Idealized Simulations of Mergers Between Squall Lines and Isolated Supercell Thunderstorms

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Background and motivation

Mergers between quasi linear convective systems ("squall lines") and isolated supercells pose a challenge to warning forecasters as the resultant changes in storm organization can present an evolving severe weather threat. Past studies have examined such merger events as a potential instigator for tornadogenesis, with a number of studies documenting cases where squall line-supercell mergers appear to coincide with the development of tornadoes (e.g., Goodman and Knupp 1993; Sabones et al. 1996; Wolf et al. 1996; Wolf 1998). More recently French and Parker (2012) documented an evolving severe weather threat in an analysis of 21 observed cases of these types of mergers. Generally speaking, any strong, long-lived tornadoes and large hail occurred with the isolated supercells prior to the merger, while severe straight-line wind reports were maximized post-merger. Furthermore, the mergers were observed to precede several key changes in storm structure. In most cases the merged system evolved into one of the patterns of bow echo organization presented in Figure 1, and a post-merger increase in low-level storm rotation following the merger was also commonly observed.

This past work demonstrates that squall line-supercell mergers can have important implications for storm morphology and, as a result, severe weather production. However, the observations used in these studies have been insufficient to determine the key processes that drive these observed changes. As a result, the present study has used idealized numerical simulations of a squall line-supercell merger to work toward developing a conceptual model to answer the following question:

What are the key dynamical processes responsible for the behavior observed when a squall line merges with an isolated supercell?

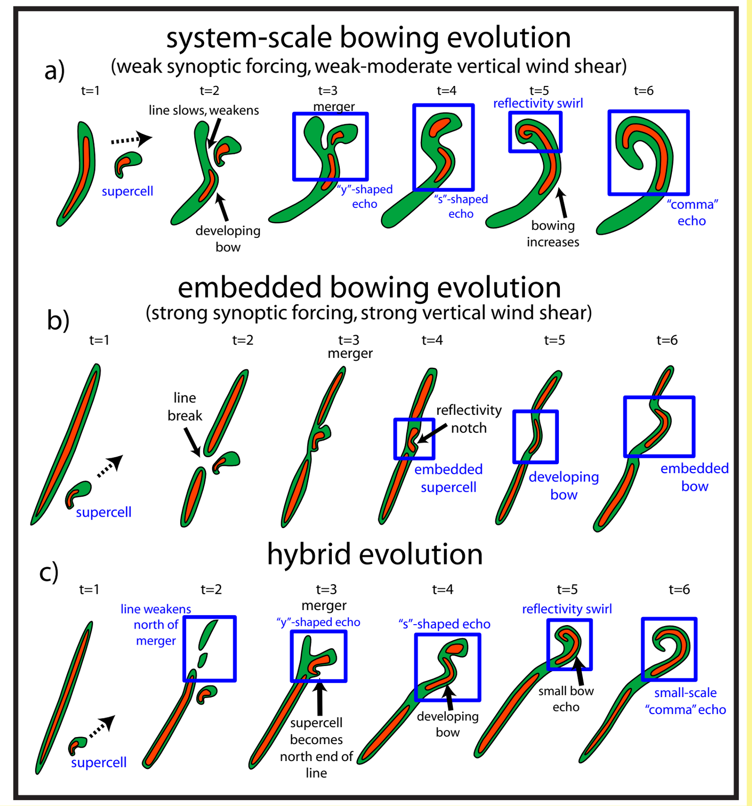


Figure 1: Schematic diagram describing the three post-merger bow echo evolutions observed by French and Parker (2012).

Squall line cold pool evolution

- Outflow from the supercell reaches the squall line's gust front well before the merger occurs, weakening the potential temperature gradient along the squall line's gust front.
  This effectively:
  i. Stalls the forward motion of the squall line gust front.
  ii. Reduces lifting along gust front.
  iii. Causes a decline in intensity along the northern portion of the squall line.
- Changes to the low-level wind profile within the supercell outflow may further contribute to the decline in low-level lifting along the squall line.
- Ultimately the supercell becomes new leading edge of the merged system.
- ***These results are consistent with pre-merger weakening of the squall line observed by French and Parker (2012), and a local distortion of the squall line's gust front near the merger observed by Goodman and Knupp (1993).***

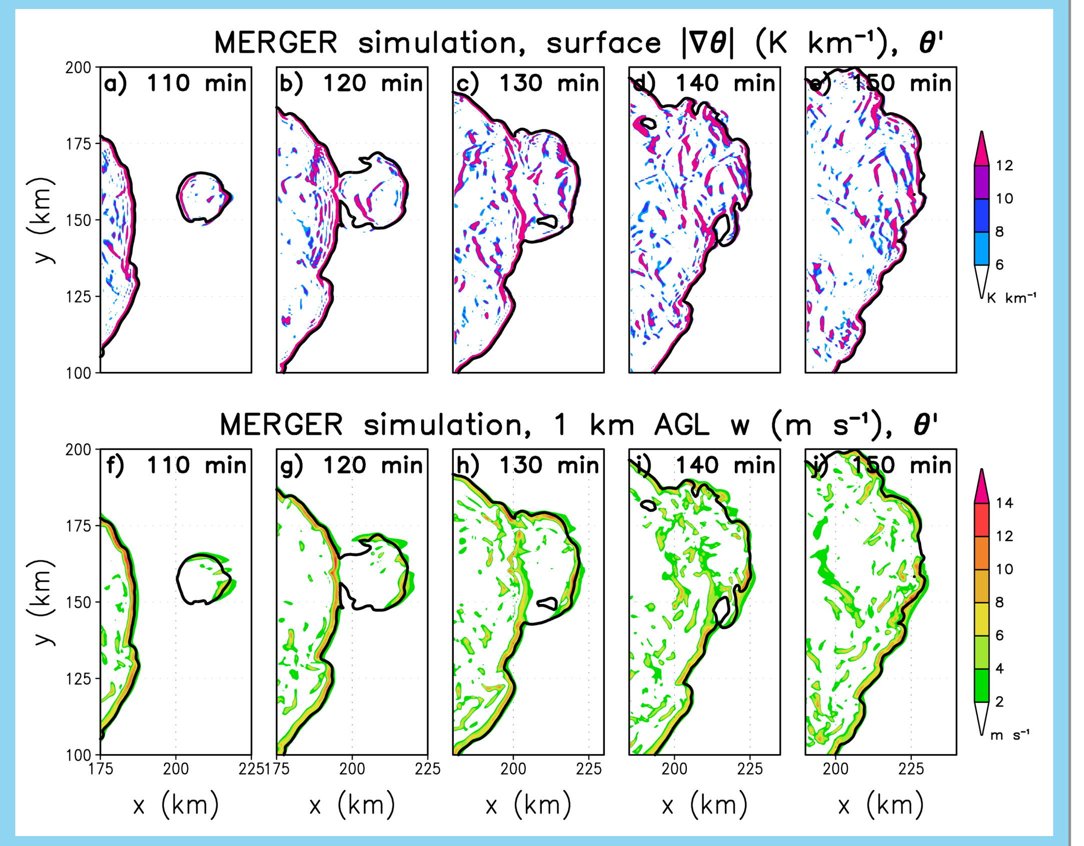


Figure 3: Plan view plots of surface potential temperature gradient (top panels) and 1 km AGL upward vertical velocity (bottom panels) shaded as shown between 110 and 150 minutes into the simulation.

Rear-inflow jet and development of bowing

- The merger leads to an increase in convective intensity, creating a warm perturbation aloft.
- This leads to a low-pressure perturbation (driven by vertical buoyancy gradients) near the leading convective line (e.g. Weisman 1993).
  - o Stronger than in NOMERGER simulation.
- A strong rear inflow jet develops in response to this pressure perturbation.
  - o RIJ is displaced south, more focused than in NOMERGER simulation.
- Trajectory analysis reveals parcels both descending from the rear, and curving in from line-end vortex, suggesting it is serving to enhance the RIJ (*not shown*).
- ***Overall, the merger plays an important role in instigating and organizing bow echo development.***

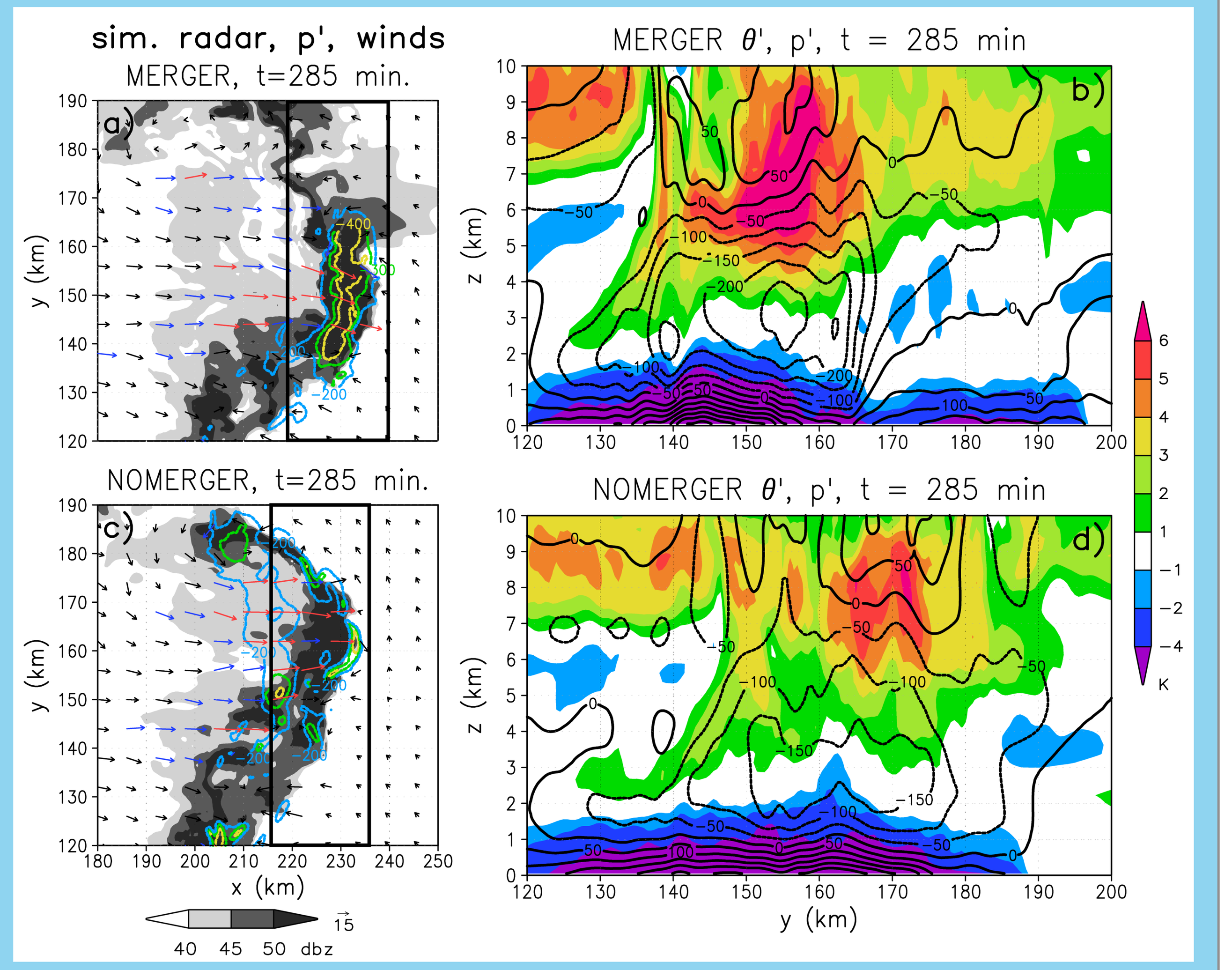


Figure 6: Left panels: plan view plots of simulated radar reflectivity, and wind vectors, at 2 km AGL and perturbation pressure averaged between 1 and 2 km AGL. Right panels: y-z cross section of potential temperature perturbation (shaded) and pressure perturbation (contours) averaged in the x-direction over the boxes shown in (a) and (c). Top panels are for the MERGER simulation, bottom panels the NOMERGER simulation.

Overview of idealized merger simulation

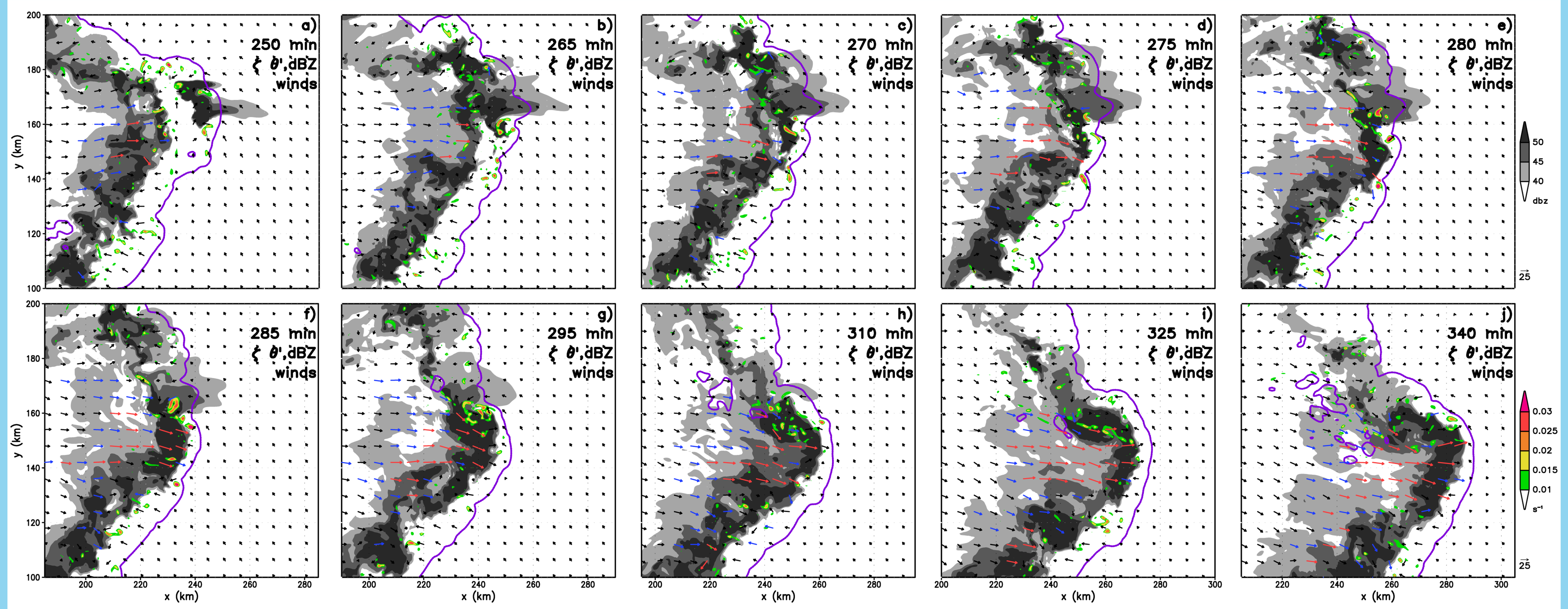


Figure 2: Simulated radar reflectivity (gray shading) and vertical vorticity (colored shading) at 1 km AGL, wind vectors at 2 km AGL (blue > 20 m s^{-1}, red >25 m s^{-1}), and - 2 K potential temperature at the lowest model level at select times between t = 250 and 340 minutes into the simulation.

Idealized simulations were run using CM1. A squall line simulation was run for 3 hours, after which the base-state vertical wind shear and storm relative helicity were increased. The model was restarted, and the supercell was triggered using a warm bubble ahead of the mature squall line.

Model configuration and parametrizations:

Horizontal grid: 500 m	*Lateral boundaries: open*
Vertical grid: 100- 250 m	*Lower boundary: free slip*
Domain: 400 x 300 x 20 km	*Coriolis : f-plane (10^{-4} s^{-1})*
Run duration: 6 hours	*Raditation scheme: none*
Microphysics: Thompson 2M	*Surface friction, fluxes: none*

- The squall line weakens locally as merger begins followed by subsequent re-intensification south of the merger. The merged supercell becomes the north end of the squall line.
- Post-merger:
  - o Low-level vertical vorticity increases over a broad area.
  - o A compact bow echo develops south of the merged supercell.
  - o A broad line-end vortex structure develops in the vicinity of the merged supercell.
- The merged system shares many qualitative similarities with observed merger cases.
- A squall line simulated in the same environment produces a broad bow echo without the intense low-level vertical vorticity (*not shown*).

Low-level vorticity evolution

- Multiple strong mesovortices develop along the leading edge of the squall line during/after merger, more so than in the NOMERGER simulation.
- Low-level vortex develops as the supercell's updraft moves rearward post-merger
  - o Descends from approx. 1km AGL.
  - o Associated primarily with updraft – tilting of baroclinic vorticity.
  - o Result is a broad region of intense vertical vorticity at the lowest model level.
  - o ***Qualitatively similar to observations of increased low-level rotation post-merger.***
- Merging of smaller vortices leads to a broad region of strong low-level cyclonic vertical vorticity at the north end of the squall line as the bow echo develops (line-end vortex).

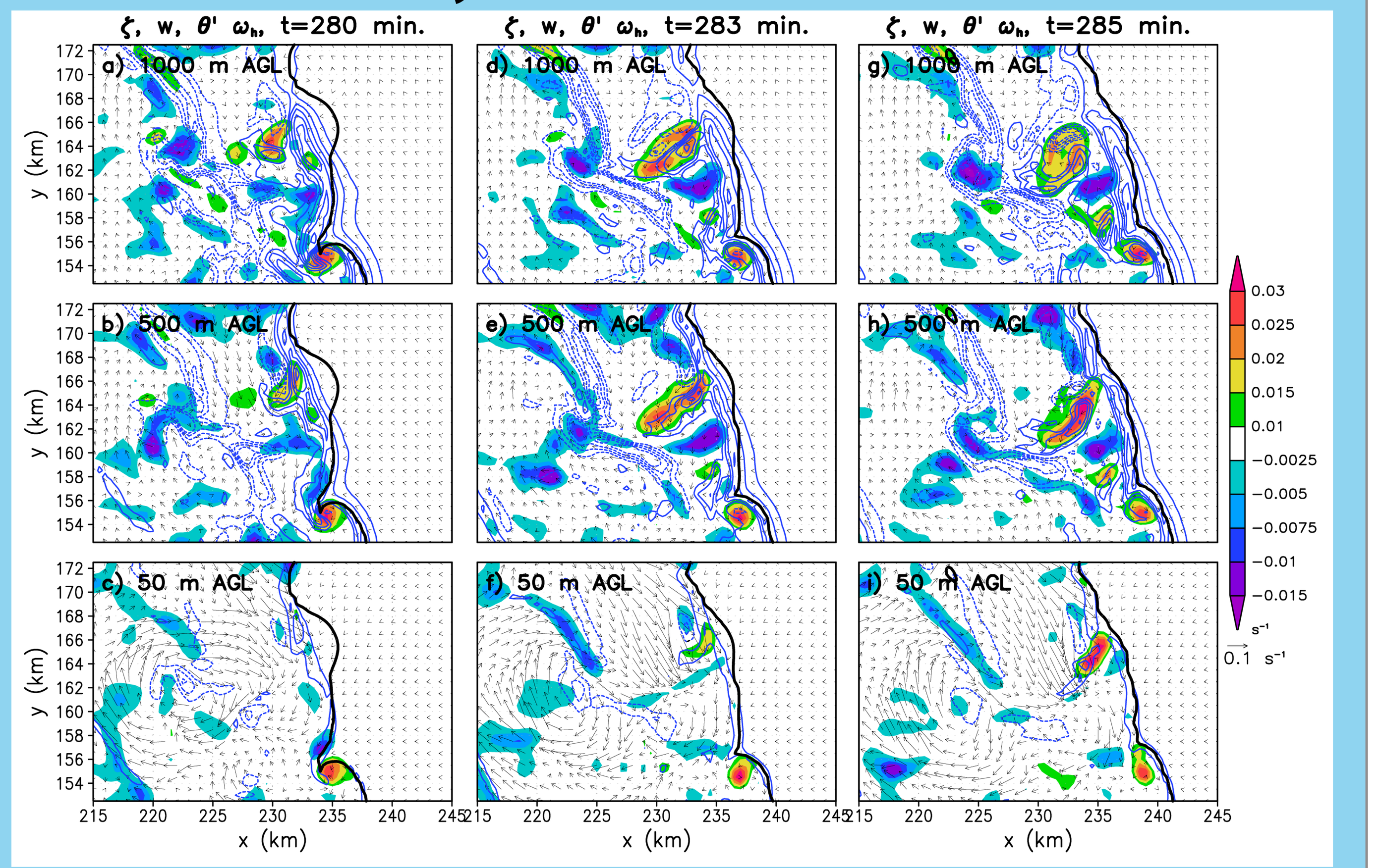


Figure 4: Plan view plots of vertical vorticity (s^{-1}, shaded as shown), vertical velocity (blue contours, every 5 m s^{-1}) and horizontal vorticity vectors (scale vector below color bar) at 1000 m (top panels), 500 m (middle panels), and 50 m (bottom panels) AGL and (left to right) t = 280, 283, and 285 minutes into the simulation. Heavy dark line denotes the -2 K surface potential temperature perturbation.

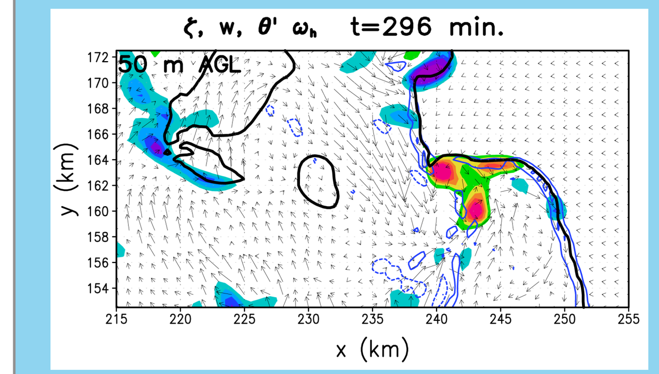
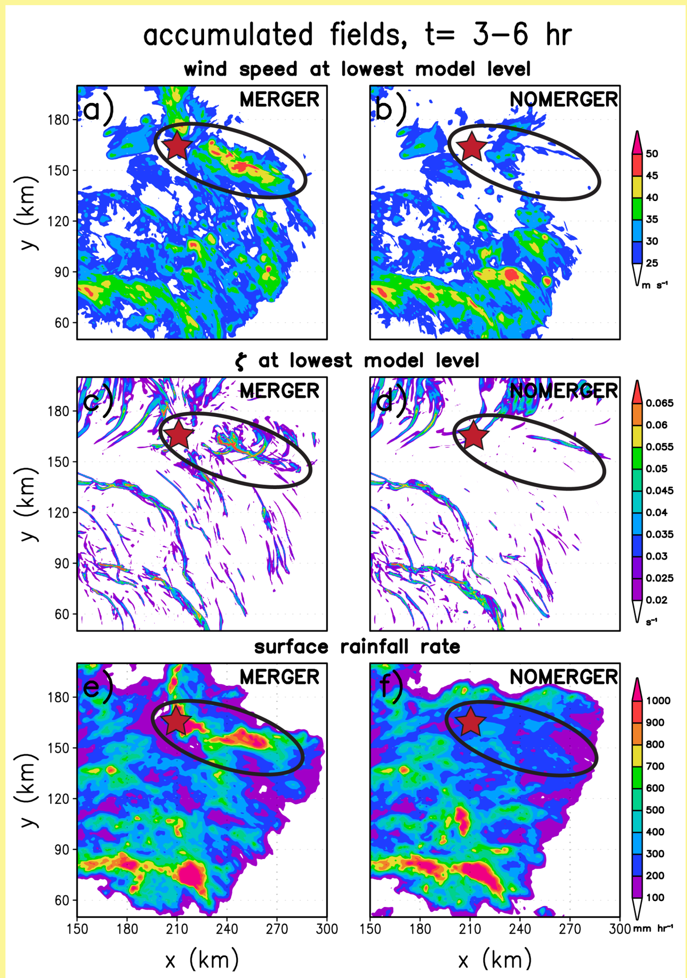


Figure 5: As in figure 4, but focusing on z =50 m AGL at t = 296 min, illustrating the intial stage of the vortex merger that leads to a broad region of low-level vertical vorticity.

Conclusions and implications



- Idealized simulations capture the salient features of observed squall line-supercell merger cases, revealing some of the key processes at work. Specifically:
  i. The merger is preceded by a weakening of the squall line's cold pool, leading to a local decline in squall line intensity. This results in the supercell being preserved during the merger and playing a dominant role in the merged system.
  ii. Following the merger, an increase in low-level vorticity in the vicinity of the merged supercell results from tilting of baroclinically-generated horizontal vorticity by the remnant supercell updraft.
  iii. The merger produces an increase in convective intensity, producing strong warming aloft. This produces a perturbation low-pressure near the leading edge of the merged system, driving a rear inflow jet that leads to post-merger bow echo development.
- Comparison to a simulation without the merger reveals that these processes promote an enhanced severe weather threat in the vicinity of the merger.
  i. Increased low-level rotation (suggests a potential tornado threat).
  ii. Increased straight line winds.

Figure 7: Swaths of fields accumulated between 3 and 6 hours into the (left column) from the lowest model level in the MERGER (right column) and NOMERGER simulations. Fields include wind speed (top panels), vertical vorticity (middle panels) and accumulated rainfall (bottom panels). The red star denotes the approximate merger location.

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