10th Conf. on Severe Local Storms
Oct. 18-21, 1977; Omaha, NE
AMS, p. 505-510

A CASE STUDY OF MESOCYCLONE FORMATION

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1. INTRODUCTION

In the late 1940's it became evident that important circulations exist with diameters too small to be detected by synoptic scale analysis, but too large to be recognized at a single site (e.g. Brooks, 1949). Fujita (1963) reviews the characteristics of such circulations (labeled mesocyclones) and presents brief accounts of several case studies.

With the advent of Doppler radar, mesocyclones associated with thunderstorm updrafts have come under close scrutiny. This type of vortex is of particular interest because of its relation to the tornado. Burgess (1976) summarizes recent findings from single Doppler radar observations. Studies such as those by McCarthy et al. (1975) and Brandes (1977) illustrate dual Doppler techniques.

Many scales of atmospheric motion have been identified and studied, including; the microscale (spatial range 0-10 km), the mesoscale (10-100 km), the sub-synoptic scale (100-1000 km) and the synoptic scale (> 1000 km). This paper describes a synoptic scale weather system within which were identified sub-synoptic, meso-and microscale circulations. In addition to standard NWS observations, data were gathered from the National Severe Storms Laboratory (NSSL) sub-synoptic surface and rawinsonde sites, WSR-57 and Doppler radars, and there were photographs from the NSSL "tornado intercept" spotters and satellite photography.

Though a multitude of forecasting parameters exist (many combinations of which successfully predicted severe activity in this case) it seems that few, if any, of these techniques directly address the problem of understanding storm dynamics. This study utilizes all of the above data sources to search out a more direct conceptualization for the formation of mesocyclones in the 26 May case.

2. EVENTS OF 26 MAY 1976

A major outbreak of severe weather occurred in south-central Oklahoma and central Texas. The vast majority of severe weather reports came from a region 40 km either side of a line from Wynnewood, Oklahoma to just south of Temple (TPL), Texas (Fig. 1).

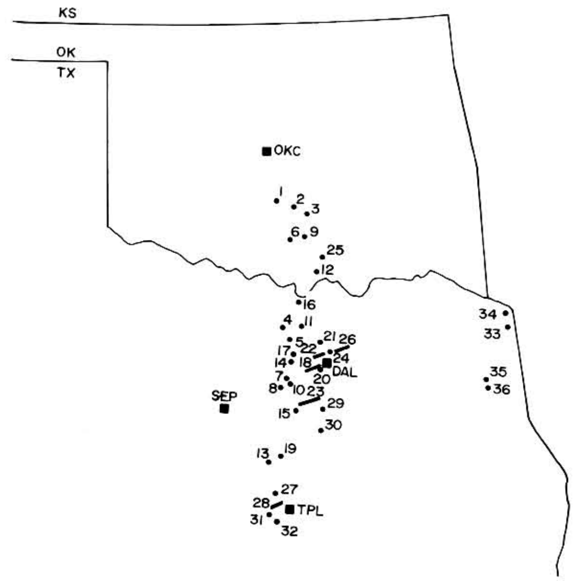

Figure 1. Mapping of the times and locations of severe weather which occurred in Texas and Oklahoma on 26 May 1976. Numbers specify time sequence.

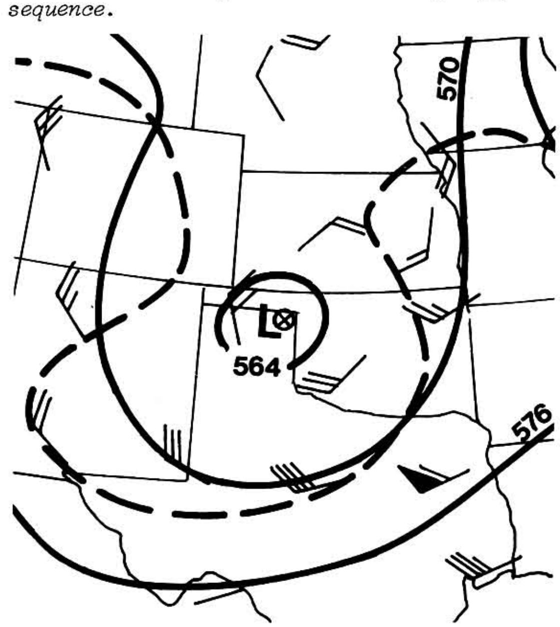

Figure 2. 500 mb analysis, 0600 CST, 26 May 1976. Heights in decameters, temperatures in °C and wind speeds in m s^{-1} where flags represent 25 m s^{-1}, long barbs are 5 m s^{-1} and short barbs 2.5 m s^{-1}.

2.1 Morning Conditions

0600 CST[1] synoptic data indicated high potential for severe activity. An advancing upper wave had deepened into a closed 500 mb low centered over the extreme northeastern Texas panhandle (Fig. 2). Numerical prognoses moved this low into central Oklahoma by early evening and indicated strong PVA. Rawinsonde data from Oklahoma City (OKC, Fig. 3) and Stephenville, Texas (SEP, Fig. 4) revealed potential instability and vertical wind structure conducive to severe thunderstorm formation (Miller, 1975). Low-level moisture advection was strongest in central portions of Texas and Oklahoma--850 mb analysis disclosed 10°C dewpoints to the east of SEP. Analysis at 0800 (Fig. 5) showed a surface cold front, which had formed during the night, extending southward toward San Angelo, Texas from a low near Fort Sill, Oklahoma.

A decidedly negative factor, regarding severe storm potential in northern and central Oklahoma, was the passage of an early morning squall line which partially stabilized the atmosphere. The southernmost end of this line passed through Norman at approximately 0800.

Soundings were released at 0900 from the nine NSSL sub-synoptic sites. Streamline analysis

[1]All times are Central Standard Time.

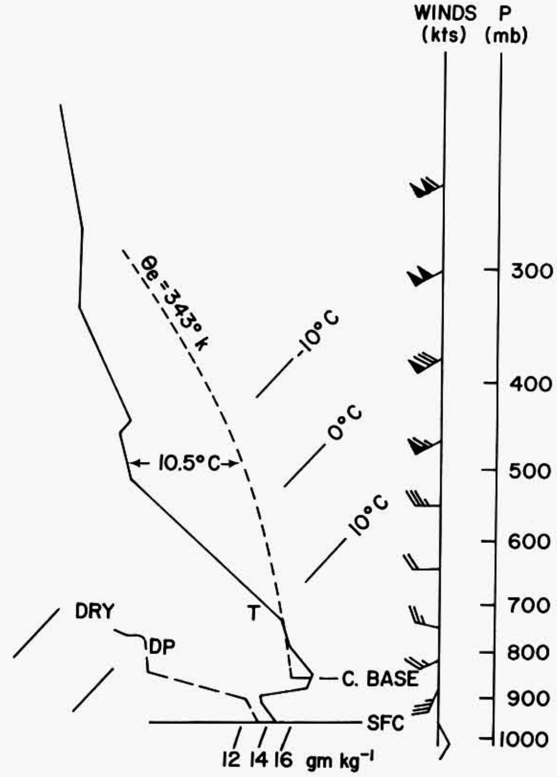

Figure 4. Stephenville, Texas sounding, 0600 CST, 26 May 1976, plotted on a Skew T-Log P diagram. Temperature (T) and dewpoint (DP) traces so indicated. Lifted parcel moist lapse rate θ_e = 343°K as shown. Wind barbs as in Figure 2.

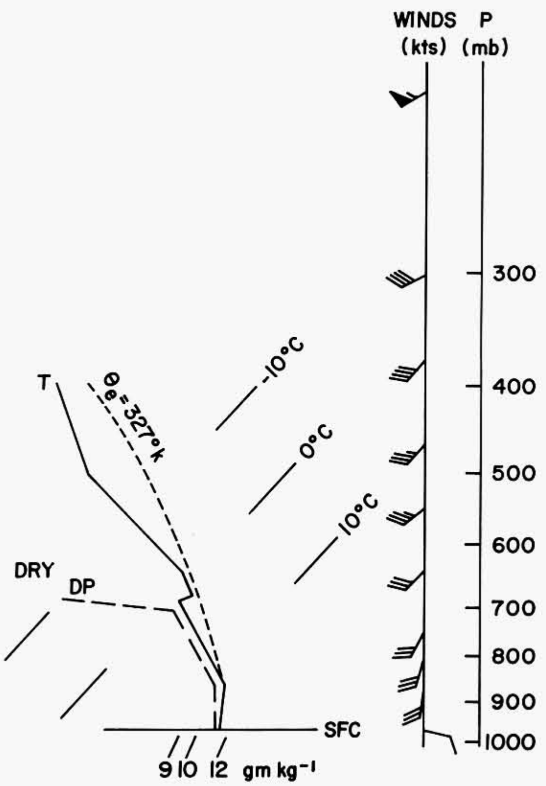

Figure 3. Oklahoma City sounding, 0600 CST, 26 May 1976, plotted on a Skew T-Log P diagram. Temperature (T) and Dewpoint (DP) trances so indicated. Lifted parcel moist lapse rate θ_e = 327°K as shown. Wind barbs as in Figure 2.

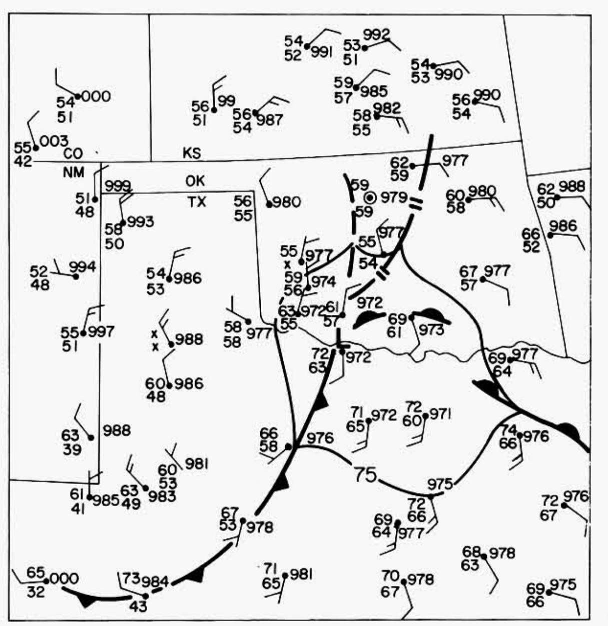

Figure 5. Surface analysis 0800 CST: 26 May 1976. Temperature and dewpoints in °F; altimeter isobars. Analyzed isobar 29.75" only.

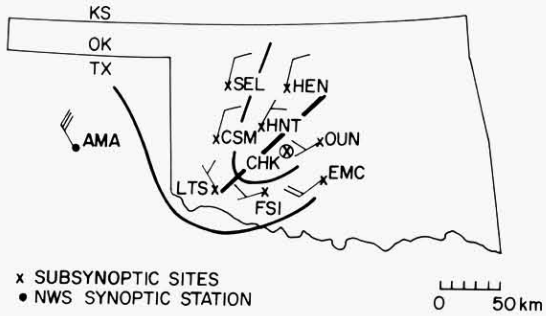

Figure 6. 900 mb streamline analysis, 0900 CST, 26 May 1976, for the nine NSSL sub-synoptic sounding sites--included is 0600 CST Amarillo (AMA) data. Wind speeds as in Figure 2.

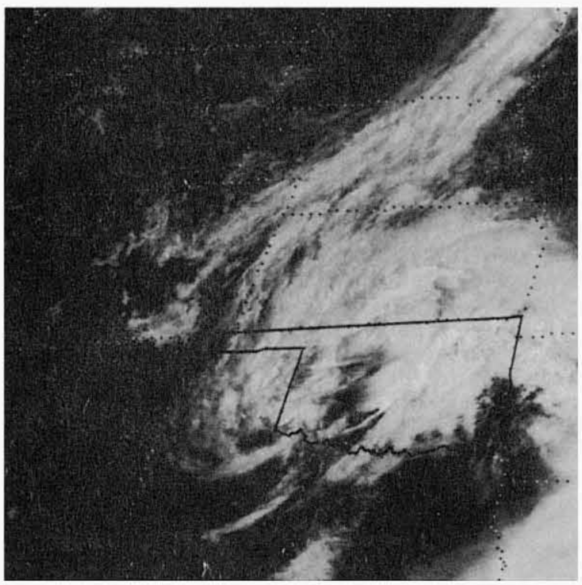

Figure 7. Satellite photo 0900 CST; 26 May 1976. Description of features given in text.

at various constant pressure levels revealed that flow within the approaching system was cyclonic about a rather sharp upper trough. Winds at all levels behind this trough were northerly--those ahead southwesterly (Fig. 6). Figure 7, the 0900 satellite photo, clearly shows the early activity moving through eastern Oklahoma, a relatively clear atmosphere in north-central Texas and the synoptic-scale disturbance, evidenced by the "comma cloud", in western Texas and southwestern Oklahoma.

Vorticity estimates ($\zeta \simeq \Delta v/\Delta x - \Delta u/\Delta y$), constructed from 0900 data for various constant pressure levels, disclosed sub-synoptic, environmental vorticity in the lower levels of order 10^{-4} s^{-1}. Similar values were given on the morning NMC, synoptic-scale 500 mb vorticity prognosis for most of Oklahoma and northern Texas.

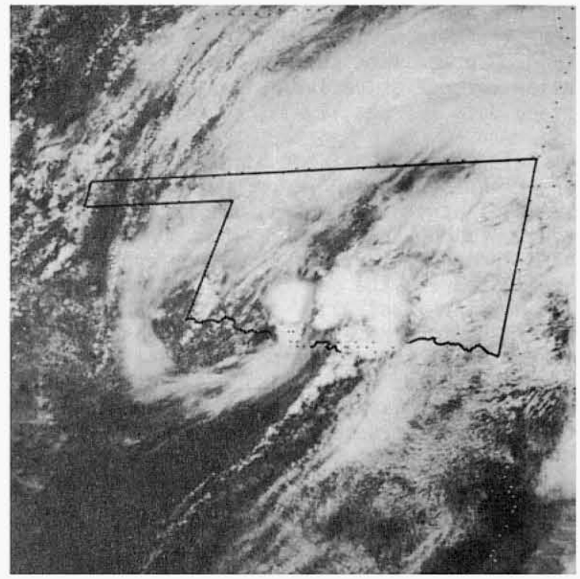

Figure 8. Satellite photo 1300 CST; 26 May 1976. Description of features given in text.

2.2 Analysis

The SEP morning sounding has been assumed to generally represent the atmosphere in north-central Texas prior to arrival of the upper trough. Relatively clear skies permitted rapid low-level heating throughout this region. The strong, low-level inversion was, however, suppressing convection. Sub-synoptic soundings released at 0900, 1300, and 1430 allowed inferences regarding temperature variations at constant pressure levels with approach of the upper trough. As the system approached the slowly moving cold front, the inversion at 850 mb began to erode. 850 mb temperature traces showed as much as 2°C cooling. Additional convergence and lifting along the front made it the preferred region for activity. Support for this contention are supplied by satellite photos (see e.g. Fig. 8) which show sudden and explosive growth along the front in north-central Texas.

The differing character of Oklahoma vs Texas storms was partially ascribable to the large difference in conditional instability (compare Figs. 3 and 4). However, buoyancy alone does not fully account for the difference. A second disparity, namely vertical wind shear differences, was apparent from the upper air data. It has been accepted for some time that storms growing in sheared environments can more readily achieve a quasi-steady, separated updraft (e.g., Newton, 1966). Furthermore, an updraft model, suggested by Alberty (1969), shows that vertical wind shear may actually reinforce vigorous, undiluted updraft cores. This model was applied to the vertical wind profiles which exhibited a strong shear in Texas, but a rather weak shear in Oklahoma. No such reinforcement was found for storms in Oklahoma, but was potentially significant in Texas.

Vorticity estimates from the 1300 NSSL soundings again produced values of order 10^{-4} s^{-1} in the vicinity of the trough. Magnitudes obtained agreed with surface vorticity values derived through objective analysis of subsynoptic surface data (Barnes, 1973).

Calculations assessed effects of new convection on the surrounding environment. In the absence of other influences, the acceleration acting on a buoyant air parcel of density ρ' rising through a layer of density ρ can be approximated via the equation of motion, i.e. $dw/dt = (-1/\rho')(\partial p'/\partial z) - g$ for the parcel and $\partial p/\partial z = -\rho g$ for the environment. By assuming $\partial p'/\partial z \approx \partial p/\partial z$ and utilizing the ideal gas law, one obtains $dw/dt \approx g(\Delta T_v/T_v)$. A factor $(-gL$, where L is the mixing ratio for liquid cloud water) may be introduced to approximate precipitation drag. By assuming a small time interval, during which the updraft is steady-state, local changes in "w" as well as horizontal advection terms may be neglected so that $w\partial w/\partial z \approx g[(\Delta T_v/T_v) - L]$. This equation neglects entrainment and the possibility of adverse pressure perturbations and is thus likely to overestimate vertical velocity. In fact, cases having positive areas similar to the present case, where actual vertical velocities have been measured, indicate that theoretical vertical motions in the lower levels can be overestimated by a factor as great as 3/2 (based on data presented in Davies-Jones, 1974). Thus, to afford values more closely approximating reality, this factor was arbitrarily inserted, i.e.

$$\frac{1}{2}\frac{\partial w^2}{\partial z} \approx .67g(\Delta T_v/T_v - L). \qquad (1)$$

Values were computed for the right hand side of equation (1) from the SEP morning sounding. Adiabatic ascent was assumed in estimating L, then equation (1) was integrated to find $w \approx F(z)$. Now, if one assumes no significant local density change and no horizontal density advection, the equation of continuity becomes $\partial w/\partial z \approx -(\partial u/\partial x + \partial v/\partial y)$ = horizontal convergence = C. Utilizing this relation with values of $\partial w/\partial z$ estimated from the SEP morning sounding, $c \approx 7(10)^{-3}$ s^{-1}.

When utilizing this method for estimating convergence into the updraft, it must be remembered that vigorous, quasi-steady state thunderstorms typically develop a well-defined mesoscale gust front. The added lifting of inflow air along this boundary need not be incorporated here, since we seek lower extremes of convergence values.

Burgess (1976), suggests that a thunderstorm mesocyclone is a necessary, but not sufficient condition for tornado production. His findings reveal the existence of a mid-cloud circulation some 30-35 minutes prior to tornado touchdown. The magnitude of this meso-circulation has only recently become known. Brandes (1977; personal communication) finds strong mesocyclones with vorticities on the order of 10^{-2} s^{-1} in tornadic storms. Thus, an intriguing question concerns the time interval required to converge larger scale, background vorticity of 10^{-4} s^{-1} (as measured earlier) to mesocyclone values near 10^{-2} s^{-1} with an updraft convergence of $7(10)^{-3}$ s^{-1} calculated above (see e.g., Kuo, 1966). Some finite time is involved, of course, for even a rapidly building thunderstorm to establish a strong, undiluted updraft (say e.g., 15 minutes). By ignoring this period we can establish a lower limit to the time required for the storm to evolve a strong mesocylone, utilizing the approximation $(1/\zeta)(d\zeta/dt) \approx -\nabla\cdot\vec{v} = c$ (i.e. the vorticity equation with only the divergence term retained) and $\zeta_f = 10^{-2}$ s^{-1}, $\zeta_o = 10^{-4}$ s^{-1} and $c = 7(10)^{-3}$ s^{-1}. Here integration yields $\ln(\zeta_f/\zeta_o) = ct$, and $t \approx$ 11 minutes.

Figure 9. Photograph of Dallas, Texas tornado, 26 May 1976, 1630 CST. Even though the condensation funnel was only about halfway to the ground, intermittent damage was occurring beneath.

The rapid mesocyclone formation time estimated for central Texas (11 minutes), along with the additional time apparently required for tornado production (i.e., 30-35 minutes) implies that in this case, one might expect severe activity within 45 minutes to an hour of storm formation. In this case, that is what occurred.

The first tornado in Texas touched down briefly at 1325, followed shortly thereafter by a second tornado at 1332 (events 4 and 5, Fig. 1). Severe activity continued throughout the afternoon. University of Oklahoma and NSSL storm intercept personnel reported lowered cloud bases, well organized updrafts and rotating "wall clouds" (Fujita, 1960) at several locations along the line in northern Texas. A large tornado, photographed in north Dallas at 1630 (Fig. 9), was associated with a large, rotating wall cloud which had been under observation by Civil Defense storm spotters since 1530. The culmination of the major activity in Texas occurred along the shores of Lake Belton (near Temple, TPL) where a tornado killed two persons, injured seven others and destroyed 41 houses, 27 mobile homes and one business.

As previously indicated, the situation in Oklahoma was somewhat different. Waves of thunderstorm activity, washing across the state from midnight onward, had furnished a recurrent stabilizing influence to an otherwise explosive

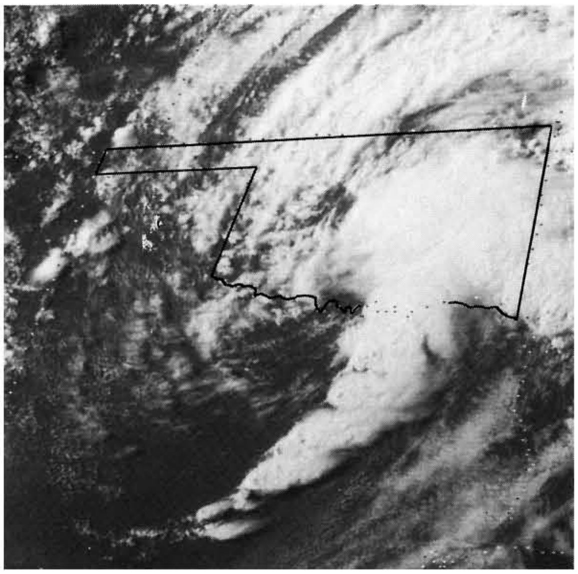

Figure 10. Satellite photo 1630 CST: 26 May 1976. Description of features given in text.

atmosphere. Thus, while radar tops of storms in Texas often exceeded 15 km (~50,000 ft) during the afternoon, the largest tops in southern Oklahoma averaged 13.5 km (~45,000 ft) and those in central portions of the state were rarely greater than 12 km (~40,000 ft).

Estimates were made of updraft strength and convergence in Oklahoma according to the method outlined above. Mesocyclone evolution times were found to be on the order of 20-30 minutes and, in fact, several mesocyclones were identified in south-central Oklahoma by NSSL Doppler radars. These circulations, however, were short-lived and extremely variable--characteristics suggesting moderately strong, but non-steady updrafts. The reason for this difference in updraft organization was postulated to be vertical wind shear. Thus, the variant behavioral characteristics of the storms were next considered on this basis. The magnitude of cloud layer winds were derived from proximity sounding data in Oklahoma and from interpolated NWS sounding data in Texas. It was noted that storms in central Texas moved generally 30°-50° to the right of the mean flow and 5 to 8 m s^{-1} slower than any observed cloud layer winds. Cells in Oklahoma traveled generally with the mean flow, except in a few isolated cases, where deviations no greater than 20° to the right were observed over short periods. Since the primary component of deviate motion is presumed to be a result of rapid growth of new cells (e.g. Marwitz, 1972), strong, right-flank updrafts probably played a large role in Texas storms. Visual evidence of flanking activity is provided by satellite photos where well-defined lines of flanking towers can be seen joined to the primary cells (Fig. 10). Likewise, NSSL and University of Oklahoma intercept personnel reported that large, well-organized flanking lines were common in Texas, but were nearly absent in Oklahoma. The location of these flanking lines is not unexpected, since the mesoscale convergence boundary is typically found in that region of the storm (Brandes, 1977).

3. IN SUMMARY

The severe weather in the south-central plains on 26 May 1976 was contained, for the most part, in a region 40 km either side of a line extending from south-central Oklahoma to central Texas. Post storm analysis of synoptic and sub-synoptic data, led the authors to the following conclusions and speculations:

1) Atmospheric conditioning began with the approach of a relatively strong, synoptic-scale disturbance which provided thermal destabilization, furnished low-level lifting and increased lower and middle level vorticity values;

2) The strength of the system near its center (in Oklahoma) acted against severe activity by forcing nearly continuous stabilizing convection;

3) Regions further from the heart of the disturbance remained free of early activity--allowing strong destabilization;

4) Thunderstorms spawned along the front in Texas developed updrafts of sufficient strength to converge existing low-level (sub-synoptic scale) vorticity to meso-cyclone values;

5) Vertical accelerations along the outflow boundaries of the flanking lines--possibly reinforced by shear-induced vertical motions--caused strong, new updraft regions to be continuously generated;

6) These new updraft regions permitted the mesocyclone to remain separated from the precipitation laden air of the main storm and further slowed the eastward motion of the storms, and;

7) Through mechanisms not yet thoroughly understood, vorticity continued to converge in portions of the mesocyclone to microscale dimensions (i.e., tornadoes were formed).

By early evening the storms had progressed only about 100 km eastward, but had remained severe throughout the afternoon. As evening approached, and diurnal cooling began, the storms lost their intensity.

It is evident that, at least in this case, updraft convergence of environmental synoptic and sub-synoptic scale vorticity is sufficient to account for the resulting thunderstorm mesocyclones. Routine prediction techniques currently allow indirect inference of these important mechanisms. A numerical model, giving forecasters expected afternoon values of low-level, subsynoptic vorticity, as well as projected values of updraft buoyancy, would provide a direct indication of mesocyclone potential. However, an added advantage might be greater comprehension of storm dynamics by the local meteorologists. There remains, of course, the possibility of meso-scale forcing offsetting or enhancing the general tendencies. Responsibility for refining model results to include local features should be handled on a local basis.

5. ACKNOWLEDGMENTS

The authors would like to express special appreciation for the following rawinsonde units: the USAF Sixth Weather Squadron (Mobile); the U.S. Army Atmospheric Sciences Laboratory, White Sands, New Mexico; the U.S. Army Field Artillery Board, Fort Sill and the Fort Sill Meteorological Support Group whose conscientious efforts supplied all of the upper air data for this study. Recognition is given to the Tornado Intercept Project for supplying the "link to reality" so important to this data set and to the Nuclear Regulatory Commission for partial support under contract NRC AT(49-25)1004. Thanks are due to Charles Clark and Jennifer Moore for graphic work and Connie Hall for typing various drafts of this manuscript.

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