7.5 MECHANISMS FOR THE PRODUCTION OF SEVERE SURFACE WINDS IN A SIMULATION OF AN ELEVATED CONVECTIVE SYSTEM

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1. INTRODUCTION

The production of severe surface winds by elevated convection remains poorly understood. By "elevated," we mean convection in environments with stable layers near the surface, such that the highest equivalent potential temperature (θ_e) is above the surface. Among the outstanding questions are: under what environmental conditions is elevated convection likely to produce severe winds?; what are the mechanisms that produce severe winds in elevated convection, and are these mechanisms different from surface-based convection?; and, can elevated convection produce severe surface winds in the absence of a surface cold pool?

Using data from the Bow Echo and MCV Experiment (BAMEX; Davis et al. 2004), and using idealized numerical simulations, we have been investigating these questions. In this paper, we present soundings that were collected in the environment of elevated mesoscale convective systems during BAMEX to identify common thermodynamic characteristics. Then, using idealized numerical simulation, we present some preliminary conclusions about the mechanisms for the production of strong surface winds from elevated convective systems.

2. OBSERVATIONS

Several examples of elevated convective systems (including bow echoes) were observed during BAMEX. Some of these cases produced severe surface winds, while others did not. We have analyzed the cases collectively to understand the thermodynamic environments that are characteristic of elevated convective systems.

Three examples that have stable layers near the surface are shown in Fig. 1. The details of these stable layers are different for all three cases. However, the important point is that none of these soundings exhibit the nearly mixed low-level thermodynamic profile that normally characterizes late-afternoon severe convection, which is most often studied in severe storm research.

The first case (Fig. 1a) occurred near a warm front in southeast Nebraska. The sounding was released ahead of the prominent bow echo that was observed during IOP7 (see, e.g., Fig. 5 by Davis et al. 2004). There is complex thermodynamic structure in the lowest several km, but overall the profile is stable, with a mean environmental lapse rate (Γ) of 5 K km^{-1}. The most unstable parcel (i.e., the parcel with the highest θ_e) is located 1.5 km above ground; a parcel raised psuedoadiabatically from this point has CAPE of 2,745 J kg^{-1}, whereas the surface parcel has negligible CAPE.

The second case (Fig. 1b) occurred in the early morning in eastern Iowa. In this case, we present an operational sounding from DVN, just after the completion of IOP12, at which time a strong squall line was beginning to produce severe winds as it crossed into southwest Wisconsin. This sounding has a shallow (~500 m) stable layer, which is probably related to nighttime radiative cooling. Similar to the previous case, the LFC from the most unstable parcel occurs at a rather high height above ground (at a pressure of roughly 700 mb). Most unstable CAPE for this sounding is 1,832 J kg^{-1}.

The third sounding (Fig. 1c) was taken to the south of a fast-moving squall line that was producing severe winds in eastern North Dakota. In this case, maximum θ_e is located ~100 mb above the surface, although the surface parcel has nearly the same θ_e. CAPE for the most unstable parcel is 1,363 J kg^{-1}, whereas CAPE for the surface parcel is 1,267 J kg^{-1}. Thus, technically this may not be an elevated convective system, depending on how the term "elevated" is defined. We include this case because of the notable stable layer in the lowest few km; mean Γ in this layer is only 4.4 K km^{-1}. Thus, in common with the other cases, there is a deep layer of stable air in the environment of this convective system.

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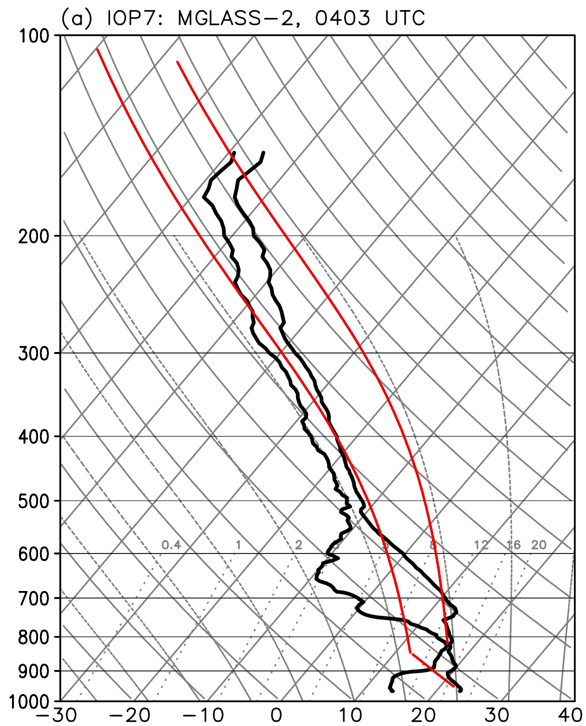

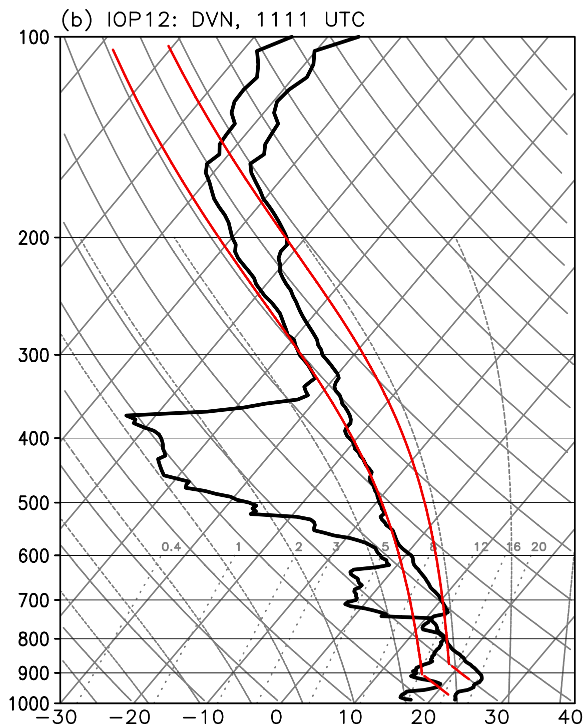

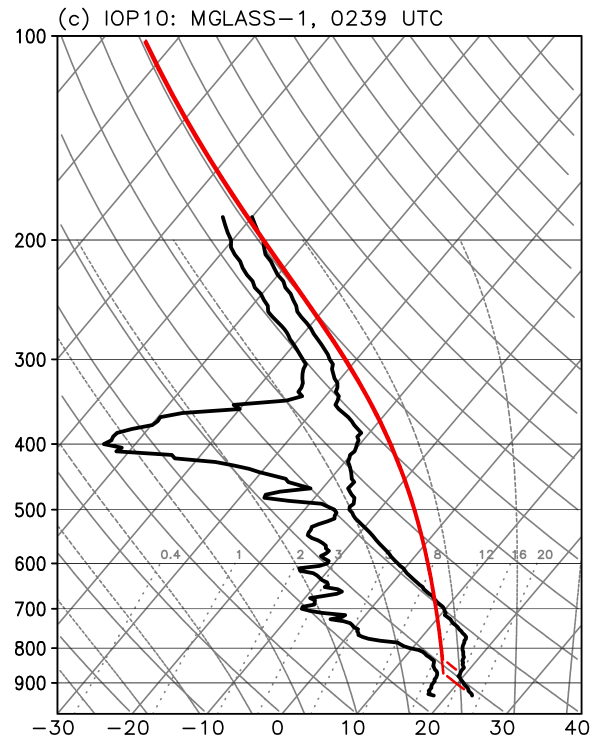

Fig. 1. Observed soundings from the near-environment of mesoscale convective systems during BAMEX. Red lines are psuedoadiabatic parcel paths that originate from the surface and from the parcel with the highest θ_e.

Another common feature among all three cases is the near-neutral (i.e., nearly dry adiabatic) thermodynamic profile that is just above the stable layer. Elevated near-neutral layers are especially prominent over deep layers in Figs. 1a and 1c. Certainly, these elevated near-neutral layers help provide significant CAPE, which is important for the generation of strong updrafts; this feature, alone, may explain the significance of these elevated near-neutral layers. On the other hand, they may help the production of deep (> 3 km) cold pools, as discussed by Bryan et al. (2005) and Bukovsky et al. (2006).

Based on our observational review of BAMEX cases, we choose to investigate thermodynamic profiles that have stable layers from roughly z = 0 to 2 km, and then near-neutral layers from roughly z = 2 to 4 km. Using idealized numerical simulations, we plan to systematically vary the depth of these layers, as well as the magnitude of stability in these layers. One example is presented in the next section.

Before proceeding, we note that the low-level shear is rather strong in all three examples. In the first two examples, there is 20 m s^{-1} of cross-line shear in the 0-2 km layer, and there is 15 m s^{-1} of shear from 0-2 km in the third example. Such low-level shear has been found to be favorable for the development of strong convective systems in several idealized numerical modeling studies. In other cases during BAMEX, we found similar regions of intense low-level shear that were isolated, and were typically associated with low-level baroclinic zones, such as warm fronts. We surmise that studies based on proximity soundings that primarily use operational soundings (e.g., Coniglio et al. 2004) may be missing these localized regions of strong low-level shear.

3. NUMERICAL SIMULATION

In this section, we present preliminary results from an idealized numerical simulation. We use an idealized framework in order to explore systematically the effects on convective systems of environmental parameters such as the depth of the stable layer and the magnitude of instability.

3.1 Methodology

The simulation is conducted with the numerical model of Bryan and Fritsch (2002). The model domain is 400 km × 80 km × 20 km, using 500 m horizontal grid spacing and variable vertical grid spacing (Δz), wherein Δz is a constant 200 m below z = 5.5 km, and is a constant 500 m above 8.5 km. The simulation uses the ice microphysics scheme of Lin et al. (1983) with modifications by Braun and Tao (2000).

The initial environment is horizontally homogeneous. The thermodynamical sounding is an idealized profile in which the static stability in several layers has been specified (Fig. 2). Similar to the observed cases, the near-surface profile is stable, with an average Γ of 4.5 K km^{-1}, which is significantly more stable than the near-surface profile in the famous Weisman-Klemp analytic sounding, which has an average lapse rate of ~7.5 K km^{-1} in the lowest 2 km. In the sounding used herein, the most unstable parcel is at z = 1 km. However, θ_e decreases by ~22 K from this point to z = 4 km, which is similar to that found in other idealized soundings (such as in the Weisman-Klemp sounding), and indicates the potential for strong cold pool development. The initial cross-line wind profile has 20 m s^{-1} of shear over the lowest 2.5 km.

Convection is initiated with a line thermal placed at the center of the domain. We find that convection is difficult to initiate in idealized (i.e., horizontally homogeneous) simulations with stable surface layers; hence, we had to use a rather intense potential temperature perturbation of +4 K for this simulation. To allow the development of three-dimensional motions, small-amplitude random perturbations are placed into the line thermal.

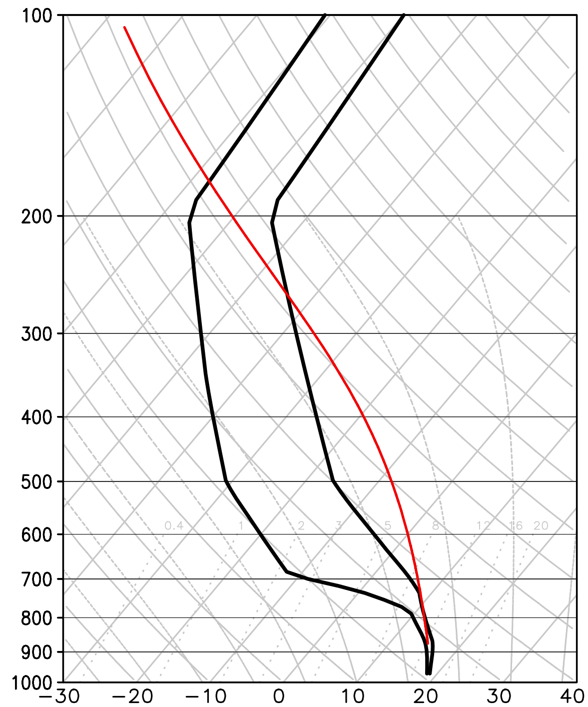

Fig. 2. Idealized sounding used for the numerical simulation. The red line is the psuedoadiabatic parcel path for the most unstable parcel.

3.2 Results

A persistent squall line is maintained throughout the entire 6 h simulation. However, for the first several hours there is no cold pool at the surface. For example, at t = 3 h (Fig. 3a), there is significant rainfall reaching the surface (estimated reflectivity > 40 dBZ); however, surface potential temperature perturbation is near zero throughout this line. Vertical cross sections of buoyancy (Fig. 4a, wherein buoyancy is defined in the standard manner, as a perturbation from the initial sounding) reveal that a cold pool exists only in the elevated near-neutral layer at z = 2–4 km. Evidently, this cold pool plays a role in triggering new cell development for the first several hours of the simulation. In fact, this cold pool may be dynamically similar to cold pools in environments with near-neutral layers at the surface. Thus, the significance of the elevated near-neutral layers may be that they promote elevated density currents.

Between t = 3–5 h, the central portion of the squall line bows forward (Fig. 3b). At this time, the low θ_e air from mid-levels finally descends to the surface (Fig. 4b), which allows for strong diabatic cooling between z = 0–2 km. Consequently, the cold pool extends *downward*, and by t = 5 h the cold pool occupies the 0–4 km layer (Fig. 4b). By this time,

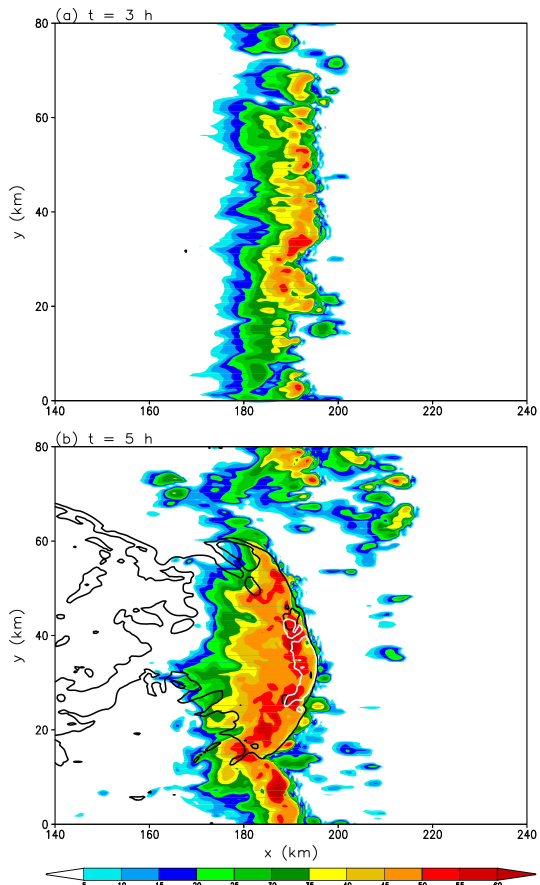

Fig. 3. Output at the surface from the numerical simulation at (a) t = 3 h, and (b) t = 5 h. Estimated reflectivity is shaded, the black contour is -2 K potential temperature perturbation, and the white contour is wind speed of 26 m s^{-1}.

severe winds (u > 26 m s^{-1}) are occurring at the surface (white contour in Fig. 3b). Thus, elevated convective environments are quite capable of producing surface-based cold pools if low θ_e air descends to the surface. However, we have not yet tested this conclusion in a broader range of simulations, which use deeper or stronger near-surface stable layers. On the other hand, analysis of observations from BAMEX supports our conclusion; for example, the analysis of the IOP7 bow echo by Bryan et al. (2005, their Figs. 2 and 3) reveals that low θ_e air (presumably from mid-levels) exists in the cold pool, which is roughly 4 km deep.

We have been analyzing passive tracers and trajectories from the simulation to diagnose the source of the strong surface winds in the simulation. In this case, there is no evidence for an "up-down" trajectory during the bow echo phase (e.g., Bernardet and Cotton 1998), whereby it is hypothesized that near-surface parcels enter the

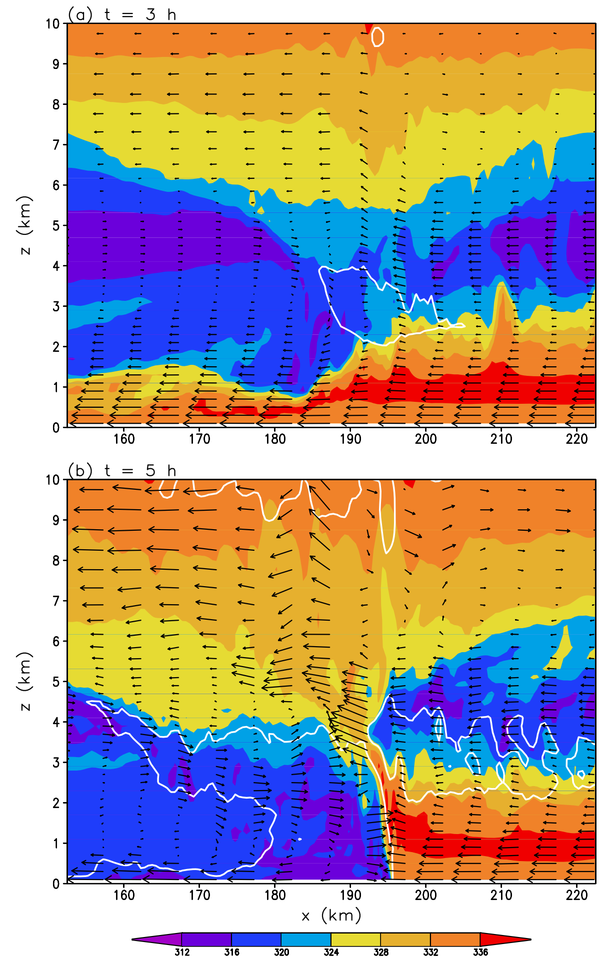

Fig. 4. Vertical cross sections through the simulated squall line, wherein (a) the cross-section is of line-averaged conditions at t = 3 h, and (b) the cross section is at y = 34 km at t = 5 h. Shading is θ_e (K), the white contour is buoyancy of -0.05 m s^{-2}, and vectors are system-relative with a vector length of 5 km equivalent to a vector magnitude of 25 m s^{-1}.

system from the front and subsequently descend into the cold pool to create strong surface winds. Rather, in this case, flow is accelerated into the back edge of the near-surface cold pool as it forms in the 0-2 km layer. Thus, our preliminary conclusion is that the severe surface winds are created by the same mechanism as described by Weisman (1992, 1993) – i.e., by acceleration of flow into the back edge of the system by horizontal pressure gradients associated with the negative buoyancy within the cold pool – although, the evolution and details of the cold pool are clearly different in elevated environments.

There are other similarities between this bow echo and ones simulated in other idealized simulations. For example, this bow echo has an elevated rear-inflow jet that extends all the way to the convective line, as well as bookend vortices. Hence, it may be the case that severe elevated convective systems are nearly the same dynamically as severe surface-based convective systems. Based on this preliminary work, it appears that the production of a surface-based cold pool may be a key factor in whether or not elevated convection produces severe surface winds. The process by which mid-level low θ_e air can descend to the surface in environments with surface-based stable layers is therefore an important topic for future research.

REFERENCES

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

Braun, S. A., and W.-K. Tao, 2000: Sensitivity of high-resolution simulations of Hurricane Bob (1991) to planetary boundary layer parameterizations. *Mon. Wea. Rev.,* **128,** 3941-3961.

Bryan, G. H., and J. M. Fritsch, 2002: A benchmark simulations for moist nonhydrostatic numerical models. *Mon. Wea. Rev.,* **130,** 2917-2928.

Bryan, G., D. Ahijevych, C. Davis, S. Trier, and M. Weisman, 2005: Observations of cold pool properties in mesoscale convective systems during BAMEX. Preprints, *11th Conf. on Mesoscale Processes,* Albuquerque, NM, Amer. Meteor. Soc., CD-ROM, JP5J.12.

Bukovsky, M. S., J. S. Kain, and M. E. Baldwin, 2006: Bowing convective systems in a popular operational model: Are they for real? *Wea. Forecasting,* **21,** 307–324.

Coniglio, M. C., D. J. Stensrud, and M. B. Richman, 2004: An observational study of derecho-producing convective systems. *Wea. Forecasting,* **19,** 320-337.

Davis, C., and Coauthors, 2004: The Bow Echo and MCV Experiment: Observations and opportunities. *Bull. Amer. Meteor. Soc.,* **85,** 1075-1093.

Lin, Y.-L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Appl. Meteor.,* **22,** 1065-1092.

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

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