STRUCTURAL CHARACTERISTICS OF A PARTICULARLY INTENSE CONVECTIVELY DRIVEN HIGH WIND EVENT

Caleb J. Midgley

Southern Ogallala Aquifer Rainfall Program
Plains, Texas

and

John L. Schroeder

Texas Tech University
Lubbock, Texas

Abstract

West Texas Mesonet (WTM) observations and WSR-88D data are examined to ascertain the forcing mechanisms involved in the 30 May 2001 Lubbock, Texas, high-wind event. The wind event was characterized by a classic bow-echo signature in the radar reflectivity data along with an elevated region of storm-relative rear-to-front flow capped by a region of storm-relative front-to-rear flow. As the storm passed over western Lubbock County, five-minute mean winds in excess of 60 knots were recorded at the WTM site at Reese Center. Damage surveys verified winds of this magnitude.

Close inspection of the life cycle of the Lubbock storm, as depicted by radar imagery, reveals several interesting characteristics, including a well-defined bounded weak-echo region (BWER) on its leading edge, a supercell to bow echo transition, and several boundary interactions. The Reese Center WTM site also indicated the presence of a bimodal signal in wind maxima as the storm passed over. The first maximum can be attributed to the initial gust front passage and subsequent momentum flux from the rear-inflow jet. The second maximum, of shorter duration and greater intensity, appears decoupled from the rear-inflow jet and may be due to vertical flux of easterly momentum air to the surface.

1. Introduction

On 30 May 2001, an intense convective windstorm tracked across portions of west central Texas, resulting in extensive crop and structural damage. Although this system did not meet the criteria for a derecho as set forth by Johns and Hirt (1987), the magnitude of the winds, along with the presence of significant hail, made this a particularly destructive system. The damage swath, based upon *Storm Data* reports (NCDC 2001), began as the storm crossed into Texas from New Mexico (Fig. 1), with the most extreme damage occurring just west of Lubbock, Texas. During the period of extreme winds, the storm exhibited a well-defined bow-echo structure with an extensive rear-inflow notch in the reflectivity data.

As first conceptualized by Fujita (1978), a bow-shaped reflectivity pattern typically is indicative of damaging winds along and to the north of the bow apex. Ensuing research has consistently verified Fujita's conceptual model, and modeling studies have given the research community a better understanding as to why such features exist (Wakimoto 2001). Entities such as the rear-inflow jet and bookend vortices have been identified as integral parts of the bow echo complex. Sensitivity studies have sought to identify the forcing for these features (Weisman 1992, 1993). In general, these studies have found that the forcing for extreme winds along the leading edge of the bow echo may be associated with vertical momentum flux of the rear-inflow jet. Also, recent research has shown that particularly intense winds may occur due to the existence of mesovortices, which preferentially form to the north of the bow apex (Weisman and Trapp 2003; Trapp and Weisman 2003).

These forcing mechanisms agree with Fujita's conceptual model with respect to the location of high winds; however, several studies have indicated other forms of forcing may be important. For instance, Schmidt and Cotton (1989) (hereafter SC89) found that a significant component of severe surface winds had a northerly component due to strong forcing from surface pressure gradients. Although a rear-inflow jet did exist, easterly momentum atop a stable boundary layer entered the leading edge of the system and subsequently entered the outflow to the rear of the leading convective cells. Likewise, Bernardet and Cotton (1998) (hereafter BC98) found similar results. In both studies, the boundary layer had stabilized, and the source of instability was elevated.

This study looks at the potential of easterly momentum flux being a significant contributor to the severe surface winds near Lubbock, Texas, on 30 May 2001. Although dual Doppler data were not available, WSR-88D data from Lubbock, Texas, showed some interesting features from which inferences can be made. Also, WTM surface observations will be used to confirm the existence of storm-scale features west of Lubbock.

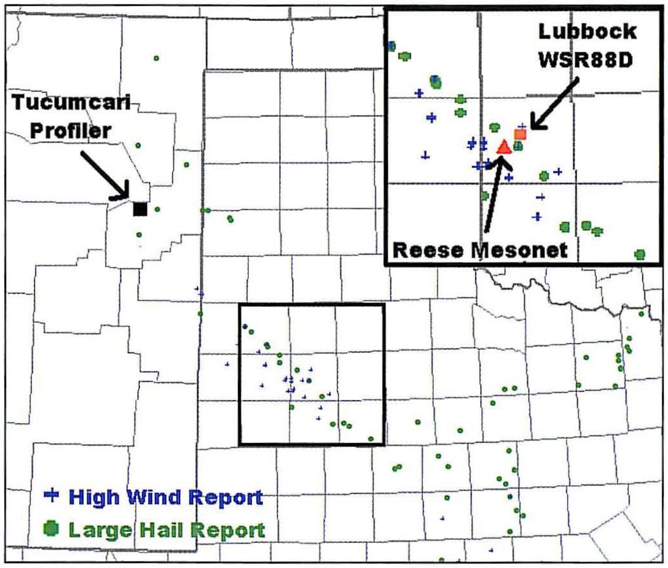

Fig. 1. Map of severe weather reports for 30 May 2001. Circles denote severe hail reports and crosses denote severe wind reports. Box in the upper right hand corner corresponds to the box over the Texas Panhandle but magnified. KLBB is the Lubbock, Texas WSR-88D radar site just north of the city [Courtesy of the NOAA/NWS/Storm Prediction Center].

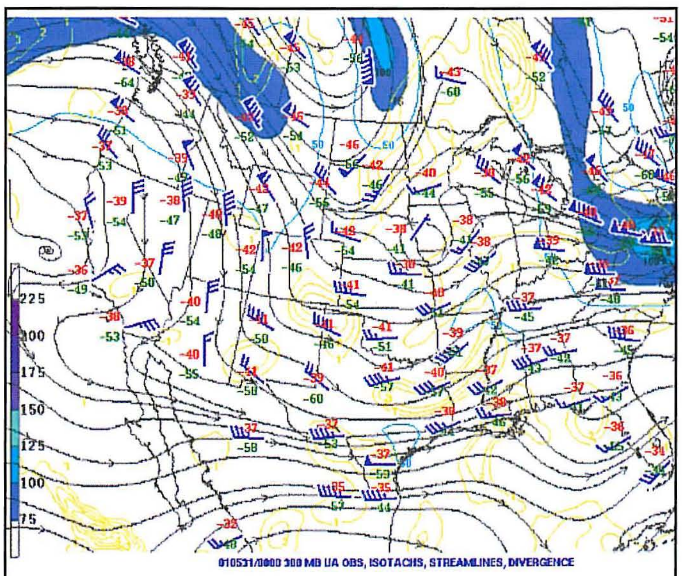

Fig. 2. The 300-mb level chart for 0000 UTC 31 May 2001. Observations are in standard notation. Streamlines and isotachs (beginning at 50 kt and in 25 kt increments above; shading as shown on the scale at left) are analyzed [Courtesy of NOAA/NWS/Storm Prediction Center].

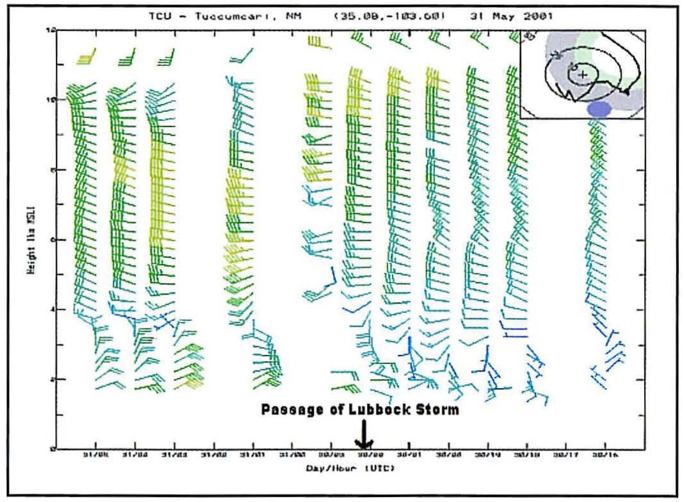

Fig. 3. Tucumcari, New Mexico, wind profiler time/height section. Wind in knots with a full barb equaling 10 knots and a half barb 5 knots [Courtesy of the Research Applications Program of the National Center for Atmospheric Research (NCAR)].

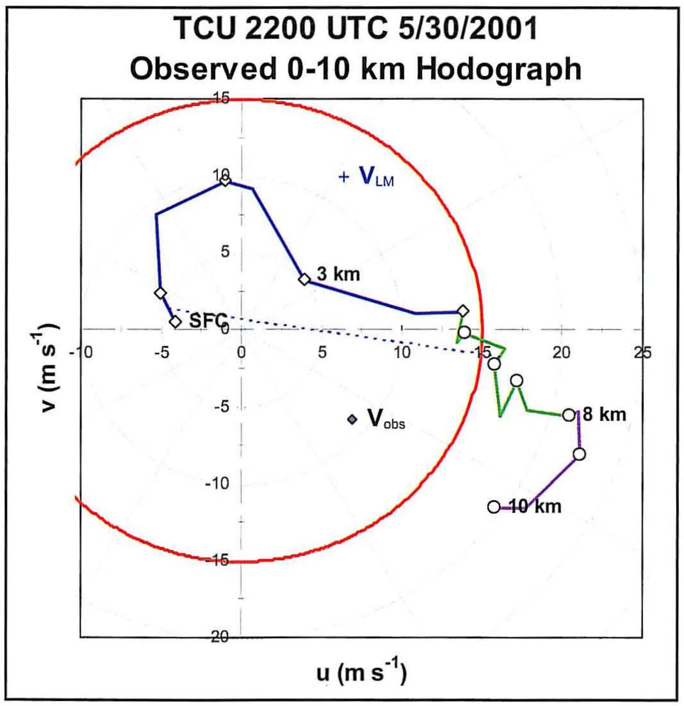

Fig. 4. Observed hodograph derived using the 2200 UTC Tucumcari, New Mexico profiler around an hour before the passage of the Lubbock storm. Rings denote wind magnitudes in meters per second. V_{obs} is the storm motion at the time of the hodograph estimated to be 310 degrees at 17 knots.

2. Synoptic and Mesoscale Environment

a. Upper-air data

At 0000 UTC on 31 May 2000, the 500-mb wind flow was northwesterly over the Texas Panhandle with magnitudes of 20-30 knots. A weakening, closed low over Kansas assisted in this flow, with heights rising over the region in association with an advancing ridge over the West Coast. There were three areas of weak cyclonic curvature; two were located over the southern Texas Panhandle and another upstream over northwestern New Mexico. A much stronger trough was located over Saskatchewan and southward over western North and South Dakota, and a fetch of stronger winds nosed southward at the 300-mb level into the four corners region (Fig. 2).

In general, deep layer shear values gradually increased throughout the day, as evidenced by the

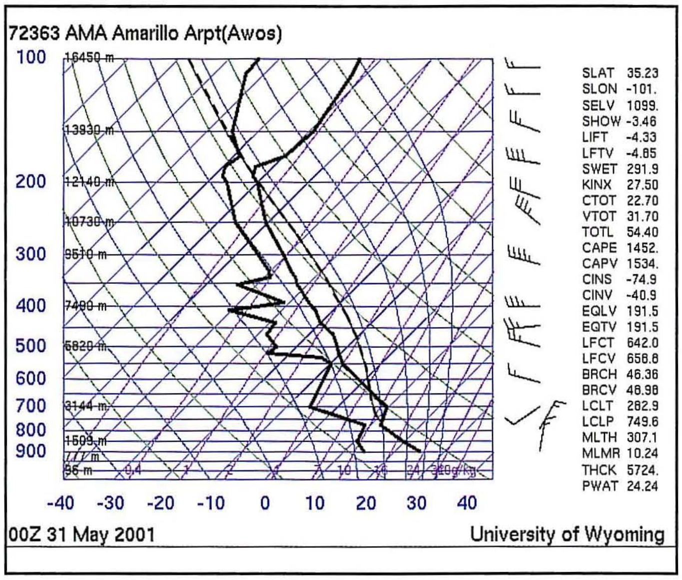

Fig. 5. Observed sounding for Amarillo, TX at 0000 UTC for 31 May 2001. Dashed line indicates lifted parcel temperature. Various sounding parameters listed on the right. [Original figure courtesy of University of Wyoming; modified for presentation.]

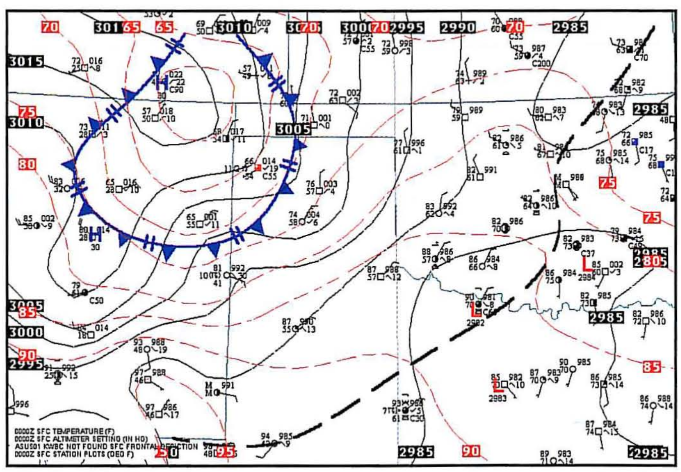

Fig. 6. Objective surface analysis valid at 0000 UTC 31 May 2001. Altimeter setting (solid, every .05 inches) and temperature (dashed, every 5 °F) analyzed. Bold dashed line indicates location of surface trough while cold front symbol indicates estimated location of the convectively generated cold pool.

Tucumcari, New Mexico profiler located along the New Mexico border (Fig. 3). The hodograph for 2200 UTC (about an hour before the passage of the Lubbock storm) shows appreciable turning of the shear vector within the lower levels (Fig. 4). The 0000 UTC Amarillo sounding reveals moderate instability in place for convection with a mixed layer CAPE of nearly 1,452 J kg^{-1} (Fig. 5). It should be noted that this sounding is probably not representative of the boundary layer near Lubbock. Dewpoint temperatures were relatively constant as one moved south, but surface temperatures were 13°F higher in Lubbock compared to the sounding at Amarillo.

Shear values fell within the range for supercells and multicell convection, with a calculated Bulk Richardson Number of 46 using the mixed layer CAPE

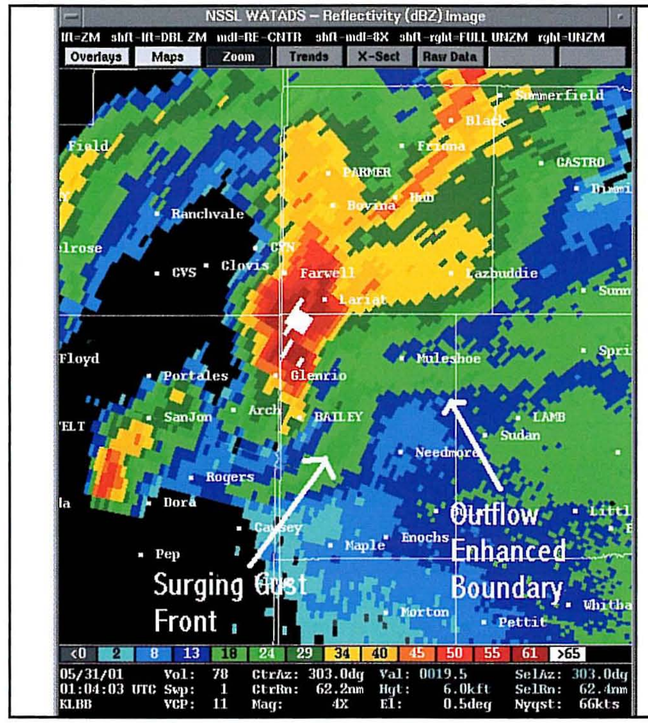

Fig. 7. WSR-88D reflectivity data (0.4° tilt) from KLBB (Lubbock, TX) centered on the Lubbock cell at 0104 UTC.

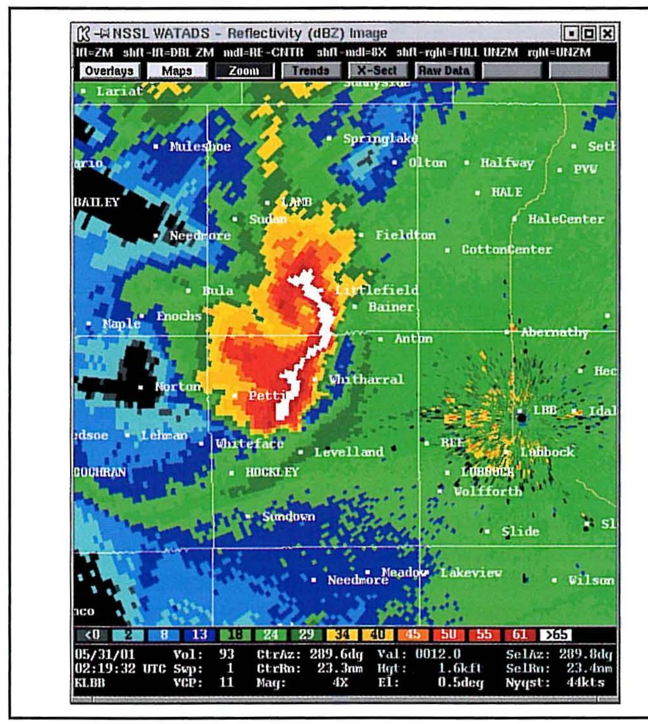

Fig. 8. WSR-88D reflectivity data (0.4° tilt) from KLBB for 0219 UTC. Note the well-defined cyclonic signature on the northern flank of the storm.

(Weisman and Klemp 1982). Bulk shear values of 39 knots (0-6 km) from the Tucumcari profiler at 2200 UTC also fall within the range for supercellular convection (Thompson et al. 2003; Bunkers 2002). Shear values probably dropped off as one moved southward

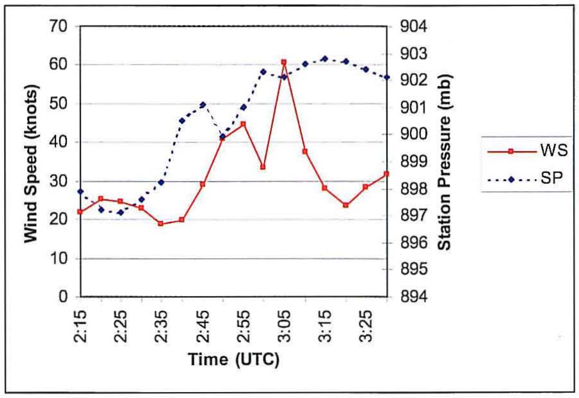

Figure 9a

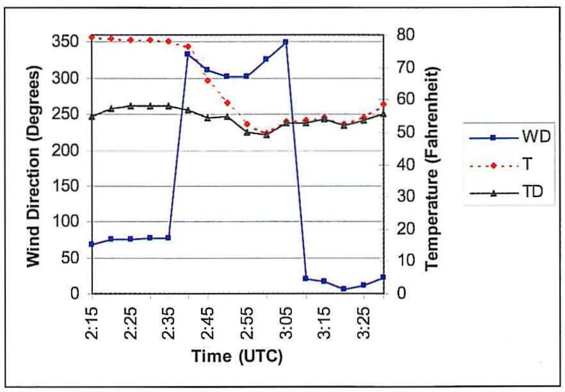

Figure 9b

Fig. 9. Reese Center WTM site 5-minute mean data time series from 0215 UTC to 0330 UTC 31 May 2001: **a.** Station pressure (SP; mb) and wind speed (WS; kt); **b.** Wind direction (WD; degrees), temperature (T; °F) and dewpoint (TD; °F).

given the weakly sheared environment found in the Midland, Texas, sounding south of Lubbock. In summation, the environment across West Texas was sheared to a moderate degree and maintained moderate to high instability; therefore, severe storms were likely if thunderstorms developed.

b. Surface data

Several interesting features were present on the afternoon of 30 May 2001. A synoptic scale surface trough/Pacific front had moved through the Panhandle, becoming stationary on a line from near Wichita Falls, Texas, to just north of Midland, Texas. In its wake, easterly upslope flow had commenced across the Texas panhandle into eastern New Mexico. A ribbon of moderately high dewpoints (greater than 50 °F) extended westward from the Red River towards Lubbock and the New Mexico border. WSR-88D reflectivity data indicated that the nearest active convection was well to the east in Oklahoma and significant outflow boundaries did not appear to be present in the Texas panhandle.

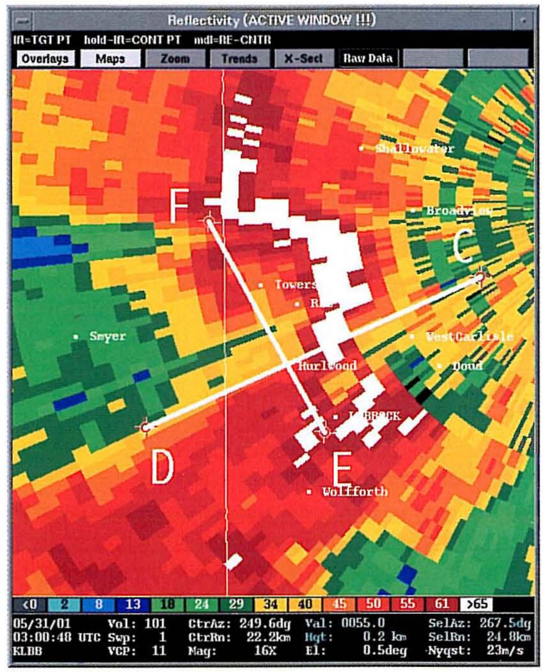

Fig. 10a. Reflectivity data (0.4° tilt) from Lubbock (KLBB) storm centered on 31 May 2001 for 0300 UTC. Reese Mesonet located near the point denoted by "Towers" on the map. Cross sections in Fig. 12 are taken along line CD and EF.

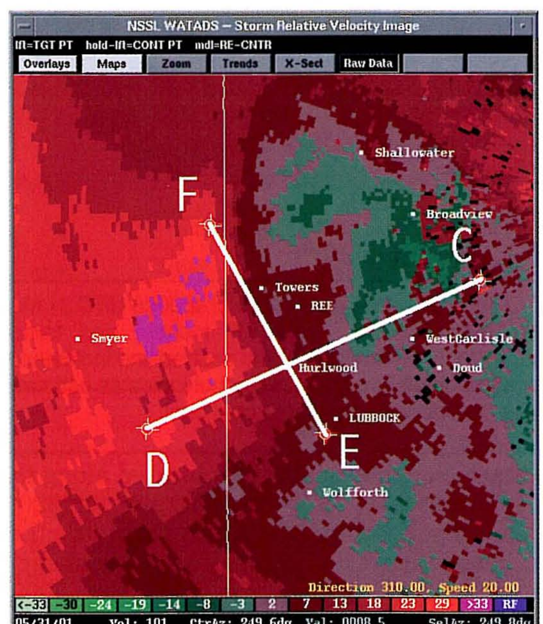

Fig. 10b. Storm-relative velocity data centered on the Lubbock storm, 31 May 2001 for 0300 UTC. Storm motion of 310 degrees at 20 knots assumed.

By 2100 UTC, convection began to develop over the higher terrain in north central New Mexico. A thermal low was intensifying over far southeastern New Mexico

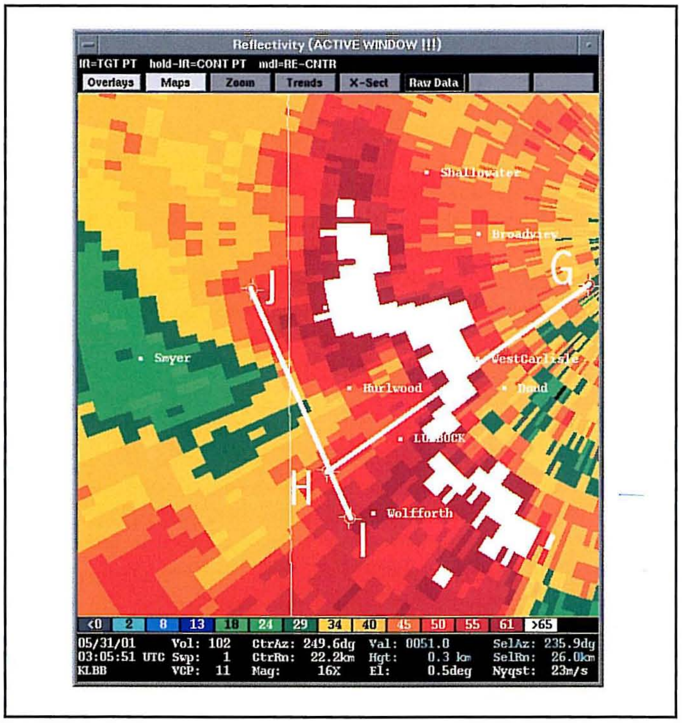

Fig. 11a. Reflectivity data (0.4° tilt) from Lubbock (KLBB) storm centered on 31 May 2001 for 0305 UTC. Wind gusts in excess of 90 knots were occurring at the Reese Center WTM site at this time. Cross sections in Fig. 13 are taken along line GH and IJ.

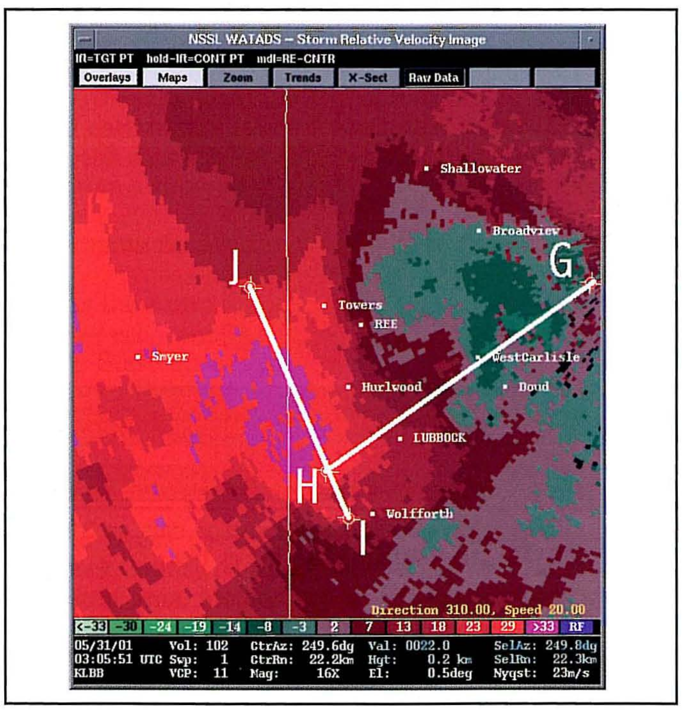

Fig. 11b. Storm-relative velocity data centered on the Lubbock storm, 31 May 2001 for 0305 UTC. Storm motion of 310° at 20 knots assumed.

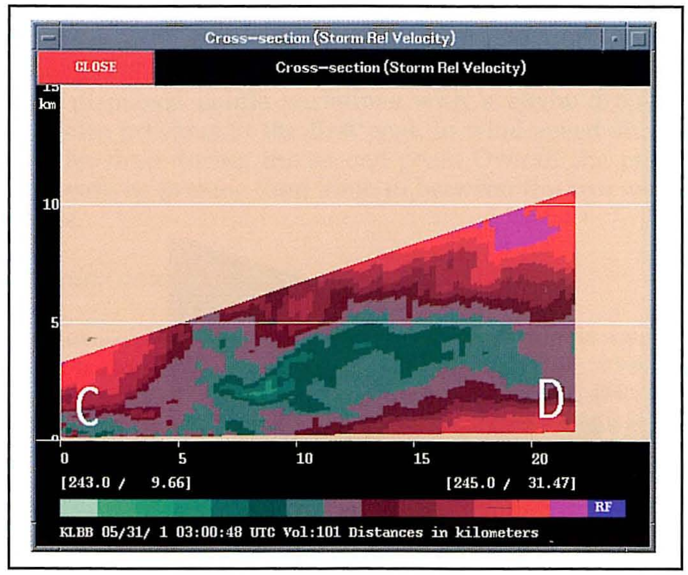

Fig. 12a. Storm-relative velocity cross section data on 31 May 2001 at 0300 UTC taken along line CD in Fig. 10.

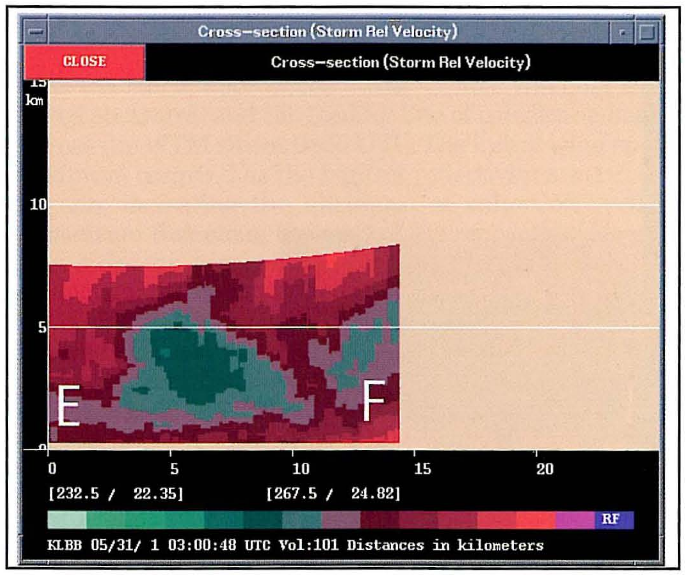

Fig. 12b. Storm-relative velocity cross section data on 31 May 2001 at 0300 UTC taken along line EF in Fig. 10.

enhancing the easterly flow behind the front. As the storms progressed southeastward, the cell in question developed west of Tucumcari, New Mexico, around 2120 UTC. Upon approaching the Texas/New Mexico border, the convection to the north weakened while the southern cell (the Lubbock cell) maintained its intensity. A large mesohigh had developed over northeastern New Mexico in response to the large area of decaying convection in that region. The ensuing pressure gradient between the thermal low to the south and the mesohigh to the north enhanced easterly flow throughout the Panhandle (Fig. 6).

3. Boundary Interaction and Storm Transition

Based on WSR-88D data alone, it is unclear whether the Lubbock cell had a persistent mesocyclone while in New Mexico. Observers in the field that day (Albert Pietrycha, personal communication) asserted that the convection did appear supercellular and the discrete appearance along with ample shear lends credence to

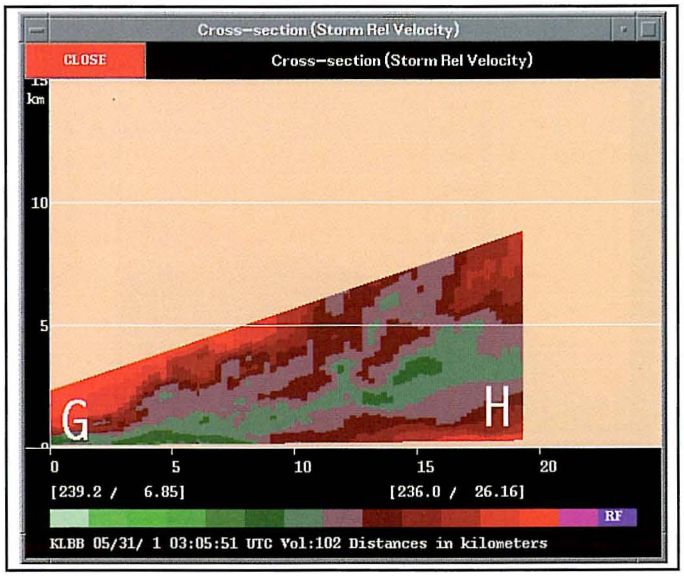

Fig. 13a. Storm-relative velocity cross section data on 31 May 2001 at 0305 UTC taken along line GH in Fig. 11.

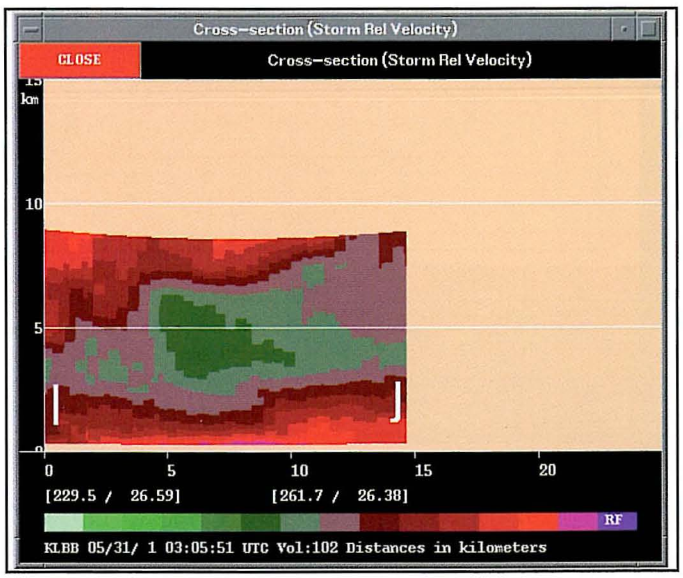

Fig. 13b. Storm-relative velocity cross section data on 31 May 2001 at 0305 UTC taken along line IJ in Fig. 11.

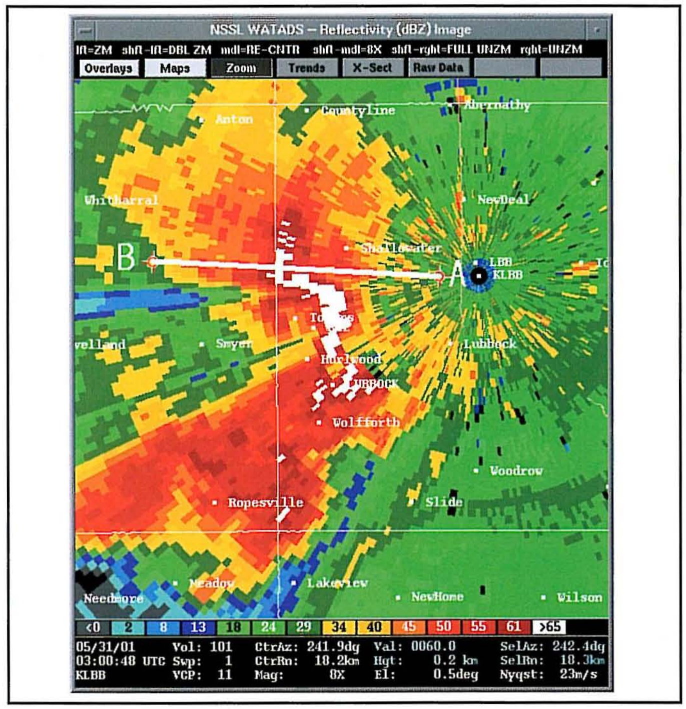

Fig. 14a. Reflectivity data (0.4° tilt) from Lubbock (KLBB) storm centered on 31 May 2001 for 0300 UTC.

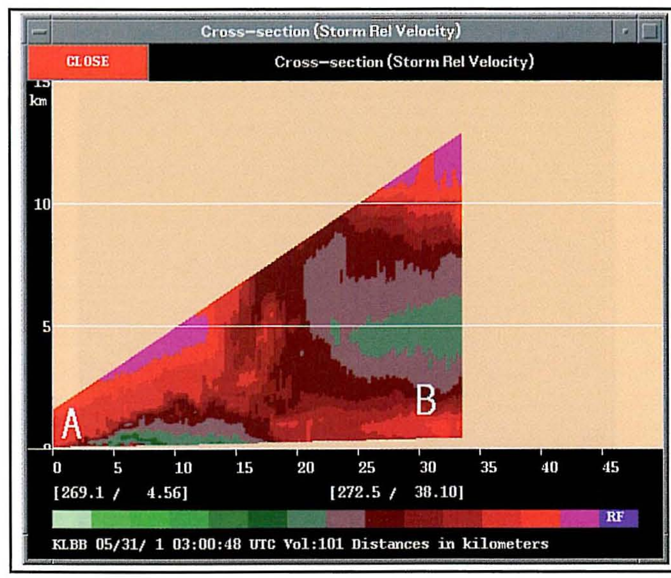

Fig. 14b. Storm-relative velocity cross section data on 31 May 2001 at 0300 UTC taken along line AB in Fig. 14a.

this. Around 0100 UTC, the Lubbock cell took on a strikingly supercellular appearance in the reflectivity field with what appears to be a hook appendage on its southwest flank (Fig. 7). The kidney-bean shaped appearance to the reflectivity field is very similar to that found in high-precipitation supercells (Moller et al. 1990). A substantial surge of outflow can be seen ahead of the appendage, possibly indicating the strengthening of a low-level cold pool. Intersecting the surging gust front is an east/west oriented boundary. Cross sectional data at this time shows the existence of a substantial weak echo region, implying extremely high vertical velocities along the leading edge of the gust front.

It has been shown that boundary interactions can serve as a source of low-level rotation for thunderstorms via tilting (Markowski et al. 1998). Although this is typically thought of as a potential mechanism for tornadogenesis, Klimowski et al. (2000) found it to be a precursor for convective mode transition in the Northern Plains from a supercell to a bow echo. Indeed, the Lubbock cell began to take on bow-echo characteristics shortly after interacting with this boundary. The Muleshoe WTM site, just north of the boundary at 0100 UTC, indicated a slight increase in dewpoint temperature along with a decrease in temperature, as the boundary passed. Density calculations involving a virtual temperature adjustment in the ideal gas law reveal that the air south of the boundary was less dense (due to a higher virtual temperature), indicating a thermally direct solenoidal circulation across the boundary. Therefore, tilting of this horizontal vorticity by the approaching gust front might have enhanced vortex development on the northern end of the convection.

Shortly thereafter, a well-defined cyclonic vortex developed on the northern flank of the Lubbock cell with a subsequent rear-inflow notch intensifying as the storm approached Lubbock (Fig. 8). A well-defined rear-inflow jet developed on the southern flank of the cyclonic vortex with ascending front-to-rear flow above this per storm-relative velocity data. Periodic reports of winds in excess of 50 knots and hail greater than 1 inch in diameter occurred during this stage of the storm's life cycle.

Observations made by a reviewer point out that the Lubbock storm accelerated substantially in forward movement after the maturation of a cold pool as evidenced by the rapidly advancing gust front. The Tucumcari profiler (Fig. 3) indicates that midlevel winds increased by at least 15 knots within the 3-6 km layer from 2300 UTC to 0300 UTC. However it is unclear whether this increase is due to the departing bow echo or associated with a larger scale feature. Therefore the increase in storm motion without a concurrent increase in midlevel winds on the larger scale would imply a weakening of the westerly storm relative midlevel winds. It should be noted that weak storm-relative winds have been associated with supercell to bow echo transitions and/or high precipitation supercell environments (Brooks and Doswell 1993). It is believed that this may be due to hydrometeors falling in close proximity to the updraft due to the lack of ventilation aloft by strong advection. As noted earlier, the Lubbock storm did indeed take on HP supercell characteristics as well as undergoing a transition from a supercellular mode to a bow-echo mode.

4. Extreme Surface Winds at Reese Center

As the storm entered Lubbock County it maintained its bow-echo signature with an expanding rear-inflow notch. Such an expansion is believed to be associated with negative θ_e advection along an intensifying rear-inflow jet (Przybylinski 1995).

a. Mesonet data

The Reese Center WTM site is located in western Lubbock County, on the western edge of the Lubbock metropolitan area. Meteorological time series data are plotted in Figs. 9a and 9b for this site. As can be seen, most variables were relatively steady until the passage of the gust front around 0235 UTC - the only exception being station pressure, which had a local minimum prior to the passage of the gust front. As the gust front passed, the wind direction abruptly changed to the northwest, the temperature decreased, and the pressure increased. Such trends are typical of a well-defined gust front as dropping temperatures signify the onset of an advancing cold pool. Two peaks can be seen in the 5-minute wind speed data following the gust front passage; one at 0255 UTC and a higher, more transient maximum at 0305 UTC. Interestingly, temperatures rose slightly as the second wind speed maximum approached, and winds veered to a more northerly direction at the surface. The station pressure displayed subtle variations with a slight drop in pressure previous to the first peak in wind speed and a smaller drop during the second peak. Overall the pressure rose by greater than 2 mb in between the two wind peaks.

b. Radar data

Storm-relative velocity data for this study is based upon a storm motion of 310 degrees at 20 knots, a value estimated by the storm tracking algorithm used for this study shortly before the midpoint in its life cycle. As stated previously, the Lubbock cell accelerated in its forward motion dramatically during its transition from a supercell to bow echo. Therefore, this value of storm-relative motion is likely an underestimate at the time damaging winds were occurring in Lubbock County. The storm-motion vector, on the other hand, deviated little throughout its lifetime. Hence the variability in storm-relative velocities due to variability in storm motion will not affect the existence of vortical and shear features only the magnitudes of storm relative inflow and outflow.

As the storm approached Reese Center, the gust front moved eastward, and the leading line of convection began to cross the WTM site at 0250 UTC. The initial wind speed maximum occurred as the highest reflectivities were over the site, indicating the likelihood of enhanced vertical momentum flux along the nose of the rear-inflow jet, perhaps aided by precipitation loading. By 0300 UTC, the leading line of high reflectivities had passed the Reese WTM site, and a temporally short wind speed minimum occurred (Fig. 9). At this time, the Reese WTM site was located just south of an east-west oriented arc of reflectivities in excess of 65 dBZ; a hook appendage was located west of Reese Center (Fig. 10a). Although no low-level rotation can be seen close to the surface, it is likely that this appendage is due to precipitation descending in a cyclonic trajectory around the elevated vortex (Fig. 10b).

By 0305 UTC, the northern vortex and its associated region of reflectivities in excess of 65 dBZ moved across the WTM site (Fig. 11a). It was at this time that the highest wind speeds occurred in the mesonet data (wind gusts reaching 91 knots), with the winds taking on more of a northerly component

In an attempt to identify coupling between momentum aloft and at the surface, cross sections of the radar data were analyzed along a radial from the KLBB radar (Line C-D in Figs. 10a and 10b). It was a fortuitous event in that the rear-inflow jet, for a time, was nearly parallel to radials west of KLBB. Another cross section was taken along an azimuth perpendicular to the rear-inflow jet (Line E-F in Figs. 10a and 10b) and crossing through the region that experienced the second maximum in winds. Cross section C-D at 0300 UTC (Fig. 12a) indicates a maximum in storm-relative velocity towards the radar occurring in the 3-4 km layer with a channel of storm-relative winds having almost zero radial velocity surrounding it and extending to the surface. Hence, we can deduce that the outflow winds along the leading edge of the gust

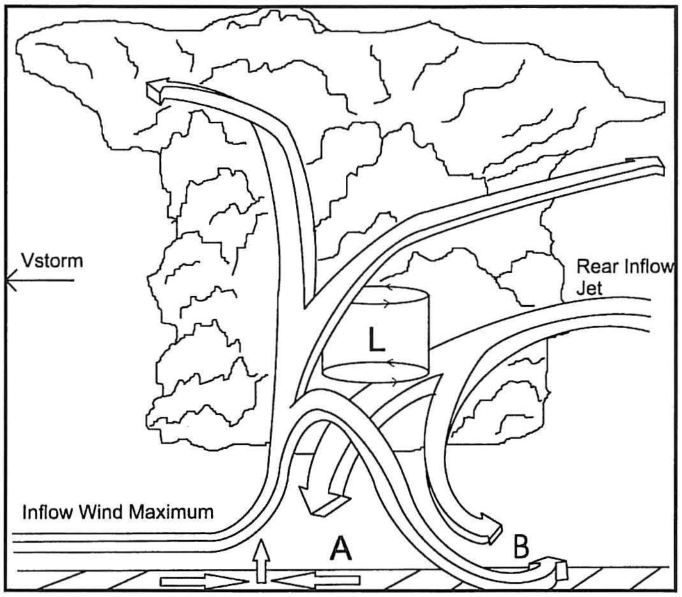

Fig. 15. Sketch of inferred storm structure from the period 0250 UTC to 0310 UTC as the storm was west of Lubbock, Texas. View is from the northeast looking southwest with the storm motion indicated by the vector Vstorm. Large arrows show storm-relative flow with small arrows at the surface indicating the location of the gust front and ensuing vertical velocity jet. Perturbation low pressure (L) and associated mesocyclone are indicated. Surface wind maxima are indicated by A and B respectively.

front are likely coupled to the rear-inflow jet by a channel of vertical momentum flux along the leading edge.

Cross section E-F also reveals some interesting information concerning storm-relative momentum to the rear of the gust front (Fig. 12b). First, the cyclonic shear zone from 2-5 km represents the cyclonic vortex; however, the storm-relative velocities appear vertically stratified and decoupled in the lower levels. Thus it appears that vertical flux of westerly momentum is not reaching the surface a certain distance behind the leading edge of the gust front or to the rear of the higher reflectivities. The Reese Center WTM data confirm this with a minimum in wind speed around 0300 UTC.

As the maximum winds occurred at Reese Center, the divergent signature had expanded (Fig. 11b) and moved over the site with impressive outbound radial velocities to the southwest of Reese. This region received considerable damage according to *Storm Data*, with National Weather Service survey teams estimating winds to have exceeded 70 knots in this region. Again, cross sections were taken to investigate the temporal continuity of the radial velocity structure (along line G-H and line I-J in Figs. 11a and 11b). Cross section G-H (Fig. 13a) shows a vertically coupled channel of similar radial velocities along a radial near the rear-inflow jet. Cross section I-J (Fig. 13b), taken within the region of greatest outbound velocities, shows the stratified structure of radial velocities, indicating that the rear-inflow jet was not coupled to the region of extreme winds. The strong outbound component implies that an easterly component was present to the rear of the leading edge of higher reflectivities. The Reese Center WTM site is located in a region of zero radial velocity which verifies the actual surface wind direction data (Fig. 9b) as the extreme winds were northerly, a direction nearly perpendicular to radials.

Certainly the region of impressive surface winds appears to be influenced by a particularly intense microburst underneath the cyclonic vortex. However, a cross section on the northern edge of the vortex at 0300 UTC just prior to the strongest winds at Reese Center (Fig. 14a) offers some additional clues as to what might have augmented precipitation loading within the microburst. Cross section A-B in Fig. 14b shows impressive front-to-rear flow rising up and over the low-level outflow at the surface. However, a region of outbound velocities appeared to separate and actually descend to the rear of the vortex. Hence, *easterly* momentum may have played an integral part in forcing the extreme winds to the west of the leading edge reflectivities. The Lubbock velocity azimuth display (VAD) wind profile showed an impressive easterly jet just above the surface (centered at 1.5 km AGL) prior to the storm. It is possible that inflow air accelerated towards the storm due to lowering pressure aloft within the northern vortex in much the same way that perturbation low pressure develops in supercellular mesocyclones (Klemp 1987).

As time progressed, the divergent signature continued to propagate with the arc of higher reflectivities to the southeast. Winds are estimated to have reached 60-80 knots in southwest Lubbock County as this signature passed. The vortex would go on to assume a steady state circulation with an overall weakening of the storm after exiting Lubbock County with sporadic reports of winds in excess of 60 knots thereafter.

5. Comparisons to Previous Research

The 30 May 2001 Lubbock storm displayed characteristics similar to systems studied by SC89 and BC98. First, it appears each of these convective storms had a significant component of easterly inflow contributing to the downdraft, which subsequently produced damaging winds. Second, this easterly flow appeared to be associated with a cyclonic circulation in each case. The third relation, albeit not as strong, is that the Lubbock storm began to propagate into an increasingly stable planetary boundary layer (PBL) when the extreme winds occurred. This is a rather weak relationship since the storms in SC89 and BC98 maintained their integrity and even intensified while moving through the stable PBL. In contrast, the Lubbock storm did not maintain a steady-state structure after encountering the stable PBL. It should be mentioned that the convection in SC89 and BC98 encountered a low-level inflow jet above the stable PBL, much like what was seen in the Lubbock VAD wind profile. It is believed that these inflow jets sustained the systems in the previous studies. Unfortunately, wind profiler and upper-air data were not available within the storm's inflow region after its passage through Lubbock; therefore, it is unclear whether the degradation of surface winds and system integrity are associated with a corresponding degradation in the low-level inflow jet.

Based on the evidence given by the WSR-88D and surface data, a model of the Lubbock storm structure is proposed (Fig. 15). It resembles that given by SC89 and BC98 with the exception that parcels along the lifting zone on the forward flank of the system have smaller buoyancy deficits (i.e., the boundary layer is not entirely stable). As can be seen, low-level inflow air atop a shallow PBL is accelerated quickly towards the storm, possibly due to the perturbation low pressure. Once this inflow air encounters the gust front, it is forced to rise with lower portions of this ascending column being negatively buoyant. At the surface, severe winds are produced immediately to the rear of the gust front due to vertical momentum flux from the rear-inflow jet and strong horizontal pressure gradients (near point A). After moving out of the gust front lifting zone, ascent along the inflow branch is forced by vertical perturbation pressure gradients due to an elevated vortex (Klemp 1987). Eventually, precipitation loading and negative buoyancy dominate, and the flow branch rapidly descends cyclonically to the rear of the storm producing a secondary wind speed maximum to the southwest of the elevated northern vortex (near point B). After moving through Lubbock County the storm structure changed dramatically, and the diagram does not represent a steady-state picture but rather a snapshot of storm structure during its period of maximum winds.

6. Conclusions

An impressive bow-echo complex moved through Lubbock, Texas, during the evening of 30 May 2001. This system produced wind gusts of 91 knots west of Lubbock with winds in excess of 45 knots along an axis of nearly 200 km in length. Severe parameters displayed moderate potential for damaging convection (MLCAPE $\leq$ 1500 J kg^{-1}; 0-6 km Bulk Shear ~ 40 knots); such values have been associated with mesocyclone dominated systems with significant outflow.

Radial velocity data of the Lubbock system suggests that a mechanism similar to that found by SC89 and BC98 may have been present. These studies show that significant forcing for severe surface winds can be attributed to easterly inflow descending to the surface and accelerating. WSR-88D volume scans near the time of the greatest surface winds indicate a channel of easterly momentum descending along the northern edge of the system. Upon reaching the surface, it appears that this channel accelerated rapidly southward away from the cyclonic vortex. It was in this portion of the storm that wind gusts exceeded 90 knots. In light of these studies, the existence of a bow echo within a stable PBL capped by an inflow-directed low-level wind maximum should be monitored closely, especially if radial velocities become rather strong to the *rear* of the leading edge reflectivities and in the vicinity of a mesocyclone.

Future studies should continue to investigate whether there is a significant component of inflow momentum that is transported to the surface. As noted by SC89 and BC98, such structures have been seen with stable boundary layers, and sensitivity studies could be done to distinguish whether low-level stability has anything to do with the structure seen in this paper. In particular, dual-Doppler analysis of more storms exhibiting this structure is needed to verify whether this is indeed a fundamental mechanism in high-wind producing convection.

Acknowledgments

The authors would like to thank Matt Bunkers for his valuable suggestions on this project and for providing the Tucumcari hodograph image. The authors also wish to express gratitude to Mark Conder for providing answers to many of the data formatting questions. Also, the authors would like to thank Dr. William Cotton of Colorado State University for his input on this project. Suggestions from other members of the first author's thesis committee, Dr. Chia Bo Chang and Dr. Richard Peterson, helped improve the study.

Authors

Caleb J. Midgley is a Project Meteorologist for the Southern Ogallala Aquifer Rainfall Program (SOAR). He received a B.S. in meteorology from the University of Kansas in 2000 as well as an M.S. in meteorology from Texas Tech University in 2003. His research interests include convective storm structure, convective initiation, and jet streak dynamics.

Dr. John Schroeder is an Assistant Professor of Atmospheric Science at Texas Tech University. He received a B.S. in Civil Engineering from the University of Missouri-Rolla in 1994, an M.S. in Atmospheric Science from Texas Tech University in 1997, and a Ph.D. in Wind Engineering from Texas Tech University in 1999. His interests include boundary layer characteristics within extreme wind events.

References

Bernardet, L. R., and W. R. Cotton, 1998: Multiscale evolution of a derecho-producing mesoscale convective system. *Mon. Wea. Rev.*, 126, 2991-3015.

Brooks, H. E., and C. A. Doswell III, 1993: Extreme winds in high-precipitation supercells. Preprints, *17th Conf. Severe Local Storms*, Saint Louis, MO, Amer. Meteor. Soc., 173-177.

Bunkers, M. J., 2002: Vertical wind shear associated with left-moving supercells. *Wea. Forecasting*, 17, 845-855.

Fujita, T. T., 1978: Manual of downburst identification for project NIMROD. SMRP Research Paper 156, University of Chicago, 104 pp. [NTIS PB-2860481.]

Johns, R. H., and W. D. Hirt, 1987: Derechos: widespread convectively induced windstorms. *Wea. Forecasting*, 2, 32-49.

Klemp, J. B., 1987: Dynamics of tornadic thunderstorms. *Ann. Rev. Fluid Mech.*, 19, 369-402.

Klimowski, B. A., R. Przybylinski, G. Schmocker, and M. R. Hjemfelt, 2000: Observations of the formation and early evolution of bow echoes. Preprints, *20th Conf. Severe Local Storms*, Orlando, FL, Amer. Meteor. Soc., 44-47.

Markowski, P. M., E. N. Rasmussen, and J. M. Straka, 1998: The occurrence of tornadoes in supercells interacting with boundaries during VORTEX-95. *Wea. Forecasting*, 13, 852-859.

Moller, A.R., C. A. Doswell III, and R.W. Przybylinski, 1990: High-precipitation supercells: A conceptual model and documentation. Preprints, *16th Conf. Severe Local Storms.* Kananaskis Park, AB, Canada, Amer. Meteor. Soc., 52-57.

NCDC, 2001: *Storm Data*. Vol. 43, No. 5. [Available from NOAA/National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801-5001.].

Przybylinski, R. W., 1995: The Bow Echo: Observations, numerical simulations, and severe weather detection methods. *Wea. Forecasting.*, 10, 203-218.

Schmidt, J. M., and W. R. Cotton, 1989. A high-plains squall line associated with severe surface winds. *J. Atmos. Sci.*, 46, 281-302.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting*, 18, 1243-1261.

Trapp, R. J., and M. L. Weisman, 2003: Low-level mesovortices within squall lines and bow echoes. Part II: Their genesis and implications. *Mon. Wea. Rev.*, 131, 2804-2823.

Wakimoto, R. M., 2001: Convectively driven high wind events. *Severe Convective Storms, Meteor. Monogr.*, No. 50, C. A. Doswell III, Ed., Amer. Meteor. Soc., 71-122.

Weisman, M. L., and J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.,* 110, 504-520.

_________, 1992: The role of convectively generated rear-inflow jets in the evolution of long-lived mesoconvective systems. *J. Atmos. Sci.*, 49, 1826-1847.

_________, 1993: The genesis of severe, long-lived bow echoes. *J. Atmos. Sci.*, 50, 645-670.

_________, and R. J. Trapp, 2003: Low-level mesovortices within squall lines and bow echoes. Part I: Overview and dependence on environmental shear. *Mon. Wea. Rev.*, 131, 2779-2803.