P1B.6 Bow Echo Embedded within a Squall Line

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1. Introduction

An intense squall line developed on 7 May 1995 in the Texas panhandle during VORTEX-95. Based on the Amarillo WSR-88D Doppler radar data (not shown), this north-south oriented squall line formed southeast of Amarillo, TX, along a cold front, moved into Oklahoma. By 2100, this squall line was about 600 km long and 100 km wide. The central part of the squall line was distorted into a bow echo after 2100 UTC and produced straight-line damage winds near Willow, OK. The scale of the bow echo ranges from a single cell thunderstorm (e.g., Lee et al. 1992) to a more organized mesoscale linear convective system (Weisman 1993). In these studies, the distortion of the radar echoes were associated with a pair of counter rotating vortices either produced by a strong downdraft or a rear inflow jet.

The NCAR Electra flew 40 km legs on the eastern side of this squall line at two different altitudes. ELDORA collected 300 m along track resolution data from 2013 to 2120 UTC (a total of 9 flight legs) with a data gap between 2055 to 2108 UTC. With additional data sources from the Amarillo WSR-88D data and surface measurements from NSSL ground team, the evolution and fine scale structure of this squall line segment and its accompanied mesocyclone were documented over a two-hour period.

ELDORA's 300 m along track resolution resolved features with a wavelength of 2 km. The Doppler radar data were edited in the NCAR SOLO software (Oye et al. 1995). The Doppler radar data were interpolated using Barnes scheme with grid spacing of 400 m in all three dimensions. The wind fields are deduced using a 3-D variational Doppler analysis technique (Gamache 1997) where the continuity equation is included in the cost function so the vertical velocity is deduced simultaneously with horizontal velocities. This approach allows the retrieval of 3-D winds above 45° elevation angle.

The evolution and fine scale structure of this squall line using primarily the dual-Doppler radar analyses from the NCAR ELDORA data have been documented in Lee et al. (2002). The evolution of the squall line over a 50-minute period is illustrated in Fig. 1. This squall line exhibited a complex structure that has not been documented in previous observational studies. A distinct mesocyclone and a hook echo were identified (12, 5) within this squall line at 2013. The storm-relative environmental flow (hereafter all winds are storm-relative unless specified otherwise) funneled into the mesocyclone (Fig. 1). The bulge and kink of the squall line are consistent with the winds suggesting that the line echo wave pattern (LEWP) of the echo (at 2035) was produced by the mesocyclone circulation. The peak updraft in upper atmosphere exceeds 60 m/s which is consistent with the CAPE exceeding 3000 J/Kg. The town Willow, OK is located near the apex (18,15) of the LEWP at 2049 (Fig. 1). It can be seen that the mesocyclone intensified between 2043 and 2049. A weak tornado was reported on Willow, OK around 2100 along the path of this squall line.

This paper further examines horizontal vortex tube structure, the bow echo structures and its relationship with the surface damage patterns in Willow using the dual-Doppler radar winds derived from ELDORA observations.

2. Horizontal vortex tubes

Strong convergence and updraft are located at the leading edge of the squall line south of the mesocyclone. Figure 2 illustrates a vertical sweep of the ELDORA data (left panels) and the corresponding vertical cross-sessions of the dual-Doppler wind synthesis along that sweep (right panels) south of the mesocyclone at 2112. Note that the ELDORA sweeps out a conical surface so these two planes are not exactly the same. A dominant feature is a front to rear inflow in the boundary layer feeding into the strong updraft into the weak echo vault. A deep rear inflow layer (up to 5 km) was evident impinging into the main updraft. The re-circulation of the main updraft (with the echo overhang) shown here was commonly observed during VORTEX-95 and has been proposed as one mechanism to form hail (e.g., Browning and Foote1976). The structure north of the mesocyclone (not shown) exhibited quite different characteristics. The convergence was relatively shallow and was located deep into the line. The primary updraft and the active convection were behind the high reflectivity feature in the ELDORA data. This is probably due to attenuation of the 3-cm radar passing through heavy precipitation in the leading edge of the line. The high reflectivity in the mid and upper levels was associated with downdraft and falling precipitation. The differences in the vertical structures (e.g., sloping of the updraft) in different part of a squall

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line have been simulated in numerical model (Weisman and Davis 1998).

Multiple horizontal vortex tubes (Doppler velocity dipoles in RHI scans) with speed exceeding 30 m/s were clearly seen along the interface between the receding flow (inflow) and approaching flow (outflow) as illustrated in Fig. 2. The most pronounced horizontal vortex tube resolved by the dual-Doppler analysis was located at x=12 km and z=7 km while other smaller vortices along the interface were not resolved. Similar horizontal vortex tubes also existed on the front end of the updraft vault associated with curling reflectivity factor.

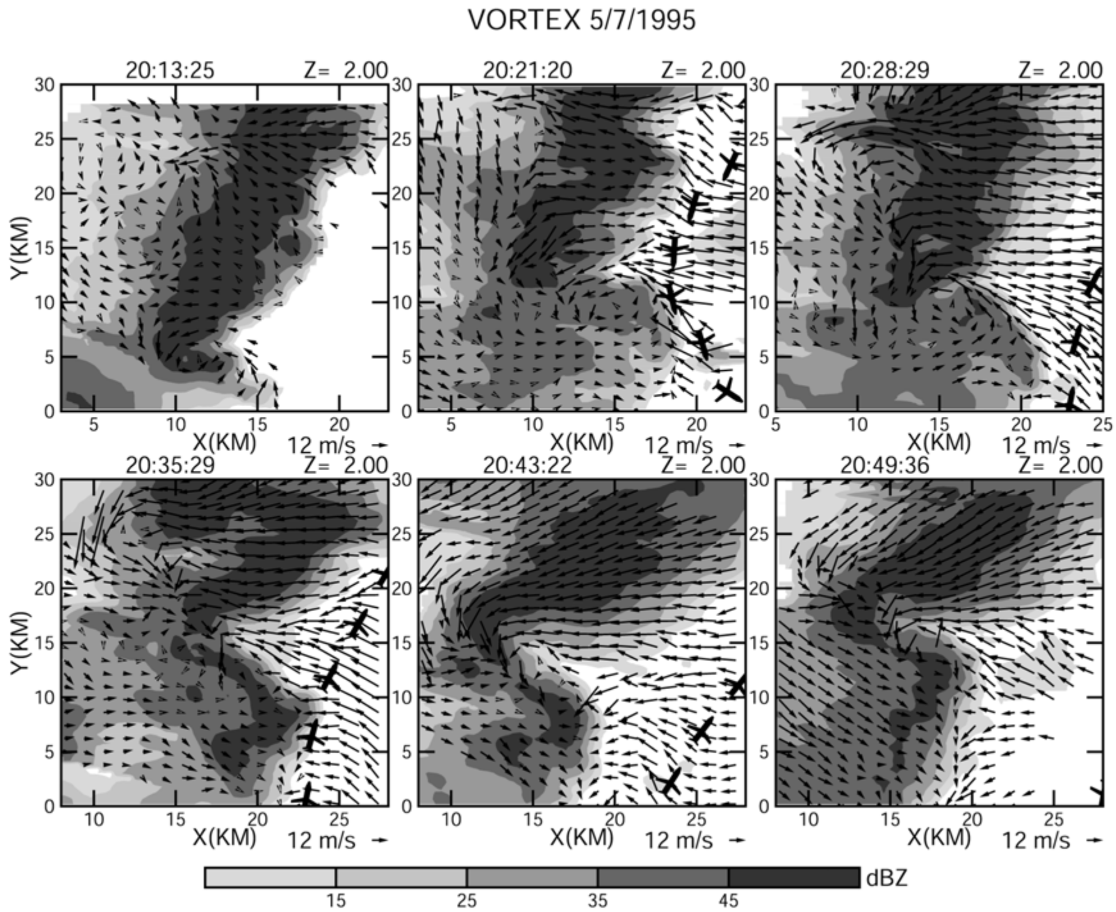
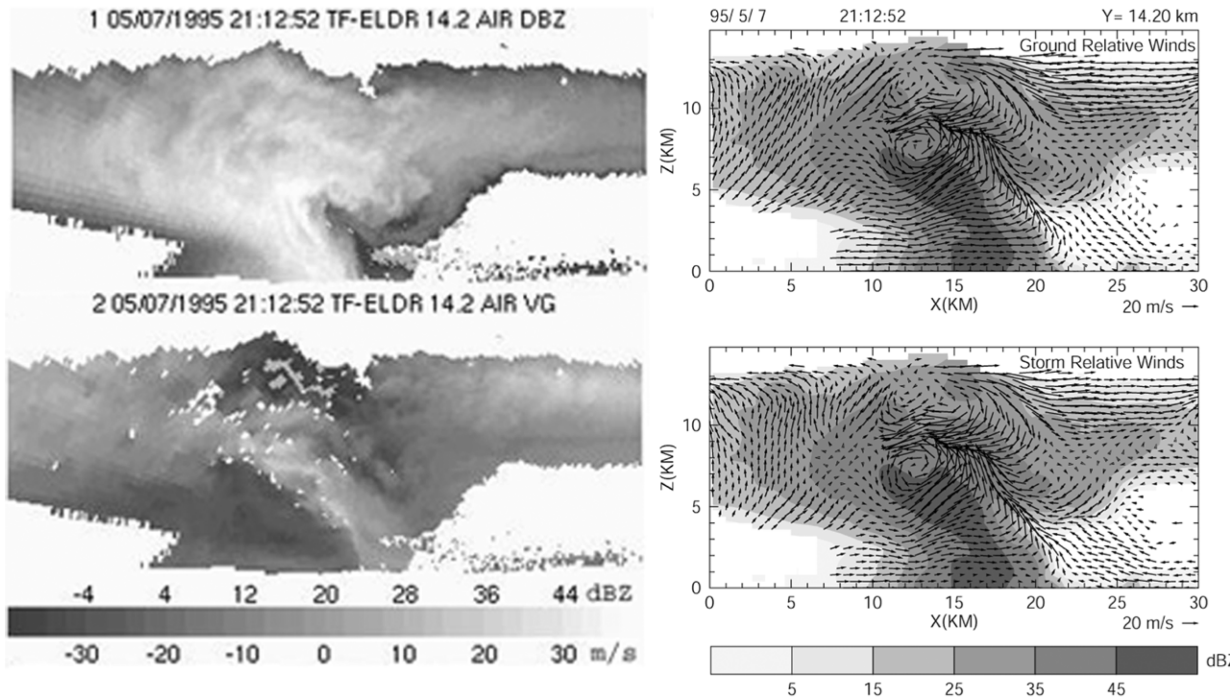


Figure 1: The horizontal cross-sections of the 7 May 1995 squall line at 2 km altitude from 2013 to 2049. The reflectivity is in gray shades and storm-relative winds are in vectors. The aircraft symbols indicate the flight track of the NCAR Electra.

3. Bow echo and surface damage

A tornado was reported by residence of Willow, OK at 2100 UTC according to the Storm Data. This time was in agreement with the passage of the squall line and the bow echo through Willow. However, damage survey performed on 8 May 1995 revealed only straight-line wind damages mostly cased by strong southerly winds (Fig. 3), a typical damage pattern produced by downbursts but not by tornados (e.g., Forbes and Wakimoto 1983). Hence, it was suspected that the damage was produced by a downburst frequently associated with bow echoes (Fujita 1978). The dual-Doppler analyses of a flight leg between 2110 and 2117 at 0.4 km above ground level are shown in Fig. 4.

The location of Willow is indicated by a white circle (21.3 km, 15 km). It is clear that Willow was on the path of the apex of the bow echo. The storm-relative winds (left panel) showed a mesocyclone with vertical vorticity exceeding 0.04 s^{-1} just west of Willow. At this level, there was no downdraft exceeding 7 m/s resolved in the synthesis. A southerly wind exceeds 20 m/s is retrieved on the east side of the mesocyclone. The mesocyclone is moving at a speed of u=10.5 m/s and v=19.1 m/s. As a result, the ground-relative winds on the east side of the mesocyclone exceeded 40 m/s from the south that is consistent with most of the damage patterns reported surrounding Willow. As a result, ground-relative winds are nearly stagnated on the west



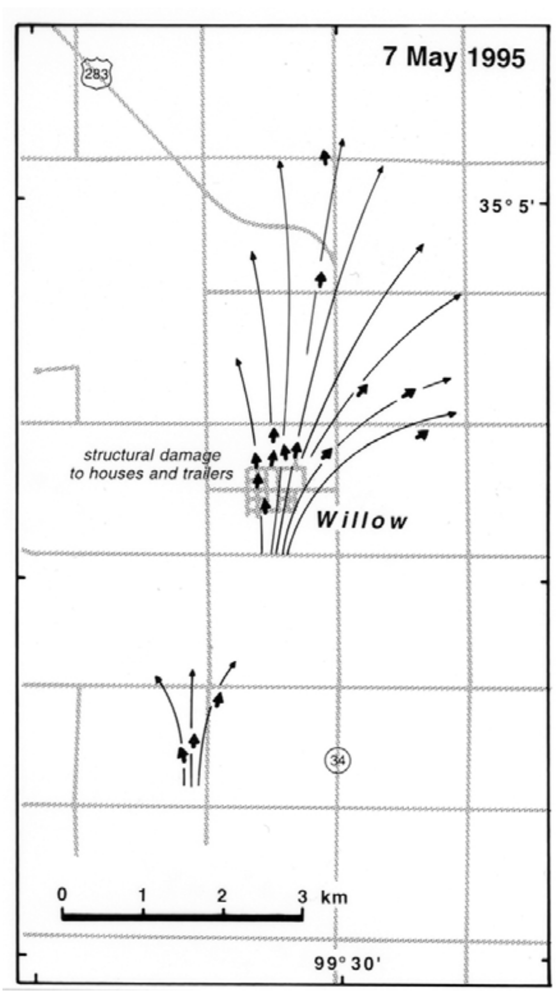


Figure 2. ELDORA conical scan data is illustrated with reflectivity (top left) and ground-relative Doppler velocity (bottom left). Ground-relative (top) and storm-relative (bottom) dual-Doppler winds on a vertical cross-section near the RHI are illustrated on the right panels.

Figure 3. Damage survey in Willow, OK during the 7 May 1995 squall line and bow echo event.

side of the mesocyclone. The asymmetric enhancement of the ground-relative wind within the mesocyclone by its fast translation speed may explain the straight-line damage pattern occurred in this event rather than the scallop damage pattern commonly seen in the tornado path. This finding is consistent with the numerical simulations by Trapp and Weisman (2003).

4. Summary

This study presents the 7 May 1995 squall line kinematic structures obtained by the NCAR ELDORA via a 3-D variational analysis technique. The structures of this squall line are unique in many aspects that have not been revealed in previous observational studies, such as the vertical velocities in a weak echo vault, the structure of anvil at high incidence angles, 3-D characteristics of a squall line, and the formation of a bow echo.

The straight line wind damages in Willow was caused by a mesocyclone whose ground-relative circulation was highly asymmetric due to the fast storm motion.

Acknowledgments:

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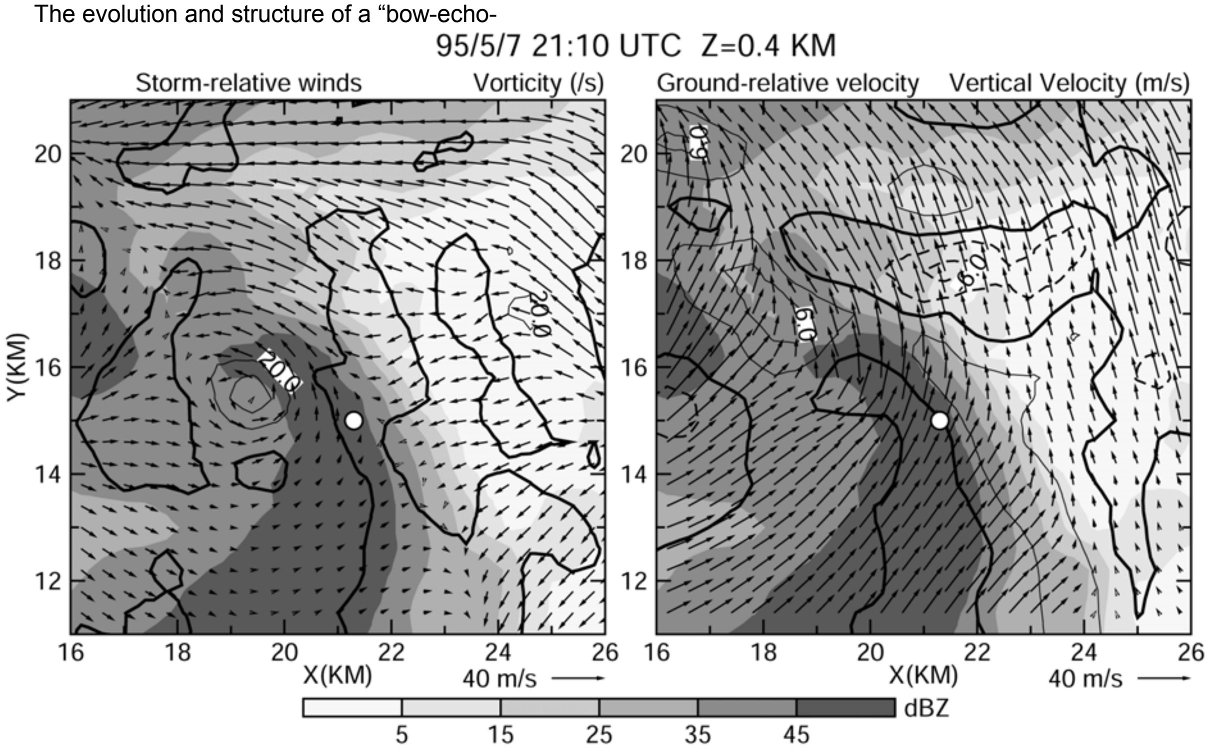

Figure 4. Dual-Doppler winds at 0.4 km AGL at 2110 near the apex of the bow echo. Reflectivity is in gray shades. Left panel consists of storm relative winds and vorticity (s^{-1}) while right panel consists of ground-relative winds and vertical velocity (ms^{-1}). Thick solid lines indicate zero vorticity or vertical velocity while solid (dash) lines indicate positive (negative) values. The white circle indicates the location of Willow, OK.