Surface Signatures of a Dry Nocturnal Gust Front

ROBERT W. SCOTT AND BERNICE ACKERMAN
Illinois State Water Survey, Champaign, IL 61820

(Manuscript received 30 June 1982, in final form 11 October 1982)

ABSTRACT

Sudden changes in surface meteorological parameters were observed to propagate across a densely-instrumented network in central Illinois during a summer night in 1979. The changes were due to the outflow from an eastward moving, organized storm system passing well north of the network. Although no precipitation was observed within 45 km of the area (i.e., its passage across the network was "dry"), the change from ambient to outflow air was seen in other surface weather indicators nearly 100 km south of the point at which the outflow is estimated to have been initiated and more than 3 h after the generating storm had dissipated.

1. Introduction

Perhaps one of the most frequently observed events during strong convective activity is the abrupt change in surface and near-surface conditions as the leading edge of a thunderstorm "outflow" passes. Commonly called a "gust front" because of the sudden surge in wind speed, its arrival is noted by 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, all are typical signatures of the gust front.

Previous studies of outflow from convective storms have generally investigated this phenomenon in the near vicinity of the storm by which it was generated, (e.g., Byers and Braham, 1949; Tepper, 1950; Charba, 1974; Goff, 1976). Although it has long been recognized that the storm outflow may be long-lived, the gust front has received less attention when distant from its source. Purdom (1979) recently presented evidence based on satellite photography that storm outflow may act as a triggering device for the growth of convective clouds well over 150 km ahead of the original storm if it moved into regions in which cumulus clouds already existed. On the other hand, no development occurred if the ambient air was devoid of convective clouds. Purdom (1982) also has reported that the intersection between two "arc clouds" which form along the leading edge of outflow air was a favored site for convective development, up to 300 km from the parent cloud.

This paper describes in some detail the systematic changes in surface conditions that occurred as a gust front from a distant storm passed over a densely instrumented network in central Illinois. In the early morning hours of 9 August 1979, a thunderstorm moving eastward across northern Illinois generated cool outflow which significantly changed surface conditions as much as 100 km to the south, and 3 h after the storm had fairly well dissipated.

Documentation of this gust front from a distant nocturnal storm was obtained during a project investigating the relationship between surface and boundary layer conditions and cloud development, and the predictability of convective rainfall from low-level convergence. The field network, operated as a part of this project, covered approximately 5600 km^2 and was located just west of Champaign, Illinois. Surface field instruments included 260 recording raingages, 65 wind sensors, 51 temperature and humidity sensors and 40 pressure instruments. The raingages covered the area with a density of 1 per 23 km^2. Wind and state parameters were measured with a station density of about 1 per 32 km^2 on an inner network of 1600 km^2, and with station spacing of 9 km in an outer network of 3000 km^2. Included in the instrument array was the 27-station Portable Automated Mesonet (PAM), operated by the National Center for Atmospheric Research, from which measurements were telemetered to a central station for recording on magnetic tape. Sensors at all other stations had analog recording.

2. Storm conditions

Two weak stationary fronts extended eastward across northern Illinois to the middle and northern Atlantic coasts on the night of 8–9 August 1979. The area south of the fronts was in southerly flow from the Gulf of Mexico, coming around the west side of a warm high pressure area centered over the southeastern United States. The upper air analyses indicated dry air over central Illinois at 700 mb, and over

---

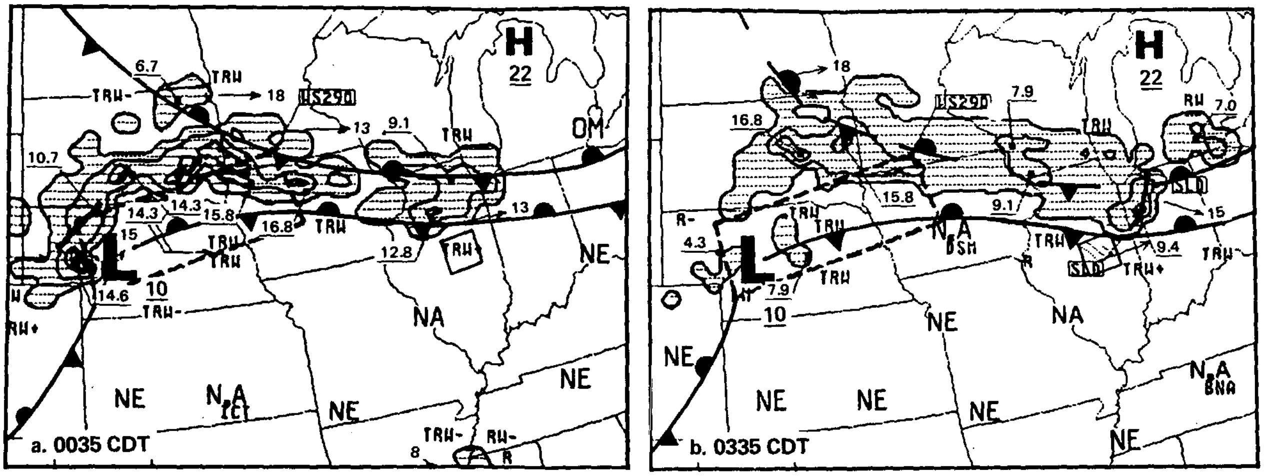
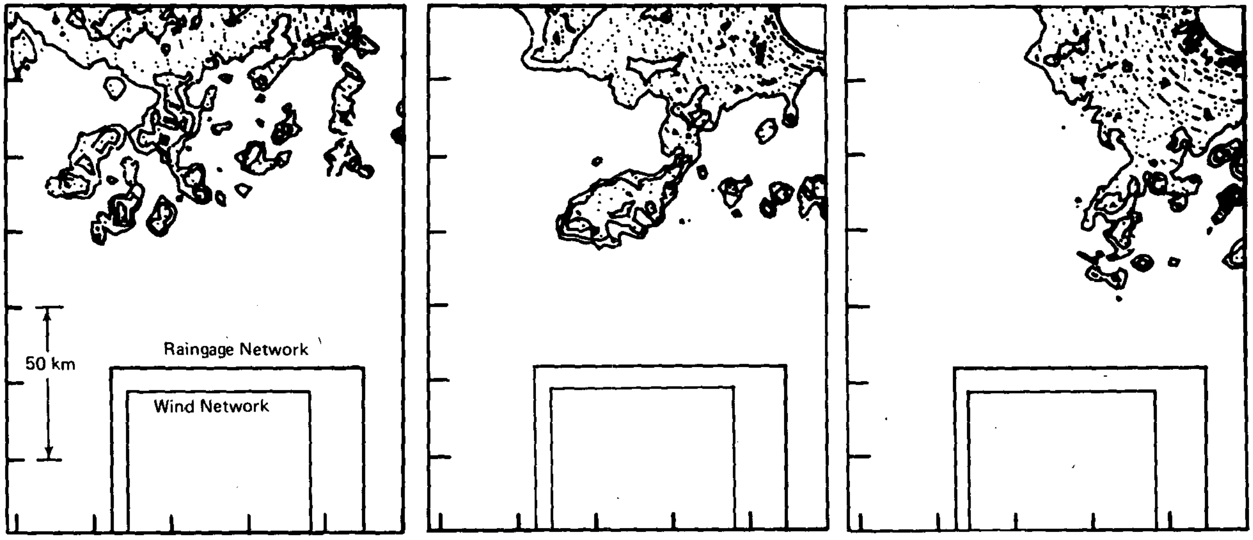


FIG. 1. National Weather Service radar summaries with fronts and pressure centers superimposed. Echo tops (small underlined numbers) and speeds have been converted into metric units. Large underlined numbers indicate maximum and minimum pressures (mb − 1000).

the entire state at 500 mb. Winds were weak and the skies nearly clear over the network.

Strong convective activity associated with the frontal systems had developed across much of Nebraska on the afternoon of the 8th with less severe thunderstorms extending eastward into Iowa. The storms moved toward the east at 12–15 m s^{-1}, with the leading edge of the storm area entering Illinois by early evening. By midnight, an area of moderate storms covered northern Illinois and continued in the region for the next few hours (Fig. 1). It was outflow air generated by this area of storms that spread southward to central Illinois.

The portion of the storm system in northeastern Illinois was monitored in a volume-scanning mode by a digitized 10 cm radar that was operated by the Illinois State Water Survey near Joliet in northern Illinois. Precipitating clouds were observed moving east-southeastward between 0100 and 0300 (all times CDT) with the strongest cells located along the southern edge of the rainband. At approximately 0130, a small group of cells organized within the general region of showers (Fig. 2). Intensities in these cells increased rapidly, maximizing around 0200. Radar reflectivities in excess of 50 dB(Z) were measured for at least 40 min centered at 0200, as the tops of the



a. 0140 CDT b. 0210 CDT c. 0240 CDT

FIG. 2. Contoured echoes from a digitized 10 cm radar in Joliet, Illinois. The radar was located in the upper right corner. The radar beam elevation was 2.2°. Reflectivity contours are 10 dB(Z) intervals with 30 dB(Z) threshold. The larger box represents the approximate boundary of the raingage network while the smaller box outlines the wind site locations.

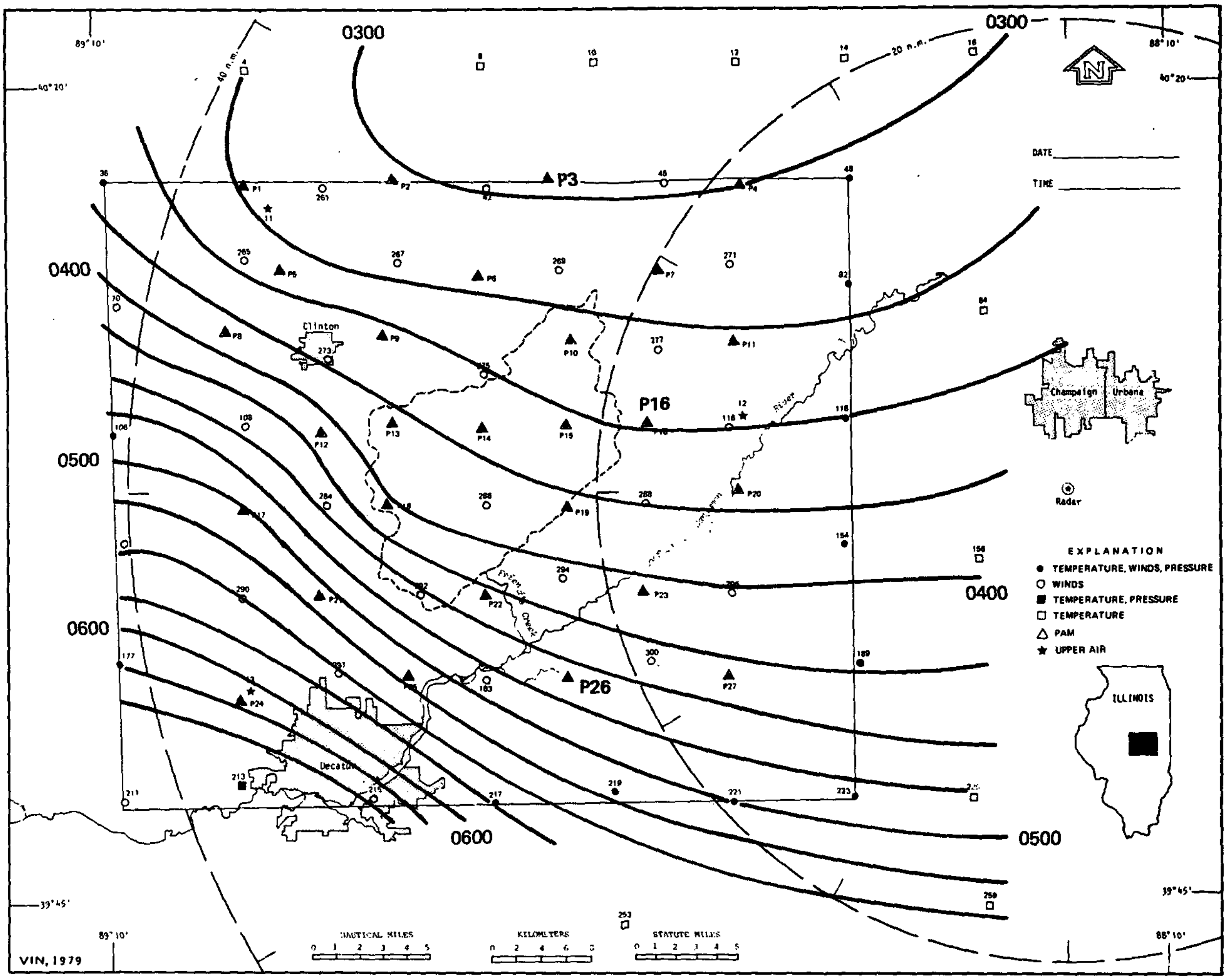


FIG. 3. Isochrones of the wind shift on 9 August 1979. Times are in CDT.

echoes reached 14.6 km. The cells decreased quickly in intensity after 0230 and had dissipated completely by 0310. At its closest point (which occurred as it was dissipating), the storm was about 25 km north of the northeastern corner of the field network.

3. Meteorological fields in the network

No rain occurred within the instrumented network during the night of 8–9 August. In fact the closest rain observed from any NWS cooperative station was 45 km north of the network. Nevertheless, changes in meteorological parameters typical of a gust front passage were observed between 0250 and 0630 at virtually all stations.

The arrival of the outflow was identified by a rapid change in wind with stronger northerly flow replacing light southerly or nearly calm winds. Isochrones of the wind shift (Fig. 3) indicate that outflow air entered the network shortly before 0300 and spread to the south and southwest. The wind shift line moved rapidly through the northern part of the network at a speed of ~ 11 m s^{-1}, but slowed considerably during the next 3½ hours. By the time it reached the southwest corner of the network, shortly after sunrise, the leading edge of the airmass had slowed to about 2.5 m s^{-1}.

In Fig. 4 are shown temporal plots of wind direction (WD) and speed (WS), equivalent potential temperature (θ_e), temperature (T) and pressure (P) measured at stations in the northern (site P-3), central (P-16) and southern parts (P-26) of the network. (See Fig. 3 for station locations.) Data plotted in Fig. 4 are 5 min averages of measurements recorded at 1 min intervals at the PAM stations. In general, the changes at these stations were representative of those at other locations in that part of the network. The variations in meteorological variables were similar at all stations. However, the change from ambient to outflow conditions was most abrupt in the north where there was

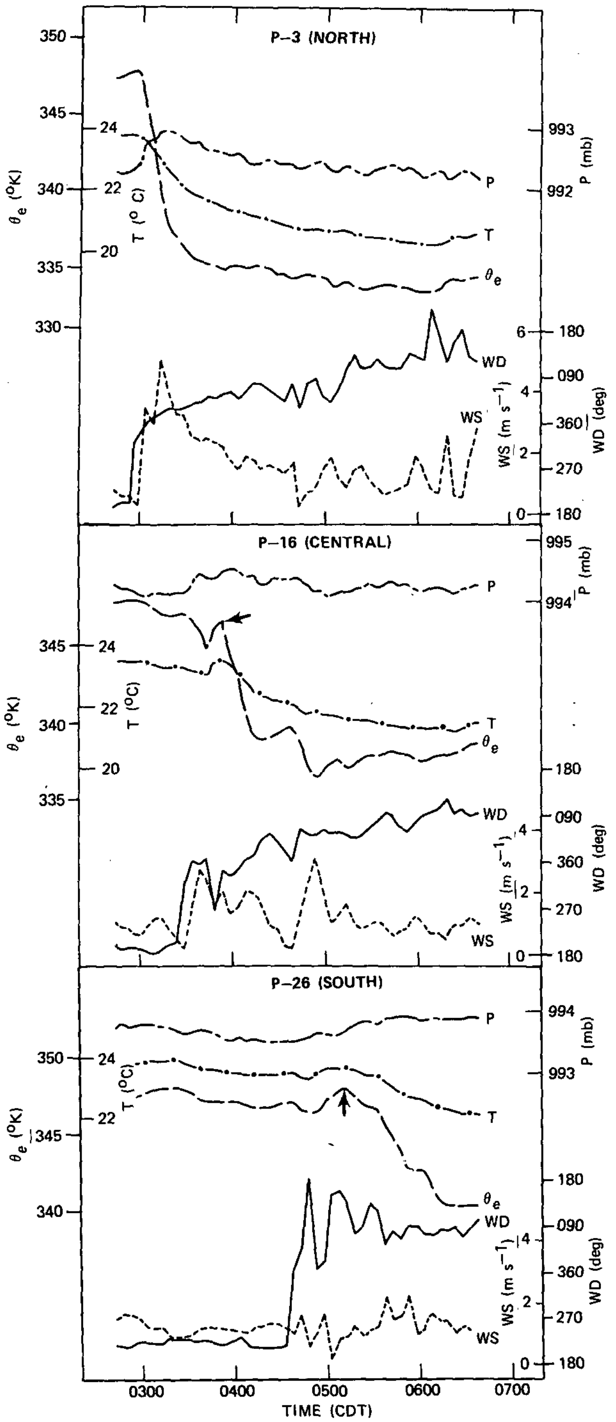


FIG. 4. Time series of meteorological variables on 9 August 1979. See text for symbol definitions. The heavy arrows indicate the "recovery temperature" in the θ_e series.

a sudden, and relatively large, change in every parameter. Further to the west and south, the changes tended to be less pronounced, both in the rate at which the change took place and in the magnitude of the change (Table 1).

The dominant signature at every station, as well as the earliest, was in wind direction. Under fairly clear skies and weak synoptic gradients, the pre-outflow surface had started to cool and the winds to die down, while the direction remained southerly. The passage of the outflow front caused the wind to shift to the north and speeds to increase in magnitude and variability. In the north, the change in direction 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 southerly to northerly directions often more than once. The passage of the wind-transition zone took up to an hour at some stations. Subsequently, the winds made a slow recovery from a northeasterly to southeasterly direction, taking about 3 h at each station.

Wind speeds also evidenced a 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., P-16 at 0328 and 0438 in Fig. 4). However, a strong gust was measured only in the northern part of the network. The highest instantaneous gust was 9.5 m s^{-1}, detected at the northeasternmost station of the network. The peak velocity decreased rapidly as the outflow moved through the network. In the south, the change in wind speed was not as much in magnitude as it was in variability (P-26 in Fig. 4).

Pressure changes during the outflow passage were relatively small (<1 mb). The largest and most rapid increase in pressure was 0.9 mb within a 2 min period, at a station in the northeast corner of the network. At most other stations the pressure change was ~0.4 mb or less, and frequently occurred slowly, particularly in the south. Although smaller, these pressure changes are not inconsistent with those reported by Byers and Braham (1949) and more recently by Wakimoto (1982) for midwestern thunderstorms. These authors reported pressure changes more commonly in the range of 1–3 mb but at locations closer to the generating storm. Cold outflows are known to be divergent and therefore the depth will tend to decrease with distance and time. The decrease in depth, and modification of temperature in the cool air by tur-

TABLE 1. Changes in meteorological parameters that occurred at stations in various parts of the network.

	Station		
Parameter	P-3 (North)	P-16 (Central)	P-26 (South)
ΔWD	180°	140°	140°
ΔWS	+4.5 m s^{-1}	+2.0 m s^{-1}	+1.0 m s^{-1}
ΔP	+0.8 mb	+0.4 mb	+0.4 mb
ΔT	−3.5°C	−2.0°C	−1.5°C
$\Delta\theta_e$	−14°K	−10°K	−7°K
Speed of wind shift line	12.8 m s^{-1}	7.6 m s^{-1}	3.4 m s^{-1}

bulent mixing at both the surface and upper interfaces should result in a lower pressure differential.

The temperature "break" was relatively small also, generally 3°C or less, with the decrease smaller in the south than in the north. However, these too were not inconsistent with the values reported in the papers cited above. Moreover the decrease in temperature was accompanied by a decrease in vapor content. The resultant change in equivalent potential temperature θ_e as outflow air replaced ambient air, was almost as pronounced as that of wind direction at most stations.

At northern sites, θ_e decreased very sharply and nearly simultaneously with the wind shift and gust. The character of the change in θ_e was substantially different in the central portion of the network, however. In this area there was an initial decrease in θ_e following the first wind shift. Then, at many stations, as the winds shifted momentarily back to a more southerly direction, θ_e increased, in some instances to values equal to or greater than those prior to the initial wind shift. These transient "recoveries" to prestorm conditions are indicated by arrows in Fig. 4 at 0350 at station P-16 and 0510 at station P-26. After the "final" wind shift, θ_e decreased steadily. The return to higher values of θ_e, the "recovery temperature," was largest in a band 15 km wide, extending northwestward from the southeast corner across the center of the network, with increases of 2 to over 4°C. This phenomenon was uncommon in the northeast where both θ_e and wind direction tended to change monotonically.

The equivalent potential temperature was nearly uniform across the network prior to the arrival of the outflow air (Fig. 5), except for evidence of a warm "urban plume" extending north from Decatur. Within an hour, however, a new air mass with lower θ_e was present over most of the northern half of the area. The strongest gradient in θ_e lagged the wind shift line by about 6–12 km. The narrow band of maximum θ_e, i.e., the transient recovery region, was just ahead of the strong θ_e gradient. As the outflow moved southward, the low θ_e values spread over the network, reaching the southwest sector by 0600.

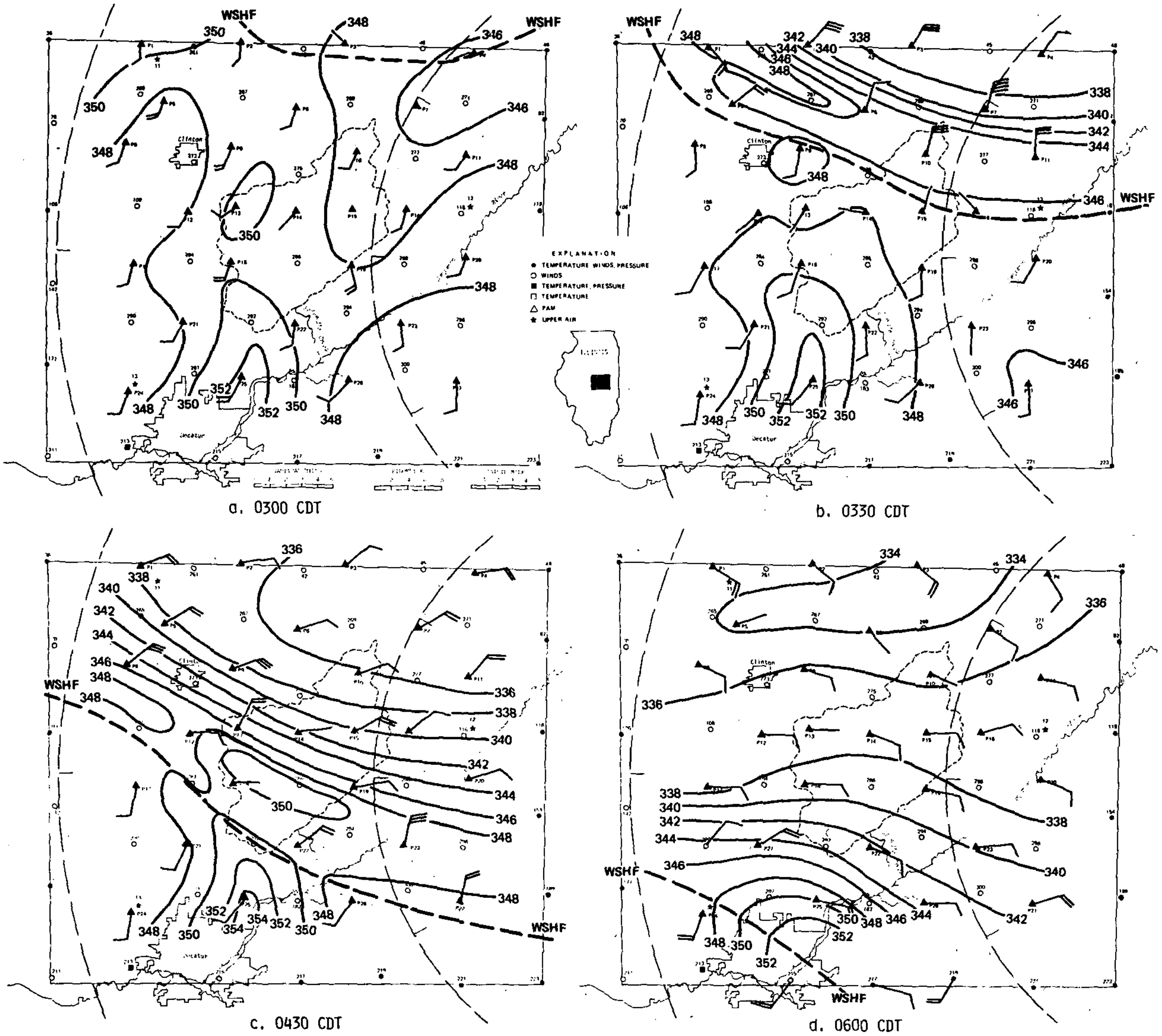
The sequence in which the initial changes occurred in the meteorological parameters was similar at all stations. Usually the wind shift occurred first, but only one minute or so ahead of the increase in pressure. The temperature break followed soon after, averaging about 4 min behind the wind shift. The peak wind speed and the pressure peak, followed the break in temperature by about 2 and 4 min, respectively. The maximum "recovery" temperature within the outflow air trailed the change in wind direction by an average of nearly 24 min.

4. Summary and discussion

Sudden changes in surface weather were observed to propagate across a densely-instrumented network in central Illinois during a summer night in 1979. Abrupt shifts in wind direction were accompanied or followed shortly by an increase in the magnitude and variability of the wind speed, a rise in pressure, falling temperatures and, even more dramatically, decreases in equivalent potential temperature. The patterns of these changes are consistent with the outward advection of thunderstorm outflow air, although no rain occurred in the network. The nearest storm was 25–30 km distant at its closest point, and the storm had largely dissipated before the weather parameters changed at most stations. The data clearly show that slowly decaying mesoscale gradients in the surface field can be due to convective storms even when the storms are significantly distant in time and space.

The sequence in which the changes in meteorological parameters occurred as the outflow air mass passed over a station agrees with that observed by other researchers at locations much closer to the generating storm. Tepper (1950) and Charba (1974) both have reported that the pressure change just "nosed out" the wind shift as the initial change in surface weather conditions as a gust front passed, with the temperature break and peak wind gust soon following. Similar results were observed by Byers and Braham (1949), except that they found no difference in the time of occurrence of the changes in the two leading variables (pressure and wind direction). Goff (1976), however, presented evidence from a variety of thunderstorm outflows, indicating that the pressure change preceded the wind shift by an average of more than 17 min, with significant variation from case to case. He found the separation (in time) between pressure change and wind shift small in formative outflows, with both large and small time differences in mature or decaying outflows. The very gradual change in pressure following the wind shift, observed in the southern part of the network on 9 August 1979 is in agreement with Goff's findings for decaying outflows while the sequence of changes in the north are in agreement with the findings of Tepper, Charba, and Byers and Braham.

It is not possible to trace the passage of the outflow from the generating storm to the network because of the large data void between the network and the nearest storm system. However, an estimate of the location and time of "origin" of the outflow was obtained by "backtracking," based on the transit of the wind shift "front" across the network. This was done by determining the time of arrival of the wind shift along a line normal to the isochrones shown in Fig. 3. These times were plotted against distance from the south edge of the network and the curve thus defined extrapolated backward in time (Fig. 6). This procedure indicated probable origin of the outflow at about 0215, from a precipitating cloud which was about 95 km distant from the southern edge of the network (Fig. 2). The measurements from a radar which was volume-scanning through the storm, indicate that the



a. 0300 CDT

b. 0330 CDT

c. 0430 CDT

d. 0600 CDT

FIG. 5. Equivalent potential temperature fields (K). Position of the wind shift line is shown by heavy dashed line marked WSHF. Each barb is equal to 1 m s^{-1}.

maximum reflectivity in the lower parts of the cloud was reached about 0210 and decreased rapidly after 0230.

Although the change in meteorological parameters was relatively rapid and monotonic at northern stations (closest to the parent storm), temporal analyses indicate a more complex structure at the leading edge of the outflow, particularly in the southern half of the network. This complexity in the "gust front" may have stemmed from a number of factors. Goff (1976) observed multiple "surges" in about half of the 20 cases he studied. The generating storm on 9 August 1979 had several cores of high reflectivity and it is possible that the outflow air from one or more cores, originating at different locations and at several different times, would tend to reinforce earlier ones which were in the process of being dissipated by other atmospheric mechanisms. However, considering the distance that the outflow travelled, a more likely explanation for the modification of the gust front would appear to be mixing by frictional and shear-generated turbulence and downward mixing of "prefrontal" air.

Charba's (1974) schematic reconstruction of a gust front based on measurements indicates significant mixing in a wake area just behind the "head" of the outflow, and some 5 km behind the leading edge, as well as in a thin surface layer in the "head" region. Similarly, Wakimoto (1982) found downward motion in about the same location from analyses of Doppler radar velocities. As the cold outflow spreads outward, the depth at the leading edge must decrease, particularly after the storm decays and the source of cool air is reduced. This would increase the probability of ambient air from above the cold dome mixing downward.

Such mixing with pre-storm air is strongly indi-

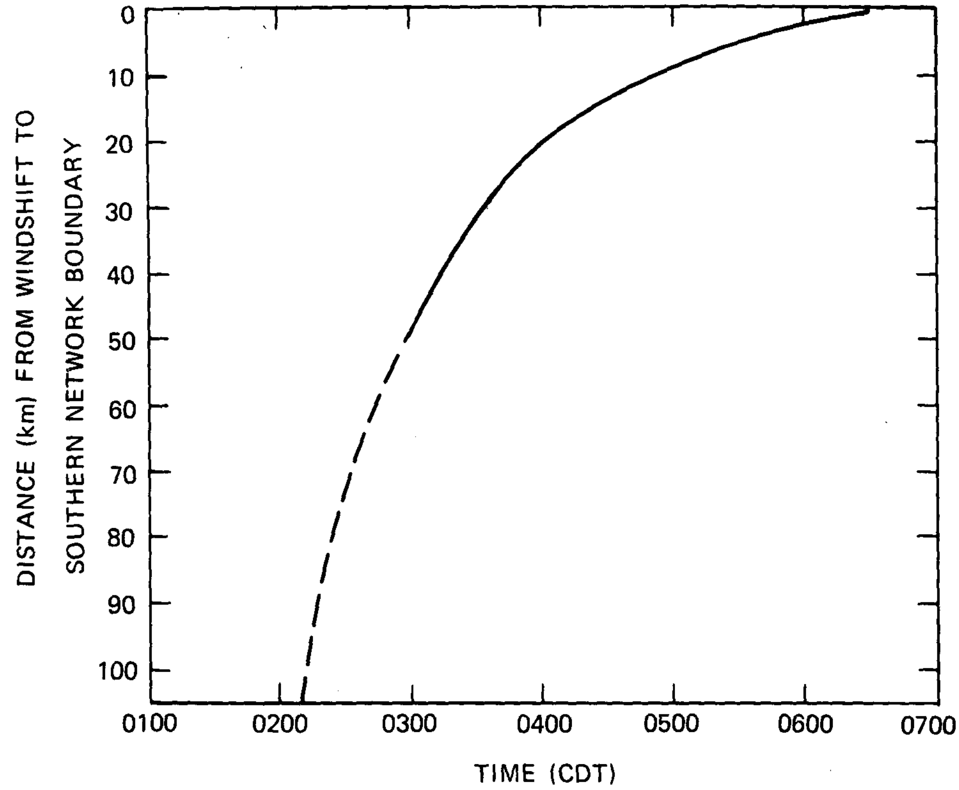


FIG. 6. Plot of time of wind shift against distance northward from the southern boundary of the network. The solid curve is based on observations in the network; the dashed line is an extrapolation backward in time to intersection with a precipitation echo detected by the radar at Joliet.

cated in our measurements by the transient "recoveries" to ambient conditions in both wind and equivalent potential temperature at most stations in the network. This was evidenced in the surface field as a decrease in θ_e directly behind the wind shift line, followed by a narrow band where it increased, and then a more rapid decrease beyond and to the north. The maximum in the θ_e field was 5–6 km behind the wind shift line.

The speculation of turbulent mixing from above is supported also by the closest upper air sounding (Fig. 7). Routine hourly surface reports plus network

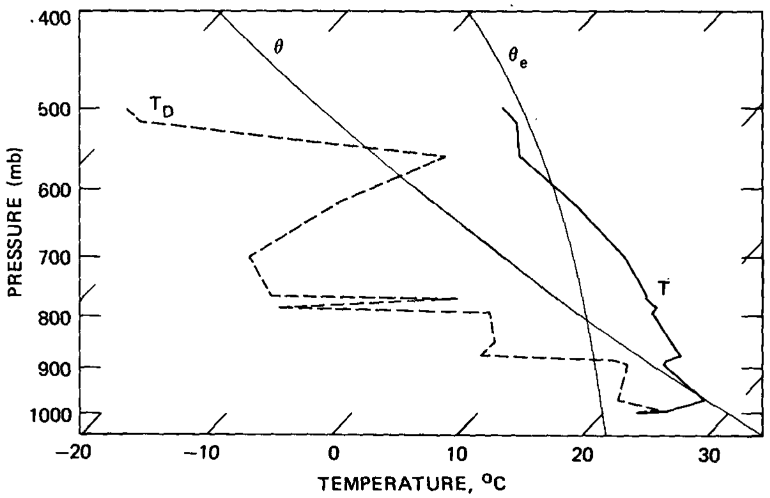


FIG. 7. Rawinsonde sounding at Salem, Illinois, valid for 0700 CDT 9 August 1979.

data indicated that the pre-outflow surface conditions were fairly uniform across central Illinois. If the same can be assumed for the planetary boundary layer, then the Salem sounding, about 125 km south, was probably representative of network conditions prior to outflow passage. The launch time for the 1200 GMT upper air sounding is actually about 1100 GMT (0600 CDT). With sunrise at 0558 CDT in early August, it is safe to assume that conditions in the lower planetary boundary layer were still largely unmodified by solar radiation, which is also indicated by the strong surface temperature inversion extending to 300 m AGL. Calculated values of θ_e were 345.4 K at the surface and 353.7 K at 70 m AGL. Thus, the concept of the temporary "recovery" as indicative of air above the outflow, mixing with outflow air and descending to the surface seems both reasonable and likely.

This analysis of the gust front from a nocturnal storm, which is common during the spring and summer in the Midwest, demonstrates how lasting the effects of even a moderate thunderstorm can be on surface meteorological conditions. The thunderstorm outflow was still well defined after travelling over 100 km and up to 3 h after the parent storm decayed. Although there was obvious convergence along the gust front, no cumulus development was observed. This is not surprising in view of the strong subsidence and very dry air above 850 mb over central Illinois. However, one could speculate that under more favorable thermodynamic stratification, the thermal, moisture and velocity gradients established by such outflows from nocturnal storms may provide a favored site for convection to develop as solar heating warms and destabilizes the surface layer.

Acknowledgments. This research was supported by the National Science Foundation, Army Research Office and Air Force Office of Scientific Research under NSF Grant ATM78-08865. The PAM system was made available by the Field Observing Facility of the National Center for Atmospheric Research which is funded by the National Science Foundation. The project in which the data were collected was commonly referred to as VIN, an acronym formed from the research organizations cooperating in the field effort (University of Virginia, Illinois State Water Survey, and NOAA).

REFERENCES

Byers, H. R., and R. R. Braham, Jr., 1949: *The Thunderstorm.* U.S. Government Printing Office, 282 pp.

Charba, J., 1974: Application of gravity current model to analysis of squall-line gust front. *Mon. Wea. Rev.*, **102,** 140–156.

Goff, R. C., 1976: Vertical structure of thunderstorm outflows. *Mon. Wea. Rev.*, **104,** 1429–1440.

Purdom, J. F. W., 1979: The development and evolution of deep convection. *Preprints 11th Conf. Severe Local Storms*, Kansas City, Amer. Meteor. Soc., 143–150.

——, 1982: Thunderstorm trigger mechanisms over the southeast United States. *Preprints 12th Conf. Severe Local Storms*, San Antonio, Amer. Meteor. Soc., 487–488.

Tepper, M., 1950: A proposed mechanism of squall lines: The pressure jump line. *J. Meteor.*, **7,** 21–29.

Wakimoto, R. M., 1982: The life cycle of thunderstorm gust fronts as viewed with Doppler radar and rawinsonde data. *Mon. Wea. Rev.*, **110,** 1060–1082.