Mergers in supercell environments. Part II: Tornadogenesis potential during merger as evaluated by changes in the near-surface low-level mesocyclone

R. M. Hastings, * Y. P. Richardson, and P. M. Markowski
Department of Meteorology, The Pennsylvania State University

1. Introduction

Storm mergers involving supercells may be linked to some tornadogenesis events. For example, in a case study of a tornado outbreak on 19 April 1996, Lee et al. (2006) found a nearly Gaussian distribution of tornadogenesis events centered on the merger time, with 54% of tornadoes occurring within 15 minutes of a merger. However, the tornadoes only occurred with 57% of the mergers. Predicting the outcome of a merger, and whether or not a tornado may occur with one, remains a challenge for severe weather forecasting.

In Part I, simulations of mergers in idealized environments provided a general framework for classifying merger types and understanding the dynamics governing merger outcome. In Part II, the possibility of tornadogenesis during merger is explored. The process of tornadogenesis may be broadly divided into three stages: the development of midlevel (1–4 km) rotation, the development of low-level (0–1 km) rotation, and the contraction of the near-surface rotation into a tornado. For the purposes of this discussion, we are primarily interested in the development of near-surface rotation (here defined with as the lowest grid point, 25 m). We shall see that, during the merger process, shallow (0–1 km) vorticity extrema with maximum magnitudes at or above 0.01 s^{-1} and horizontal scales of 2–5 km develop along convergence lines associated with the system. These convergence lines may be boundaries separating storm outflow from ambient air, such as the primary rear-flank gust front, or internal boundaries, such as secondary gust fronts.

The discussion below employs the results of the numerical experiments in Part I. In these experiments, the horizontal grid spacing is 500 m, which is too coarse to resolve a tornado, and the final contraction of rotation into tornado. Thus, we use near-surface vortex intensification as a proxy for tornadogenesis. The work presented herein is preliminary, with a more complete discussion in a forthcoming publication.

2. Vortex intensification during merger

Near-surface vortex intensification during mergers may be broadly divided into brief (∼10 min), shallow events that occur in conjunction with downdrafts and outflow surges, and longer duration events that occur when the shallow vorticity maxima become collocated with the low-level mesocyclone. In many cases, there is initially no rotation in the lowest 1–1.5 km beneath the mesocyclone until a shallow vortex propagates to that point.

In the simulations, downdrafts comprise multiple outflow surges, during which low-θ_e air is brought to the surface in bursts that last 10–20 minutes. The surges are associated with divergence in the surface wind field, and attendent convergence along its edges. Multiple surges result in multiple convergence zones, which may remain internal to forward- or rear-flank downdraft regions, or may propagate outward to replace or reinforce the primary gust fronts. An example of such a downdraft burst in an isolated storm is shown in Fig. 1. As discussed in Part I, the changes in precipitation distribution associated with mergers causes similar bursts to occur during merger.

The near-surface vortex intensification begins aloft, when a vortex couplet appears around 1 km above the surface. Preliminary trajectory analyses suggest this couplet forms by the tilting of horizontal vorticity that has been baroclinically generated within the downdraft. These vorticity extrema are brought to the surface, (Fig. 2a) where they encounter convergence zones associated with neighboring outflow surges (Fig. 2b). This encounter may occur shortly after the air reaches the surface, although in some cases the vorticity extrema may be advected along the surface for a few minutes before encountering the convergence lines. The encounter with the convergence line results in the stretching and subsequent intensification of the vortices.

A typical time scale for such a vortex is ∼10 min. Because the vorticity-rich parcels within the vortex are lifted by the vertical motion at the convergence line, the maintenance of the vortex requires a persistant vorticity supply from neighboring downdrafts. In this case, the vortices propagate along the convergence lines, deepening and intensifying, and frequently merging with other shallow vortices (Fig. 2c). The longevity of these vortices may be significantly extended if they propagate to a location beneath the midlevel mesocyclone, essentially becoming the low-level mesocyclone. Deep, long-lasting vortices that oc-

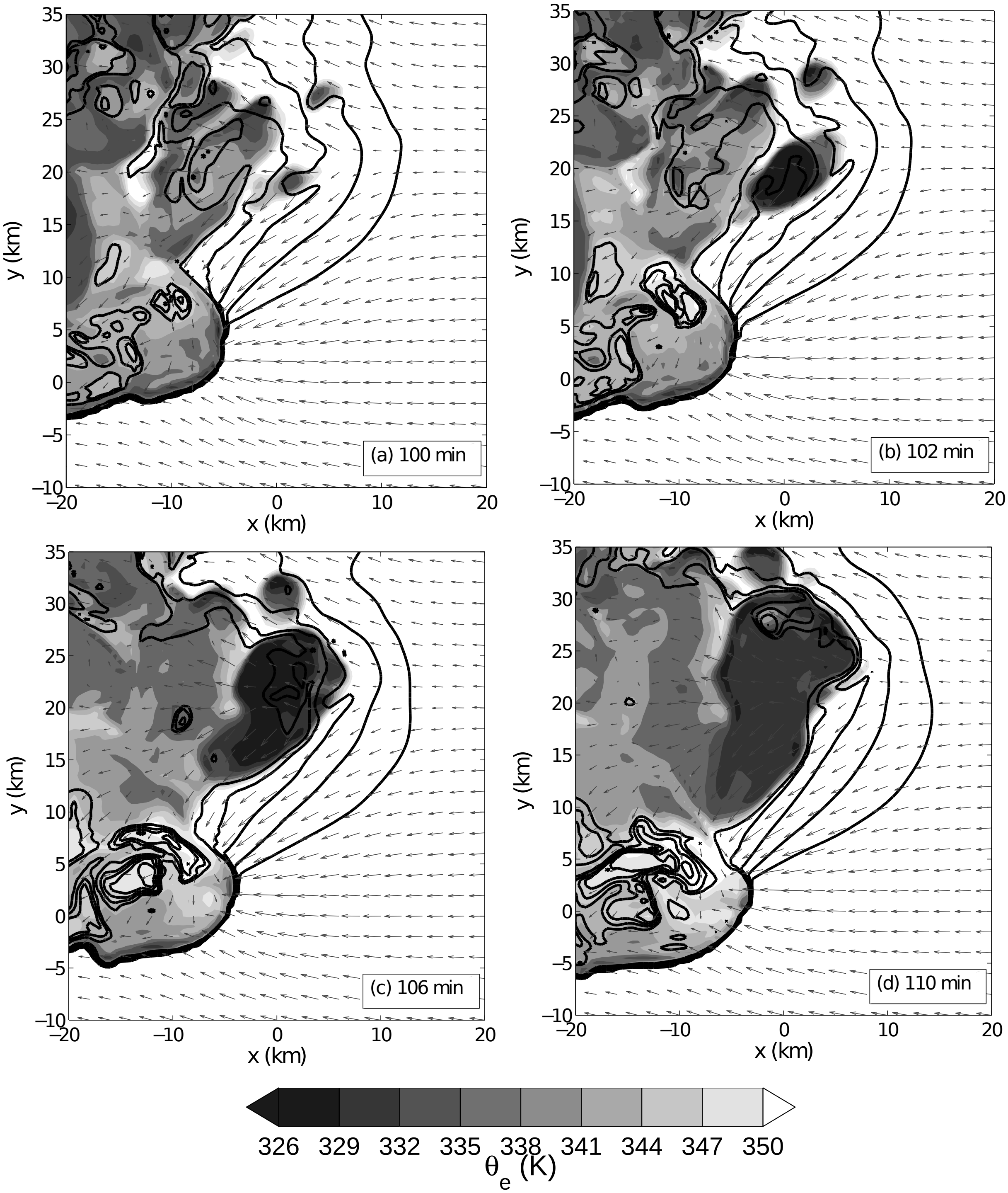

FIG. 1. Evolution of left-flank downdraft surge. θ_e shaded, θ'_ρ contoured every 1 K from -5 to -1 K, horizontal winds spaced every 1.5 km. (a) 100 min, 320–325 K θ_e intrusion at $x = 0$ km, $y = 20$ km marks beginning of surge. (b) 102 min, (c) 106 min and (d) 110 min, the downdraft brings air with θ_e less than 320 to the surface. This air originates from the precipitation melting level, around 4 km AGL. The density current associated with the downdraft pushes outward as negatively buoyant air is transported to the surface.

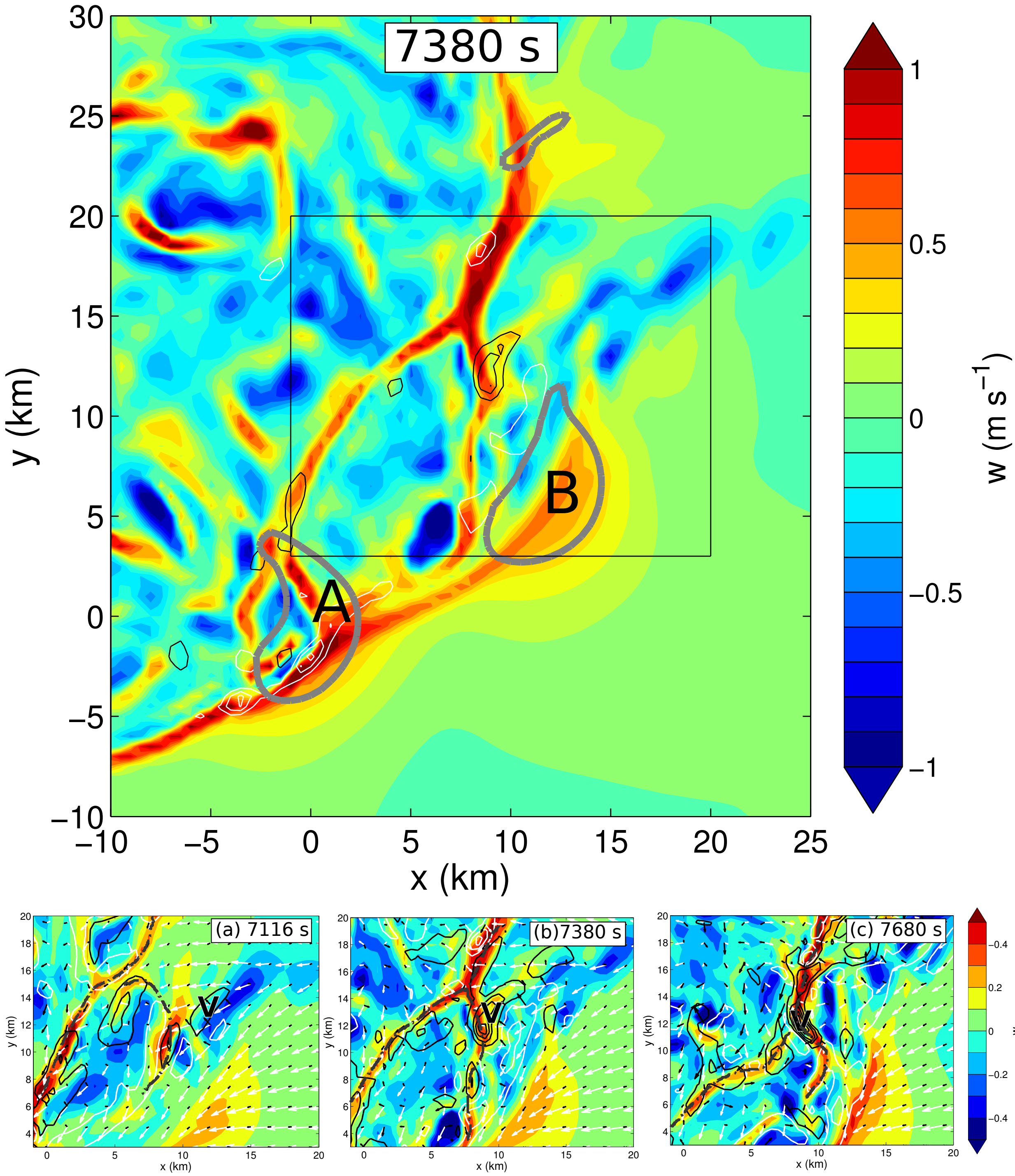

FIG. 2. The development and intensification of a near-surface (lowest grid point, 25 m) vortex couplet in association with outflow surges. Top: Type I merger in progress. 25 m vertical velocity color-shaded, 2.5 km 15 m s^{-1} vertical velocity contoured in gray, positive (negative) 25 m vertical vorticity contoured in black (white) every 4×10^{-3} s^{-1}. The old cell is marked with A, and the new cell is marked with B. The rectangle marks the region detailed in (a)-(c), below. At this time, B is still relatively immature, without a well-developed mesocyclone. Before the merger, A had a low-level mesocyclone. (a) The initial couplet appears near the surface, straddling a downdraft. The cyclonic member is marked with a V. (b) The vorticity maximum (V) is transported along the surface until it encounters a convergence line, at which point it strengthens. (c) Vorticity maxima continue propagating along the convergence line, occasionally merging. Color shading and contours as above. Horizontal velocity (vorticity) in black (white) arrows. Convergence lines marked with dash-dot gray lines.

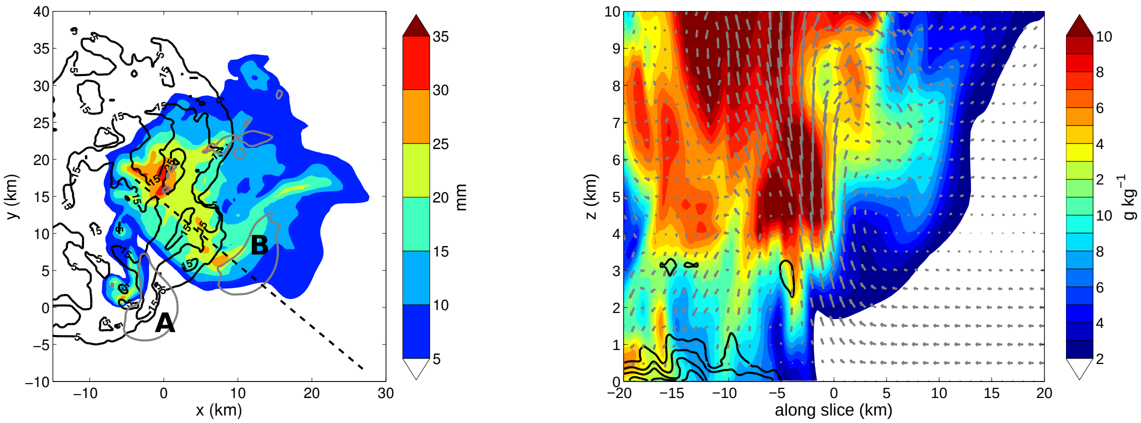

FIG. 3. Example of outflow surge with Type I merger following an increase in precipitation at 7140 s. (a) Precipitation from B is transported downshear, to the north and northeast. There it combines with the left flank of A. Color shading is total condensate vertically integrated from the surface to 4 km color-shaded, cold pool strength (integrated buoyancy from surface to -0.15 m s^{-2}) contoured in black every 10 m s^{-1} starting at 5 m s^{-1}, 2.5 km AGL 10 m s^{-1} updraft contoured in gray, black dashed line indicates location of slice for (b). (b) Precipitation mixing ratio color-shaded, negative buoyancy contoured in black every 0.05 m s^{-2} starting from -0.15 m s^{-2}, winds parallel to slice.

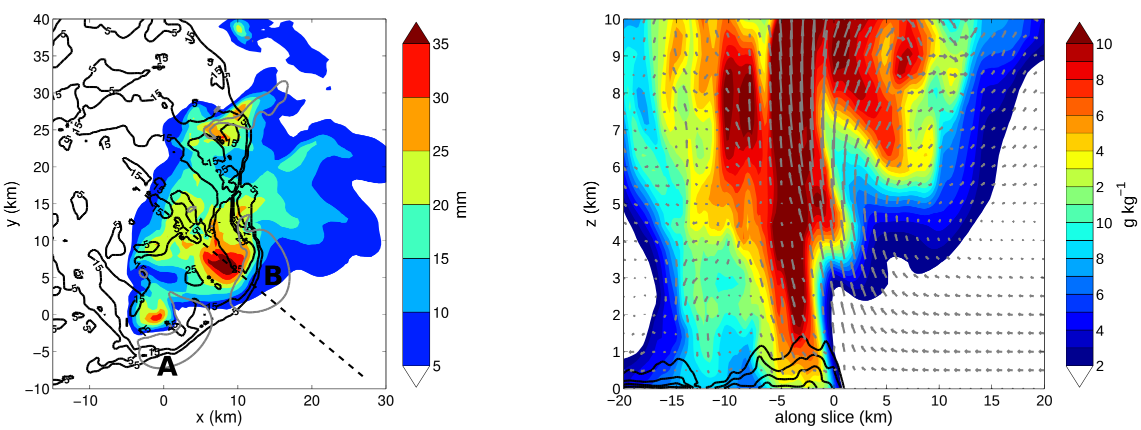

FIG. 4. As Fig 3 at 7800 s. As cell B develops an RFD, there is an increase in precipitation, which is now reaching the surface, with a correspondiing surge in the cold pool (with a strength over 25 m s^{-1} and a tightening of the buoyancy gradient at the surface).

cur in such a situation could indicate the possibility of tornadogenesis.

3. Predicting outflow surges

The importance of outflow surges for vortex intensification makes understanding the mechanisms behind them critical for predicting where such intensification may occur. Though any downward forcing, including vertical gradients in the linear and nonlinear dynamic perturbation pressure fields, may contribute to downdrafts, buoyancy seems to play the most significant role controlling when and where the outflow surges observed herein occur.

In Part I, we discussed the role of cold pool surges in determining the outcome of Type I and Type IV mergers. The cold pool surge occurs when a local increase in precipitation leads to a decrease in buoyancy. This local increase occurs when the separate updrafts deposit precipitation in the same area (Figs. 3–4). This mechanism is nearly identical to one identified by Finley et al. (2001) in a simulation of a particular supercell undergoing multiple mergers before transitioning to a bow echo.

4. Discussion

Vortex intensification during storm merger appears to be closely tied to outflow surges. The convergence zones associated with the surges stretch vorticity that has been brought to the surface by neighboring downdrafts, resulting in shallow vortices. If the vortices persist, they tend to deepen and intensify as they propagate along surge-associated convergence zones. Though the numerical experiments discussed herein are too coarse to resolve the final contraction of vorticity into a tornado, some insight into the possibility of tornadogenesis may be gleaned by considering the evolution of the low-level mesocyclone during the merger.

With Type I mergers, cell B does not develop a mesocyclone until well into the merger. The low-level mesocyclone associated with A is disrupted during the merger, although above 1–1.5 km, the mesocyclone persists until the major outflow surge that occurs between the cells results in a transition to a bow echo. Subsequently, the dominant vorticity features of the system are the bookend vortices with diminished tornado potential compared to the original supercell.

The overall dynamics of Type II and Type III mergers resemble that in an isolated storm. The demise of updraft A in both mergers is associated with an RFD surge for B. Such surges are now believed to play a role in the genesis and maintenance of tornadoes. Type III mergers, which frequently resemble cyclic mesocyclogenesis, do show intense mesocyclones following the merger.

The strongest post-merger mesocyclones are found with Type IV storms. During the merger, both cells briefly have strong low-level mesocyclones. As the cold pool surge occurs and the storm reorganizes into an outflow-dominated HP supercell, the mesocyclone associated with B dissipates while the mesocyclone associated with A intensifies. Shallow vortices produced along this outflow propagate toward the main updraft, where they merge to form larger vortices and grow upward into the pre-existing mesocyclone.

This preliminary work provides some insight into the relationship between storm merger and tornadogenesis, primarily by identifying mechanisms responsible for near-surface vortex intensification. Additional forthcoming work will consider this in more detail, and attempt to identify locations in the merging systems where the shallow vortices are more likely to form, as well as offer a more complete picture of the evolution of the low-level mesocyclone as it relates to the shallow vortices.

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References

Finley, C. A., W. R. Cotton, and R. A. Pielke, Sr., 2001: Numerical simulation of tornadogenesis in a high-precipitation supercell. Part I: Storm evolution and transition into a bow echo. *J. Atmos. Sci.*, **58**, 1597–1629.

Lemon, L. R. and C. A. Doswell III, 1979: Severe thunderstorm evolution and mesocyclone structure as related to tornadogenesis. *Mon. Wea. Rev.*, 1184–1197.

Lee, B. D., B. F. Jewett, and R. B. Wilhelmson, 2006: The 19 April 1996 Illinois tornado outbreak. Part II: Cell mergers and associated tornado incidence. *Wea. Forecasting*, **21**, 449–464.