AN EXAMINATION OF THE EASTERN NEBRASKA AND WESTERN IOWA FLASH FLOOD EVENT OF 6-7 AUGUST 1999

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Abstract

Flash flooding occurs each summer in eastern Nebraska and western Iowa. While 10-inch rains are extraordinary, it is not uncommon to have at least one excessive rain event during the annual convective season. A significant flash flood occurred in east central Nebraska and western Iowa the night of 6 August 1999 into the morning of 7 August 1999. Antecedent hydrologic conditions limited the loss of life, however considerable property damage resulted as the heavy rain fell over the urbanized areas in eastern Nebraska and western Iowa.

Several flash flood ingredients came together over the area. These meteorological factors are typical of similar events in the Plains of the United States. The frontal type flash flood pattern, as described by Maddox et al. (1979), became established during the afternoon of 6 August 1999 with a west to east warm front near the Kansas and Nebraska border. Strong inflow of moist, unstable air normal to the surface front contributed to the development of convection on the cool side of the surface front. An intensifying convergent nocturnal low-level jet (LLJ) transported high θe air northward above the surface front, which increased thermodynamic instability and enhanced the upward motion. While individual thunderstorm cells moved northeast, backward cell development relative to the mean cell motion vector persisted for a prolonged period (Chappell 1986) playing a significant role in the character of this heavy rain event. These cells moved northeast, growing to maturity and producing heavy rain. During the intensification of the low-level jet, a gradual change in propagation increased storm cell mergers. The result of these factors was a quasi-stationary convective event producing very heavy rains. The use of pattern recognition, knowledge of flash flood forecasting techniques, and utilization of real-time and forecast data, enabled the National Weather Service (NWS) operational forecasters to anticipate the flash flood potential. This case illustrates the importance of understanding the hydrometeorological processes that lead to the production of heavy rain and flash flooding, allowing the successful issuance of a flash flood watch prior to the nocturnal event. Short-term monitoring of cell movement and new cell initiation was integral to forecasting the evolution of the convective system and the location of the heaviest nocturnal rainfall. In addition, this case will be compared with another heavy rain event to identify common features utilized for the anticipation of heavy rain events.

1. Introduction

Flash flooding from the heavy convective rains on 6-7 August 1999 resulted in over 35 million dollars in property damage over a 4,000 square mile area in eastern Nebraska and western Iowa. Figure 1 illustrates an analysis of the 24-h distribution of rainfall accumulation as reported by NWS cooperative observers, Automated Local Evaluation in Real-Time (ALERT) rain gages, and from the use of precipitation estimate products from the NWS Omaha Weather Surveillance Radar – 88 Doppler (WSR-88D). The majority of damage occurred in the Omaha, Nebraska and Council Bluffs, Iowa metropolitan areas. Washed out roads and bridges, flooded businesses and basements, collapsed walls, and damaged vehicles accounted for most of the property losses. Douglas, Burt, and Washington counties in east central Nebraska and Pottawattamie County in western Iowa were declared Federal disaster areas. Tragically, one fatality occurred along Cole Creek (for creek location references see Fig. 2) in east central Omaha, as an elderly man was swept away while checking on his basement.

Since 1871, the official rainfall observation point in the Omaha, Nebraska area has moved to a variety of locations. In 1997, the official observation point moved from Omaha's Eppley Airfield, to the current NWS Forecast Office in Valley, Nebraska. The wettest 24-hour period in Omaha's *official* record book remains at 7.03 inches from 26-27 August 1903. Despite not being an *official* record for Omaha, the flash flood event of 6-7 August 1999 was meteorologically significant, producing 10.48 inches of rain at Omaha's Eppley Airfield in a 24-hour period (for location references see Fig. 3). An unofficial report of 13 inches of rain fell in Treynor, Iowa in Pottawattamie County and 14.5 inches of rain fell in two separate five-gallon straight-sided bucket surveys at Wales, Iowa in northwest Montgomery County. Statistics obtained from the Iowa State Climatologist, Harry Hillaker, revealed that only four times in the last century (period of data

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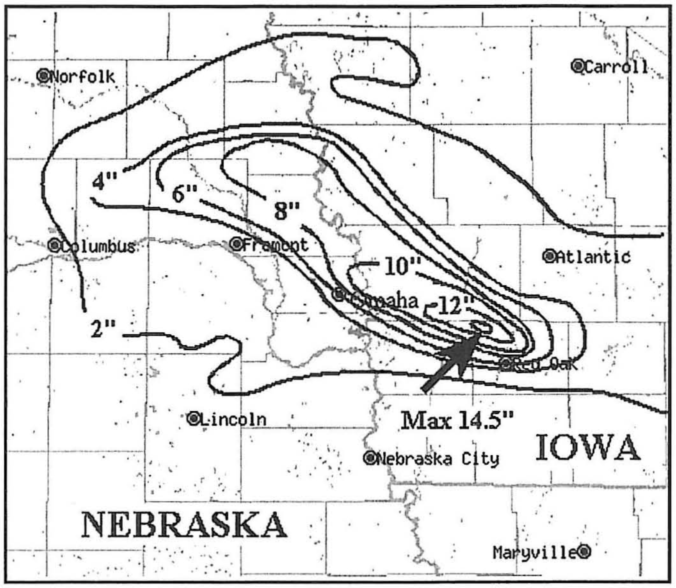

Fig. 1. Subjective analysis of the 24-hour rainfall accumulation in inches for the period ending 0700 CDT 7 August 1999 (based on rainfall gages, bucket surveys, and utilization of WSR-88D precipitation estimate products).

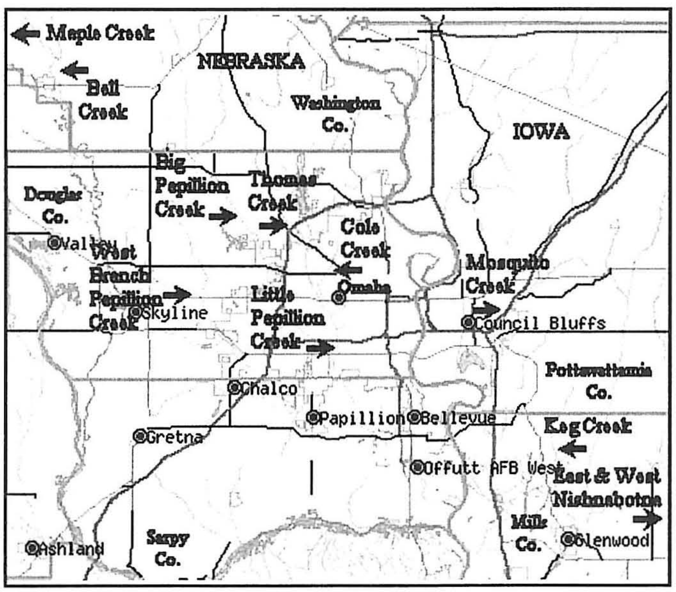

Fig. 2. Map of creek and river locations referenced in eastern Nebraska and western Iowa.

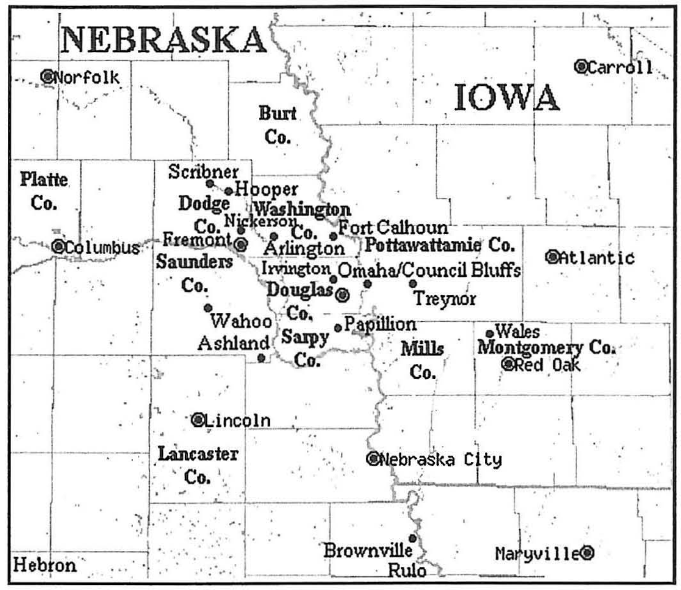

Fig. 3. Map of cities and counties referenced in eastern Nebraska and western Iowa.

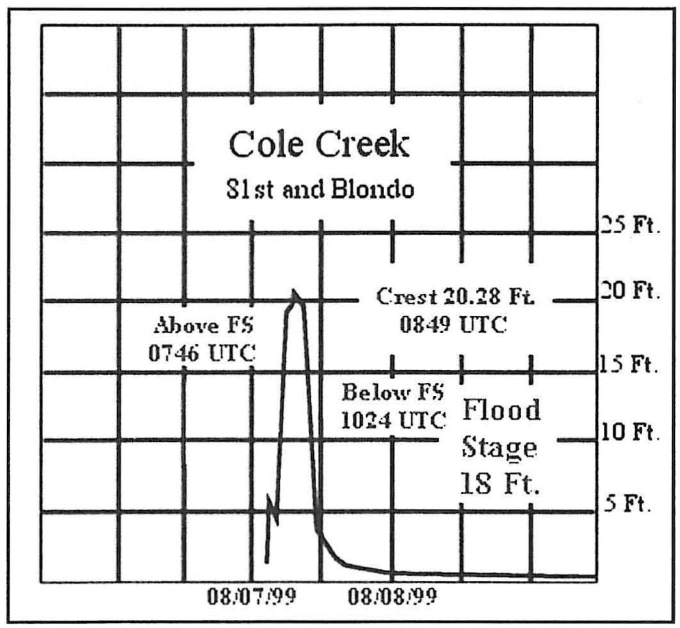

Fig. 4. Hydrograph from the Cole Creek ALERT gage, with stage height in feet and time in UTC.

1900-1999) have official rainfalls of 12 inches or greater been reported (personal communication, Hillaker, H.J., 2001). Hillaker noted that it was routine for the NWS to conduct bucket surveys from the mid 1950's to the early 1970's. These unofficial rainfall reports of 13 to 14.5 inches were consistent with the location and amounts as depicted in products from the NWS Omaha WSR-88D.

The rainfall amounts during the 24-hour period surpassed 100-year rainfall amounts, with a 100-year flood on the Little Papillion Creek at Irvington. Flooding occurred along the Maple Creek, the Little and Big Papillion Creeks, the Missouri River, the East and West Nishnabotna Rivers and the Nishnabotna River. Due to the location of the heavy rains and prior period of hot and dry weather, hydrologically, the event was not as significant as it could have been. In addition, the late night occurrence of the event reduced the number of people driving in flooded areas.

Several papers have documented well the meteorological aspects of particular flash flood cases (e.g., Maddox et al. 1978; Caracena et al. 1979; Schwartz et al. 1990; and Petersen et al. 1999). This paper examines the meteorological processes that contributed to this flash flood event. Improved understanding of the processes that are conducive to heavy rainfall, utilization of analysis data and weather prediction models, and anticipating flash

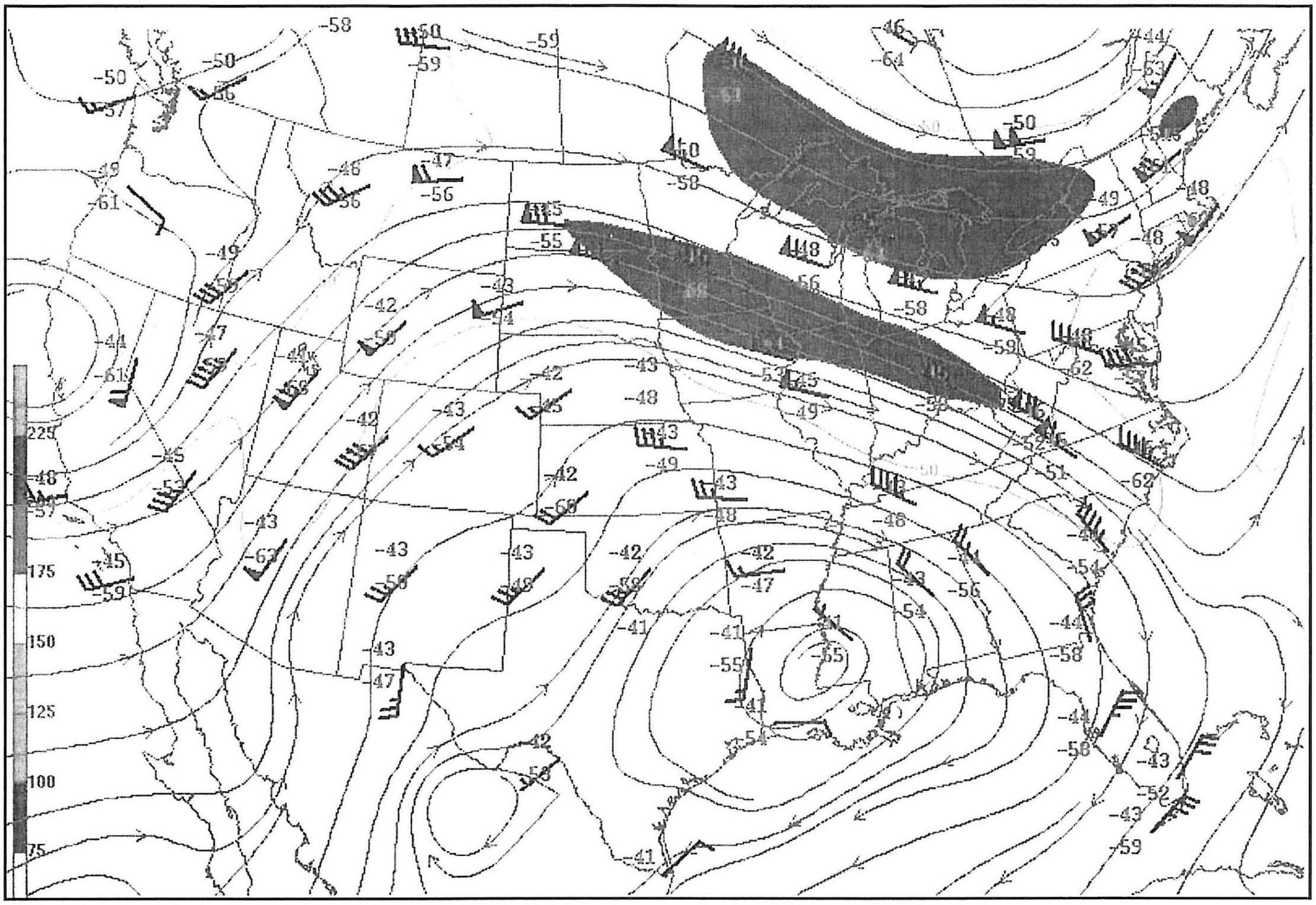

Fig. 5. 1200 UTC 6 August 1999 250-mb objective analysis (station plot in standard notation, arrowed lines = streamlines, isotachs at 50 kt and higher at 25 kt intervals, shaded areas ≥ 75kt). (Analyzed maps are from NWS/Storm Prediction Center online at http://www.spc.noaa.gov/obswx/maps/)

flooding will allow forecasters to more accurately forecast these potentially life-threatening events.

2. Data Sources

The operational forecaster integrates data from numerous sources in order to develop a four dimensional picture of anticipated weather. The NWS Forecast Office at Omaha/Valley, Nebraska (OAX) routinely launches radiosondes and had successful flights at both 1200 UTC 6 August and 0000 UTC 7 August 1999. There were no significant data voids at 1200 UTC. However, there were some stations missing 850-mb wind data at 0000 UTC. Low-level wind data were supplemented by Velocity Azimuth Display (VAD) wind profile data (VWP product) from the WSR-88D and the wind profiler networks. These observations were utilized in the NWS National Centers for Environmental Prediction (NCEP) numerical weather prediction models. The NWS forecaster uses the Advanced Weather Interactive Processing System (AWIPS) to display objective analysis data (including Local Analysis Prediction System (LAPS) products and Mesoscale Surface Analysis System (MSAS) data), a variety of NCEP model forecast data, Geostationary Operational Environmental Satellite (GOES) imagery, and WSR-88D imagery. WSR-88D imagery includes reflectivity data, velocity data, 1-h, 3-h, and storm total precipitation (STP) accumulation. Additional diagnostic tools include the Personal Computer Gridded Interactive Display and Diagnostic System (PCGRIDDS; Petersen 1992) and the SHARP skew-T/hodograph program (Hart and Korotky 1991). Hourly Web page data for the NWS Rapid Update Cycle 2 (RUC 2) from the NWS Storm Prediction Center's (SPC) Web page was also available approximately 25 minutes after the hour (http://www.spc.noaa.gov/compmap/). This near real-time data allowed the operational meteorologists to peruse an array of atmospheric variables to evaluate the potential for convection. The WSR-88D Algorithm Testing and Display System (WATADS), utilized post-event, allowed the WSR-88D archive Level II radar data to be reviewed for this study. See the WATADS Web site (http://www.nssl.noaa.gov/~watads/) for additional information.

Flash flood guidance, a threshold used by operational forecasters, is the amount of rainfall over a given county

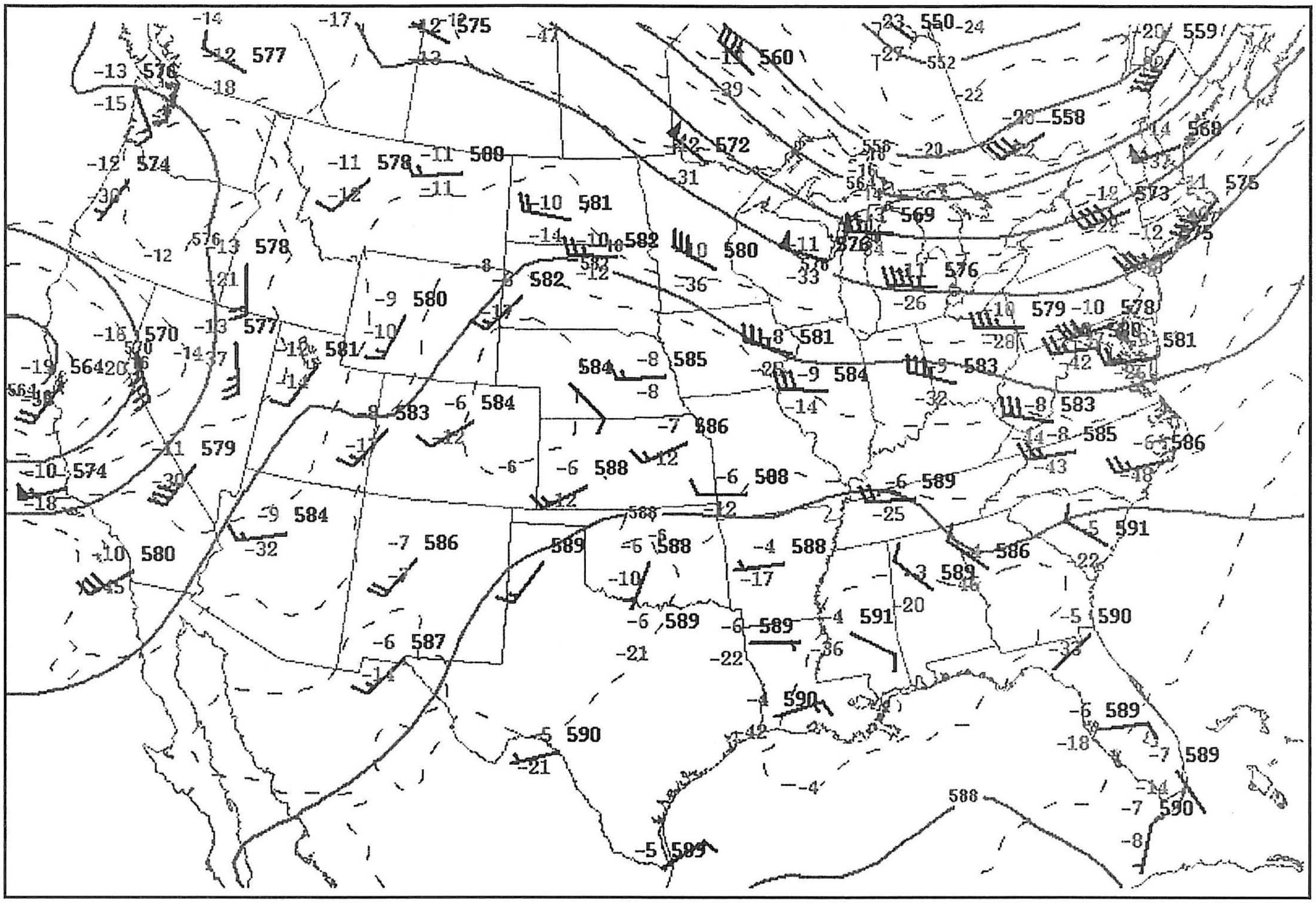

Fig. 6. 1200 UTC 6 August 1999 500-mb objective analysis (station plot in standard notation, solid lines = contours of geopotential height in dm, dashed lines = isotherms in °C).

needed to produce stream flash flooding. This guidance is an internal product issued by the NWS Missouri Basin River Forecast Center (MBRFC) and is empirically derived based on years of data. Urbanization is not taken into consideration and these values are to be used as guidance only. The MBRFC produces 1-h, 3-h, and 6-h flash flood guidance available via AWIPS generally around 1600 UTC and 0100 UTC daily. The ALERT network is operational with river gages and precipitation gages for several locations in the Omaha metropolitan area. The NWS office has access to this real-time precipitation and river stage data. Satellite precipitation estimates (SPE) are issued by the Satellite Analysis Branch/National Environmental Satellite, Data & Information Service (NESDIS). Automated surface observing systems (ASOS) are operational at local airports. Cooperative (COOP) observers are available to report rainfall totals, however, 24-hour rainfall amounts are typically reported between 1200 UTC and 1300 UTC daily.

3. Event Chronology

The flash flooding of 6-7 August 1999 developed as a result of excessive rainfall greater than 3 to 4 inches over a wide area across east-central Nebraska and southwest Iowa. OAX forecasters issued a flash flood watch at 2310 UTC 6 August 1999 based on the diagnosis described in this article. The initial heavy rains resulted from continued thunderstorm regeneration from near Columbus, Nebraska eastward across Dodge County in the Scribner area. Considering the fact that two significant west-east streams flowed across this area, the first flash flood warning was issued for Dodge County, Nebraska at 0117 UTC 7 August. Two hours later at 0317 UTC another flash flood warning was issued for Washington County, Nebraska. Scribner in Dodge County received 7.8 inches of rain for the 24-hour period ending at 1200 UTC 7 August 1999, while Fort Calhoun in Washington County reported 9.29 inches in that same time period. Real-time flooding reports in these counties were slow to become available, since much of the flooding occurred in agricultural areas. However, post-flood surveys showed that flooding was extensive in rural areas of Washington County, where satellite rainfall rates of 2.4 inches per hour were estimated between 0100 UTC and 0400 UTC. Stream flooding continued in Dodge and Washington Counties into the evening of 7 August.

The west-east axis of heavy rainfall rates shifted to a more northwest to southeast axis between 0400 UTC and

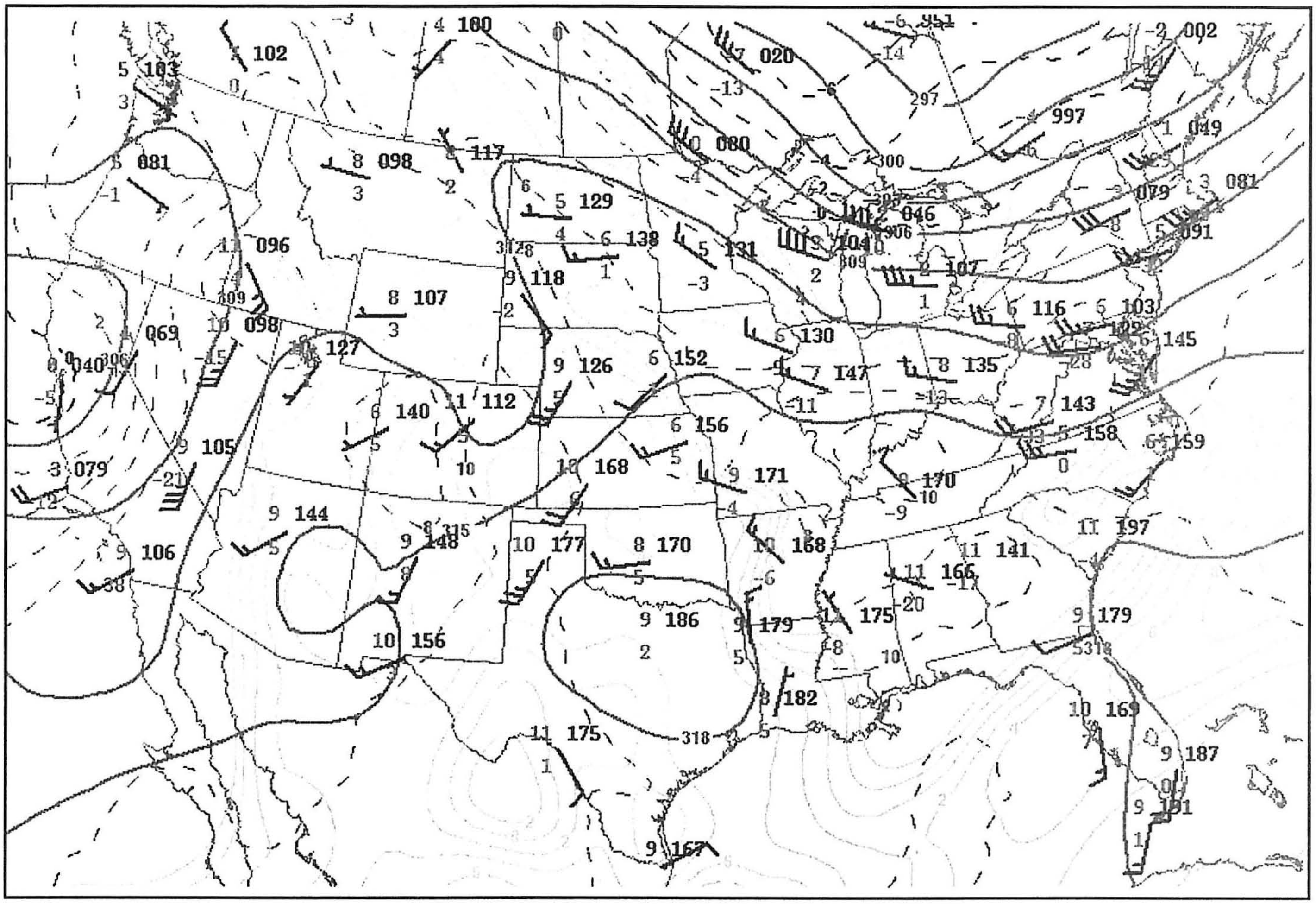

Fig. 7. 1200 UTC 6 August 1999 700-mb analysis (station plot in standard notation, thick solid lines = contours of geopotential height in dm, dashed lines = isotherms in °C, thin solid lines = isodrosotherms in °C).

0800 UTC of 7 August. This change in the focus of excessive rainfall after 0400 UTC resulted in rainfall rates of approximately 2 to 2.5 inches per hour for the Omaha/Council Bluffs area between 0530 UTC and 0730 UTC based on WSR-88D product estimates. Street flooding occurred most rapidly, with the lag time increasing from small streams to the larger streams. The examination of hydrographs from the ALERT system indicated that flood crest times on 7 August 1999 ranged from 0849 UTC on the lower reach of Cole Creek in Omaha (Fig. 4), to around 1200 UTC on the Papillion Creek near Offutt AFB south of Omaha. The Missouri River responded with flood crests of 4 feet above the flood stage at Brownville the evening of 7 August, to 2.5 feet above the flood stage at Rulo, Nebraska the morning of 8 August 1999.

During this flash flood and the following river flood event, 15 flash flood warnings and 23 flash flood statements were issued. Seven flood warnings were issued with 31 subsequent flood statements.

4. Synoptic Overview

The SPC analysis of the upper-air data (available online at http://www.spc.noaa.gov/obswx/maps/) valid 1200 UTC 6 August 1999, indicated divergent flow at 250 mb over Nebraska and South Dakota, on the anticyclonic side of the subtropical jet that extended from the Dakotas to the Ohio Valley (Fig. 5). A strong midlevel anticyclone was present over the southeastern United States with the 500-mb ridge of high pressure from Texas, stretching north through the Plains states, to the Dakotas (Fig. 6). A closed circulation of low pressure was centered just off the California coast with a mid-tropospheric trough from northwest Colorado through western Wyoming and western Montana. A weak midlevel short-wave trough appeared on NCEP's morning Eta initialization over western Nebraska. SPC's objective 700-mb height analysis showed that a trough of low pressure stretched from Montana to northeast Colorado (Fig. 7). This analysis of the radiosonde data revealed deep moist inflow with 700-mb dewpoints of 4 to 6°C noted in a large area from Texas, Oklahoma, and Kansas into Nebraska and 850-mb dewpoints in western Kansas of 14°C (not shown). The precipitable water (PW) analysis from the 1200 UTC 6 August 1999 run of the NWS Eta model showed a large area of 1.8 inches or greater stretching from Texas north to central Nebraska (Fig. 8). Additional subjective analysis of mean sea-level pressure showed the center of low pressure was over southwest Nebraska with a warm front curved east-southeast into central Kansas.

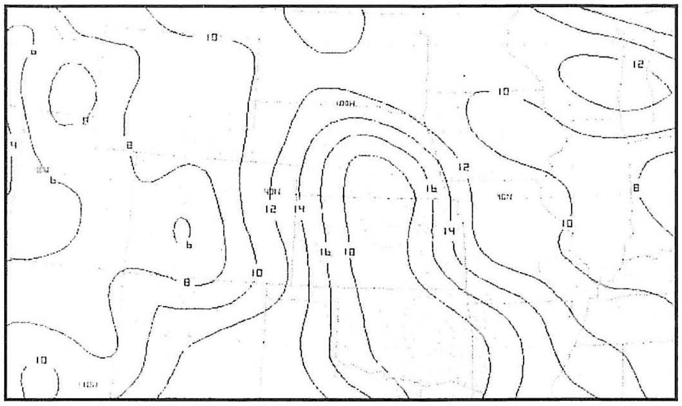

Fig. 8. 1200 UTC 6 August 1999 Eta objective initial analysis of precipitable water (solid lines = precipitable water in inches shown at a contour interval of two tenths of an inch, negative dashed lines = upward vertical velocity, contoured 1 μbar s^{-1}).

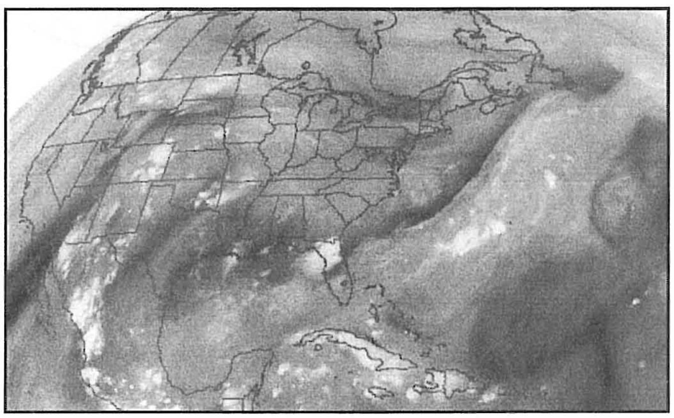

Fig. 9. 0015 UTC 7 August 1999 GOES 6.7 micron water vapor imagery.

Over the next 12 hours, deep-layer upward vertical motion was forecast. The 6-h forecast from the 0000 UTC Eta model run indicated persistent positive 850 mb to 250 mb differential divergence over eastern Nebraska (not shown). General rainfall amounts of 1.25 inches fell during the 12 hours between 1200 UTC 6 August and 0000 UTC 7 August 1999, which was prior to the heavy rain event in the cool sector north of the surface front over eastern Nebraska and western Iowa. These rains of 1 inch in 12 hours and 2 inches in 24 hours were important as the rainfall alerted the forecasters to an increase in soil moisture content, increased potential for runoff rates, and that the flash flood guidance values may be a little high. Recent rainfall was included in an excessive rainfall checklist developed by the NWS Weather Forecast Office near Philadelphia and was incorporated in a forecast techniques and applications article (Opitz et al. 1995) to assist forecasters in identifying conditions conducive to flash flooding. While a comprehensive flash flood checklist was developed at OAX in 1995, the paper checklist was not used in anticipating this particular event by the duty meteorologist. The replacement for the checklist was the development of an AWIPS "procedure" that served as a checklist of the fields to be examined. To assure the understanding of the significance of the parameters and fields included in this procedure, a set of flash flood reference notes was kept in the operations area. These notes contained the old paper checklist, and various quick operational references. The utilization of the AWIPS procedure in combination with the recognition of the favorable flash flood pattern and forecast conditions prompted the forecaster to issue a flash flood watch at 2310 UTC 6 August 1999.

The upper-air analysis data valid 0000 UTC 7 August 1999 showed that the mid-tropospheric trough shifted east and extended from northeast New Mexico to eastern Montana. Diffluent 250-mb flow continued over eastern Nebraska (not shown). A "moisture plume" was noted on the 0015 UTC 6.7 micron water vapor satellite imagery (Fig. 9), with mid and high-level moisture extending from the intertropical convergence zone (ITCZ) over southern Mexico north through the Rockies into the Plains states. Deep moisture was over southwest Nebraska and western Kansas evidenced by 850-mb dewpoints of 17°C (Fig. 10) and a large area of 6°C dewpoints over Colorado and western Kansas at 700 mb (not shown). This moisture was advected northward by mean 30 kt, 850 mb-700 mb layer winds over western Kansas. Surface dewpoints had risen to the lower 70s (°F), and PW values swelled to around 2 inches (nearly 200% of normal) for parts of eastern Nebraska.

Beebe and Bates (1955) and others have shown that the structure of a jet streak can be important in generating and maintaining convection. In the anticyclonically curved jet case, upper-level divergence produces upward vertical motion in the right entrance region of the jet. This is also an area of weak inertial instability, which is more conducive to divergent flow. This divergent flow more readily evacuates air being brought up through the convective updraft. The main portions of the polar jet and the subtropical jet were well to the northeast over the Great Lakes, however, a persistent jet streak maximum was over South Dakota. Eastern Nebraska and western Iowa were in a favorable location of upper-level divergence. As discussed by Junker et al. (1999) upper-level divergence was associated with most of their heavy rain cases. It was noted that the divergence-associated events were more extreme with larger areal coverage and stronger dynamics. In addition, their study concluded that the heavy rain was located in the gradient south of the maximum values of the 250-mb divergence field. This sloped ascent probably took place as the potentially unstable parcels were lifted to the north. These parcels appeared to have released their instability prior to reaching the area of maximum 250-mb divergence, thus the heavy rain area being located in the gradient to the south. This pattern was supported with the 2100 UTC RUC analysis data where 250-mb upper-level divergence was maximized in far northeast Nebraska and western Iowa (Fig. 11), while the heavy rainfall was occurring in the gradient area in east central Nebraska.

The flash flood type in this case was determined to be a classic frontal type pattern as described by Maddox et al. (1979). This frontal pattern is characterized by a weak 500-mb shortwave trough moving along a quasi-stationary synoptic-scale frontal boundary (usually oriented E-W). Maddox's study showed that the PWs on the warm

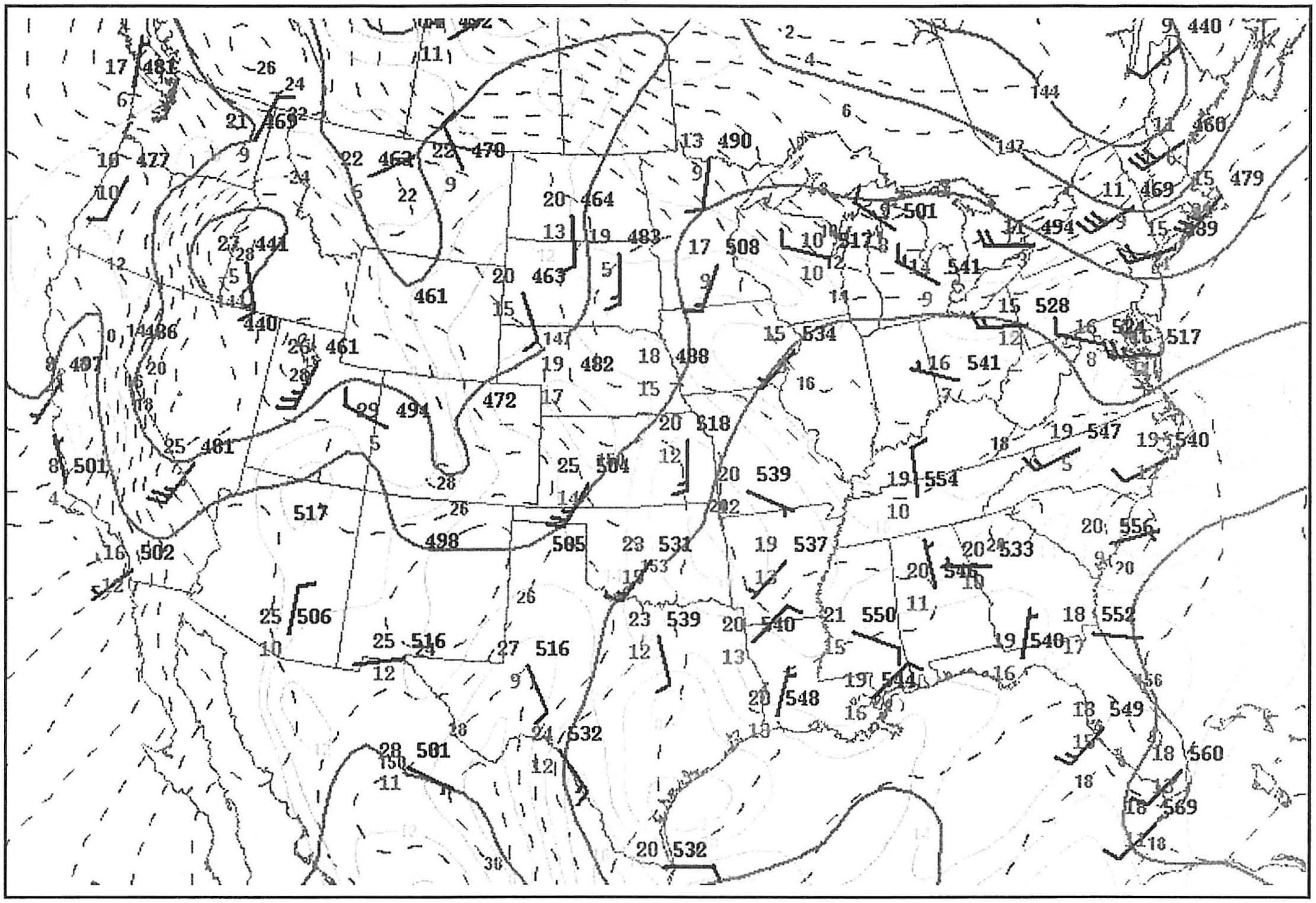

Fig. 10. 0000 UTC 7 August 1999 850-mb objective analysis (station plot in standard notation, thick solid lines = contours of geopotential height in dm, dashed lines = isotherms in °C, thin solid lines = isodrosotherms in °C).

side of the frontal boundary averaged around 160% of normal.

Abundant moisture to the south of the front was indicated in Topeka's 0000 UTC sounding (Fig. 12) with 1.64 inches PW or about 160% of normal. Saturation thicknesses for Topeka were around 579 decameters with a PW of 1.70 inches. This inflow of high PW air would support deep convection over eastern Nebraska (Funk 1991). Thickness diffluence was forecast to continue from 0000 UTC 7 August and shift east into western Iowa by 1800 UTC 7 August. According to Funk (1991), it has been observed that convection develops near or within regions of 1000-500 mb thickness diffluence. As discussed by Funk (1991), identifying broad areas of thickness diffluence can make it difficult to pinpoint the exact location of the heavy rain. Forecast diffluent thickness fields indicate a change in the thermal wind. The change can be a result of a change in winds aloft, at the surface, or both. Thus, another tool for estimating the meso-beta element (MBE) movement would be to examine the motion vectors as described by Corfidi et al. (1996).

Corfidi et al. (1996) developed a conceptual model that combines this advective component of the MBE movement (the 850-300 mb mean wind vector) and the propagation component (which is equal and opposite to the low-level jet) to determine the MBE movement. In this case, the winds aloft were nearly parallel to the surface front (Fig. 13). The 850-300 mb mean wind vector allowed new cells to form along the axis defined by the mean wind and to train along this axis. As illustrated in Fig. 14, the Corfidi MBE motion vectors indicated a pronounced change from 300° to 360° between 0000 UTC and 0600 UTC 7 August 1999.

The 850-mb axis of the equivalent potential temperature (θe) at 0000 UTC extended from eastern Colorado across Kansas into southern Nebraska and southwest Iowa (Fig. 15). Convection has been shown to develop along or near the θe ridge axis in the presence of unstable air and a lifting mechanism (Shi and Scofield 1987; Juying and Scofield 1989). This θe axis was forecast to remain over much of the same area by the Eta model for the next twelve hours. Additional analysis of greatest θe advection at 0000 UTC was over northeast Nebraska and was forecast by the Eta model to shift into western Iowa by 0600 UTC and eastern Iowa by 1200 UTC. The 1000-500 mb layer lifted index axis was similar to the theta-e axis with lower lifted index (LI) values in Kansas. This too suggested the potential for regenerative cells developing back toward the higher θe air (Shi and Scofield 1987).

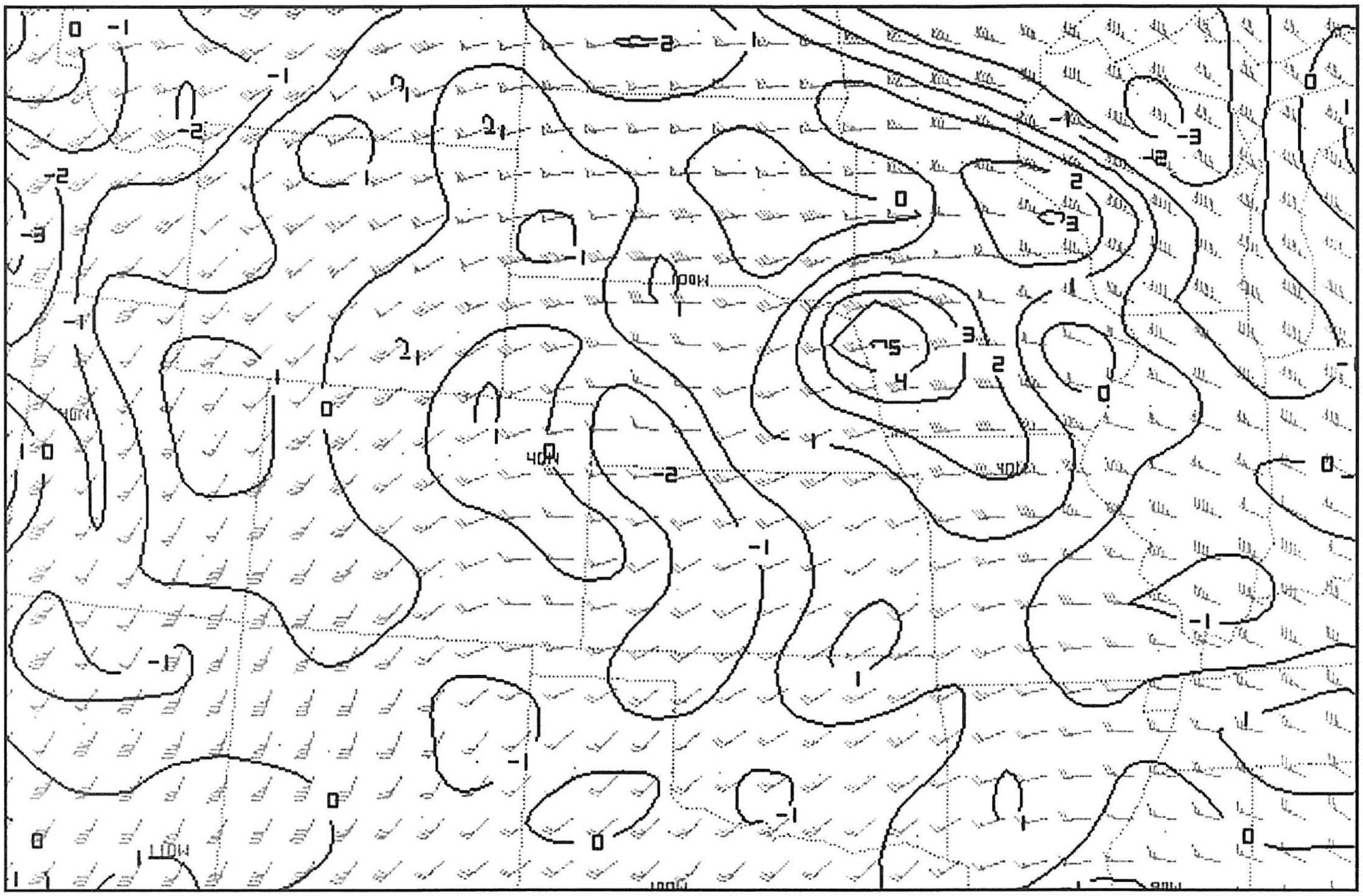

Fig. 11. 2100 UTC 6 August 1999 RUC objective initial analysis of 250-mb divergence. Values shown at a contour interval of 1×10^{-5} s^{-1}.

Both 850-mb moisture transport and moisture flux convergence initially at 0000 UTC were maximized over east central Nebraska and west central Iowa, respectively (not shown). Junker et al. (1999), in an effort to develop a synoptic climatology of extreme rainfall events from 1993 cases, used a number of 850-mb composites to determine the location of where the heaviest rainfall occurred. In their study, it was found that the heavy rain was northeast (or downwind) of the strong 850-mb moisture transport maximum and the location of the strongest 850-mb moisture flux convergence was to the north and west of the heaviest rainfall. Utilization of the 0000 UTC RUC initialization and 6-h forecast of 850-mb moisture transport and moisture flux convergence suggested heavy rain in eastern Nebraska. Noteworthy features of the RUC products were a lack of eastward progression of the mixing ratio flux convergence and a large increase (50%) in the magnitude of the moisture transport between 0000 UTC and 0600 UTC.

Low-level thermodynamic forcing played a key role in this heavy rain case. In addition, the interaction of the low-level front with the upper-level jet streak enhanced vertical motion. It has been documented by Junker et al. (1999) that more of the heavy rain cases were associated with 850-mb warm advection as compared to 500-mb or 300-mb differential positive vorticity advection. In addition, Augustine and Howard (1991) considered low-level thermodynamic forcing in their study of active mesoscale convective complex (MCC) periods versus inactive MCC periods. Their research asserted that the most important characteristics of active MCC periods were low-level thermal forcing and conditional instability. Further, a favorable strong mid or upper-level anticyclone was in the southeastern United States as the MCC traveled on the periphery of the midlevel ridge. While it is impossible to determine which mechanism was responsible for the majority of the vertical motion, it can be said that both played a part in this heavy rain event.

Thus, the synoptic stage was set for intense deep convection, and several flash flood ingredients were expected to continue into the nighttime hours. Based upon analysis of these favorable precursory conditions for a heavy rain event, a flash flood watch was issued at 2310 UTC 6 August 1999. The next section will discuss the evolution of the evening convective rains and the occurrence of severe weather in eastern Nebraska and western Iowa.

5. Convective Initiation and the Potential for Severe Weather

A careful analysis of the 0000 UTC 7 August 1999 surface data (Fig. 16) showed a warm front extended from the center of surface low pressure in northwest Kansas across

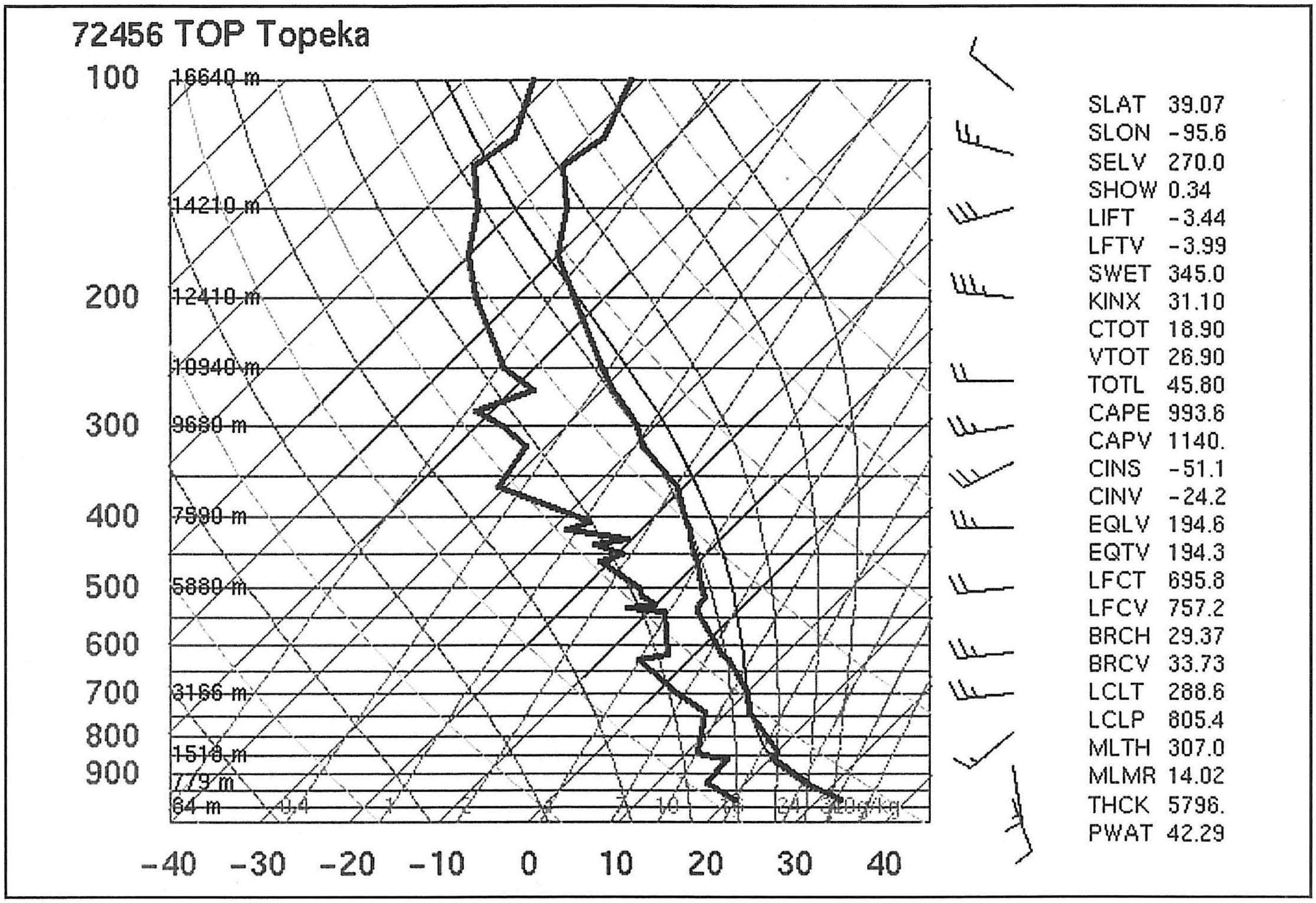

Fig. 12. Observed Topeka, Kansas (TOP) sounding at 0000 UTC 7 August 1999 (from University of Wyoming online at http://weather.uwyo.edu/upperair/sounding.html).

southern Nebraska into northern Missouri. Widely scattered thunderstorms remained north of the surface warm front in Nebraska with an area of showers in Iowa as a midlevel shortwave trough moved very slowly across the region. Note the distinct outflow boundary north of the warm front. Due to the differential diabatic heating across the front between the warm sector and the cloudy, rain-cooled air, a sharp temperature gradient developed. Very warm and moist air was located to the south of the front and included temperatures in the lower 90s and dewpoints in the lower 70s (°F). To the north of the surface front, cool and moist air was found with temperatures from 65 to 75°F and dewpoint depressions in the moist air around 2°F. Surface convergence along the front increased throughout the afternoon, with southwest winds over western Kansas and south/southeasterly winds in eastern Kansas. The increase in winds was due to the differential diabatic heating from the east slopes of the Rockies across the Plains and a gradual lowering of surface pressure over this same area. This pattern of increasing surface geostrophic winds as a result the hydrostatic lowering of pressure of the higher terrain to the west was discussed by Augustine and Caracena (1994).

The location of the afternoon maximum in surface geostrophic winds over north central Kansas into southern Nebraska (not shown) was an indicator of where the elevated nocturnal low-level jet (LLJ) would be expected (Augustine and Caracena 1994). The location of the surface geostrophic wind maximum and the location of frontogenesis combined to signal enhanced upward vertical motion in the watch area in southern Nebraska. At 2100 UTC, 850-700 mb frontogenesis (Petterssen 1956) was located over eastern Nebraska and western Iowa (Fig. 17) and was forecast to continue during the period.

In addition to the threat of flash flooding, forecasters were also aware of the potential for severe weather. The lifted index (LI) and the convective available potential energy (CAPE), both measures of instability, showed that the greatest instability was located in west central Kansas (with best LI's of -6 and CAPES of 3000-4000 J kg^{-1}). According to Miller (1972), Total Totals index values (TT) less than or equal to 50 were associated with weak thunderstorms. TT values the afternoon of 6 August were from 45 to 50, suggesting a low threat for severe weather. The 2100 UTC run of the 40 km resolution RUC from the SPC composite Web page indicated that most of the area had a K index from 35 to 40 across the Omaha County Warning Area (CWA). The 2100 UTC RUC forecast had a K index of 44 into southeast Nebraska between 0300 UTC and 0600 UTC. Traditionally, K index

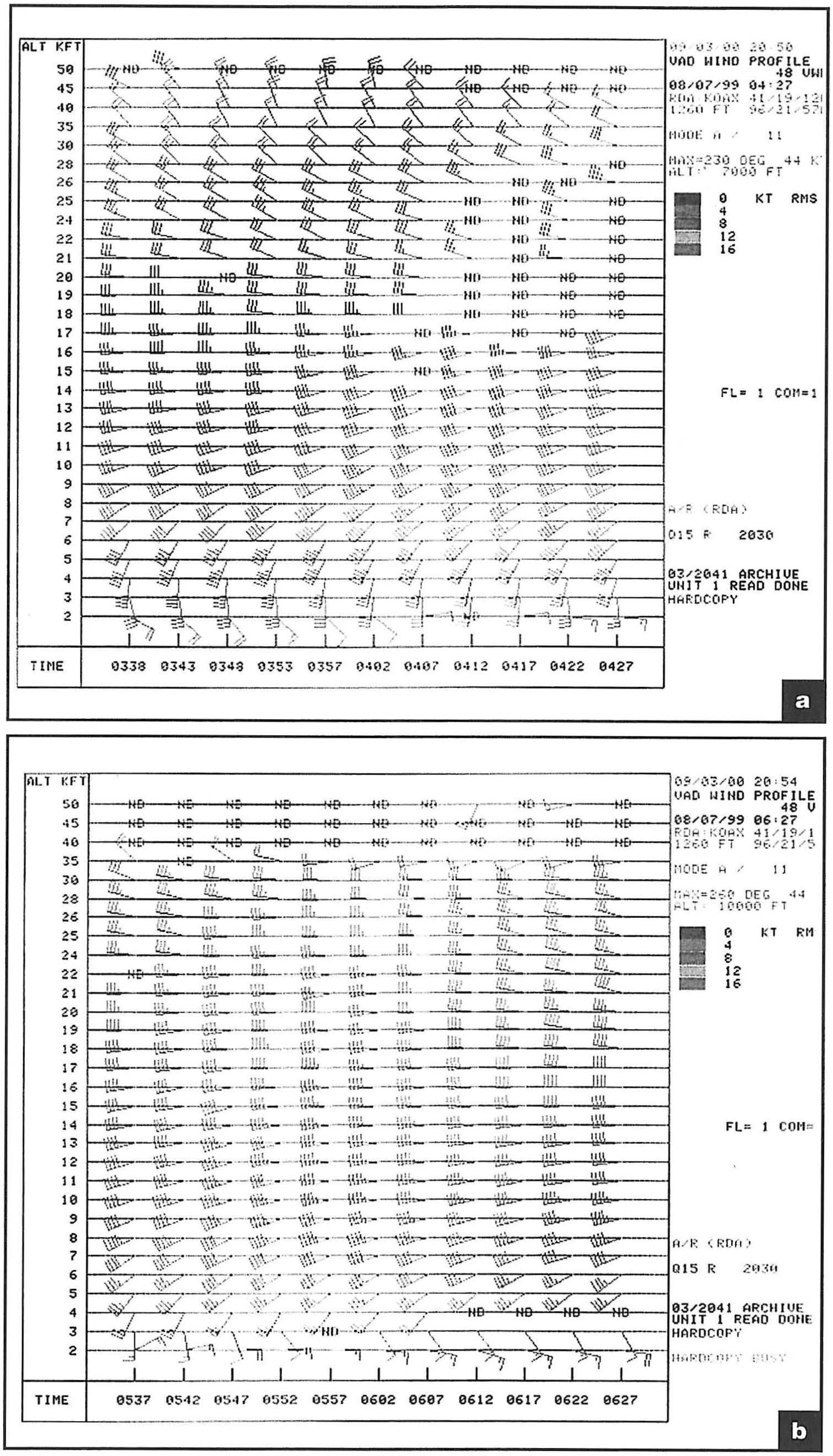

Fig. 13. KOAX WSR-88D VAD wind profile (wind in kt, altitude in kft MSL, radar level 1260 ft MSL): (a) 0338-0427 UTC 7 August 1999 and (b) 0537-0627 UTC 7 August 1999.

values in excess of 30 are indicative of a higher probability of thunderstorms in the air mass and a higher areal coverage. This very high K index far exceeded the mean values of 36 to 38 for heavy rain found by Glass et al. (1995) and Maddox et al. (1979). Glass et al. (1995) found that most heavy rain centroids were located on the eastern or northern periphery of the maximum with higher values extending south or west.

The 0000 UTC sounding from OAX had a storm relative (SR) helicity from 0-3 km of 322 m^2 s^{-2}. The OAX hodograph wind profile showed significant veering (120° of veering from the surface to 3 km) with height. Wind speeds were in excess of 35 kts above 2 km (Fig. 18). The forecast SR helicity value of 322 m^2 s^{-2} was based on the 30R75 technique (SHARP), and was indicative of the potential for organized supercell activity (Davies-Jones et al. 1990). Due to the elevated nature of these evening storms in the colder air, the effective SR helicity was above the lowest levels and was expected to yield a lower value. An estimate of the effective SR helicity was taken from the point above the lowest stable layer (.8 km) for a depth of 3.0 km (to 3.8 km). The modified hodograph yielded a lower estimated effective SR helicity of 222 m^2 s^{-2}. Sufficiently deep stable layers have been shown to inhibit tornado formation and surface damaging winds, however, convection associated with an elevated layer of instability has not been shown to inhibit large hail (Grant 1995).

During the early evening of 6 August, forecasters focused their attention on two areas of convection. The main area was multicell convection well to the north of the surface warm front, extending from near Columbus in Platte County to Hooper in Dodge County (about 40 miles northwest of Omaha and 80 to 100 miles north of the surface front). The four panel WSR-88D radar reflectivity images in Fig. 19 begin at 2249 UTC 6 August and end at 0557 UTC 7 August. The multicell thunderstorms repeatedly initiated over Platte County and moved east northeast with the

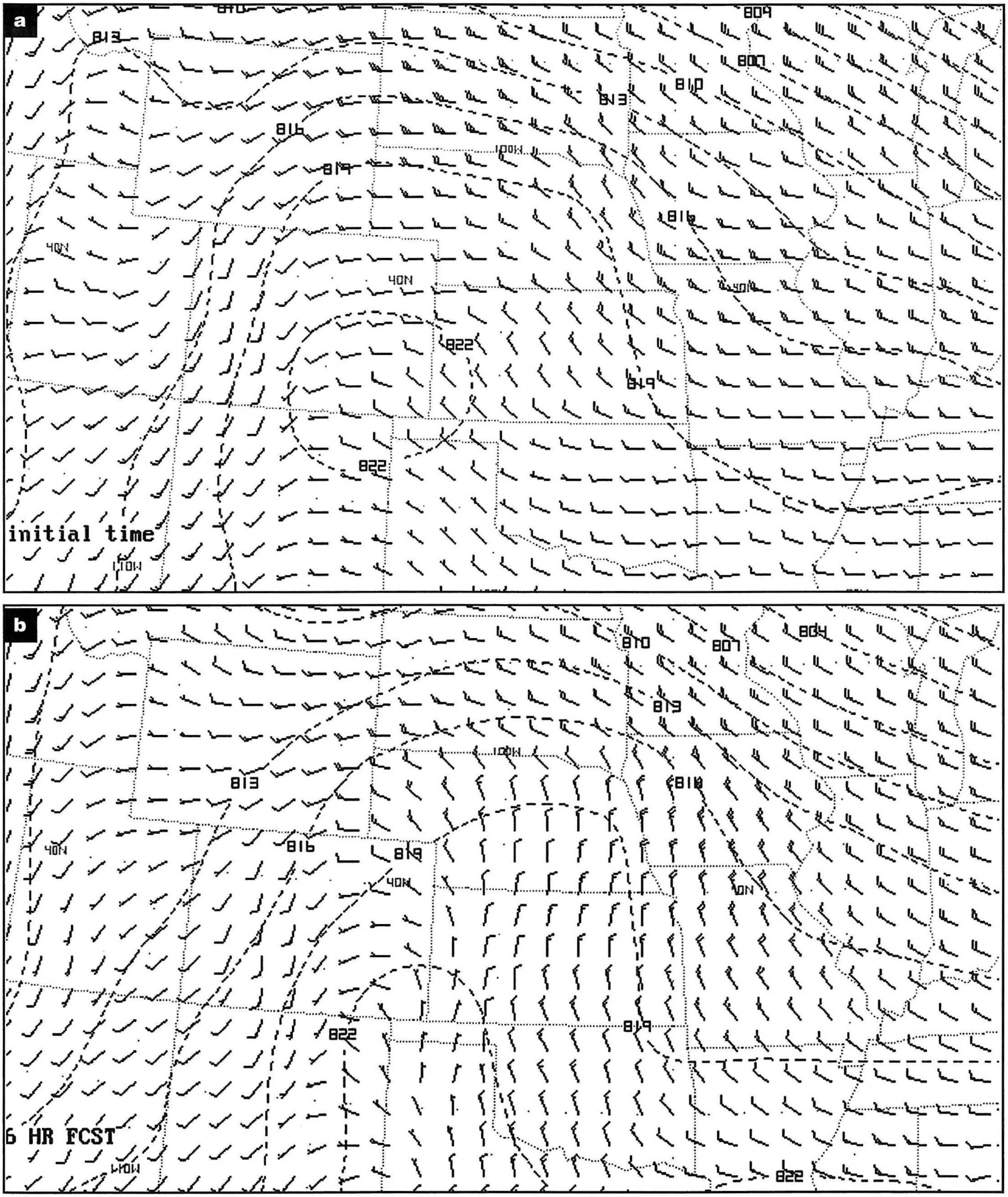

Fig. 14. (a) Eta 0000 UTC 7 August 1999 objective analysis of the Corfidi vectors overlaid with the 850 mb to 300 mb thickness (wind in kt, dashed lines = thickness); (b) Eta model 6-h forecast valid at 0600 UTC 7 August 1999.

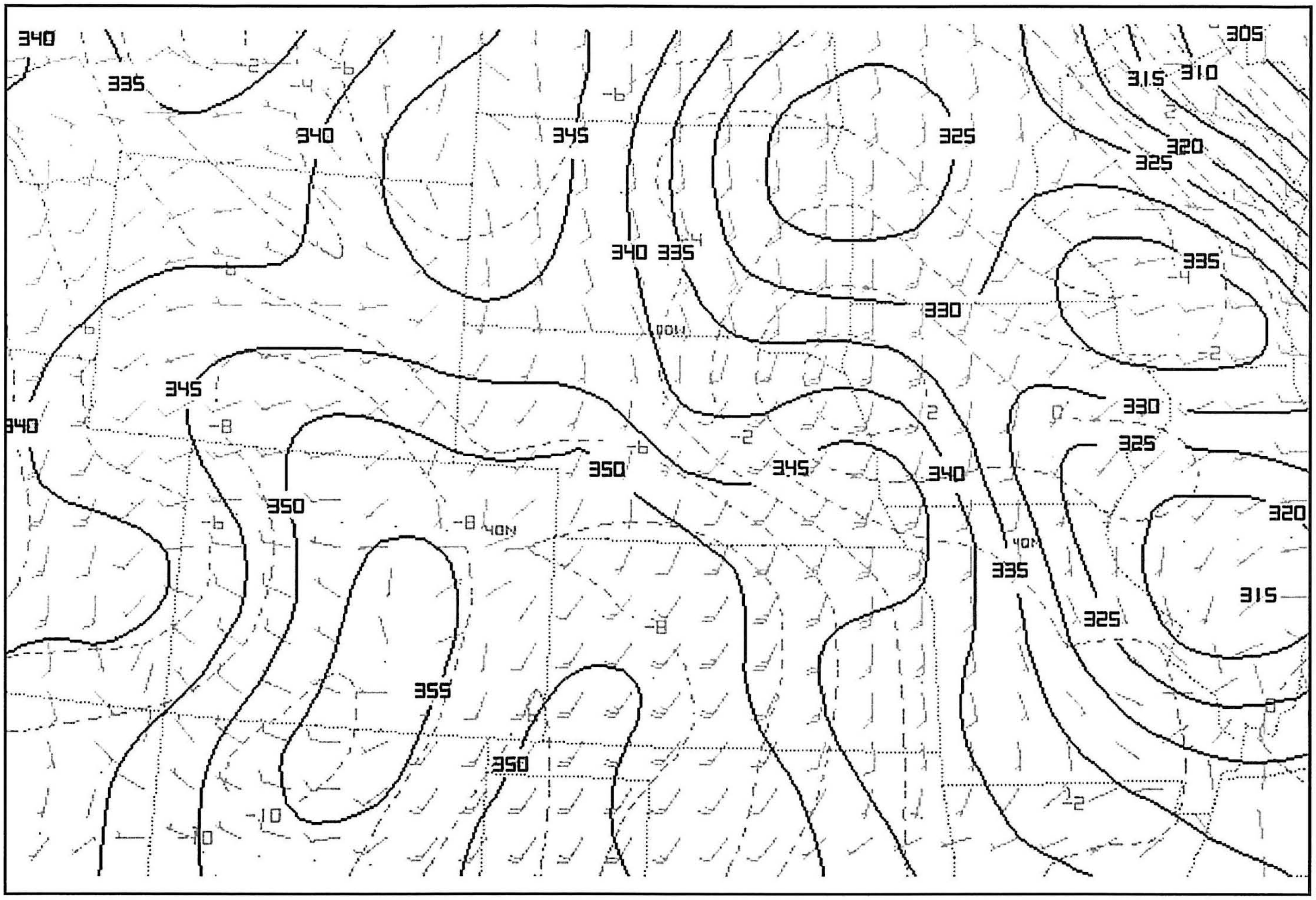

Fig. 15. Objective initial analysis of 850-mb θe, wind, and lifted index, valid 0000 UTC 7 August 1999 (solid lines = θe in ° K, dashed lines = lifted index in °C).

mean cloud layer wind vector across Dodge, Burt, and Washington Counties. Note the continued regeneration of thunderstorms in Platte County, even at 0557 UTC 7 August. These storms were generally along or on the northern fringe of the flash flood watch. The other area consisted of two isolated thunderstorm clusters that developed to the southwest of Lincoln (Lancaster County) in south central Nebraska and eventually merged with the larger main precipitation area. The first cell developed around 2300 UTC 6 August and moved northeast across Lancaster County. There were no severe weather reports with this cell until it merged with an outflow boundary of the northern cluster of storms. A second isolated thunderstorm cluster developed around 0230 UTC 7 August farther southwest over south central Nebraska near Hebron, taking the same path toward Lincoln. Storms to the south exhibited splitting cell characteristics where the inflow was closer to being surface based.

Only isolated severe weather events were reported. Nickel-sized hail occurred at 0130 UTC 7 August at Ashland in Saunders County and a 52 kt thunderstorm wind was reported at 0210 UTC in Papillion in Sarpy County. Three other damaging wind reports occurred in Mills and Montgomery counties in southwest Iowa between 0415 UTC and 0640 UTC (Fig. 20). Cunning (1986) and Watson et al. (1988) documented that some thunderstorms transform nocturnally from severe weather producers to heavy rain producers. It was reasoned that this transition occurred due to the thunderstorm system decoupling from cooling of the boundary layer, and from the fact that as the convective system expands, mesoscale circulations develop. These mesoscale circulations moisten the local environment, reduce the wind shear and increase the precipitation efficiency of the thunderstorms (Marwitz 1972).

6. Storm Propagation and the Heavy Rain Event

As summarized by Weaver (1979) at least three factors contribute to storm motion; the relative strengths of the mean cloud layer wind vector, thunderstorm-induced convergence, and the orientation, strength, and movement of mesoscale boundary-layer convergence regions. The orientation and persistence of the cluster of storms in east central Nebraska were indicative of pronounced convergence north of the surface front. In addition, the outflow due to evaporative cooling from the individual storms pushed southward to reinforce the existing surface front. As a result, the frontal boundary across southern Nebraska remained quasi-stationary rather than

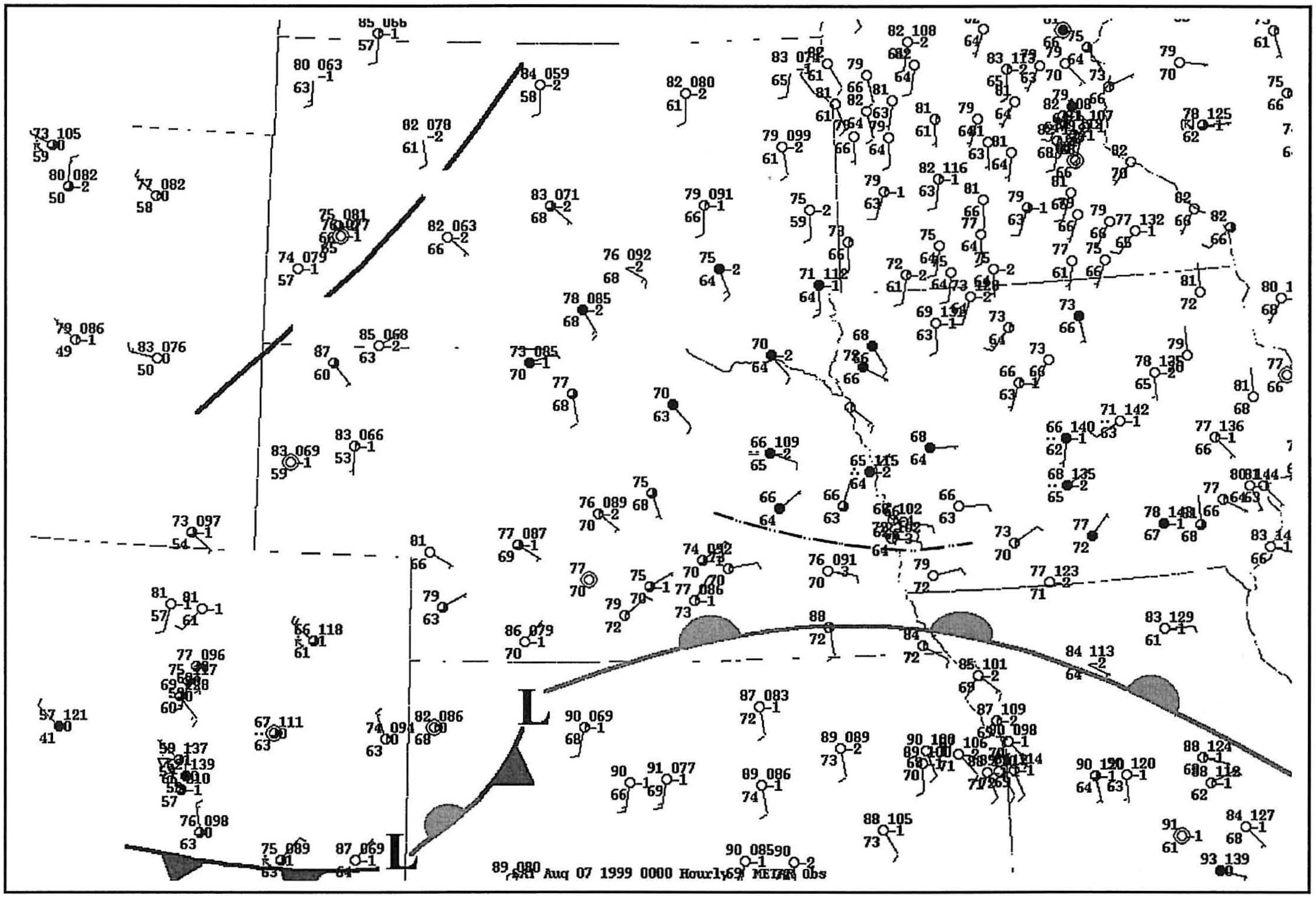

Fig. 16. Subjective surface analysis valid 0000 UTC 7 August 1999. Station model in standard notation.

moving northward. The MBEs of the cluster of thunderstorms over east central Nebraska and western Iowa generally traveled from a direction between 240° and 270° at around 20 to 25 kt for much of the nine-hour period between 2100 UTC 6 August and 0530 UTC 7 August. New cell development, which was opposite to the mean cell motion, occurred on the rear flank of the system. This active convection occurred south of Norfolk (OFK) and was anchored over Platte County for an extended period of time (Fig. 19). Chappell (1986) illustrated that the effect of new cell development opposite to the mean cell motion was to create a quasi-stationary system. Noting the quasi-stationary character of the system could enable the forecaster to verify and adjust the area included in the flash flood watch. Utilizing a time lapse of the WSR-88D base reflectivity products, initially the cells developed and moved northeast with the mean cloud layer wind vector. As the cells grew to maturity they produced excessive rainfall and flash flooding. By 0150 UTC 7 August, Scribner in Dodge County, about 40 miles northeast of Columbus, had reported 4.8 inches of rainfall and flash flooding. Scribner's rainfall for the event totaled 7.8 inches with peaks in rainfall between 2200 UTC 6 August and 0000 UTC 7 August and between 0400 and 0500 UTC 7 August. Through 0530 UTC, a time lapse of the STP product (not shown) indicated that the east or northeast movement dominated the storms producing the heaviest rain. However, after 0600 UTC the STP time lapse showed a more southward movement of the MBEs. A succession of storms that produced heavy rain over Washington County moved southeast into Douglas and Pottawattamie counties. Omaha's Eppley Airfield located in northeast Douglas County received 10.48 inches of rain, peaking between 0600 UTC and 0800 UTC when 5.34 inches fell. The VWP product showed the trend of the wind profiles during the night (Fig. 13). Using the vector moment approach of Corfidi et al. (1996) the forecaster could have observed the veering of the LLJ and a more westerly component of the cloud layer advection winds. Thus, the utilization of the VWP trend between 0400 UTC and 0800 UTC suggested that an increased southward component of MBE movement would occur.

Satellite precipitation estimates were issued by the Satellite Analysis Branch/National Environmental Satellite, Data and Information Service (NESDIS) between 0000 and 0600 UTC 7 August highlighting the heavy rainfall amounts. For more information on satellite precipitation estimates see http://www.ssd.noaa.gov/PS/PCPN/program.html. Other sources of rainfall estimates included those generated by the WSR-88D, the

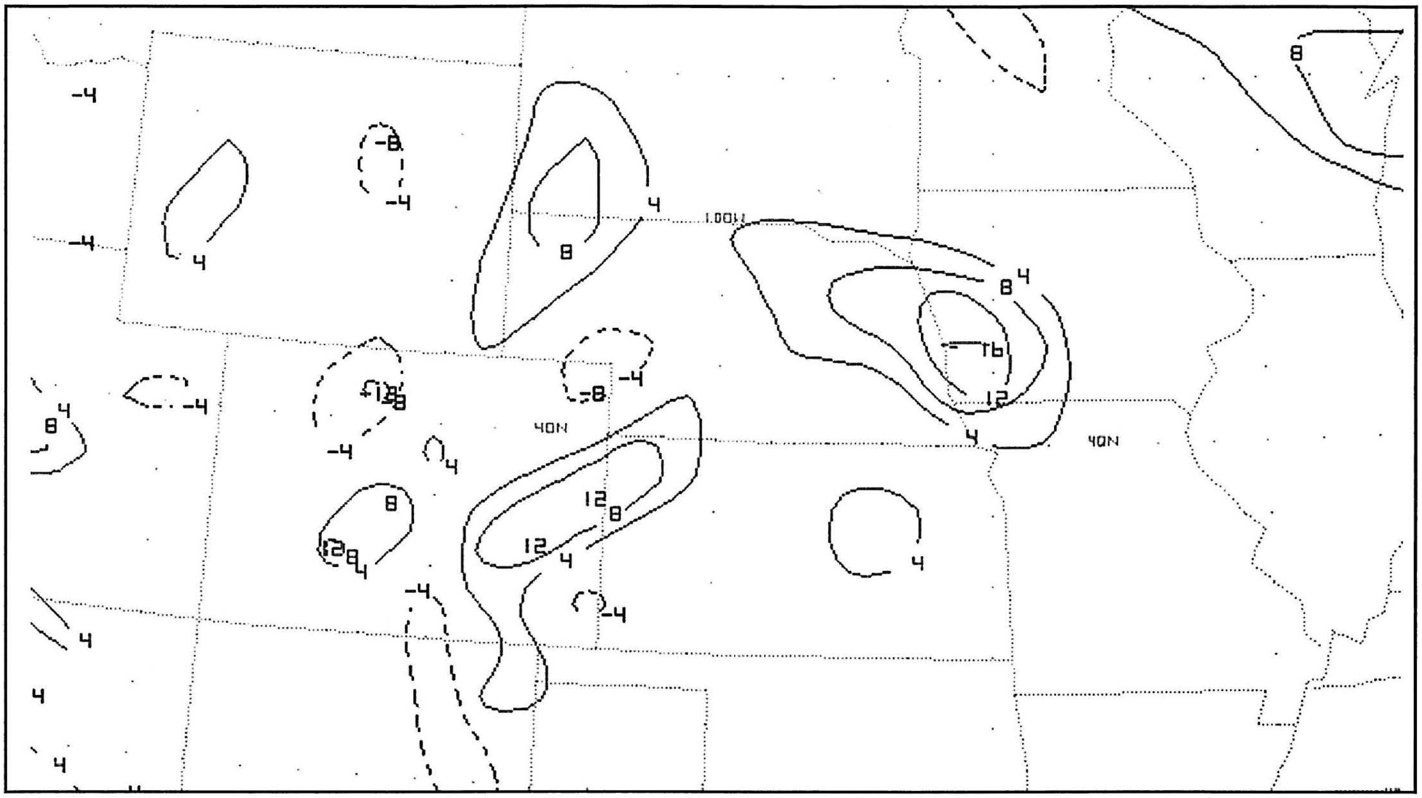

Fig. 17. Objective initial analysis of 850 mb to 700 mb Petterssen frontogenesis at 2100 UTC 6 August 1999. Solid lines indicate frontogenesis and dashed lines indicate frontolysis. Contoured every 4x10^{-10} K m^{-1}s^{-1}.

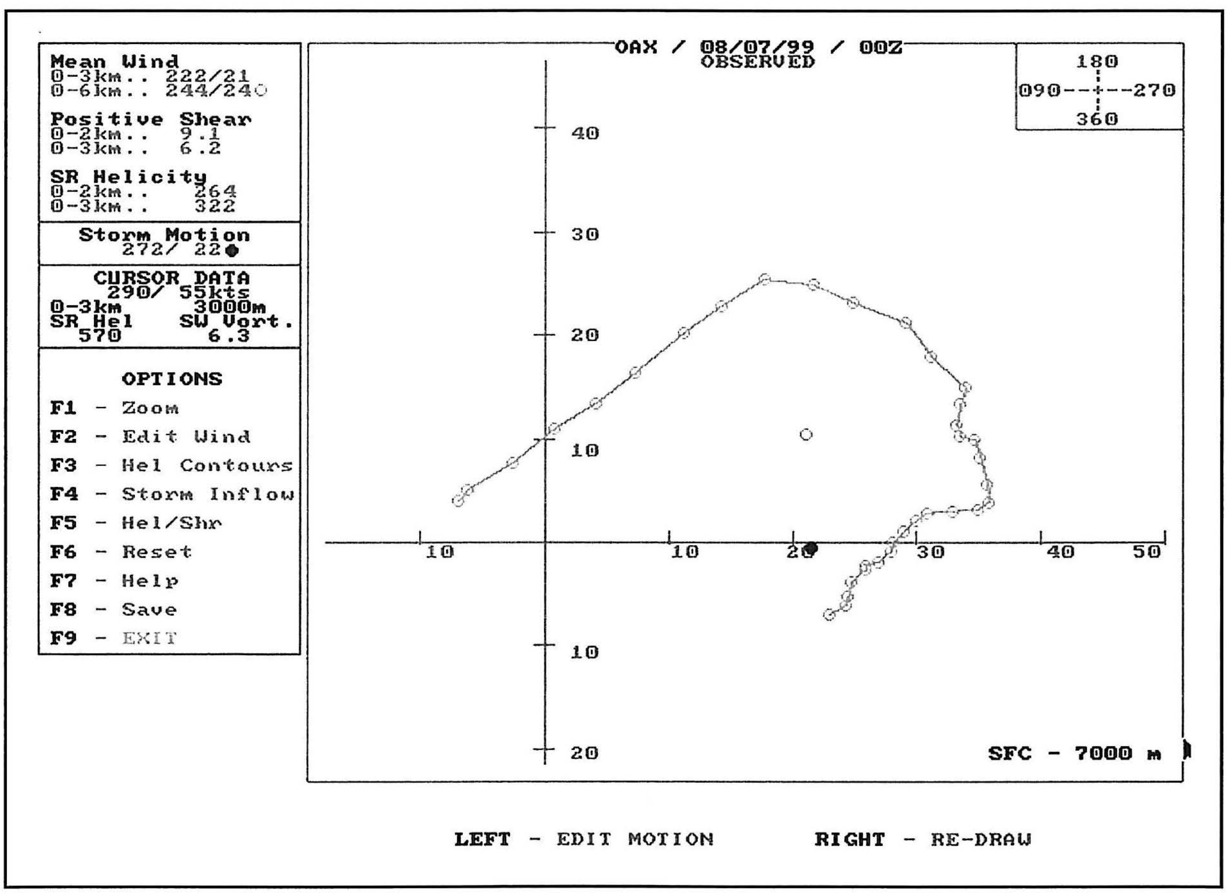

Fig. 18. Observed Omaha, Nebraska (OAX) hodograph at 0000 UTC 7 August 1999.

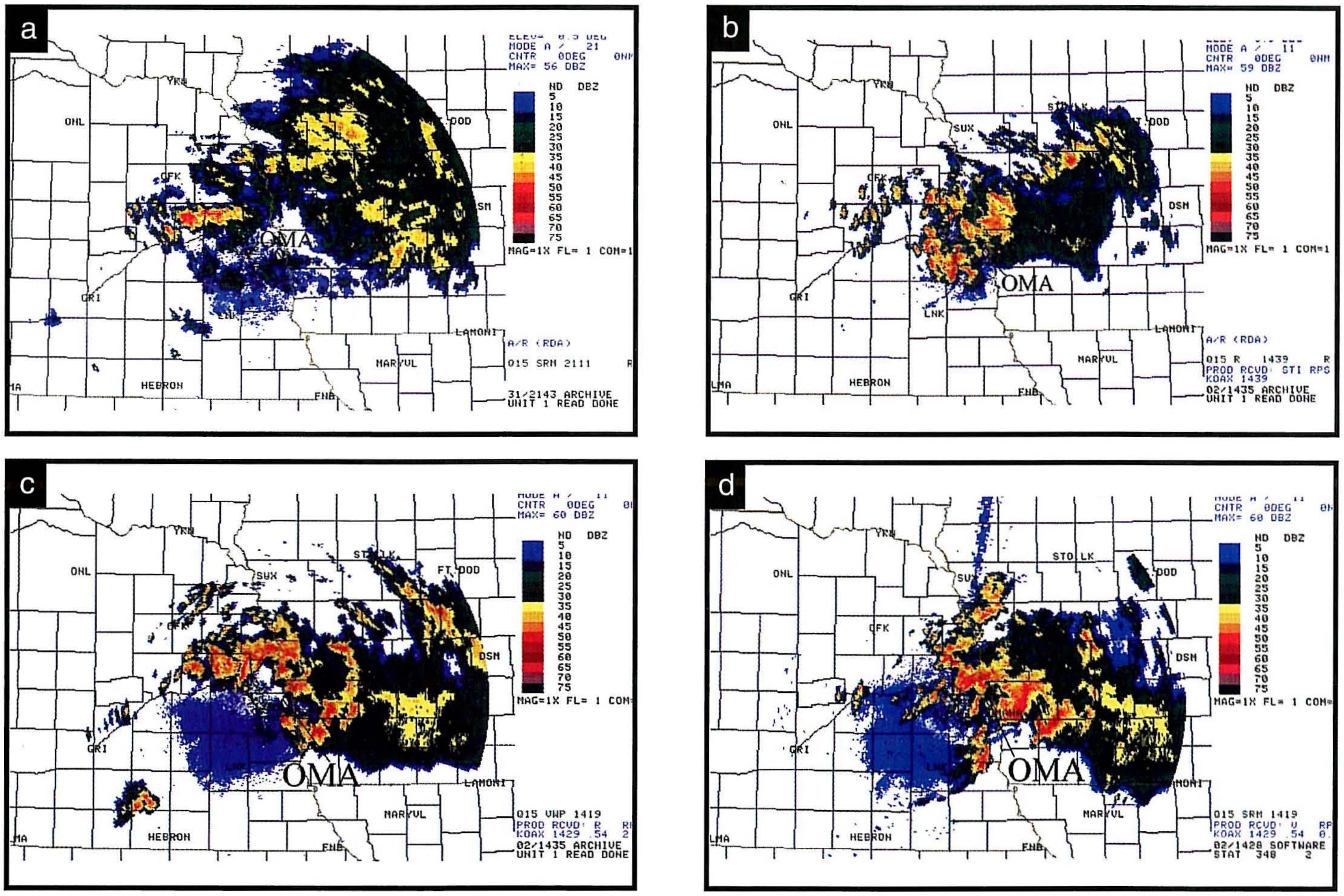

Fig. 19. WSR-88D equivalent reflectivity (dBZ) images. Radar located at Valley, Nebraska, which is just west of Omaha. Elevation angle is 0.5°. Range is 124.0 nautical miles (n mi). Resolution is 0.54 n mi: (a) 2249 UTC 6 August 1999; (b) 0158 UTC 7 August 1999; (c) 0357 UTC 7 August 1999; and (d) 0557 UTC 7 August 1999.

ALERT system, cooperative observer reports, and those of the automated surface observing sites. Together, these indicated the very heavy rainfall rates between 0400 UTC and 0900 UTC.

Rainfall rate was defined by Doswell (1996) with the following equation:

$$R = Ewq \qquad (1)$$

The rainfall rate (R) is a function of the precipitation efficiency (E), the ascent rate (w), and the mixing ratio of the rising air (q). One can only speculate as to which variables contributed the most to increase rainfall rates during this heavy rain event. Mixing ratios at 850 mb during the event ranged from 12 to 16 g kg^{-1} (not shown). The environment was nearly saturated and evaporation minimal. Upward vertical motion fields were forecast to remain about the same intensity with a maximum over eastern Nebraska between 0000 UTC and 0600 UTC, however the location of maximum upward vertical motion shifted slightly east into Iowa and the magnitude of the maximum increased. Past studies (Caracena et al. 1979; Maddox et al. 1978; Petersen et al. 1999 and others) illustrate the presence of a moist warm layer. The warm cloud depth of 4.1 km enhanced the growth of water droplets by coalescence, enhancing precipitation efficiency of the environment (personal communication, Chappell, C.F., 1994). The rainfall estimates in the SPEs ranged from 1.8 inches to nearly 3 inches for a three-hour period and 0.8 to 1.6 inches for hourly rates. Through 0559 UTC the WSR-88D STP estimates were greatest over northern Dodge County and southern Burt County, with a large area of 4 inches or more (Fig. 21).

After 0530 UTC there was a gradual change in the storm propagation. The primary anchor of the system continued to be further west where new cells developed near Columbus in Platte County. A secondary mesoscale anchor focused new cell development over Washington County in the most active portion of the convective system. These cells appeared to propagate to the south with their resultant system movement to the southeast. The 1200 UTC 7 August WSR-88D STP product shows the much larger area of six inches or more through Washington County (Fig. 22). This fits the conceptual model of Corfidi (1996) (which is based on landmark concepts on convective system motion from Newton and Katz 1958; Newton and Newton 1959; Chappell 1986; and Shi and Scofield 1987), which relates the mean flow in the cloud layer, the propagation component and movement of the MBE (Fig. 23). This change in the movement

Fig. 20. Severe weather reports in eastern Nebraska and western Iowa from 0000 UTC to 1200 UTC 7 August 1999. "H" indicates a severe hail report and "W" indicates a severe wind report.

of the MBEs resulted in increased mergers and accretion of cells. The 1200 UTC STP product illustrates the southeast progression of rainfall in excess of six inches into Douglas, Pottawattamie, northern Mills, and northern Montgomery counties.

In most cases, warnings were issued based on a comparison of the STP product to the MBRFC flash flood guidance. Whenever the guidance was at least equaled, then it was determined that any additional rain would be flood-producing runoff. Thus, when additional thunderstorms approached saturated areas, WSR-88D rainfall rate products of one-hour precipitation (OHP) and three-hour precipitation (THP) were examined. If the rainfall rate was significant and no decrease in intensity was expected, a flash flood warning was issued. Time lapses of STP and OHP were very important to monitor.

7. Hydrologic Conditions

The hydrologic conditions prior to the flash flood event were relatively dry as the month of July was unusually hot and humid with subnormal rainfall (Office of Hydrology 1999). July regional rainfall estimates as a percentage of normal ranged from 50% to 70% for the month in east central Nebraska and close to 100% of normal for western Iowa. The three-hour flash flood guidance from the Missouri River Basin Forecast Center ranged from two and a half to three inches. Values in this range are common in a dry soil environment.

The ALERT network with its 19 river gages provided useful real-time rainfall data and stream readings to operational forecasters at the National Weather Service at Omaha/Valley. The network had gage sites along the Big Papillion Creek, the north, west, and south branch of the Papillion Creek, the Little Papillion Creek, Thomas Creek, and Cole Creek (Fig. 2). The 24-hour rain that is considered a 100-year rain (Hershfield 1961) is six and one half inches (Fig. 24). The ALERT rain gage network supplemented the WSR-88D estimates with 5-minute updates. Seven of the nineteen gages on the ALERT system exceeded this 100-year rain threshold. The hydrograph at the Cole Creek site in midtown Omaha (Fig. 4) showed the "flashiness" of the five-mile north-south creek. Creek readings rose from just 5 to 6 ft during the evening of 6 August 1999, to above the flood stage of 18 ft at 0746 UTC 7 August 1999, to a crest of 20.28 ft at 0849 UTC, then back below flood stage at 1024 UTC. In addition to these sites, the Bell Creek in Washington County, and the Mosquito and Keg Creeks in Pottawattamie County had significant flooding. These rain gage and hydrograph displays help in the flash flood forecast and warning process.

8. Summary and Conclusions

Portions of the most heavily populated areas of eastern Nebraska and western Iowa received inundating rains that produced flash flooding, extensive damage, and one fatality during the nighttime hours of 6-7 August 1999. The heavy rain and subsequent flash flooding was the result of regeneration of convective cells north of a surface warm front. In addition to the training of convective cells for a prolonged period, rainfall rates of the system peaked between 0500 UTC and 0700 UTC and resulted in an area of rainfall in excess of the expected 100-year 24-hour rainfalls.

A number of synoptic and mesoscale observations resulted in the timely issuance of the flash flood watch. The forecaster analyzed the surface map and was alerted to the presence of an west-east surface warm front over southern Nebraska. A weak shortwave trough associated with on-going loosely organized convection was exiting the area and gave the forecaster confidence that convection would not be hindered by the existence of a midlevel cap of warm air. Examination of SPC's 2100 UTC RUC composite chart showed that the maximum of warm advection was in east central Nebraska, however the best instability was still to the west of this area, suggesting the possibility of back-building storms (Glass et al. 1995). The 2100 UTC RUC K index values were around 40 and were forecast to increase to around 44 in southeast Nebraska between 0300 UTC and 0600 UTC. Precipitable water values were around 2.00 inches. Both parameters exceeded the mean values associated with flash flooding by Glass et al. (1995) and Maddox et al. (1979). GOES 6.7 micron water vapor imagery confirmed the existence of a moisture plume from the ITCZ into the central Plains and the availability of deep tropical moisture. Strong, moist, low-level warm inflow existed and was forecast to continue into the night. The forecaster, based on these synoptic and mesoscale observations determined that a frontal type flash flood event was possible. Meteorological conditions suggested that rainfall intensities could exceed the 2.5 to 3.0 inch 3-hour flash flood guidance rainfall threshold values. At 2310 UTC, a flash flood watch was issued for eastern Nebraska and parts of southwest Iowa.

The area was on the periphery of a midlevel anticyclone in the southeastern United States, and the approach of a weak mid-tropospheric shortwave assisted in the initiation and continuation of a favorable environment for convection (Maddox et al. 1979). Stronger dynamic support was also present due to warm advection and the heaviest rain fell in the gradient to the south of the maximum upper-level divergence. Further examination of the current and expected wind profiles showed that the low to midlevel flow was nearly unidirectional with some veering aloft. Frontogenesis existed in the vicinity of the maximum warm advection and the area of maximum mixing ratio flux convergence enhanced upward motion.

The initial convection was focused in a linear pattern along an axis of the 850-300mb mean wind vector. Farther to the south, the convection initiation was isolated in nature. The isolated storms failed to produce severe weather until they merged with outflow from the larger convective area. The storms that formed in a line farther to the north produced occasional severe weather with mainly marginal high wind reports. Heavy rain was the primary weather threat during the event. The MBEs of the system were progressive during a period in excess of 10 hours as winds were nearly parallel from the surface through the lower and mid troposphere. Increased storm mergers were noted as propagation changed from southwest to south during the peak heavy rain period. The resultant initial heavy rain pattern formed as a west to east linear pattern in eastern Nebraska then transitioned to a northwest to southeast pattern from eastern Nebraska into western Iowa. The utilization of near real-time WSR-88D STP, OHP, and THP products, MBRFC flash flood guidance, SPE's, and ALERT rain gage and hydrograph displays, increased the forecasters' ability to issue timely flash flood warnings during this nocturnal heavy rain event.

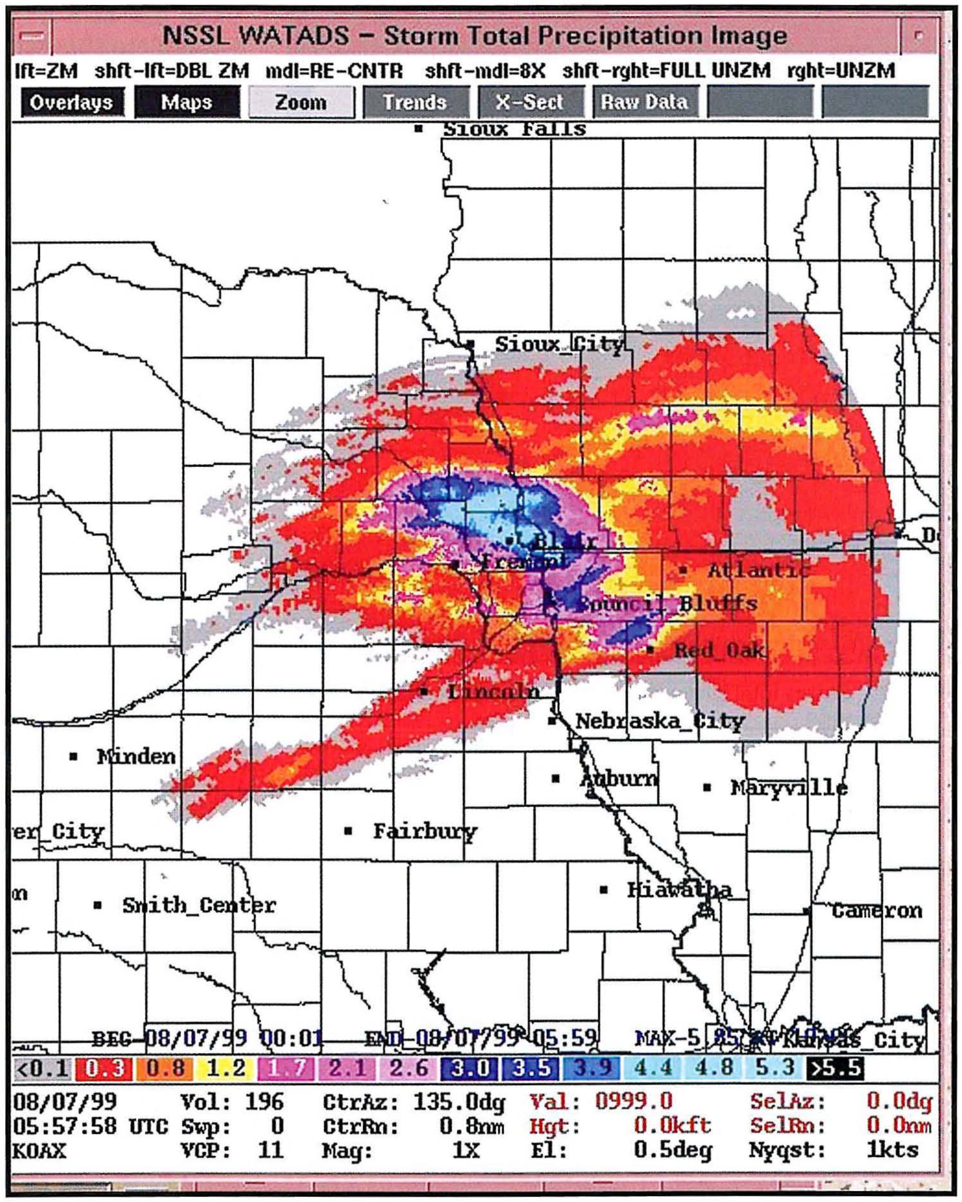

Fig. 21. Storm total precipitation in inches through 0559 UTC 7 August 1999.

In summary, there are a number of parameters from this heavy rain event that are documented in other studies (e.g., Maddox et al. 1978; Caracena et al. 1979; Schwartz et al. 1990; Junker et al. 1999; Petersen et al. 1999; and others) that would be helpful references in the anticipation of a heavy rain and subsequent flash flooding event. Rochette and Moore (1996) identified several of these parameters in their north central Missouri case from 6 June 1993. Their elevated mesoscale convective system case listed ten key features that were also common to this event.

1) the presence of a slow-moving east-west oriented surface front;

2) the presence of a low-level (850 mb) wind maximum, oriented normal to the surface boundary;

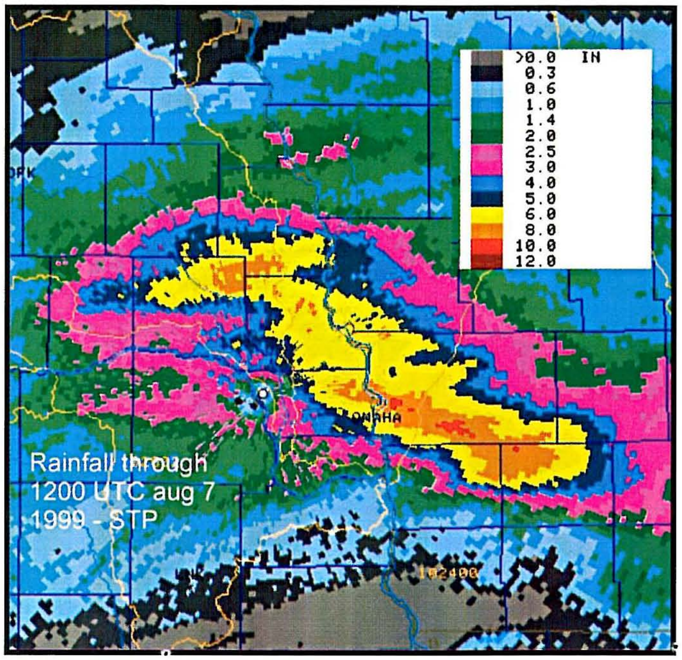

Fig. 22. Storm total precipitation in inches through 1200 UTC 7 August 1999.

3) deep moisture available (both at the low and mid-levels), in and upstream of the focus region;

4) a gradient of low-level θe over the focus region;

5) a maximum of low-level temperature/θe advection in the focus region;

6) an elevated layer of convective instability over a stable boundary;

7) a low-level maximum of moisture convergence in/upstream of the focus region;

8) a 500-mb ridge over the focus region;

9) a weak 500-mb shortwave upstream of the focus region; and

10) an area of upper-level (300-200mb) divergence over/north of the focus region.

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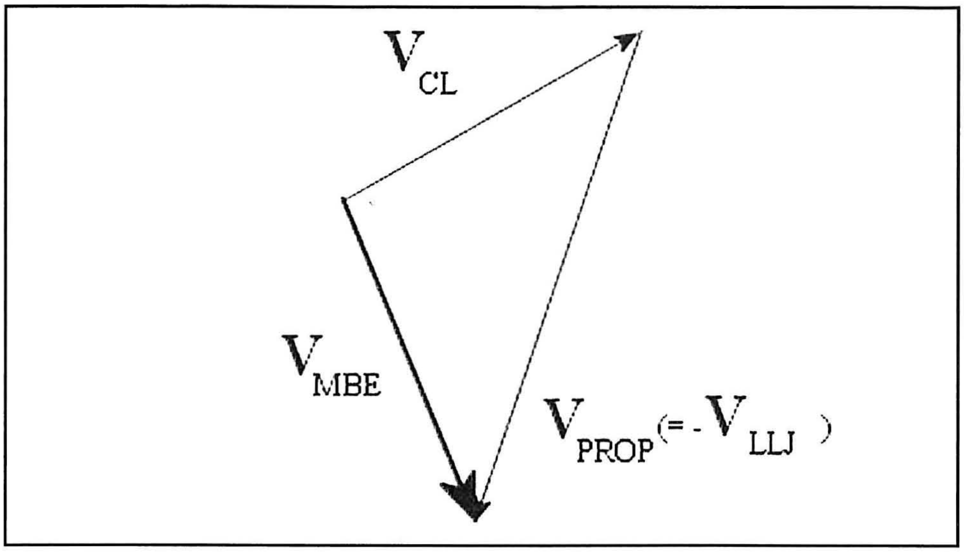

Fig. 23. Conceptual model of MBE movement (VMBE). The VMBE is the vector sum of the mean flow in the cloud layer (VCL) and the propagation component (VPROP). The magnitude and direction of VPROP are assumed to be equal and opposite to those of the low-level jet (VLLJ) (Corfidi et al. 1996).

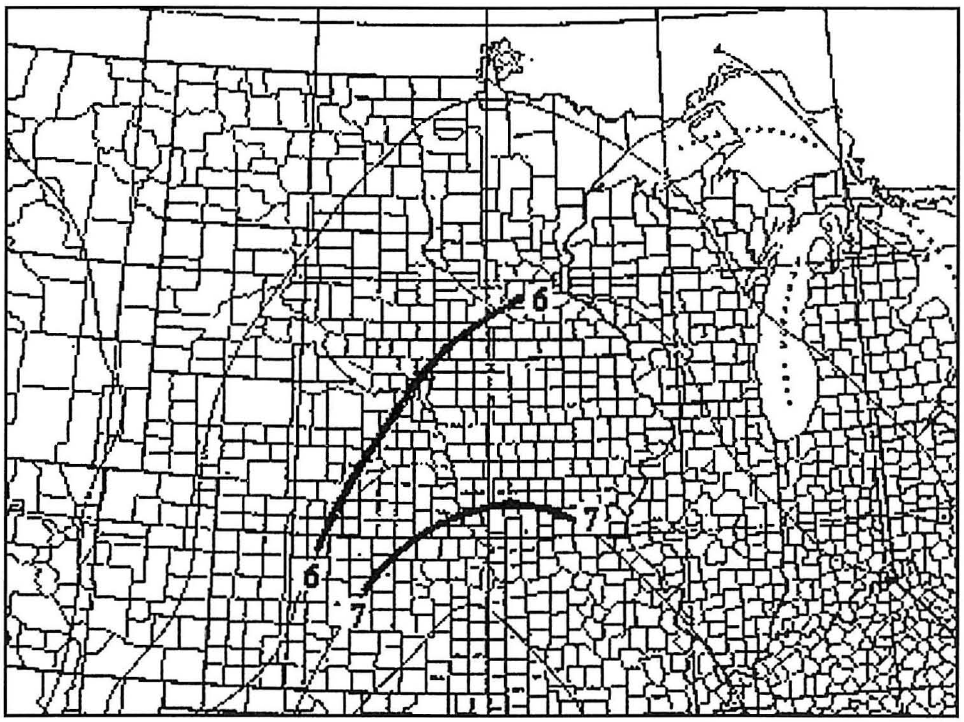

Fig. 24. 100-year 24-hour rainfall in inches (Hershfield 1961).

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