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OUTFLOW FROM A NOCTURNAL THUNDERSTORM

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Meteorology Section
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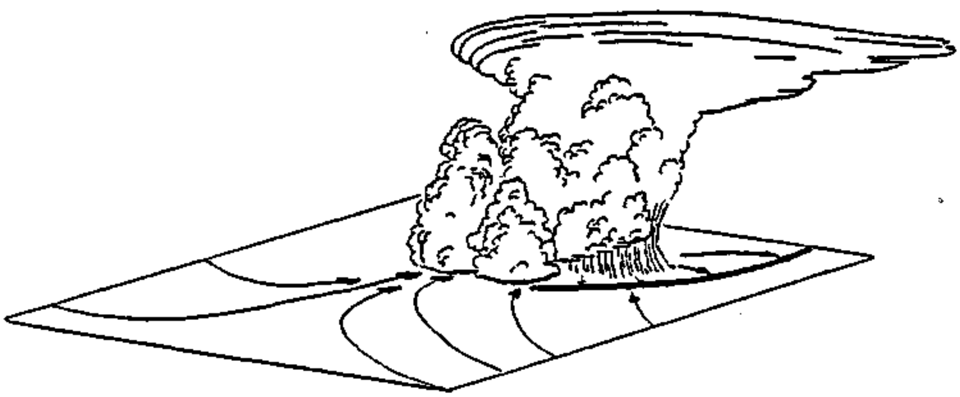

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ABSTRACT

An investigation of a dry nocturnal gust front moving over a dense network of meteorological instruments in east central Illinois is presented. The outflow was generated out of an eastward moving, organized storm system passing north of the network. Although no precipitation was measured in the network, a change from ambient to outflow air was observed in other meteorological parameters more than 100 km south of the point at which the outflow is estimated to have initiated.

ACKNOWLEDGMENTS

This report was prepared under the general supervision of Bernice Ackerman, Head of the Meteorology Section, State Water Survey Division, Illinois Institute of Natural Resources. Sincere thanks is given to the Field Observing Facility of the National Center for Atmospheric Research for the use of their PAM data in this study. Appreciation is extended also to Irene Conroy for her assistance in figure preparation, to the Graphic Arts staff of the Water Survey under the supervision of John Brother for their work, and to Rebecca Runge for typing the manuscript.

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INTRODUCTION

Perhaps one of the most frequently observed events during strong convective activity is the abrupt change in surface and near surface conditions due to the passage of a thunderstorm outflow. Commonly called a "gust front" because of the sudden surge in wind speed, signatures of its arrival are known well to even the most casual observer of weather. Large changes in wind direction, an abrupt increase in pressure, and a sudden drop in temperature, usually just prior to the onset of rainfall, are all typical characteristics of an outflow passage.

Previous research on storm outflows has been considerable (e.g., Byers and Braham, 1949; Tepper, 1950; Charba, 1974; and Goff, 1976). In general, these studies have investigated this phenomenon quite close to the thunderstorm by which it was generated. The characteristics of long-lived outflows, however, have received less attention. Purdom (1979) recently presented evidence using satellite photography that such outflows often may act as a triggering device for the growth of convective clouds well over 150 km ahead of the original storm. He found this to occur as outflow air moved into regions already covered by cumulus clouds. However, no development was noted in clear areas.

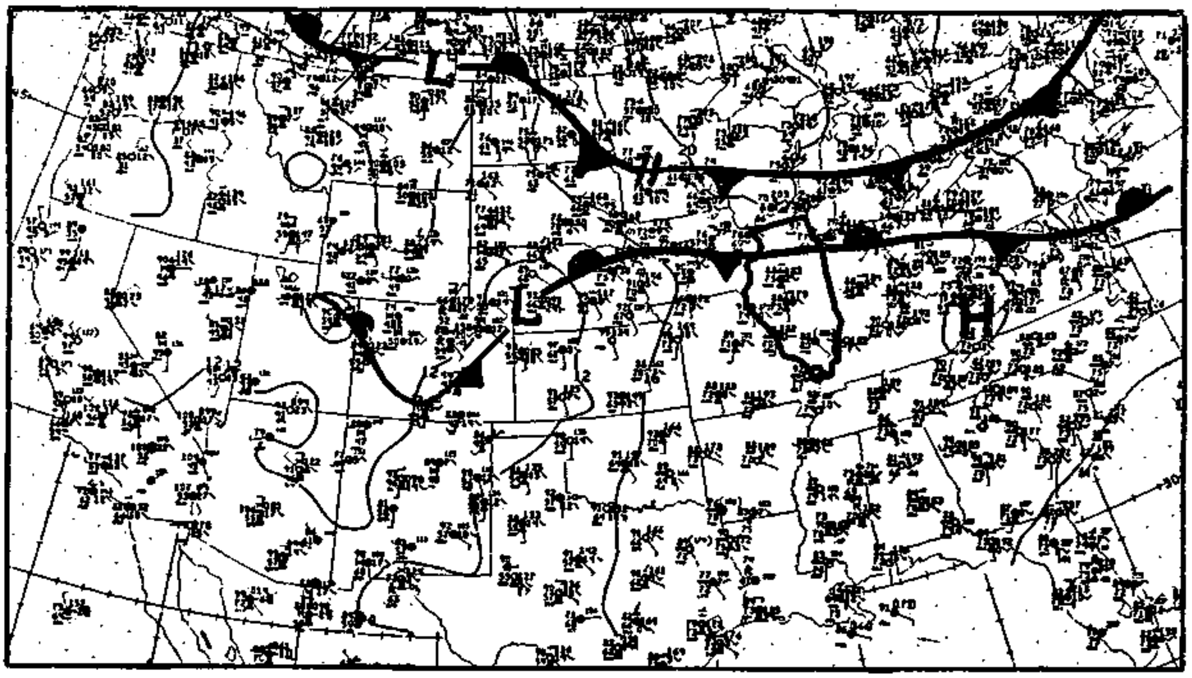
A unique opportunity to investigate a dry nocturnal gust front arose during the night of 8-9 August 1979. On this particular evening, the outflow from a severe thunderstorm moving eastward across northern Illinois produced a significant signature in the densely-instrumented network operated in this project, 100 km to the south. This network, which covered approximately 5400 km , was located just west of Champaign, Illinois. Surface field equipment included 260 raingages and 38 wind sensors all with analog recorders, 24 hygrothermographs, 13 microbarographs and the 27-station Portable Automated Mesonet (PAM) from the National Center for Atmospheric Research.

STORM CONDITIONS

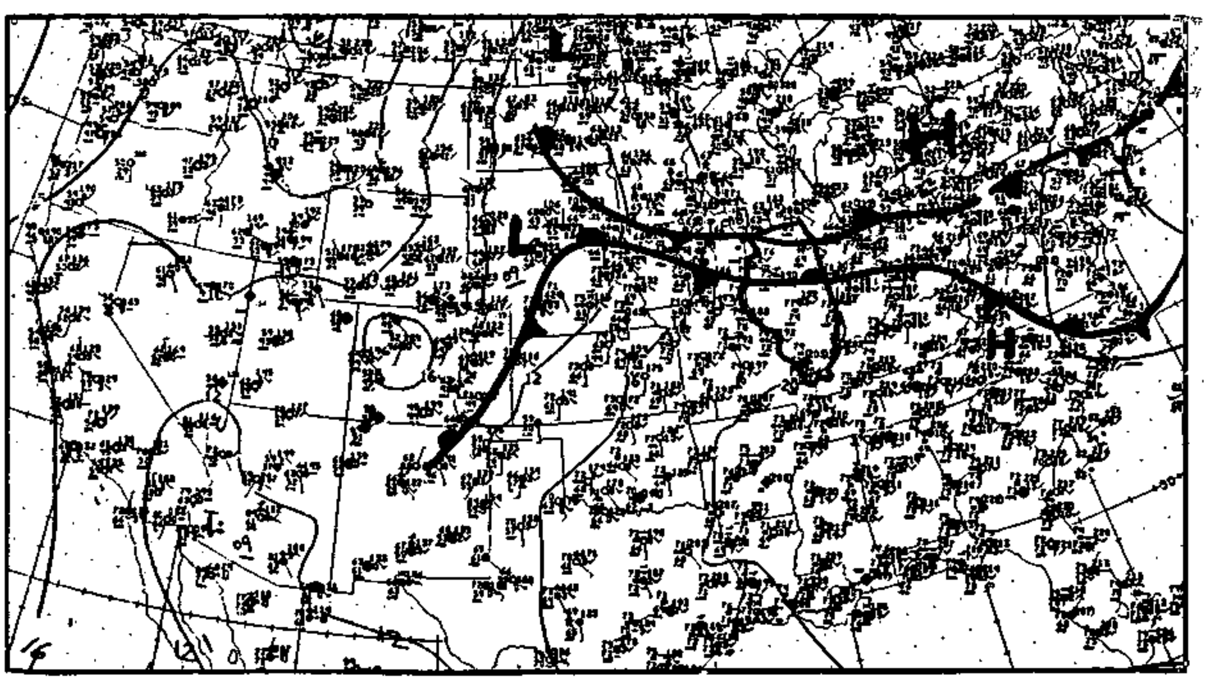
A large area of low pressure located at the surface over the northern and central Great Plains generally dominated the weather across the central United States early on 9 August (Fig. 1a-b). Two weak stationary fronts stretched eastward from this region across northern Illinois to the middle and northern Atlantic coasts. Moisture levels were relatively high south of the fronts due to deep southerly flow from the Gulf of Mexico coming around the west side of the high pressure over the southeast.

In the upper air, convergence occurred across northern Illinois at both the 850 mb and 700 mb level (Fig. 1c-f). Although very dry conditions existed over the region throughout the period at 700 mb and above (Fig. 1e-h), quite moist air at 850 mb overrode the surface frontal positions from the central Plains to Illinois. Despite the presence of ridging over most of Illinois, rain storms continued to develop between the two frontal boundaries as it moved eastward from Nebraska.

Strong convective activity existed across much of Nebraska on the afternoon of the 8th with less severe thunderstorms extending eastward into Iowa. Movement of the precipitation was towards the east at 12-15 m s^{-1}, the leading edge of which had reached Illinois by early evening. By midnight, an area of moderate storms covered northern Illinois and maintained its influence over the region for the next few hours (Fig. 2). It was outflow air from this area of storms that spread southward and was detected in the dense field network in central Illinois.

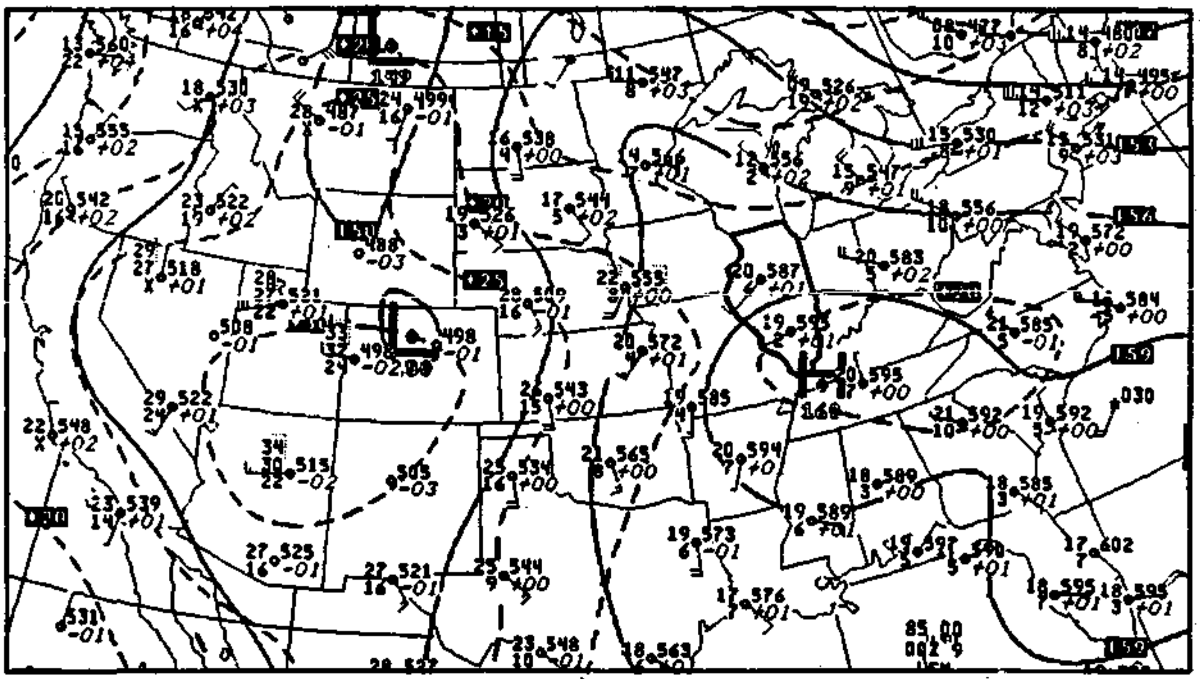


a. Surface chart at 1900 CDT on 8 August 1979.

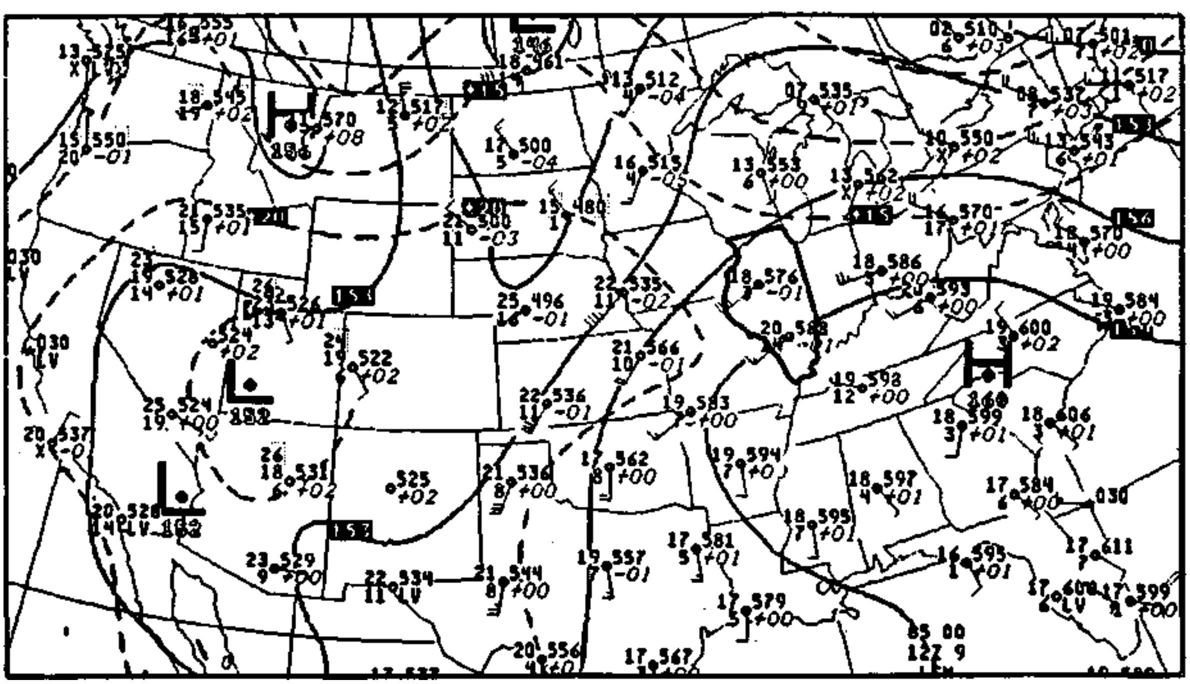


b. Surface chart at 0700 CDT on 9 August 1979.

Figure 1. Synoptic analyses on 8-9 August 1979.

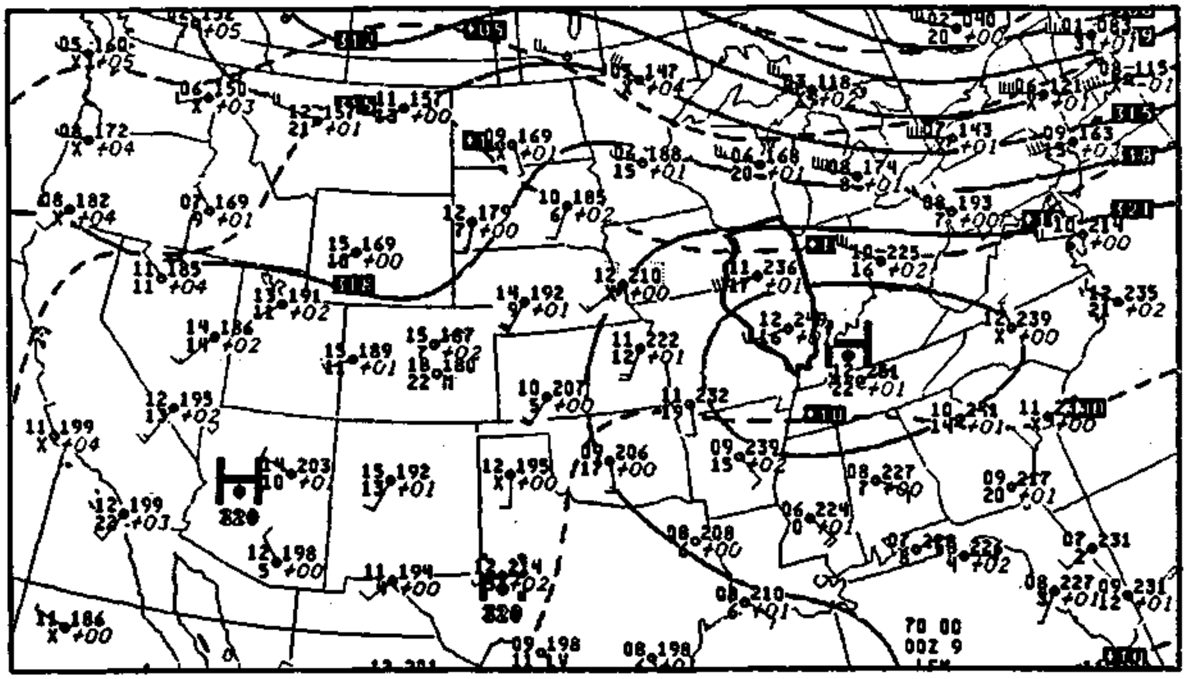


c. 850-mb chart at 1900 CDT on 8 August 1979.

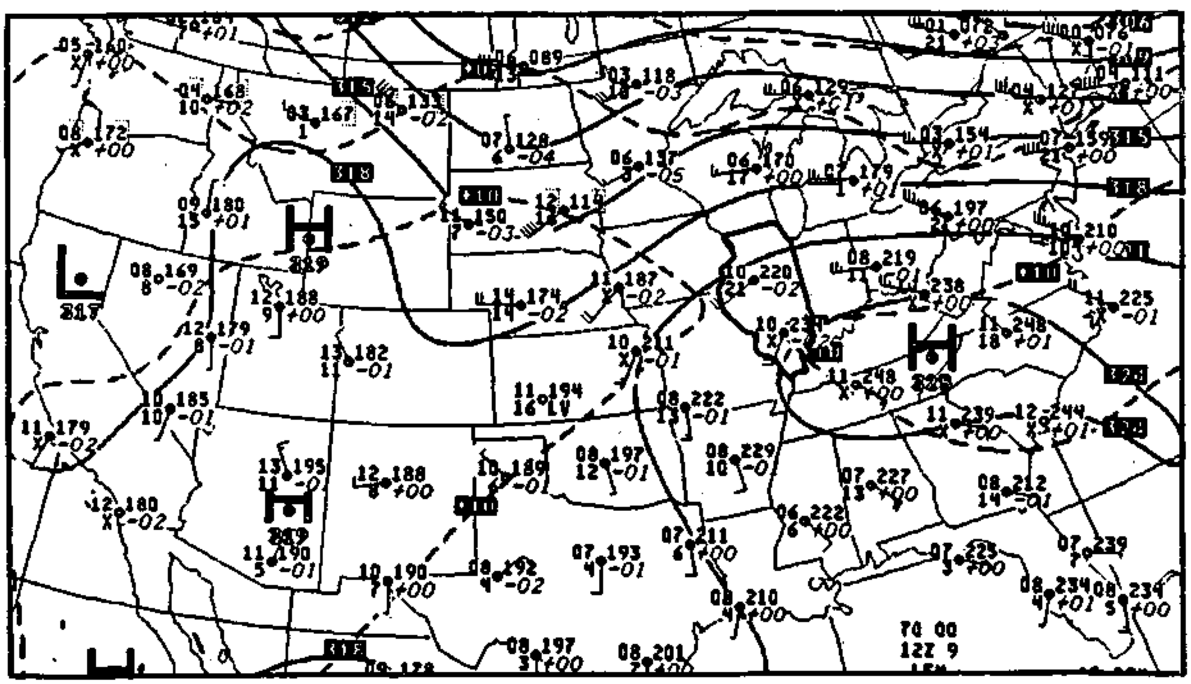


d. 850-mb chart at 0700 CDT on 9 August 1979.

Figure 1. (Continued)

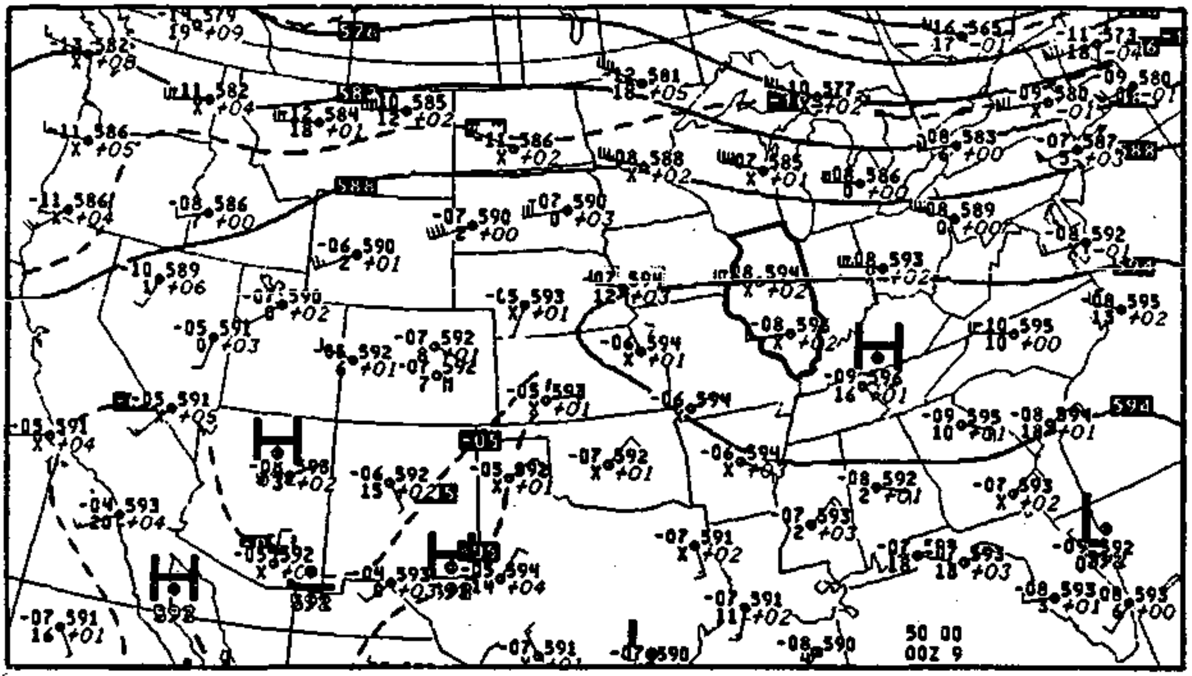


e. 700-mb chart at 1900 CDT on 8 August 1979.

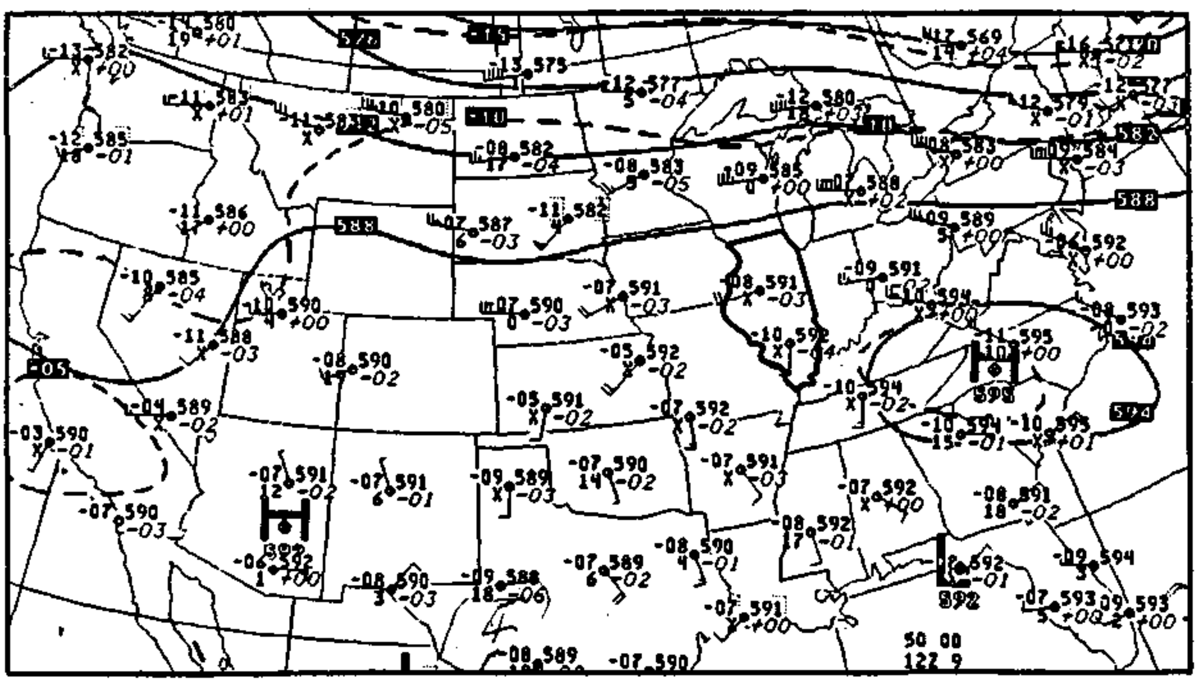


£. 700-mb chart at 0700 CDT on 9 August 1979.

Figure 1. (Continued).



h. 500-mb chart at 0700 CDT on 9 August 1979.



g. 500-mb chart at 1900 CDT on 8 August 1979.

Figure 1. (Concluded)

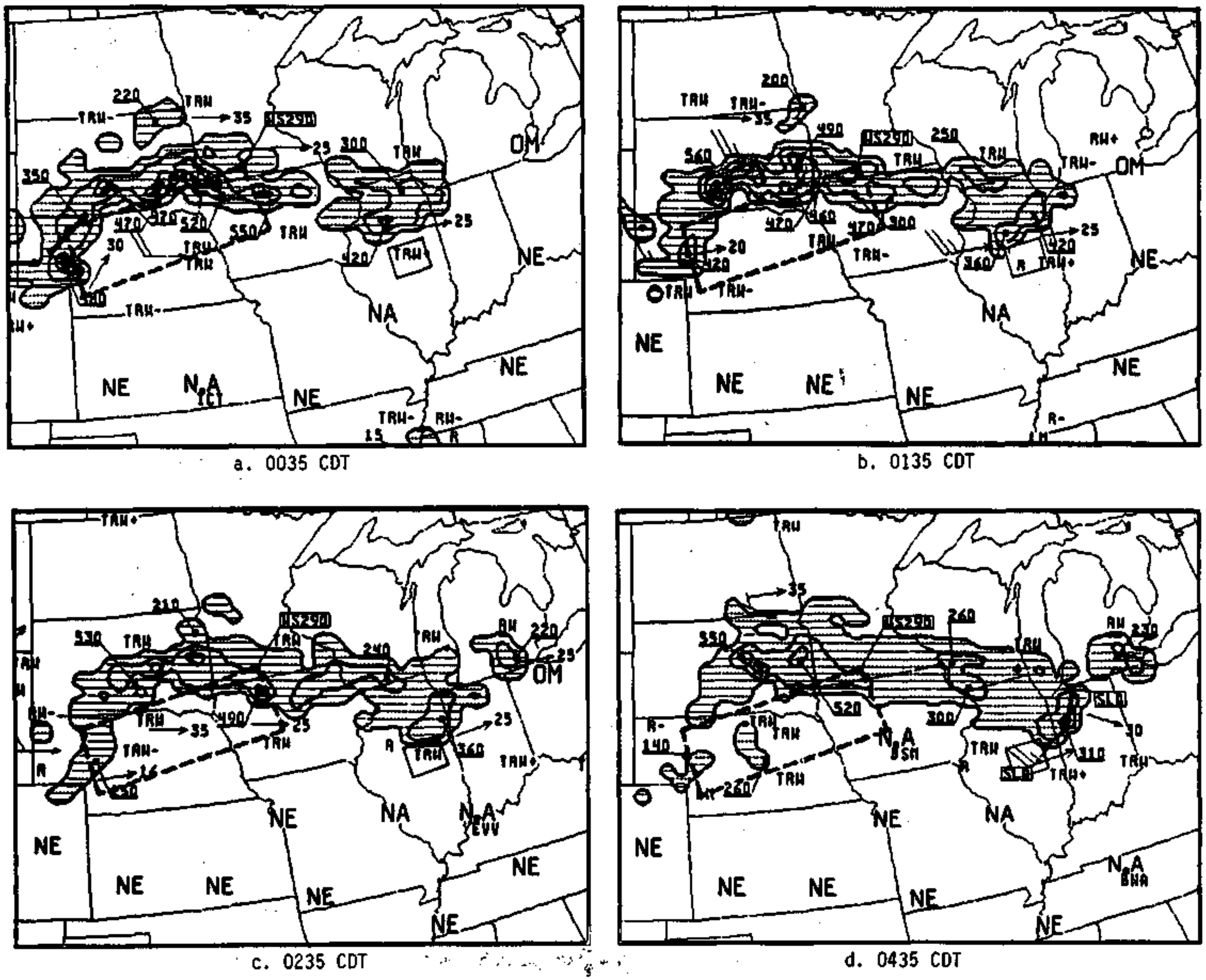


Figure 2. Radar summaries on 9 August 1979. The VIN network is indicated over east central Illinois.

Analyses of the digital record from an Illinois State Water Survey, 10-cm radar, operating near Joliet, Illinois are presented in Figure 3. Precipitation was observed moving east-southeastward across northern Illinois early on 9 August, with the strongest cells located along the southern edge of the rain band. At approximately 0130 CDT*, a small organized group of cells formed within the region of more intense showers. Intensities increased rapidly, maximizing around 0200. At this time the main cells were located 40-45 km north of the northwestern corner of the surface network.

Radar reflectivities were measured in excess of 50 dbz for at least 40 minutes, centered at 0200, and echoes reached 14.6 km. The cells decreased quickly in intensity after 0230, dissipating completely by 0310 by which time they had progressed to a point about 25 km north of the northeastern corner of the network.

METEOROLOGICAL FIELDS IN THE NETWORK

No precipitation was measured at any network station during the passage of the outflow from this system. However, strong changes in other meteorological parameters were observed which are characteristic of a gust front. The first indication of outflow air occurred just before 0250 in hygrothermograph measurements from the northernmost stations in the network. However, the best indicators of the gust front passage were found at wind sites farther south where a nearly instantaneous change in the wind occurred as stronger northerly flow replaced light southerly or nearly calm winds.

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*All times in this report are in Central Daylight Time.

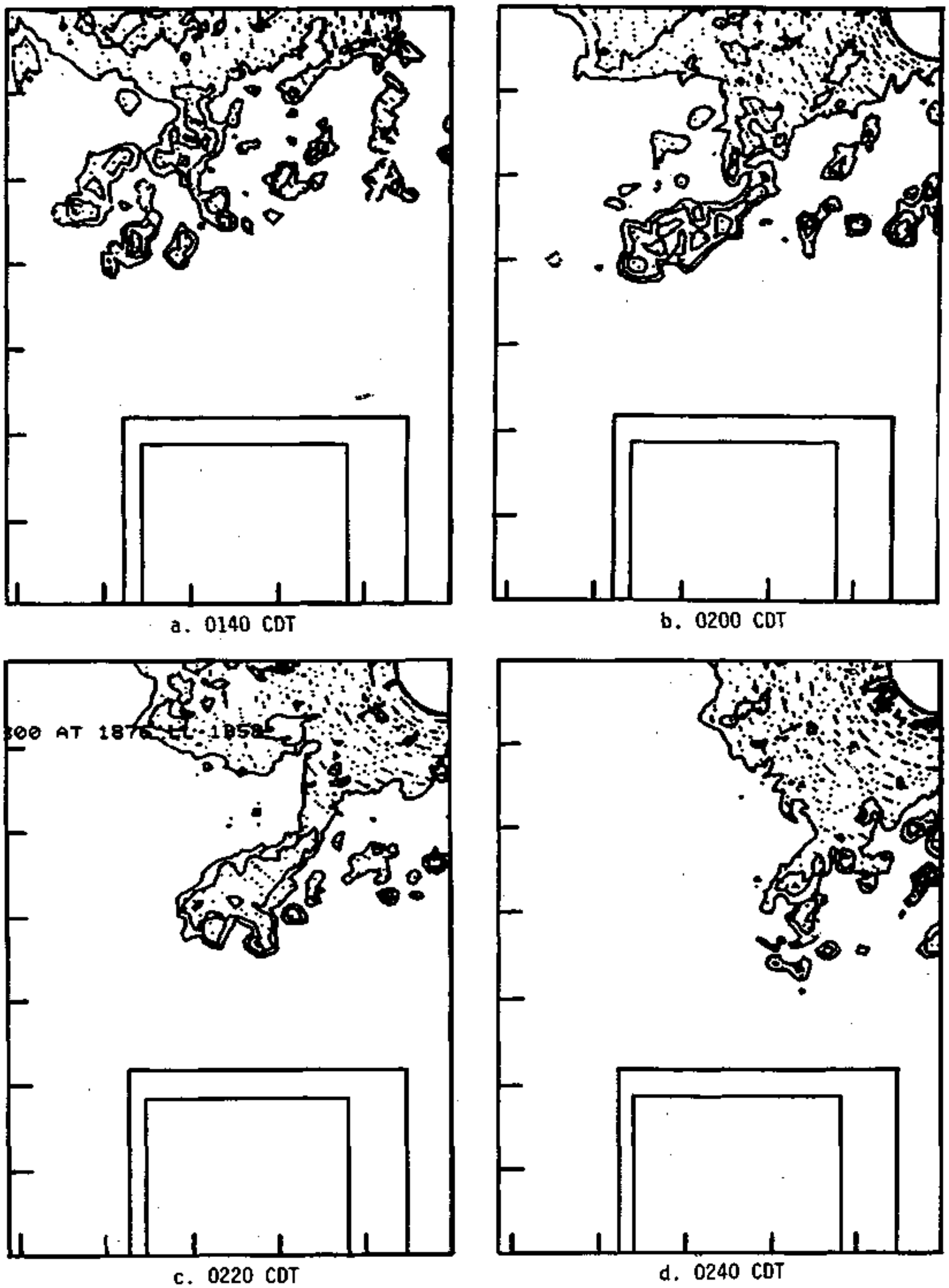

Figure 3. Radar echoes from the "HOT" radar in Joliet, IL on 9 August 1979. The radar was located in the upper right corner. Tic marks along the axes are every 25 km. The radar beam elevation is at 2.2°. Reflectivity contours are 10 dbz intervals with 30 dbz threshold. The larger box represents the approximate boundary of the rain gage network while the smaller box outlines the wind site locations.

Isochrones of the windshift (Fig. 4) reveal that the motion of the leading edge of the outflow air was generally toward the south. The boundary moved rapidly through the northern part of the area at a speed of approximately 11 m s^{-1}, but slowed considerably during the next 3 1/2 hours, coming to a near standstill in the southwest just after 0630 CDT.

The character of the modification of surface conditions also changed with time. In Figure 5 are shown temporal plots of wind direction (WD) and speed (WS), equivalent potential temperature (θ_e), temperature (T), and pressure (P) measured at locations in the north (site P-3), center (P-16), south (P-26), and west-northwest (P-8). The values plotted are five-minute averages of one-minute data. The sequence of events at these sites were representative of all stations in their general area. The graphs for sites P-3, P-16, and P-26, which were located along a north-south line in the network, are vertically stacked so as to indicate the temporal lag and change in structure of the outflow boundary as it moved southward.

In general, the change from ambient to outflow conditions was most abrupt in the north (Fig. 5a), where every variable revealed a sudden, nearly discontinuous and relatively large change. Further to the west and south, however, the changes were less pronounced and for some variables non-existent.

The most obvious change at every site occurred in wind direction. Initially, winds were very light (approximately 1 m s^{-1}), coming from the south-southwest. With the passage of the outflow boundary, however, the wind direction shifted to the northeast. In the north, this change occurred as a singular and sudden shift. Elsewhere the winds were more erratic, with a period of transition during which the winds shifted back and forth from a southerly to a northerly direction more than once. This modification of

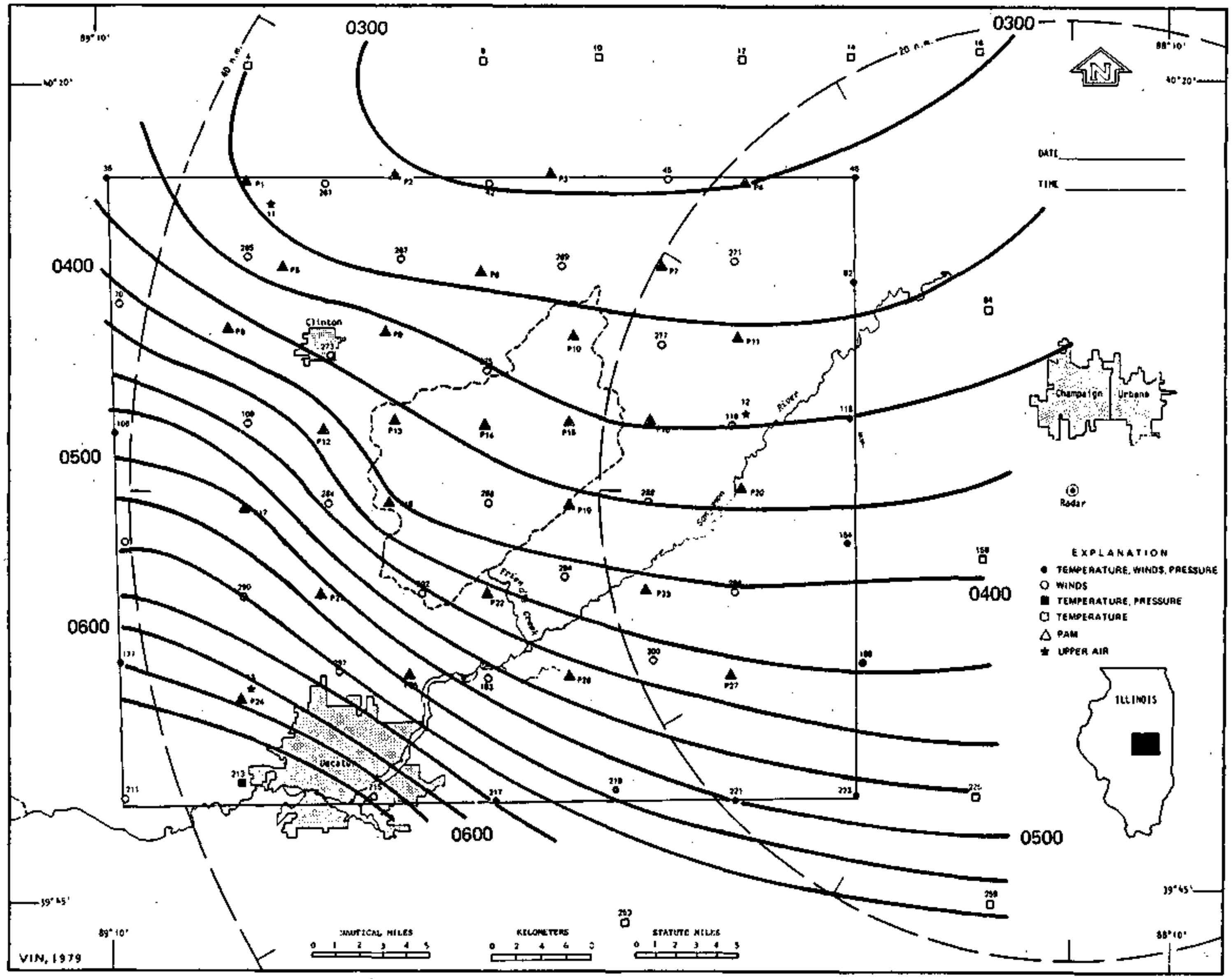

Figure 4. Isochrones of windshift on 9 August 1979. Times are in CDT.

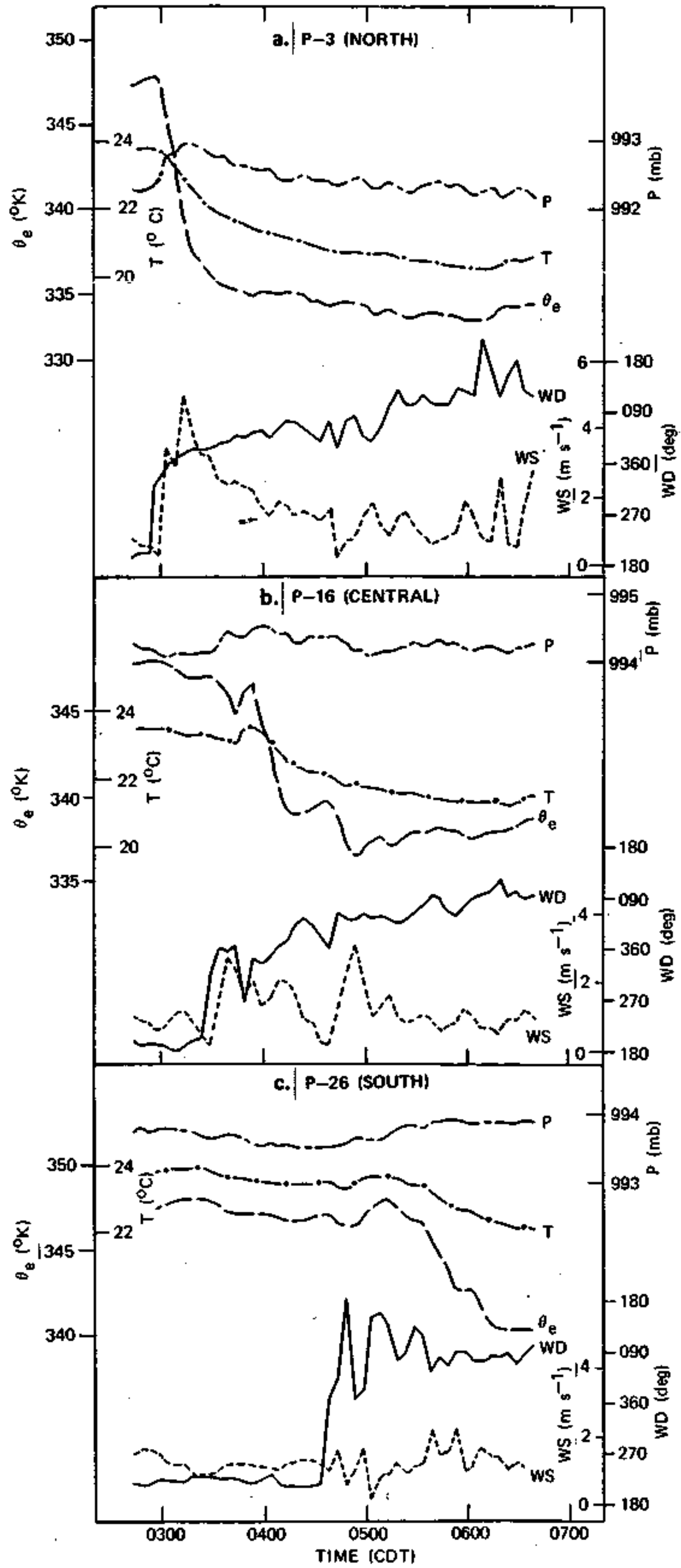

Figure 5. Temporal analyses of different meteorological parameters on 9 August 1979.

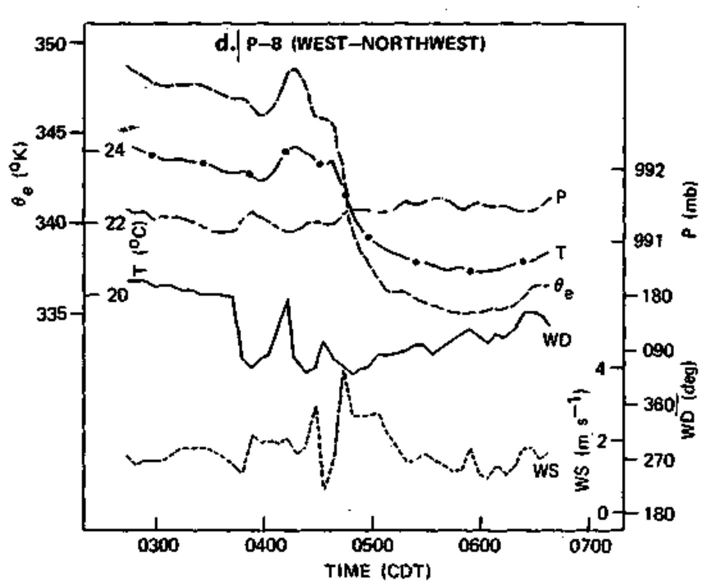

Figure 5. (Concluded)

the "outflow front" could have been due to (a) erosion of the leading edge by frictional and shear generated turbulence and subsequent downward mixing of displaced pre-frontal momentum, or (b) possible multiple surges generated by the storm as it passed north of the network.

The passage of the transition zone took up to an hour at some sites. Subsequently, the winds made a slow "return" from a northeasterly to southeasterly direction, taking about three hours at each station and indicating the passage of a transient phenomenon.

Wind speeds also showed evidence of complex structure at the interface between ambient and outflow air. In connection with nearly every shift in wind direction toward the northeast, an increase in wind speed was observed (e.g., Sites P-8 at 0348, 0418, and 0435 CDT and P-16 at 0328 and 0438 in Fig. 5). A true wind gust accompanying the outflow was short-lived, with the highest winds recorded in the northeast. An instantaneous gust of 9.5 $m\ s^{-1}$ was detected in the analog recording at one site although the one-minute speeds from digital data were only about one-half as high. The strength of the gust decreased rapidly as the outflow moved through the network and was barely noticeable in the south (Fig. 5c). It must be recalled that these measurements were made 40-100 km south of the thunderstorm cell which created the outflow and frictional dissipation and mixing would tend to decrease the strength of the wind gust. Therefore, it is not surprising that the gust appears much weaker than that typically observed very close to thunderstorms.

The changes in pressure during the outflow passage were small, suggesting the presence of a very shallow "dome" of outflow air. Considering the relatively low peak wind speed, a small pressure difference between the ambient and outflow conditions was expected. The largest increase in pressure was a 0.9 mb rise within two minutes at a northeastern site. However, most increases were around 0.5 mb or less. For the most part, pressure variations during the passage of the outflow were unremarkable.

Perhaps the most interesting of the traces in Figure 5 are those of equivalent potential temperature and temperature. Since the patterns of change in the two variables paralleled each other, discussion will be limited to θ_e only.

A large decrease in θ_e was observed at most of the stations in the network as outflow air replaced ambient air. At northern sites a rapid decrease in θ_e began with the passage of the outflow front. However, the character of the change was substantially different in the central portion of the network. Following the first windshift, sites: in this area initially recorded a decrease in θ_e. However, at many stations as the winds shifted momentarily back to a more southerly direction, θ_e began to rise, in some instances to values exceeding those prior to the initial wind shift. Largest increases occurred in a band extending northwestward from the southeast corner across the center of the network (Fig. 6). Almost no increase was observed in the northeast where the transition was sharpest and the "air-mass" interface had a singular structure, or in the southwest where the transition zone was most diffuse. After the final windshift, most sites in the center of the network recorded a steady decrease in θ_e.

Variations in this parameter are perhaps best seen in the spatial analyses shown in Figure 7. A nearly uniform field existed across the network at 0300 CDT (except for evidence of a warm "urban plume" just north of Decatur). One hour later, however, the effect of the outflow was readily

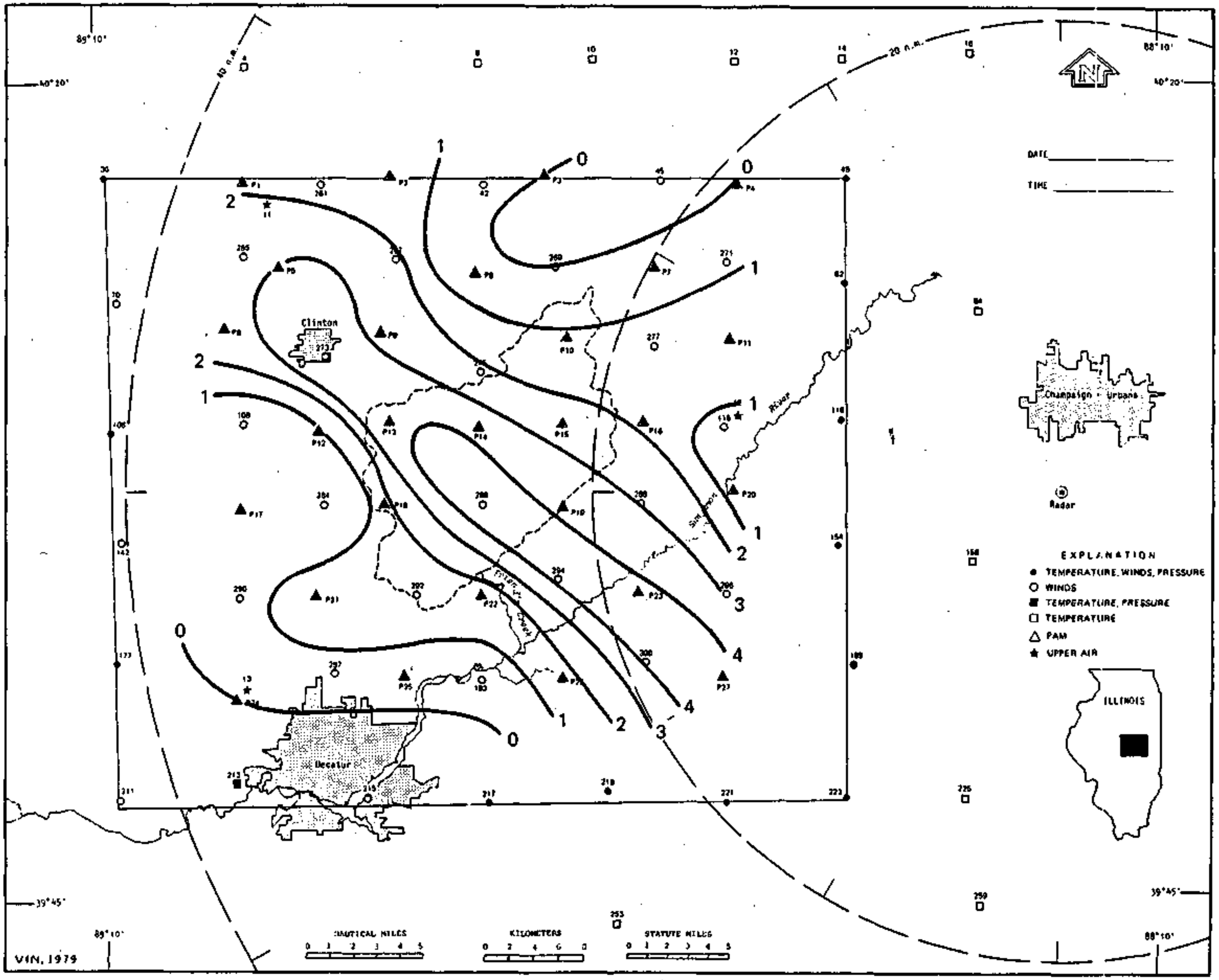

Figure 6. Magnitude of increases in θ_e at PAM sites after passage of first windshift (K°).

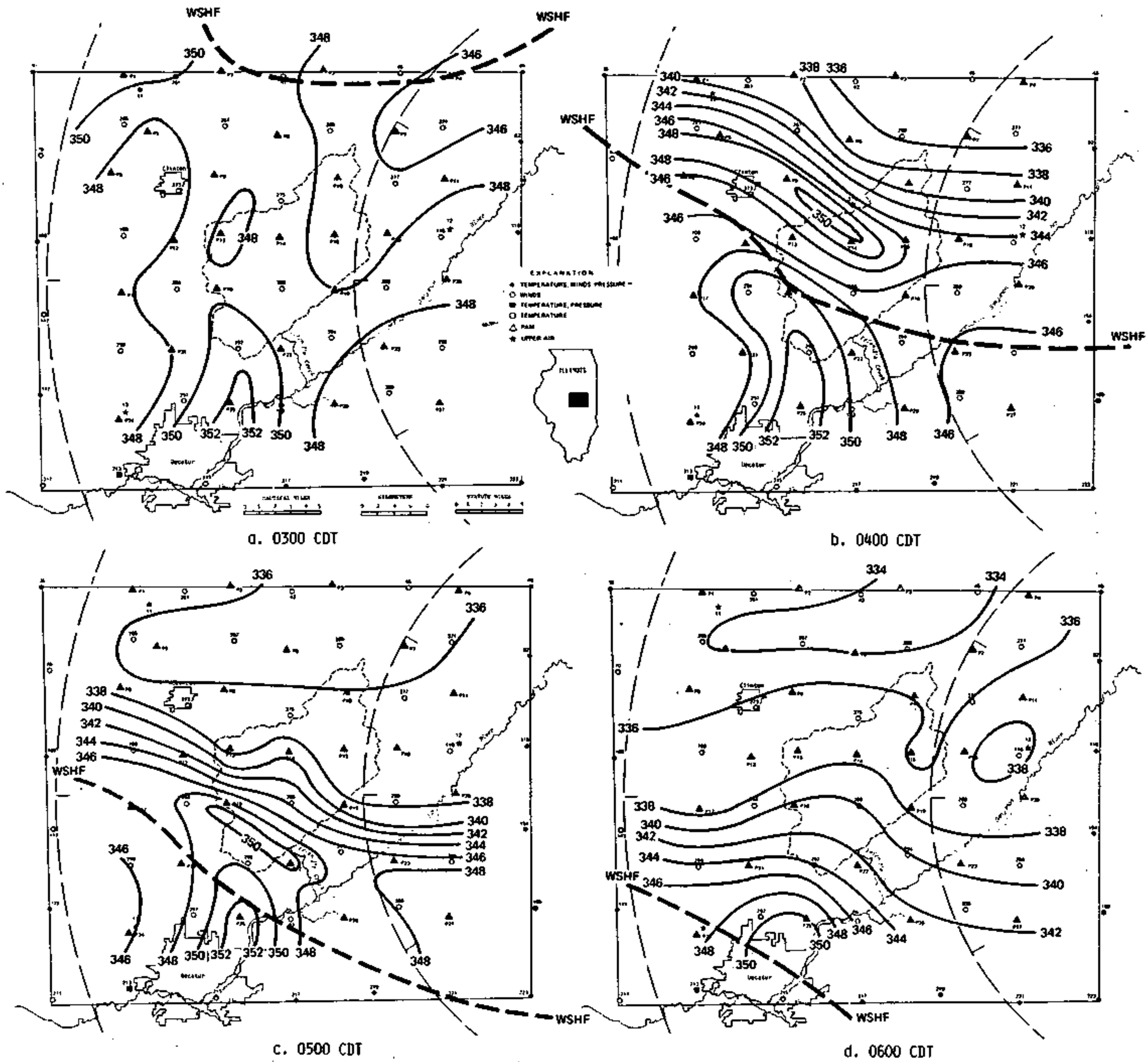

Figure 7. Equivalent potential temperature (K°) on 9 August 1979. Hourly positions of the windshift (WSHF) line are shown in each chart.

visible over the northern half of the area. The windshift line moved across the network about 10 km ahead of the narrow band of maximum θ_e values, with the region of decreasing θ_e following immediately. As time progressed, the lower θ_e values spread over nearly the entire network. Only sites in the extreme southwestern part of the area did not experience a decrease in θ_e. This was due, in part, to modification of the outflow air from frictional effects. However, localized insolation also deteriorated the thermal gradient since the outflow moved over this region after sunrise. (The warm "plume" disappeared after passage of the outflow.)

Minimum values of θ_e observed in the north were about 334°K. According to the 1900 CDT sounding on the evening of 8 August at Peoria, Illinois (about 70 km to the northwest) air with θ_e of that value occurred at about 810 mb.

It was pointed out in the previous discussion that eventual changes in all parameters were the greatest and most abrupt in the north. Table 1 gives an indication of the variation in the difference between ambient and outflow air as the outflow moved southward across the network. Besides the variables already discussed, the speed of the windshift line through each region is included.

The sequence in which the initial changes occurred in the meteorological parameters did not differ greatly. In general, the windshift was encountered first, but only one minute ahead of the pressure jump. The temperature break soon followed, averaging about 4 minutes behind the windshift. Next in order were the peak wind speed and the pressure peak, 2 and 4 minutes later, respectively. The temperature peak within the outflow air trailed the shift in direction by an average of nearly 24 minutes.

Table 1. Variations in meteorological parameters between ambient to outflow air.

Parameter \ Region	North	Northwest	Central	South
ΔWD	180°	125°	140°	140°
ΔWS	+4.5 m s^{-1}	+2.5 m s^{-1}	+2.0 m s^{-1}	+1.0 m s^{-1}
ΔP	+0.8 mb	+0.3 mb	+0.4 mb	+0.4 mb
ΔT	-3.5°C	-2.9°C	-2.0°C	-1.5°C
$\Delta\Theta_e$	-14°K	-12°K	-10°K	- 7°K
Speed(WNDSHFT)	12.8 m s^{-1}	3.3 m s^{-1}	7.6 m s^{-1}	3.4 m s^{-1}

These temporal differences agree favorably with research by Tepper (1950) and Charba (1974) both of whom reported that the pressure jump just nosed out the windshift as the initial change in the ambient conditions, with the temperature break and peak wind gust soon following. Similar results were observed by Byers and Braham (1949), except that no time difference was noticed between the two leading variables. From all of these studies, it would appear that the initial indication of an outflow "front" comes from an almost simultaneous change in pressure and wind direction. Goff (1976) differs sharply from this view, however, presenting evidence of a variety of thunderstorm outflows in which the pressure jump preceded the windshift by an average of more than 17 minutes. He found the pressure jump/windshift separation small only in formative outflows, with both large and small differences in mature or decaying outflows.

DISCUSSION

Due to the large data void between the VIN network and the storm system, it is difficult to pinpoint the time of the outflow initiation.

The origin time of the outflow was estimated by "backtracking" the windshift to the storm using network data. The procedure used was to draw a line normal to the windshift isochrones in Figure 4. The line chosen ran from about 6 km east of site P-3 to 1 km southeast of station #215. Setting the southern border of the wind sites at 0 km, the time of the windshift was plotted as a function of distance from points at 10-km intervals, northward through the network. A curve was fitted to these points and then extrapolated backward to 105 km, the estimated distance of the closest radar echoes to the southernmost sites (Fig. 8). From this extrapolation the time of the origin of the outflow from the storm was estimated to be about 0210 CDT.

Radar analyses at 0.6° elevation indicated that the maximum reflectivity in the lowest levels detectable in the storm system also occurred about 0210 CDT (Fig. 9). Given the range of this cell to the radar (which has a 1.0° beam width), these measurements would have been centered at about 1800 m AGL. Byers and Braham (1949) have shown a close relationship between heavy rains, downdrafts, and the cold thunderstorm outflow. This leads to an estimated time for the initiation of the outflow at approximately the same time as the maximum near-surface reflectivity. The evidence strongly suggests that the outflow may have originated in this group of cells.

In Figure 3b, several centers of maximum reflectivity can be seen at 2.2° beam elevation (height of center of beam, just under 5000 m AGL). It is possible that outflow air from more than one of these cores spread across the network reinforcing the initial outflow. Goff (1976) observed "multiple surges" in half of the 20 cases he studied. The temporal analyses in Figure 5b, c, and d suggest that this may have been the case.

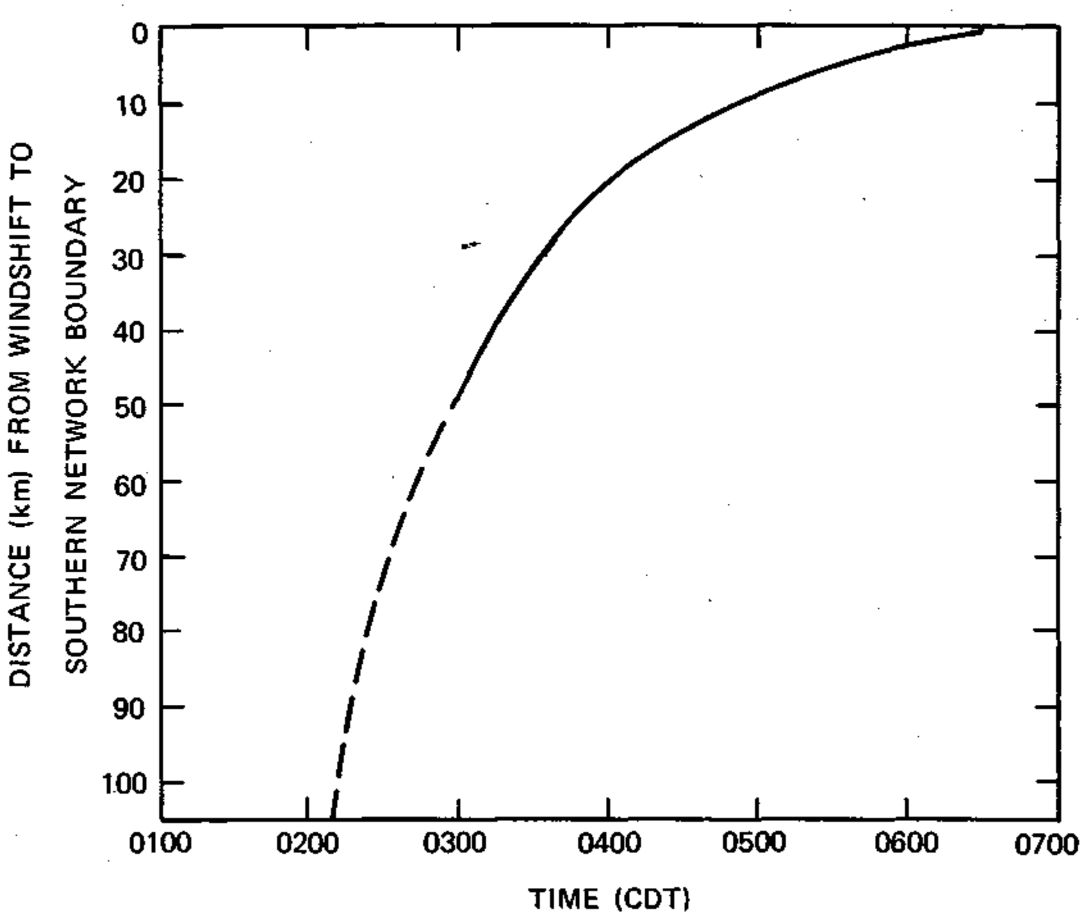

Figure 8. Backward (in time) extrapolation of windshift to estimate time of outflow initiation.

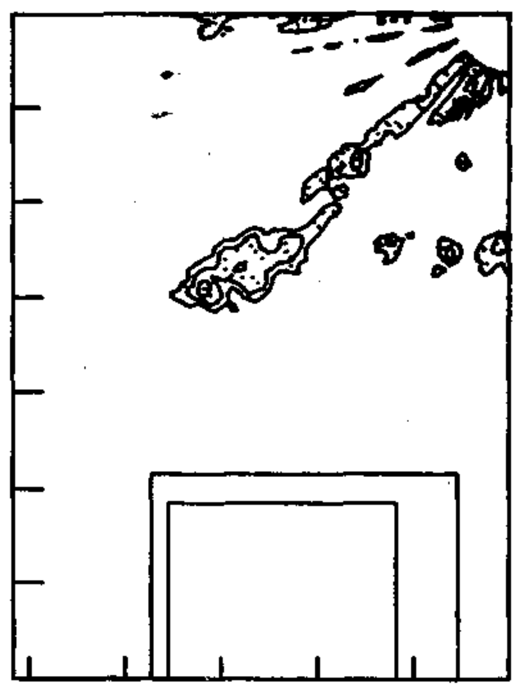

Figure 9. Same as Figure 2, except at 0210 CDT and with a beam elevation of 0.6°.

Explanation of the increase in θ_e, however, is not quite as obvious, but may be explained from upper air conditions. Routine hourly surface data indicate that the pre-outflow surface conditions in the network were fairly uniform across central Illinois. Similar surface conditions were reported at the Salem, Illinois (SLO) rawinsonde site 125 km to the south. The routine synoptic analysis indicated that the pre-outflow atmosphere in the lowest 1500 m was fairly uniform across central and southern Illinois as well. Therefore, the rawinsonde at SLO was probably representative of the conditions inside the network.

According to normal operating procedures, soundings valid at 1200 GMT are actually launched at 1100 GMT (0600 CDT). Therefore, since sunrise on 9 August was at 0558 in Champaign, the surface and near surface conditions were still largely unmodified by solar radiation at the time of the rawinsonde measurements in the lower boundary layer. The sounding (Fig. 10) shows a surface temperature inversion extending to 300 m AGL. The value of θ_e was 345.4°K at the surface, but just 70 m aloft it was 353.7°K. Winds at the surface were 1 m s^{-1} from the south-southwest, increasing to just over 4 m s^{-1} from the southwest at 300 m.

These data also could explain the variations in the meteorological variables observed at the leading edge of the outflow over part of the network. As an outflow moves farther and farther from its point of origin, its depth is gradually reduced. This could allow for substantial amounts of air just above the surface to be entrained and mixed down to ground level in the wake of the "frontal" boundary. This could explain the rise in θ_e and the change back to southerly momentum observed for a short time after the initial windshift. Largest increases in θ_e (Fig. 5) were over 4°K, well under the 8.3°K difference from the surface to 70 m seen in the

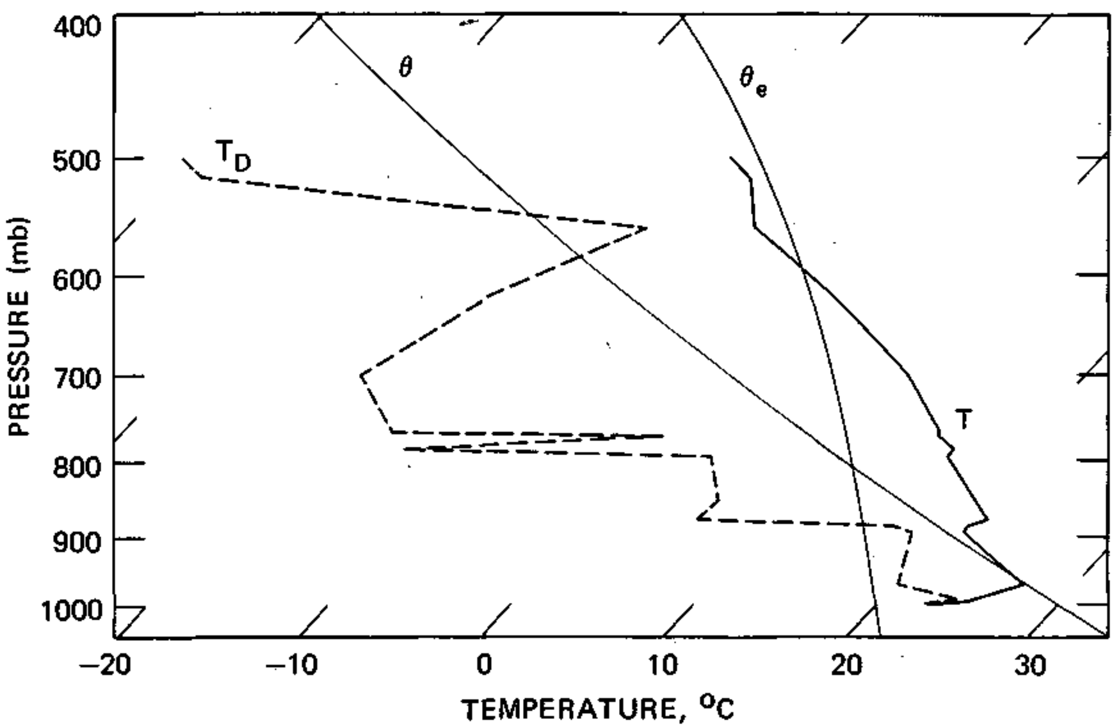

Figure 10. Rawinsonde sounding at SLO valid for 07.00 CDT on 9 August 1979.

SLO sounding. Increases were not observed in the northeast since the outflow air had sufficient depth to prevent mixing to the surface. The southwest recorded no increases in θ_e simply because by this time even the gradient along the leading edge of the outflow and its speed had weakened considerably. At the same time, the rising sun quickly modified the thermal gradient in the surface layer.

This incident, which is not unique, demonstrates how lasting the surface effects of even a moderate thunderstorm can be. The outflow investigated here traveled over 100 km to reach the southernmost sites in the network and was observed at least 3 hours after the storm decayed. Despite the obvious convergence along the gust front, no cumulus development was observed. Hourly observations from Willard Airport in Champaign reported only scattered clouds between 1200 and 1500 m, before and after the outflow passage. This tends to support Purdom's (1979) observation that deep convection usually does not occur along a gust front if conditions in the air ahead are unfavorable for convection.

The importance of this research is that it presents evidence of a possible triggering device for convective storms well removed from pre-existing systems. It may be that the nocturnal convective rains often experienced in the central United States are initiated by such long-traveling gust fronts entering a mesoscale region with thermodynamic stratification favorable for convection but not when such stratification does not exist.

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