Record Flood-Producing Rainstorms of 17–18 July 1996 in the Chicago Metropolitan Area. Part I: Synoptic and Mesoscale Features

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ABSTRACT

A unique rainstorm in northern Illinois produced 43 cm of precipitation in mid-July 1996, the highest 24-h precipitation amount ever recorded officially in the upper Midwest. Rains exceeding 20 cm fell over an area of 4400 km^2, creating extremely damaging flash floods in portions of Chicago and its suburbs. Measurements from 496 rain gauges, including 80 recording gauges in the heavy rain area, made it possible to accurately define this storm.

The heavy rains were the result of two massive mesoscale convective systems, one in the afternoon and one at night. These systems formed to the north of a nearby stationary warm front. Several factors contributed to the excessive rainfall. Excessive moisture was present to the southwest of the warm front over Iowa and western Illinois; atmospheric moisture content was enhanced by surface evaporation from a very wet surface created by heavy rains the previous day, creating a conditionally unstable atmosphere. A cool air mass transported by easterly winds off Lake Michigan strengthened and slowed the movement of the warm front. A low-level jet oriented perpendicular to the warm front resulted in rising motion north of the warm front. These factors (instability, moisture availability, lifting mechanism) combined to form intense storms. This paper, the first of a three-part series, describes the storm in detail, including its morphology and causes, and the resulting rainfall distributions.

1. Introduction

Rainfall amounts in 24 h in an area of northeastern Illinois ranged from 35 to 43 cm (14–17 in.) during 17–18 July 1996. These values greatly exceeded those expected to occur once in 100 years (23 cm) and were the greatest on record for any official weather station in the upper Midwest. The 43 cm of rain broke the prior record for Illinois of 41.8 set on 14 June 1957. Rains were heaviest in an area containing an abnormally large number of rain gauges, a factor allowing detection of the record rainfall and very definitive time- and space scale analyses. The large-scale flash flood produced by these rains was sufficiently unique to warrant an extensive study of the storm's dimensions, causes, hydrometeorological characteristics, and impacts and responses (Angel et al. 1997). This paper, the first of three, describes the storm, including its morphology and causes. It serves as a prologue for the two other papers that describe the hydrometeorological evaluation [see Angel and Huff (1999)] and the flood and the resulting societal impacts and responses to the flooding [see Changnon (1999)].

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Heavy rains fell across portions of Wisconsin, Illinois, and Indiana during a 36-h period that began at 0800 local standard time (LST) on 17 July 1996. A three-state isohyetal pattern reveals that the heaviest rains, more than 20 cm, fell in a band across northeastern Illinois with more than 15 cm over an area of 13 600 km^2 (Fig. 2). Although rural and urban areas were both affected, the major impacts of the storm occurred in the Chicago metropolitan area (Fig. 2), where rains exceeded 25 cm.

The heaviest rainfall across northern Illinois fell in less than a 24-h period. The earliest rain in northeastern Illinois began at 1000 LST on 17 July; the rainfall ended by 0800 LST 18 July. Maximum hourly rainfall amounts in the storm area exceeded 1.3 cm for 20 consecutive hours. Large hail (>7-cm diameter), damaging lightning, and three tornadoes also occurred in northern Illinois on 17 July.

The National Weather Service (NWS) WSR-88D radar near Chicago indicated strong convective activity throughout the storm with reflectivities of 50 to 60 dB*Z* lasting for 20 hours. Maximum heights of echo tops during most of the storm period were greater than 14 km, reaching the maximum (>17 km) during the 2000–2300 LST period on 17 July. Echoes that attain these heights are highly indicative of the presence of severe weather in Illinois (Grosh 1978).

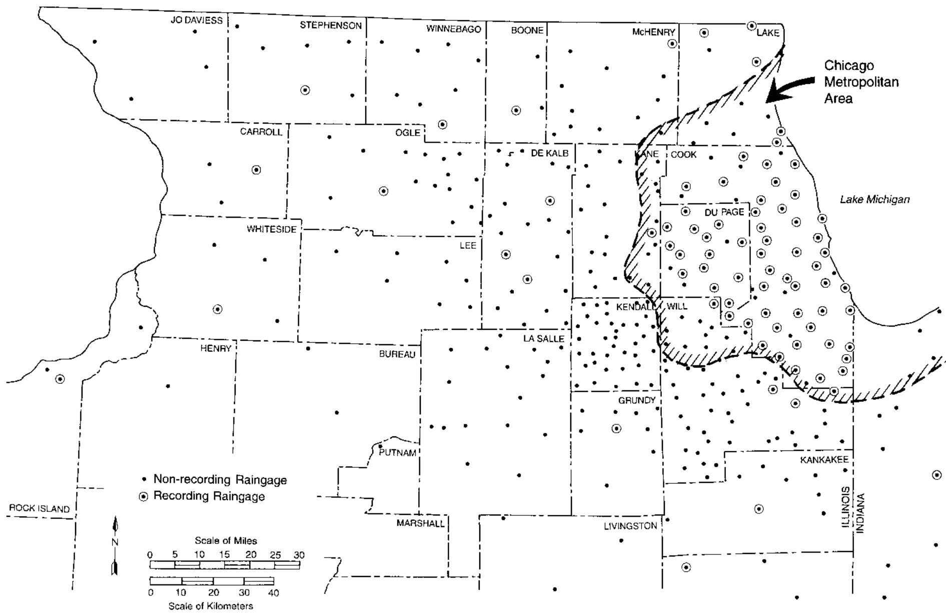

FIG. 1. Illinois locations where storm rainfall amounts were collected.

2. Rainfall data

A meaningful analysis of a severe convective rainstorm depends on obtaining extensive rainfall data in and near the core of the storm. Rainfall data for the 17–18 July storm came from three sources: 1) bucket surveys conducted by county farm agents and groups of scientists traveling through the core area, 2) special rain gauge networks operated by various local governmental entities, and 3) rain gauges operated by various federal and state agencies.

Bucket surveys collected 107 point rainfall measurements in northern Illinois. Bucket surveys are field searches in vehicles to locate persons in the area who had rain gauges or collection vessels outside (like buckets) that measured the storm total. Most of these field measurements were collected in and near the areas experiencing 10 cm or more of total storm rainfall.

There were five networks of densely spaced rain gauges in the storm's center. One network had 25 recording rain gauges over an area of 2000 km^2, and a second network was part of a statewide network that had four recording rain gauges in the storm area (1500 km^2). Three area counties were also operating dense rain gauge networks: two networks collected daily rainfall data from 42 cooperative rain gauge observers and 36 cooperative observers, respectively; and a third county had a network of 14 recording rain gauges. Additionally, the Metropolitan Water Reclamation District of Greater Chicago had 15 recording rain gauges scattered throughout the Chicago urban area.

Rain gauges operated by various state and federal agencies were the third source of rainfall data. The NWS had 203 nonrecording rain gauges with daily amounts of rain from the storm across a three-state area that included Illinois, Indiana, and Wisconsin. In Illinois, daily rain gauge values in and near the storm area came from 51 NWS stations, plus 14 recording rain gauges distributed in the Illinois storm area. The U.S. Army Corps of Engineers had six recording rain gauges in northeastern Illinois. Moreover, three cities in the region each had a recording gauge and the Argonne National Laboratory maintained a recording gauge. Thus, for the heavy rain area in Illinois, data came from 316 rain gauges, of which 80 were recording rain gauges (Fig. 1). Such extensive recorded rainfall data allowed a detailed temporal analysis of this storm. In addition, data were available for most of the storm from the WSR-88D radar operated by the NWS at a site southwest of Chicago.

3. Total storm rainfall

Figure 2 shows the total storm rainfall pattern for Illinois, Indiana, and Wisconsin. An area of greater than 20 cm (8 in.) of rainfall extends from just southeast of Freeport through southern portions of the Chicago metropolitan area (outlined in Fig. 1). The area receiving 20 cm or more rainfall in 20 h or less covered 4400 km^2. The area receiving 15 cm or more rainfall extended from southern Wisconsin across northern Illinois and eastward into northern Indiana, covering 9460 km^2. The storm rainfall pattern is more uniform than found in past rainstorms, reflecting a different, more areally consistent series of meteorological factors causing the storm than exist in most others (Silberberg 1996; Huff et al. 1958).

Figure 3 is a map of the total storm rainfall based on the measurements of the NWS WSR-88D radar. This pattern and Fig. 2, which is based on 557 rain gauge

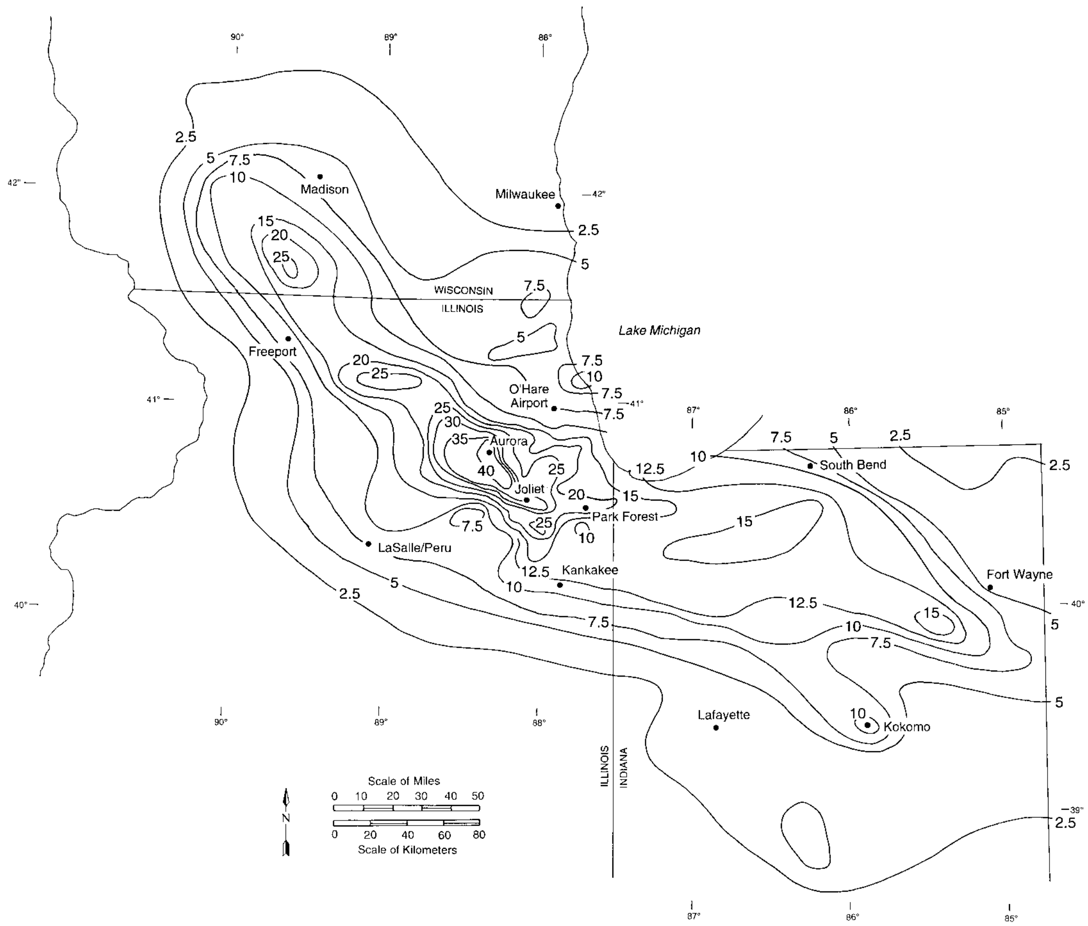

Fig. 2. The total rainfall (cm) for the storm of 17–18 July 1996.

measurements, show generally similar features. Both maps indicate that the heavy rain area of the storm entered northern Illinois in the same location, extended southeastward, and then assumed a more easterly orientation from Chicago into Indiana. The radar's total storm pattern agreed well with the rain gauge pattern, but many gauge–radar comparisons based on hourly point amounts showed large differences (Westcott 1997). The close agreement in total storm rainfall holds promise for the real-time use of radar-defined storm totals in responding to flash floods.

4. Temporal distribution

The temporal distribution of the heavy rainfall on 17–18 July is illustrated by the time-distribution curves for five rain gauges in and near the center of the storm (Fig. 4). The DeKalb gauge is in the western end of the high rainfall zone (Fig. 2), and the easternmost gauge (gauge 25) is close to Chicago's southern edge (Park Forest) and the storm's eastern end. All of these time distributions show that the rain fell primarily during two periods, each with heavy rainfall.

The first heavy rainfall period began late on the morning of 17 July. Varying amounts of rain fell from a series of showers and thunderstorms during the afternoon, with the most heavy rain rates ending by 1800 LST on 17 July. However, some rain gauges continued to experience convective storms producing up to 1 cm h^{-1} between 2000 and 0000 LST on 17 July. The second heavy rain period began between 0000 and 0100 LST on 18 July. Heavy rains occurred at all rain gauges from that time until between 0500 and 0700 LST on 18 July. Rainfall from subsequent rainshowers continued until 1000 LST on 18 July.

These time distributions reveal that both the afternoon storm system and the subsequent nocturnal storm system were composed of a series of convective showers. Gauge 15 near Lemont registered slightly over 13.2 cm in the afternoon storm and then 14 cm in the nocturnal storm, nearly equal amounts. At the other four recording gauges, the nocturnal rain period was the much heavier of the two. Investigations of other severe convective rainstorms in the Midwest have shown that the heaviest rains during a 24-h day typically occur during the nocturnal hours (Huff et al. 1958; Huff and Changnon 1964).

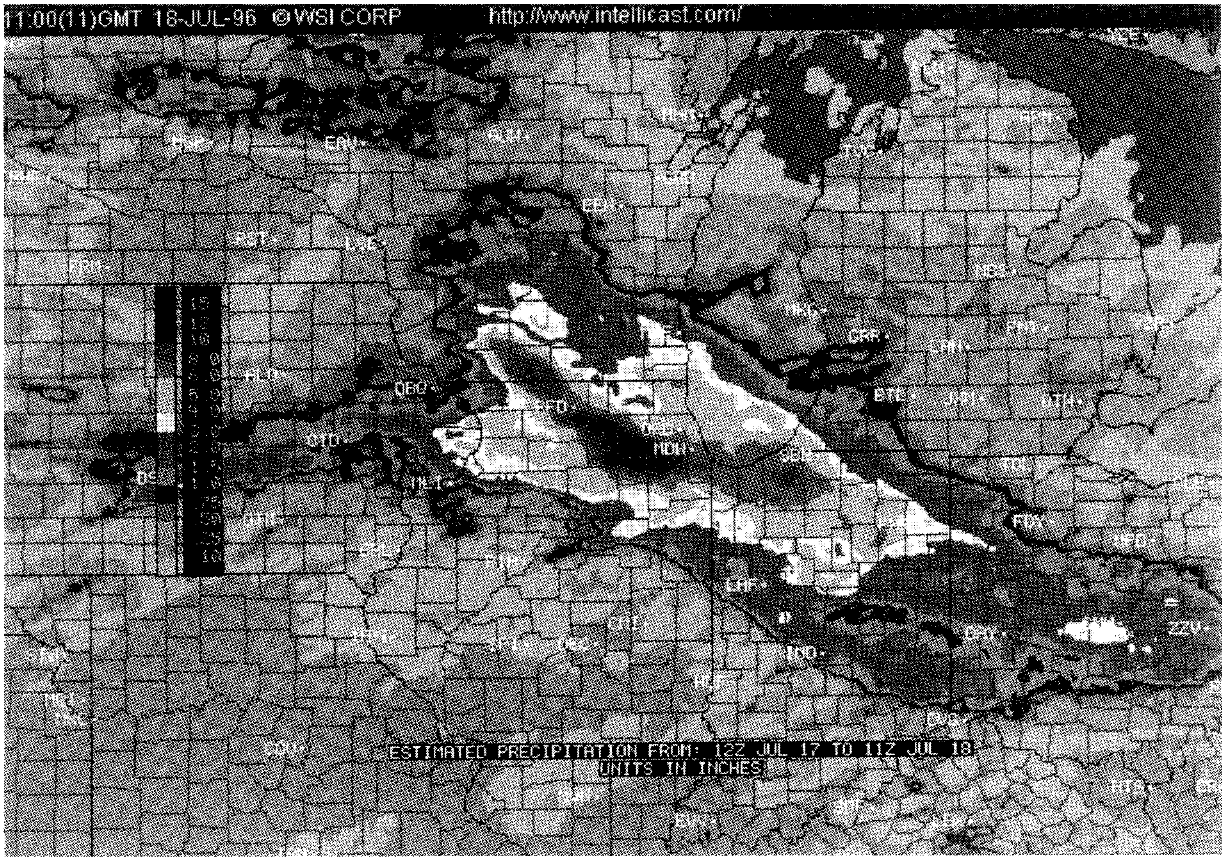

FIG. 3. The total storm rainfall as defined by a WSR-88D weather radar system for 17–18 July 1996.

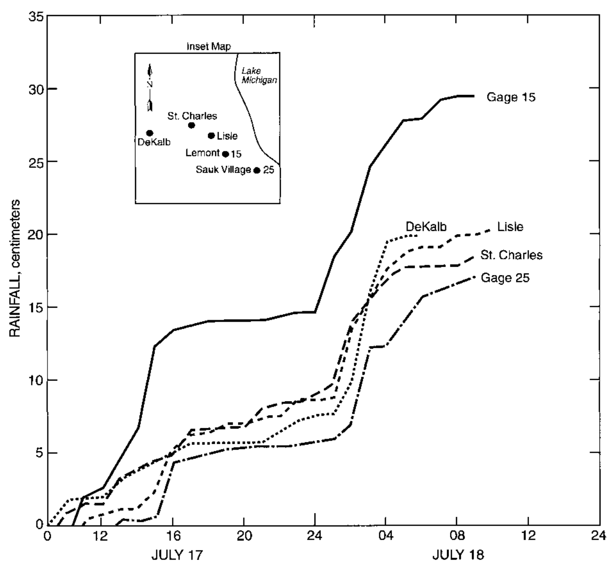

FIG. 4. The temporal distribution of the 17–18 July 1996 storm rainfall at five recording rain gauges. Indicated times are hours in LST.

5. Storm morphology and synoptic environment

The morphology of the rainstorms of 17–18 July was analyzed using synoptic weather data and radar data from the WSR-88D radar located at Romeoville, Illinois. Meteorological conditions before and during the storms over northern Illinois were very conducive to the generation and maintenance of mesoscale convective systems (MCSs). Interestingly, the same weather system that produced the 17–18 July rainstorm in Illinois produced heavy rainfall in Iowa and Nebraska on 16 July that resulted in over 25 cm of rainfall. This weather system then moved east from the Midwest into Canada, producing more than 31 cm rainfall in the province of Quebec on 19–20 July (Milton and Bourque 1997). Ten persons were killed by the storms and resulting floods in Canada, compared to six killed in the Illinois storm, and two in the Iowa storm.

The synoptic situation at 1200 UTC on 17 July 1996, prior to the beginning of the first major rainfall episode, features a warm front extending from a low in northern Nebraska to southern Illinois (Fig. 5a). Dewpoint temperatures to the south of the front in Missouri were approximately 22°C with air temperatures of approximately 26°C. North of the front in northern Illinois, air temperatures of 21°C and dewpoint temperatures of

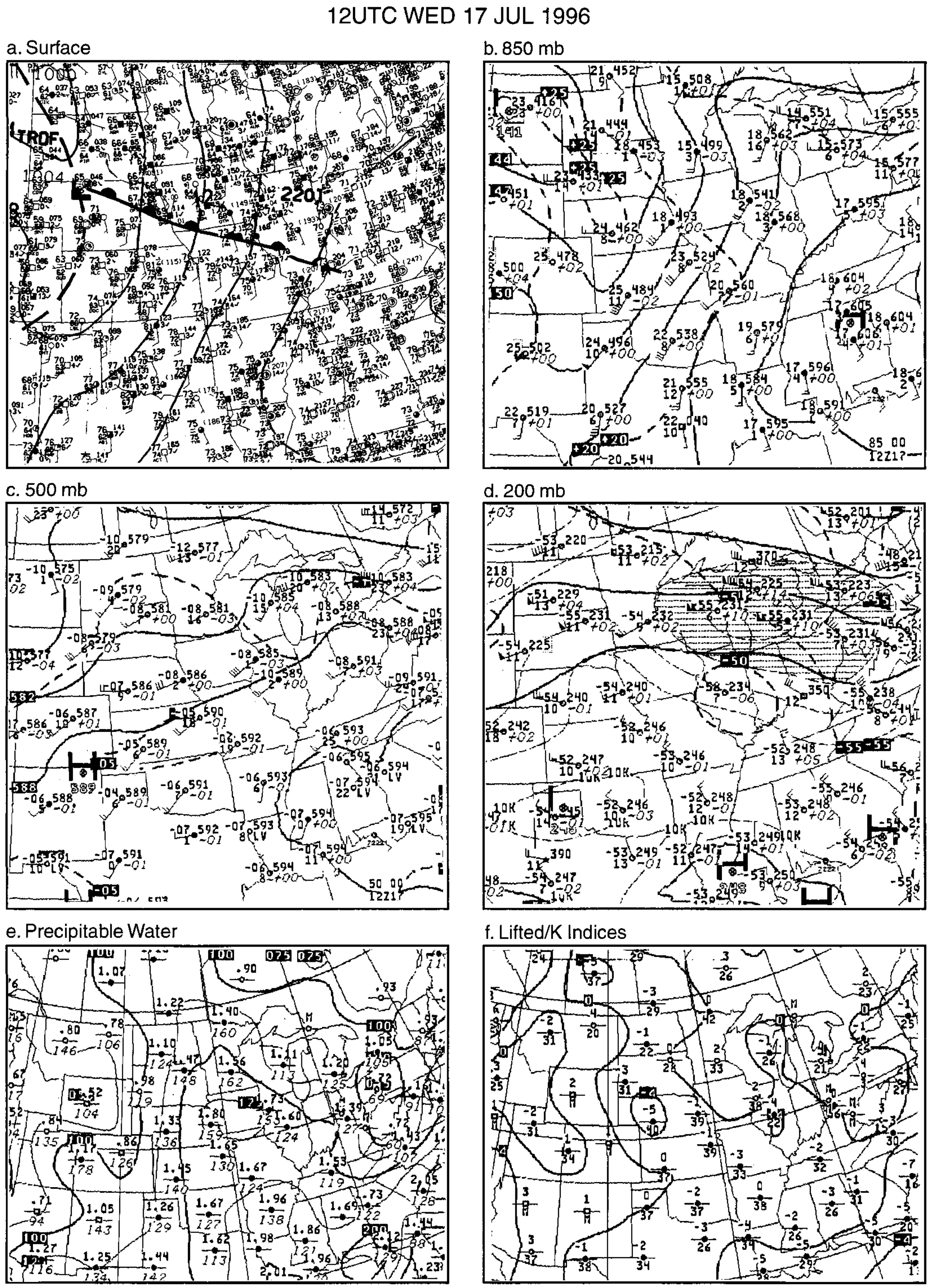

FIG. 5. Synoptic analyses at 1200 UTC Wednesday, 17 July 1996, including (a) surface pressure, (b) 850-hPa heights (solid) and temperature (dashed), (c) 500-hPa heights (solid) and temperature (dashed), (d) 200-hPa heights (solid) and isotach (dashed), (e) precipitable water (top) and percent of normal (bottom), and (f) lifted (top) and K index (bottom).

18°C were present. The flow at 850 hPa (Fig. 5b) features a strong low-level jet extending from Texas to Iowa, with the wind speed exceeding 15 m s^{-1} in some places. Dewpoint temperatures in Iowa at 850 hPa exceeded 15°C. At 500 hPa (Fig. 5c), a weak short-wave trough is present in southern Minnesota. At 200 hPa (Fig. 5d), there is a strong upper-level jet streak extending from Wisconsin toward the eastern seaboard. The accelerating flow on the right rear flank (entrance region) of the jet streak over Iowa and Minnesota suggests divergence and dynamic forcing of midtropospheric ascent. Precipitable water over Iowa is in excess of 4 cm (Fig. 5e), which is more than 150% of normal. Thus, atmospheric water vapor was plentiful for this storm system. The K index (Fig. 5f) is approaching 40°C in eastern Iowa, indicating a potential for heavy rainfall.

By 0000 UTC on 18 July 1996, the surface warm front (Fig. 6a) had moved to the north and east by about 250 km and was located from southern Minnesota into central Indiana. Air temperatures to the south of the front were approximately 32°C, while dewpoint temperatures were around 24°C. To the north of the front, air temperatures were much cooler, in the range of 21°–24°C, while dewpoint temperatures were around 21°C. At 850 hPa, the low-level jet had shifted to the east (Fig. 6b); wind speeds of around 15 m s^{-1} were present from eastern Kansas into northern Illinois. At 500 hPa, wind speeds were low (Fig. 6c), generally less than 20 m s^{-1}. Thus the upper-level flow conditions were favorable for slow-moving nocturnal MCSs. At 200 hPa (Fig. 6d), the upper-level jet streak had moved well to the east, suggesting that upper-level forcing was not an important factor in causing the nocturnal convection.

Precipitable water values (Fig. 6e) were now in excess of 5 cm in eastern Iowa, or almost 200% of normal. Thus, excessive amounts of atmospheric water vapor were available for convective systems. The development of MCSs over Iowa on 16 July had saturated most of that state and also portions of northwestern Illinois. This allowed considerable evaporation to occur during the morning and afternoon of 17 July and probably contributed to the excessively high atmospheric water vapor contents. This moisture served to increase the gradient in equivalent potential temperature across a warm front that slowly advanced northwestward to a position just south of the northern third of Illinois where the heavy rains later occurred. Values of the K index (Fig. 6f) were around 40°C, suggesting a continuing potential for heavy rainfall.

During the daytime hours of 17 July, development of easterly flow at the surface over northern Illinois transported cool, damp air from Lake Michigan across northern Illinois, and this made a further contribution to the strengthening and slow movement of the surface warm front. Resulting atmospheric conditions in the vicinity of the surface warm front were strongly unstable with the level of free convection located only 1 km above the surface.

From 1100 to 1300 LST on 17 July, convective rain cells developed, forming two lines of storms: 1) a northwest–southwest line of cells in western Illinois and 2) a north–south line of cells west of Lake Michigan. Many of these cells merged as the two lines moved through northern Illinois at midday.

At 1400 LST on 17 July, there were four discrete areas of thunderstorms (identified as a–d in Fig. 7) across northern Illinois within a west–east zone extending from the Iowa–Illinois border on the west to Lake Michigan. This large area with its many echoes drifted to the east and east-southeast, becoming stronger by 1600 LST (Fig. 7) as more intense cells developed. Sporadic tornadic activity occurred between 1435 and 1755 LST on 17 July, produced by the easternmost cells in this large echo area, and large hail fell from two of the western cells in the line. By 1800 LST on 17 July (Fig. 7), the area of storms had merged into a single unit, and the individual storms were moving southeast. This area of strong afternoon storms produced the heavy rains across northeastern Illinois (Fig. 4).

New thunderstorm cells were also beginning to develop at 1800 LST on 17 July (Fig. 7), and by 1830 LST, echo area g had formed a new large echo area across northern Illinois. New storms were also developing in southern Wisconsin (echoes e and f). The three initial echo areas (echoes a–c) increased in both area and intensity by 2000 LST on 17 July, and the original (afternoon) MCS was moving southward. New isolated cells also began development in northern Illinois at 1830 LST where the record rains continued, and these new cells merged to form a small line (echo h in Fig. 7). Development of the low-level jet at 1800 LST on 17 July led to an accelerating plume of very moist air ascending diagonally along the warm front. This plume readily reached the thunderstorm initiation level by 1900 LST on 17 July and a supercell thunderstorm that later caused a tornado and large hail developed over northwestern Illinois. The ascending moist plume continued to strengthen and led to development of the evening mesoscale convective system.

This second mesoscale convective system exhibited multiple axes of developing thunderstorms, moving to the east-southeast from extreme eastern Iowa, southwestern Wisconsin, to northern Illinois. These thunderstorms strengthened rapidly as they moved across northern Illinois and by 2030 LST on 17 July, the three westernmost areas of convection in Illinois (f–h) had become large and intense and were slowly moving to the east. In northeastern Illinois, these areas merged into the main northwest–southeast heavy precipitation axis that was oriented parallel to the surface warm front. Other heavy rain-producing thunderstorms that formed in southwestern Wisconsin traveled eastward.

The echo areas consolidated between 2200 and 0000 LST on 18 July (Fig. 7) with some new cell growth after 2300 LST on 17 July. A continuous line of strong cells oriented northwest–southeast from south-central

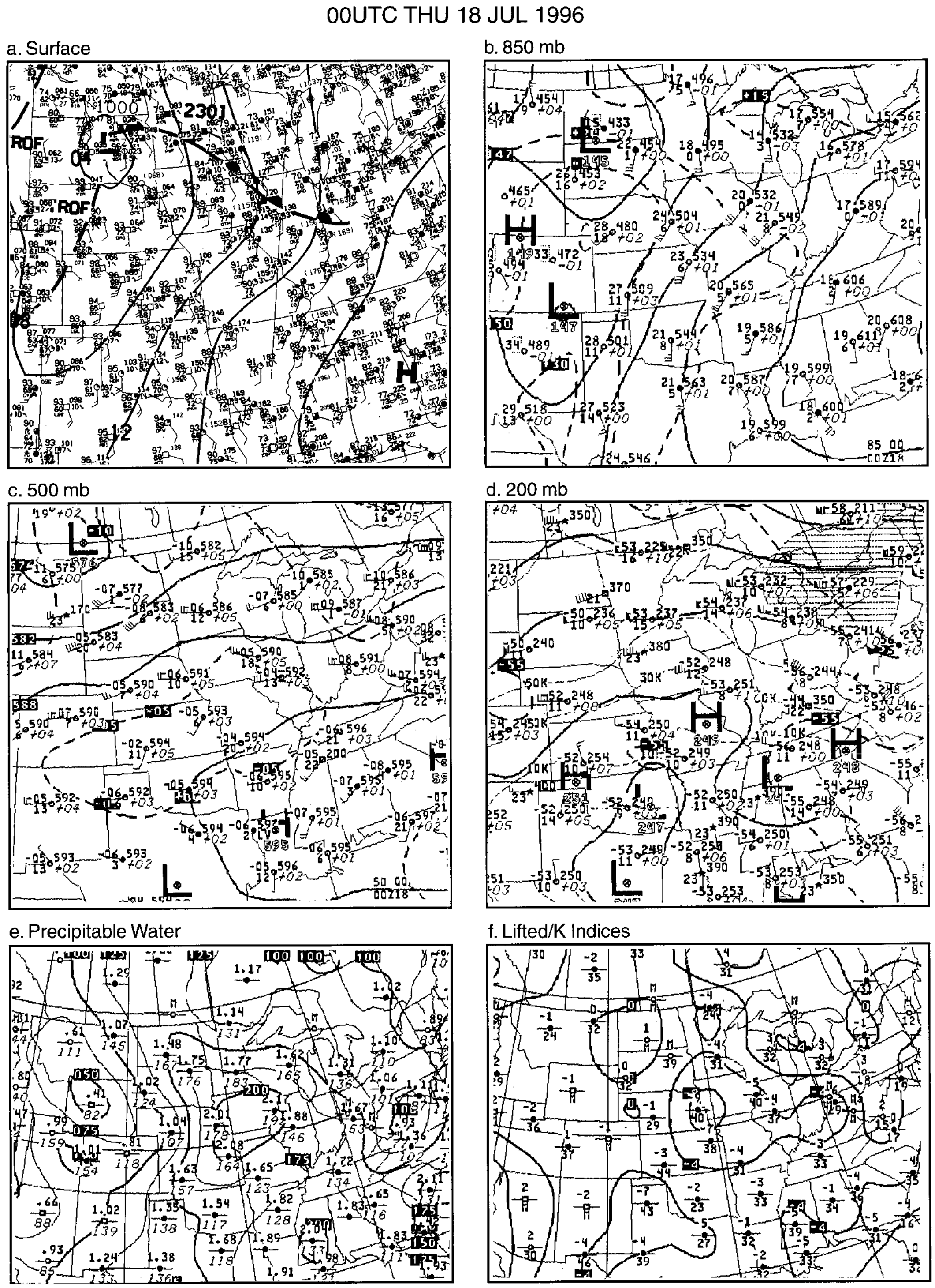

FIG. 6. Synoptic analyses at 0000 UTC Thursday, 18 July 1996, including (a) surface pressure, (b) 850-hPa heights (solid) and temperature (dashed), (c) 500-hPa heights (solid) and temperature (dashed), (d) 200-hPa heights (solid) and isotachs (dashed), (e) precipitable water (top) and percent of normal (bottom), and (f) lifted (top) and K index (bottom).

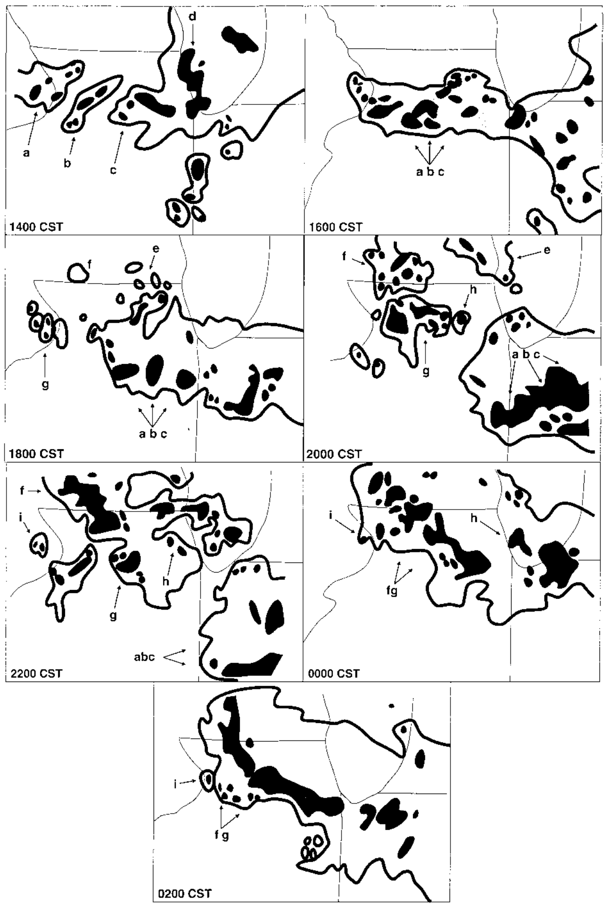

FIG. 7. Major echo areas (a–j) at select times during the storm from 1400 LST 17 July 1996 to 0200 LST 18 July 1996.

Wisconsin to the southern tip of Lake Michigan and into northern Indiana existed by 0000 LST on 18 July. The echoes had merged into one long intense echo area in northeastern Illinois at 0200 LST on 18 July (Fig. 7). Thereafter, this echo region became stationary through the Chicago area and continued to produce heavy precipitation. The behavior of the heavy precipitation line in the nocturnal mesoscale convective system (Fig. 7) was the result of a westward veering of the low-level jet during the night. This jet weakened by 0400 LST on 18 July, and the system began moving to the east and weakening, heralding the end of the rainstorm.

6. Summary

A record rainstorm struck portions of three states (Illinois, Indiana, and Wisconsin) and was a record rain event in and near the Chicago metropolitan area on 17–18 July 1996. As a case study of a major flash flood, it offers useful information on the storm dimensions for hydrological design purposes, about the storm's causes for forecasting purposes, and about the resulting impacts and responses, which is information useful for more effective planning for future mitigation and response activities, particularly in metropolitan areas.

A warm front, which became stationary across northern Illinois largely due to the presence of cool lake air, formed the zone in which this severe rainstorm developed and maximized.

In the core of the heavy rain area, 24-h totals ranged from 35 to 43 cm, representing values well in excess of 100-yr return values, and more than 15 cm fell over 9460 km^2. The heavy rainfall was a result of two periods of rain, one on the afternoon of 17 July and one during the early morning of 18 July.

The nocturnal storms were further focused in the area by the veering of the low-level jet during the night. What resulted was a record rainstorm, producing 43 cm of rain in less than 24 hours at one location, a record amount for the upper Midwest, with more than 20 cm of rains over 4400 km^2. The record rainfall amounts and storm pattern was well defined by rain gauges with 316 including 80 recording gauges, in the heavy rain areas of Illinois.

There were 11 hours when more than 2.5 cm of rain fell in the storm's core. In addition, the storm produced large hail, damaging lightning, and hail damage to crops and property. Echo tops frequently exceeded 17 km, a key indicator of damaging severe weather in the Midwest. The storm rainfall patterns derived from rain gauges and WSR-88D radar were in close agreement, supporting the use of radar-derived rainstorm patterns for real-time responses during flash floods. The storm's isohyetal pattern was exceptionally well defined, including the detection of the record heavy rainfall amounts by an extremely large number of rain gauges in the storm area, many due to county- and government-sponsored dense rain gauge networks. In the heavy rain area there were 80 recording rain gauges and 236 nonrecording gauges, presenting a density useful for performing a highly detailed hydrometeorological analyses of the storm [see Angel and Huff (1999)].

Detailed meteorological and forecasting analyses of this storm (Silberberg 1996; Merzlock 1996) revealed that the developing storm conditions were detected and could be forecast with accuracy. Important to the good forecasting of the heavy rain potential were the gridded isentropic forecasts, and the radar and satellite data were extremely helpful in the near-term forecasting.

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