U. S. DEPARTMENT OF COMM
Luther H. Hodges, Secretary
WEATHER BUREAU
F. W. Reichelderfer, Chief

NATIONAL SEVERE STORMS PROJECT

REPORT No. 18

The Thunderstorm Wake of May 4, 1961

by
Dansy T. Williams
National Severe Storms Project, Kansas City, Mo.

Washington, D. C.
August 1963

CONTENTS

THE THUNDERSTORM WAKE OF MAY 4, 1961[1]

Dansy T. Williams
National Severe Storms Project
Kansas City, Mo.

ABSTRACT

The nocturnal thunderstorms occurring over the National Severe Storms Project Beta Network during the night of May 3-4, 1961 have been studied to show the features of the *thunderstorm wake*. In this region, to the rear of the active thunderstorm, there is a fall in surface pressure which is called the *wake depression*. It is a hydrostatic pressure fall which results as warm, dry air is produced aloft by subsidence at the trailing edge of the thunderstorms. The thunderstorm wake is most pronounced in the dissipating *thunderstorm system*, and the warm, dry air produced may locally reach the surface, as the *warm wake*.

The warm, dry air may have its moisture restored rapidly by horizontal advection and by the evaporation of the earlier rainfall. The production of considerable warm, dry air aloft and the rapid acquisition and vertical transport of moisture from the surface provides an air mass which continues to be thermodynamically favorable for additional thunderstorm activity.

I. INTRODUCTION

During the spring of 1961, the National Severe Storms Project operated a small-scale surface network in south-central Oklahoma. Identified as the Beta network, it consisted of 36 stations spaced in oblique checkerboard fashion at 10 to 15-mi. intervals. Observations of surface pressure, temperature, relative humidity, wind, and rainfall were recorded continuously in graphic form. Sample records of pressure, temperature, and relative humidity are shown in figure 1. A detailed index and description of this network has been prepared by Fujita [1]. Methods of analyzing the data have been described by Williams [2]. The data have been used for a number of case studies.

The nocturnal thunderstorm case of May 3-4, 1961, was featured by the *thunderstorm wake*, a volume to the rear of the active thunderstorms characterized by pressure falls at the surface and by temperature rises and humidity falls aloft that extended locally down to the surface. It is the purpose of this paper to report on this feature. Additional features of the case are described in a more extensive work [3] which is on file at NSSP, Kansas City, Mo.

---

[1]Portions of this paper have been presented at the Conference on Severe Storms, Norman, Oklahoma, February 13-15, 1962.

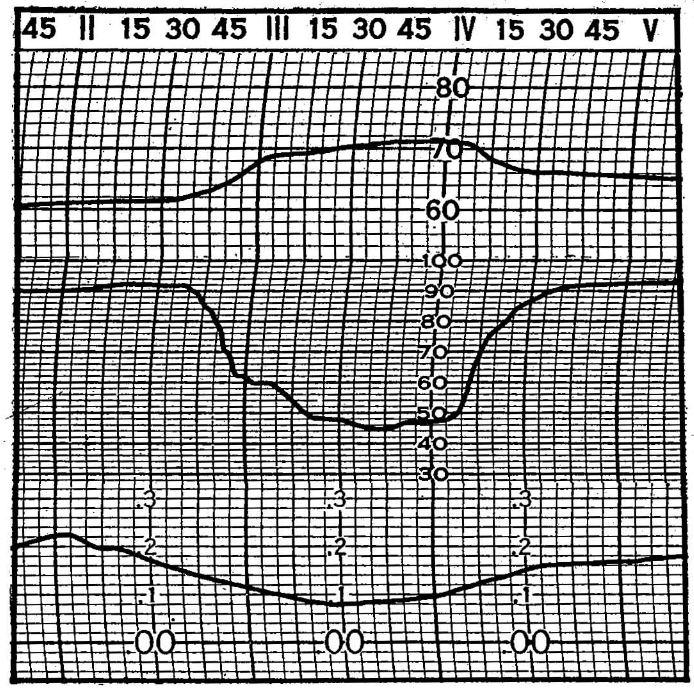

Figure 1.- Microbarograph, thermograph, and hygrograph traces from Station 22 for 0130-0530 CST, May 4, 1961. The warming and desiccation occurring with the pressure fall may be noted.

2. BETA NETWORK ANALYSES

The basic analyses were made with respect to pressure and radar, temperature, relative humidity, and rainfall at 5-min. intervals for the period 1900 CST, May 3, to 1100 CST, May 4. Due to space limitations only a few of the analyses are presented: a series at 30-min. intervals from 0100-0500 CST, May 4, shown in figures 2-10. The northern row of stations, numbers 1-6, have been cropped in the figures, since the features of interest did not extend that far north.

In the sea level pressure analyses the isobars are drawn at 0.02 in. Hg intervals. High and low centers are indicated by "H" and "L," with central values labelled. The leading edges of pressure rises and the troughs of pressure falls are indicated by heavy solid and heavy dashed lines, respectively. Further identification is provided by the encircled letters and numbers, the number designating the appearance of each type of line over the network from a beginning time of 1900 CST, May 3. Radar echoes, as traced from the scope photographs of the WSR-57 at Will Rogers Field, Oklahoma City, are shown as stippled areas. Values of circuit attenuation (estimated) are indicated.

In the temperature analyses the isotherms are drawn at 2° F. intervals. Warm and cold centers are indicated by "W" and "C," and central values are labelled. The leading edges of temperature rises and the troughs of temperature falls are indicated by warm and cold front symbols, respectively. Further identification is provided by the encircled letters and numbers.

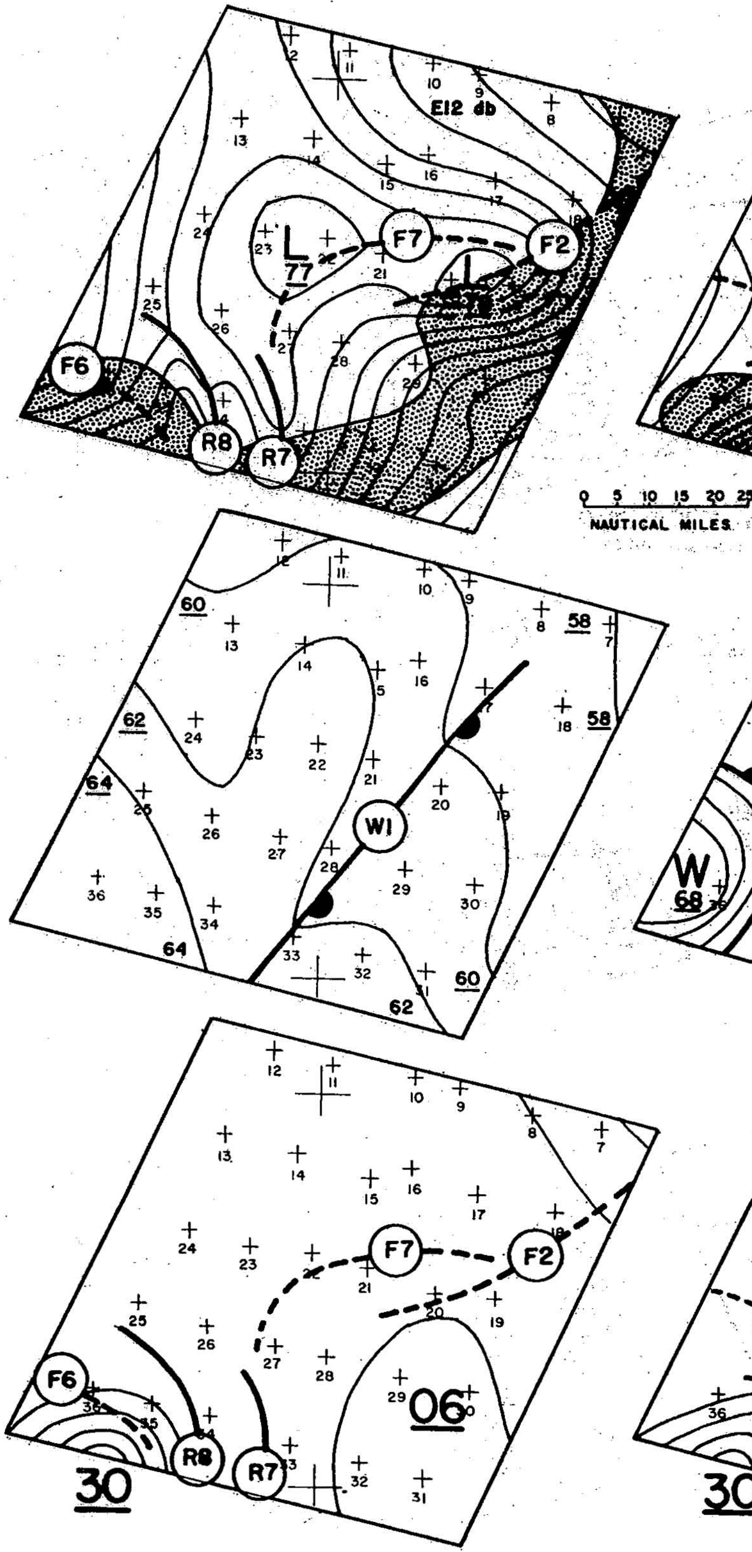

Figure 2.- Beta network analyses of pressure and radar (upper), temperature (middle), and rainfall (lower) for 0100 CST, May 4.

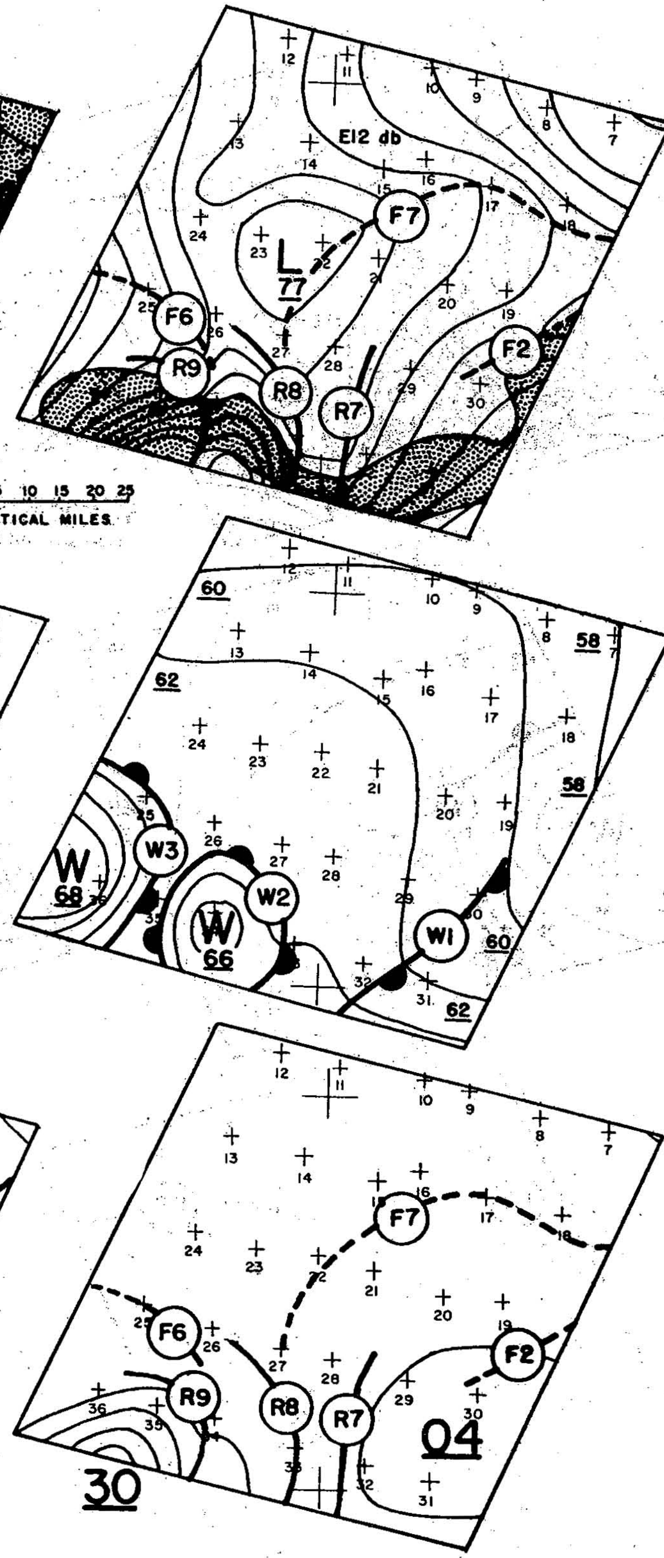

Figure 3.- Beta network analyses for 0130 CST, May 4.

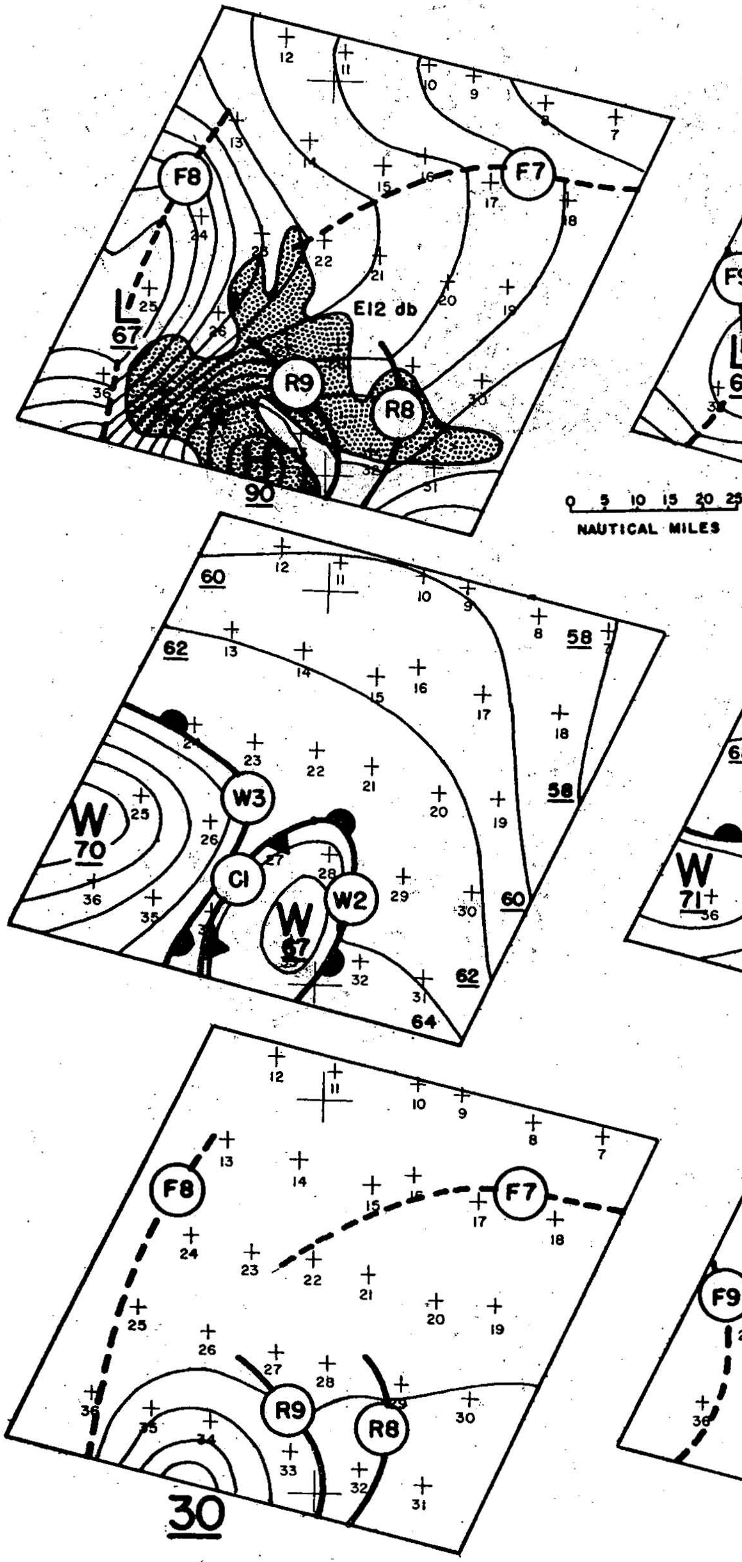

Figure 4.- Beta network analyses for 0200 CST, May 4.

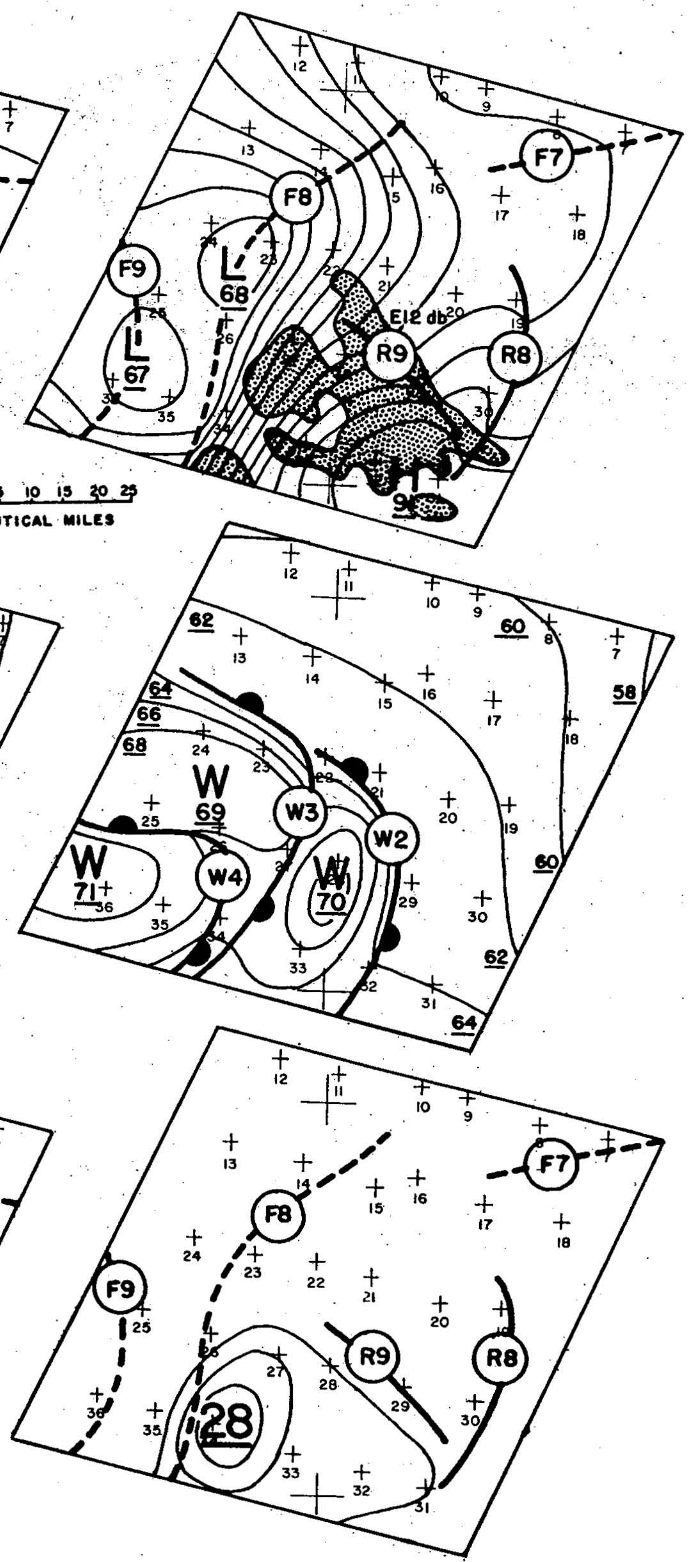

Figure 5.- Beta network analyses for 0230 CST, May 4.

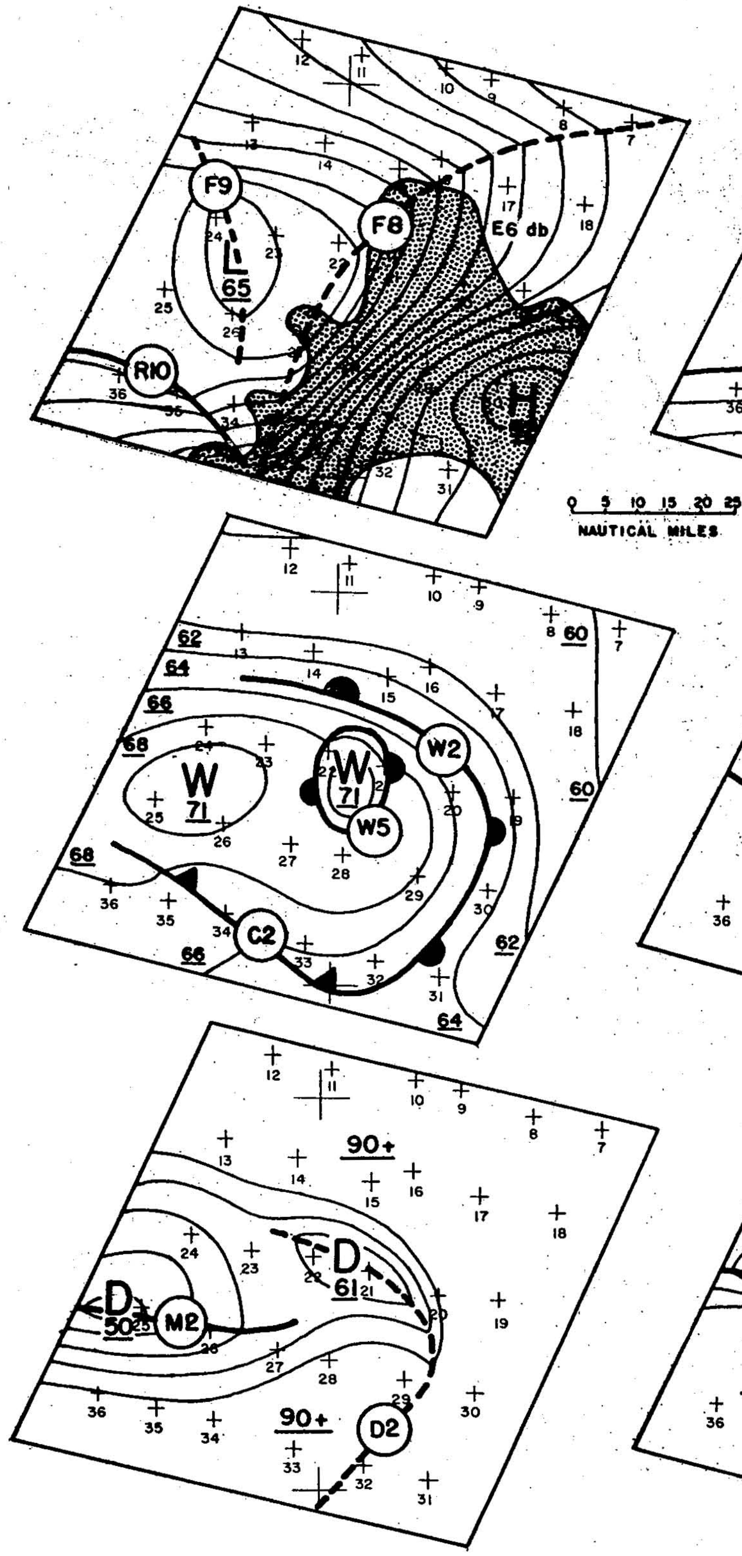

Figure 6.- Beta network analyses of pressure and radar (upper), temperature (middle), and relative humidity (lower) for 0300 CST, May 4.

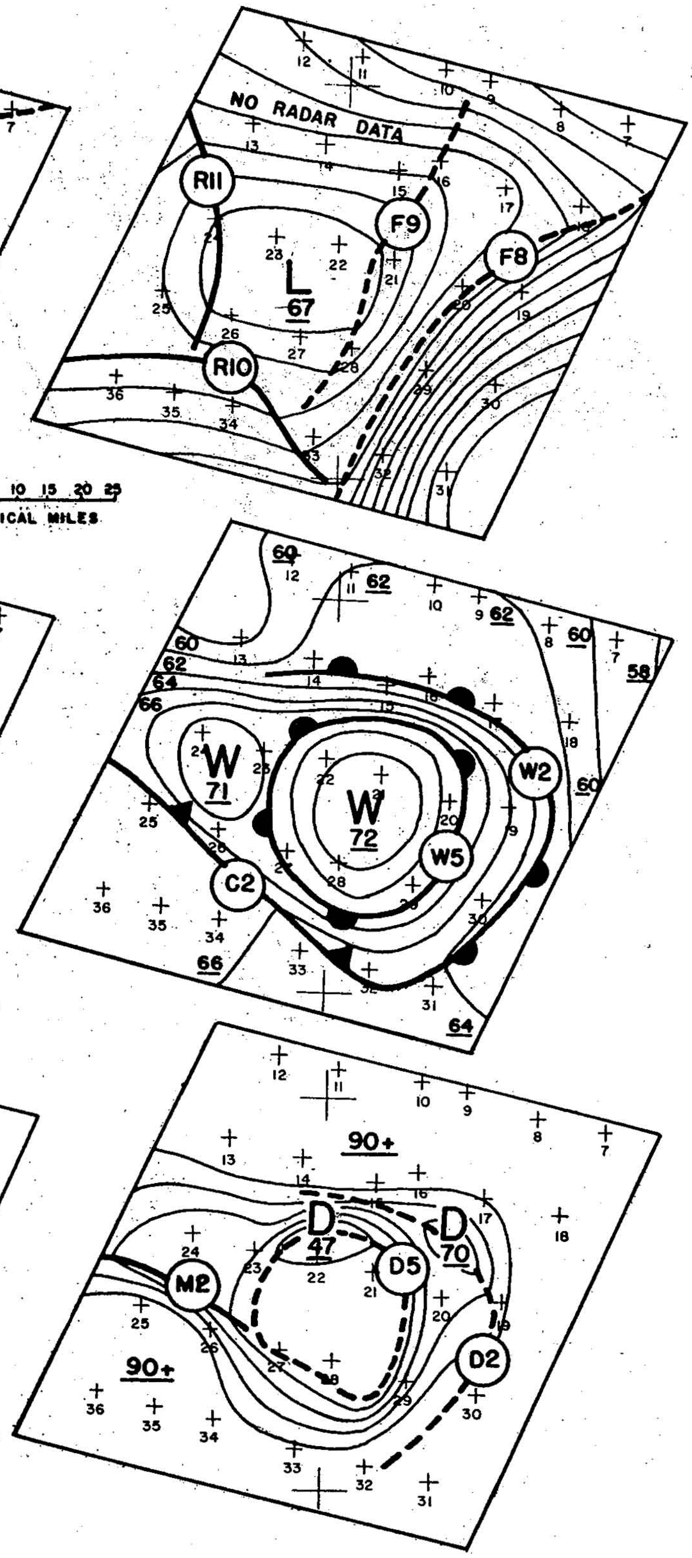

Figure 7.- Beta network analyses for 0330 CST, May 4.

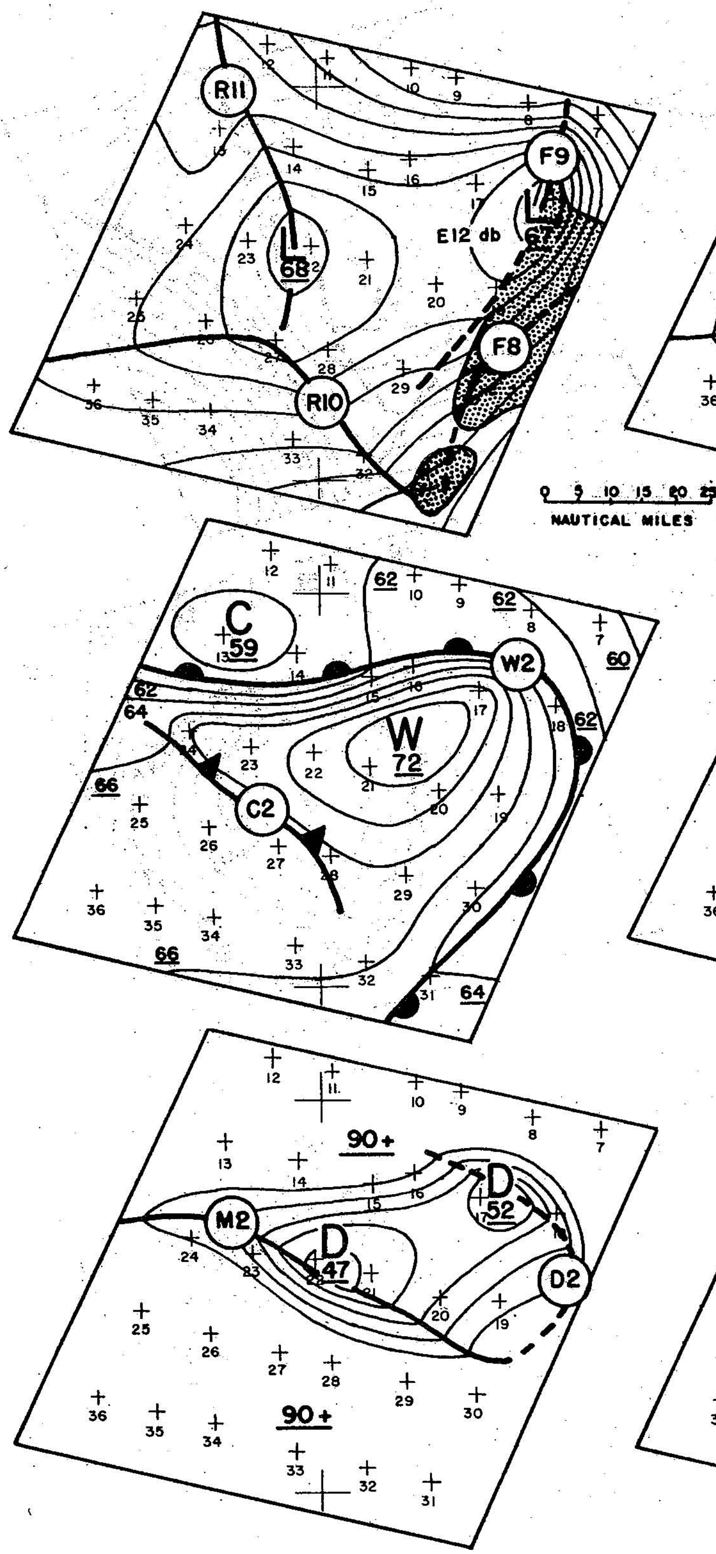

Figure 8.- Beta network analyses for 0400 CST, May 4.

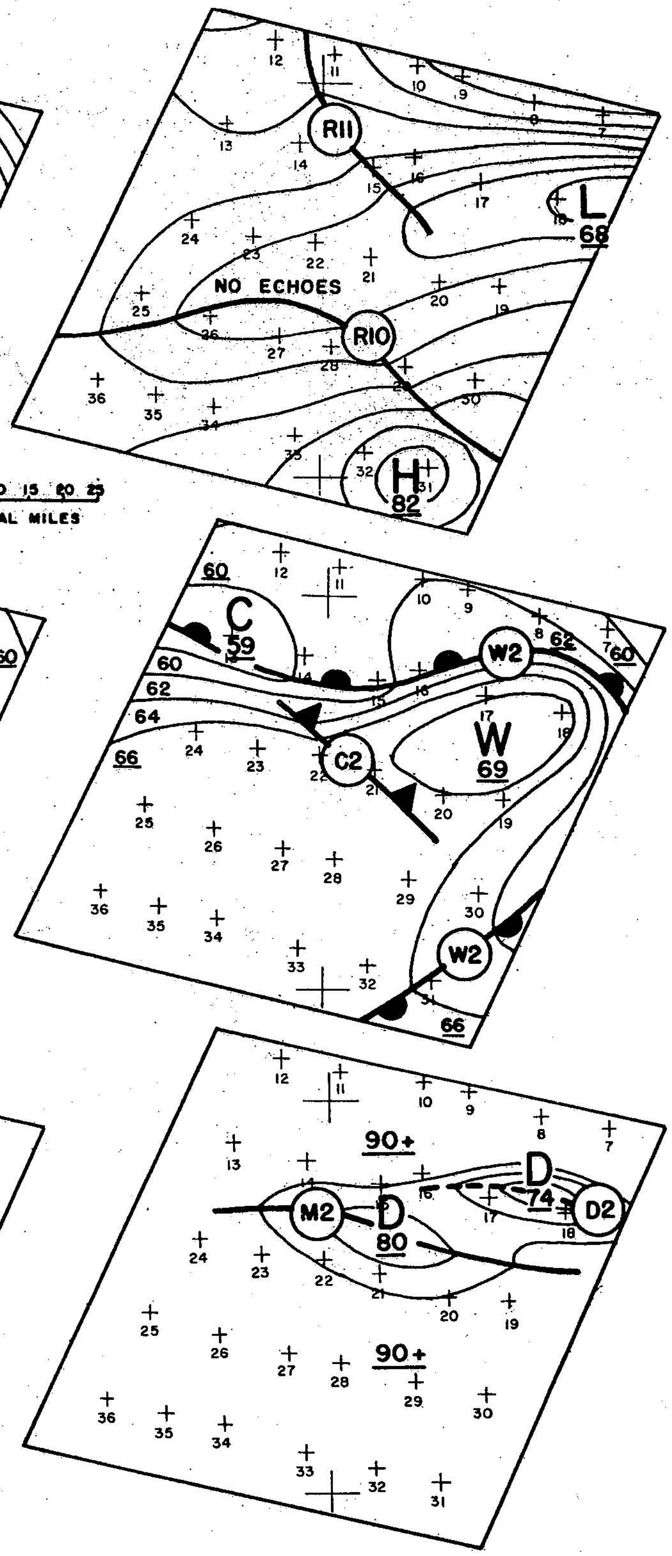

Figure 9.- Beta network analyses for 0430 CST, May 4.

In the rainfall analyses the isohyets are drawn at 0.10 in. (30 min.)$^{-1}$ intervals, and maximum values have been indicated. The first isohyet represents the extent of measurable rainfall. Pressure change lines have been added. Rainfall analyses are shown only to 0230 CST, since rainfall thereafter was limited to the extreme southeastern portion of the network, with amounts that did not exceed 0.05 in. (30 min.)$^{-1}$.

In the relative humidity analyses the isopleths have been drawn at 10 percent intervals. Moist and dry centers are indicated by "M" and "D," and central values are labelled. The leading edges of humidity rises and the troughs of humidity falls are indicated by heavy solid and heavy dashed lines, respectively. Further identification is provided by the encircled letters and numbers. Relative humidity analyses are shown only for 0300-0500 CST, this being sufficient to demonstrate the manner in which the humidity changed.

Numerous change lines were present over the network during the period 0100-0500 CST. The warm, dry areas corresponded generally to areas of pressure fall, but not all of the pressure falls were so featured. Temperatures rose by as much as 11° F. to values that exceeded any observed previously. Humidities fell to as low as 45 percent from values that were above 90 percent. The warming and desiccation occurred generally in the echo-free air to the rear of the thunderstorms and in areas of diminishing or no rainfall. The radar echo

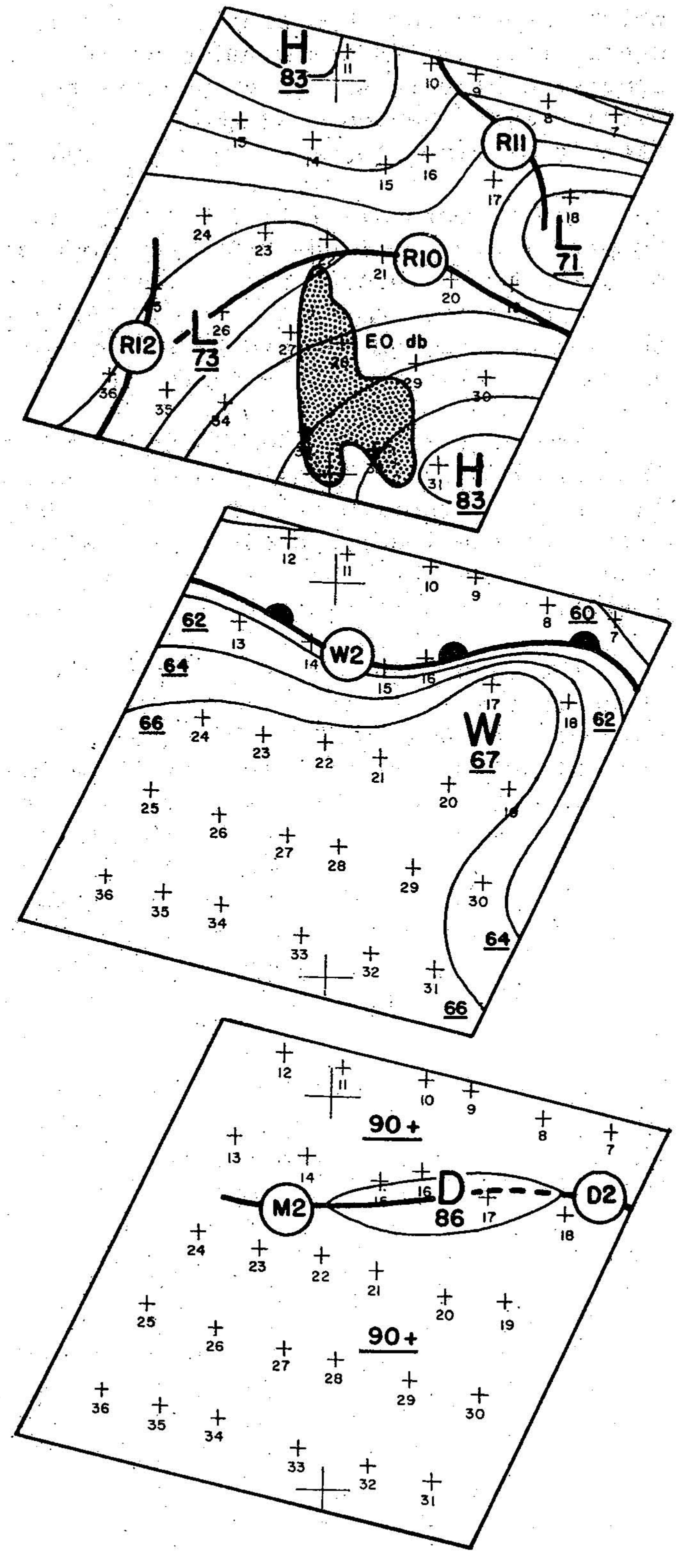

Figure 10.- Beta network analyses for 0500 CST, May 4.

which was present when temperature rise line W2 was generated, was separated nearly into two as the warming progressed. Both rise lines W2 and W5 were generated at points within the network. The remaining rise lines were in existence when they entered the network. There was a tendency for the temperature rise lines to merge, and by 0400 CST all of them were contained in W2.

The temperature fall lines, C1 and C2, which followed the rises, were comparatively small; by 0500 CST temperatures were still 66°-67° F. in the area where the changes had occurred. The humidity rises, M1 and M2, which accompanied the temperature falls, were much greater, however; by 0500 CST the humidities had reached 90 percent or more everywhere except at Station 27, where the value was 86 percent.

Temperature rises and humidity falls, following the passage of daytime thunderstorms, are usually interpreted as a recovery of these features, following the temperature falls and humidity rises that may have occurred earlier near the leading edges of the storms. Such could not have been the case with the above storms, since temperature and humidity changes were negligibly small at the onset of the storms.

The temperature rises and humidity falls, following the passage of thunderstorms, are more common than is generally known. A preliminary analysis of the 1962 and 1963 Beta network data showed many such occurrences, most of which were with respect to nighttime thunderstorms. In the bulk of these, the temperature rises amounted to less than 10° F., but there were three cases in which rises of 15°-20° F. occurred. Occurrences outside the Beta network have been documented in which the temperatures attained were near 100° F. Strong winds and low humidities accompanying the rises have even withered vegetation as well as alarmed residents. These extreme occurrences are quite local and are experienced only rarely. Garrett[2] has termed these phenomena, "heat bursts." The occurrences of May 4 were not of this intensity.

The pressure falls to the rear of the thunderstorm have been called pressure pulses [4], depression waves [5, 6, 7], and wake depressions [8]. The latter term has been used by Fujita, but in a recent paper [9] he indicates that it should be abolished, since the phenomenon sometimes occurs with respect to a storm which is not moving; hence, has no "wake." Nevertheless, the term is very descriptive, and since the pressure falls considered here were with respect to moving storms, they will be termed *wake depressions*. The associated temperature rises and humidity falls will be termed *warm wakes*, and the volume characterized by the wake depression, the warm wake, and the echo-free air to the rear of the thunderstorm will be called the *thunderstorm wake*. The volume of both the active thunderstorm and the thunderstorm wake will be called the *thunderstorm system*.

---

[2] Richard Garrett is Meteorologist in Charge, WBAS, Topeka, Kansas. He has used the term, "heat burst," in correspondence and conversation with the author. The term is very descriptive, but it is doubtful that there is any addition of heat in the process.

3. MECHANISM OF THE WAKE DEPRESSION

The wake depression could result from a decrease in mass of the column or from vertical accelerations on the mass. The increase in temperature at the surface in close association with the wake depression indicates that a reduction in mass is accomplished by warming.

Warming aloft is indicated also by the 0501 CST sounding at ADM (Ardmore, Okla.) in figure 11, which was made in close proximity to pressure fall lines F8 and F9. The portion of the sounding from 941 to 512 mb. suggests strongly that warming and desiccation had occurred by subsidence. However, the warm, dry air did not reach the surface at ADM, as was the case in portions of the network to the north and west. The fall in pressure at ADM began at 0357 CST, and by 0501 CST a net fall of 0.14 in. Hg had occurred.

There was no sounding immediately prior to the passage of the pressure fall lines, so it can only be assumed that the warm, dry layer at 0501 CST occurred as pressures fell. An estimated sounding for 0357 CST was obtained by considering the manner in which the warm, dry layer might have occurred. This could have resulted from the addition of heat, horizontal advection of warmer air, or subsidence through the layer with respect to an initial lapse rate less than the dry adiabatic rate.

Addition of heat by insolation may be ruled out, since the warming ocurred prior to sunrise. Latent heat of condensation may have been released earlier, but the extreme dryness of the layer indicates that none was being released at 0501 CST.

A small portion of the warming was due to horizontal advection. Panofsky's equation of thermal advection [10], which gives the instantaneous rate from winds aloft data, showed warm advection at 0501 CST that ranged from 3.1° C. $hr.^{-1}$ at 900 mb. to near zero at 650 mb.

It is concluded that the desiccation and the remainder of the warming was accomplished by subsidence. Assuming the layer to have been saturated prior to subsidence, a coincident curve of temperature and moisture was constructed by locating the points from which parcels would have had to descend to produce the 0501 CST values of mixing ratio and temperature, less the effects of horizontal advection. This curve was assumed to approximate the 0357 CST temperature-moisture curve from 950 to 550 mb.

The temperature and moisture values at 0501 CST and the assumed values for 0357 CST were converted to virtual temperature, and these were used in the hydrostatic equation to yield the pressure change at the surface. This was computed to be 0.21 in. Hg, a value somewhat larger than the observed fall of 0.14 in. Hg. Lack of better agreement could result from (1) drift of the sounding balloon into a more intense portion of the pressure fall, (2) disregard of hydrostatic changes above 550 mb., (3) inaccuracy of the assumed sounding for 0357 CST, and (4) neglect of vertical accelerations.

The first possibility does not appear significant. The observation point was approximately 15 n. mi. south-southwest of the center of lowest pressure, and the winds aloft maintained the sounding instrument in approximately the same position with respect to the center for at least the first 15 minutes of the observation.

The second possibility could have been appreciable. Although the mean horizontal advection from 550 mb. to the top of the sounding was slightly warm, a rather cold tropopause of -68.6° C. at 179 mb. at 0501 CST indicates that high-level cooling might have occurred, and such cooling would have reduced the net pressure fall.

As to the third possibility, the assumed moisture and temperature values could certainly be in error. In particular, it appears that the layer might have been somewhat less than saturated at 0357 CST, and this would have resulted in a somewhat lesser value of the pressure fall.

As to the fourth possibility, the changes in surface pressure due to vertical accelerations would have been negligibly small. Mean vertical velocities that would have been required to effect the temperature and moisture changes at ADM in the layer from 950 to 550 mb. from 0357 to 0501 CST are shown in figure 12. The maximum downward speed was computed to be 64 cm. sec.$^{-1}$ at the 750 mb. level. Vertical velocities at the 850, 700, and 500 mb. levels were computed also by a dynamic-kinematic method [11] and are shown also in figure 12. In this computation the maximum downward speed was 33 cm. sec.$^{-1}$ at the 700-mb. level. The difference in values is due to the methods used. In the former, a point value at ADM, averaged with respect to the time period 0357-0501 CST, was obtained. In the latter an instantaneous value at 0501 CST, areally averaged with respect to a circle of 60 n. mi. radius from ADM, was obtained. In either case the accelerations involved in reaching the velocities would have resulted in negligibly small pressure changes.

It is concluded that the wake depression near ADM at 0501 CST resulted from warming and desiccation in a layer from just above the surface to 550 mb. and that the warming and desiccation occurred primarily from subsidence motion. The subsidence appears to be a typical feature of the thunderstorm wake. However, a description of its mechanism, as related to the overall thunderstorm system, is beyond the limits of the data available for this case.

4. THE WARM WAKE

The local extent of the warm wake at the surface has been shown in figures 2-10. That the warm wake may be of greater extent aloft is indicated by the wake depressions which occurred without surface warming and by the 0501 CST ADM sounding in figure 11. Evidence of similar but lesser amounts of warming and desiccation are indicated, also, by the 0530 CST sounding at OKC (Oklahoma City, Okla.) and by the 0502 CST sounding at LTS (Altus, Okla.) shown in figures 13 and 14. The small sectional charts in figure 15 show the areal distribution of the warmer air at several constant pressure levels. The warmer air sloped northwestward with height, with a warm center over ADM at 900 and 800 mb. and a warm ridge along an axis from OKC to SPS (Wichita Falls, Tex.) at 700 and 600 mb. The question arises as to why the warm wake should be so extensive aloft and so local at the surface. A partial answer is found by considering the surface fields of horizontal velocity divergence.

The divergence field at 0230 CST, May 4, computed from the surface wind data with respect to a 20 n. mi. measuring interval, is shown in figure 16. The divergence field may be compared with the pressure and temperature analyses for the same time in figure 5. Pressure fall lines F8 and F9 were present in an area of convergence, and the center of maximum convergence was located roughly in the area of lowest pressure. Pressure rise lines R8 and R9 were present in an area of positive divergence, and the center of maximum divergence was located near the center of the radar echo and a short distance northwest of the area of highest pressure. The newly formed warm area to the rear of temperature rise line W2 was contained in a region of positive divergence, but the warm areas to the rear of W3 and W5 were largely in regions of convergence.

Vertical motions at a small height above the surface would have been upward in the regions of surface convergence and downward in the regions of surface divergence. With the warm wake generated aloft by downward motion an interface bounding the lower extent of the warmer temperatures would be established some distance above the surface in regions of surface convergence. Such appeared to have been the case at ADM where the warm wake did not reach the surface. The only region in which a warm wake could extend down to the surface would be in a region of surface divergence. This was true with respect to W2, where the surface warming was present in a region of surface divergence. Surface divergence would be necessary to permit the warm air to reach the surface; however, once the warm air had reached the surface, convergence would not destroy it. It would persist until horizontal advection carried it away, or until other processes modified it. Such appears to have been the case with respect to W3 and W4, which were generated prior to moving into the network.

It appears, then that a time sequence of events is responsible for the warm wake aloft, the wake depression, and the warm wake at the surface. First, subsidence motion produces a layer of warm, dry air aloft. The resulting increase in mean virtual temperature of the column then produces the wake depression. The resulting pressure gradients establish a wind field which results in surface convergence in the wake depression. The convergence induces upward motions in a shallow layer above the surface, and this prevents further descent of the warm, dry air. Warm, dry air can reach the surface only in a corridor between the thunderstorm and the wake depression, which is characterized by positive divergence. In many instances, this corridor might not exist, and there would be no warm wake at the surface. The comparative rarity of warm wakes at the surface, and their local extent when they do occur, indicates that this is usually the case.

Fujita [8] has shown that the stage of thunderstorm activity corresponds to the relative amounts of excess pressure and deficit pressure of the system. Late stages of thunderstorm activity are characterized primarily by deficit pressure; i.e., the wake depressions are more pronounced than the pressure rises. Using Fujita's classification, it was found that the systems occurring over the Beta network during the late evening hours of May 3 were primarily developing or mature systems. Those occurring during the early morning

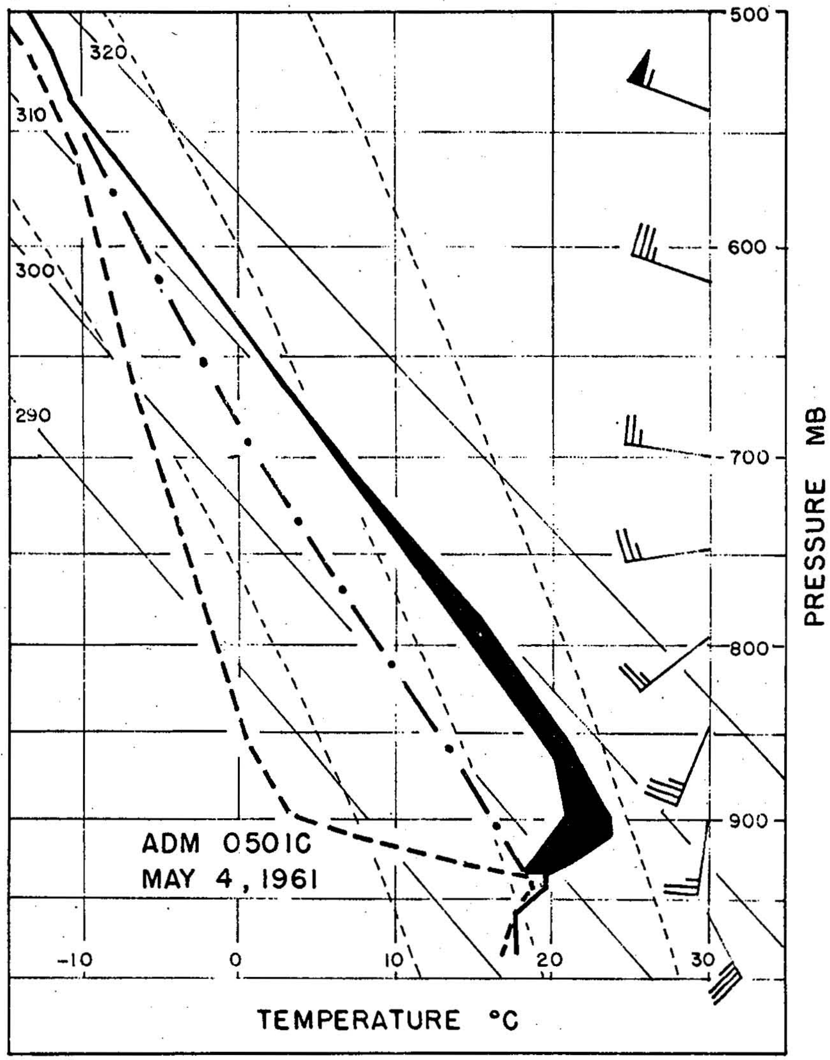

Figure 11.- Sounding from the surface to 500 mb. at Ardmore, Okla., 0501 CST, May 4. The heavy solid line is temperature, and the heavy dashed line is dew point. The heavy dash-dot-dash line is the assumed 0357 CST coincident curve of temperature and dew point. The shaded area shows the portion of the warming due to horizontal advection from 0357-0501 CST.

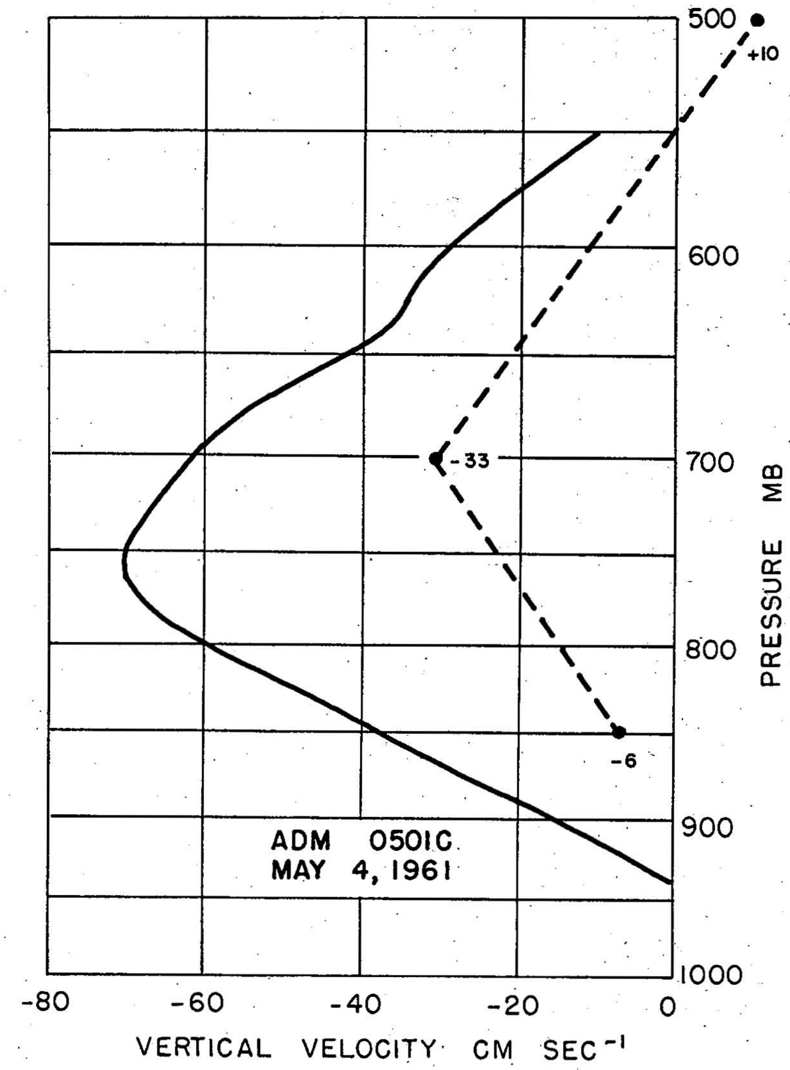

Figure 12.- Distribution of mean vertical velocity with height from the surface to 500 mb. at Ardmore, Okla. Mean vertical velocities that would have been required to produce the temperature and moisture changes from 0357-0501 CST are shown by the heavy solid line. Mean vertical velocities with respect to the area at 0501 CST, as computed by the dynamic-kinematic method, are shown by the heavy dashed line.

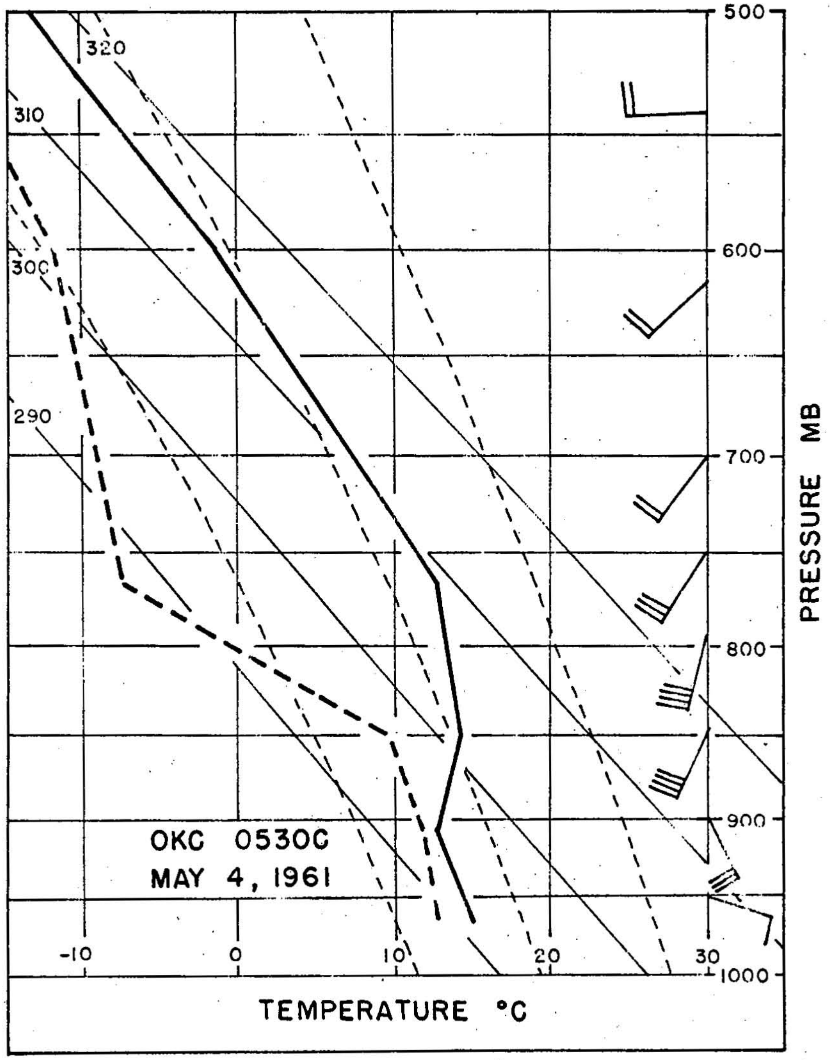

Figure 13.- Sounding from the surface to 500 mb. at Oklahoma City, Okla., 0530 CST, May 4.

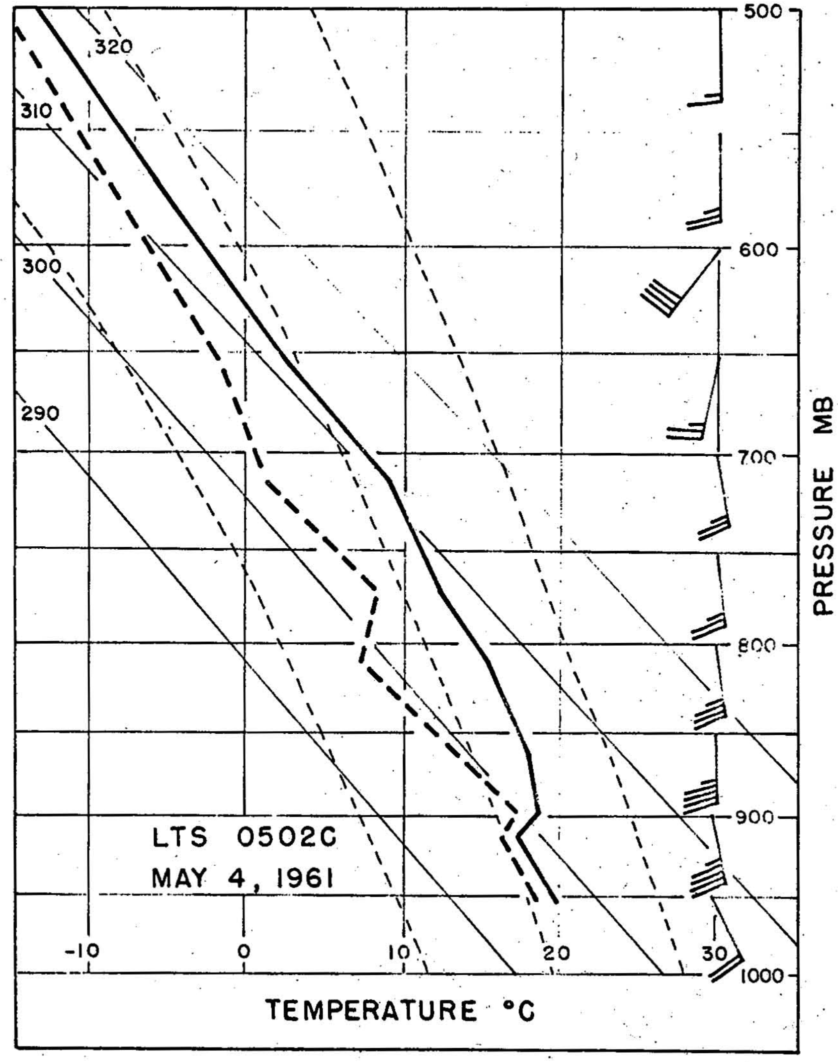

Figure 14.- Sounding from the surface to 500 mb. at Altus, Okla., 0502 CST, May 4.

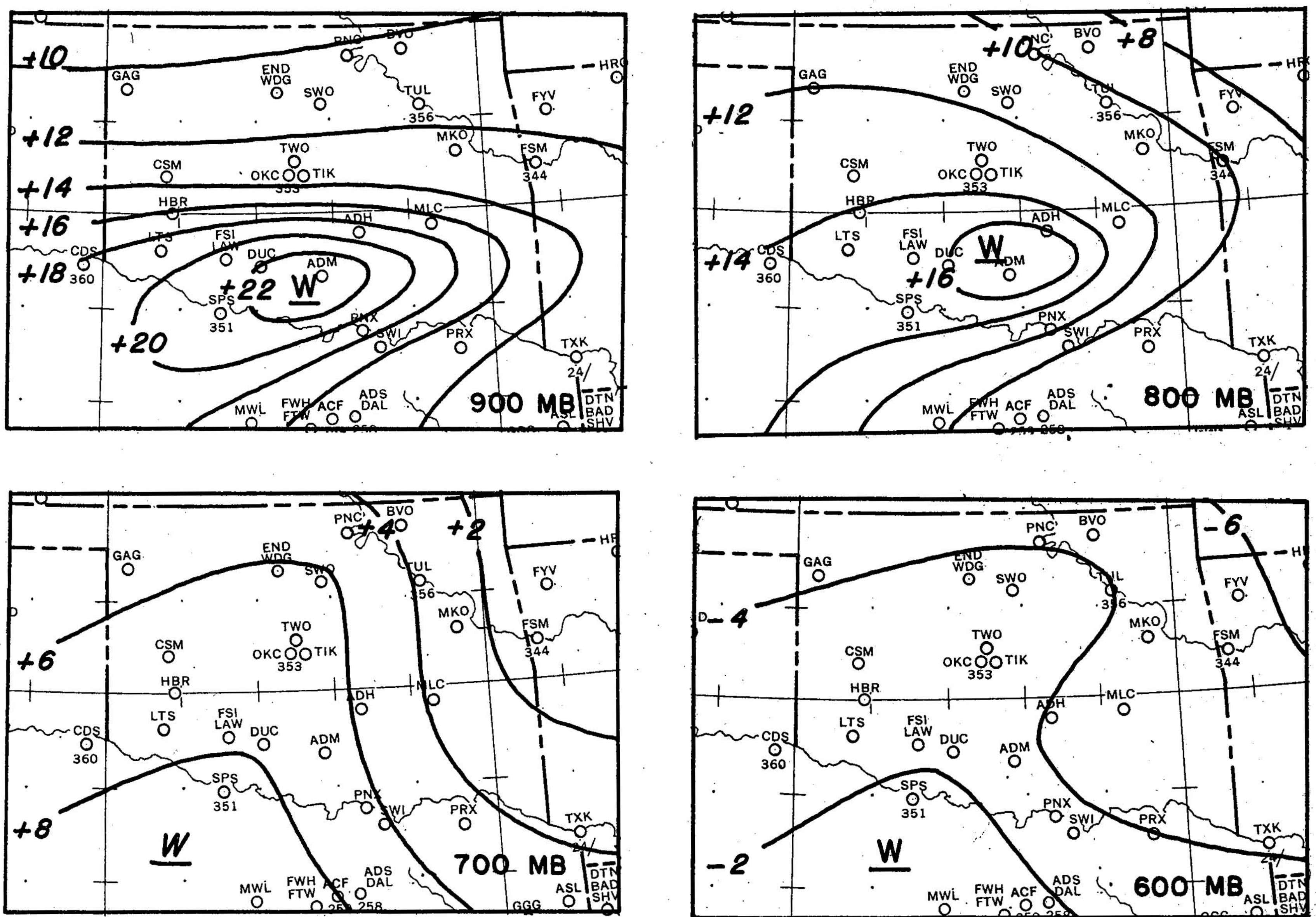

Figure 15.- Sectional charts of temperature at 0600 CST, May 4, for 900, 800, 700, and 600 mb. Isotherms are drawn at 2° C. intervals.

hours of May 4 were primarily dissipating or remnant systems. The systems during the late evening were not characterized by warm wakes. The substantial warm wakes occurred from 0115 to 0500 CST on May 4, when the thunderstorm activity was diminishing. It appears, then, that the warm wake is most characteristic of dissipating thunderstorms.

5. MODIFICATION OF THE WARM WAKE

The warm air was quasi-permanent, although the dryness was not. The continued presence and sharp boundary of the warm air at 0800 CST, May 4, is shown in figure 17. It was, in fact, maintained into the afternoon of May 4, as a quasi-stationary front across the Beta network. Average humidities recovered rapidly, however, with values at 0500 CST within 1 percent of those at 0100 CST.

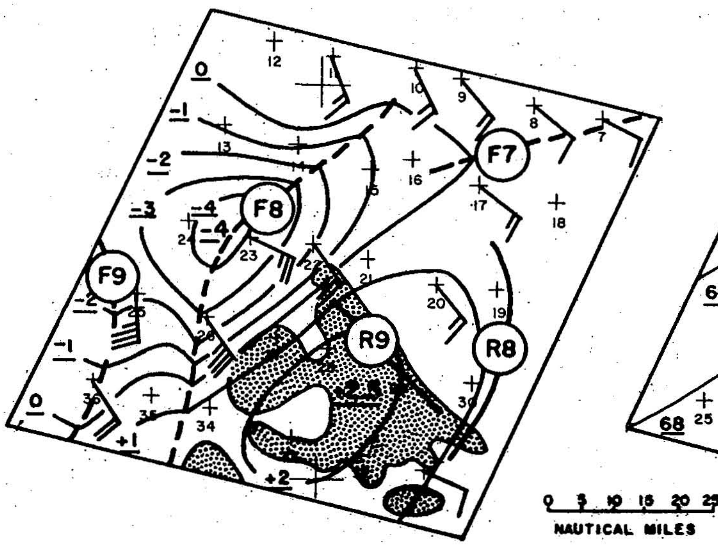

Figure 16.- Horizontal velocity divergence at the surface, 0230 CST, May 4. Isopleths are drawn at 1 x 10^{-4} sec.$^{-1}$ intervals. Surface winds are plotted with a whole barb equal to 10 kt., and the positions of the pressure change lines have been added. Radar echoes are also shown.

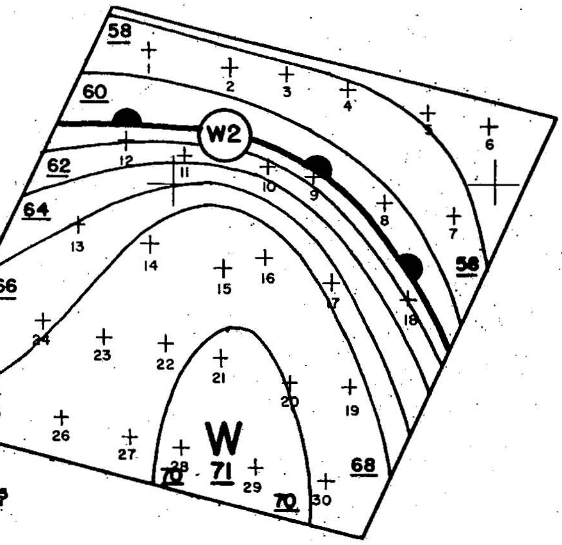

Figure 17.- Beta network temperature analysis for 0800 CST, May 4.

It was noted, also, that the amounts of temperature and humidity change varied appreciably in the same local area. For example, the humidity fell to only 80 percent at Station 19 at 0405 CST, while it fell to 54 percent at Station 18 at 0420 CST and to 45 percent at Station 17 at 0420 CST. Corresponding temperature rises for these stations were 5.0°, 8.5°, and 11.0° F, respectively. Questions arise as to why the temperature and humidity changes were so appreciably different at adjacent stations and why the humidity recovered while the temperature did not.

The non-uniformity of the changes may have been due to variations in the processes causing them. However, it was noted that the humidity falls appeared to have been less in the regions of the heavier rainfall. This suggests that the evaporation of the earlier rainfall had raised the humidity of the newly produced dry air and that continued evaporation had shortened the time that the air remained dry.

This hypothesis was tested by comparing the total rainfall for the period 1900 CST, May 3, to 0500 CST, May 4, with the average *humidity deficit* for the period 0100 to 0500 CST, May 4. The average humidity deficit was obtained at all stations by averaging their humidities at 5-min. intervals from 0100 to 0500 CST and subtracting this value from the humidity value present prior to the passage of the first humidity fall line, D1. An analysis of the average humidity deficit is shown in figure 18. Maximum deficit values were approximately along a line connecting stations 17, 22, 23, 25, and 36. Minimum values were present along boundaries which marked the area of the humidity falls.

The total rainfall at stations 7, 8, and 13-36 for the period 1900 CST, May 3, to 0500 CST, May 4, is shown in figure 19. One may note some similarity in the isopleths of figures 18 and 19; e.g., at Station 36 a large value of the humidity deficit corresponds to a small amount of rainfall, while at Station 19 a small value of the humidity deficit corresponds to a large amount of rainfall

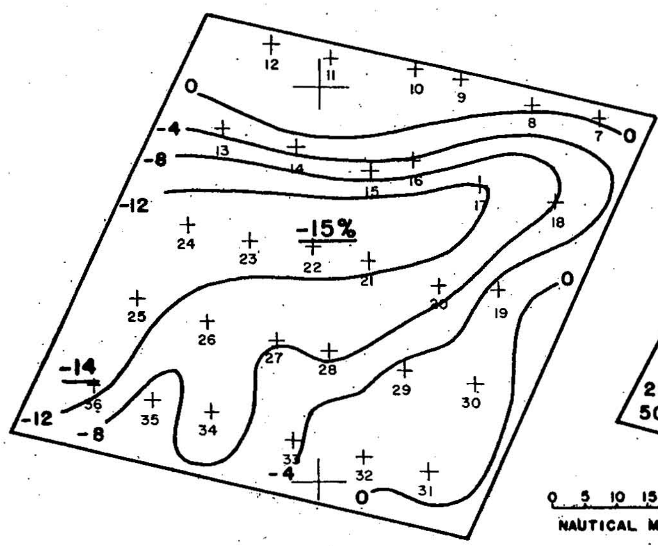

Figure 18.- Average humidity deficit analysis for the period 0100-0500 CST, May 4. Isopleths are drawn at 4 percent intervals.

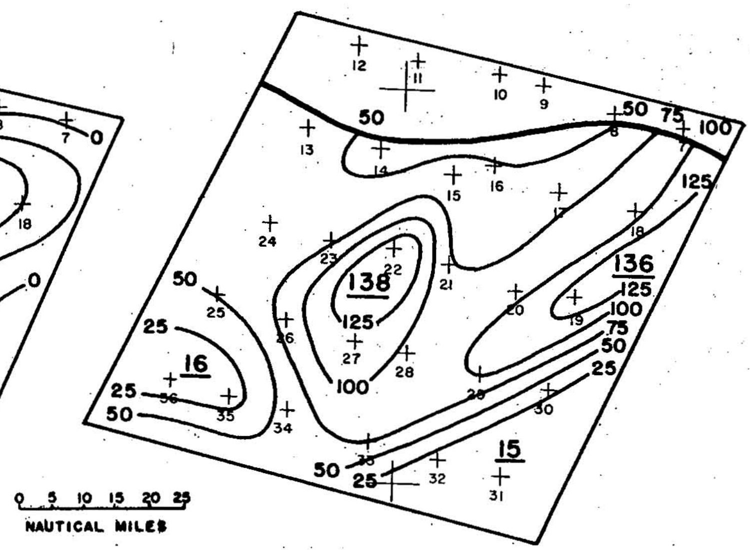

Figure 19.- Total rainfall for the period 1900 CST, May 3, to 0500 CST, May 4. Isohyets are drawn at 0.25 in. intervals.

To test the goodness of the correspondence, the scatter diagram shown in figure 20 was constructed. Only Stations 17-30 and 33-36 were used. Most of the stations near the boundary of the area affected were deleted, since small values of the humidity deficit there would likely result from the weakness of the processes causing them. The diagram shows a fair grouping of all stations, except Stations 22 and 35. Station 35 probably should have been deleted, since it was near the southern boundary of most of the humidity fall lines. There is no apparent explanation for the poor fit of Station 22. An envelope enclosing all stations, except Stations 22 and 35, was constructed, and a median curve was fitted within the envelope. The median curve shows that the humidity deficit decreased as rainfall amounts increased, with the decrease most rapid for rainfall amounts in excess of one inch. The correspondence is considered quite good in view of the fact that other factors, such as runoff rate, loss of moisture into the ground, nature of the ground surface, and the effects of wind, were ignored.

To determine whether the evaporation of rainfall was the only modifying process, the small area including stations 17-20, 22, and 28-29, outlined in figure 21, was considered. Station 21 could not be used due to a malfunction of its thermograph. This area was traversed primarily by change lines W2, W5, D2, and D5, and was selected to avoid the complications of too many overlapping change lines. Although it was stated previously that the warm air was quasi-permanent, temperatures did fall somewhat as humidities rose. The amounts of fall, however, were not so great as the previous rises, which suggests that the cooling was accomplished by the evaporation of the earlier rainfall. One needs to determine, however, whether the temperature falls were in agreement with the amount of evaporation that would have been required to produce the observed humidity rises.

The major portions of the changes occurred in 15 minutes' time or less. Table 1 shows the 15-min. changes of temperature, relative humidity, and mixing ratio that occurred. Inclusive times of the changes are also given. On the average, temperature fell 3.5° F., humidity rose 27 percent, and mixing ratio increased by 2.6 gm. kg.$^{-1}$.

In order to ascertain the amounts of change due to evaporation, the wet bulb temperatures of stations in the warm, dry air were computed. These were then used with the temperatures observed 15 min. later to ascertain the increments of relative humidity and mixing ratio that would have been required to reduce the temperatures, assuming

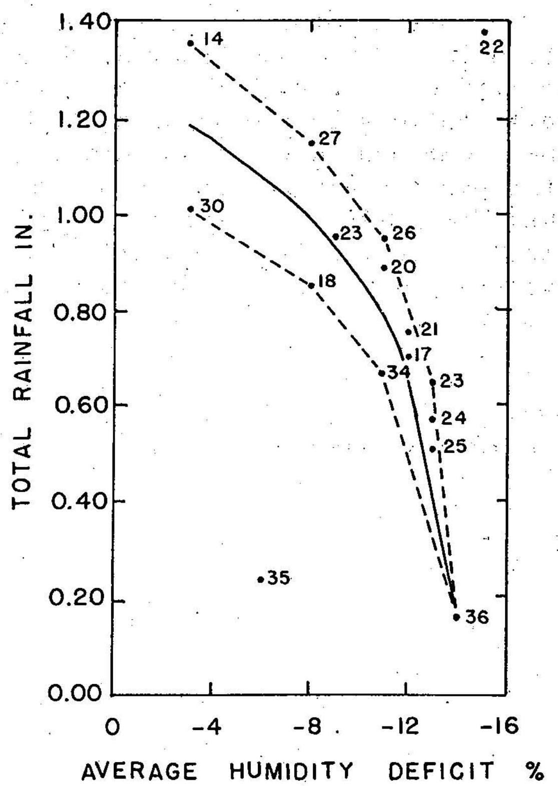

Figure 20.- Scatter diagram of the average humidity deficit and the total rainfall. The envelope of values is indicated by the dashed lines. The median curve is a solid line.

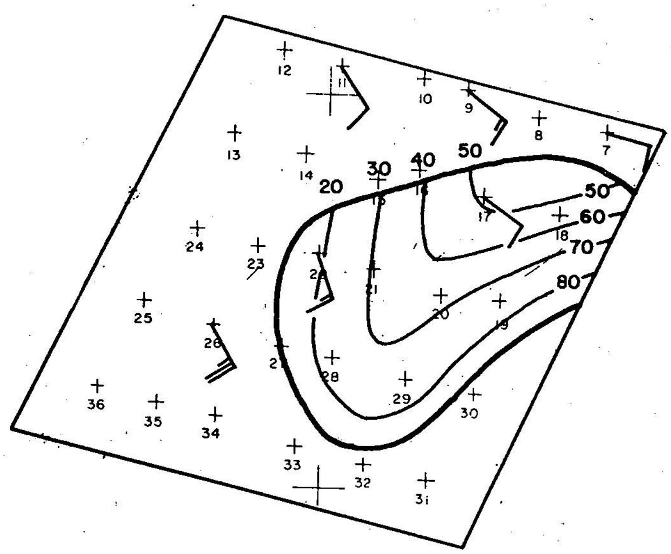

Figure 21.- Analysis of the percentages of moisture increase due to evaporation and advection from 0330 to 0440 CST, May 4. Isopleths are drawn at 10 percent intervals. The upper numbers refer to the percentage of moisture increase due to evaporation, while those to the right refer to the percentage of increase due to advection.

that the wet bulb temperature did not change. The required values are shown in table 1. Cooling by evaporation would have been more than adequate to effect the temperature changes. On the average, a 13 percent increase in relative humidity, or 0.8 gm. kg.$^{-1}$ increase in mixing ratio, would have reduced the temperatures to the observed values. It is quite apparent that the observed changes could have been due only in part to the immediate evaporation of moisture into the warm, dry air.

Table 1. Increments of temperature, relative humidity, and mixing ratio for selected 15-min. periods over a small area traversed by W2, W5, D2, and D5.

Station	Time Period	ΔT	Observed		Required		Excess	
	CST	(°F.)	ΔRH (%)	ΔW (gm.)	ΔRH (%)	ΔW (gm.)	ΔRH (%)	ΔW (gm.)
17	0420-0435	-6.5	34	3.0	23	1.5	11	1.5
18	0425-0440	-2.5	16	1.3	11	0.6	5	0.7
19	0405-0420	-1.5	17	1.6	7	0.4	10	1.2
20	0415-0430	-3.0	23	2.3	12	0.7	11	1.5
22	0405-0420	-3.0	29	3.3	10	0.6	19	2.7
28	0330-0345	-4.0	35	3.8	15	0.9	20	2.9
29	0340-0355	-4.0	33	3.2	16	0.9	17	2.3
Average	---------	-3.5	27	2.6	13	0.8	14	1.8

The mixing ratio increments over and above those required by evaporation are also shown in table 1. They range from 0.7 to 2.9 gm. kg.$^{-1}$. The smaller increments were generally near the northern boundary of the area considered. The percentages of increase are shown in figure 21.

The wind observations indicated a general southeasterly flow over the area considered. Winds, averaged for the period, 0330-0440 CST, are plotted in figure 21. They indicate advection from the south-southeast. Since the air outside the area considered was nearly saturated, ample moisture would have been available to raise the humidities in the area of advection. This being the case, stations near the southern boundaries of the area would have had their humidities increased rapidly by advection. Stations more distant from this boundary would have had a longer time for evaporation to increase their humidities. Such is indicated by the isopleths in figure 21.

It is concluded that the rapid recovery of moisture was accomplished by the combined effects of evaporation of earlier rainfall and advection of moist environmental air. Advection was most effective overall, but for stations most distant from the advection source, evaporation accounted for as much as 50 percent of the moisture increase.

The quasi-permanence of the warm air from the thunderstorm wake and its tendency to recover moisture suggests a process by which warm, moist air may become available for future thunderstorm activity. The dissipating thunderstorm system produces warm, dry air over a considerable area at low and intermediate levels. Moisture is acquired rapidly by the evaporation of the earlier rainfall and by advection. Vertical transport of the moisture may be iniated by low-level convergence in the wake depression and further maintained by daytime heating, which results in additional evaporation of any remaining rainfall. These processes then provide the low-level depth of warm, moist air which is typically required for thunderstorm activity. Above this depth, the remaining warm, dry air of the thunderstorm wake would act as a restraint to convection, until such time as it might be penetrated by upward motions from below.

These processes suggest a cycle of thunderstorm occurrences. Such is frequently the case. Thunderstorms occurred again over the Beta network between 0800 and 1100 CST on May 4, and also during the evening and night of May 4-5. The cycle would be broken, of course, when and if other parameters required for activity were lacking.

6. A MODEL OF THE THUNDERSTORM WAKE

A model of the thunderstorm wake is shown in figure 22. It is a vertical time section of potential temperature and relative humidity from the surface to 300 mb. The section is a composite of assumed and actual soundings, adjusted in time to fit the surface data at Station 22 for the period 0130-0530 CST, May 4. The assumed 0357 CST ADM sounding was placed at 0226 CST, and the 0501 CST ADM sounding was placed at 0330 CST, the time of passage of pressure fall line F9 at Station 22. The 0502 CST LTS sounding was assumed to represent conditions 3 hours later at 0630 CST, and was used to interpolate the portion of the section from 0330 to 0530 CST. The portion of the section from 0130 to 0226 CST was extrapolated. Portions of the section near the surface were adjusted to fit the surface data at Station 22. Profiles of these data are shown below the section with pressure change lines R8 and F9 and the associated radar echo indicated.

The section can be considered only an approximation. As constructed, it is quasi-consistent hydrostatically with the observed pressure changes at Station 22, but since the temperature and moisture fields above 300 mb. were not considered, complete consistency was not sought.

Arrow vectors indicate the probable vertical velocities. They were constructed proportional to the slope of the isentropes, and generally the values of relative humidity decrease downward in regions of downward motion and upward in regions of upward motion. The net effect of the subsidence motion is indicated to be an undercutting of the thunderstorm on its trailing edge, which would result in the visible cloud tilting to the rear with height.

A composite time section of the thunderstorm has been constructed by Newton [12], using soundings of the Thunderstorm Project [13]. This composite, redrawn to the scale of the model in figure 22, is shown in figure 23. It shows the active thunderstorm, as well as most of the thunderstorm wake. The dryness aloft is well shown, and slight warming is also indicated. The warm, dry air did not extend to the surface, however. Although the thunderstorm wake in figure 22 appears exaggerated with respect to that in figure 23, the correspondence is considered to be satisfactory. Newton's data were with respect to mature daytime thunderstorms in which the thunderstorm wake is less pronounced.

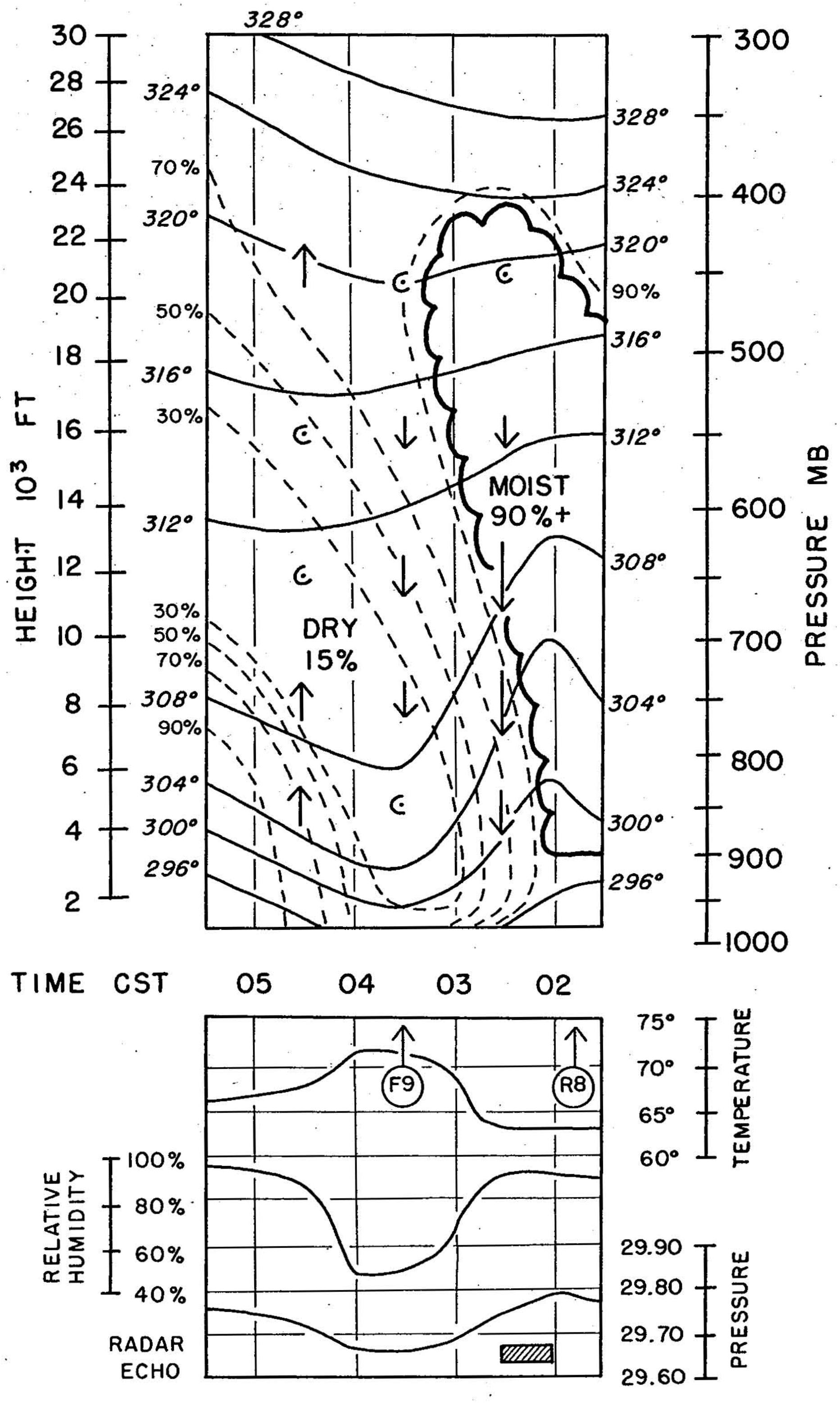

Figure 22.– Composite vertical time section of the thunderstorm wake. Isentropes at 4° K. intervals are shown as solid lines, and isopleths of relative humidity at 20 percent intervals are shown as dashed lines. The probable outline of the visible thunderstorm is indicated within the region in which relative humidity exceeds 90 percent.

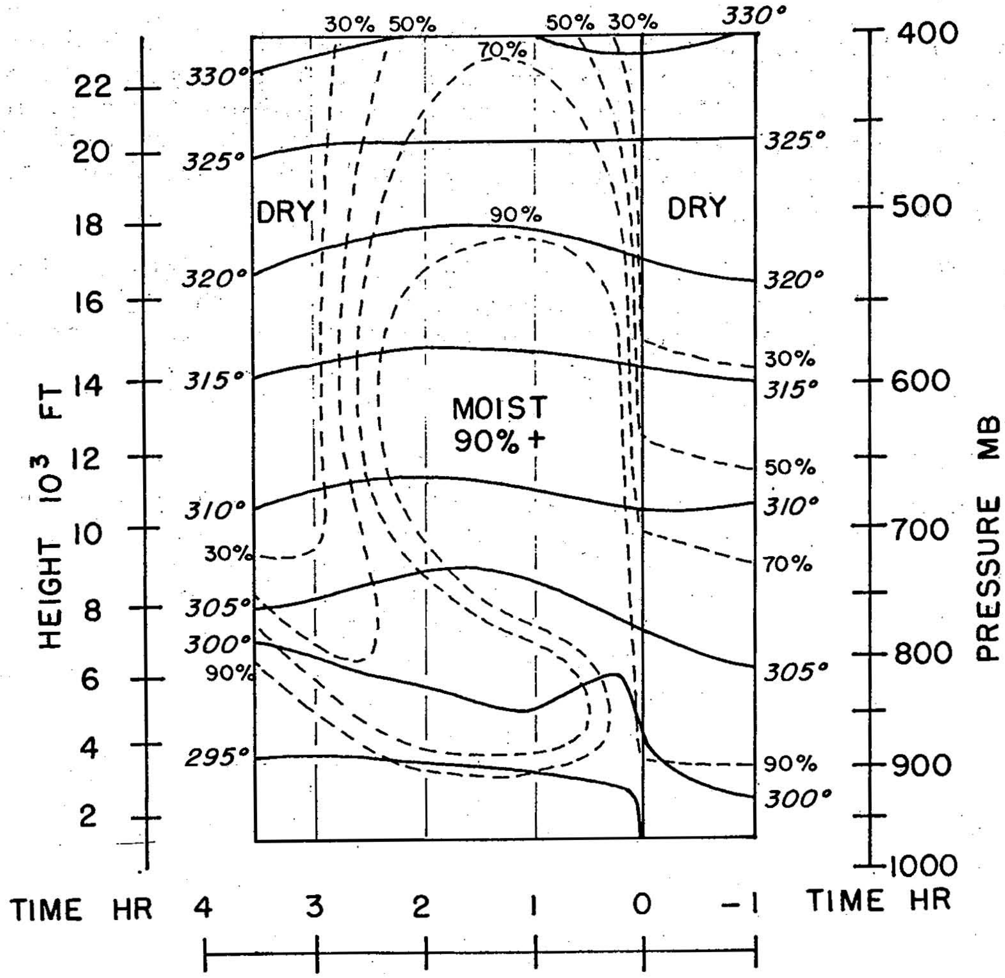

Figure 23.- Newton's composite vertical time section of a mature thunderstorm.

7. SUMMARY

The thunderstorm wake is a volume to the rear of the active thunderstorm, which is characterized by diminishing radar echoes and rainfall, a wake depression, and a warm wake. The wake depression is a hydrostatic pressure fall, which results primarily from the production of warm, dry air aloft. The warm, dry air, which is termed the warm wake, is produced by subsidence to the rear of the thunderstorms.

The warm wake aloft is more extensive than at the surface. Descent of the warm, dry air to the surface occurs only locally; most of the air remains aloft because of the convergence field generated by the wake depression.

The thunderstorm wake is most pronounced with respect to dissipating thunderstorm systems.

The warm temperatures which reach the surface are quasi-permanent, but moisture is restored rapidly by horizontal advection and by the evaporation of earlier rainfall. These processes result in the formation of an air mass which is thermodynamically favorable for additional thunderstorm activity.

ACKNOWLEDGMENTS

The author desires to acknowledge the assistance of Mr. Robert W. Smith, who read many of the graphic records, and both Mr. Smith and Mr. Harold L. Coleman, who traced the radar echoes. Acknowledgment is also made to the several authors who have made meso-scale studies and who are not specifically referenced. An excellent bibliography of their work is contained in a compilation by Fujita [9]. Finally, the author is grateful to Mr. C. F. Van Thullenar, Director, and Dr. C. W. Newton, Chief Scientist, of NSSP, whose guidance and encouragement permitted the preparation of this paper.

REFERENCES

1. Fujita, T., "Index to the NSSP Surface Network," *National Severe Storms Project Report* No. 6, U.S. Weather Bureau, Washington, D.C., April 1962.

2. Williams, D. T., "Analysis Methods for Small-Scale Surface Network Data," *National Severe Storms Project Report* No. 17, U.S. Weather Bureau, Washington, D.C., July 1963.

3. Williams, D. T., "The Nocturnal Thunderstorms of May 3-4, 1961, in South-Central Oklahoma," U.S. Weather Bureau, Kansas City, Mo., September 1962. (Unpublished.)

4. Brunk, Ivan W., "The Pressure Pulsation of 11 April 1944," *Journal of Meteorology*, vol. 6, No. 3, June 1949, pp. 181-187.

5. Tepper, M., "The Application of the Hydraulic Analogy to Certain Atmospheric Flow Problems," *Research Paper* No. 35, U.S. Weather Bureau, Washington, D.C., October 1952.

6. Williams, D. T., "Pressure Wave Observations in the Central Midwest, 1952," *Monthly Weather Review*, vol. 81, No. 9, September 1953. pp. 278-289.

7. Williams, D. T., "A Surface Study of a Depression-Type Wave," *Monthly Weather Review*, vol. 82, No. 10, October 1954, pp. 289-295.

8. Fujita, T., "Results of Detailed Synoptic Studies of Squall Lines," *Tellus*, vol. 4, 1955, pp. 405-436.

9. Fujita, T., "A Review of Researches on Analytical Mesometeorology," *Research Paper* No. 8, Mesometeorology Project, University of Chicago, February 1962.

10. Panofsky, H., *Introduction to Dynamic Meteorology*, The Pennsylvania State University Press, University Park, Pa., 1956, pp. 100-102.

11. Williams, D. T., "A Dynamic-Kinematic Method for Computing Vertical Motion," U.S. Weather Bureau, Kansas City, Mo., February 1963. (Unpublished.)

12. Newton, C. W., "Structure and Mechanism of the Prefrontal Squall Line," *Journal of Meteorology*, vol. 7, No. 3, June 1950, pp. 210-222.

13. Byers, H. R., and R. R. Braham, *The Thunderstorm*, U.S. Weather Bureau, Washington, D.C., 1949.