13.4 TORNADOGENESIS WITHIN QUASI-LINEAR CONVECTIVE SYSTEMS. PART II: PRELIMINARY WRF SIMULATION RESULTS OF THE 29 JUNE 1998 DERECHO

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1. INTRODUCTION

Within Quasi-Linear Convective Systems (QLCSs) such as bow echoes, mesoscale vortices on many different spatial scales have been documented. Cyclonic and anticyclonic mid-level vortices often form on the northern and southern ends of the convective system, respectively. These vortices have spatial scales ranging from tens to hundreds of kilometers and can last for several hours to days at a time. Within bow echoes, they are capable of enhancing the rear inflow jet by 30-50% (Weisman 1993). Numerical simulations by Weisman and Davis (1998) have shown that the vortices form by tilting of either environmental or system-generated horizontal vorticity at the line ends by the system updrafts.

Observational (e.g., Przybylinski 1995) and numerical (Weisman and Davis 1998) studies have also documented the existence of meso-γ scale vortices formed along the leading edge of QLCSs. These vortices tend to be short-lived, low-level and are often associated with tornadoes typically producing F0-F1 damage, although stronger damage has been associated with these tornadoes. Moreover, they tend to form north of the bow apex. While numerical simulations have elucidated the genesis mechanisms for the mid-level line-end vortices, the processes responsible for the formation and evolution of the low-level, meso-γ scale vortices are not well understood.

In Part I of this paper, eleven radar-detected, low-level vortices formed at the leading edge of the 29 June 1998 derecho that traversed over southeastern Iowa into central Illinois, were documented. At least five of these low-level vortices were tornadic and ten of the vortices were observed north of the bow apex. The objective of this study is to numerically investigate the genesis mechanisms of these vortices and determine why they tend to form north of the bow apex.

2. EXPERIMENTAL DESIGN

In pursuant of our objectives, the Weather Research and Forecast (WRF) model (Skamarock et al. 2001) has been utilized to simulate the 29 June 1998 bow echo event. The model domain is 500 km x 500 km in the horizontal and extends to 17.5 km in the vertical. The horizontal grid resolution is 2 km while a stretched grid varying from 0.2 km near the surface to 0.7 km near the top of the domain is employed in the vertical. All simulations are run with coriolis forcing and ice microphysics. An 18 UTC sounding from Lincoln, Ill was modified to best represent the bow echo-producing environment over southeastern Iowa and Illinois. This sounding was used to initialize the model domain and is shown in Fig. 1. The sounding is characterized by large instability and strong low-level shear. The Convective Available Potential Energy, 0-2.5 km shear and Bulk Richardson Number are 3689 J kg^{-1}, 19.8 ms^{-1} and 82.2, respectively. Previous numerical and observational studies have shown that environments characterized by large instability and strong 0-2.5 km shear are conducive to bow echo formation. Storms within the model were initiated by introduc-

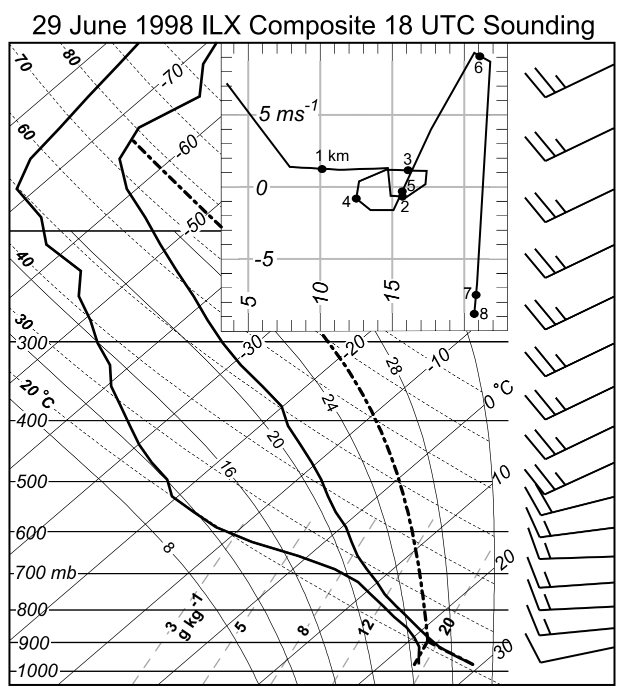

Figure 1. Composite 18 UTC sounding at Lincoln, Ill on 29 June 1998. The dash-dotted line represents the surface-based parcel path. Wind barbs are in ms^{-1} (half barb = 5 ms^{-1}, full barb = 10 ms^{-1}). The inset diagram is the hodograph.

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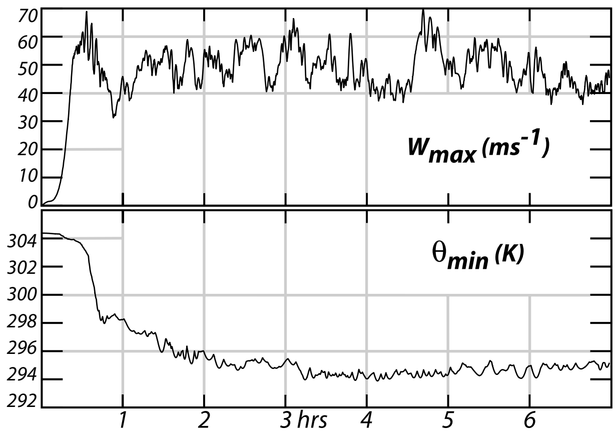

Figure 2. Time series of maximum vertical velocity (W_{max}) and minimum potential temperature (θ_{min}) observed anywhere in the model domain.

ing five warm thermal bubbles having a 2 Kelvin perturbation spaced every 40 km and oriented near perpendicular to the low-level shear vector.

3. SYSTEM EVOLUTION

An indication of the strength of the leading edge updrafts and cold pool generated in the simulated QLCS is shown in Fig. 2. Plotted are time series for the entire simulation time of seven hours of maximum vertical velocity (W_{max}) and minimum potential temperature (θ_{min}) observed anywhere in the model domain. Vertical velocities in excess of 60 ms^{-1} are produced in the leading edge updrafts with sustained magnitudes of 40-60 ms^{-1} during the entire seven-hour period. The simulation also produced a cold-pool deficit of about 10 Kelvin and is consistent with an observed deficit of approximately 8-11 Kelvin (not shown).

A more complete depiction of the system evolution can be seen in Fig. 3. At two hours into the simulation (Fig. 3a), individual cells can be seen along a line that is approximately 200 km in length. By four hours (Fig. 3b), a pronounced bow echo has formed on the southern end of the system. Continuous leading edge updraft is observed along the bow echo with the strongest magnitudes located near the bow apex. Contrasting to the earlier time period, the rainwater is extending further rearward of the leading edge. This observation com-

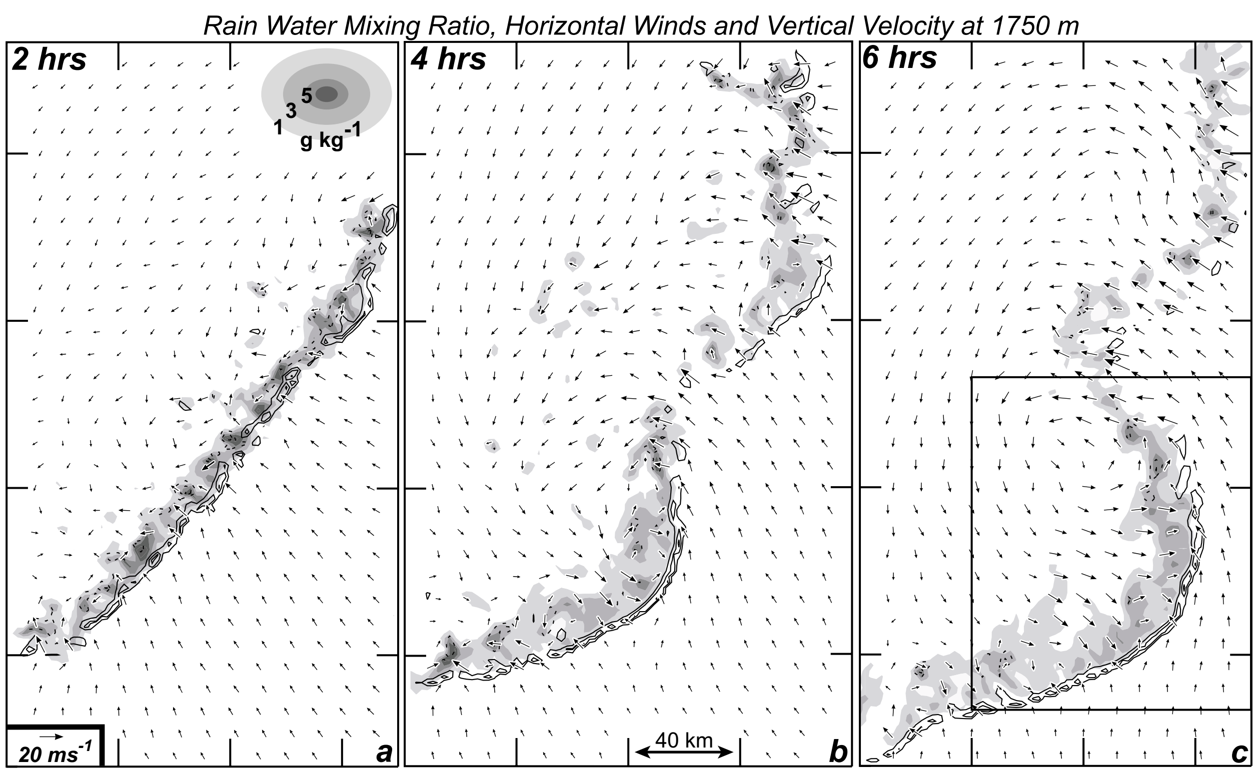

Figure 3. Evolution of the QLCS at a) two, b) four and c) six hours at 1750 m. Rain water mixing ratio (g kg^{-1}) is shown in gray while vertical velocities are contoured in thin black lines every 4 ms^{-1}. The zero line has not been plotted for figure clarity. The vector field is the system-relative horizontal winds. The boxed area in c) represents the area shown in Fig. 4.

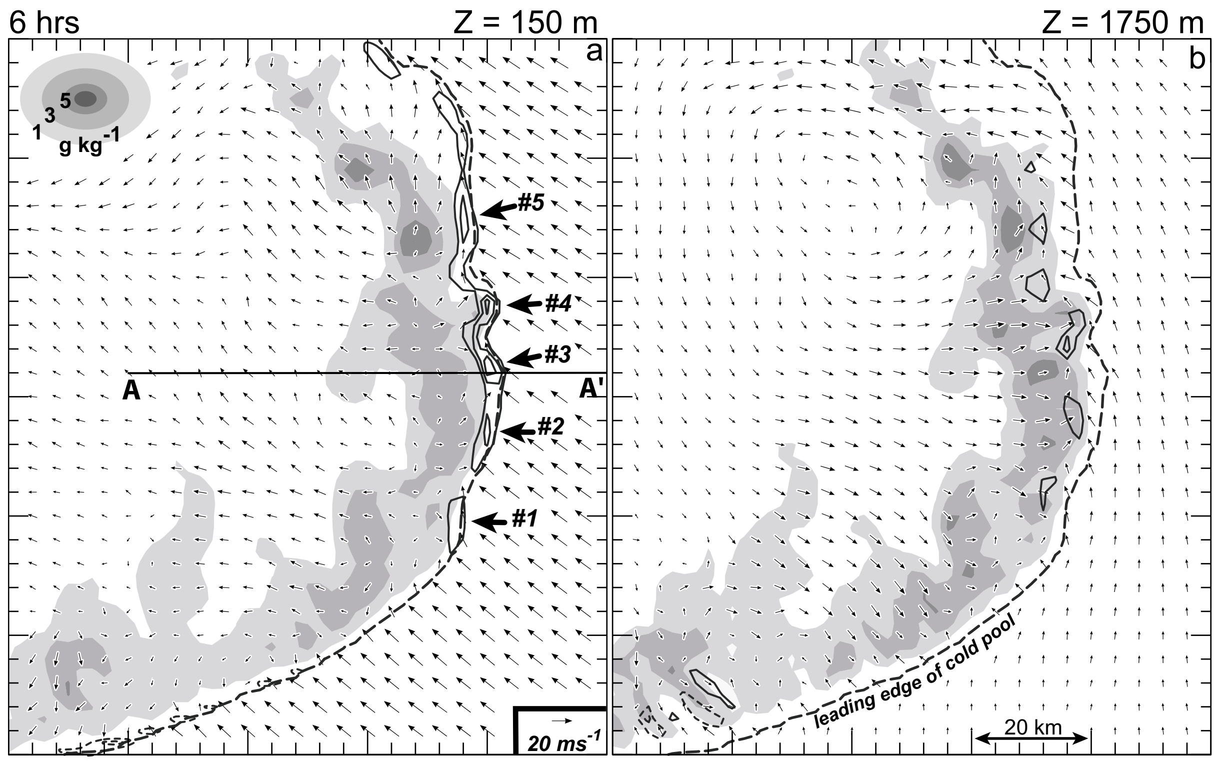

Figure 4. Detailed structure of the leading edge of the bow echo is presented at (a) 150 m and (b) 1750 m. The domain shown is the area within the box in Fig. 3c. Rain water mixing ratio (g kg^{-1}) is shown in gray. Vertical vorticity is contoured with thin black lines every 2 x 10^{-3} s^{-1} with positive values starting at 4 x10^{-3} s^{-1} (solid lines) and negative values starting at –4 x 10^{-3} s^{-1} (dashed lines). The thick dashed line is the 304 K potential temperature contour and represents the leading edge of the cold pool. System-relative horizontal winds are also plotted.

bined with the development of a well-defined rear inflow jet, suggest that the system updrafts have tilted upshear at this time. Dominant cyclonic and weak anticyclonic bookend vortices have developed on the northern and southern ends of the bow echo, respectively. By six hours (Fig. 3c), the bow echo system-scale features have grown in scale. A dominant cyclonic bookend vortex and rear inflow jet extending nearly 100 km rearward of the leading edge, are observed. Noteworthy is that the overall orientation, scale and strength of the bow echo system-scale features at this time are consistent with the observed features presented in Part I of this study (their Fig. 3).

4. LOW-LEVEL VORTICES

Results shown in the previous section suggest that the simulation has captured many of the system-scale features that were observed with the 29 June 1998 bow-echo event. The detailed structure along the leading edge of the simulated bow echo is now discussed.

Shown in Fig. 4 is the portion of the domain in the boxed area in Fig. 3c. Striking in Fig. 4a is the zone of enhanced vertical vorticity at low levels north of the bow apex. Only weak negative vertical vorticity is observed south of the bow apex. Five cyclonic vortices are apparent north of the apex. These vortices are characterized by vertical vorticity magnitudes of at least 4 x 10^{-3} s^{-1}, have spatial scales of 5-10 km and form just behind the leading edge of the system-generated cold pool. Some vertical vorticity associated with these circulations exists at 1750 m (Fig. 4b), however, a better sense of the vertical extent of the vortices can be seen in the vertical cross section through vortex #3 in Fig. 5. In Fig. 5a, the cold pool depth is approximately 1.5 km. Also evident is the large gradient of rain water just behind the leading edge of the cold pool.

The location of vortex #3 is shown in Fig. 5b. It is located just behind the leading edge of the cold pool, in the gradient of potential temperature and vertical velocity. The strongest vorticity values are found at low levels, with values of 8 and 4 x 10^{-3} s^{-1} extending to 1 and 1.5 km, respectively. Analyses of the other vortices shown in Fig. 4 exhibit similar structures as that shown for vortex #3 in Fig. 5.

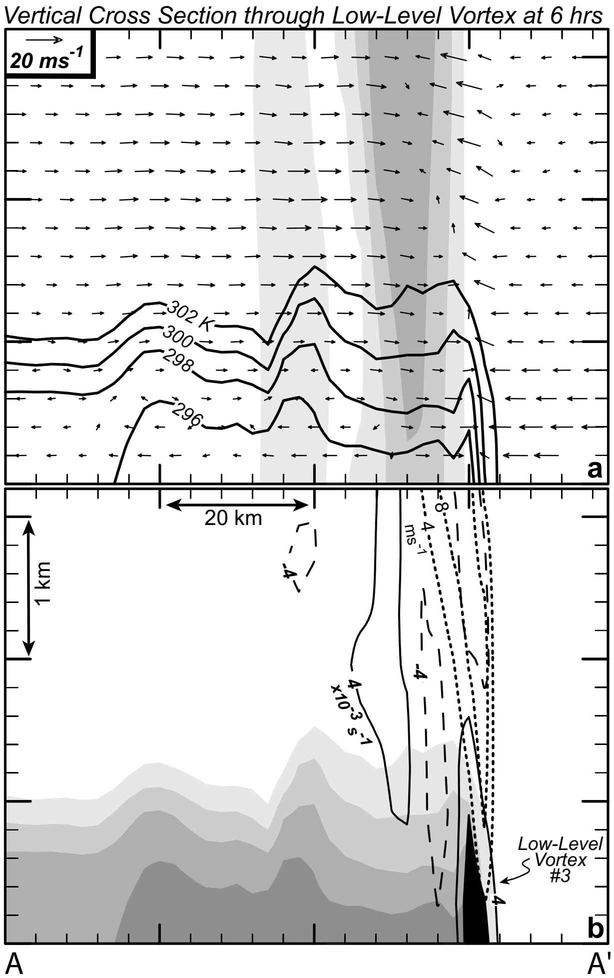

Figure 5. Vertical cross section through vortex #3 shown in Fig. 4a. a) Rain water mixing ratio is shaded gray while potential temperature is contoured in black. Winds in the plane of the cross section are also shown. b) Potential temperature is plotted in gray while vertical vorticity is in solid (positive) and long-dashed (negative) contours. Values greater than $8x10^{-3}s^{-1}$ are shaded black. Short dashed lines are vertical velocity (ms^{-1}).

5. CONCLUSIONS AND FUTURE WORK

Preliminary simulation results using the Weather Research and Forecast (WRF) model of the 29 June 1998 derecho event over southeastern Iowa and central Illinois have been presented. This event produced copious straight-line wind damage along with several short-lived, low-level, tornadic circulations that produced F0-F1 damage. All but one of the circulations were observed north of the bow echo apex.

The simulation presented herein reproduced the salient system-scale features of the 29 June 1998 event. In particular, the model produced a QLCS with a strong bow echo on the southern portion of the system. Associated with the bow echo was a prominent rear inflow jet that extended nearly 100 km rearward of the leading edge of the system. A dominant cyclonic and weaker anticyclonic bookend vortex was observed on the northern and southern ends of the bow echo, respectively. The orientation and timing of these simulated features are consistent with the observed event.

At the leading edge of the bow echo, a zone of significant positive vertical vorticity was observed north of the bow apex. Weaker negative vertical vorticity was observed to the south of the bow apex. Within the zone of positive vertical vorticity, low-level vortices having spatial scales of 5-10 km were observed. These vortices were characterized by the strongest rotation near the surface and extended vertically to 1.5-2 km. An analysis of these and all other vortices that formed within the simulated QLCS showed that average vortex lifetime was 53 minutes, consistent with the observed range of lifetimes (24-78 minutes).

While these preliminary results are promising, some caution is in order when interpreting the detailed structure of the simulated vortices as the horizontal grid resolution is only 2 km and the model code is still under development. Simulations are currently being carried out with 1 km horizontal resolution to better resolve the vortices forming north of the bow apex. Future analyses will also examine the genesis mechanisms of the vortices and attempt to explain why they are observed north of the bow apex.

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References

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

Skamarock, W.C., J.B. Klemp, and J. Dudhia, 2001: Prototypes for the WRF (Weather Research and Forecasting) model. *Preprints Ninth Conf. Mesoscale Processes*, Fort Lauderdale, FL, Amer. Meteor. Soc., J11-J15.

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

____, and C.A. Davis, 1998: Mechanisms for the generation of mesoscale vortices within quasi-linear convective systems. *J. Atmos. Sci.*, **55,** 2603-2622.