Synoptic Weather Patterns Associated with the Milwaukee, Wisconsin Flash Flood of 6 August 1986

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ABSTRACT

A flash flood occurred at Milwaukee, Wisconsin on 6 August 1986 as a result of >6 in. (15.2 cm) of rain, much of it falling over a 2-h period. Several possible contributing factors to the excessive rainfall are addressed, as well as a brief overview of the radar imagery and the local National Weather Service (NWS) forecasts issued during the event.

Conventional weather analyses and infrared satellite imagery are used to describe the synoptic-scale weather patterns and cloud features associated with the flash flood. The synoptic patterns are compared with a meteorological composite for heavy rain-producing weather systems associated with relatively warm-topped cloud signatures imbedded in comma-shaped cloud features, as described by Spayd (1982). This composite is referred to as a cyclonic circulation system (CCS). A comparison between the observed synoptic patterns and those predicted by the operational numerical model forecasts is also discussed. A climatological survey is performed to document the frequency of heavy rainfall events associated with weather systems similar to the CCS composite during seven warm seasons.

Results show that the synoptic weather patterns attending the Milwaukee flood were similar in many respects to the CCS composite. While the numerical models were deficient in accurately predicting rainfall amounts, they were more than adequate in forecasting some of the features of the CCS composite. The climatology shows that weather systems resembling the composite appear infrequently on a given day during the warm season. However, rainfall in excess of 5 in. (12.7 cm) occurred in a preferred location of nearly 60% of the cases in which these systems were identified.

This article lends support to the value of *pattern recognition* from satellite imagery, conventional weather analysis, and forecast model output to alert forecasters to the potential for heavy rainfall.

1. Introduction

On 6 August 1986, thunderstorms produced rainfall in excess of 5 in. (12.7 cm) over downtown Milwaukee, Wisconsin during a 2-h period. Flash flooding resulted, leaving two fatalities and millions of dollars in damage. All previous rainfall records for storm duration, ranging from 5 min to 24 h, were broken (Storm Data 1986).

Heavy rainfall events such as this are an almost daily occurrence somewhere across the United States during the June–September warm season. Tropical cyclones and mesoscale convective systems (MCS) are often thought to account for many of these events (Scofield and Oliver 1981; Maddox and Grice 1986). These systems are often observed in infrared (IR) imagery from the operational geostationary satellite (*GOES*), which indicates an easily detectable cold cloud signature, signifying the presence of deep convection, such as the MCS shown in Fig. 1 over the southern Great Plains states (labeled A).

However, forecasters are well aware that localized heavy rainfall has been known to occur from weather systems that leave no dramatic cold cloud signature in the satellite imagery. Such weather systems have been collectively termed Subtle Heavy Rainfall Signatures, or SHARS (Spayd and Scofield 1983), to characterize relatively warm-topped (low equilibrium level) convection evident in IR imagery that yields excessive rainfall. Spayd and Scofield provided a variety of examples of subtle cloud signatures associated with extreme rainfall events and defined several different categories of SHARS based on differences in cloud organization apparent in the IR imagery.

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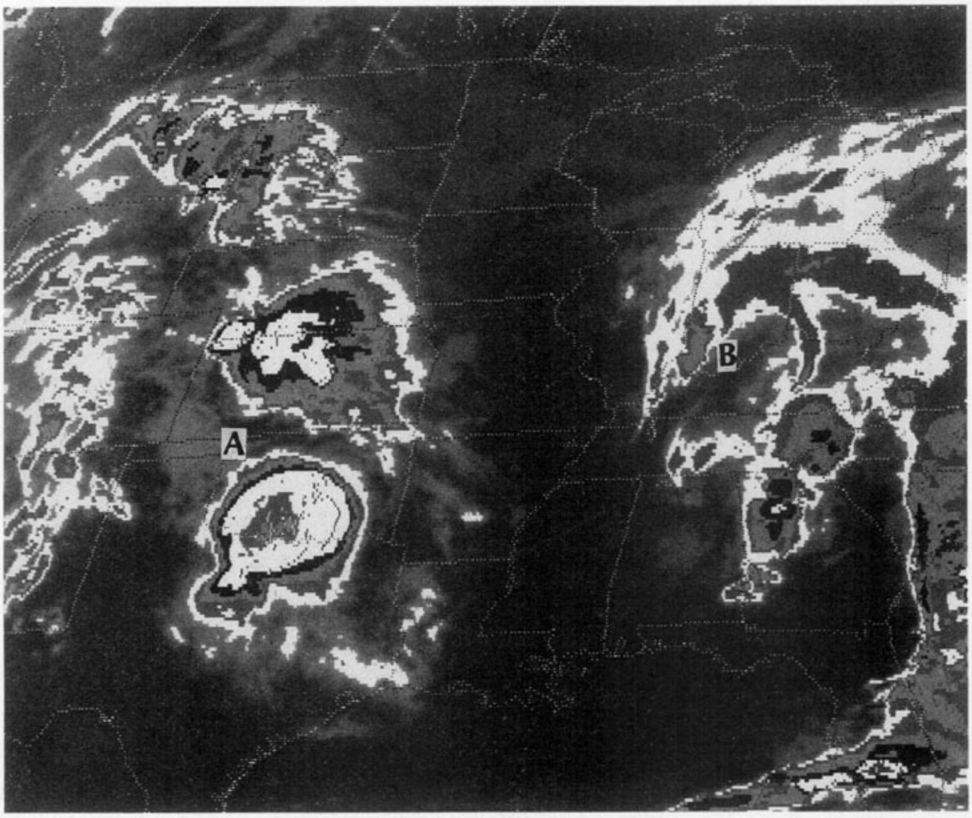

FIG. 1. Infrared satellite image at 0701 UTC 27 May 1981. The terms A and B refer to features discussed in the text.

One of the SHARS systems identified by Spayd and Scofield was termed a synoptic-scale cyclonic circulation, here abbreviated as a 'cyclonic circulation system' or CCS. The CCS was described by Spayd (1982) as a slow-moving weather system characterized by a distinct cyclonic or comma-shaped cloud organization in the satellite imagery. While Fig. 1 shows a variety of cloud systems, several with cold cloud tops indicative of deep convection, heavy rainfall >6 in. (15.2 cm) occurred instead over southwestern Indiana in connection with the relatively warm-topped comma-shaped cloud signature over the Ohio Valley (labeled B). Cloud-top temperatures in southwestern Indiana were in the −41° to −52°C range while temperatures at the core of the MCS over southern Oklahoma were colder than −80°C (Spayd 1982).

Spayd (1982) produced composite 500-mb, 850-mb, and surface charts and an averaged sounding for five cases that he characterized as CCS signatures from the IR imagery. The composite, therefore, can serve as a guide for forecasters to identify the threat of heavy rainfall from such weather systems utilizing analysis and forecast charts.

In this paper, the Milwaukee heavy rain event of August 1986 is first described through satellite imagery and conventional weather analyses and then compared to the CCS composite, which is described in detail. Convergence fields and the effects of surface friction are discussed as important contributing factors to the excessive rainfall. Then, the National Meteorological Center (NMC) numerical model forecasts of the Milwaukee system are briefly described to determine if some of the gross features of the composite were predicted by the models for 6 August 1986, and if the model forecast suggested a potential for heavy rainfall. A climatology of weather systems chosen to be representative of the composite features associated with the CCS was produced and related to the presence of heavy rain occurrences ⩾5 in. (12.7 cm).

It is envisioned that the CCS composites can enable forecasters to recognize certain synoptic-scale patterns from conventional analyses or model forecast output that suggest the potential for heavy rainfall.

2. Overview of the Milwaukee flood of 6 August 1986

a. Rainfall and satellite imagery

Between 1700 UTC and 2000 UTC 6 August 1986, >6 in. (15.2 cm) of rain associated with thunderstorms fell in downtown Milwaukee (Fig. 2). The isohyet analysis in Fig. 2 reveals the localized extent of the rainfall, with the greatest amounts, in excess of 7 in. (17.8 cm), occurring south of the Mitchell International Airport (MKE) and on the northwest side of

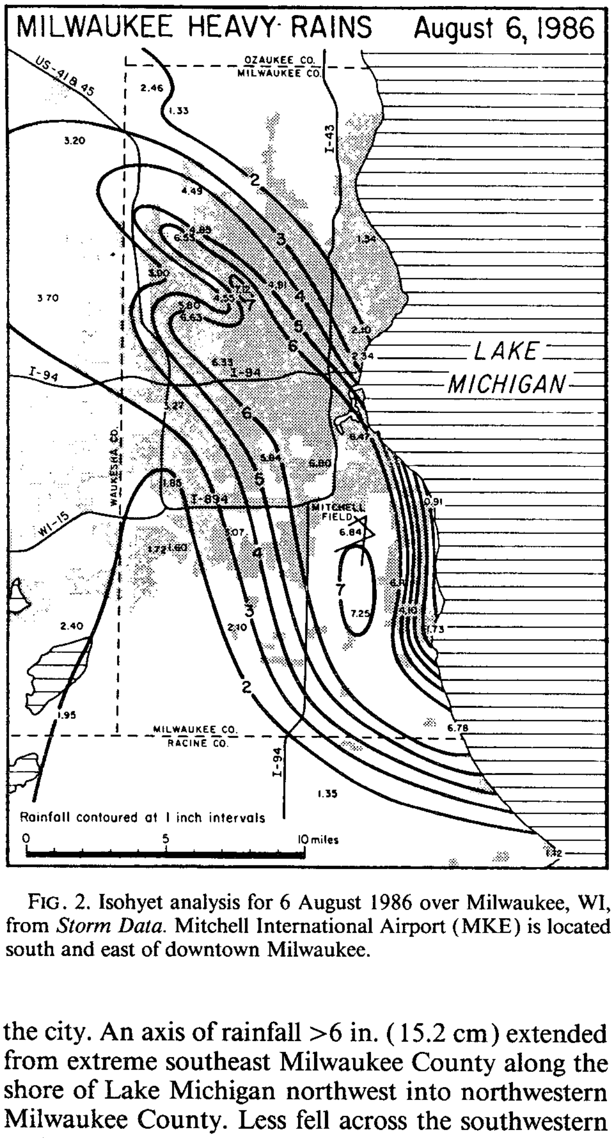

FIG. 2. Isohyet analysis for 6 August 1986 over Milwaukee, WI, from *Storm Data*. Mitchell International Airport (MKE) is located south and east of downtown Milwaukee.

the city. An axis of rainfall >6 in. (15.2 cm) extended from extreme southeast Milwaukee County along the shore of Lake Michigan northwest into northwestern Milwaukee County. Less fell across the southwestern and northeastern sectors of the county with a large gradient of rainfall from MKE eastward to the lake shore. One site reported <1 in. (2.5 cm) only 5 km from MKE where 6.84 in. (17.4 cm) fell, a gradient of 3 in./mile (4.75 cm/km).

Over much of Milwaukee, storm rainfall began around 1600 UTC and continued until 2200 UTC. At MKE, 3.06 in. (7.77 cm) fell between 1700 and 1800 UTC with an additional 2.18 in. (5.54 cm) falling in the following hour. The heaviest rain fell over northwestern Milwaukee County later in the afternoon, around 2000 UTC.

A sequence of *GOES-IR* imagery at 2-h intervals between 1400 and 2000 UTC is displayed in Fig. 3 to highlight the evolution of the cloud feature associated with the flood. The satellite sequence clearly shows the evolution of the cloud mass into a well-defined comma shape, similar to that shown in Fig. 1 over the Ohio Valley. Milwaukee was located under the northwest segment of the cloud shield with a rapidly intruding dry wedge to the south over southern Illinois. As the system evolved during the afternoon of the sixth, clouds remained anchored over southeastern Wisconsin as the trailing cloud band to the south moved rapidly eastward. Cloud-top temperatures over the Milwaukee area remained relatively warm, as computed using the Man-computer Interactive Data Access System (McIDAS), and averaged −43°C at 1800 UTC over a 36 km^2 area, in contrast to a cluster of nonflood producing thunderstorms over North Dakota (not shown) that exhibited temperatures of −58°C. Further evidence for the lack of potential for deep convection over the Midwest was given by the equilibrium level temperatures of −41°C at Peoria, Illinois, utilizing the morning sounding at 1200 UTC 6 August, prior to the onset of the heavy rainfall.

b. Conventional weather analyses

The 500-mb, 850-mb and surface charts at 1200 UTC 6 August are shown in Fig. 4, approximately 5 h prior to the onset of heaviest rains at Milwaukee. Two easily identifiable short-wave troughs are noted on the 500-mb analyses (Fig. 4a). One extends across Wyoming and Montana while the other is located across the Midwest, its axis extending from Wisconsin to Arkansas. Milwaukee lies just downwind of the trough axis where the 500-mb flow weakens, as shown by the 5-kt wind speed at Green Bay. Throughout the Midwest trough, 500-mb temperatures are fairly uniform across a large domain indicative of a nearly barotropic environment at this level.

At 850 mb (Fig. 4b), a nearly closed circulation beneath the 500-mb trough is found over southeastern Iowa with strongest wind speeds of 30 kt (15 m s^{-1}) from a southwest direction across central Illinois. A dewpoint temperature of 12°C was noted at Peoria, Illinois (PIA) within or immediately north of the axis of the southwesterly low-level jet streak. Since little upper-level data exists in the vicinity of Milwaukee, it is difficult to determine the low-level wind field over southeastern Wisconsin. However, it appears that Milwaukee lies well to the northwest of the jet over central and southern Illinois in a region where the 850-mb geopotential height gradient is weakening to the north and low-level wind directions become south to southeasterly.

At the surface (Fig. 4c), a stationary front is analyzed from northwestern Minnesota into northern Wisconsin. Of greater significance, a weak low with a central sea-level pressure of approximately 1010 mb was located near the Iowa–Illinois border beneath the 850-mb low center. A weak cold front or trough extended from the low center to the southwest across Missouri into southeast Kansas. A pressure trough and line-of-wind direction change extended east from the low across northern Illinois into northern Indiana. To the

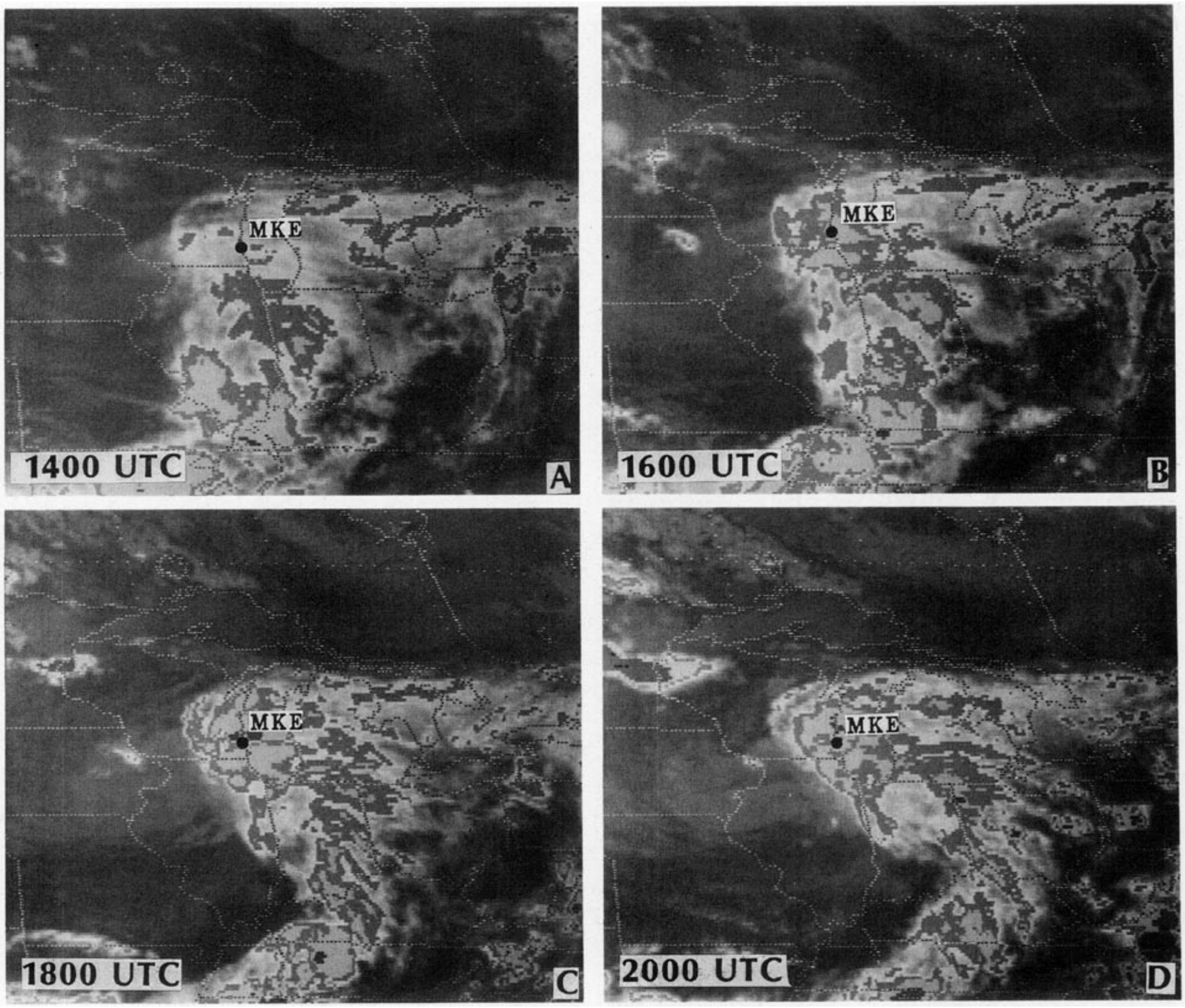

FIG. 3. A 2-h sequence of enhanced infrared satellite images from 1400 to 2000 UTC over the midwestern U.S. The sequence is prior to and during the heavy rainfall in Milwaukee.

north of this line, surface winds were primarily from an easterly direction while they were mostly southerly south of the line. Only slight changes in temperature or dewpoint temperature are observed across this line, but dewpoint temperatures approached 70°F (21°C) in the Chicago area (not shown due to the density of observing stations).

By 0000 UTC 7 August, a time following the heavy rain event, the 500-mb trough (Fig. 5a) has moved to the east of the Milwaukee area, but Milwaukee appears to remain in a region of little height gradient and weak wind speeds. The 850-mb analysis (Fig. 5b) shows a slight filling of the low center as it moved eastward to northeastern Illinois. Milwaukee appears to lie in a region of weak easterly to southeasterly wind speeds with the southwesterly low-level jet streak now located over Ohio. The surface analysis (Fig. 5c) shows that the surface low has moved eastward into north-central Illinois with a trailing trough across south-central Illinois into central Missouri, where it became stationary. Two boundaries are observed east of the low center. A wind-shift line extends from near the low-center north of Chicago across southern Lake Michigan into southwestern Michigan and northwestern Ohio. This boundary separates the primarily easterly flow north of the boundary from southeast to southwesterly winds south of the boundary. Overcast skies and rain showers characterized both sides of this boundary. A second boundary extended east-southeast from the low across central Indiana and western Ohio and separated the overcast, rainy airmass from a warmer, drier airmass to the south. This is the area over which the relatively cloud-free dry slot seen in earlier satellite images (Fig. 3) is observed to pass.

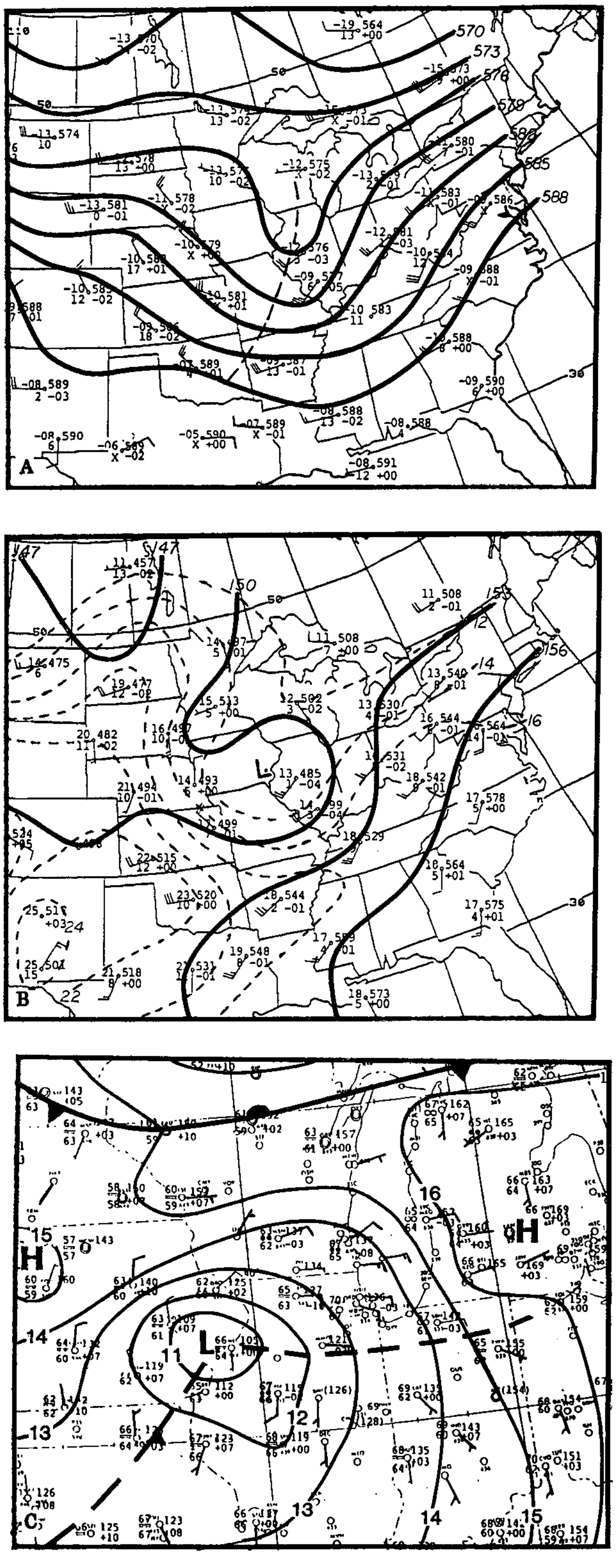

FIG. 4. The (a) 500 mb, (b) 850 mb, and (c) surface analyses for 1200 UTC 6 August 1986. Height and pressure contours are solid and isotherms are dashed. Trough axes at 500 mb are indicated by a dashed line. At the surface, wind shift lines are indicated by the thick dashed line.

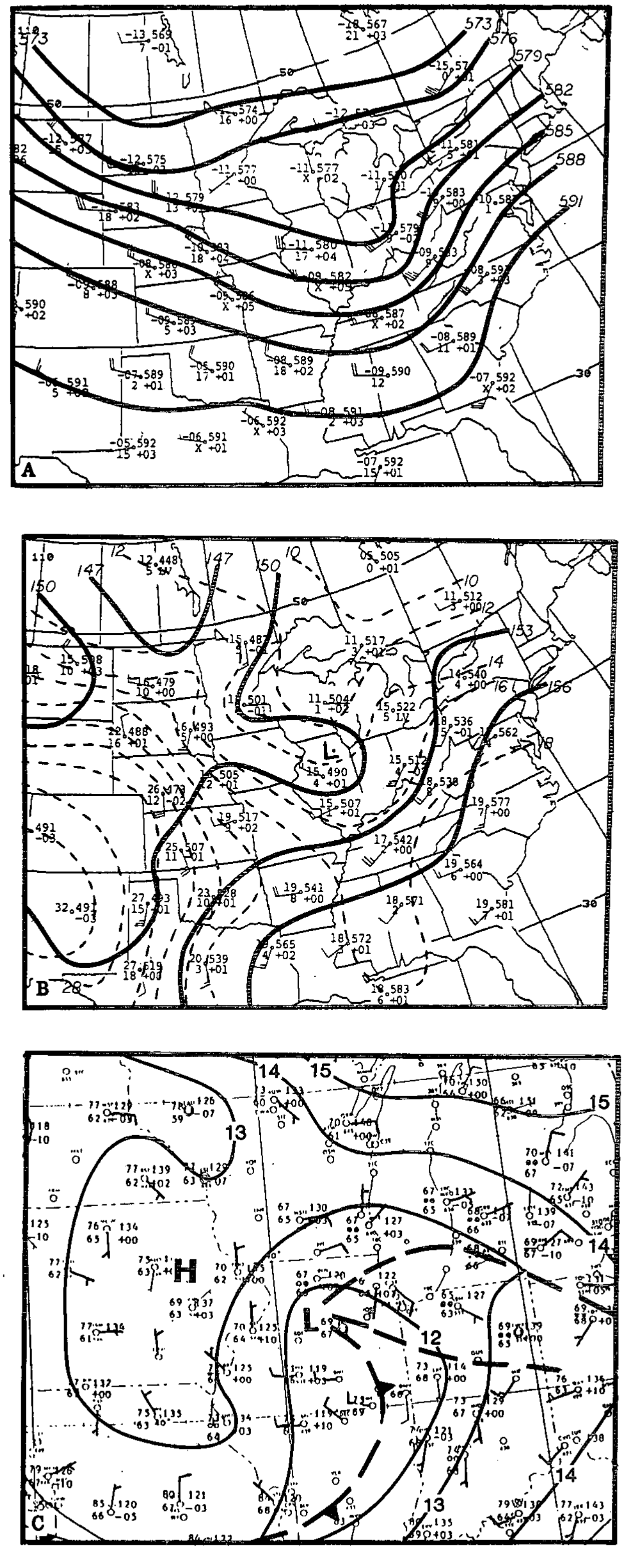

FIG. 5. As in Fig. 4 except for 0000 UTC 7 August 1986.

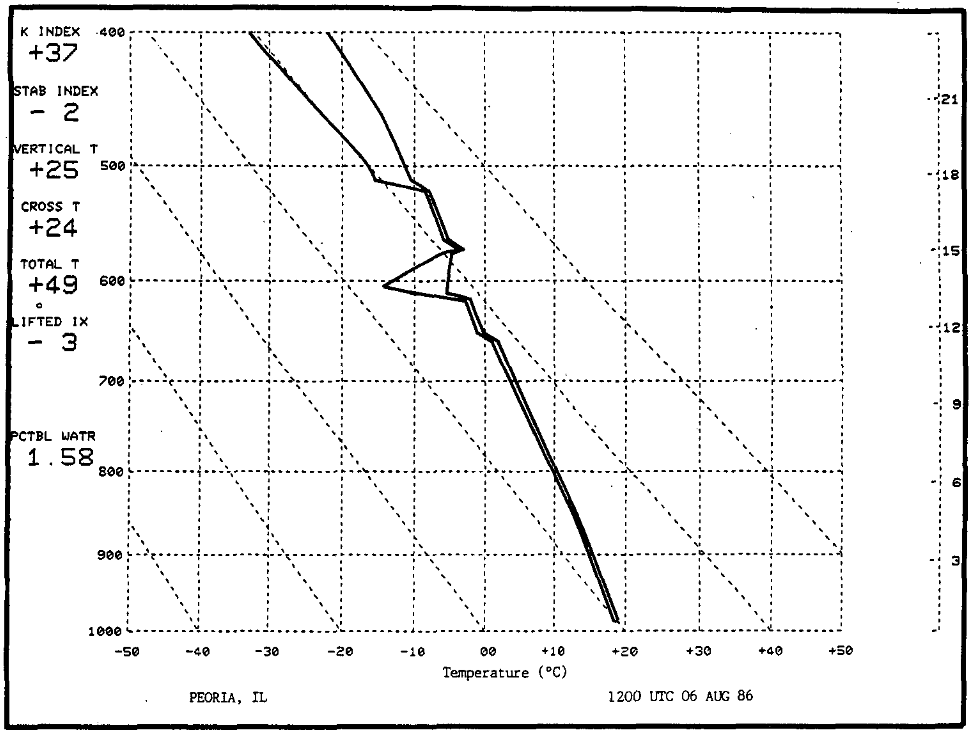

FIG. 6. A skew-T thermodynamic diagram from the surface to 400 mb for the Peoria, Illinois sounding at 1200 UTC 6 August 1986.

c. Possible factors for the extreme rainfall

The heavy rain event occurred as a 500-mb trough crossed the Midwest with Milwaukee located beneath a region of relatively weak wind speeds at that level. Weak upper-level wind speeds may have contributed to the slow movement of the thunderstorms. The 850-mb low passed just to the southeast of the region with a southwesterly low-level jet streak also remaining to the south of the region. Southeasterly to easterly winds at low levels were probably present during the event. At the surface, low pressure passed to the southwest of Milwaukee with the city remaining on the cool side of a wind shift boundary that was associated with the convergence of cool, moist air north of the boundary and warmer air to the south with dewpoint temperatures of 65°–70°F (18°–21°C).

McNulty (1988) summarized the parameters that were necessary to produce significant convection, including storms producing sufficiently intense rainfall to possess a potential for flash flooding, and noted four major conditions: 1) unstable air or a source of destabilization, 2) moisture, 3) synoptic-scale lift, and 4) low-level convergence. An indication of instability is provided by the lifted index and Showalter stability index at Peoria, Illinois at 1200 UTC 6 August (Fig. 6). A lifted index of −3 and a Showalter index of −2 both indicate moderate instability. The K index was 37. The availability of moisture is provided by the precipitable water from the sounding (approximately 1.6 in.; 4 cm), which is more than 40% greater than the average August value at Peoria (1.1 in. or 2.8 cm). Synoptic-scale lift is provided by the presence of the 500-mb trough (see Fig. 4a) and associated vorticity maxima. Low-level convergence was probably a key element in the production of the heavy rainfall and was associated with a well-defined wind shift boundary and associated pressure trough located north of Chicago. Mesoscale surface analyses prior to and subsequent to this time (not shown) indicated this to be a northward-moving boundary. Coast guard observations indicated surface winds of 20 kt (10 m s^{-1}) beginning at 1200 UTC between Milwaukee and Chicago. NOAA data buoy no. 45007, located in Lake Michigan about 30 miles (48 km) east-northeast of the Wisconsin–Illinois border, measured a gradual increase in its sustained easterly surface wind from 8 kt (4 m s^{-1}) at 0800 UTC to 20 kt (10 m s^{-1}) at 1500 UTC. Gusts at the buoy reached 20 kt (10 m s^{-1}) as early as 1200 UTC and peaked at 24 kt (12 m s^{-1}) around 1500 UTC. Winds subsided thereafter to below 20 kt after 1800 UTC. As this boundary passed to the north, surface winds shifted to the southeast and decreased in speed following passage. During the most intense rainfall at Milwaukee's Mitchell International Airport, winds veered into the south and gusted to 23 kt (12 m s^{-1}) before backing to easterly around 2100 UTC.

Surface divergence fields derived from 47 stations,

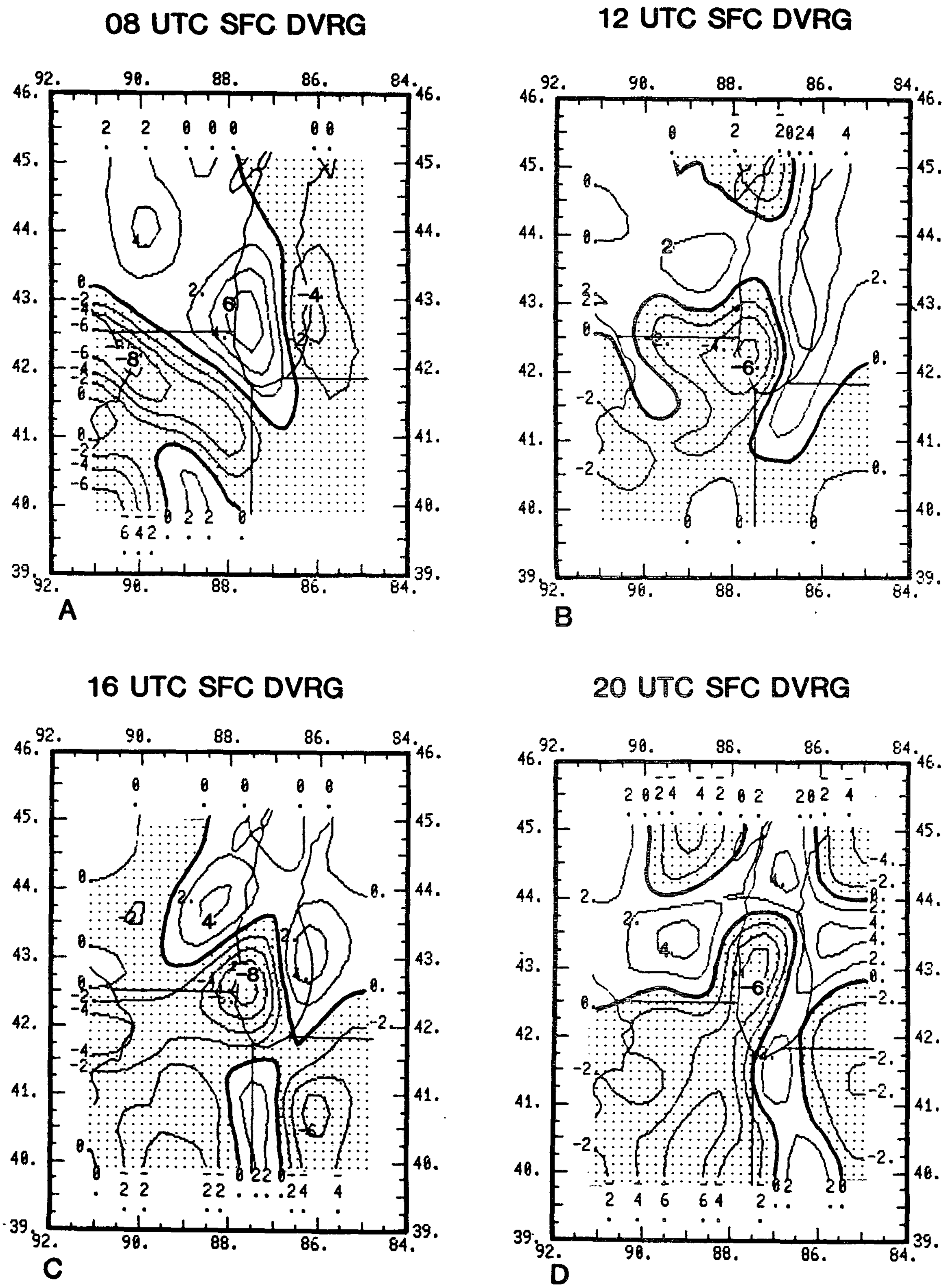

FIG. 7. Surface wind divergence fields ($\times 10^{-5}\ s^{-1}$) at 0800, 1200, 1600, and 2000 UTC 6 August 1986. Contour interval is $2 \times 10^{-5}\ s^{-1}$ and negative values indicate convergence.

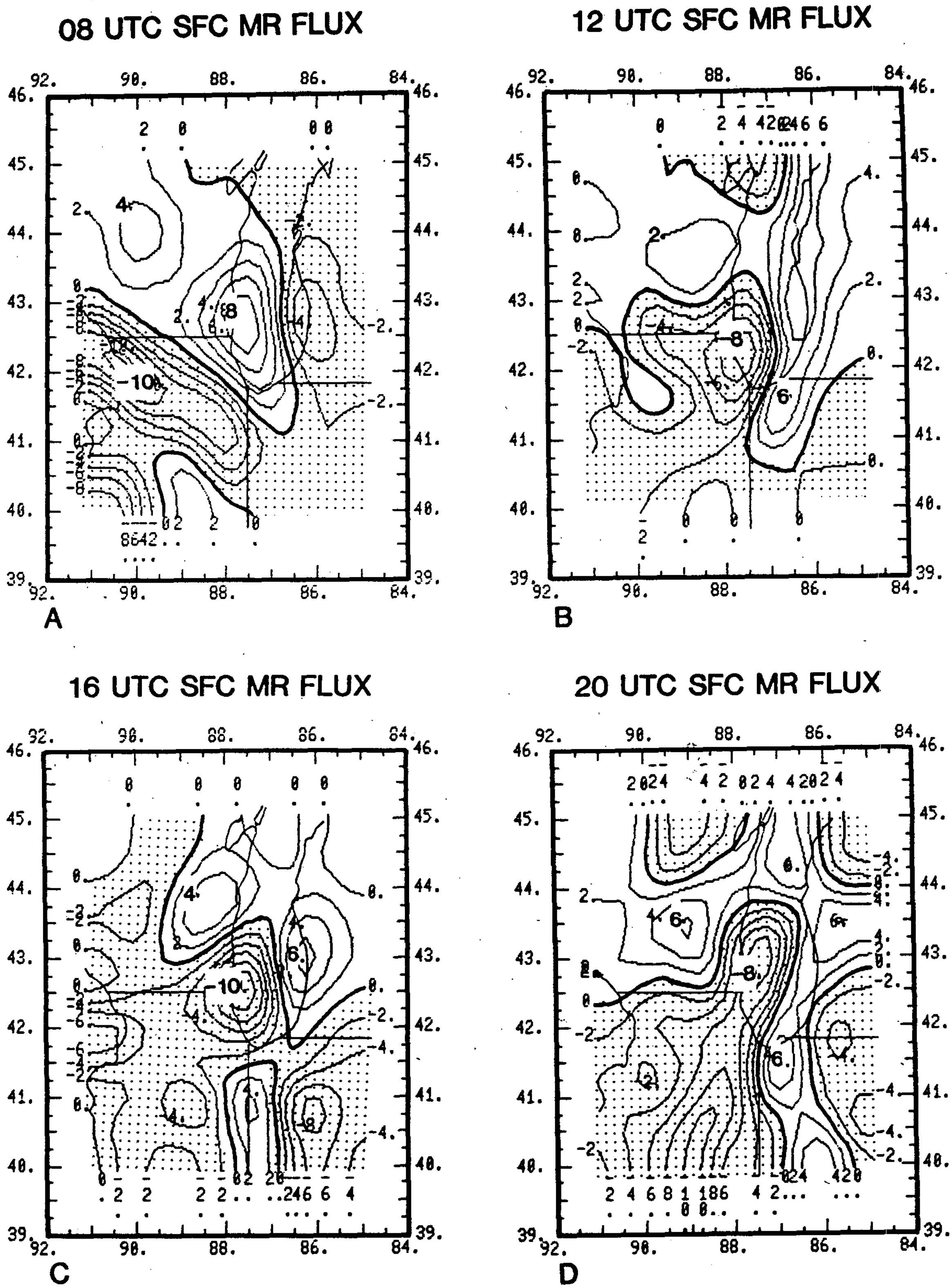

FIG. 8. As in Fig. 7 except moisture flux divergence fields ($\times 10^{-7}\ s^{-1}$). Contour interval is $2 \times 10^{-7}\ s^{-1}$.

including Coast Guard, C-Man and buoy reports[1], were interpolated to a 25 × 21 grid having a 0.25° lat and longitude spacing using a Barnes (1964) objective analysis technique. Divergence of the wind field and moisture flux divergence were computed for each grid point and plotted. Time sequences of wind divergence and moisture flux divergence fields are displayed in Figs. 7 and 8, respectively, with negative values indicating convergence. Figure 7 and 8 are both similar, indicating that the advection of moisture was small and that wind convergence was the primary contributor to the locally intense moisture divergence/convergence fields. An abrupt change in the surface divergence fields over southern Lake Michigan developed between 0800 and 1200 UTC. A relatively strong convergence/divergence couplet became established by 1200 UTC from southern Lake Michigan to western lower Michigan. Of interest is a secondary center of divergence in central Wisconsin. These centers and their large gradients persisted for the next 4 h. After 1600 UTC, some spreading of the centers and displacement occurred. The 2-h change of moisture flux convergence shown in Fig. 9 depicts these trends. The flood-producing rains weakened considerably after 2000 UTC.

Bothwell (1988) has summarized the following points of Doswell (1982), Hirt (1982) and Weaver (1979): 1) It takes several hours for moisture flux convergence to initiate convection, 2) It is often the change in moisture flux convergence that is more significant than the magnitude of the absolute value of moisture flux convergence, and 3) Storms can develop in the area where the gradient of moisture convergence is large. Development occurs on the moist side of the moisture flux convergence axis.

In an east-to-west oriented warm front (in this case, a well-defined boundary in the wind field), the moisture flux convergence is located in the vicinity of the front. However, with additional lifting along the frontal surface, the heaviest rain occurs north of the front and moisture convergence maximum.

It is presumed that the relatively dramatic and narrow band of low-level forcing in the wind convergence field fueled several storms with abundant amounts of convectively-unstable and moisture-rich air. Rainfall rates exceeding 8 in. (20 cm)/h (utilizing a 5-min interval) at two recording rain gages in Milwaukee attest to the extreme precipitation efficiency (Doswell 1985). Therefore, it appears that the 20-kt (10 m s^{-1}) wind speed maximum to the north of the wind shift boundary was a critical element that changed a typically showery system into a prodigious rain producer over a small portion of southeastern Wisconsin.

Another possible factor for the extreme rainfall over southeastern Wisconsin is surface friction. Roeloffzen et al. (1986) note that coastlines represent a marked discontinuity in surface roughness. Air flowing over the discontinuity can undergo frictional convergence leading to a secondary circulation in the boundary layer and consequently to a vertical motion field that may have a strong influence on the weather in the coastal zone. In potentially unstable airmasses, frictional convergence may cause a stationary zone of heavier shower activity.

The effects of surface friction in generating vertical motion during the 6 August 1986 Milwaukee flood have been estimated on a 0.5° × 0.5° lat-long grid centered on Milwaukee using the equation of Graystone (1962). The equation relates horizontal diffential wind stress to frictionally induced vertical motion. The wind stress is assumed proportional to the product of the drag coefficient (surface roughness) and the square of the horizontal wind speed. Experimentally derived values of drag coefficient over land and lake and the angle between the geostrophic and actual wind, as given by Graystone, are used in this investigation.

The contributions to vertical motion from friction at 2-h intervals beginning at 1400 UTC are shown in Fig. 10. At 1400 UTC, weak ascent and subsidence are noted along the western shore of Lake Michigan with ascent from Milwaukee southward. As easterly winds increased over the southern half of the lake during the morning hours (1600 UTC), frictionally induced rising motions intensified along the western shoreline. By 1800 UTC, relatively strong ascent is noted over most of southeastern Wisconsin following the onset of heaviest rainfall over Milwaukee.

The surface roughness gradient between eastern Wisconsin and western Lake Michigan, coupled with a strong easterly wind component, produced ascent over the region and may have been an additional contributing factor to the concentration of heavy rainfall within 30 km of the western shore of Lake Michigan.

d. Radar summary

A review of radar film from the NWS Marseilles, IL WSR 74S 10 cm radar located 190 km southwest of Milwaukee indicated two separate echo clusters characterized by cyclonic rotation over northern Illinois and southeast Wisconsin that were not associated with the heavy rainfall in Milwaukee. Several cells within the clusters were seen moving northwestward within the north-to-northeast motion of the echo patterns. While these two features were identified a posteriori from the radar film, it is difficult in the present NWS operational real-time environment to recognize such features. It is hoped that the Next Generation Weather Radar (NEXRAD) system will afford such real-time capability when it comes on-line in the next few years.

The radar signature of the Milwaukee storm was characterized by a teardrop shape (see Fig. 11) oriented from northwest to southeast to a point on the southeast flank of the echo. After 1700 UTC, this "point" periodically redeveloped and "ingested" feeder cells from the southeast. In terms of recognized flash flood signatures, this feature was a persistent echo exhibiting

[1] Automated diagnostic programs available to the Weather Service as of October 1989 do not include these observations.

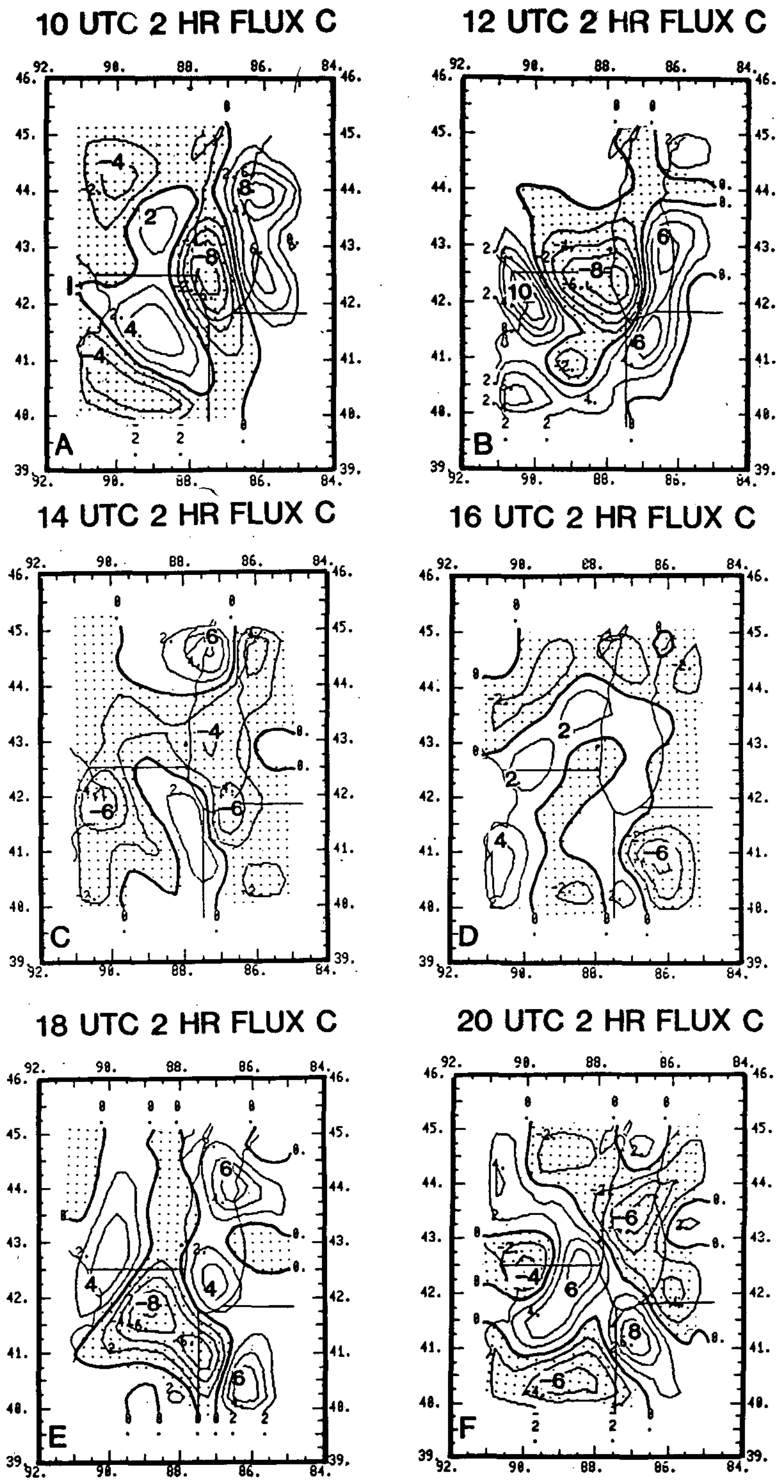

FIG. 9. The 2-h change fields of surface moisture flux divergence ($\times 10^{-7}$ s^{-1}) ending at 1000, 1200, 1400, 1600, 1800, and 2000 UTC. Contour interval is 2×10^{-7} s^{-1}.

no appreciable movement for approximately 3 h as smaller echoes merged into the region from the south-southeast.

Maximum observed Digitizal Video Integrator and Processor (DVIP) levels during the Milwaukee episode was 3, which translates to official NWS convective rainfall rates of 1.1–2.2 in. (2.8–5.6 cm)/h. This was well below the documented 8 in. (20 cm)/h rainfall rate for this event. However, a DVIP level 4 was observed as late as 1528 UTC just west of Kenosha, Wis-

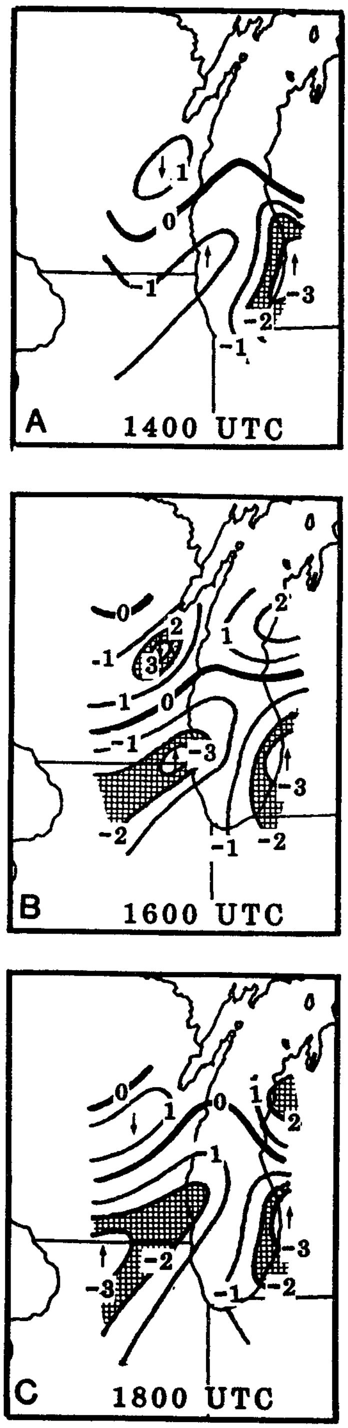

FIG. 10. Vertical motions in μb s^{-1} due to surface friction.

consin (40 km south of Milwaukee) with a storm top of 29 000 feet (8.8 km). Radar limitations allow the inference that the Milwaukee convection could have been DVIP level 4, which offers a maximum rainfall rate of 4.5 in. (11.4 cm)/h, still well short of the observed rate.

e. Local NWS forecasts

The 0900 UTC 6 August forecast issued by the Milwaukee office of the NWS stated that there was a 90% chance of light rain that day. Model output statistics (MOS) from the limited fine mesh (LFM) model forecast initialized at 0000 UTC 6 August predicted only a 50% chance of measurable rainfall at Milwaukee during the 12-h period ending at 0000 UTC 7 August. The MOS 12-h best probability rain category (QPF12) was <0.25 in. (0.64 cm) for that time period, though the probability of thunder was a fairly significant 32%. The national forecast prepared by the forecast branch of the National Meteorological Center (NMC) for the 24-h period ending at 1200 UTC 7 August did not foresee >0.25 in. (0.64 cm) rainfall for Wisconsin.

At 1315 UTC, the nearshore marine forecast from Kenosha north to Port Washington, WI was updated to a small craft advisory, reflecting forecaster awareness of the strong surface winds along the nearshore waters south of Milwaukee. The routine 1500 UTC public release spoke of "rain continuing." At 1720 UTC, the Milwaukee office issued a special weather statement which included a radar summary and a special rainfall observation of 4.3 in. (10.9 cm) at Burlington, Wisconsin about 35 km southwest of Milwaukee. A sewage treatment plant in the same community reported 2.5 in. (6.3 cm) with all other reports to that time under 0.75 in. (1.8 cm). A flash flood warning was issued at 1803 UTC for all of Milwaukee County as heavy rain enveloped the Milwaukee region. Since heavy rainfall occurred at the NWS office in Milwaukee, forecasters reacted swiftly to the unfolding situation. The lead time of the warning was approximately 20 min for the southern end of the county, when the first reports of damage were received, to approximately 2 h at the northwestern end of the county.

3. Comparison of the Milwaukee synoptic patterns with the CCS composites and NMC model forecasts

a. Comparison with the CCS composites

Composite 500-mb, 850-mb, and surface charts and a sounding were generated by Spayd (1982) from five CCS cases that produced flash floods over the eastern United States. The composites are shown in Figs. 12–15 and highlight the location of heaviest rainfall with respect to 500-mb vorticity and streamlines, 850-mb winds and dewpoint temperatures, sea-level pressure and surface frontal configurations and surface dewpoint temperature. A composite sounding was included to demonstrate average temperature and winds at mandatory pressure levels in the vicinity of the heavy rainfall. A strict comparison with the sounding should not be made since it was based on actual soundings close to but not necessarily in the region experiencing heavy rainfall.

The 500-mb, 850-mb and surface charts and a reconstructed sounding from 6 August 1986 will be compared to the composites to assess their similarities.

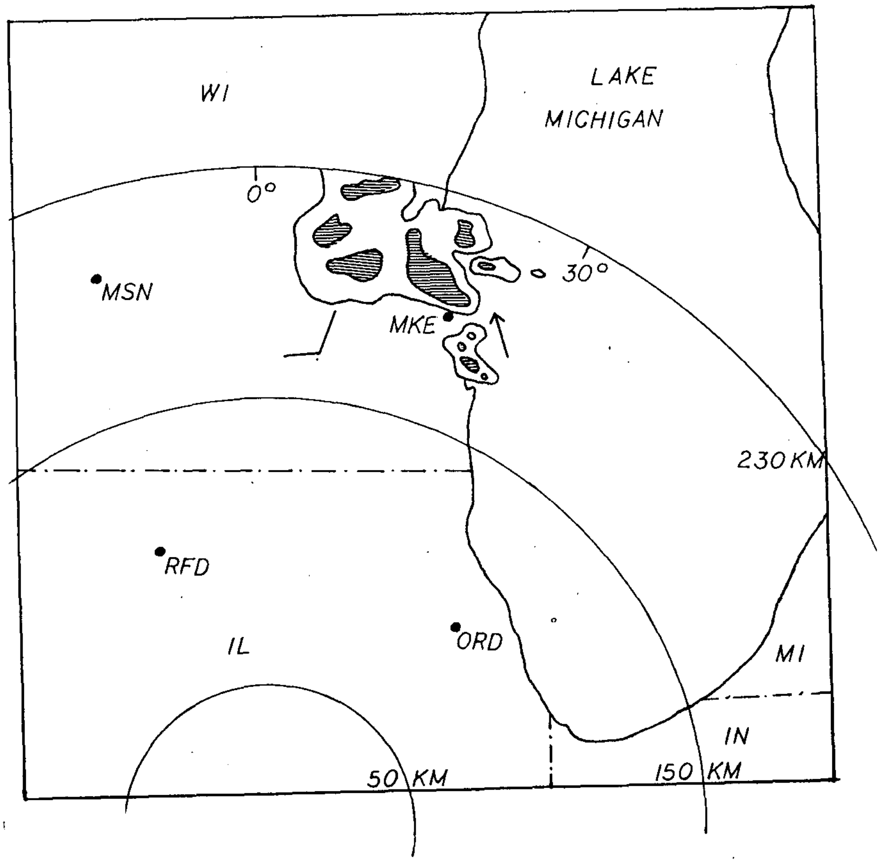

FIG. 11. Approximate representation of the NWS Marseilles, Illinois 10-cm weather radar showing only the echo patterns over southeastern Wisconsin at 1800 UTC. Where DVIP level 2 is found, region is shaded. Arrow indicates cell movement and wind barb indicates area movement.

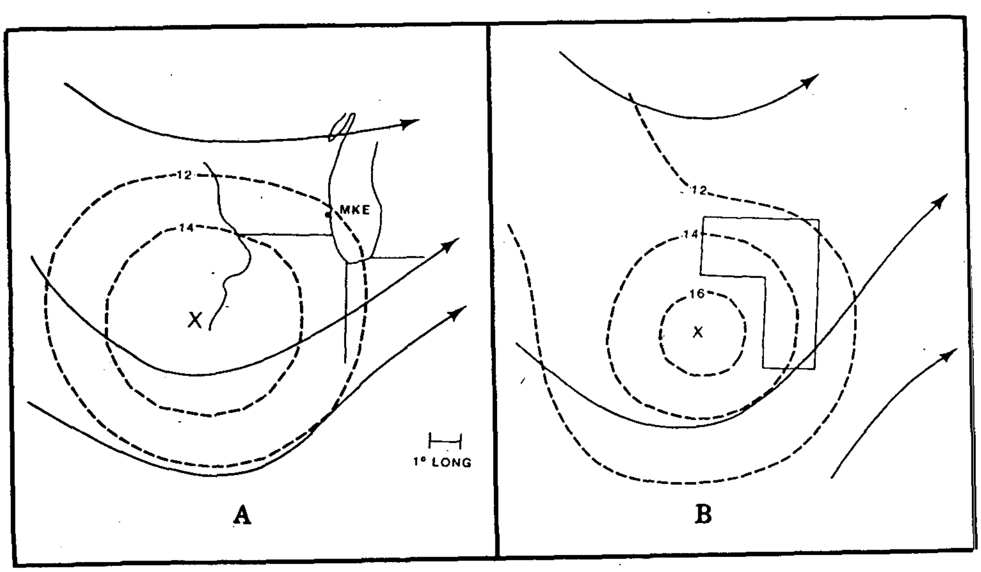

FIG. 12. The (a) 500-mb analyses from the global spectral model at 1200 UTC 6 August 1986 and (b) 500-mb SHARS cyclonic circulation system (CCS) composite. Streamlines are solid arrows and dashed lines are isopleths of absolute vorticity in units of 10^{-5} s^{-1}. Boxed areas in the composite indicate the preferred regions for flash flooding.

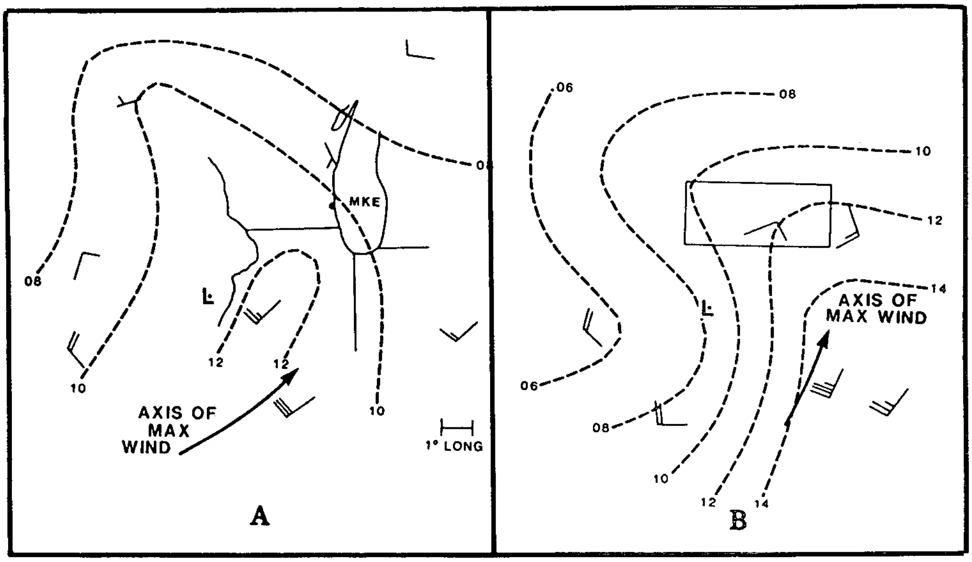

FIG. 13. As in Fig. 12 except at 850 mb. Arrow depicts axis of jet and isodrosotherms are dashed in units of °C. Wind speeds are in knots.

At 500 mb, the CCS composite (Fig. 12b) depicts a fairly intense center of absolute vorticity associated with a relatively circular pattern of vorticity gradients moving in an east-northeasterly direction, with the flash flood area occurring about 2°–3° to the east, northeast or north of the vorticity center. A similar streamline pattern is seen in both the analysis at 1200 UTC 6 August (Fig. 12a) and the composite. Maximum absolute vorticity values in the observed trough, utilizing the vorticity analyses from the global spectral model, exceeded $14 \times 10^{-5}\ s^{-1}$. Milwaukee is located north and east of the maximum vorticity in the preferred region of flash flood potential as outlined by rectangles in the composite.

In the 850-mb composite, the heavy rainfall formed about 2°–3° north to northeast of the 850-mb low center (Spayd 1982), as depicted in Fig. 13b. As noted by Spayd and Scofield (1983), the 850-mb composite also shows the flash flood area located to the *north and west* of the maximum wind speeds, differing from the composites produced by Maddox et al. (1979) that show the 850-mb jet nosed directly into the region of flash flood potential. Average dewpoint temperatures at 850 mb ranged between 10° and 12°C. The 850-mb analysis at 1200 UTC 6 August (Fig. 13a) shows a jet axis over central Illinois directed toward northeastern Indiana, south and east of Milwaukee. The 850-mb charts at 1200 UTC 6 August and 0000 UTC 7 August (Figs. 4b and 5b) show that the 850-mb low tracked to the south of Wisconsin, while analyzed 850-mb dewpoints were near 10°C over Milwaukee, both similar in gross appearance to the features shown in the composite.

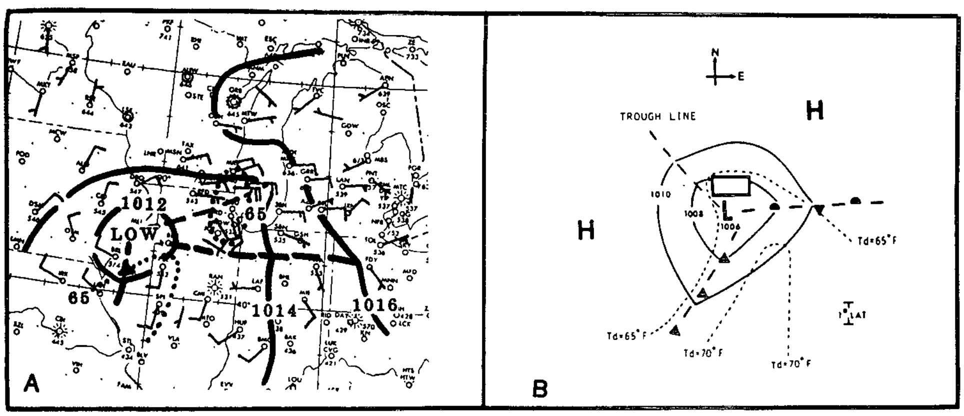

FIG. 14. As in Fig. 12 except at the surface. Surface analysis is from observations at 1400 UTC. Isodrosotherms are dashed in units of °F and isobars are solid in units of mb.

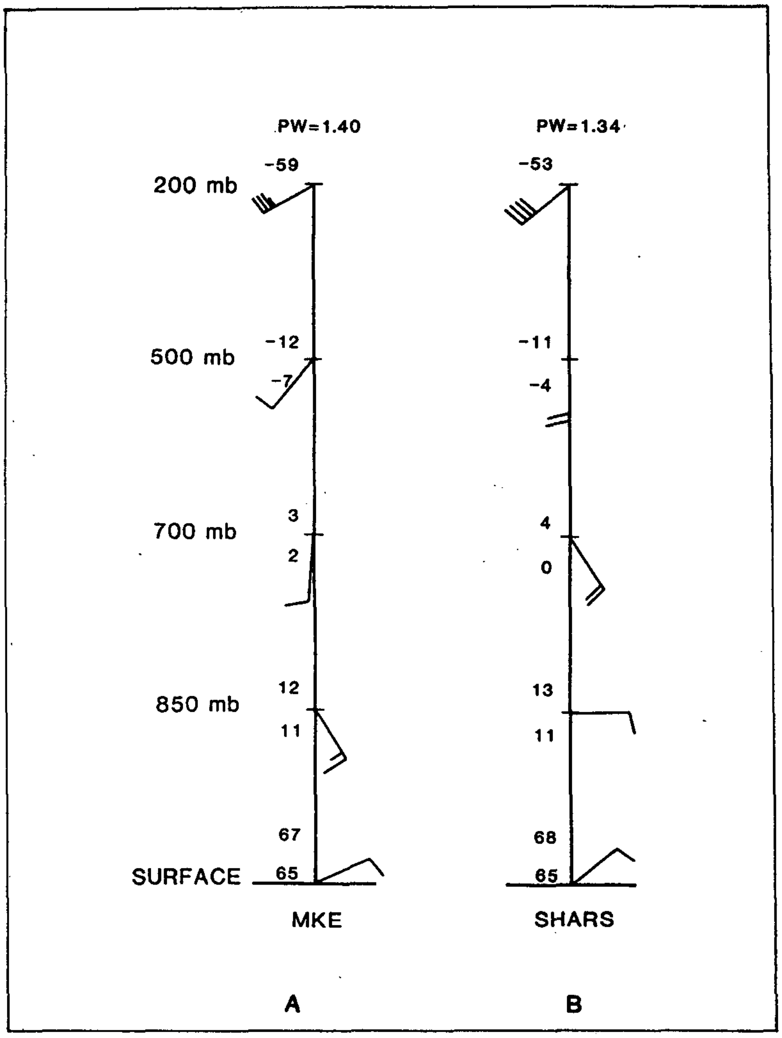

FIG. 15. The (a) vertical profile over MKE extrapolated from the 1200 UTC 6 August 1986 analysis and (b) SHARS composite profile. Temperatures and dewpoints are in °C except at the surface where they are in °F. Wind speeds are in knots. PW denotes precipitable water in inches.

At the surface, the composite (Fig. 14b) places the heavy rainfall to the north and east of the surface low pressure center, north of a stationary frontal boundary. During the heavy-rain period in Wisconsin on 6 August, the surface low propagated across northern Illinois, a similar track with respect to the composite. Dewpoint temperatures >65°F (18°C) were similar in both the analysis and composite.

A vertical profile of wind, temperature and dewpoint temperature at Milwaukee in Fig. 15 was constructed for Milwaukee from NMC analyses at 1200 UTC 6 August. The profile was constructed utilizing subjective analyses of these quantities at 850, 700, 500, and 200 mb. Actual 1200 UTC 6 August data from Milwaukee were used for the surface values. Both composite and extrapolated soundings show a distinct veering of winds with height, with light east-northeasterly winds at the surface becoming southerly to southwesterly in the middle to upper troposphere. Temperatures and dewpoint temperatures were also quite similar in both profiles, especially at the surface and 850 mb. Values of precipitable water, as averaged from 1200 UTC soundings at Peoria and Green Bay, were also nearly identical. Differences include a greater change in the wind direction with height and lower wind speeds at 700 and 500 mb at Milwaukee.

b. Comparison with the NMC model forecasts

To assess the performance of the operational models in predicting both rainfall amounts and some of the features depicted by the CCS composite, 36-h forecasts of accumulated 12-h precipitation valid at 0000 UTC 7 August and 24-h forecasts of the 500-mb and sea-level pressure fields valid at 1200 UTC 6 August are compared (Fig. 16). The model forecasts by the limited fine mesh model (LFM) and the nested grid model (NGM) provide the basis for the comparison.

The NGM (Fig. 16a), which did not predict excessive precipitation amounts, did predict 12-h rain amounts in excess of 0.5 in. (1.3 cm) for a region covering northeastern Illinois, southwestern Michigan, northwestern Indiana and southeastern Wisconsin, including Milwaukee. A maximum rainfall of 1.08 in. (2.7 cm) was forecast just north of Chicago. The LFM, however, predicted a large region of light precipitation over the lower Great Lakes but did not highlight a region of heavier precipitation with a maximum 12-h amount of only 0.25 in. (0.6 cm). Historically, quantitative precipitation forecasts (QPF) have typically been a weak element of NMC guidance (Keyser and Uccellini 1987), particularly during the summer convective season, when subtle low-level boundaries can focus convection, such as those shown in the surface charts in Figs. 4c and 5c. In this case, the NGM provided a more realistic expectation of heavy precipitation, although predicted amounts were greatly underestimated in southeastern Wisconsin.

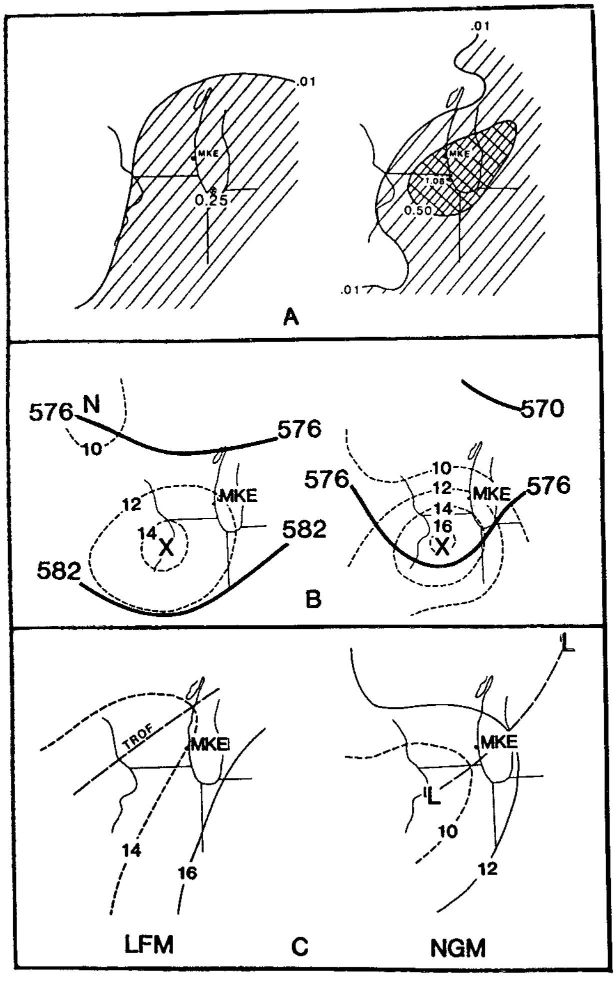

FIG. 16. (a) The 36-h LFM (left) and NGM (right) forecasts of 12-h accumulated precipitation valid at 0000 UTC 7 August. Values are in inches. (b) The 24-h 500 mb LFM (left) and NGM (right) forecasts valid at 1200 UTC 6 August. Contour heights are solid lines labeled in decameters and isopleths of vorticity are dashed lines labeled in units of 10^{-5} s^{-1}. (c) As in panel b except surface forecast. Isobars are solid lines in units of +1000 mb. The pressure trough axis is indicated by a dashed line.

Both models provided an adequate depiction of the 500-mb trough and its associated vorticity advection patterns southwest of Milwaukee at 1200 UTC 6 August (Fig. 16b). The models were slightly fast with the movement of the vorticity center. The LFM predicted a surface trough stretching from southwestern Wisconsin to eastern Wisconsin while the NGM forecast predicted the trough position more accurately across northern Illinois, with a 1008-mb low along the Iowa-Illinois border (Fig. 16c). Therefore, some of the gross features of the CCS pattern, in particular the 500-mb vorticity field and the location of the surface low, were predicted adequately by the models, especially the NGM. Forecasters familiar with the CCS composite could have recognized some simple features off the model output and been vigilant that such features may signify that localized heavy rainfall was a possibility.

4. Climatology

In section 3, it was shown that the synoptic weather patterns associated with the Milwaukee flood were similar to the CCS composite and that some of these patterns were reasonably well forecast by the operational models. To address how often such patterns are observed and what percentage of cases during the lifetime of the pattern are associated with the occurrence of heavy rainfall, seven warm seasons, 1 June–15 September from 1981 to 1987 were examined to identify weather systems similar to the CCS composite defined by Spayd (1982). The screening for warm-season CCS's was performed based on 500-mb, 850-mb and surface criteria shown in Table 1 that matched the overall appearance of the composites shown in Figs. 12b, 13b and 14b. Cases were considered to be CCS systems when they met *all* the conditions described in Table 1. Initially, cases were selected from the 500-mb height and vorticity fields from the NMC spectral model analyses. The spectral analyses were used because of their consistent availability during the 7-yr period and because of their expected availability well into the future.[2] The 500-mb surface was examined to identify trough systems exhibiting vorticity values $\geq 14 \times 10^{-5}$

[2] It should be noted that had other analyses employing different grid spacing (for example, the NGM initial analysis) been chosen to select cases, it is likely that the number of cases selected would have been different since the vorticity values would have been affected by the grid spacing.

TABLE 1. Table of Criteria identifying summertime cyclonic circulation systems (CCS's) that are similar to the composite of Spayd (1982).

Level of screening[a]	Pressure level	Parameter	Limits	Chart
1	500 mb	absolute vorticity	+ maximum center east of Rocky mountains + circular closed isopleth + 14×10^{-5} s^{-1} or greater in at least one of three successive analysis periods + no westward component of movement of center + no association with tropical disturbances	spectral
2	500 mb	height	+ 5700 m or greater at the vort max	spectral
3	850 mb	height	+ identifiable center of low heights	NMC
4	850 mb	dewpoints	+ greater than or equal to 10°C northeast of 850 mb low	NMC
5	850 mb	jet axis	+ south and east of preferred heavy rain region	NMC
6	surface	pressure	+ identifiable low or trough (may need reanalysis)	NMC
7	surface	dewpoints	+ greater than or equal to 17°C	NMC

[a] Level of screening refers to the order in which criteria are applied. The verification begins with identification of a vorticity center at 500 mb, then assuming the criteria are met at this level, the screening continues at 850 mb and so on. No reference to rainfall is made until all seven screening levels are answered positive.

s^{-1}, no tropical origins, and no westward translation. Cases selected were then checked at 850 mb and the surface. Cases were eliminated if they did not exhibit an identifiable center of low heights at 850 mb, if 850-mb dewpoints were <10°C in the preferred area of heavy rainfall as outlined by Spayd (boxed in Fig. 13b), if no surface low center or trough were present, and if surface dewpoints were <17°C north of the surface trough, again in the preferred region of heavy rainfall as defined by Spayd (boxed in Fig. 14b). Following identification of a CCS system, rainfall analyses from NMC and *Storm Data* were checked for the occurrence of a rainfall > 5 in. (12.7 cm) within the left forward quadrant of the propagating 500-mb vorticity maxima (Fig. 17).

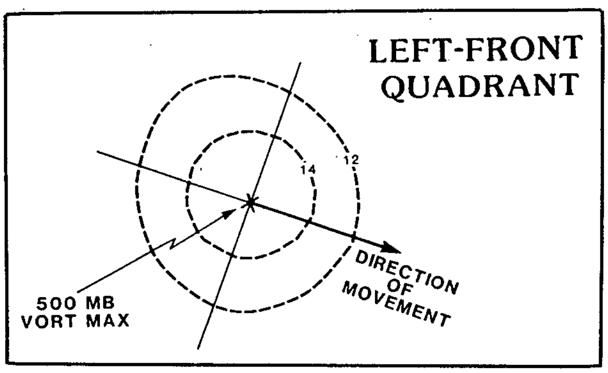

FIG. 17. Coordinate system used in the selection of cyclonic circulation system. Thick arrow indicates the forecast direction of movement of the vorticity center. This direction differs for each system. Solid lines delineate the quadrants.

During the seven warm seasons, 19 systems were identified that met the criteria specified in Table 1. The dates and locations of these systems are given in Table 2. All but one of these events occurred north of 37°N, possibly reflecting the association of these systems with the northward-retreating polar jet during summertime. A split or sag in the jet stream may occur over the northern United States in summer and the table suggests a preference over the Great Lakes region. Of the 19 systems, 11 (58%) were associated with at least one report of rainfall exceeding 5 in. (12.7 cm) in the left-forward quadrant of the propagating 500-mb vorticity maximum (Fig. 17). Six of these 11 were associated with flash flooding, as documented in *Storm Data.*

Although it is not the intent of this paper to rely on satellite imagery as a forecast tool, it is valuable to compare the imagery of these CCS cases to Spayd's results. Spayd (1983) arbitrarily defined warm-top convection as cloud-top temperatures warmer than −62°C. A review of the GOES IR imagery (and the enhancement curve) for the 11 excessive rain producers in Table 2 indicated that 8 of the 11 cases were clearly associated with warm-top convection, supporting Spayd's association of warm-top convection with a synoptic-scale CCS.

5. Summary and discussion

The Milwaukee flash flood of 6 August 1986 was the result of a narrow region of heavy rainfall >6 in. (15.2 cm) across Milwaukee County in southeastern Wisconsin. At Milwaukee's Mitchell International Airport, more than 3 in. (7.6 cm) fell in 1 h. An analysis of satellite imagery indicated that the storm was as-

TABLE 2. Dates and states of 19 cyclonic circulation systems occurring during the warm seasons (1 June–15 September) from 1981 through 1987.

Date	Location
24 August 1981	eastern N. Dak., S. Dak., and western Minn.
27 August 1981*	eastern Minn. and western Wis.
29 August 1981	Wis.
4 September 1981**	southeast Mich. and northwest Ohio
11 July 1982**	south-central Wis.
22 July 1982**	northeast Ill. and western Wis.
21 June 1983	northern Pa.
27–29 June 1983*	Nebr. and Iowa
11 August 1983**	northwest N.Y.
2 July 1984	eastern Ky. and southern Ohio
6 June 1985	southern Okla. and northern Tex.
1–2 July 1985**	southwest Ohio
26 August 1985	western Lake Erie
8–9 September 1985*	central Minn.
6 August 1986**	southeast Wis.
14 August 1986	N. Dak. and Minn.
1–2 July 1987**	central Ind. and western Ohio
18–19 July 1987*	N. Dak. and S. Dak.
8–9 August 1987	S. Dak., Minn., and Iowa

* Systems which were associated with heavy rains in excess of 5 in. (12.7 cm) in 24 h somewhere in the left forward quadrant with respect to the movement of the 500 mb vorticity center.

** Indicates a flash flood event as recorded in *Storm Data*.

sociated with relatively shallow or warm-topped convection embedded within a comma-shaped cloud pattern.

A relatively-strong surface moisture flux divergence/convergence couplet signaled the potential for significant convection in advance of the heavy rain over southeastern Wisconsin. Frictional convergence may have contributed to the concentration of the lift needed to produce excessive rainfall rates well above the indicated DVIP rates observed from the Marseilles, Illinois weather radar.

A comparison of the synoptic-scale weather patterns associated with this event and those depicted in the CCS pattern described by Spayd (1982) revealed several striking similarities. These similarities were demonstrated by the occurrence of the heavy rainfall (a) to the north and east of an upper-level vorticity maximum associated with a relatively circular pattern of vorticity gradients, (b) to the northeast of the 850-mb low center in regions of relatively weak low-level flow, (c) to the northwest of the 850-mb jet axis, and (d) near a surface frontal boundary or trough (for example, a stationary front) with dewpoint temperatures exceeding 64°F (18°C).

A brief examination of the NMC operational models for this case shows that the operational models did not predict the extreme rainfall but did predict several features of the CCS composite 24 h or more prior to the event. The brief climatology suggests that these patterns can be identified from conventional weather analyses and that they appear to occur mainly across the northern United States during the summer months. While such events are rare on a given warm season day, results indicate that such patterns are associated with heavy rain events in nearly 60% of the 19 cases identified. The model forecasts for these other 18 cases were not examined.

The operational value of pattern recognition models, as previously stated by Goree and Younkin (1966), is that it provides forecasters a means for an initial assessment of the potential for a given weather problem such as heavy rainfall. Others, such as Weiss (1988), have employed the use of such models in predicting severe weather associated with baroclinic systems. This study represents a first step in the application of a conceptual or composite model to identify the potential for heavy rainfall associated with modest summer troughs. Unlike wintertime, when a CCS is often associated with an easily detectable and temporally coherent heavy snow band, the distribution of excessive rainfall in summertime CCS's is frequently discontinuous in both space and time. Further research is needed to identify and refine all the contributing elements associated with summertime synoptic-scale circulation systems. Improvements in the detection of summertime CCS's could help forecasters identify potentially life-threatening short-duration rain events.

While flash flooding in the central and eastern United States is often associated with tropical cyclones and their remnants or with the three basic meteorological patterns (termed synoptic, frontal, and mesohigh events) described by Maddox et al. (1979), there appears to be a class of events that are different. The synoptic-scale cyclonic circulation or CCS identified by Spayd (1982) resembles that of a winter precipitation producer in that the heaviest precipitation occurs in conjunction with cyclonic vorticity advection to the north and northeast of both the surface and 850-mb low centers.

A significant difference from the Maddox composites is the location of the heavy rainfall in the CCS to the *northwest* of the 850 mb or low-level jet axis. More research is necessary to distinguish this pattern from other, more conventional views of meteorological conditions attending flash flood events (i.e., Maddox et al. 1979).

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