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P1.6 THE LAHOMA STORM DEEP CONVERGENCE ZONE: ITS CHARACTERISTICS AND ROLE IN STORM DYNAMICS AND SEVERITY

Leslie R. Lemon[1]* and Stephen Parker[2]

[1]Loral Defense Systems-East
Independence, MO 64055
Telephone: (816)-373-9990

[2]National Weather Service Office
North Platte, NE
Telephone: (308)-532-4936

1. INTRODUCTION

Browning and Ludlam (1962), Browning (1965), and others have emphasized the symbiotic character and sustained separation of updraft and downdraft in supercell storms. Indeed Browning emphasized this as a discriminating factor in supercell structure. However few others, with the exception of Lemon and Burgess (1992), hereafter LB, have discussed the nature and importance of the region between drafts. LB documented what they referred to as the "Deep Convergence Zone", DCZ, coincident with the storm gust front in low levels and extending upward along its length to an average depth of 10 km AGL to occasionally 13 km AGL. Further, convergence values averaged in excess of 1.0 X $10^{-2}s^{-1}$, with WSR-88D data revealing radial shears of 38 ms^{-1} in less than 2 km. LB discussed the importance of the DCZ and noted that the storm's mesocyclone and a gust-front tornado were located on this narrow zone, and that surface large hail fall and damaging winds occurred with or within a few kilometers behind the discontinuity.

Here, in this preliminary study, we examine a very similar storm to the Cashion wind and hailstorm of LB: the extremely severe Lahoma, OK storm of 17 August 1994. The structure of these storms is virtually identical to the Wokingham storm, the first to be identified as a "Severe Right" and, now, "supercell" storm by Browning and Ludlam (1960, 1962) (Fig. 1). These storms with a front to back updraft-downdraft orientation are now called "Heavy Precipitation" (HP) supercells (Moller et al., 1990). Like the Cashion storm, the Lahoma storm also possessed a very prominent and persistent DCZ.

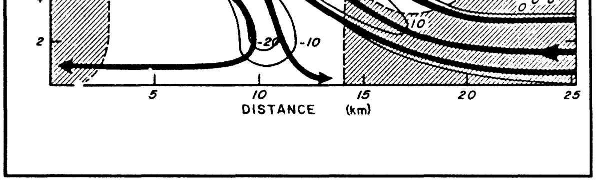

Figure 1. Inferred streamlines relative to the storm and isopleths of vertical velocity (m s^{-1}) within a vertical section along the direction of storm movement of the Wokingham supercell hailstorm. Storm motion is from left to right. The unshaded area corresponds to radar reflectivity in excess of 30 dBZ. (After Browning and Ludlam, 1960).

The characteristics of the Lahoma DCZ, as well as its role in storm structure and dynamics, are examined in this study using the

* *Corresponding author address:* Leslie R. Lemon, Loral Defense Systems-East, 16416 Cogan Dr., Independence, MO 64055, e-mail 102177.2336@compuserve.com

central Oklahoma KTLX WSR-88D as the primary data source. We find that radial shears and convergence values are maintained for nearly 1.5 hours and reach extremes along this zone through a considerable depth that even surpass those of LB. These are undoubtedly related to the extremely severe weather produced by the storm. Although the Lahoma storm spawned only one brief confirmed F1 tornado, its extraordinarily severe weather is noteworthy. Two recorded wind gusts of over 50 m s^{-1} (113 mph), hail as large as 11.4 cm X 16.5 cm, and a 100 km long, 6 to 13 km wide, swath of hail and accompanying F1 wind damage (non-tornadic) were produced (Fig. 2). Animals were killed, home roofs and siding were stripped and penetrated by many large hailstones (diameters ***averaging*** 4 to 8 cm), and mobile homes were reduced to mere shells of steel supports.

What we call the "Lahoma storm" was the right flank of an evolving multicellular storm complex that extended over 100 km to the east-northeast. We began data analysis at 1915 (UTC) when it was a multicellular hailstorm, and end at 2105 as it evolves into a weakening bow echo. The storm became a supercell (a storm having a mesocyclone) at 1944. As it moved from ~ 350° at 18 m s^{-1}, it underwent a complex evolution developing a series of mesocyclones M1, M2, and a bow echo (Conway et al., 1966) with "bookend vortices" including a meso-anticyclone, AM, and cyclonic M3 (Fig. 2.) Tornadic Vortex Signatures (TVS) were also detected, at least one of these associated with a tornado. Mesocyclones were centered on the DCZ and are analogous to the extratropical cyclone, with "warm sector" inflow and "cold sector" outflow, Lemon and Doswell (1979) (Fig. 3). The series of M1, M2, and perhaps AM, appear to be responsible for the continuous damage swath (Fig. 2).

Because of limited space here, we are unable to include a detailed description of storm history and evolution nor radar images. Instead we develop a model of the storm DCZ based on two hours of radar data (Fig. 3). (Representative PPI images and vertical cross sections will be shown at the conference). The reader is also referred to Conway et al. (1996) (his figure 4) elsewhere in this volume for storm radar images. (Other environmental and storm aspects are also considered elsewhere in this volume, Janish, et al. 1996, Morris and Shafer, 1996).

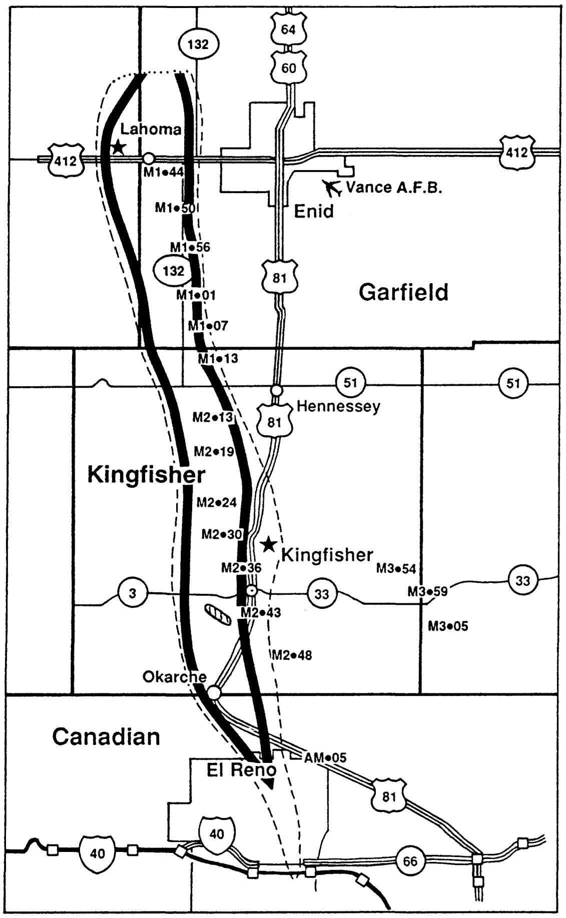

Figure 2. Lahoma storm damage swath through north-central and central Oklahoma. Concentrated F1 wind and hail damage is enclosed by the bold contour while the dashed contour encloses more isolated damage. Dotted line indicates northern limit of damage survey and the star west of Lahoma indicates location of the Lahoma Oklahoma Mesonet site. Mesocyclone (M1, M2, M3) and meso-anticyclone (AM) locations and identifiers are shown accompanied by their respective times after the hour. Times are sequential from 1944 to 2105. Tornado location is west (left) of M2 at "43" or 2043.

2. DCZ CHARACTERISTICS AND EVOLUTION.

From the inception of WSR-88D data analysis (when the storm was ~180 km to the northwest), the most consistent pattern in the velocity data is that of the Deep Convergence Zone. The DCZ extended from the edge of the supercellular right-front flank of the complex to the left flank, well outside the analysis domain into a region containing non-severe ordinary cells. As in the LB study, this convergence zone could be readily identified because the low-level inflow approaching the updraft and the mid- and high-level environmental inflow into the storm downdraft were both largely parallel to the radar viewing angle. Thus, the DCZ boundary orientation itself is essentially normal to viewing angle. However, if this zone is observed when the radar beam is parallel to its orientation, only the associated azimuthal shear would be sampled.

Of course with single Doppler, only one component of motion is observed, and total air flow could be significantly different than radially observed. Undoubtedly, horizontal flow out of the radial reference frame does occur, but because velocity gradients are so large and correlated vertically and laterally along an extensive zone, substantial convergence and vertical motion is inevitable.

We summarize characteristics of the Deep Convergence Zone using the Figure 3 schematic and the letter identifiers in the figure. Primary data sources for figure synthesis include WSR-88D vertical cross sections and .25 km base data. Figure 3 is confined to the supercell and mesocyclonic portion of the storm. Although this figure is based on radar data synthesis from the Lahoma storm (preserving both scale and feature slope), the resemblance to the synoptic scale frontal system is remarkable.

- DCZ velocity shears. In order to accurately calculate velocity gradients, 250 m digital, "truthed" B-scan plots were examined for most volume scans (Conway, et al. 1995). The maximum 250 m gate-to-gate velocity differences were calculated in the zone and recorded. Typical "background" gate-to-gate values all along the DCZ were 1 to 3 X $10^{-2}s^{-1}$. Within and to the west of the mesocyclones (A-B-C), typical values were 7 X $10^{-2}s^{-1}$ to 1 X $10^{-1}s^{-1}$. The largest radial gate-to-gate velocity difference was 54 ms^{-1} (2.18 X $10^{-1}s^{-1}$) at a height of 4.8 km AGL.

- Velocity distribution in DCZ vicinity. On either side of the boundary, horizontal velocities increased as flow approached the boundary, reaching a maximum ~4 km from the DCZ and then decelerating into it. At times, in region B-C on the updraft side, ground-relative flow accelerated up to the boundary reaching ~+ 20 m s^{-1}, where in 250 m (at the point of sign reversal), velocities change to ~ -20 m s^{-1} or even less. In storm-relative inflow and updraft, rising just ahead of the discontinuity, horizontal velocities toward the boundary peaked in mid-levels (4.5 km AGL to 7 km AGL) and occasionally near the earth's surface. To the rear of the DCZ, on the downdraft side, horizontal velocities accelerated toward the boundary with peak values typically from ~5.5 km AGL to 9.5 km AGL. There was a general descent of higher velocity values from 8 to 12 km AGL in the far rear-flank portions of the echo downward and into the boundary, indicative of a rear-inflow jet.

- DCZ associated spectrum widths. Spectrum widths in updraft ahead of the boundary are uniformly low, less than ~4 m s^{-1}, from the lowest levels observed up to 6 to 9 km AGL. Behind the boundary, values are variable and high, from 6 to 10 m s^{-1}. Within the boundary itself, values are often exceptionally high, averaging ~8 m s^{-1} to 10 m s^{-1} but ranging from as low as 4 ms^{-1} (C-D) up to 15 ms^{-1} (A-B-C).

- DCZ horizontal extent. DCZ length is considerable, extending more than 50 km (accounting for waves and bends) through the storm portions studied.

- DCZ depth. Average DCZ depth is from radar horizon (as low as 700 m) up to ~10 km AGL. Greatest vertical extent is ~13.8 km AGL.

- DCZ width. Velocity gradients, and especially spectrum widths, suggest that the DCZ is the region of intense mixing between drafts and is confined to a zone only .25 km to 4 km across, averaging ~2 km.

- DCZ storm-relative slope with height. Prior to mesocyclone formation, the zone was nearly vertical or sloped down-shear, toward the updraft. To the east of the mesocyclones (C-D) the slope was generally upshear toward the rear edge of the reflectivity core. From the mesocyclone to the right storm flank (A-B-C), slope was more upright and most often upshear averaging 35° from the vertical. During the bow-echo phase (Conway et al., 1996) the slope in mid- and low-levels became greater averaging 65° upshear from the vertical (at 20:54).

While within the Lahoma storm we can not be certain when or how the DCZ formed, in the Cashion storm, development appears on the upshear edge of the intensifying updraft and is likely related to blocking of the environmental flow by the updraft (Brown and Crawford, 1972). Prior to mesocyclone formation, there was a slow strengthening in zone convergence (radial shears). But with mesocyclone formation, radial shears increased by a factor of 4 or more in the mesocyclone vicinity (A-B-C).

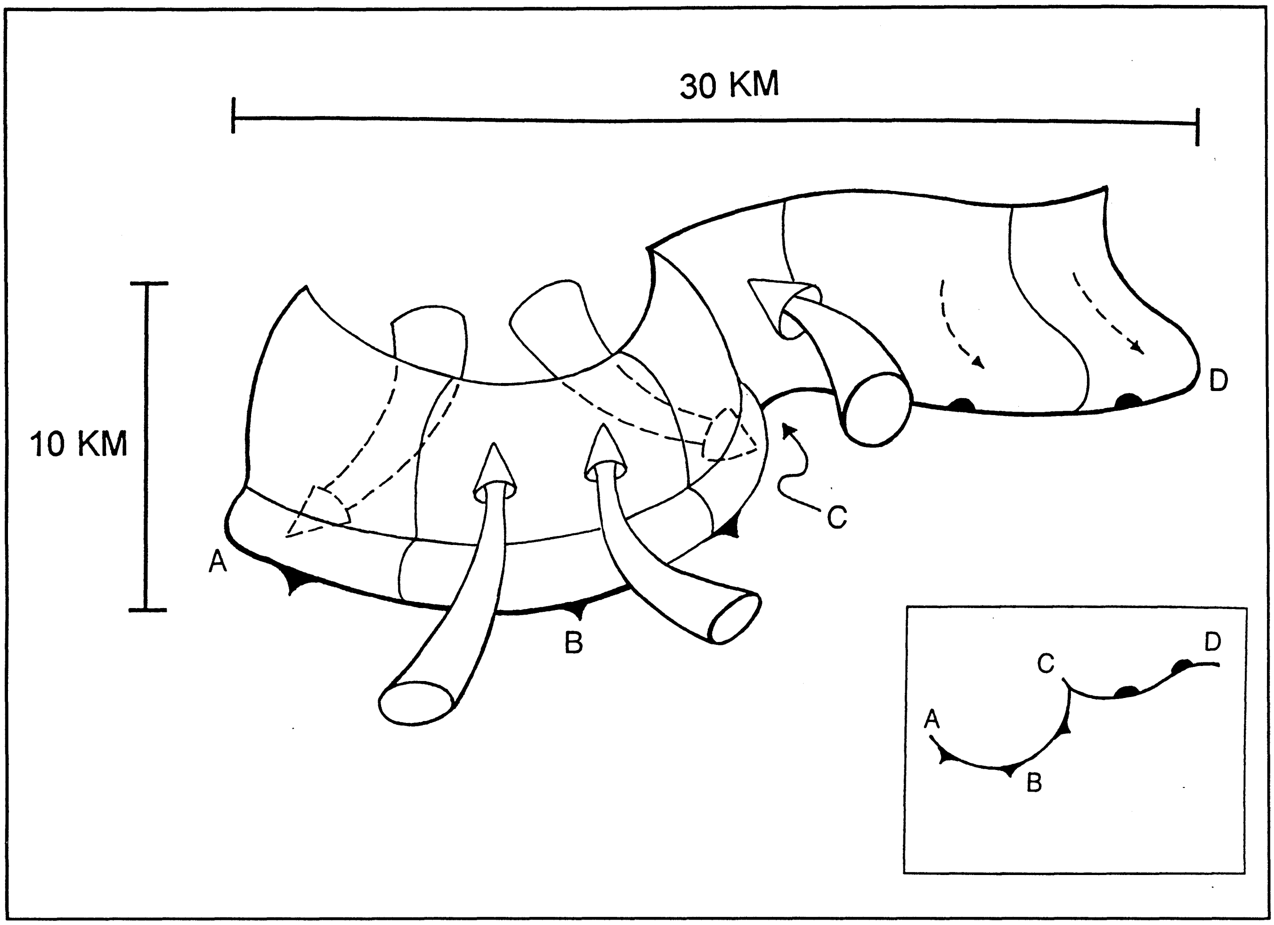

Figure 3. Three-dimensional, synthesized, Deep Convergence Zone schematic through supercell mesocyclone, location (C). The intense gradients described in text are confined to the DCZ surface itself. Inset is plan view. Supercell updraft is located from B to C with BWER, and storm summit in vicinity of B. Arrows indicate storm-relative flow; dashed arrows indicate, in perspective, flow behind the DCZ surface. Storm motion is toward reader.

3. DCZ IMPORTANCE TO STORM DYNAMICS AND SEVERITY

3.1 *Importance to Updraft and hail growth*

As in LB, we conclude that this zone is the boundary separating the major storm drafts. The most intense and deep portions of the DCZ are found nearly coincident with the strong reflectivity gradients bordering the WER and BWER (A-C, Fig. 3). The primary supercell updraft is located from B to C and storm summit is typically directly above location B. Further, strong, storm-relative, radial inflow from ahead of the storm could be followed into the updraft region, where it rose abruptly along and ahead of the DCZ. It has been shown conclusively that WER's and BWER's are accompanied by broad, smooth, and uniform updrafts (Browning, 1978). Our observations indicate that these updrafts are aligned along the DCZ, extend an average distance of 8 km ahead of the boundary and continue upward into the high reflectivity regions of the overhang and reflectivity core aloft. Spectrum widths indicate the updraft remains smooth, often well into the high reflectivities of the overhang where it becomes more turbulent. Most theories suggest that updrafts in mid-cloud levels must attain speeds comparable to the fall speeds of large hailstones. This is possible only when updraft speeds approach parcel theory values during ascent, suggesting little mixing with environmental air. In the Lahoma case, very high spectrum widths are confined to the DCZ bordering the updraft on the upshear side. ***Intense mixing with environmental air is confined within the narrow DCZ zone, effectively shielding the updraft from***

destructive mixing affects of dry, potentially cold, low equivalent potential temperature air. This is also consistent with the findings of Strach, et.al, (1975) that the most intense aircraft-measured turbulence was centered about the "strongly sheared updraft/downdraft interface". ***In light of the extreme shears and turbulence in this narrow zone and the very smooth character of updraft flow only a kilometer or two away, this interface is like a "fluid wall" between updraft and downdraft.***

Observations of flow acceleration aloft on either side of the boundary suggest that the DCZ is associated with a negative horizontal gradient of perturbation pressure. Maximum accelerations, and perhaps the largest pressure deficit, are evidenced by the strongest horizontal flow near and relative to the zone in mid-levels. The pressure deficit drives the flow toward the DCZ and also serves to augment convergence values within the updraft itself. Additionally, there is significant acceleration horizontally across the updraft, carrying rapidly growing hail in the supercooled liquid water of the updraft. These hailstones are suspended by the strong updraft until reaching the vicinity of the DCZ, where significant updraft ceases, lift is lost, and the hail descends toward the surface. This motion across the updraft, upshear towards the DCZ, helps limit hail growth but also helps prevent precipitation accumulation within the updraft (Browning, 1978).

3.2 *DCZ Importance to Downdraft Augmentation and Maintenance*

Mixing of cloudy, high equivalent potential temperature air from the updraft into downdraft is destructive to the downdraft. The DCZ largely confines that mixing to the zone itself. Brooks and Doswell (1993) note that these "Pakwash"-like extreme wind storms are characterized, among other things, by weak mid-level, storm relative winds. But this begs the question: with mid-level, light, storm-relative inflow (as in this case), how is the downdraft maintained? The DCZ offers one explanation. The associated pressure trough draws ambient environmental air into the storm from the rear and accelerates it into the boundary and precipitation cascade region, sustaining and augmenting the downdraft. The strong downdraft is focused in a narrow convergence region (within a few kilometers of the DCZ). This forces vigorous descent, not only due to negative buoyancy, but also mass convergence over a considerable depth. The confined nature of the descent amplifies rear-flank downdraft and low-level outflow winds. This accelerated earthward descent also minimizes hail melting. However, inflow feeding the downdraft must be properly matched with negative buoyancy to help maintain the circulations by replenishing the removed mass. High-level, differential, storm-relative flow supplies this in the Lahoma storm case. Soundings, wind profilers, WSR-88D storm-relative velocity products, and vertical cross sections consistently suggest a storm-relative inflow from ~8 to 12 km AGL. Further, radar products also suggest continuity from these levels as a descending jet. Finally, Browning and Ludlam's (1960, 1962) Wokingham model, which fits this storm and the HP Supercell in general, includes the same flow regime (Fig. 1).

Predominance of broad spectrum widths in the downdraft aloft indicate a very turbulent region. Turbulence in the downdraft suggests forced descent above that created by the negative buoyancy, i.e., mid-level convergence in the downdraft and DCZ region. Turbulent descent assures mixing and distribution of dry, potentially cold, environmental air throughout the downdraft.

3.3 *DCZ Association with Severe Weather*

In analysis of the Cashion storm LB indicated that surface severe weather was very closely associated with the DCZ. The same relationship is also found in this study. The location of the most intense radial shears coincides with the most severe surface weather (Fig. 2, A-C). The Lahoma, Oklahoma mesonet site (Fig. 1) received a sustained five-minute wind of ~ 37 m s^{-1}, 3-second wind gusts to 50 m s^{-1}, and extremely large hail with DCZ passage (Morris and Shafer, 1996). Witnesses described the approaching discontinuity as a "black mass of dust and cloud to the ground" accompanied by a "roar". Gust front/DCZ passage was marked by an immediate wind shift to the north, rapidly falling temperatures, blowing "dirt" (from plowed fields), night-like darkness, and zero visibilities. Within two to five minutes of passage, extremely large and damaging hail began as the wind reached its peak. These very high winds lasted for ~10 minutes while shifting to the east.

4. SUMMARY AND DISCUSSION

The Deep Convergence Zone played an important role in Lahoma storm dynamics, structure, and severity. In the WSR-88D velocity data, it is the most consistent storm characteristic. Radial shears and associated convergence values observed over a considerable depth, are the most intense measured. As with the Cashion storm (LB), the zone was there throughout the two hour analysis period, and is the location of mesocyclones and TVSs. The ~2 km wide zone is the boundary between two major air streams, dry, potentially-cold mid-level inflow feeding downdraft on one side and very warm, moist, low-level inflow feeding the updraft on the other side. Air stream mixing is effectively confined to this zone. As such, airmass thermodynamic characteristics on either side of the boundary are radically different. In fact, the ultimate source regions for the air streams may be thousands of kilometers apart. Gradients of equivalent potential temperature are large and baroclinic forces strong. The DCZ is the boundary between primary storm updraft and downdraft and, therefore, horizontal gradients of vertical motion are also very large. More than a passive draft interface, it is a pressure trough accelerating flow horizontally from both sides through a considerable depth, further enhancing convergence. The tilting term of the vorticity equation and baroclinic vorticity generation along the DCZ strongly encourage mesocyclone and TVS development (Rotunno, 1986). With little doubt, the very narrow zone shields the updraft from the destructive influence of upshear environmental entrainment and also plays a prominent role in hail formation. Finally, the DCZ focuses, augments, and sustains intense downdraft by continuously drawing in and converging potentially cold negatively-buoyant air. At the same time, it limits destructive upshear transport and mixing of warm, cloudy, updraft air with that in the downdraft.

Mid-level convergence has been correlated with damaging surface winds. Several authors show that velocity differences of 20 m s^{-1} to 25 m s^{-1} are sufficient for damaging winds. Przybylinski, et al. (1994) in the study of a damaging squall line find these differences across a 3 to 6 km distance (convergence of 4 to 8 X $10^{-3}s^{-1}$). Here, the same and larger velocity differences over a considerable depth were frequently measured in distances of 250 m. This may account for the extreme severity of the Lahoma storm.

Kropfli and Miller (1976) indicate essentially the same zone in a modest northeast Colorado multicell hailstorm, while Burgess and Lemon (1991) include WSR-88D data that clearly depict such a zone through a deep layer in a tornado and giant hail producing storm. It is unknown if damaging winds occurred in either of these cases. Przybylinski (in press), using WSR-88D image products, has further indicated the existence of the same convergence zone configuration in mid and upper-levels in a multicellular squall line that produced wide spread damaging winds. Finally, operational detection of such deep and intense convergence zones, even at considerable range, suggest the presence of damaging surface winds below radar horizon.

However, several questions remain. How much does the detection of the DCZ depend on radar viewing angle? Does the DCZ develop and dynamically lead to the associated pressure deficit or does the pressure deficit develop and lead to the DCZ? How general is this feature in severe or even non-severe convective storms? Does the existence of such a deep convergence zone differentiate severe and non-severe storms? Are there convective storms that do contain such a zone but are not severe? Are there severe storms that do not possess a DCZ? What are the differences in storms that exhibit both the DCZ and produce significant "straight-line", downburst, or mesocyclonic winds and those that do not? Are there differences in the strength and depth of such zones in tornadic versus non-tornadic supercellular severe storms? Answers await further research.

(References available on request).