2	3	2	0	1	0
B	2	no	28	23	5	0	1	0	0	1
C	2	no	5	3	2	2	0	0	0	0
D	1	no	2	2	2	1	0	0	0	0
E	3	no	8	5	1	2	1	0	0	0
F	0									
G	0									

*Y = *youth;* M = *mature;* D = *dissipation*
**I = *independent of other cells;* L= on *left flank;* R = *on right flank*
****Average speed is based on all 15-minute values; maximum and minimum are from any 15-minute period*
Note: m = missing data, not measurable on network

and durations from 45 to 127 minutes, but these values were greatly affected by the percent of the cell on the network since none was totally defined. Four-of the cells developed along the right flank of an existing cell.

Speed values, as averaged for the network duration of each cell, varied from 15 to 40 mph and their mean was 29 mph. Maximum speeds between any two 15-minute periods ranged from 18 to 48 mph. Three directions of motion were noted. Four of the seven cells moved from the SW, two from the WSW, and one from the SSW. Area average rainfall values varied from 0.24 inch up to 1.09 (cell A). Point maximum values were all over 0.5 inch with more than 1 inch produced by five cells. All cells were classed according to their rain pattern, and all were defined as being in their mature stage during part of their presence on the network. Cells A, B, and C were classified as being in their youthful, mature, and dissipation stages while on the network, and thus were nearly completely defined.

Cell A produced six hailstreaks and the only damaging hail from storms in the evening squall line. Eight of the 14 hailstreaks with these 7 cells were quite small, from 0.1 to 4.0 square miles (table 9).

Further temporal interpretation of the hail and rain production of the evening rain cells is shown in figure 29. Here the three longest lived cells in the network (cells A, C, and E) have been sequentially portrayed with respect to their individual 15-minute values of hail area, rain, and speed. In their earlier phases (first 15 to 30 minutes), the cells moved fastest and produced their greatest hailfall vol-

Table 10. Characteristics of 16 Hailstreaks Produced by the Evening Squall Line System

Hail-streak number	Begin time, CDT	Duration (min)	Areal extent (sq mi)	Maximum length (mi)	Speed (mph)	Maximum stone size (in)	Average point duration of hail (min)	Hail location from rain core*	Maximum point rain in streak (in)	Average point difference in rain-hail start (min)
42	1928	3	1	2	36	0.3	1	C	0.7	2
43	1930	6	2	2	38	0.3	6	L	0.2	6
52	2021	11	2	4	38	m	11	R	0.4	0
53	2025	31	23	17	28	0.8	3	R	0.1	3
54	2026	12	7	7	41	0.5	5	C	2.0	2
55	2030	7	6	7	36	m	1	L	0.3	3
56	2034	8	5	5	27	m	1	R	0.9	3
57	2035	3	2	3	39	m	1	L	0.2	6
58	2043	12	13	12	45	0.5	6	C	0.3	2
59	2043	3	1	2	m	0.2	1	R	0.3	0
60	2045	6	5	5	45	0.3	2	R	0.3	0
61	2046	6	3	4	38	m	5	C	2.0	5
62	2046	5	2	3	36	0.4	3	R	1.5	9
63	2051	11	2	3	38	m	9	L	0.7	15
64	2107	5	2	3	41	m	1	C	1.6	5
65	2148	6	3	3	38	0.3	2	L	0.9	13

*C = *center of rain core;* R = on *right flank;* L = *on left flank*
Note: m = missing data

umes. As they slowed, the area of rainfall rapidly increased, peaking 15 to 30 minutes after the hailfall area maximum was obtained. Maximum point rainfall amounts occurred either during or 15 minutes after the rain area maximum. Two cells indicated increased speed as they dissipated and/or departed from the network. Thus, heavy rain appeared to be a function of storm maturity and slowing. The cell slowing may represent a result rather than a cause of heavier rain. As the enormity of the storm grew in the atmosphere, its rain area essentially produced a frictional drag.

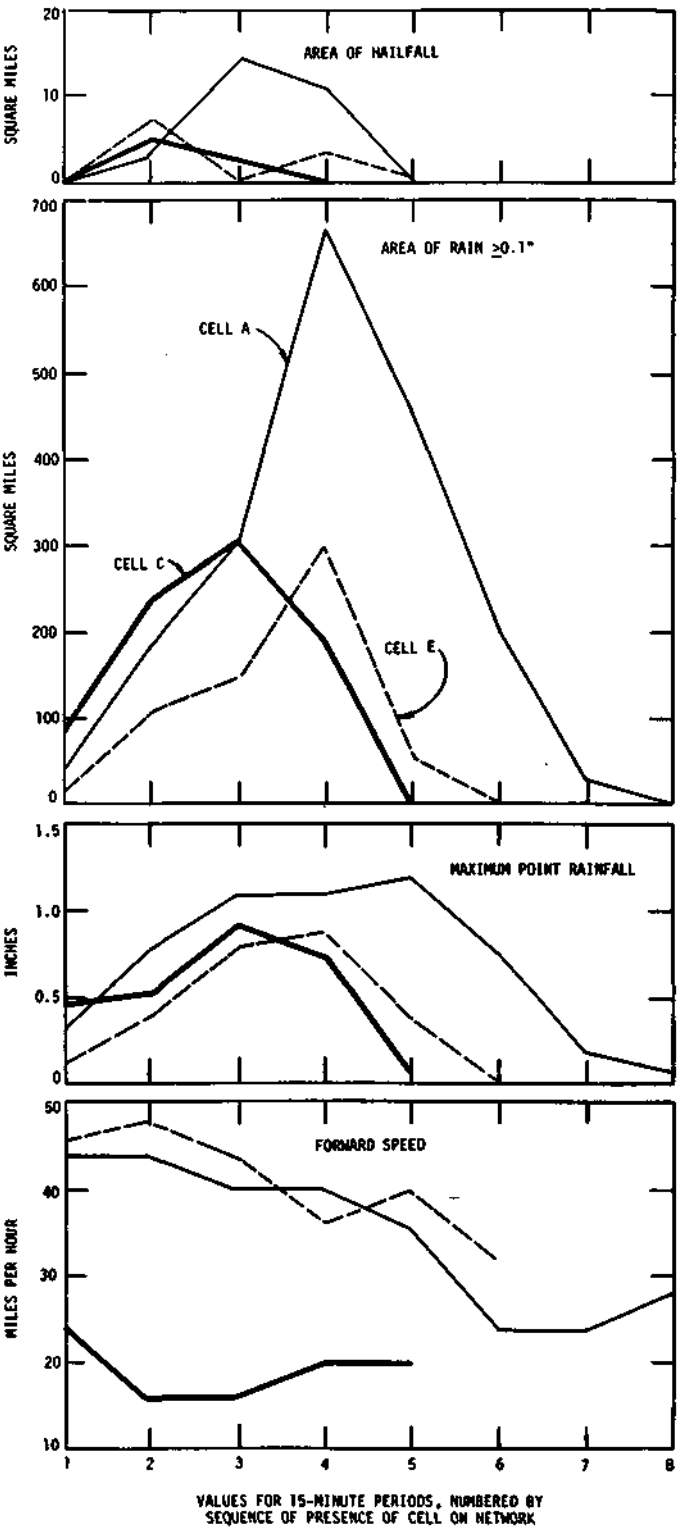


Figure 29. Temporal variations in rain and hail for selected rain cells in squall line

The evening squall line system produced 16 hailstreaks, and their characteristics are indicated in table 10. All but two occurred in the 2021-2154 period, and all were shor,t-lived and small. Their speeds were quite high, averaging 38 mph, compared with the average of 28 mph for the afternoon streaks. Hailstone sizes were small and point durations were short, as would be expected from the high speeds. Their locations within rain cells varied widely with six on the right flank, five in the core, and five on the left flank. Maximum point rainfall amounts in the hailstreaks varied greatly, from 0.1 to 2.0 inches. The point differences between rain starts and hail starts averaged for each hailstreak were generally small indicating the hail was close to the forward edge of the rain. These differences in start times were smaller than most noted in the earlier storms on 15 May.

Total Rain and Hail

The total rainfall pattern for the evening storm system (squall line plus cold front) is depicted in figure 30. The pattern strongly reflects the passage of the two major rain cells, A and E. The 1765-square-mile area (network) average rainfall was 0.94 inch. Rainfall exceeding 2 inches covered 131 square miles, and 1-inch or greater rain fell over 630 square miles.

The 16 hailstreaks were widely scattered and produced hail over only 67 square miles. Although the rainfall production and rain cells were not unlike those of the morning system, the evening system produced markedly different (less) hail.

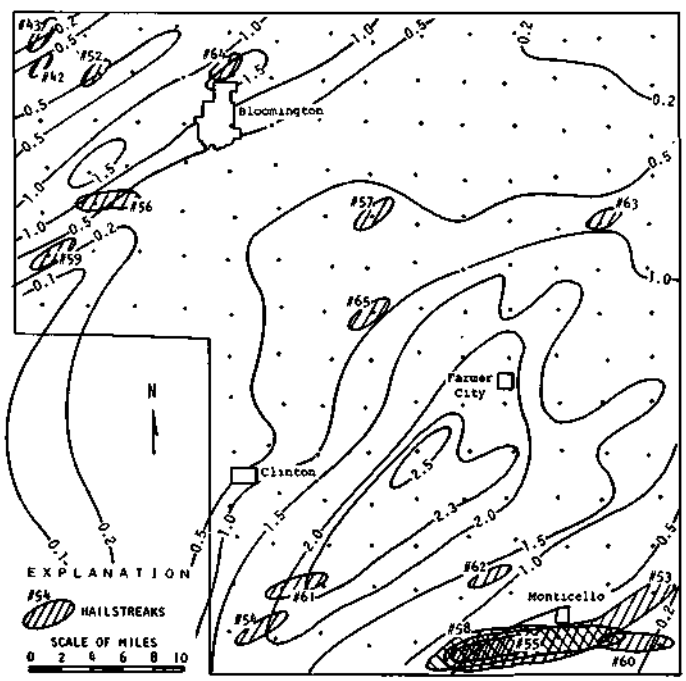


Figure 30. Patterns of total rain and hailstreaks for the squall line-cold front system

The occurrence of this heavy short-duration (14-hour) rainstorm largely within the confines of a densely gaged 1550-square-mile recording raingage network afforded a unique opportunity to study such a storm. Although the synoptic weather conditions of this May storm were not necessarily typical of those found in many prior severe rainstorm cases, this May storm illustrated in detail the one condition that is common in all such storms and thus necessary to achieve 10-inch or heavier point rainfalls in 24 hours or less in Illinois. This common denominator is the passage of two or more heavy rain systems in one relatively small area within 24 hours with maximization of most of the systems in this same small area. Hence, semistationary synoptic weather conditions conducive to repeated developments of heavy rain systems (squall lines, massive air-mass storm complexes, steady-state storms, etc.) must exist in or near Illinois. The resulting rain systems must then move away from the formation zone in the same general direction, and finally they must maximize their rain production or slow at about the same location. If any condition (formation, direction of motion, or maximization) does not exist, 10-inch rains will not occur. If the maximization does not repeatedly occur in the same location, there will be more widespread 2- to 6-inch amounts and no 10-inch values downwind of the "formation zone" for the rain systems.

In the case of the 15 May storm, the rain systems were partially self-perpetuating since the atmospheric after-effects of the morning storm system were instrumental in the formation and maximization of the afternoon steady-state storm system. Then, the steady-state system essentially bred the feeder storm system. The maximization of the squall line system in the network may have been accidental or may have resulted from the increased available moisture due to evaporation.

There were 19 major rain cells (table 11) in the four rain systems, and two of these cells (the steady-state and feeder storm system) were immense multicellular storms. All 19 cells were so large and long-lived that none was completely defined in the 1550-square-mile network. The cells showed a distinct tendency for right flank or independent development, and their speeds were remarkably uniform. Motions varied from SSW to WNW with considerable variation among cells in both systems that had more than one cell.

All systems produced considerable hail with a summation of all hailstreaks yielding hailfall over 1664 square miles (table 11). Hailstreak sizes varied considerably (from 0.1 to 788 square miles), but the 0.1 to 4.0 square mile size was most common. The 113 hailstreaks in this 14-hour storm period represented 42 percent of the total hailstreaks that occurred in the network in 1968.[11] The six tornadoes represented 50 percent of the total in Illinois.in 1968.

Classification of the formation locations of 113 hailstreaks with respect to their associated precipitation core, where this could be determined, revealed that 39 were on

Table 11. Summary of Rain Cells and Hailstreaks for Four Rain Systems and Entire Storm in the Central Illinois Network on 15 May

Rain system	Number of rain cells	Number of rain cells by sizes (sq mi)					Number of rain cells developing at given locations from other cells				Average cell speeds (mph)			Number of rain cells with motions from given directions				
		0-100	101-200	201-300	301-400	Over 400	Independent	Right flank	Left flank	Not known	Mean	Max	Min	SSW	SW	WSW	W	WNW
Morning	10	4	1	1	3	1	4	4	1	1	29	37	23'	0	0	6	2	2
Steady-state	1	0	0	0	0	1	1	0	0	0	36	36	36	0	0	0	1	0
Feeder	1	0	0	0	0	1	0	1	0	0	24	24	24	0	0	1	0	0
Squall line	7	1	0	2	3	1	1	4	1	1	30	40	15	1	4	2	0	0
Storm total	19	5	1	3	6	4	6	9	2	2	30	40	15	1	4	9	3	2

	Number of hailstreaks	Maximum number of streaks with 1 rain cell	Areal extent of hailstreaks (sq mi)			Number of hailstreaks per given size (sq mi)					Number of streaks in given locations from rain core		
			Entire system	Max in 1 streak	Min in 1 streak	0.1-4	4.1-8	8.1-12	12.1-16	Over 16	Right	Left	Center
Morning	48	14	434	62	2	13	16	9	5	5	16	11	17
Steady-state	22	22	936	788	1	13	2	2	1	4	7	12	2
Feeder	27	27	214	41	1	12	6	3	4	2	10	8	8
Squall line	16	6	80	23	2	8	4	0	1	1	6	5	5
Storm total	113 /	27	1664	788	1	46	28	14	11	12	39	36	32

	Average hailstreak duration (min)	Average hailstreak speed (mph)	Average point hail duration (min)	Average difference in rain-hail start times (min)
Morning	15.7	31.4	3.5	3.7
Steady-state	15.0	32.7	3.6	25.1
Feeder	15.3	28.6	4.9 "	46.0
Squall line	8.4	37.6	3.6	4.6
Storm mean	14.3	32.1	3.9	17.6

the right flank, 32 in the center, and 36 on the left flank (table 11). Temporal analyses showed that most hailfall areas moved forward slightly faster than the speed of their associated rain core, although 38 percent of the hailfall areas moved either slower or at the same speed. These differences indicate many hailfalls were being generated by mechanisms not directly associated with the main rain core of the storm. Thus, hailfall areas at any given time were found to be distributed throughout all portions of a rain cell.

In general, the major rain cells on 15 May had their greatest hail production in a 15- to 30-minute period of their early stages (youthful and mature) when their speed was greatest and their rain areas were enlarging and intensifying. The typical rain cell sequence in the next 15 to 30 minutes was for hail production to largely stop, rainfall to maximize (both point and area), and cell speed to decrease 25 to 50 percent. In the final stage of these rain cells, there was no hail, rain was rapidly diminishing, and the cell speed was increasing. Thus, the model rain cell for 15 May was large in areal extent and went through three distinct phases: 1) fast-moving, heavy-widespread hail, and heavy rain rates but low point totals; 2) slower moving, light hail, high rainfall rates, widespread rain, and high point totals; and 3) fast-moving, no hail, moderate rain rates, and low point totals.

Hailfall point durations varied widely (1 to 45 minutes) as did hailstreak durations (4 to 90 minutes). Hailstreak differences between systems were notable. Squall line hailstreaks were much shorter in duration. The hailstreaks produced by the morning system and the squall line system were located notably nearer the front edge of rainfall than those in the other two systems. Hailstreak average speeds and point durations were very similar in all systems (table 11) except the feeder storm system which had slower speeds and consequently longer point durations.

The most interesting and unusual hail condition on 15 May was the immense wall of ice, which was about 8 by 30 miles for 60 minutes, produced by the steady-state storm. This fantastic production of hail resulted in a "design" hailstreak that existed for 90 minutes, covered 788 square miles, produced point hail durations of up to 45 minutes, and produced large hail (2-inch stones), high hailfall energies, and much crop and property damage.

The great severity of the entire 15 May storm and its rain systems is further reflected in table 12. Here the maximum point rainfall amounts produced by each system anywhere in the network are expressed as their recurrence interval. The maximum 15-minute to 2-hour values produced by the steady-state storm all represented once in 200-year or greater frequencies. The maximum 3-hour amount (6.69 inches at gage 135) produced by the combined steady-state and feeder storm systems represented a value expected to occur at least once in 760 years.

Certainly, the excessive rain rates (table 12), the super 788-square-mile hailstreak, and the six tornadoes make the steady-state storm the single most significant rain system on 15 May. This study also presents the first detailed surface portrayal of this classic type of storm.

Knowledge of the internal structure of this giant steady-state storm is meager, as has been the case for most such storms, but the detailed time analyses of the rainfall and hailfall suggest that the super hailstreak developed as the steady-state storm attained its maturity (maximum size) and an organization (shape) that allowed a uniform, strong, low-level inflow of moist air into its broad (30-mile wide) front. Importantly, the storm's entire forward edge just before and during most of the super hailstreak was quite straight and oriented NE-SW so as to be perpendicular to the strong low-level inflow. The storm's shape, as depicted by radar and by the surface rainfall, went from an irregular N-S oriented mass to a J-shape, and finally to a W-E oriented mass. The super hailstreak dissipated as the central portion of the steady-state storm, which was moving faster than the northern and southern flanks, changed the storm's shape and became separated from the feeder-cell area on its right flank.

The enormous size and complexity of this steady-state storm reveals that upper air measurements adequate to describe this storm's mechanics would require a large task force of well-instrumented aircraft. Since such a commitment is unlikely, and since storms are infrequent and hard to predict, it seems likely that study and knowledge of such storms for many years may have to depend on inferences that can be drawn from the rare occurrences in areas where detailed surface data or radar data (or both) are available.

Table 12. Frequency of Maximum Point Network Rainfall in Each System

System	Recurrence interval (yr) for given durations				
	15-min	30-min	1-hr	2-hr	3-hr
Morning	17	8	5	5	3
Steady-state	230	420	520	200	760
Feeder	45	55	140	240	
Squall line	23	40	60	70	40

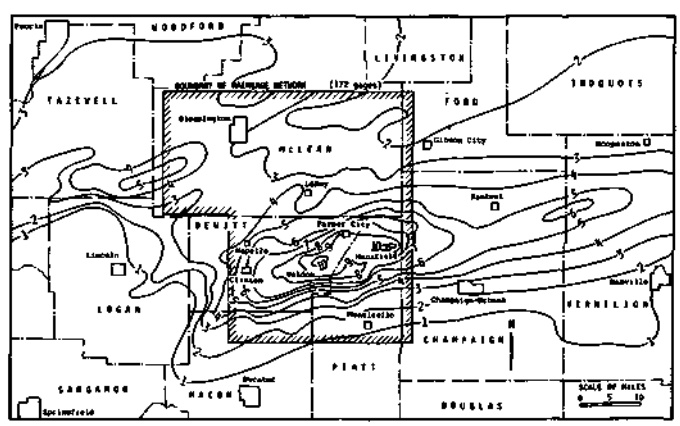


Figure 31. Total rainstorm Isohyetal map for 15-16 May in central-eastern Illinois

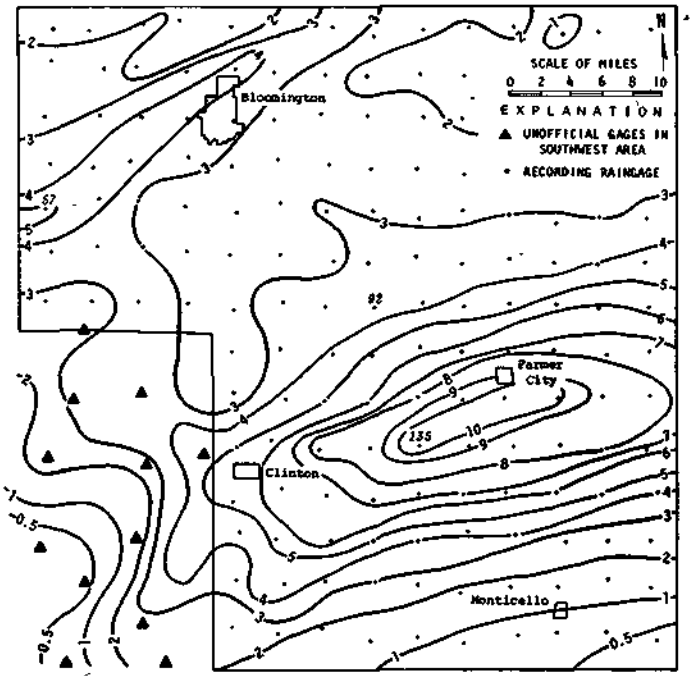


Figure 32. Total rainstorm isohyetal map for 15 May in Central Illinois Network

Total Rain

The areas of heaviest rainfall occurred in central and eastern Illinois, and the isohyetal pattern for the rainstorm is depicted in figure 31. Most of the rainfall occurred on 15 May although some heavy amounts occurred early on 16 May in extreme eastern Illinois. Certainly, the heaviest rain (7 inches or more) was all concentrated in the 1550-square-mile raingage network, although extensive areas of 4 inches or more extended to the east and west of the network. The relatively narrow E-W orientation of the storm area agrees with that found in most earlier Illinois severe rainstorms.[2,8,7] Rainfall of 3 inches or more and 4 inches or more fell over 2868 and 1275 square miles, respectively.

The total rainfall pattern in the network is displayed in greater detail in figure 32. This clearly reflects how the rain systems maximized largely within the lower center area of the network. The area-depth values appear in table 13. Ten inches fell over 16 square miles, and 5 inches or more over 350 square miles.

The area-depth curves for the four systems and the total storm appear in figure 33. The two heaviest rain systems (steady-state and feeder systems) did not produce network-wide rainfall, whereas the more widespread systems (morning and squall line) that had lesser point amounts produced measurable rain over the entire network.

Table 13. Area-Depth Values for Total Rainfall on 15 May in the Central Illinois Network

Area (*8q mi*) for given rainfall equalled or exceeded (in)										
0.6	1	2	3	4	5	6	7	8	9	10
1705	1635	1330	864	513	350	259	175	108	44	16

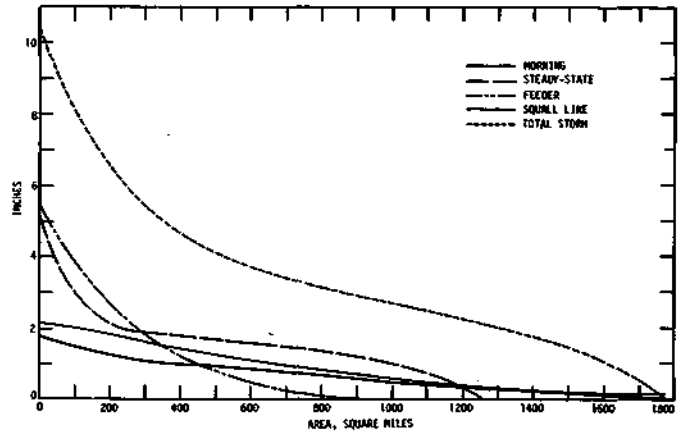


Figure 33. Area-depth curves of four rain systems and total storm on 15 May

Practically all the network rainfall fell within the 12-hour period 0930-2130 CDT, and the point maximum 12-hour amounts throughout the network were each expressed as the recurrence interval they represented. These were plotted and used to construct the map shown on figure 34. Two gages (123 and 124) had 12-hour amounts expected to recur at least once in 900 years, as extrapolated from existing recurrence interval values.[17] All points within the 100-year or greater interval formed an area of 267 square miles. The 15 May storm achieved its greatest significance in rainfall production based on its 12-hour values. The greatest recurrence interval values achieved in 1-, 2-, and 3-hour periods (table 12) were less' than the 12-hour frequencies. The 10-inch rainfalls in 12 hours in this 15 May storm exceed most of the 12-hour values previously noted in other Illinois storms.[6]

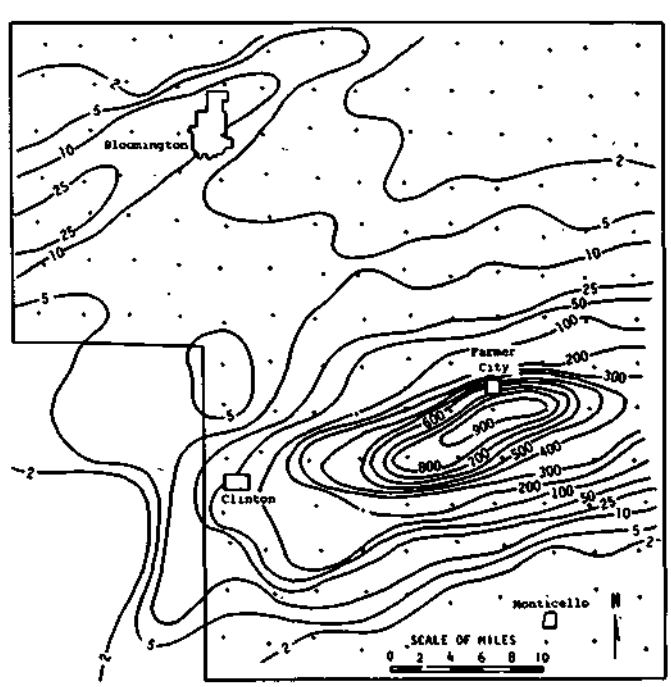


Figure 34. Recurrence Intervals, years, for maximum 12-hour rainfall amounts in Central Illinois Network

Total Hail

The 15 May rainstorms were also exceptional hail-producing mechanisms. The number of hailstorms at points in central-eastern Illinois were used to construct figure 35. An unbroken area 110 miles long (E-W) and ranging from 20 to 50 miles wide (N-S) had one or more hailstorms. Several areas in the Bloomington-Farmer City-Clinton region had three or more hailstorms, many of which were damaging to property and crops.

Figure 36 displays the percent of crop losses on each of 130 farms with paid insurance losses from the storms on 15 May. Fortunately, the major crops (corn and soybeans) were in early growth stages so that they were not severely damaged by hail. Wheat is not grown extensively, but it was in a more hail-susceptible stage, and damages were great with several farms around Clinton having 100 percent wheat losses. Many of the crop losses shown in figure 36 were largely a result of the super hailstreak produced by the steady-state storm. Property damages from hail included broken glass in dwellings and automobiles, and heavily dented siding on dwellings.

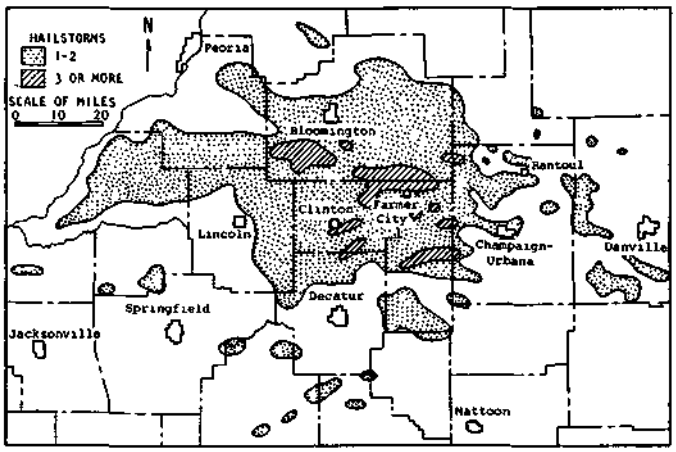


Figure 35. Pattern for total hailstorm frequency in Illinois on 15 May

A 900-square-mile area within the 1550-square-mile raingage network had hailpads. One-square-foot hailpads were installed alongside the 96 raingages forming the area shown in figure 37. The number of separate hailfalls at each location was obtained from the recording raingage traces *(see figure 3),* and these were used to con-

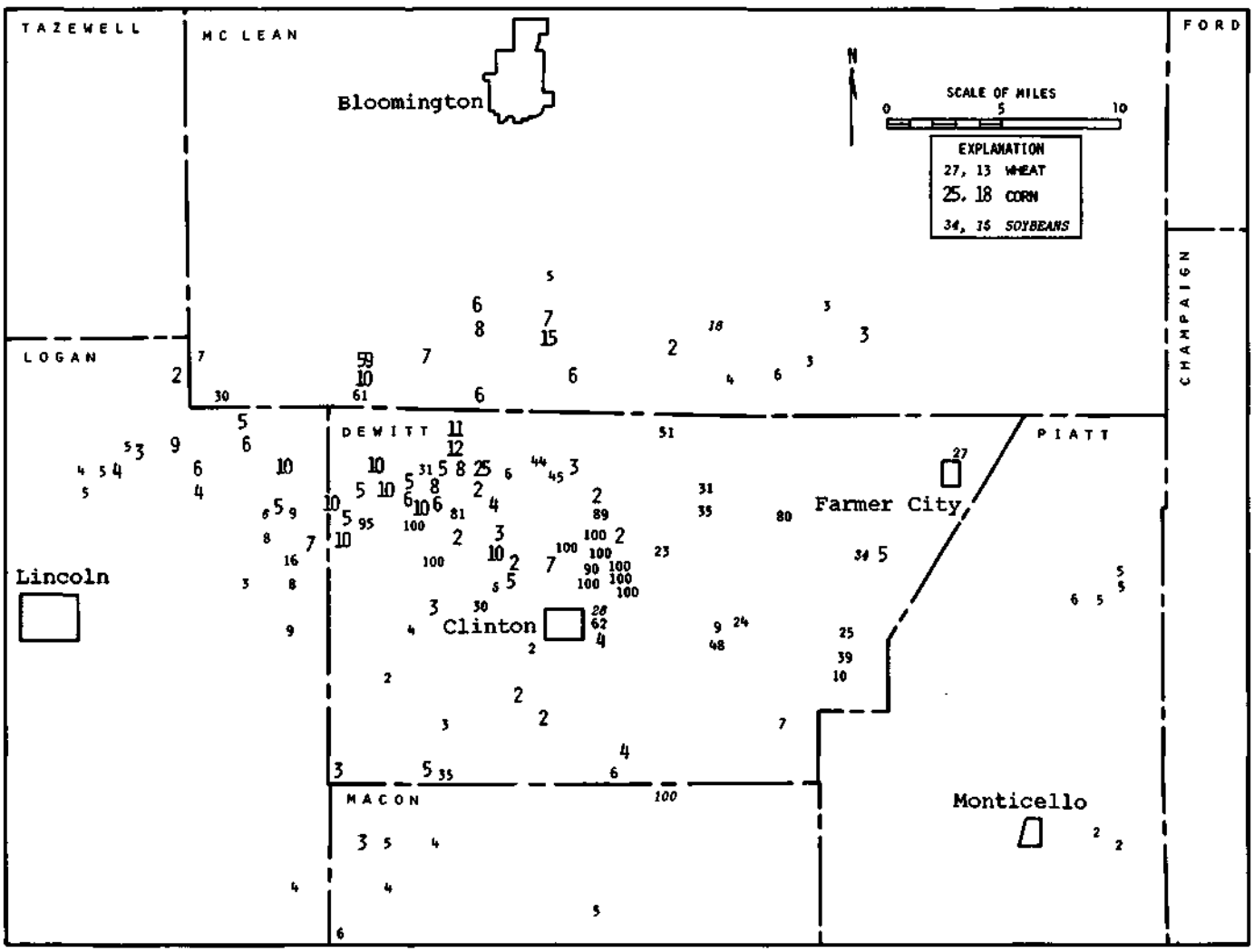


Figure 36. Crop-hail percent loss from 15 May storms at individual farms

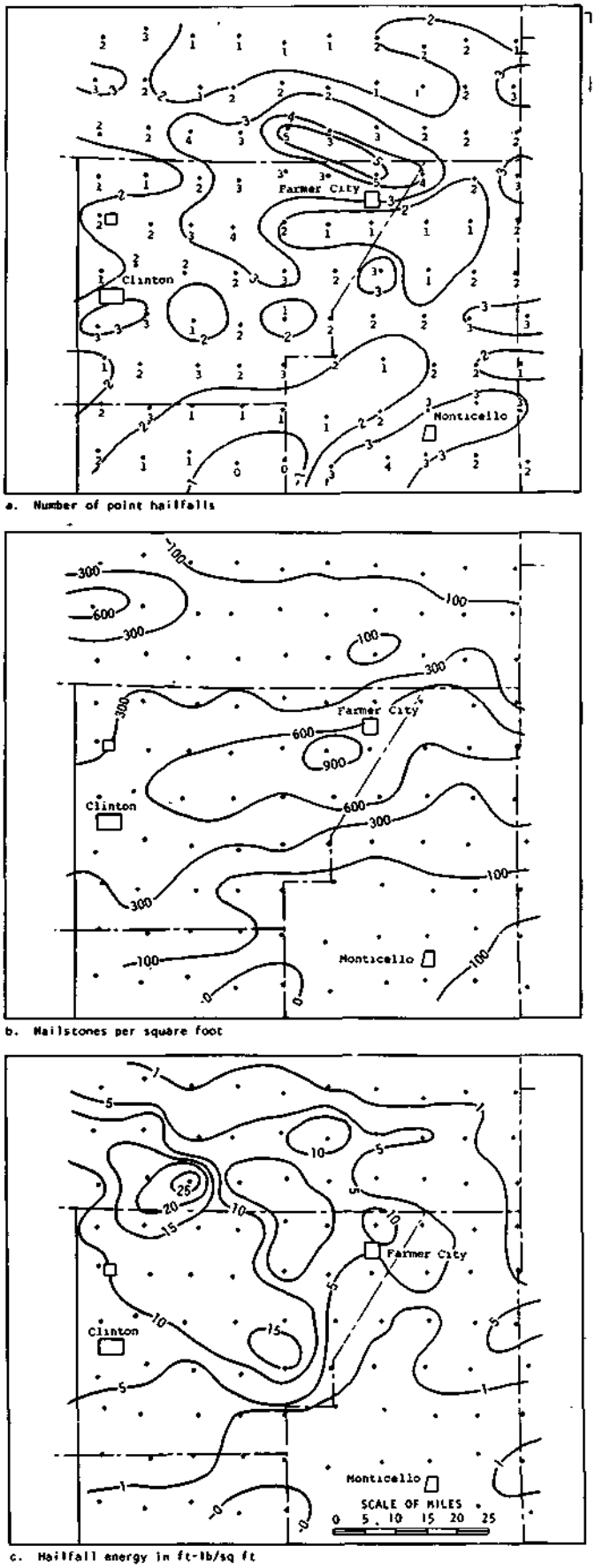


Figure 37. Hailfalls, hailstones, and hail energy in 900-square-mile portion of network with hailpads

struct the pattern shown in figure 37a. Two gages (190 and 191) had no hail, but all others had one or more hailfalls. Two gages (93 and 109) had five hailfalls in the 14-hour storm period, and large areas had three or more distinctly separate hailfalls. The number of hailstones per square foot, as determined from the hailpads, was used to construct the pattern shown in figure 37b. One hailpad (at gage 122) had 1026 hailstones, and a large. number of pads had 600 or more hailstones on 15 May. The average number of hailstones per square foot in a hailfall is 24,[11] and the maximum number ever observed within the network in the 1967-1968 period was 1406."

The energy imparted by the total hailfalls at each hailpad was calculated.[9] The resulting point values were used to develop the pattern in figure 37c. One gage (91) had a maximum energy of 27.4 ft-lb/ft^2, the second largest observed value on any hailstorm day in 1967-1968.[11] The large hailstones and prolonged hailfall in the super hailstreak resulted in most of the large energy values shown north and east of Clinton. The 113 hailstreaks on 15 May produced the most severe, widespread hailstorm day observed on the network in the 1967-1969 period.

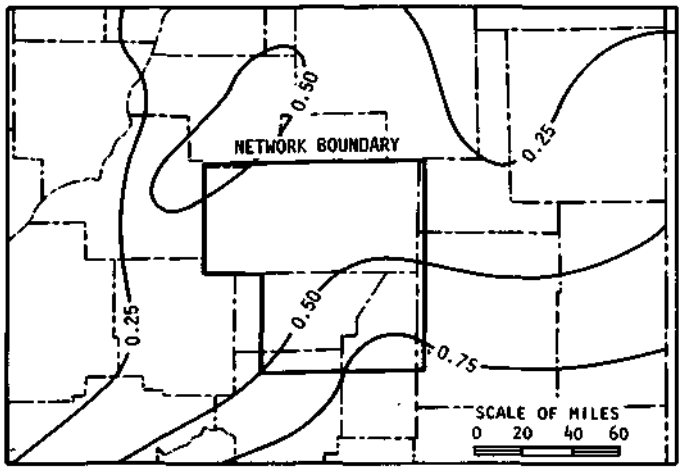
Hydrologic Analysis

The heavy rainfall of the 15 May storm produced severe flooding in local river valleys, widespread standing water in fields that resulted in drowned crops, and many washed-out bridges and fills on railroads and highways (figure 1). With the exceptional 15-minute to 12-hour rainfalls (table 12 and figure 34), runoff was accordingly excessive.

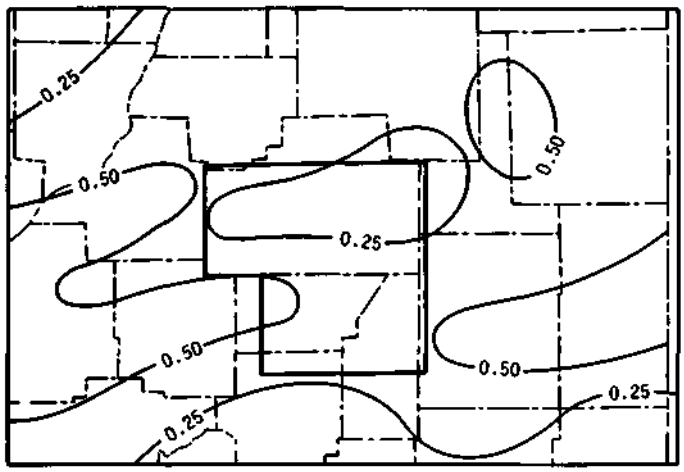
The antecedent rainfall in the storm area in the 5 days prior to the storm (figure 38a) ranged from less than 0.25 inch to slightly more than 0.75 inch. The normal 5-day point rainfall in May is 0.7 inch, and thus the antecedent storm rainfall was generally below normal. Rainfall in the 5 days after the storm (figure 38b) throughout the storm area was mostly between 0.25 and 0.5 inch, also below normal.

The time distributions of rainfall produced by the 15 May storms are portrayed in figures 39 and 40. The rainfall curves at five locations selected in central-eastern Illinois are shown in figure 39. The morning storm system is shown at all five locations in varying magnitude, followed by the afternoon (steady-state and/or feeder storm) systems, and subsequently by the evening squall line-cold front rainfall system. The nearly continuous rainfall at gage 135 in the network (figure 39) reveals the effect of maximization of the steady-state, feeder, and squall line systems at this one location.

The 1550-square-mile network data were used to construct figure 40 which portrays the temporal change of



a. Rainfall, inches, 5 days prior to 15 May



b. Rainfall, inches, 5 days following 15 May

Figure 38. Five-day rainfall patterns before and after 15 May

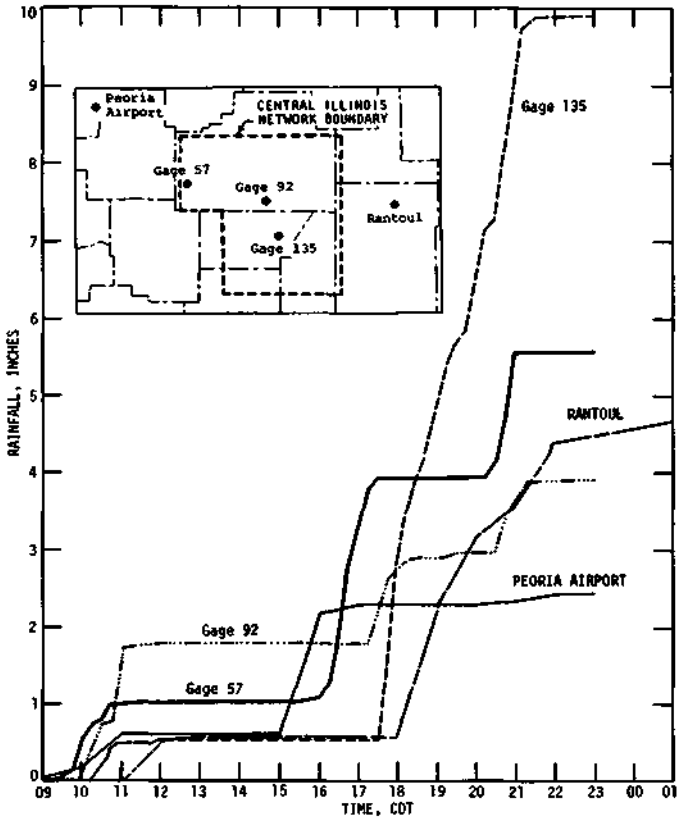


Figure 39. Rainfall curves at five selected raingage locations

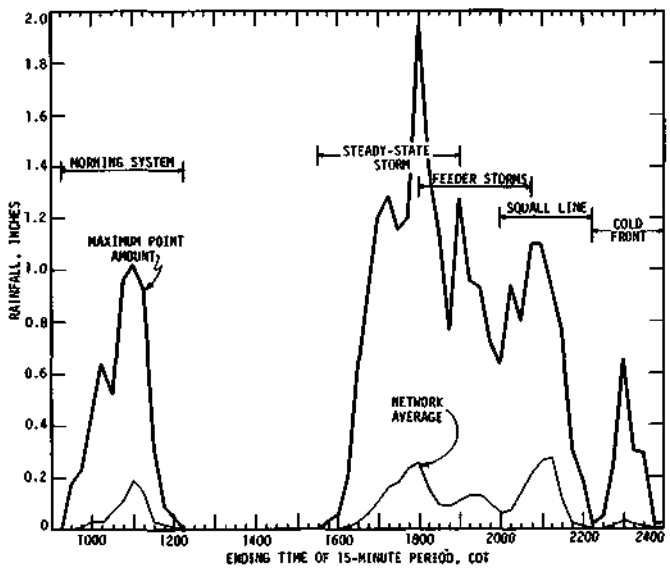


Figure 40. Temporal distribution of network average rainfall and maximum point rainfall based on 15-minute values for 15 May

rain in the network as based on the network average and network maximum point rainfall values for each 15-minute period. Also labeled are the general beginning and ending times of the rain systems showing the 3-hour rainless period after 1215 CDT. In general, the network average rainfall maximized in the 15-minute periods when the point maximum rainfall values also peaked. However, the highest network average 15-minute value was 0.27 inch which occurred with the squall line when maximum point rainfall was 1.10 inches.

The raingage network encompassed most of four small basins which had streamgages (figure 41). The hydrographs of these four basins are depicted in figure 42. Prior to the storm, discharges at all four gages were less than 200 cfs, considered base flow because of the light antecedent rainfall (figure 38a). All four basins began to experience increased runoff by 1500 on 15 May with Kickapoo Creek and Salt Creek increasing most rapidly. These two basins are located (figure 41) where the morning storm system rainfall was greatest (figure 19). By 2400 CDT on 15 May the discharge on Salt Creek was 6200 cfs, that on Kickapoo Creek was 3000 cfs, that on the Sangamon River was 1200 cfs, and that on Friends Creek was 300 cfs. As shown by figures 41 and 32, the Friends Creek Basin is centered to the south of the heaviest rainfall.

The peak runoff attained on Kickapoo Creek at Waynesville came at 0300 on 16 May (5400 cfs), and the peak of 5600 cfs on Friends Creek at Argenta was at 0900 on 16 May. Peaks on Salt Creek and the Sangamon River Basins, the larger basins, consequently came later and were much larger. The peak on the Sangamon at

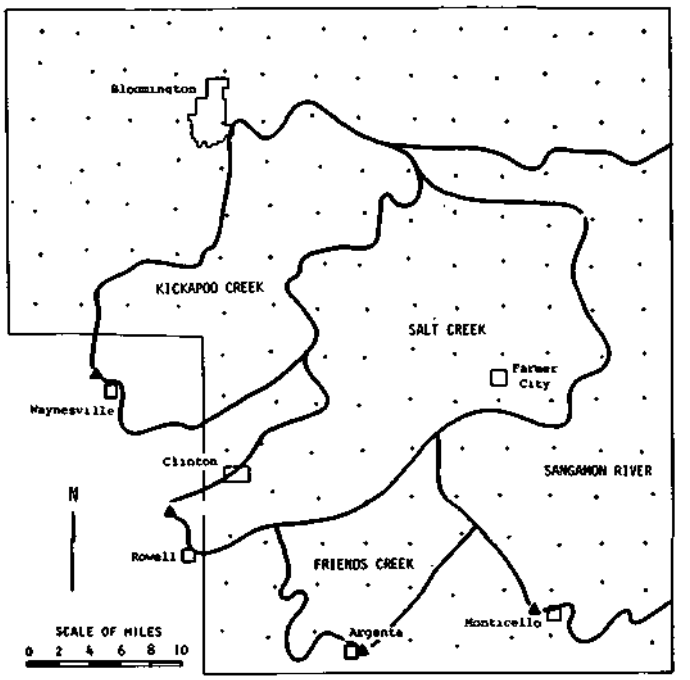


Figure 41. Basins with streamgages located largely within network areas of heavy rainfall

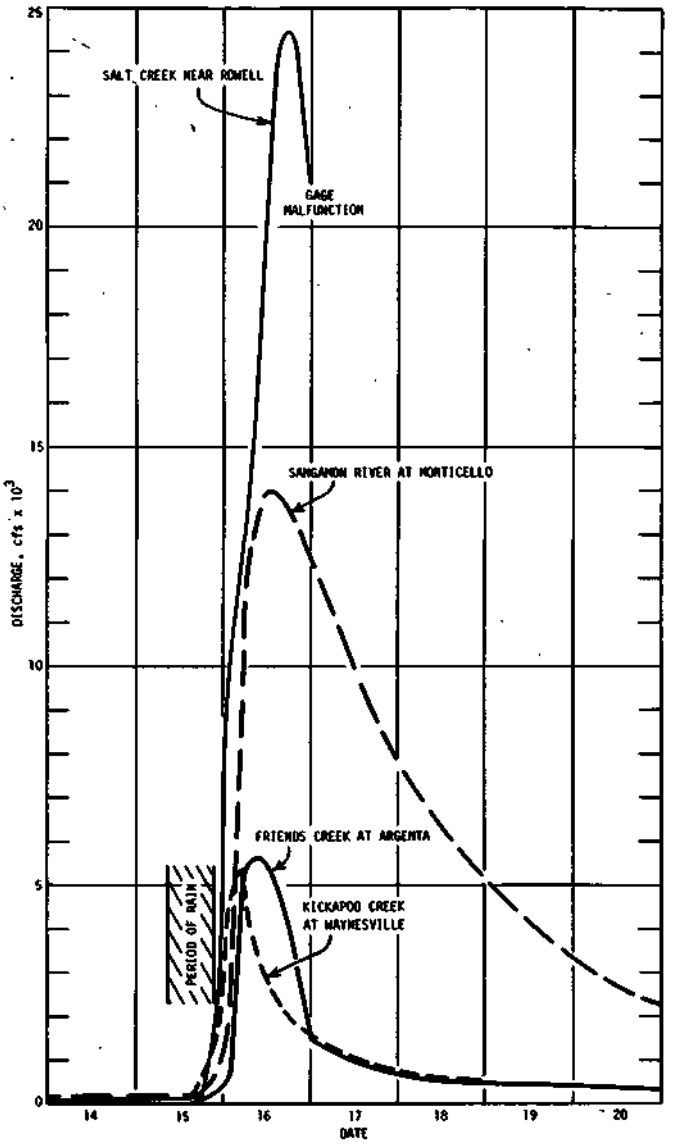


Figure 42. Hydrographs of runoff for four basins greatly affected by the 15 May storm

Monticello was 14,000 cfs at 1200 on 16 May, about 15 hours after the heavy rain ended. The greatest discharge rate noted was 20,400 cfs on Salt Creek, and this came at 1500 CDT on 16 May. Excessive rainfall on this basin resulted in considerable valley flooding *(note figure 1)*, and field storage of water.

Thus, peak runoff was attained on all four affected basins within 3 to 15 hours after the storm ended.

Near base flow was attained by 19 May on the Kickapoo Creek and Friends Creek Basins, but storm-related runoff was still present on the Sangamon at the end of 20 May.

Storm Damages

The exact amount of crop and property damage from the 15 May storms in central Illinois could not be determined. The U. S. Weather Bureau estimate is between $500,000 and $10,000,000." However, the De Witt County Board of Supervisors determined that the total storm damage in that county alone was $5,135,000. This included $362,000 from damages to roads and bridges, $929,000 to public property, $3,670,000 loss in private property, $90,000 in damages to sewers and from sewage, and $83,-000 for cleanup costs. Damages in Logan County were estimated at $2,012,000, indicating that the total storm damage was likely well in excess of $10,000,000.

The flooding caused considerable unmeasured soil erosion, labeled the "worst ever" by Champaign and De Witt County farms advisors. Also many area farmers eventually had to replant several thousand acres because the young corn and soybean plants were washed away or rotted because of flooding. The excessive runoff washed out 15 bridges, 2 homes in Clinton, and numerous fills on railroads and highways; 1 person was drowned when his automobile was caught in a flash flood. Mud deposition by the flooding along a 15-block area in Clinton was a major problem.

Four persons were killed and at least 56 injured by the tornadoes at Wapella and Waynesville. Ten others were injured by lightning.

The destruction of 94 high voltage electric transmission towers of utility companies (*see figure 1*) resulted in 8-hour or longer power outages in the Lincoln-Clinton area. Certain industries in Lincoln had to be closed for two days because of wind damage and the power failures.

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