

UNIVERSITY OF OKLAHOMA
GRADUATE COLLEGE

SUPERCELL-LIKE STORM-SCALE AND TORNADO-SCALE PROCESSES IN
SIMULATED AND OBSERVED QUASI-LINEAR CONVECTIVE SYSTEMS

A DISSERTATION
SUBMITTED TO THE GRADUATE FACULTY
in partial fulfillment of the requirements for the
degree of
Doctor of Philosophy

By
MORGAN ELIZABETH SCHNEIDER
Norman, Oklahoma
2025

SUPERCELL-LIKE STORM-SCALE AND TORNADO-SCALE PROCESSES IN
SIMULATED AND OBSERVED QUASI-LINEAR CONVECTIVE SYSTEMS

A DISSERTATION APPROVED FOR THE
SCHOOL OF METEOROLOGY

BY THE COMMITTEE CONSISTING OF

Dr. Michael Coniglio (Chair)

Dr. Matthew Flournoy

Dr. David Bodine

Dr. Cameron Homeyer

Dr. Robert Palmer

Dr. Caleb Fulton

Acknowledgments

My Ph.D. has been an exercise in learning what I'm capable of with the right support, and I am so lucky to have the support system I've had. I visited OU for the first time as a high school senior in 2014, and a year later I was moving to Norman for my freshman year. If someone had told me then that I'd be walking away from here 10 years later with a Ph.D., I don't think I would have believed it. I can hardly believe it even now.

First, I owe so much to my family. I don't think there are enough words for 28 and a half years of support, but I'm going to try anyway. They've always supported me and everything I've done, and I wouldn't be where I am without them. To Dad, my love for weather and storms started with you, your habit of running outside with the camcorder during tornado warnings, and that old storm spotter's guide in the basement. To Mom, I never would have made it here without everything you've always done for me—from pushing me to do my best in high school to helping me fill out college and scholarship applications to supporting me from Chicago after I decided to go to the university 800 miles from home and then proceeded to stay there for 10 more years. And to Nick, you've been there to celebrate and commiserate about all things college, marching band, and grad school. I'm glad we were both in Norman for a while, and I'm proud of you. Finally, in 2020, I made the questionable decision to take home two free kittens, Matilda and Penny, who turned out to be the best/worst/cutest work-from-home coworkers ever. Their companionship kept me sane, especially during the pandemic.

Thank you to all my friends for the movie nights, board game nights, ghost hunting nights, brewery bingo nights, Flapjack Friday nights, D&D nights, sitting-on-the-couch-watching-reality-TV nights, and all the other nights. There are literally too many of you to name. We've carried each other through a global pandemic and half a decade of good days and bad days and classes and research. I love you and I wouldn't

have made it through grad school in one piece without you. I don't know where all that time went, but I'm so glad to have spent it with you guys.

They say it takes a village, and I've had an enormous village of people who have guided me along my trajectory through grad school (pun unfortunately intended). I've had so many incredible mentors, which I am lucky to be able to say. First and foremost, I am beyond grateful to my advisors, Matt Flournoy and Mike Coniglio, for literally everything. I started my Ph.D. with not much foundation in severe storm dynamics besides the very basics—my research experience up to that point was a combination of tornado debris, radar signal processing, turbulence, and randomly, geomagnetism. Over the last four years, I've gained so much expertise about storm dynamics, modeling, observations, and fieldwork through all of your guidance. Matt, thank you for literally always believing in me, often a lot more than I've believed in myself. Mike, I can't begin to summarize how much I've learned about science and research from you. I'm leaving my Ph.D. with so much more confidence in myself as a researcher than I started with, and the constant support from both of you has been a huge part of that.

Throughout college, I have had so many great mentors. Almost 10 years ago(!), Cameron Homeyer just happened to be assigned as my undergraduate academic advisor, and he has seen me through basically everything ever since. Thank you for being my Science Dad! I am also grateful to the CASS (now BLISS) group, who took a chance on me as a sophomore and introduced me to research and fieldwork. Before they were on my Ph.D. committee, David Bodine and Bob Palmer were my M.S. advisors at the ARRC, and Caleb Fulton was in my M.S. research group. I met David for the first time at Visiting Student Weekend, where he proceeded to place my dream hybrid meteorology/electrical engineering research project right in front of me. Of course I accepted that offer, and that was easily the right decision. I had such a good experience working with them that I decided to stick around another four years for a Ph.D. My love for all things radar comes from David and Bob, as does almost everything I know about signal processing. I've leaned on their guidance and research philosophy throughout grad school, and I will continue to do so through the rest of my career.

There is a whole village's worth of people in NSSL and CIWRO alone who have been part of my journey in one way or another. I've gotten so much valuable feedback on my work during the small research group meetings with Lauren, Isabelle, and Tony as well as SPARK group meetings. I'm also grateful to have been part of the paper reading

group discussions, which helped me develop the strong foundation in severe storm dynamics that I needed, and just as importantly taught me how to critique science and the limitations of methods and interpretations. Apart from the actual dedicated groups I've been in, I've learned just as much from all the random conversations I've had with people in the office, in the NWC hallways, at conferences, over drinks, and all sorts of other places. I consider myself very lucky to have worked in such a collaborative, supportive work environment. Finally, I owe an enormous shoutout to NSSL IT for rescuing all my data when my hard drive decided to die... three months before my defense. You're lifesavers.

Fun fact: even though I've only been at CIWRO and NSSL since 2021, this whole thing actually started in the backseat of a mobile mesonet in 2019. Being on Erik Rasmussen's Probe 2 crew during TORUS 2019 opened all the doors that ultimately led me here. Conversations with Erik inspired the research proposal that earned me the GRFP fellowship, and he was the one I reached out to about Ph.D. opportunities at NSSL. One thing led to another, Erik brought in Matt and Mike, and having my own funding made it possible for them to take me on as a student. The last four years of my life would have looked very different without Erik!

After that first major field experience on TORUS, I knew for sure I wanted to keep doing that. Six years, five more field campaigns, two and a half leadership roles, and one TIME's Top 100 photo later, I think I succeeded at "keep doing that." Being a PI on the PERiLS campaign was one of the most valuable learning experiences I've had in grad school. First and foremost, the second chapter of my dissertation wouldn't exist at all without Laura Shedd, Brandon Cohen, Min-Duan Tzeng, Boonleng Cheong, Dale Sexton, Pat Skinner, Addison Alford, Nathan Kuhr, and Cesar Salazar, who all volunteered multiple days of their time to be on my RaXPol crew during PERiLS. I am grateful to David Bodine for helping me get RaXPol onto PERiLS, from creating a budget to submitting the proposal and managing the funds. Thanks to Boonleng Cheong and David Schwartzman for supporting my proposal as co-PIs. So many thanks to Tony Lyza and Alan Gerard for their unwavering support and confidence in me throughout the project. Despite being a student among professors and research scientists, they trusted me as a scientist and stood up for me whenever I needed it. One final (ACK) of appreciation goes to the NOAA PI team for coordinating mission strategies with me and treating me like an equal while I learned the ropes of

being a first-time PI. I'm grateful to anyone who talked me down from a radar-induced crisis (which happened in at least three different states, and once on a dirt road at 2:30 A.M.) and didn't judge me while I openly cried in a mall parking lot in Alabama. Shoutout to John in Jonesboro for being the only mechanic in town willing to be within 15 yards of a Duramax engine, letting me bring in RaXPol without an appointment, taking the extra time to find the problem by the next morning, and doing that all for *free*. Honorable mention goes to Shadrachs Coffee, and also to the Hilton Garden Inn bar for not kicking us out even though we weren't even staying there and we may or may not have held a séance in their establishment (we did not).

At 9:22 P.M. on February 26, 2023, my house was hit by an EF-2 tornado. The support we received in the aftermath was overwhelming. To Sean Ernst: Thank you for ignoring me and showing up at our door anyway after I told you not to, and for sacrificing two tires and one tire jack. To Anna Wanless: Thank you for giving us a safe place to stay while we figured out what came next. To Mel Schroers: Thank you for writing emails to professors, texting my mom back, organizing the yard clean-up, telling everyone what to do, and all the other things I'm sure I'm forgetting. To Elisa and Brian Murillo-Greene: I'm so lucky to know you. Thank you for sharing your home with me. Tell Rose she was the best emotional support dog. To my brother: Thank you for letting my cats live with you for over a week even though you're super allergic to them. To everyone who helped clean up our yard: You skipped work on a Monday to pick up enough shingles and chunks of fence to fill two trash bins and several trash bags. Someone brought a generator and a Shop-Vac to literally vacuum roofing insulation out of the grass. You definitely inhaled fiberglass dust for us. There are far too many people to name individually, so if you supported me in any way, thank you. Thinking about that amount of support makes me tear up to this day.

I could keep going, but I have to stop somewhere, so I'll leave it at this: of all the places I could have spent the last 10 years, I'm glad I spent them here.

Table of Contents

Acknowledgments	iv
List Of Tables	x
List Of Figures	xi
Abstract	xv
1 Introduction	1
1.1 Research background	1
1.2 Research objectives	9
2 Mesocyclone Evolution in a Simulated QLCS-Supercell Merger	11
2.1 Introduction	11
2.2 Data and methods	13
2.2.1 Model setup	13
2.2.2 Vortex identification and trajectory analysis	17
2.3 Results	19
2.3.1 Mesocyclone evolution	19
2.3.2 Trajectory and vorticity analysis	28
2.4 Conclusions	44
3 Close-Range Radar Observations of QLCS Tornadogenesis Failure Processes During PERiLS	47
3.1 Introduction	47
3.2 Data and methods	50
3.2.1 RaXPol and mobile mesonet data	50
3.2.2 Analysis and correction methods	55
3.3 Case overview	56
3.4 Results	60
3.4.1 Nontornadic vortex evolution	60
3.4.2 The role of the cold pool	72
3.4.3 Inferred processes contributing to tornadogenesis failure	74
3.4.4 Vorticity worms	77
3.5 Conclusions	80
4 Conclusions and Future Work	83

List Of Tables

2.1	CM1 model configuration parameters.	14
2.2	Number of parcels in the MERGER low-level mesocyclone at 200 min, 210 min, and 220 min.	29
3.1	Select RaXPol specifications and operating parameters during PERiLS on 3 March 2023. Adapted from Pazmany et al. (2013).	52
3.2	Observed beam heights ARL of the lowest and highest tilts at ranges of 10 km, 5 km, 2 km, and 1 km from the radar.	54

List Of Figures

2.1	Timeline of convection initialization for the cold dam and tendency nudging techniques.	15
2.2	Skew T -log p diagram and hodograph of the quasi-steady base state environmental profile beginning at the 10-m AGL vertical level. Select environmental thermodynamic and kinematic parameters are listed. . .	16
2.3	Simulated radar reflectivity at the lowest model level for the MERGER (left column), QLCSONLY (center column), and SUPERCELL (right column) simulations at (a)–(c) 180 min, (d)–(f) 195 min, (g)–(i) 210 min, (j)–(l) 225 min, and (m)–(o) 240 min. Black contours denote maximum 0–1 km $w = 5 \text{ m s}^{-1}$	20
2.4	As in Fig. 2.3, but with θ'_ρ at the lowest model level shaded. Black contours denote maximum 0–1 km $w = 5 \text{ m s}^{-1}$, and pink contours denote minimum 0–1 km $\text{OW} = -0.001 \text{ s}^{-2}$. Ground-relative wind vectors at the lowest model level are plotted every 22 grid points. . . .	21
2.5	Time-heights of minimum OW (s^{-2} ; shaded) in $10 \text{ km} \times 10 \text{ km}$ boxes following (a) the MERGER pre- and post-merger mesocyclone, (b) a QLCSONLY mesovortex, and (c) the SUPERCELL mesocyclone. Maximum w is contoured in black at the 10 m s^{-1} (thin gray), 15 m s^{-1} (thin black), and 20 m s^{-1} (thick black) levels. The vertical dashed line at 210 min denotes the time of the merger. For the QLCSONLY mesovortex, the boxes follow the y position of the MERGER mesocyclone boxes, but are adjusted in the x direction to the position of the QLCSONLY leading edge.	24
2.6	Time series of maximum 0–2 km UH for the MERGER pre- and post-merger mesocyclone (red), QLCSONLY mesovortex (black), and SUPERCELL mesocyclone (blue) following the same $10 \text{ km} \times 10 \text{ km}$ boxes as described in Fig. 2.5, except for the following difference: Before 210 min, the MERGER line in (a) follows the pre-merger mesocyclone as in Fig. 2.5a, while the MERGER line in (b) follows the segment of the pre-merger QLCS that merges with the supercell. After 210 min, both panels show the same post-merger UH time series for MERGER because the merged mesocyclone becomes the new leading edge of the MERGER QLCS. The QLCSONLY and SUPERCELL time series are the same in both panels. The vertical dashed line at 210 min denotes the time of the merger.	26
2.7	As in Fig. 2.6, but for maximum 2–5 km UH.	27

2.8	Trajectories of all parcels in the MERGER mesocyclone at 200 min (left), at 210 min (center), and at 220 min (right). The trajectories are shaded by (a)–(c) height AGL z (km), (d)–(f) parcel thermal buoyancy B (m s^{-2}), and (g)–(i) source region. Source regions are colored as low-level inflow (gold), mid-level inflow (red), supercell outflow (light blue), and QLCS outflow (dark blue).	30
2.9	Time series of median parcel (a)–(c) z (km), (d)–(f) B (m s^{-2}), (g)–(i) w (m s^{-1}), and (j)–(l) ζ (s^{-1}) of MERGER parcels from all source regions, starting 15 min before parcels ascend into the low-level mesocyclone. The 25th and 75th percentiles of each variable are shaded. Each 15-min block follows parcels in the mesocyclone at 200 min (left), at 210 min (center), and at 220 min (right).	33
2.10	Time series of median (a)–(b) w (m s^{-1} ; black), (c)–(d) total $ \omega $ (s^{-1} ; dark blue), (e)–(f) ζ (red) and $ \omega_{\mathbf{H}} $ (blue), and (g)–(h) ω_{SW} (light blue) and ω_{CW} (purple) of the MERGER mid-level inflow parcels, starting 15 min before they ascend into the mesocyclone. 25th and 75th percentiles are shaded. Positive ω_{CW} is oriented to the left of the storm-relative parcel velocity vector. Similar to Fig. 2.9, the time series are divided into 15-min blocks following parcels in the mesocyclone at 210 min (left) and 220 min (right).	36
2.11	Plan views of the median trajectories for MERGER mid-level inflow parcels in the low-level mesocyclone at (a) 210 min and (b) 220 min. Trajectories are shaded by their median height AGL (km). Vectors show parcel $\omega_{\mathbf{H}}$ (silver) and storm-relative velocity (black). The 30 dBZ contour for simulated lowest-level radar reflectivity at 210 min and 220 min is underlaid (gray).	37
2.12	X-Z cross sections of θ'_ρ (shaded) and p' (contoured every 1 hPa, with red denoting $p' > 0$ hPa and blue denoting $p' < 0$ hPa) at (a) 208 min and (b) 218 min, with the median trajectory overlaid for MERGER mid-level inflow parcels in the low-level mesocyclone at 210 min and 220 min, respectively, and shaded by median parcel w . Time is annotated along the trajectories.	39
2.13	Plan views of θ'_ρ at the lowest model level at (a) 208 min and (b) 218 min, with the median trajectory overlaid for MERGER mid-level inflow parcels in the low-level mesocyclone at 210 min and 220 min, respectively, and shaded by median parcel w . Time is annotated along the trajectories.	40

2.14	Time composites of parcel-centered ζ tendency terms for tilting (left) and stretching (right) for the MERGER mid-level inflow parcels. Top: composite ζ tendencies during descent (203–208 min) for parcels in the low-level mesocyclone at 210 min. Middle: composite ζ tendencies during descent (214–218 min) for parcels in the low-level mesocyclone at 220 min. Bottom: composite ζ tendencies during residence within the rotor (218–219 min) for parcels in the low-level mesocyclone at 220 min.	41
2.15	Time composites of parcel-centered $ \omega_H $ tendency terms for tilting (left), stretching (center), and baroclinic generation (right) for the MERGER mid-level inflow parcels. Top: composite $ \omega_H $ tendencies during descent (203–208 min) for parcels in the low-level mesocyclone at 210 min. Middle: composite $ \omega_H $ tendencies during descent (214–218 min) for parcels in the low-level mesocyclone at 220 min. Bottom: composite $ \omega_H $ tendencies during residence within the rotor (218–219 min) for parcels in the low-level mesocyclone at 220 min.	42
3.1	(a) Instrument configuration for the PERiLS IOP on 3 March 2023 in the Clarksdale subdomain (yellow outline) with the locations of the C- and X-band mobile radar network, mobile radiosonde systems, RaXPol, and NSSL mobile mesonets labeled. (b) Zoomed-in locations of RaXPol and the NSSL mobile mesonets along U.S. Hwy. 165 in position for the vortex intercept mission.	51
3.2	500-hPa geopotential heights (black lines), temperature (dashed red lines), and winds (barbs and shaded) from SPC mesoanalysis valid at 0800 UTC 3 March 2023. Image from Storm Prediction Center archive.	57
3.3	Mean sea-level pressure (black lines) and winds (barbs) from SPC mesoanalysis valid at 0800 UTC 3 March 2023. Image from Storm Prediction Center archive.	58
3.4	850-hPa geopotential heights (black lines), temperature (dashed red and blue lines), dewpoint (green lines), and winds (barbs) from SPC mesoanalysis valid at 0800 UTC 3 March 2023. Image from Storm Prediction Center archive.	59
3.5	Skew T -log p diagram and hodograph of the observed vertical thermodynamic and wind profiles from an upper-air sounding from the NSSL Lidar and mobile sounding system at 0702 UTC, along with calculated and derived environmental and convective parameters. Image from the Earth Observing Laboratory PERiLS 2023 field catalog.	60
3.6	COW Doppler velocity observations at the 1.2° tilt at (a) 0749:52 UTC, (b) 0800:22 UTC, (c) 0809:22 UTC, (d) 0819:52 UTC, (e) 0824:22 UTC, and (f) 0830:22 UTC. The black squares show the location of the tornadic and nontornadic mesovortices. Data: (Wurman and Kosiba 2023).	61

3.7	RaXPol radar reflectivity factor PPIs at 2.4° elevation from volumes at: (a) 0820:00 UTC, (b) 0820:30 UTC, (c) 0821:00 UTC, (d) 0821:30 UTC, (e) 0822:30 UTC, (f) 0823 UTC, (g) 0823:30 UTC, (h) 0824:00 UTC, (i) 0824:30 UTC, and (j) 0825:00 UTC. (Note: there is no 0822:00 UTC volume due to brief transceiver malfunctions.)	63
3.8	As in Fig. 3.7, but for radial velocity (m s^{-1}).	64
3.9	From the RaXPol volume at 0820:30 UTC: (a) PPI of column-maximum ζ' (s^{-1}) with white markers showing the trace of a cross section through the NTV. Lines surrounding the overhead trace of the NTV (solid black) and the azimuth of the reconstructed RHI (dashed black) are overlaid. (b) Composite vertical cross-section of ζ' magnitude (s^{-1}) along the NTV trace between the solid black lines in (a). (c) Reconstructed RHI of radial velocity (m s^{-1}) along the dashed black line in (a).	65
3.10	As in Fig. 3.9, but at 0821:00 UTC.	66
3.11	As in Fig. 3.9, but at 0821:30 UTC. Note that this volume is shallower than the others due to missing sweeps at higher tilts.	67
3.12	As in Fig. 3.9, but at 0822:30 UTC.	68
3.13	As in Fig. 3.9, but at 0823:00 UTC.	69
3.14	Time-height plot showing vertical profiles of maximum ζ' within the NTV between 0820:00–0825:00 UTC.	70
3.15	As in Fig. 3.14, but for V_{rot}	71
3.16	Radial velocity PPIs at the 2.4° tilt with 2-min subsets of the time-space converted mobile mesonet circuit (square and triangle markers), shaded by derived θ'_v (K). (a) Radial velocity at 0821 UTC with θ'_v between 0819–0821 UTC. (b) Radial velocity at 0823 UTC with θ'_v between 0821–0823 UTC. (c) Radial velocity at 0824:30 UTC with θ'_v between 0823–0825 UTC. (d) Radial velocity at 0823 UTC with mobile mesonet θ'_v and wind vectors from the full circuit.	73
3.17	PPIs of ζ' at the 0.9° tilt at (a) 0820 UTC, (b) 0820:30 UTC, (c) 0821 UTC, and (d) 0821:30 UTC. Ground traces of all NTVs in the initial vortex cluster are denoted by white circle markers. Vorticity worms are annotated by the black lines.	79

Abstract

While supercells are responsible for a majority of long-lived significant tornadoes, tornadoes occur frequently in both supercellular and linear convective modes. Quasi-linear convective systems (QLCSs) and embedded mesovortices are responsible for up to 25% of tornadoes in the United States, and this proportion is even higher in the Southeastern United States. Whether supercell mesocyclones and QLCS mesovortices possess fundamentally distinct characteristics and dynamics is an active topic of discussion. In this work, results from idealized simulations and observational datasets of Southeastern QLCSs suggest that the mechanisms involved in both storm-scale and tornado-scale rotation are widely variable, and many of these processes strongly resemble known mesocyclone and tornado processes in supercells.

Idealized simulations are used to study the evolution of rotation in a QLCS-supercell merger in an observed high-shear, low-CAPE environment in the Southeast. Mergers between QLCSs and isolated supercells have been linked to the generation and intensification of low-level rotation. In this work, the post-merger mesocyclone is stronger, deeper, and more persistent than mesovortices in a non-merging QLCS, suggesting that the merged mesocyclone retains its supercellular characteristics after the merger. Trajectory analysis reveals that parcels from near the top of the boundary layer are a key supercell-like feature of the merged mesocyclone, with distinct vorticity generation processes from the other source regions. These parcels follow an up-down trajectory before entering the mesocyclone. The predominant mechanism for vertical vorticity generation is upward tilting of primarily crosswise horizontal vorticity via the updraft, but upward tilting and downward tilting in the downdraft are also present. Horizontal vorticity is generated during descent via tilting and baroclinic processes. After the merger, horizontal vorticity is also amplified during descent via strong stretching within a developing low-level rotor. The vertical vorticity generation processes are primarily those that are typically associated with supercells, but have been seen in QLCS mesovortices as well. By contrast, the horizontal vorticity generation mechanisms are

those that are typically seen with QLCS mesovortices. These simulations reveal that the merged mesocyclone is characterized by a combination of supercell- and QLCS-like features and processes.

The QLCS processes seen in the idealized simulations are contrasted by observations of comparable resolution obtained by the Propagation, Evolution, and Rotation in Linear Storms (PERiLS) field campaign. In particular, the Rapid-scanning X-band Polarimetric (RaXPol) mobile radar collected close-range, low-level observations of a nontornadic mesovortex and a cluster of transient tornado-scale vortices in a severe QLCS. The processes inferred from observations appeared to differ from those diagnosed in the simulations. As these nontornadic vortices (NTVs) form, they rapidly advect back into the cold pool and dissipate, with only one NTV persisting for >3 min after forming from the merging of two weaker NTVs. Radar observations show that the NTVs are substantially tilted from surface to cloud base, dissipate in a top-down direction, and never develop strong near-surface rotation. Mobile mesonet surface measurements reveal a weak cold pool ($\theta'_v \approx -1.1$ °C), which may have caused tornadogenesis failure by (1) limiting baroclinic horizontal vorticity generation along the gust front, preventing the development of strong surface rotation, and (2) displacing the NTV from the leading updraft, preventing the amplification of vertical vorticity via surface convergence and upward vertical pressure gradient accelerations. Immediately prior to and during the genesis of the cluster of NTVs, low-level radar velocity fields reveal line-parallel streaks of enhanced vertical vorticity, or “vorticity worms,” in the near inflow of the nontornadic mesovortex, suggesting their potential role in NTV genesis. The role of the cold pool in tornadogenesis failure and the implication of vorticity worms in NTV genesis are both similar to tornado-scale processes in supercells—the rearward displacement of a vortex from the parent updraft due to cold pool weakness is known to contribute to tornado dissipation in supercells, and vorticity worms have been found in the highly sheared near-surface inflow of simulated and observed tornadic supercells but have not yet been examined in QLCS environments or in nocturnal surface layers.

Chapter 1

Introduction

Quasi-linear convective systems (QLCSs) are responsible for an estimated 18–25% of tornadoes across the United States, and this proportion is even higher in the Southeast United States (Trapp et al. 2005; Smith et al. 2012; Ashley et al. 2019). Despite this, the variety of mechanisms that produce QLCS tornadoes is relatively unclear, resulting in lower probability of detection, higher false alarm rates, and shorter warning lead times than supercell tornadoes (Brotzge et al. 2013; Anderson-Frey et al. 2019; Gibbs and Bowers 2019). In the Southeast, the fatality rates and societal impacts of tornadoes are compounded by a convergence of unique meteorological conditions and socioeconomic vulnerability, including higher frequency of nocturnal, cold season, and QLCS tornadoes, greater population density, and manufactured home density (Ashley 2007). The prevalence of QLCS tornadoes in the Southeast underlies a need for improvements in our ability to detect and predict them, motivating further investigation into how and why they occur.

1.1 Research background

Different convective organizational modes are often associated with different severe weather hazards (Gallus et al. 2008; Smith et al. 2012). Supercell thunderstorms are the predominant producers of significant tornadoes and large hail (Doswell and Burgess 1993; Davies-Jones et al. 2001; Smith et al. 2012), while QLCSs are typically

responsible for widespread severe straight-line winds (Fujita 1978; Przybylinski 1995; Wakimoto 2001). While supercells are responsible for a majority of long-lived significant (EF2+) tornadoes, tornadoes occur frequently in both supercellular and linear convective modes.

Most of our knowledge of severe convection and tornadoes is based on observational and modeling studies of supercell tornadoes (for comprehensive reviews of current knowledge on supercell and tornado dynamics, see Markowski and Richardson 2009; Davies-Jones 2015; Fischer et al. 2024). The mechanisms that drive rotation in supercell mesocyclones are well-understood. Mesocyclone rotation is typically several km in depth, extending from ~ 1 km AGL or lower to well into the mid-levels (> 3 km AGL). Rotation first develops aloft via the tilting and stretching of horizontal streamwise environmental vorticity by the updraft (Rotunno 1981; Davies-Jones 1984). The development of low-level ($< \sim 1$ km AGL) rotation requires positive vertical vorticity closer to the surface. If tilting by the updraft is to generate vertical vorticity near the ground, more abrupt tilting of horizontal vorticity than what the mid-level updraft can provide is necessary. The processes responsible for the development of mesocyclone rotation near and just below cloud base include a combination of reorientation of barotropic vorticity (e.g., Davies-Jones 1984; Dahl 2017; Coffer et al. 2023; Fischer et al. 2024) and baroclinically generated vorticity in storm-cooled air (e.g., Davies-Jones and Brooks 1993; Markowski and Richardson 2009; Dahl 2015). Horizontal vorticity is re-oriented into the vertical direction and transported downward in the downdraft before ascending (e.g., Rotunno and Klemp 1985; Davies-Jones and Brooks 1993; Trapp and Weisman 2003; Markowski and Richardson 2009; Dahl 2015). Near-surface ($< \sim 250$ m AGL) cyclonic vertical vorticity is then generated by tilting and stretching via the updraft, creating rotation below the updraft base. Coherent sources of vorticity (e.g., “streamwise vorticity currents” or “vorticity rivers”) generated baroclinically along

storm outflow may be important to low-level rotation development (Dahl et al. 2014; Orf et al. 2017; Schueth et al. 2021; Finley et al. 2023). Other work suggests that upward tilting and stretching of environmental barotropic horizontal vorticity, which could be generated via low-level wind shear or surface friction, may contribute significantly to mesocyclone rotation below 1 km (e.g., Rotunno et al. 2017; Roberts and Xue 2017; Boyer and Dahl 2020; Coffey et al. 2023; Fischer et al. 2024).

The most damaging QLCS tornadoes and straight-line winds are frequently associated with embedded strong mesovortices (e.g., Fujita 1978; Forbes and Wakimoto 1983; Przybylinski 1995; Weisman and Trapp 2003; Trapp and Weisman 2003; Atkins et al. 2004, 2005; Trapp et al. 2005; Wakimoto et al. 2006a; Atkins and St. Laurent 2009a,b; Schenkman et al. 2012; Lyza et al. 2017). Mesovortices are typically shallower and more transient than supercell mesocyclones, with rotation extending to approximately 3 km above the surface and persisting for an hour or less. There are multiple proposed sources for rotation development and maintenance in mesovortices: (1) release of horizontal shearing instability (HSI) along the leading edge of the gust front (e.g., Forbes and Wakimoto 1983; Przybylinski 1995; Lee and Wilhelmson 1997a,b; Wheatley and Trapp 2008; Conrad and Knupp 2019); (2) tilting of baroclinic crosswise vorticity via an updraft or downdraft (e.g., Davies-Jones and Brooks 1993; Bernardet and Cotton 1998; Trapp and Weisman 2003; Wheatley and Trapp 2008; Atkins and St. Laurent 2009b; Richter et al. 2014); (3) tilting of streamwise horizontal vorticity via the updraft (e.g., Atkins and St. Laurent 2009b; Schenkman et al. 2011; Parker and Dahl 2015; Boyer and Dahl 2020), similar to mechanisms for low-level supercell mesocyclone formation; and more recently, (4) tilting of frictionally induced horizontal vorticity within a low-level rotor via the updraft (Schenkman et al. 2012; Xu et al. 2015). The range of findings from past work suggests that the mechanisms responsible for QLCS rotation may vary on a case-by-case basis, and some studies have found that

multiple simultaneous mechanisms can contribute to the development of a mesovortex (e.g., Atkins and St. Laurent 2009b; Flournoy and Coniglio 2019).

The accepted conceptual model for supercell tornadogenesis is detailed in Davies-Jones (2015), and is comprised of three stages: (1) development of mesocyclonic rotation, (2) production of surface vertical vorticity, and (3) concentration of rotation into a tornadic vortex. The low-level mesocyclone provides enhanced upward acceleration below the cloud base via a dynamically induced pressure deficit, which drives the stretching of surface vertical vorticity for tornadogenesis. There have been multiple proposed pathways for the development of surface vertical vorticity, but the primary accepted pathway is the Davies-Jones and Brooks (1993) downdraft mechanism, where near-surface baroclinic horizontal vorticity is generated as descending parcels encounter buoyancy gradients in the downdraft. The horizontal vorticity is partially tilted into the vertical as parcels approach the surface, resulting in predominantly positive vertical vorticity at the surface. Tornadogenesis occurs when the surface vertical vorticity contracts and intensifies. Surface friction has an important role in this stage by interrupting cyclostrophic balance near the surface, resulting in a shallow, intense inflow layer and development of a corner flow region. Fischer et al. (2024) further divides the third stage into two substages: (3a) stretching and organization, and (3b) transition. The stretching and organization substage of tornadogenesis encompasses the converging of disorganized surface vertical vorticity patches under the updraft and subsequent amplification via stretching. After organizing and intensifying, the near-surface vortex transitions out of cyclostrophic balance as surface friction decelerates the rotational flow within the tornado boundary layer (Fischer and Dahl 2022). The now-imbalanced inward pressure gradient acceleration creates strong near-surface inflow that abruptly “turns the corner” into the central updraft. Once the corner flow region forms, the downdraft mechanism is no longer needed for the tornadic vortex to maintain surface

vertical vorticity. Tornado maintenance is dominated by the “in-and-up” mechanism, where surface vertical vorticity is produced by the abrupt upward tilting of surface horizontal vorticity in the corner flow (e.g., Rotunno et al. 2017; Boyer and Dahl 2020; Fischer and Dahl 2022).

The processes for QLCS tornadogenesis and maintenance are comparatively less understood. Past work has shown that baroclinic generation of near-surface horizontal vorticity is important in QLCS mesovortices (e.g., Trapp and Weisman 2003; Weisman and Trapp 2003; Wheatley and Trapp 2008; Atkins and St. Laurent 2009b; Flournoy and Coniglio 2019). Baroclinity is also implied to be important in QLCS tornadogenesis (McDonald and Weiss 2021), but the precise role of the cold pool in QLCS tornadogenesis is unknown. Some early work found HSI release and vortex sheet roll-up to be a mechanism for simulated nonsupercell tornadogenesis along an outflow boundary (Lee and Wilhelmson 1997a,b). More recently, Schenkman et al. (2012) and Tochimoto and Niino (2022) found that frictionally generated horizontal vorticity was a crucial source of surface vorticity for tornadogenesis in simulated QLCSs. Schenkman et al. (2012) additionally found that the frictionally generated vorticity was amplified within a low-level horizontal rotor behind the gust front before being ingested into the developing tornadic vortex. Boyer and Dahl (2020) found that the in-and-up mechanism is primarily responsible for surface vertical vorticity in existing tornadoes in both simulated supercells and QLCSs, but did not address the initial generation of surface vertical vorticity during tornadogenesis.

QLCS mesovortices and tornadoes are notoriously difficult to observe and predict due to their transience and our limited understanding of the processes involved in their formation and evolution. As with supercells, most mesovortices do not produce tornadoes (although the frequency of tornadic mesovortices is less documented), and our ability to diagnose the tornadic potential of a pretornadic mesovortex is relatively

weak. QLCSs tend to produce weaker tornadoes than supercells (EF1 or lower; Trapp et al. 2005; Smith et al. 2012), but are still responsible for an estimated 10% of significant (EF2+) tornadoes (Smith et al. 2012), and the reasons for this disparity are unclear. Mesovortices that produce tornadoes and severe winds frequently form along the leading edge of bow echoes (e.g., Weisman and Trapp 2003; Trapp and Weisman 2003; Wakimoto et al. 2006b,a). Tornadic and pretornadic mesovortices tend to be stronger, deeper, and longer-lived than their nontornadic counterparts (e.g., Atkins et al. 2004, 2005; Blind-Doskocil 2023).

Recent QLCS tornado research has provided more insight into factors potentially influencing the tornadic potential of QLCSs. Lovell and Parker (2022) found that simulated QLCS tornado-like vortices were associated with common reflectivity features like gust front cusps, bow echoes, and hook echo-like structures, suggesting that local cold pool morphology (and potentially its influence on baroclinic vorticity production) likely plays a prominent role in QLCS tornadogenesis. This would be consistent with past supercell tornado studies, which have shown that the characteristics of the rear-flank downdraft (RFD) are important to supercell tornadogenesis and maintenance. Higher tornadic potential in supercells is typically associated with warmer, less negatively buoyant cold pools (e.g., Markowski et al. 2002; Grzych et al. 2007; Hirth et al. 2008; Lee et al. 2012; Flournoy et al. 2020). The RFD is also an important source of surface convergence and baroclinity, so a balance between too-strong and too-weak RFD buoyancy deficits is needed for tornado formation and maintenance in supercells. By comparison, cold pool and microphysical processes in QLCSs and their role in tornado formation are substantially less understood. McDonald and Weiss (2021) found that tornadic mesovortices are associated with stronger cold pools than nontornadic mesovortices in Southeastern QLCSs. Recently, Kuster et al. (2024) found that tornadic and wind-damaging mesovortices tend to be accompanied by low- and

mid-level specific differential phase (K_{DP}) cores in polarimetric radar observations, indicating that tornadic potential in a QLCS is associated with enhanced precipitation production within the mesovortex. This finding is consistent with past research linking tornadic potential in QLCSs with both stronger, deeper mesovortices (implied by the presence of mid-level K_{DP} cores) and stronger cold pools (low-level K_{DP} cores could indicate stronger precipitation loading, resulting in locally intense downdrafts and outflow). However, these features are largely either impossible to directly observe in an operationally meaningful way (e.g., cold pool strength) or develop with little lead time—before the introduction of polarimetric capabilities to the operational radar network, Trapp et al. (1999) found that the mean lead time between detection of a pre-tornadic vortex signature and tornadogenesis in a QLCS was only 5 min. More recently, Davis and Parker (2014), Sessa and Trapp (2020), and Blind-Doskocil (2023) all found that the lead time between detection of a pretornadic mesovortex and tornadogenesis is often 10 min or less.

Southeast QLCS mesovortices and tornadoes are even more difficult to anticipate. This is in part because QLCSs and tornadoes in the Southeast frequently occur in unique environments characterized by strong wind shear and low convective available potential energy (CAPE) (Schneider et al. 2006; Smith et al. 2012). These high-shear, low-CAPE (HSLC) environments are defined as having $\leq 500 \text{ J kg}^{-1}$ of surface-based CAPE (SBCAPE) and $\geq 18 \text{ m s}^{-1}$ of 0–6-km bulk wind shear (Schneider et al. 2006; Sherburn and Parker 2014). HSLC convection is especially common in the Southeast during the cold season and overnight (e.g., Kis and Straka 2010; Sherburn and Parker 2014; Sherburn et al. 2016), and is estimated to be responsible for approximately half of all significant (EF2+) tornadoes and 45% of all QLCS tornadoes in the United States (Schneider et al. 2006; Thompson et al. 2012). HSLC convection and QLCS mesovortices tend to have shallow updrafts and lack the mid-level rotation present

in high-CAPE supercells, and are therefore driven primarily by low-level processes that are difficult to observe (Davis and Parker 2014). Despite their frequency in the Southeast, HSLC QLCS tornadoes have been studied far less than those occurring in more typical high-shear, high-CAPE environments and supercells, resulting in higher false alarm rates, lower probability of detection, and shorter warning lead times (e.g., Brotzge et al. 2013; Davis and Parker 2014; Anderson-Frey et al. 2016).

Whether the mechanisms for storm- and tornado-scale rotation are significantly different between supercells and QLCSs is a topic of substantial discussion. Traditionally, it is assumed that the dynamics of QLCS mesovortices are distinct from supercell mesocyclones. While the Trapp and Weisman (2003) mechanisms are generally accepted as the primary route for QLCS mesovortex formation, the release of HSI may play a more prominent role in HSLC environments. HSI release is a compelling theory for mesovortex genesis in the Southeast in particular due to the prevalence of HSLC environments, where the highly sheared low-level winds are readily conducive to vortex sheet development and subsequent roll-up into cyclonic vortices along a QLCS gust front without the need for a strong mid-level updraft. Other potential support for distinction between QLCS and supercell processes is the importance of the gust front as a vorticity source for mesovortex and tornadogenesis. Baroclinic generation of crosswise horizontal vorticity along the cold pool contributed to mesovortex genesis in a modeled QLCS in Flournoy and Coniglio (2019), and a low-level horizontal rotor behind the gust front was crucial to amplifying ambient horizontal vorticity leading to tornadogenesis in a simulated QLCS in Schenkman et al. (2012). Finally, the fact that QLCS tornadoes tend to be significantly weaker and shorter-lived than supercell tornadoes could imply different mechanisms for the generation and maintenance of vorticity in QLCSs. In all, it would be reasonable to assume that the driving processes are inherently different.

However, there is also considerable evidence supporting the idea of similar mechanisms for storm- and tornado-scale rotation in supercells and QLCSs. Strong low-level wind shear is an important driver of tornadic potential and development of low-level rotation in both supercells and QLCSs in any thermodynamic environment. Maintenance of a strong low-level updraft is critical for the tilting and amplification of vorticity at the surface in the tornadogenesis process. Many observed and simulated QLCS mesovortices form in ways that are wholly inconsistent with HSI—some may form in isolation or at irregular spacings, while others may form in cyclonic-anticyclonic pairs—implying that other processes must contribute to QLCS mesovortex and tornado formation. These other hypothesized mechanisms for mesovortex formation, as outlined earlier in this section, bear much stronger resemblance to supercell mesocyclone formation mechanisms. While the exact sources of vorticity may be different due to distinct storm morphologies and structures, the processes involved in generating and amplifying vertical vorticity for low-level mesovortex and tornado formation may be more similar than different. Ultimately, our knowledge about the dynamics and genesis of mesovortices and tornadoes in Southeast QLCSs is still too limited to draw definitive conclusions about any similarity or dissimilarity to supercells.

1.2 Research objectives

The overarching goal of this dissertation is to examine the processes involved in the development and maintenance of storm-scale and tornado-scale rotation in Southeast linear storms using a combination of numerical simulations and field campaign observations. The broad research questions guiding this work are:

- What is the nature of *storm-scale* processes in a Southeast QLCS?
- What is the nature of *tornado-scale* processes in a Southeast QLCS?

- Are any of these processes common to both QLCSs and supercells, or are they fundamentally distinct?

In Chapter 2, an idealized modeling study of a QLCS-supercell merger in a Southeast HSLC environment is conducted to evaluate the impacts of a merger on the evolution of a simulated mesocyclone and sources of low-level storm-scale rotation. In Chapter 3, an observational study of a nontornadic mesovortex examines the potential mechanisms for tornadogenesis failure in a Southeast QLCS using high-resolution observations from rapid-scanning radar and mobile mesonets. Finally, the overall conclusions from these studies and avenues for future work are presented in Chapter 4.

Chapter 2

Mesocyclone Evolution in a Simulated QLCS-Supercell Merger

2.1 Introduction

Storm interactions and mergers can complicate the processes relating to the formation and evolution of rotation in supercells and QLCSs. Past studies on storm mergers have focused largely on mergers between supercells (e.g., Hastings and Richardson 2016; Flournoy et al. 2022; Lyza and Flournoy 2023; Fischer and Dahl 2023; Fischer et al. 2023; Nixon et al. 2024). Mergers between supercells and QLCSs have been comparatively less studied, and most existing work has been observational case studies of individual merger events (Fujita 1978; Goodman and Knupp 1993; Sabones et al. 1996; Wolf et al. 1996; Wolf 1998; Calianese et al. 2002; Sieveking and Przybylinski 2004; French 2017). Goodman and Knupp (1993) found that tornado formation and intensification were preceded by a QLCS-supercell merger, suggesting that interaction of the QLCS gust front with the supercell rear flank downdraft (RFD) may have contributed to tornadogenesis through enhanced convergence and baroclinity, resulting in increased tilting, amplification, and generation of vorticity (similar to RFD internal surges in supercells; e.g., Lee et al. 2012; Kosiba et al. 2013; Schenkman et al. 2014). In a comparison of tornadic and nontornadic merger case studies, French (2017) showed that QLCS-supercell mergers can have both constructive and destructive effects on

tornadogenesis. However, these past studies focus primarily on the role of mergers in severe weather hazards like tornadoes and damaging straight-line winds, leaving open questions about their impacts on above-surface storm-scale features.

Some of these observational studies and some simulation studies have examined the influence of QLCS-supercell mergers on storm morphology. Most of these have found that the supercell becomes the new leading edge of the QLCS while a prominent bowing segment develops south of the merged mesocyclone (e.g., Goodman and Knupp 1993; Wolf et al. 1996; Wolf 1998; French and Parker 2012b, 2014; French 2017). In French and Parker (2012b), two predominant evolutionary patterns of QLCS-supercell merger systems were found: a system-scale bowing pattern, where the supercell becomes the line-end vortex at the northern end of a large bow echo, and an embedded bowing pattern, where the supercell becomes the northern end of a smaller embedded bowing segment that develops within the QLCS. In idealized simulations of QLCS-supercell mergers, French and Parker (2014) found that bow echo and severe wind development arose from a combination of localized cold pool strengthening due to increased precipitation, a strong descending rear-inflow jet resulting from downward buoyancy-induced pressure perturbation accelerations, and outflow enhancement by intense counter-rotating line-end vortices. These features were not present in a non-merging QLCS simulation, indicating that the processes for bow echo formation were instigated and amplified by the merger. An earlier qualitative analysis of vorticity evolution in a simulated merger by French and Parker (2012a) suggested that the supercell’s RFD forced the QLCS rear-inflow jet to the surface, forming a region of strong vertical wind shear and horizontal vorticity where an intense low-level vortex then developed out of the remnant mesocyclone. They speculated that updraft tilting of the horizontal vorticity was an important driver for the formation of this vortex, and that

these processes were directly resultant from the merger. However, none of these studies have performed a quantitative analysis of storm-scale vortex evolution and rotation mechanisms in mergers.

There is a need for more detailed study on the influence of QLCS-supercell mergers on storm-scale processes specifically relating to the generation, intensity, and evolution of rotation. Motivated by the findings from French and Parker (2012a) and French and Parker (2014), this work will use idealized simulations to address the following questions regarding storm-scale vortex characteristics and processes in QLCS-supercell mergers:

1. How do vortex characteristics evolve during a QLCS-supercell merger, and how do they compare to vortex characteristics in an isolated supercell or QLCS?
2. What processes drive the evolution of rotation in a QLCS-supercell merger?

This study will primarily focus on how these characteristics and processes change before and after the merger with the goal of determining the nature of low-level vortex formation and maintenance mechanisms in a merger—i.e., whether these mechanisms are analogous to supercell mesocyclone processes, QLCS mesovortex processes, or potentially a combination of both.

2.2 Data and methods

2.2.1 Model setup

This work uses Cloud Model 1 (CM1; Bryan et al. 2003) release 19.5 to simulate a QLCS-supercell merger (“MERGER”), a control QLCS without the merging supercell (“QLCSONLY”), and an isolated supercell (“SUPERCELL”). A uniform horizontal grid spacing of 125 m was used across the full 360 km $\times$ 360 km $\times$ 15.08 km grid to

resolve storm-scale features. The vertical grid spacing is stretched from 20 m in the lowest 300 m to 280 m above 12 km. Lateral boundary conditions are open radiative in x and periodic in y , and the bottom boundary is semi-slip. More details on the model setup are given in Table 2.1.

Table 2.1: CM1 model configuration parameters.

Parameter	Description
Domain extent	$360 \text{ km} \times 360 \text{ km} \times 15.08 \text{ km}$
Horizontal grid	$\Delta x = \Delta y = 125 \text{ m}$
Vertical grid	104 scalar levels starting at 10 m $\Delta z = 20 \text{ m}$ below 300 m, stretched to 280 m
Microphysics	NSSL two-moment (Ziegler 1985; Mansell 2010; Mansell et al. 2010)
Subgrid-scale	TKE (Deardorff 1980)
Lateral boundaries	Open radiative x , periodic y
Bottom boundary	Semi-slip with $C_D = 0.0014$ (Coffer and Parker 2017)

In the MERGER and QLCSONLY simulations, the QLCS was initialized at 0 s by a cold dam at $x = -125 \text{ m}$ with a depth of 4000 m and minimum θ' of -8 K to emulate linearly forced convection initiation. In the MERGER and SUPERCELL simulations, the supercell was initialized 85 km ahead of the QLCS using the tendency nudging technique from Flournoy and Rasmussen (2023) over the first 3600 s of the simulation. The tendency nudging area was an oblate bubble centered at 3500 m above the surface, with a horizontal radius of 5000 m and vertical radius of 1500 m. Heating tendency was maximized at the center of the bubble and decreased outward toward the edges. Between 0–1800 s, the heating tendency S ramped up linearly from 0 K s^{-1} to a maximum magnitude of $S_0 = 0.021 \text{ K s}^{-1}$, was held constant at

S_0 for 1 s, then ramped down linearly back to 0 K s⁻¹ between 1801–3600 s (Fig. 2.1). Tendency nudging was used for supercell initiation instead of a traditional warm bubble to emulate gradual, time-varying forcing and mitigate premature tornado-like vortex development (Flournoy and Rasmussen 2023). In the MERGER simulation, both initialization methods were employed simultaneously to generate a QLCS and a supercell in the same domain.

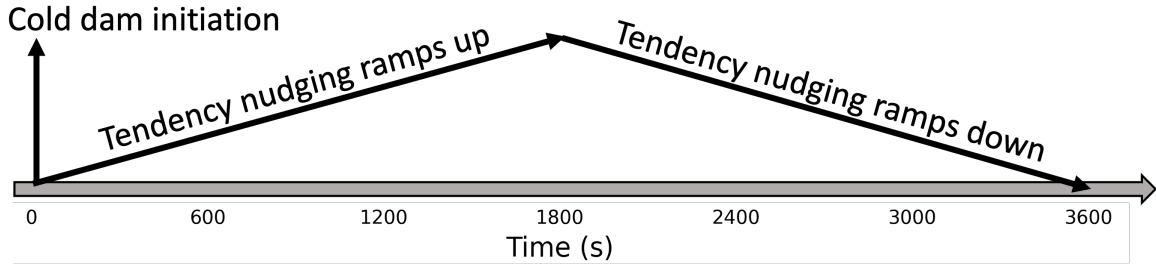


Figure 2.1: Timeline of convection initialization for the cold dam and tendency nudging techniques.

The base state environment was an observed environmental sounding from the Propagation, Evolution, and Rotation in Linear Storms (PERiLS) field campaign (Kosiba et al. 2024). The sounding was collected by the National Severe Storms Laboratory mobile sounding facility at 1959 UTC on 30 March 2022 (Waugh 2023). Simulations were initialized with random surface θ perturbations of ± 0.25 K or smaller throughout the domain. Additionally, a Coriolis acceleration was applied to the perturbation winds with $f = 0.8 \times 10^{-4}$ s⁻¹. Because both the semi-slip bottom boundary and Coriolis acceleration result in gradual changes in the low-level base state wind profile, the environmental profile was first simulated in a dry run with the same configuration as in Table 2.1 to obtain a quasi-steady state low-level wind profile, as in Coffey and Parker (2017). The resulting environmental profile after 4 h was then used as the base state for all three simulations (Fig. 2.2). This profile is representative of high-shear, low-CAPE (HSLC) environments frequently associated with severe thunderstorms in

the southeastern United States (Schneider et al. 2006; Thompson et al. 2012; Davis and Parker 2014; Sherburn and Parker 2014; Anderson-Frey et al. 2016).

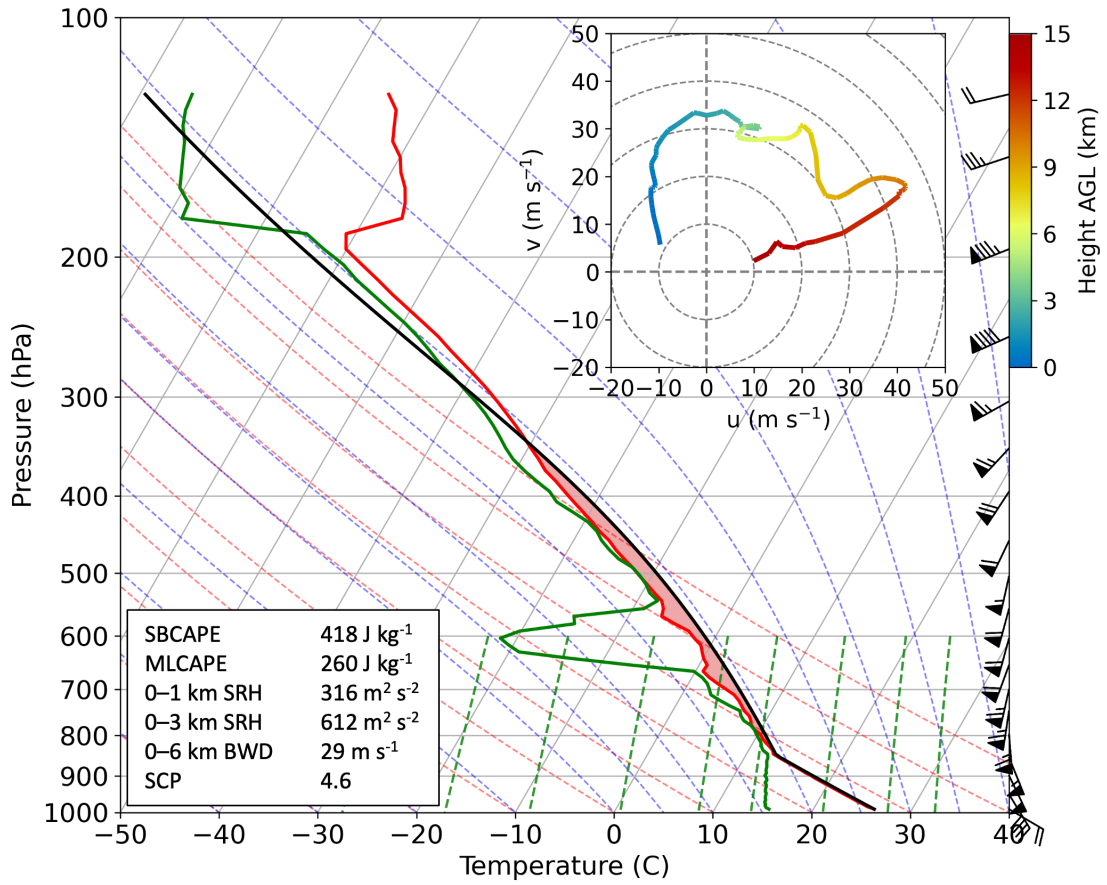


Figure 2.2: Skew T -log p diagram and hodograph of the quasi-steady base state environmental profile beginning at the 10-m AGL vertical level. Select environmental thermodynamic and kinematic parameters are listed.

2.2.2 Vortex identification and trajectory analysis

Low-level storm-scale rotation was quantified using the Okubo-Weiss parameter (OW; Okubo 1970; Weiss 1991), given by

$$\text{OW} = \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 - \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)^2, \quad (2.1)$$

where u and v are the x and y components of velocity, respectively. OW is used to isolate rotation from deformation in the flow field, and is negative where rotation is more significant than deformation. The criteria for vortices used here are modified from the criteria used in Sherburn and Parker (2019) and Lovell and Parker (2022) for identifying vortices in QLCSs simulated in HSLC environments. Here, mesocyclones and mesovortices are considered to be contiguous regions of maximum vertical velocity $w \geq 5 \text{ m s}^{-1}$ and minimum OW $\leq -0.001 \text{ s}^{-2}$ within at least the lowest 1 km AGL. Identification and tracking of vortices was done subjectively.

To analyze the evolution of storm-scale processes in the MERGER mesocyclone, parcel trajectories were initialized in CM1 from a restart at 180 min and integrated forward in time for one hour, with initial parcel positions ahead of the merger location in all three simulations. Parcels were spaced every 200 m horizontally and every 50 m vertically from 10 m to 2000 m AGL. A total of 5,000,000 parcels were initialized in the MERGER and QLCSONLY simulations, and 1,600,000 in the SUPERCELL simulation. Parcels are defined as being in a low-level mesocyclone at a given time if they have (1) height of $100 \text{ m} \leq z \leq 1000 \text{ m AGL}$, (2) vertical velocity $w \geq 5 \text{ m s}^{-1}$, and (3) vertical vorticity $\zeta \geq 0.01 \text{ s}^{-1}$, and (4) are within a $10 \text{ km} \times 10 \text{ km}$ box surrounding the subjectively identified low-level mesocyclone. Horizontal vorticity components are interpolated from the model grid to parcel locations. This includes the

x and y components of vorticity (ξ and η , respectively); horizontal vorticity magnitude $|\boldsymbol{\omega}_H|$, given by

$$|\boldsymbol{\omega}_H| = \sqrt{\xi^2 + \eta^2}; \quad (2.2)$$

and streamwise (ω_{SW}) and crosswise (ω_{CW}) vorticity, given by

$$\omega_{SW} = \frac{u_{SR}}{|\mathbf{V}_{SR}|} \xi + \frac{v_{SR}}{|\mathbf{V}_{SR}|} \eta \quad (2.3)$$

and

$$\omega_{CW} = \frac{v_{SR}}{|\mathbf{V}_{SR}|} \xi - \frac{u_{SR}}{|\mathbf{V}_{SR}|} \eta, \quad (2.4)$$

where $\mathbf{V}_{SR}$ is the storm-relative parcel velocity vector and u_{SR} and v_{SR} are the x and y components of $\mathbf{V}_{SR}$.

Vorticity tendency terms are calculated from model output to infer vorticity generation processes for parcels ingested into the MERGER mesocyclone. These calculations are based on the vorticity budget calculations from Boyer and Dahl (2020), but they are not integrated due to limitations from the model configuration. The tendency budgets for ξ , η , and ζ are given as

$$\frac{d\xi}{dt} = \underbrace{\left(\xi \frac{\partial u}{\partial x} \right)}_{\text{Stretching}} + \underbrace{\left(\eta \frac{\partial u}{\partial y} + \zeta \frac{\partial u}{\partial z} \right)}_{\text{Tilting}} + \underbrace{\frac{1}{\rho^2} \left(\frac{\partial \rho}{\partial y} \frac{\partial p}{\partial z} - \frac{\partial \rho}{\partial z} \frac{\partial p}{\partial y} \right)}_{\text{Baroclinic generation}} + \underbrace{\left(\frac{\partial F_z}{\partial y} - \frac{\partial F_y}{\partial z} \right)}_{\text{Turbulence/Diffusion}}, \quad (2.5)$$

$$\frac{d\eta}{dt} = \underbrace{\left(\eta \frac{\partial v}{\partial y} \right)}_{\text{Stretching}} + \underbrace{\left(\xi \frac{\partial v}{\partial x} + \zeta \frac{\partial v}{\partial z} \right)}_{\text{Tilting}} + \underbrace{\frac{1}{\rho^2} \left(\frac{\partial \rho}{\partial z} \frac{\partial p}{\partial x} - \frac{\partial \rho}{\partial x} \frac{\partial p}{\partial z} \right)}_{\text{Baroclinic generation}} + \underbrace{\left(\frac{\partial F_x}{\partial z} - \frac{\partial F_z}{\partial x} \right)}_{\text{Turbulence/Diffusion}}, \quad (2.6)$$

and

$$\frac{d\zeta}{dt} = \underbrace{\left(\zeta \frac{\partial w}{\partial z} \right)}_{\text{Stretching}} + \underbrace{\left(\xi \frac{\partial w}{\partial x} + \eta \frac{\partial w}{\partial y} \right)}_{\text{Tilting}} + \underbrace{\frac{1}{\rho^2} \left(\frac{\partial \rho}{\partial x} \frac{\partial p}{\partial y} - \frac{\partial \rho}{\partial y} \frac{\partial p}{\partial x} \right)}_{\text{Baroclinic generation}} + \underbrace{\left(\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y} \right)}_{\text{Turbulence/Diffusion}}. \quad (2.7)$$

where u , v , w , ξ , η , and ζ are as above, ρ is density, p is pressure, and $\mathbf{F}$ represents diffusion and subgrid-scale turbulence. The effect of each term on overall horizontal vorticity generation or destruction can be determined by substituting the terms from Eqs. 2.5 and 2.6 into the following equation for $|\boldsymbol{\omega}_H|$ tendency, given as

$$\frac{d|\boldsymbol{\omega}_H|}{dt} = \frac{1}{|\boldsymbol{\omega}_H|} \left(\xi \frac{d\xi}{dt} + \eta \frac{d\eta}{dt} \right). \quad (2.8)$$

Because the vorticity budgets are not integrated, the evolution of horizontal and vertical vorticity generation processes is examined in a primarily qualitative analysis.

2.3 Results

2.3.1 Mesocyclone evolution

All three simulations have mature storms with persistent updrafts and low-level rotation by 180 min. The QLCSONLY simulation has a mature slab updraft and shallow, transient low-level vortices along the leading edge of the cold pool, with intense convective precipitation and several small bowing segments along the line (center column, Figs. 2.3 and 2.4). The convective intensity of the QLCS remains relatively steady throughout the 1-h analysis time period—there are no marked increases in updraft speeds, precipitation intensity, cold pool strength, or low-level vortex formation and persistence. The SUPERCELL simulation also has a persistent low-level updraft and developing rotation by 180 min (right column, Figs. 2.3 and 2.4). The low-level rotation and rear-flank cold pool in the supercell continually strengthen between 180 and 240 min, with a large, intense low-level mesocyclone developing by 225 min.

As in the two control simulations, both the QLCS and supercell in the MERGER simulation have persistent updrafts and low-level rotation by 180 min, with the merger

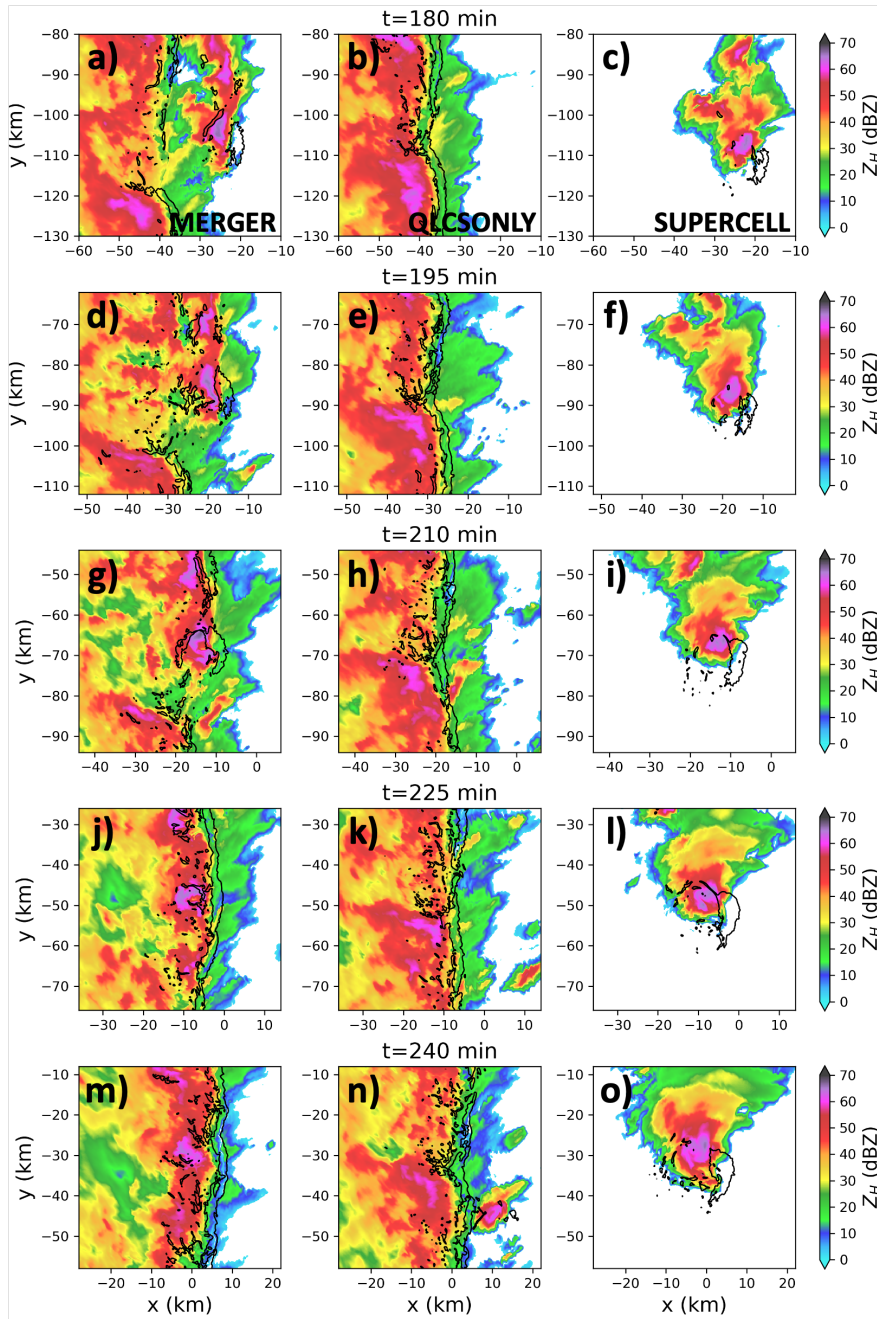


Figure 2.3: Simulated radar reflectivity at the lowest model level for the MERGER (left column), QLCSONLY (center column), and SUPERCELL (right column) simulations at (a)–(c) 180 min, (d)–(f) 195 min, (g)–(i) 210 min, (j)–(l) 225 min, and (m)–(o) 240 min. Black contours denote maximum $0-1$ km $w = 5$ m s $^{-1}$.

occurring at 210 min (left column, Figs. 2.3 and 2.4). Evolution of the MERGER

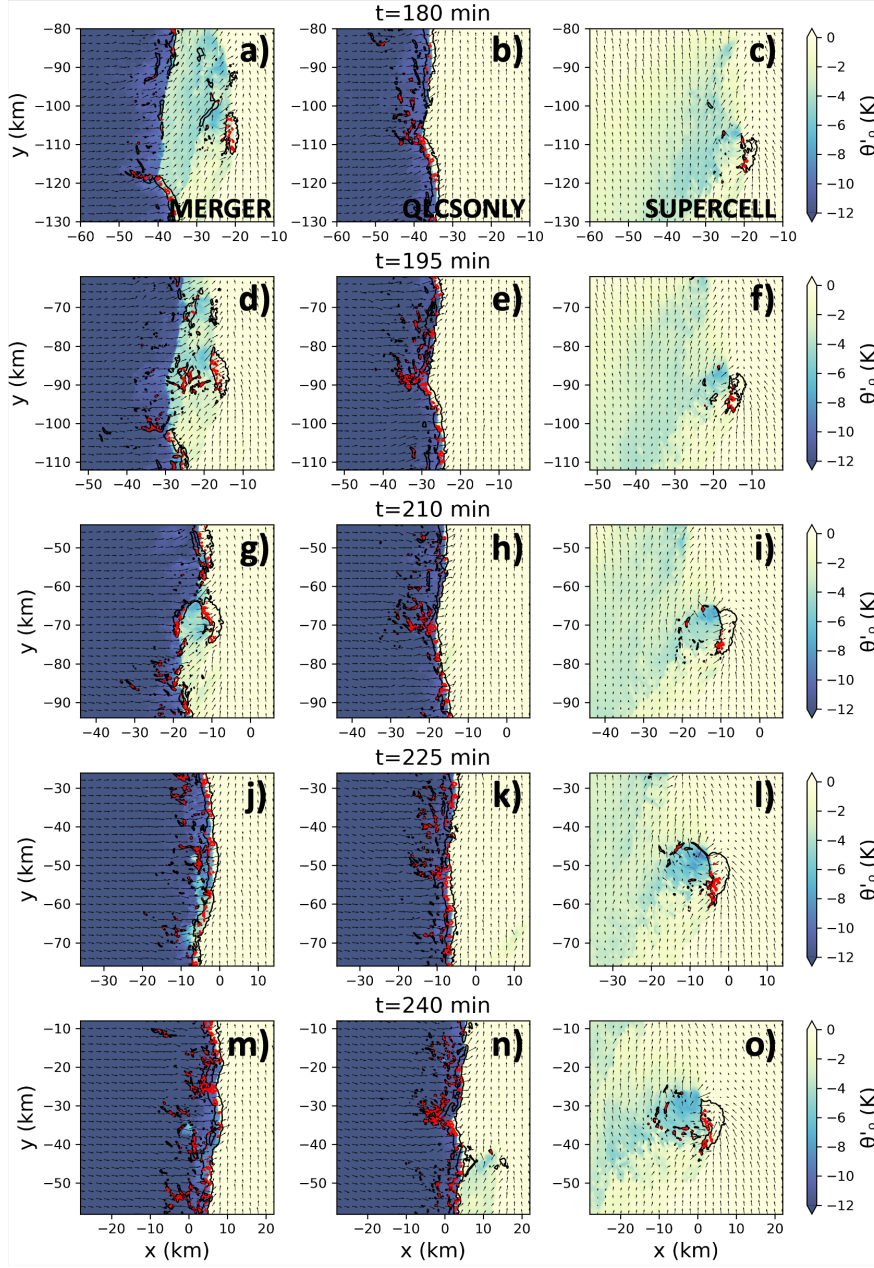


Figure 2.4: As in Fig. 2.3, but with θ'_p at the lowest model level shaded. Black contours denote maximum 0–1 km $w = 5 \text{ m s}^{-1}$, and pink contours denote minimum 0–1 km $OW = -0.001 \text{ s}^{-2}$. Ground-relative wind vectors at the lowest model level are plotted every 22 grid points.

simulation is very similar to the evolution of QLCS-supercell mergers in previous studies (Goodman and Knupp 1993; French and Parker 2012b, 2014). Compared to the

QLCSONLY, the portion of the MERGER QLCS behind the leading supercell initially has less intense precipitation, a much weaker updraft, and few vortices along its leading edge. The decline in convective intensity (Fig. 2.3a,d) and weakening of the θ'_p gradient (Fig. 2.4a,d) continues as the QLCS updraft encounters the supercell cold pool, as observed in Goodman and Knupp (1993) and French and Parker (2014). The MERGER supercell is initially more intense than the SUPERCELL simulation, with a broader low-level updraft and rotation. When the supercell merges with the approaching QLCS at 210 min, it becomes the new leading edge of the convective line and the northern portion of a large developing bow echo (Fig. 2.3g). The remnant supercell remains the most intense portion of the line after the merger, and low-level vortices develop and intensify rapidly along the leading edge of the bow echo (Fig. 2.4j,m). The QLCSONLY simulation does not exhibit this large bowing segment or rapid formation of low-level vortices. These differences between the MERGER, QLCSONLY, and SUPERCELL simulations imply that the QLCS-supercell interaction influences both pre-merger supercell evolution and post-merger low-level vortex production.

The vertical structure and temporal evolution of the MERGER and SUPERCELL mesocyclones and a QLCSONLY mesovortex are shown in Fig. 2.5 to characterize the impacts of the merger on the vertical structure of the merging mesocyclone. The MERGER pre-merger supercell develops a low-level mesocyclone beginning at 190 min, with w reaching 10 m s^{-1} below 200 m AGL and 15 m s^{-1} at 500 m AGL (Fig. 2.5a). The MERGER mesocyclone then intensifies rapidly during and after the merger, especially in the mid levels where updraft speeds strengthen to $w > 20 \text{ m s}^{-1}$ and rotation intensifies rapidly to $\text{OW} < -1.2 \text{ s}^{-2}$. At 225 min, the mid-level updraft begins to weaken, but enhanced OW persists at both low and mid levels through the end of the 1-h period. For consistency in describing the MERGER simulation,

“mesocyclone” is used to refer to the remnant post-merger mesocyclone even after the supercell merges with the QLCS.

Before 210 min, the QLCSONLY mesovortex initially has stronger low-level OW, but rotation is very shallow (~ 1 km deep) and transient, and updraft speeds throughout the lowest 4 km are consistently the weakest of all three simulations (Fig. 2.5b). The overall intensity of the QLCSONLY mesovortex does not change significantly at any point during the 1-h time period. In contrast, the SUPERCELL mesocyclone shows steady intensification comparable to the MERGER mesocyclone, but there are clear differences in their evolution. Intensification of the mid-level SUPERCELL mesocyclone tends to lag ~ 5 – 10 min behind that of the mid-level MERGER mesocyclone, as SUPERCELL mesocyclone updraft speeds above 2 km do not reach $w > 20 \text{ m s}^{-1}$ until around 215 min (Fig. 2.5c). While rotation above 2 km in the SUPERCELL mesocyclone rapidly strengthens to $\text{OW} < -1.2 \text{ s}^{-2}$ at 190 min (~ 30 min earlier than the MERGER mesocyclone), it quickly weakens after 200 min and does not redevelop until around 230 min. This early mid-level rotation is somewhat present in the MERGER mesocyclone as well, but is much weaker than in the SUPERCELL simulation. The SUPERCELL simulation does not develop a substantial low-level mesocyclone until around 215 min. While a low-level updraft develops in the SUPERCELL simulation around 195 min, there is little low-level rotation until 215 min, and the overall intensity of the SUPERCELL low-level mesocyclone is not comparable to the MERGER low-level mesocyclone until nearly 230 min.

The earlier intensification of the low-level MERGER mesocyclone is similar to results from French (2014), which found that a supercell ahead of an approaching QLCS had increased low-level vorticity compared to an isolated supercell due to QLCS-induced environmental perturbations. The differences between MERGER and SUPERCELL mesocyclone evolution suggest that an approaching QLCS can modulate

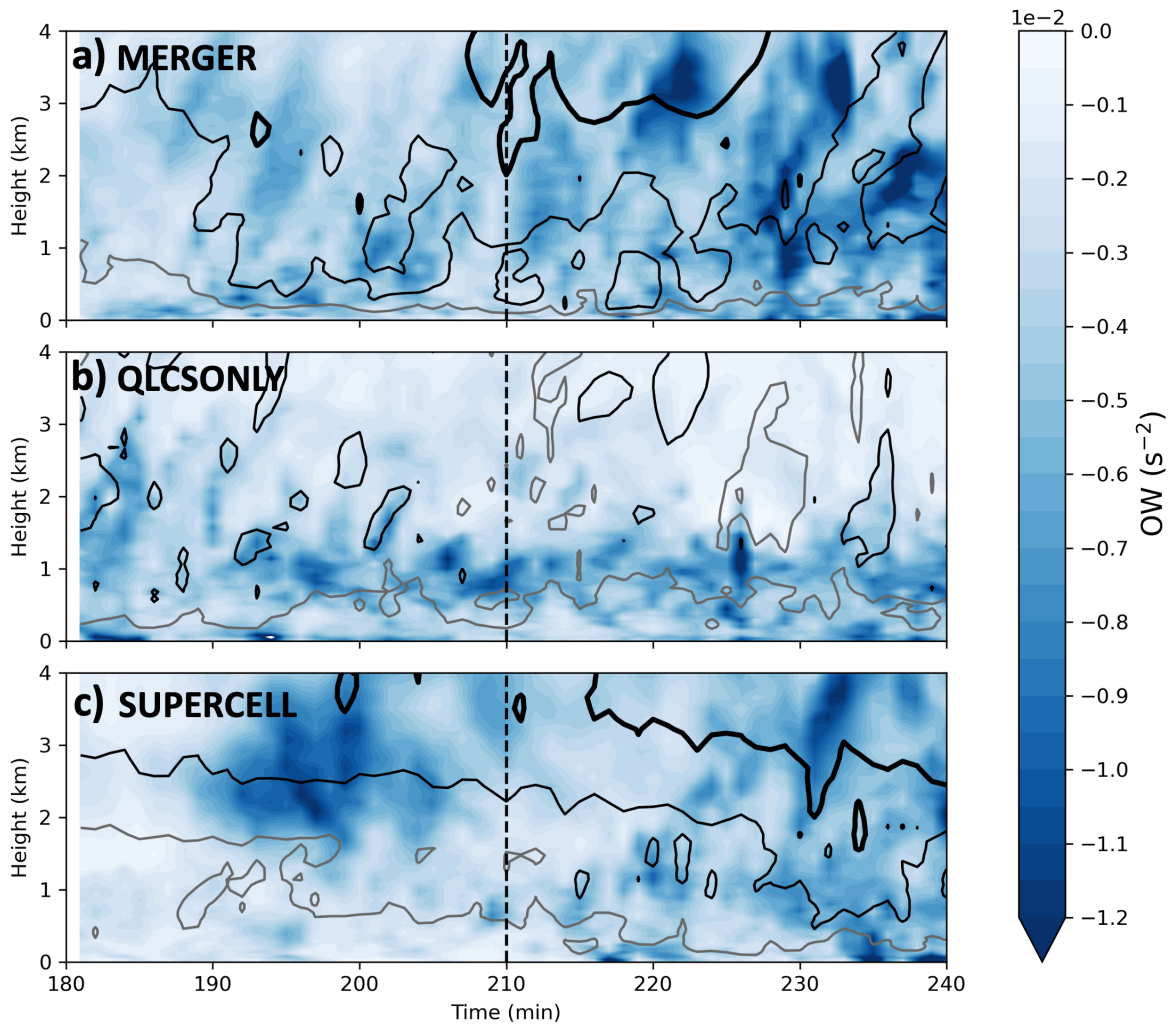


Figure 2.5: Time-heights of minimum OW (s^{-2} ; shaded) in $10 \text{ km} \times 10 \text{ km}$ boxes following (a) the MERGER pre- and post-merger mesocyclone, (b) a QLCSONLY mesovortex, and (c) the SUPERCELL mesocyclone. Maximum w is contoured in black at the 10 m s^{-1} (thin gray), 15 m s^{-1} (thin black), and 20 m s^{-1} (thick black) levels. The vertical dashed line at 210 min denotes the time of the merger. For the QLCSONLY mesovortex, the boxes follow the y position of the MERGER mesocyclone boxes, but are adjusted in the x direction to the position of the QLCSONLY leading edge.

the characteristics of a nearby supercell, and that unique physical processes associated with Q LCS-supercell mergers may further modify storm evolution. Importantly, Fig. 2.5 shows that the QLCSONLY mesovortex is persistently weaker and shallower than the MERGER mesocyclone, while the SUPERCELL mesocyclone eventually exhibits

comparable depth and intensity. The characteristics and evolution of the MERGER mesocyclone appear overall more similar to a supercell mesocyclone than a QLCS mesovortex.

The evolution of low- and mid-level mesocyclone intensity throughout the merger can be quantified using updraft helicity (UH) for further comparisons between simulations (Figs. 2.6 and 2.7). Before 210 min, the MERGER low-level mesocyclone is consistently more intense than the SUPERCELL low-level mesocyclone, with 0–2 km UH centered around $\sim 750 \text{ m}^2 \text{ s}^{-2}$ and occasionally exceeding $1000 \text{ m}^2 \text{ s}^{-2}$ while the SUPERCELL mesocyclone only reaches $\sim 650 \text{ m}^2 \text{ s}^{-2}$ (Fig. 2.6a). The larger 0–2 km UH in the MERGER mesocyclone is a result of its stronger low-level rotation and updraft (Fig. 2.5a,c). The MERGER and SUPERCELL mid-level mesocyclones are more comparable in strength before 188 min and between 198–208 min; however, the MERGER mesocyclone spikes to much larger 2–5 km UH magnitudes ($\sim 1400 \text{ m}^2 \text{ s}^{-2}$) than the SUPERCELL mesocyclone ($\sim 850 \text{ m}^2 \text{ s}^{-2}$) between 188–198 min (Fig. 2.7a), despite the SUPERCELL having stronger rotation above 2 km AGL during this time (Fig. 2.5c). The larger 2–5 km UH in the MERGER mesocyclone can be attributed to the stronger mid-level updraft speeds in the pre-merger supercell. These differences further support the potential role of QLCS-supercell mergers in modifying pre-merger supercell evolution. Between 208–210 min, the MERGER mesocyclone strengthens in both low and mid levels as it begins to merge with the QLCS, with the mid-level mesocyclone intensifying dramatically. Unsurprisingly, the pre-merger portion of the MERGER QLCS has much weaker 0–2 km and 2–5 km UH than the QLCSONLY mesovortex before 210 min (less than $500 \text{ m}^2 \text{ s}^{-2}$) due to the interaction of the MERGER QLCS with the supercell cold pool (Figs. 2.6b and 2.7b).

The MERGER mesocyclone is much stronger than both the SUPERCELL mesocyclone and QLCSONLY mesovortex immediately after the merger. In the 5 min

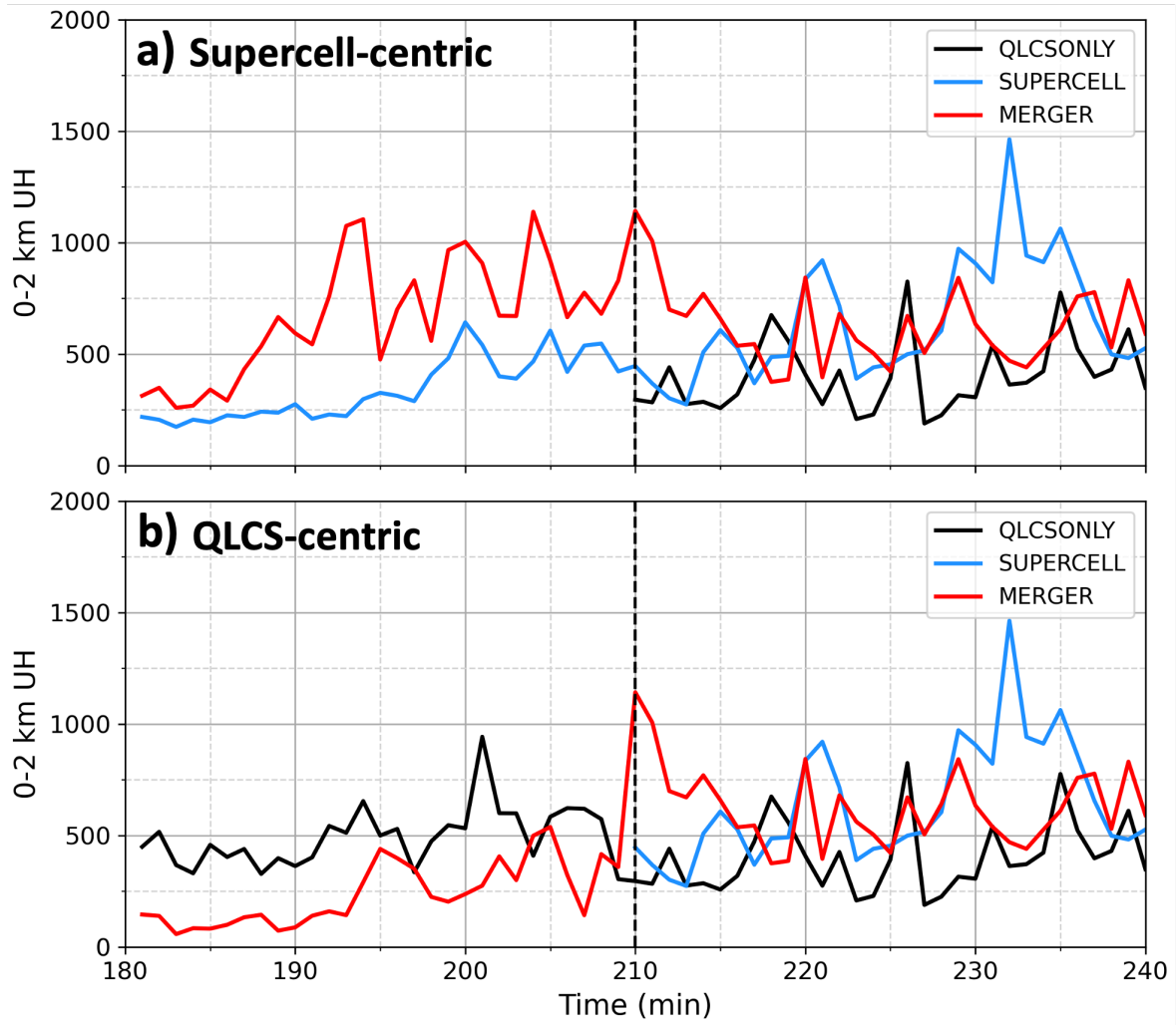


Figure 2.6: Time series of maximum 0–2 km UH for the MERGER pre- and post-merger mesocyclone (red), QLCSONLY mesovortex (black), and SUPERCELL mesocyclone (blue) following the same $10 \text{ km} \times 10 \text{ km}$ boxes as described in Fig. 2.5, except for the following difference: Before 210 min, the MERGER line in (a) follows the pre-merger mesocyclone as in Fig. 2.5a, while the MERGER line in (b) follows the segment of the pre-merger QLCS that merges with the supercell. After 210 min, both panels show the same post-merger UH time series for MERGER because the merged mesocyclone becomes the new leading edge of the MERGER QLCS. The QLCSONLY and SUPERCELL time series are the same in both panels. The vertical dashed line at 210 min denotes the time of the merger.

following the merger, the merged mesocyclone peaks at $1200 \text{ m}^2 \text{ s}^{-2}$ of 0–2 km UH and nearly $1800 \text{ m}^2 \text{ s}^{-2}$ of 2–5 km UH. After 215 min, the MERGER mesocyclone weakens

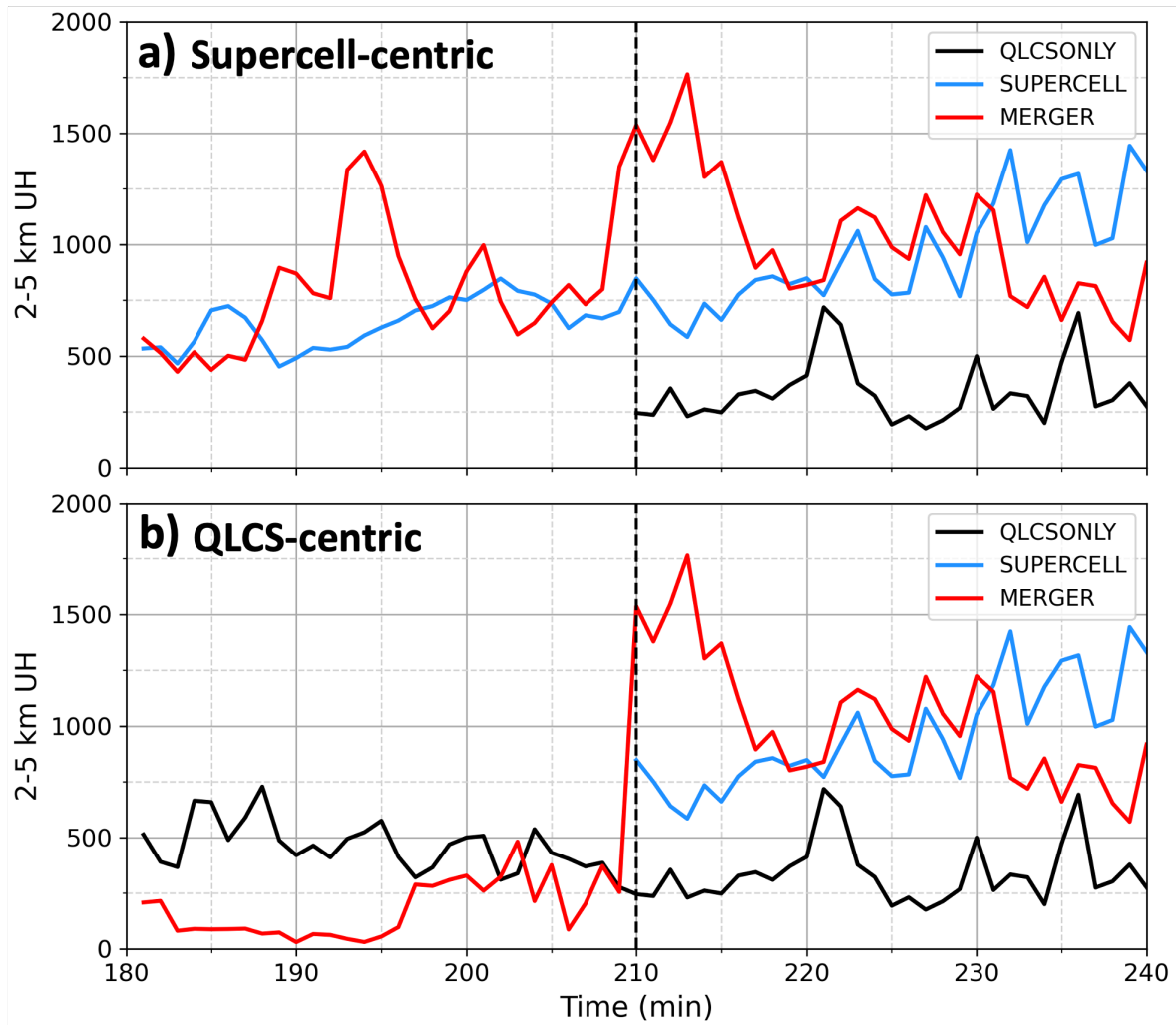


Figure 2.7: As in Fig. 2.6, but for maximum 2–5 km UH.

in the low levels and becomes comparable in strength to the SUPERCELL mesocyclone, while remaining slightly stronger than the QLCSONLY mesovortex (Fig. 2.6). In the mid levels, the MERGER mesocyclone also weakens by 220 min to the same strength as the SUPERCELL mesocyclone, but is much stronger than the QLCSONLY mid-level mesovortex (Fig. 2.7). The MERGER and SUPERCELL mesocyclones have similar intensity in both low and mid levels until the SUPERCELL mesocyclone begins to rapidly intensify around 230 min. During this time, the MERGER mesocyclone

remains slightly stronger than the QLCSONLY mesovortex in the low levels and substantially stronger in the mid levels.

The MERGER mesocyclone intensity after the merger is generally more comparable to the SUPERCELL mesocyclone than the QLCSONLY mesovortex at both low and mid levels. This suggests that the MERGER mesocyclone retains its pre-merger structure and characteristics, with the merged mesocyclone becoming an embedded supercell-like structure within the QLCS rather than being “absorbed” and transitioning to a more typical QLCS mesovortex. This is consistent with findings from French and Parker (2012b) for mergers occurring in strongly forced environments and with the simulated merger evolution in French and Parker (2012a). The difference is far more pronounced in the mid levels, where the much larger 2–5 km UH in the MERGER mesocyclone implies deeper supercell-like updraft rotation rather than the shallower rotation of QLCS mesovortices. In contrast, the smaller differences in 0–2 km UH of the MERGER mesocyclone and QLCSONLY mesovortex suggest a more similar intensity in low levels. All of these results raise two questions: (1) Do the overall supercell-like characteristics of the MERGER mesocyclone mean that the dynamics of the MERGER mesocyclone are also more supercell-like? (2) Do the differences in low- and mid-level MERGER mesocyclone evolution imply the presence of both QLCS-like and supercell-like processes in the post-merger mesocyclone?

2.3.2 Trajectory and vorticity analysis

To assess the evolution of processes related to low-level rotation, we examine how bulk trajectory characteristics vary during the analysis period, starting with identifying the source regions of parcels in the low-level mesocyclone at various times as defined in Section 2.2.2. Source regions were determined based on their starting height and buoyancy at 180 min. In the MERGER, there are four distinct source regions that

evolve over the course of the merger (Fig. 2.8). Parcels entering the pre-merger supercell low-level mesocyclone at 200 min originate from low-level environmental inflow and the supercell’s forward-flank outflow (Fig. 2.8a,d,g). By 210 min, two additional source regions emerge (Fig. 2.8b,e,h). One is a mid-level environmental inflow stream originating from the environment aloft (around 1.5 km AGL) and south of the merger location. The other is the QLCS outflow, with parcels from near the surface within the QLCS cold pool entering the merged mesocyclone from the rear. The QLCS outflow source becomes increasingly dominant over time, and the mid-level parcel source remains present for at least 10 minutes after the merger (Fig. 2.8c,f,i). The total number of parcels in the low-level mesocyclone at 200, 210, and 220 min is given in Table 2.2, along with the number of parcels from each source region.

Table 2.2: Number of parcels in the MERGER low-level mesocyclone at 200 min, 210 min, and 220 min.

Time	Total	Low-level inflow	Mid-level inflow	Supercell outflow	QLCS outflow
200 min	1548	1370 (88.5%)	0	178 (11.5%)	0
210 min	708	539 (76.1%)	65 (9.2%)	96 (13.6%)	8 (1.1%)
220 min	350	132 (37.7%)	51 (14.6%)	26 (7.4%)	141 (40.3%)

By comparison, mesovortices in QLCSONLY have only two source regions of three possible, excluding supercell outflow (not shown): low-level environmental inflow and QLCS outflow. The QLCSONLY parcel source regions do not show appreciable changes throughout the 20-min period. The SUPERCELL mesocyclone has all three possible source regions, excluding QLCS outflow (not shown): low-level environmental inflow, mid-level environmental inflow, and low-level outflow. Parcels entering the SUPERCELL mesocyclone from both the low-level inflow and low-level outflow sources are

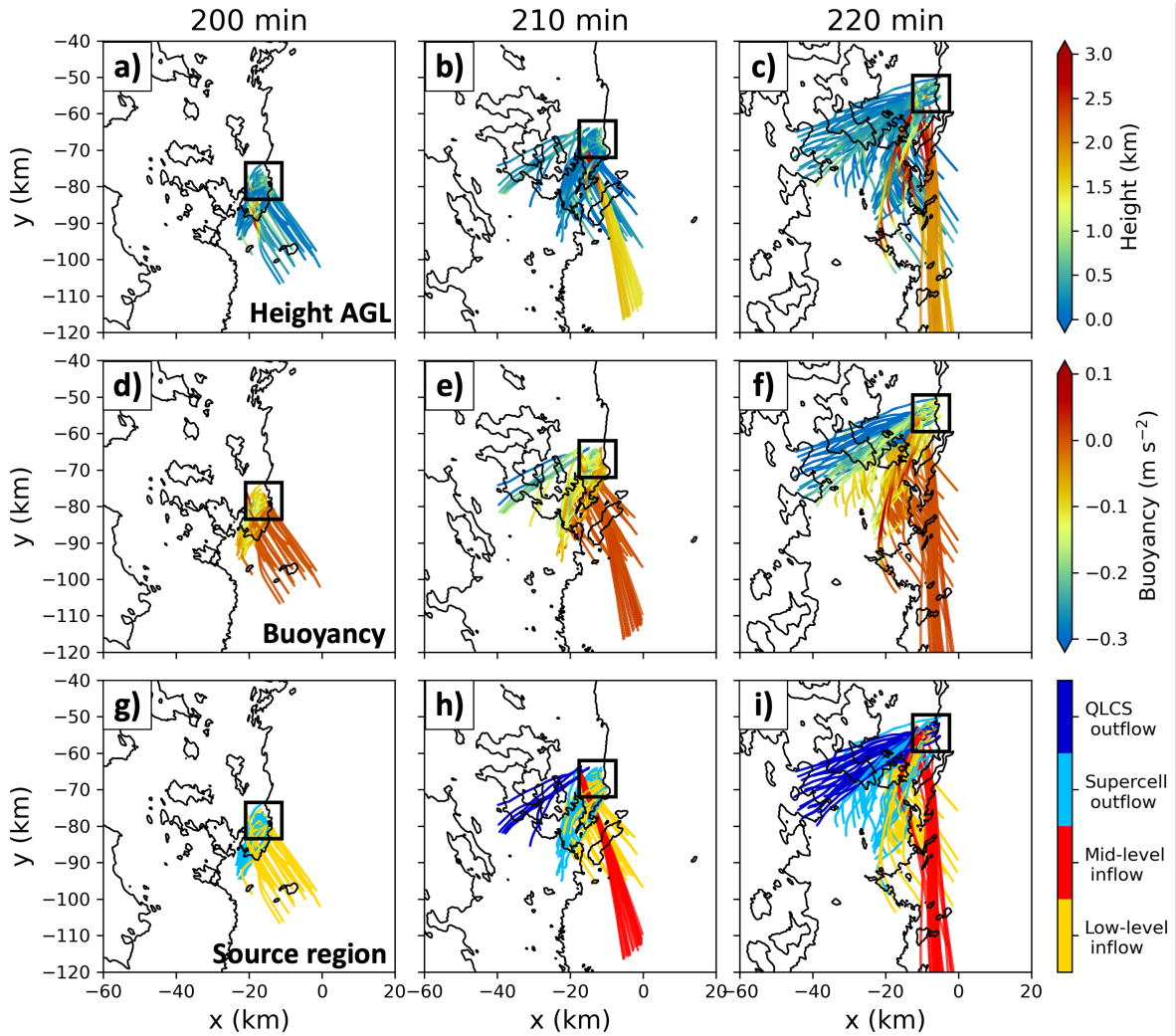


Figure 2.8: Trajectories of all parcels in the MERGER mesocyclone at 200 min (left), at 210 min (center), and at 220 min (right). The trajectories are shaded by (a)–(c) height AGL z (km), (d)–(f) parcel thermal buoyancy B (m s^{-2}), and (g)–(i) source region. Source regions are colored as low-level inflow (gold), mid-level inflow (red), supercell outflow (light blue), and QLCS outflow (dark blue).

present throughout the 20-min period, while the mid-level inflow source does not appear until 220 min when the mid-level mesocyclone begins to intensify. The mid-level inflow source that develops around the time of mid-level intensification is yet another similarity between the MERGER and SUPERCELL mesocyclones, which further supports the persistence of supercellular characteristics after the merger. This could also

reflect supercell-like mechanisms for the development and intensification of rotation in the merged mesocyclone. Given our focus on the evolution of low-level rotation in the MERGER simulation, and because that simulation features the most source regions and greatest variability during the analysis period, we focus on trajectory analysis of the MERGER simulation for the remainder of the chapter. Time series of the characteristics of parcels entering the pre-merger mesocyclone at 200 min and the merged mesocyclone at 210 and 220 min are shown in Fig. 2.9 for further analysis.

The low-level inflow and supercell outflow parcels in the MERGER mesocyclone maintain relatively steady characteristics over time, along with the QLCS outflow parcels when they are present after the merger. Most low-level inflow and supercell outflow parcels entering the pre-merger mesocyclone at 200 min remain close to the surface before beginning rapid ascent around 198 min, with some parcels briefly undergoing weak ascent and descent before entering the updraft (Fig. 2.9a,g). Low-level inflow parcels feature very small magnitudes of ζ until they ascend rapidly (Fig. 2.9j). Supercell outflow parcels have predominantly negative ζ between 186–193 min, which becomes positive during ascent around 195 min and negative again during descent around 197 min; however, median ζ magnitudes remain small until the rapid ascent after 198 min. Parcels entering the merged mesocyclone at 210 min and 220 min from these two source regions largely exhibit the same behavior; the same is true for the new QLCS outflow source region for parcels entering the mesocyclone at 210 and 220 min. In Fig. 2.9h,i,k,l, parcels from the low-level inflow and both outflow sources generally have small or near-zero ζ magnitudes until beginning their rapid ascent, with some parcels gaining more substantial negative ζ during brief descent.

The evolution of parcels in the mesocyclone at 210 min suggests this period of brief descent may be an important stage for ζ generation (Fig. 2.9h,k). Low-level inflow and supercell outflow parcels descend and gain substantial negative ζ around 208 min,

while Q LCS outflow parcels do not. By 210 min, the parcels that descended have much larger cyclonic ζ magnitudes than the parcels that did not—nearly twice the magnitude. These differences are also present leading up to 220 min, though less pronounced (Fig. 2.9i,l). At all stages of the merger, ζ generation is most significant during rapid ascent into the mesocyclone, implying that updraft processes (e.g., horizontal vorticity tilting and ζ stretching) are the most important factor in the generation of cyclonic ζ for parcels that originate in low levels. However, the negative ζ generated in some parcels during periods of descent and resulting enhanced positive ζ in the mesocyclone suggests that downdraft processes may still have an important role in cyclonic ζ generation and intensification.

The evolution of mid-level inflow parcel characteristics is different from any of the other sources. The rest of this analysis will focus on the mid-level inflow source, and “parcels” will refer to just the mid-level parcels unless stated otherwise. These parcels originate from the environment at a height of 1.5 km AGL and undergo ascent and then substantial descent before finally entering the mesocyclone (Fig. 2.9b,c,h,i). This updraft-downdraft path is similar to the “up-down” downdraft trajectory identified as a feature of derecho-producing mesoscale convective systems by Bernardet and Cotton (1998), and later seen in a supercell by MacIntosh and Parker (2017). In both of these studies, this path is characterized by dynamically forced ascent ahead of a mesovortex followed by strongly forced descent due to negative thermal buoyancy, after which parcels reach the surface and accelerate horizontally away from a dynamic high pressure perturbation. Forced ascent of the mid-level parcels is clear in Fig. 2.9b–c and e–f, which shows initially neutral parcel buoyancy quickly becoming negative as parcels ascend in the up-down trajectory. Parcel buoyancy remains negative through descent and subsequent ascent into the mesocyclone. Descent of the mid-level parcels appears

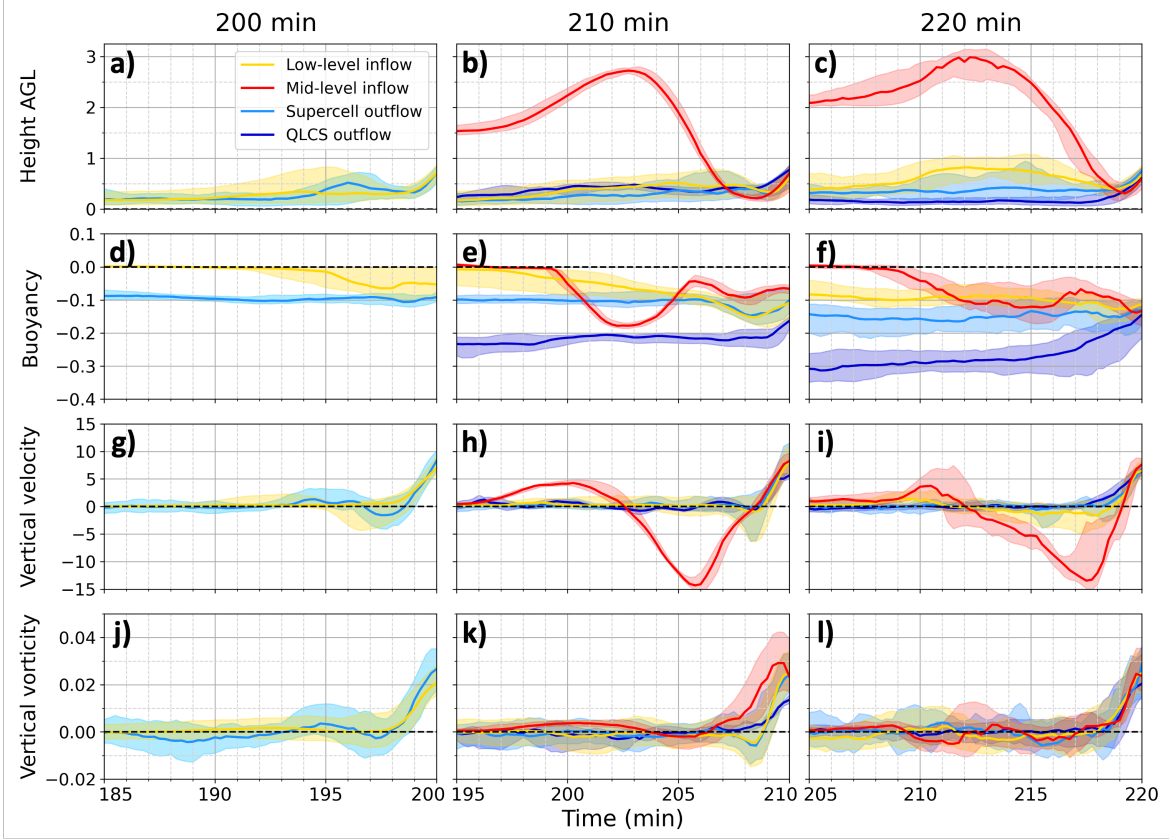


Figure 2.9: Time series of median parcel (a)–(c) z (km), (d)–(f) B (m s^{-2}), (g)–(i) w (m s^{-1}), and (j)–(l) ζ (s^{-1}) of MERGER parcels from all source regions, starting 15 min before parcels ascend into the low-level mesocyclone. The 25th and 75th percentiles of each variable are shaded. Each 15-min block follows parcels in the mesocyclone at 200 min (left), at 210 min (center), and at 220 min (right).

at least partially forced by strongly negative buoyancy, consistent with past findings from studies like Bernardet and Cotton (1998) and Weisman and Trapp (2003).

Like the other source regions, the mid-level parcels have very small ζ magnitudes until they ascend into the mesocyclone (Fig. 2.9h–i and k–l). In parcels approaching the mesocyclone at 210 min, median ζ is slightly positive during the initial ascent, then becomes weakly negative after parcels begin to descend and accelerate downward. ζ becomes positive again as parcels decelerate in their descent, and then increases rapidly when they begin to ascend into the mesocyclone after 208 min. For parcels

entering the mesocyclone after the merger at 220 min, median ζ is again slightly positive during initial ascent, but becomes negative after 209 min, just before the ascending parcels start to decelerate—however, the distribution of parcel ζ during deceleration is skewed positive. Median ζ oscillates between weakly positive and negative while the parcels accelerate downward between 212–217 min, then becomes positive again as parcels decelerate in their descent. ζ increases rapidly when parcels ascend into the mesocyclone at 219 min.

In general, parcels acquire positive ζ during periods of upward acceleration and negative ζ during periods of downward acceleration. The rapid increase in ζ during ascent into the mesocyclone is consistent with findings from Rotunno et al. (2017) and Boyer and Dahl (2020) showing that tilting via the updraft is the dominant mechanism for cyclonic ζ generation in mature supercells and QLCSs. However, the small positive ζ acquired as parcels decelerate in their descent (206–208 min in Fig. 2.9k, 217–219 min in Fig. 2.9l) is reminiscent of the Davies-Jones and Brooks (1993) downdraft baroclinic mechanism for upward vortex line tilting via the downdraft, and suggests that residence within the downdraft could be an important period for cyclonic ζ generation. The generation of cyclonic ζ during strong descent is an important characteristic unique to the mid-level inflow source.

The evolution of vorticity components along parcel trajectories can help to further characterize ζ generation processes, and is shown in Fig. 2.10 and Fig. 2.11. Parcels in the mesocyclone at 210 min initially have positive ω_{SW} and ω_{CW} , with a median $|\omega_H|$ magnitude of 0.02 s^{-1} (Fig. 2.10e,g). During the ascent portion of the up-down trajectory (195–203 min), ω_{SW} remains positive and nearly constant while ω_{CW} decreases and becomes negative, and horizontal vorticity becomes predominantly streamwise. In this framework, the transition of crosswise horizontal vorticity from “positive” to “negative” implies that the crosswise component evolves from pointing left of the storm-relative

wind vector to the right (as in Fig. 2.11a). As parcels descend and accelerate between 203–206 min, the horizontal vorticity vector flips to become predominantly crosswise, with ω_{SW} decreasing to near-zero as ω_{CW} increases sharply to around 0.02 s^{-1} . As parcels decelerate in their descent between 206–208 min, ω_{CW} continues to increase sharply, and ω_{SW} also becomes slightly positive. As parcels ascend in the mesocyclone after 208 min and ζ increases rapidly as shown earlier, ω_{CW} and $|\boldsymbol{\omega}_H|$ magnitude both decrease sharply.

The transition of the parcel horizontal vorticity vector from primarily streamwise to primarily crosswise during descent is illustrated in Fig. 2.11a. As parcels descend from their peak height of 2.75 km AGL, the $\boldsymbol{\omega}_H$ vector orientation rotates clockwise from westward to northwestward while the magnitude remains approximately constant (corresponding to the increase in ω_{CW} and decrease in ω_{SW} between 203–206 min in Fig. 2.10g). Reorientation of the $\boldsymbol{\omega}_H$ vector takes place during most of the parcels' residence time within the downdraft. The $\boldsymbol{\omega}_H$ vector orientation then becomes constant and the magnitude increases dramatically as the descending parcels decelerate and begin to ascend (corresponding to the continuing increase in ω_{CW} and $|\boldsymbol{\omega}|$ magnitude after 206 min in Fig. 2.10e,g). This suggests that ζ is generated via conversion of low-level crosswise vorticity, which is acquired and amplified during descent. This will be explored further below.

In Fig. 2.10f,h, the evolution of vertical and horizontal vorticity for parcels in the mesocyclone at 220 min is similar to 210 min, but there are some important differences for the parcels entering after the merger. Between 205–210 min, as parcels accelerate in the ascent portion of the up-down trajectory, ω_{SW} and ω_{CW} both increase, with $|\boldsymbol{\omega}_H|$ increasing to around 0.03 s^{-1} . As parcels decelerate in their ascent between 210–212 min, ζ and ω_{CW} become negative, and ω_{SW} decreases while remaining positive. As parcels descend and accelerate downward between 212–218 min, ω_{SW} continues to

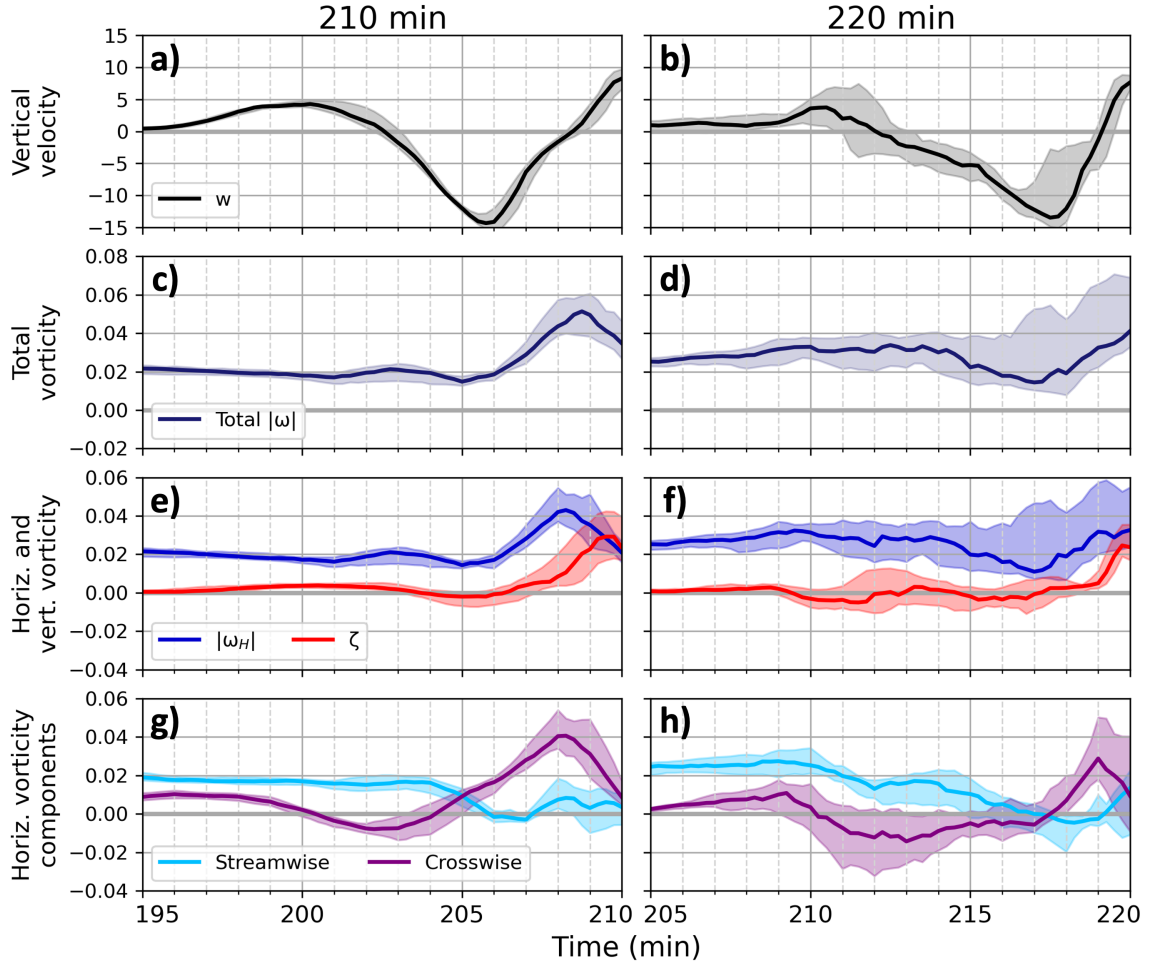


Figure 2.10: Time series of median (a)–(b) w (m s⁻¹; black), (c)–(d) total $|\omega|$ (s⁻¹; dark blue), (e)–(f) ζ (red) and $|\omega_H|$ (blue), and (g)–(h) ω_{SW} (light blue) and ω_{CW} (purple) of the MERGER mid-level inflow parcels, starting 15 min before they ascend into the mesocyclone. 25th and 75th percentiles are shaded. Positive ω_{CW} is oriented to the left of the storm-relative parcel velocity vector. Similar to Fig. 2.9, the time series are divided into 15-min blocks following parcels in the mesocyclone at 210 min (left) and 220 min (right).

decrease, and magnitudes of negative ω_{CW} gradually decrease as well. $|\omega_H|$ and total $|\omega|$ also decrease considerably during this time. When parcels are in their peak descent at 218 min, ω_{SW} becoming slightly negative and ω_{CW} becomes positive. Between 218–219, as parcels decelerate in their descent, ω_{CW} increases rapidly along with $|\omega_H|$, while ω_{SW} remains slightly negative. After 219 min, parcels begin ascent into the

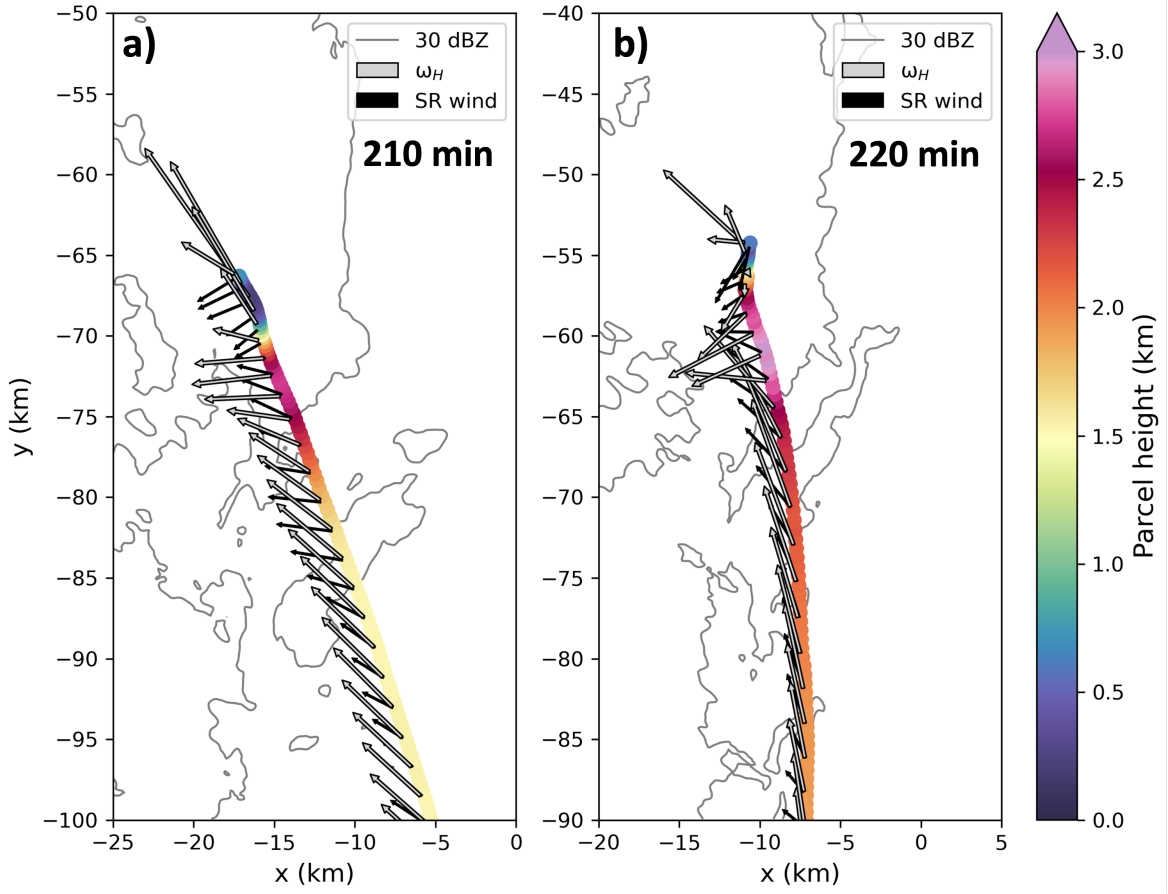


Figure 2.11: Plan views of the median trajectories for MERGER mid-level inflow parcels in the low-level mesocyclone at (a) 210 min and (b) 220 min. Trajectories are shaded by their median height AGL (km). Vectors show parcel ω_H (silver) and storm-relative velocity (black). The 30 dBZ contour for simulated lowest-level radar reflectivity at 210 min and 220 min is underlaid (gray).

mesocyclone. During ascent after 219 min, ζ increases rapidly as shown before, and median ω_{CW} decreases sharply while ω_{SW} rapidly increases.

The effects of the merger on vorticity generation are evident in Fig. 2.11. As before, the horizontal vorticity vector for parcels in the mesocyclone at 220 min transitions from primarily streamwise to primarily crosswise during descent, but the subsequent amplification of ω_{SW} and decrease in ω_{CW} after 219 min indicates another reorientation of the vorticity vector from crosswise back to streamwise during ascent. This reorientation back to streamwise is not seen in the parcels approaching the mesocyclone before

the merger. In Fig. 2.11a, the horizontal vorticity vector reorients clockwise during descent from westward to northwestward, becoming nearly orthogonal to the storm-relative velocity vector, and does not continue rotating during ascent. However, in Fig. 2.11b the vorticity vector reorients counterclockwise during descent and continues to rotate, eventually performing a full 360° rotation between the start of descent and acceleration into the mesocyclone. This is consistent with the evolution of horizontal vorticity from streamwise to crosswise and back to streamwise in Fig. 2.10h. While the overall evolution of vertical vorticity appears to be similar throughout the merger, these results imply that the *mechanisms* for vorticity generation may be different before and after the merger.

The changes in vorticity evolution and generation processes throughout the merger could reflect the development of different storm-scale features and structures before and after the merger. Parcels in the mesocyclone at 210 min first cycle through the pre-merger supercell updraft, then into the rear-flank downdraft where they rapidly descend into the supercell's cold pool (Fig. 2.12a). The parcels then ascend from near the surface into the updraft of the merged mesocyclone as they are forced back and over the QLCS cold pool. As in French and Parker (2012a), the merged mesocyclone then moves rearward and persists behind the gust front (visible in the parcel traces in Fig. 2.13b). Parcels in the mesocyclone at 220 min also cycle through an initial weak updraft and a locally intense downdraft. However, these parcels descend well behind the cold pool leading edge, where the trajectory wraps around a local warm perturbation in the cold pool associated with strong unsaturated descent in the downdraft (Figs. 2.12b and 2.13b). As the parcels exit the downdraft and start to ascend, their trajectories slightly curve back forward toward the leading edge, suggesting a developing rotor-like feature with the mesocyclone located on its upward branch.

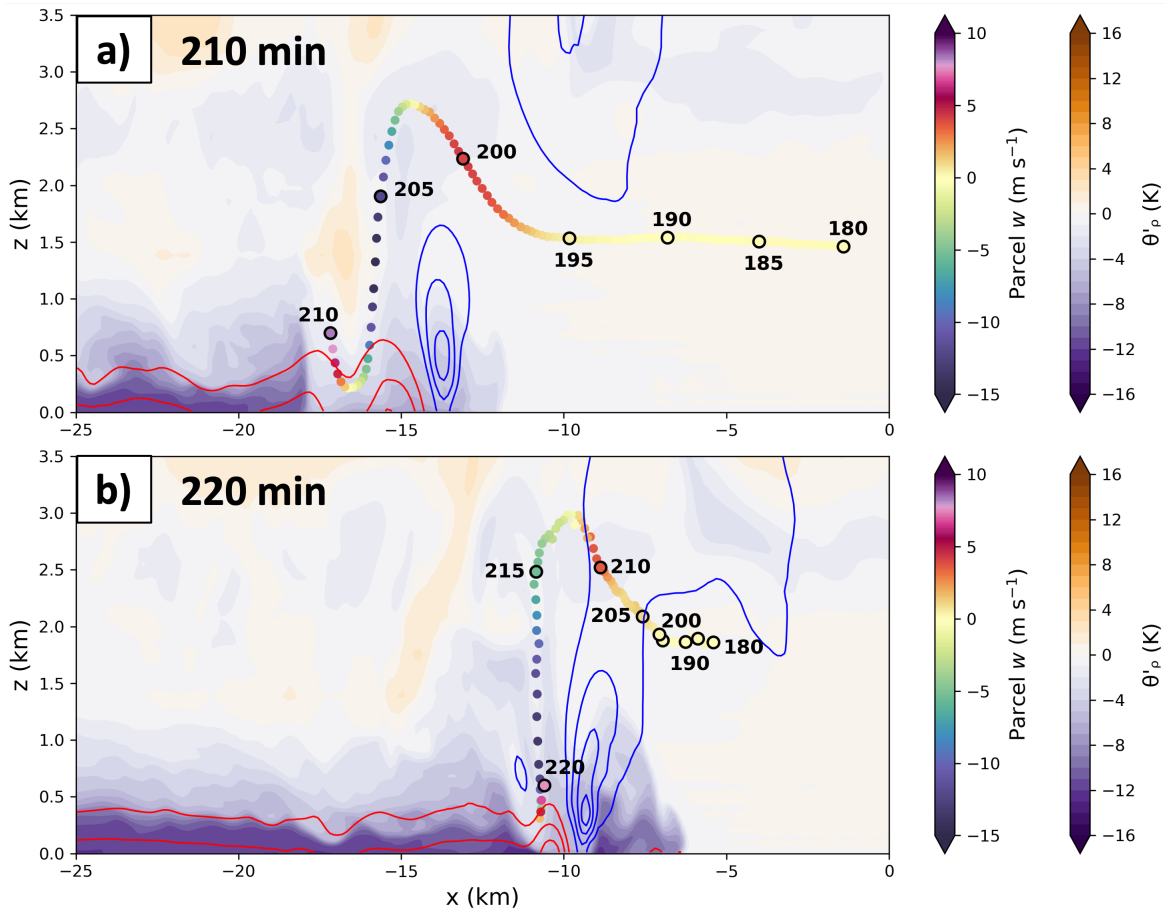


Figure 2.12: X-Z cross sections of θ'_p (shaded) and p' (contoured every 1 hPa, with red denoting $p' > 0$ hPa and blue denoting $p' < 0$ hPa) at (a) 208 min and (b) 218 min, with the median trajectory overlaid for MERGER mid-level inflow parcels in the low-level mesocyclone at 210 min and 220 min, respectively, and shaded by median parcel w . Time is annotated along the trajectories.

To show changes in vorticity generation mechanisms before and after the merger, Figs. 2.14 and 2.15 show time-composited vorticity tendency fields during important portions of the parcel trajectories. At each time, the tendency terms are calculated in 2-km wide boxes centered on each parcel position and height AGL, which are composited to create a mean tendency field for that time. The mean tendency fields are then composited again over time to capture the bulk vorticity tendency characteristics during key periods of the trajectories.

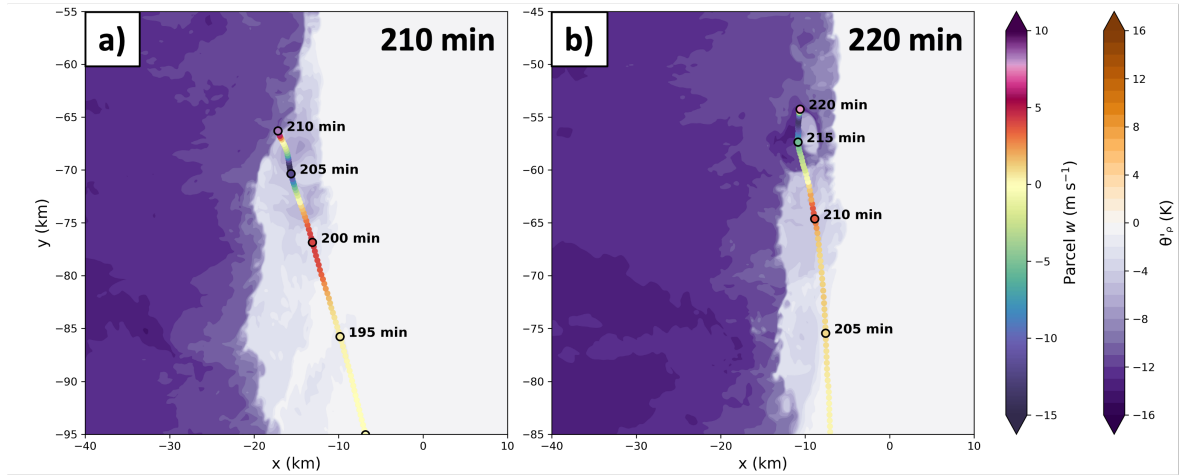


Figure 2.13: Plan views of θ'_ρ at the lowest model level at (a) 208 min and (b) 218 min, with the median trajectory overlaid for MERGER mid-level inflow parcels in the low-level mesocyclone at 210 min and 220 min, respectively, and shaded by median parcel w . Time is annotated along the trajectories.

For parcels that enter the mesocyclone at 210 min (Fig. 2.14a–b), tilting is the predominant mechanism for vertical vorticity generation within the downdraft between 203–208 min, with little contribution from stretching. Stretching contributes more strongly to the ζ budget in the final two minutes (not shown). During this time, the parcels are in a region of upward tilting, which is consistent with the transition from negative to positive ζ during descent. Since the horizontal vorticity is almost purely crosswise by 208 min, upward tilting of crosswise vorticity during the transition from descent to ascent is likely the primary mechanism for cyclonic ζ production in the mesocyclone at 210 min. To clarify how horizontal vorticity is acquired and amplified, Fig. 2.15a–c shows that tilting and baroclinity contribute to $|\omega_H|$ generation during descent. $|\omega_H|$ generation from tilting is likely associated with the transition from descent to ascent right at 208 min. Fig. 2.12a shows parcels descending just ahead of the QLCS cold pool, which is likely where baroclinically generated vorticity is acquired. Since the storm-relative parcel velocity is nearly orthogonal to the QLCS leading edge

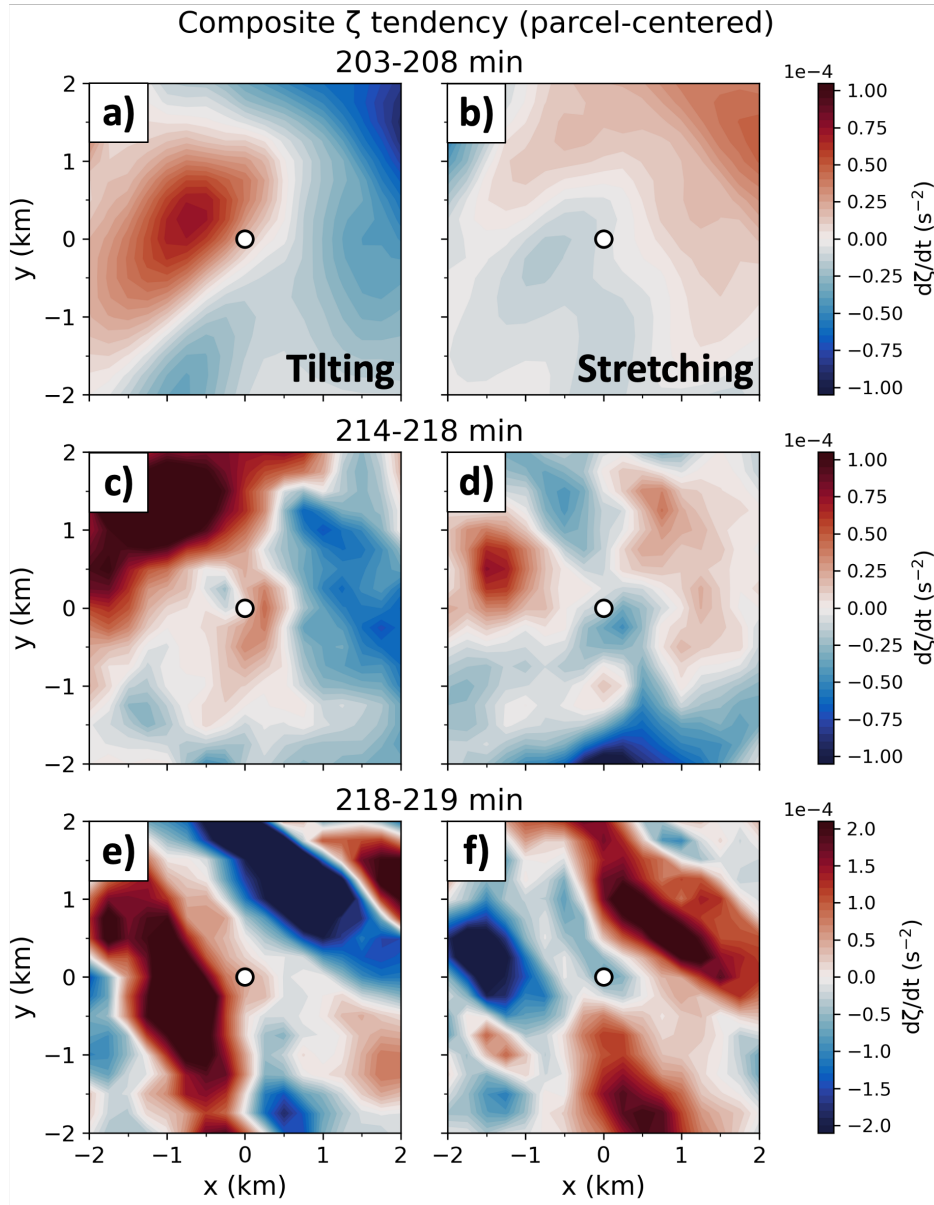


Figure 2.14: Time composites of parcel-centered ζ tendency terms for tilting (left) and stretching (right) for the MERGER mid-level inflow parcels. Top: composite ζ tendencies during descent (203–208 min) for parcels in the low-level mesocyclone at 210 min. Middle: composite ζ tendencies during descent (214–218 min) for parcels in the low-level mesocyclone at 220 min. Bottom: composite ζ tendencies during residence within the rotor (218–219 min) for parcels in the low-level mesocyclone at 220 min.

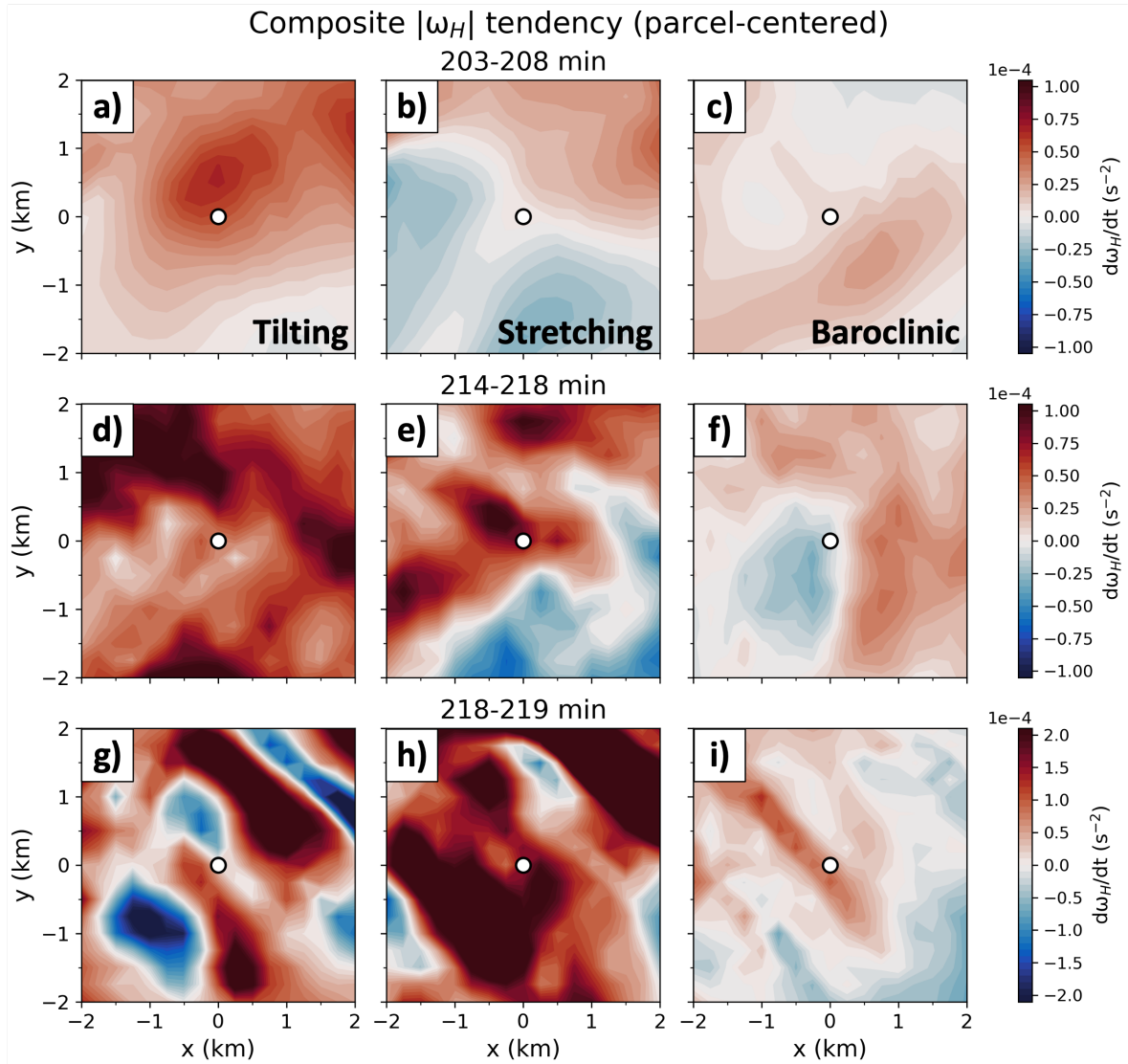


Figure 2.15: Time composites of parcel-centered $|\omega_H|$ tendency terms for tilting (left), stretching (center), and baroclinic generation (right) for the MERGER mid-level inflow parcels. Top: composite $|\omega_H|$ tendencies during descent (203–208 min) for parcels in the low-level mesocyclone at 210 min. Middle: composite $|\omega_H|$ tendencies during descent (214–218 min) for parcels in the low-level mesocyclone at 220 min. Bottom: composite $|\omega_H|$ tendencies during residence within the rotor (218–219 min) for parcels in the low-level mesocyclone at 220 min.

at this time (see Fig. 2.11a), baroclinity likely contributes substantially to the rapid increase in ω_{CW} during descent *before* 208 min, which is then tilted upward and stretched during ascent into the mesocyclone.

For parcels that enter the updraft at 220 min, tilting contributes positively to ζ generation while stretching contributes negatively during descent (Fig. 2.14c–d). This is consistent with Fig. 2.10f, which shows a less pronounced increase in ζ during descent than in Fig. 2.10e. During this time, Fig. 2.15d–f shows that stretching and tilting contribute strongly to $|\omega_H|$ generation during descent, while baroclinity contributes negatively to $|\omega_H|$. This is in direct contrast to the downdraft during 203–208 min, where stretching was negligible and baroclinity was positive. In the downdraft during 214–218 min, stretching is the most significant source of $|\omega_H|$ generation. While parcels are in the rotor-like feature (Fig. 2.14e–f), positive tilting and negative stretching of ζ approximately offset each other. However, the parcels are on the edge of a very strong region of upward tilting most likely associated with the mesocyclone. This again implies that upward tilting via an updraft is the most significant contributor to cyclonic ζ generation in the merged mesocyclone. In Fig. 2.15g–i, tilting, stretching, and baroclinity all act to generate $|\omega_H|$. As noted previously, the downdraft around 220 min is associated with a warm surface perturbation in the cold pool, creating a baroclinic zone where the parcels descend behind the leading edge. However, stretching is by far the most significant source of $|\omega_H|$ within the rotor.

The presence of upward tilting within the downdraft for both sets of parcels suggests that the Davies-Jones and Brooks (1993) downdraft baroclinic mechanism may play an influential role in low-level cyclonic ζ production before and after the merger. At the same time, parcels in the downdraft appear to have also interacted with a region of downward tilting earlier in their descent. This is consistent with findings from Boyer and Dahl (2020), which showed similar acquisition of negative ζ via downward tilting in a downdraft that was then tilted upward in an updraft to generate cyclonic near-surface ζ . Finally, Rotunno et al. (2017) and Boyer and Dahl (2020) both found that upward tilting of horizontal vorticity via the updraft is the primary mechanism for

cyclonic ζ generation in mature supercells and QLCSs, and this appears to be the most significant source of ζ in the merger mesocyclone in our simulations as well. Both the downdraft baroclinic and the “in-and-up” mechanisms for ζ generation appear to be present before and after the merger.

By contrast, the sources of ω_H change over the course of the merger. Before the merger, the primary mechanism for ζ generation is upward tilting of primarily crosswise vorticity, which was generated along the leading edge of the QLCS cold pool during descent. A similar process was seen in Flournoy and Coniglio (2019), where ζ generation in a QLCS mesovortex was due to upward tilting of primarily crosswise horizontal vorticity along a gust front. This process is also suggested to occur in supercells by Rotunno et al. (2017) and Boyer and Dahl (2020). After the merger, horizontal vorticity generation and amplification is primarily associated with a low-level rotor collocated with the merged mesocyclone. This rotor is similar to a low-level rotor seen in a simulated QLCS in Schenkman et al. (2012). In their work, the rotor was found to be an important region for the amplification of horizontal vorticity via stretching, which contributed directly to QLCS tornadogenesis. The rotor in this work appears to play a similar role in horizontal vorticity amplification before upward tilting via the updraft. This mechanism is only present *after* the merger, demonstrating that the merger influenced the physical storm-scale processes associated with mesocyclone vorticity generation and augmentation.

2.4 Conclusions

The overarching objective of this work was to evaluate the impacts of a QLCS-supercell merger on storm-scale evolution using idealized simulations from CM1, with a primary

focus on underlying physical processes related to the generation and evolution of rotation and how those processes may change during a merger. Consistent with previous work by Goodman and Knupp (1993), French and Parker (2012b), French and Parker (2014), and others, these simulations show that the merging supercell is important in modifying the structure and evolution of the QLCS. The merger results in a prominent bow echo with the supercell as its leading edge and enhanced mesovortex production along the leading edge, which is also characteristic of strong bow echoes that occur in QLCSs without mergers. Importantly, the merged supercell mesocyclone retains supercell-like characteristics, with updraft rotation remaining deeper, more intense, and more persistent after the merger than a typical QLCS mesovortex. These findings motivated more detailed study into the evolution of storm-scale processes in the MERGER mesocyclone and how they compare to processes conventionally attributed to either supercells or QLCSs.

Retention of supercell-like characteristics in the MERGER mesocyclone is evident in trajectory analysis. The MERGER mesocyclone develops a mid-level inflow source just before the merger, with these parcels originating from the environment at a height of 1.5 km AGL near the top of the boundary layer. This source region is also present in the SUPERCELL mesocyclone, suggesting that the presence of the mid-level inflow source in the merged mesocyclone may be a reflection of the enhanced mid-level updraft rotation and associated dynamic pressure perturbations. Moreover, this implies that processes for the development, intensification, and maintenance of rotation in the MERGER mesocyclone are similar to processes seen in isolated supercells. The evolution of mid-level inflow parcel trajectories entering the mesocyclone reveals changes in vorticity generation processes throughout the merger.

Before the merger, the primary mechanism for ζ generation is upward tilting via the updraft of predominantly crosswise low-level horizontal vorticity, which was generated

baroclinically and amplified during descent. After the merger, ζ generation still occurs primarily due to upward tilting via the updraft, but horizontal vorticity is amplified significantly in a low-level rotor that develops after the merger. The pre-merger baroclinic and post-merger rotor mechanisms for ω_H generation are both associated with QLCS mesovortices (Schenkman et al. 2012; Flournoy and Coniglio 2019), while the processes found for ζ generation are associated with both supercells and QLCSs (Davies-Jones and Brooks 1993; Rotunno et al. 2017; Boyer and Dahl 2020). Furthermore, the mid-level inflow source region is itself a supercell feature, but the up-down trajectory those parcels follow has been seen in both QLCSs (Bernardet and Cotton 1998) and supercells (MacIntosh and Parker 2017). Thus, this simulation of a QLCS-supercell merger features a *combination of “QLCS-like” and “supercell-like” mechanisms for the evolution of rotation*, with inflowing source regions and trajectory vorticity tendencies changing throughout the merger.

The implication from these results that QLCS-supercell mergers are associated with a combination of supercell-like and QLCS-like processes raises larger questions that warrant future study. Do these processes take place in all QLCS-supercell mergers? Are conventionally “supercell-like” and “QLCS-like” processes truly distinct from each other, or can all of these processes occur in any rotating updraft, with or without a merger? Finally, are the storm-scale processes in these simulations actually reflective of processes that occur in mergers in the real world—and how do we appropriately observe them?

Chapter 3

Close-Range Radar Observations of QLCS

Tornadogenesis Failure Processes During PERiLS

3.1 Introduction

Among decades of field campaigns seeking to observe and understand supercell tornadoes, the Propagation, Evolution, and Rotation in Linear Storms (PERiLS) project in 2022 and 2023 was the first major field campaign to specifically target QLCS tornadoes (Kosiba et al. 2024). The overarching objective of PERiLS was to collect comprehensive datasets targeting poorly understood QLCS processes, including (1) mesovortexgenesis, (2) tornadogenesis, (3) QLCS environments, and (4) cold pool processes. High-resolution datasets are crucial to observing the evolution of QLCS processes, particularly relating to mesovortex and tornadogenesis due to their rapidly evolving nature. Therefore, rapid-scan mobile radars were an important component of the project for targeting mesovortex and tornadogenesis processes. The work in this chapter provides an observation-based analysis to supplement the investigation of mesovortex processes identified in the QLCSONLY simulation in Chapter 2.

There is an extensive body of past work studying supercell tornadoes using rapid-scanning mobile radars. High-resolution radar observations have been used to study tornado structure and dynamics, especially at low levels within a tornado, to validate simulation-based conceptual models of tornado vortex structures and their evolution

(e.g., Wurman and Gill 2000; Bluestein et al. 2003a, 2004; Kosiba et al. 2008; Wurman et al. 2010; Kosiba and Wurman 2010; Wakimoto et al. 2011, 2012; Tanamachi et al. 2012, 2013; Wurman and Kosiba 2013; Kosiba and Wurman 2013; Wakimoto et al. 2015; Bluestein et al. 2018; Mahre et al. 2018). Rapid-scanning radars are also ideal for observing the rapidly evolving, small-scale, and very-low-level processes involved in tornadogenesis (e.g., Bluestein et al. 2003b; Wurman et al. 2007; Kosiba et al. 2013; Houser et al. 2015; Bluestein et al. 2019; Houser et al. 2022) and tornado dissipation (e.g., French et al. 2014; Houser et al. 2015; Griffin et al. 2019; McKeown et al. 2020). Tornado damage and debris have also been studied using rapid-scanning radar to resolve wind maxima and small-scale debris processes (e.g., Bluestein et al. 2007; Wakimoto et al. 2020, 2022).

By contrast, there are very few rapid-scan radar studies of QLCS mesovortices and tornadoes. In a study of QLCS mesovortices using 1-min targeted sector scans from a fixed X-band polarimetric radar network, Mahale et al. (2012) found that severe wind associated with embedded mesovortices can produce tornado-intensity damage, and that the mesovortices had a differential reflectivity (Z_{DR}) arc signature during periods of intensification. The same QLCS event was also analyzed by Newman and Heinselman (2012) using an S-band phased array radar with 1-min volumetric updates, and they found the same association between embedded mesovortices and the production of tornado-intensity straight-line winds. Both studies concluded that high-resolution radar data is important for better detection, understanding, and prediction of QLCS mesovortices. Newman and Heinselman (2012) further concluded that rapid-update volumetric radar observations of mid-level processes are crucial for detection and prediction of QLCS processes that precede severe weather production. Blind-Doskocil (2023) later analyzed the characteristics of tornadic and nontornadic mesovortices during PERiLS using the University of Illinois C-band on Wheels (COW) mobile radar

(Wurman et al. 2021), which performed low-level scans every 3 min during the 2022 field phase and every 90 s during the 2023 field phase. They found that tornadic mesovortices had stronger rotational velocities, smaller diameters, and longer lifetimes than nontornadic mesovortices. They also found that the time between when a mesovortex is detected and when it first produces a tornado is frequently ≤ 10 min, highlighting the need for high-resolution observations of potentially tornadic mesovortices to capture these processes.

On 3 March 2023, a tornadic QLCS targeted by PERiLS in southeastern Arkansas produced multiple mesovortices near the observing network. The University of Oklahoma Rapid-scanning X-band Polarimetric (RaXPol) mobile radar and National Severe Storms Laboratory (NSSL) mobile mesonets successfully sampled a nontornadic mesovortex at very close range (< 6 km), allowing the resolution of small-scale storm features very close to the surface (i.e., within tens of meters) to be analyzed with coordinated surface observations along transects surrounding the mesovortex. During the period when the mobile mesonets were transecting, RaXPol captured the rapid formation and dissipation of multiple nontornadic vortices within the mesovortex. The strongest and most persistent of these nontornadic vortices is analyzed in depth to investigate the potential processes involved in tornadogenesis failure. The science questions we seek to address in this work are as follows:

1. What are the characteristics of the nontornadic vortex in rapid-scan radar data, and how do they evolve?
2. How do the surface characteristics of the environment and cold pool relate to the evolution of the nontornadic vortex?
3. What physical processes may have inhibited QLCS tornadogenesis?

The close-range RaXPol observations and simultaneous mobile mesonet transects comprise a novel set of targeted observations uniquely suited for studying small-scale, rapidly evolving phenomena like QLCS mesovortices and tornadoes. The objective of this work is to present a detailed high-resolution radar analysis of the evolution of the nontornadic vortex, which will be supplemented with analysis of surface environment and cold pool characteristics to ultimately clarify the processes involved in QLCS tornadogenesis failure.

3.2 Data and methods

3.2.1 RaXPol and mobile mesonet data

RaXPol is a rapid-scanning mobile radar designed for observing severe storms at high spatiotemporal resolution (Pazmany et al. 2013). Rapid-scanning mobile radars were a key component of the PERiLS campaign instrumentation to capture the rapidly evolving and frequently transient nature of QLCS mesovortices and tornadoes. In addition to the primary objective of sampling low-level mesovortices at close range, a secondary objective of the RaXPol mission was to coordinate observations with the NSSL mobile mesonets as they performed circuit transects around the target mesovortex. This coordinated “vortex intercept” mission was planned to obtain a detailed set of targeted mesovortex observations nested within the larger storm-scale network of PERiLS mobile radars and other instrumentation platforms (Fig. 3.1).

RaXPol is a mobile parabolic dish radar with a maximum scanning rate of 180° s^{-1} for 2-s sweeps. Operating in rapid-scanning mode results in short dwell times, which leads to insufficient decorrelation between samples. To ensure that enough independent samples are collected to meaningfully estimate radar moments without sacrificing

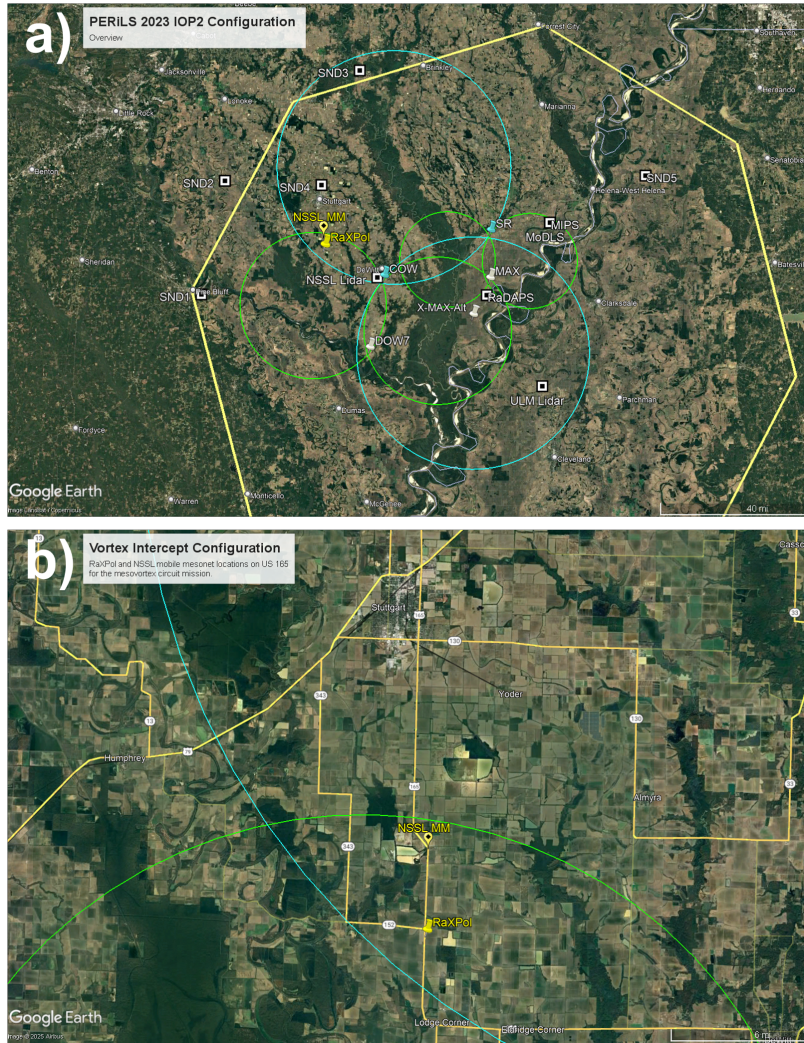


Figure 3.1: (a) Instrument configuration for the PERiLS IOP on 3 March 2023 in the Clarksdale subdomain (yellow outline) with the locations of the C- and X-band mobile radar network, mobile radiosonde systems, RaXPol, and NSSL mobile mesonets labeled. (b) Zoomed-in locations of RaXPol and the NSSL mobile mesonets along U.S. Hwy. 165 in position for the vortex intercept mission.

scanning speed, RaXPol employs frequency hopping techniques, where the transmit frequency is shifted between consecutive pulse pairs to speed up the decorrelation time. A complete description of RaXPol's design and specifications can be found in Pazmany et al. (2013). More details on select specifications and parameters used during PERiLS are shown in Table 3.1.

Table 3.1: Select RaXPol specifications and operating parameters during PERiLS on 3 March 2023. Adapted from Pazmany et al. (2013).

Parameter	Value
Peak transmit power	20 kW
Center frequency	9.73 GHz
Bandwidth	40 MHz
3-dB beamwidth	1.0°
Maximum rotation rate	180° s ⁻¹
Range resolution	30.0 m
Pulse repetition time	0.25 ms
Nyquist velocity	30.8 m s ⁻¹

The NSSL mobile mesonets are mobile surface observing platforms equipped with a roof-mounted suite of sensors and a data logger. These sensors include a fast-response temperature sensor, slow-response temperature and relative humidity sensor, pitot tube pressure sensor, propeller anemometer, and a fluxgate magnetometer for recording vehicle speed and heading (Straka et al. 1996; Waugh 2012). The temperature and humidity sensors are housed inside a U-tube to shield the sensors from the effects of solar radiation heating and evaporative cooling of surface condensation while ensuring proper aspiration of the sensors (Waugh 2012). Vehicle speed and heading data from the magnetometer are used to correct for vehicle motion in the raw wind speed observations. Mobile mesonet data are recorded at a frequency of 1 Hz. A more detailed description of the initial and current mobile mesonet design and specifications can be found in Straka et al. (1996) and Waugh (2012). The two mobile mesonets used in this analysis are referred to individually as Probe 1 and Probe 2.

Measured variables were de-biased for each mesonet by spatially interpolating the observations from nearby platforms (within 5 km) to the location of a mesonet observation at a given time, then computing the bias magnitude as the mean difference between the spatially interpolated value and the observed value over a 30-s bias correction window (Pardun et al. 2025). An additional correction was applied to the u and v wind components specifically during vehicle heading changes, as the lateral acceleration from turning results in systematic wind errors (E. Rasmussen, personal communication). Correcting this wind bias requires using wind measurements from at least three data points before and after a turn to triangulate the expected correct wind vector during the turn (T. Pardun, personal communication). This derived wind vector is compared to the measured wind vector during the turn to determine u and v offsets for wind measurements during turns. A constant offset was applied to the temperature observations from Probe 1 to correct a warm bias of approximately $+1.2^{\circ}\text{C}$ in the fast-response temperature (T_{fast}) data. This bias was identified by comparing Probe 1 T_{fast} to Probe 2 T_{fast} and the slow-response temperature data from both mesonets, and the offset was determined by comparing the measurements during a time period when the mesonets were positioned together before the start of the circuit.

RaXPol’s observing strategy during PERiLS was designed to fulfill the need for low-level radar data with high spatial resolution and fast volumetric update times. During the intensive observation period (IOP), RaXPol collected 30-s rapid volumes of plan-position indicator (PPI) sweeps using a $180^{\circ} \text{ s}^{-1}$ scanning speed, with 13 tilts at elevation angles every $\sim 1.5^{\circ}$ between approximately 1.0 – 19.0° plus two transition sweeps between successive volumes (note that the actual elevation angles may be close but not exactly equal to the planned elevation angles). In contrast to the fixed network configuration of most other mobile radars on PERiLS, RaXPol’s mission was to operate in a common mobile radar “roaming” mode to opportunistically target potentially

tornadic mesovortices at a range of 10 km or less to sample the wind and precipitation fields at very low levels. The observed beam heights of the lowest and highest tilts at various ranges are shown in Table 3.2. Importantly, the beam height of the lowest tilt was around 157 m above radar level (ARL) at the maximum target range of 10 km. At a 2-km range—the closest range from RaXPol to the observed mesovortex during this IOP—RaXPol was able to sample at a height of approximately 31 m ARL at the lowest tilt. The depth of a full volume ranges from approximately 3 km at a 10-km range to around 600 m at a 2-km range.

Table 3.2: Observed beam heights ARL of the lowest and highest tilts at ranges of 10 km, 5 km, 2 km, and 1 km from the radar.

Range	Height of lowest tilt	Height of highest tilt
10 km	157.1 m	3222.6 m
5 km	78.5 m	1611.3 m
2 km	31.4 m	644.5 m

Targeting and positioning decisions were made with the NSSL mobile mesonets to collect simultaneous transects near the target mesovortex as part of the vortex intercept coordinated mission. The transect strategy involved performing a circuit maneuver in order to obtain surface observations in a closed circuit around a mesovortex. Two mesonets are initially positioned together along a north-south road ahead of an approaching mesovortex. To carry out the circuit maneuver, the mesonets drive in opposite directions just ahead of the mesovortex (the forward leg of the circuit), wait stationary as the mesovortex passes over the road (the north and south legs of the circuit), then re-converge to their starting positions behind the mesovortex (the rear leg of the circuit). The combined transects from the two mobile mesonets form a closed

circuit surrounding the mesovortex, allowing bulk properties like surface convergence and horizontal heterogeneities in the cold pool to be inferred.

3.2.2 Analysis and correction methods

To identify and analyze tornado-scale circulations observed by RaXPol, pseudovorticity fields are inferred from the Doppler velocity fields. Vertical pseudovorticity, denoted as ζ' , is estimated as the azimuthal derivative of Doppler velocity, given by:

$$\zeta' = \frac{2}{r} \frac{\Delta V_r}{\Delta \theta}, \quad (3.1)$$

where V_r is Doppler velocity, r is the distance from the radar, and θ is the azimuthal angle in radians, and Δ represents a central finite difference. Pseudovorticity maxima were tracked manually in range, azimuth, height, and time to obtain the positions, vertical structure, and basic evolution of any vortices. An advection correction was applied to remove any artificial vortex tilt or shape caused by storm translation during volumes. The storm motion vector during each volume was estimated from the mesovortex motion during the 2 min surrounding the analysis time, and the gridded fields were advected forward or backward to the central grid time. The advection-adjusted volumes were then interpolated to a common $10 \times 10 \times 2$ km³ Cartesian grid with 30-m grid spacing using the Py-ART Barnes objective analysis scheme (Helmus and Collis 2016). These methods are the same as in Houser et al. (2016), and more details on the technique are contained there. Reconstructed range-height indicator (RHI) fields are retrieved from along-radial cross sections through the advection-corrected volumes. It is important to note that RHI reconstruction also assumes that the actual storm structure does not change significantly during the course of the volume scan. Because there are only 2 s between successive sweeps and ~ 24 s between the first and last sweep

in a volume, we feel that the update times are rapid enough for this assumption to reasonably hold, even for rapidly evolving phenomena.

The mobile mesonet sensor suite directly measures air temperature, relative humidity, atmospheric pressure, and wind speed and direction. These observations are used to calculate other quantities, including potential temperature θ and virtual potential temperature θ_v . To calculate perturbations of these quantities, the base state is assumed from the mobile mesonet observations within the pre-storm environment prior to the circuit. Mesonet data are also used to qualitatively evaluate bulk spatial properties, such as surface convergence and thermodynamic gradients around the mesovortex, using time-space conversion techniques as in Markowski et al. (2002). Time-space conversion of the mesonet data uses storm motion estimates to transform quasi-stationary time series observations into an estimated spatial field. This transformation is based on the Taylor (1938) frozen-field hypothesis and assumes that the observed feature does not change significantly over the averaging time period. For this analysis, the distance traveled by the mesovortex between consecutive RaXPol 30-s volumes was used to derive storm motion estimates at the start time of each volume. Time-space conversion was then applied to any mobile mesonet observations within 60 s of the start of each RaXPol volume to estimate the mesovortex-relative positions of the observations throughout the circuit observing period.

3.3 Case overview

The second IOP of PERiLS Year 2 took place in southeastern Arkansas during the overnight and early morning hours of 3 March 2023. The potential for a severe QLCS in the PERiLS domain was identified as early as 23 February, and the IOP was declared on 27 February in response to forecasts of a supportive thermodynamic and kinematic

environment for tornadic storms in the Mississippi Delta region. Throughout the day and overnight hours of 2–3 March, a negatively tilted 500-mb trough and associated 100-kt jet streak moved across Texas, resulting in increasingly divergent upper-level flow, synoptic-scale ascent, and surface cyclogenesis across Arkansas throughout the night (Figs. 3.2 and 3.3). In response to the strengthening surface low, a warm front progressed northward into Arkansas from the Gulf, forming an expansive warm sector with deep low-level moisture over the mid-Delta (Fig. 3.4). Linear forcing via a strong cold front supported the initiation and maintenance of a severe QLCS.

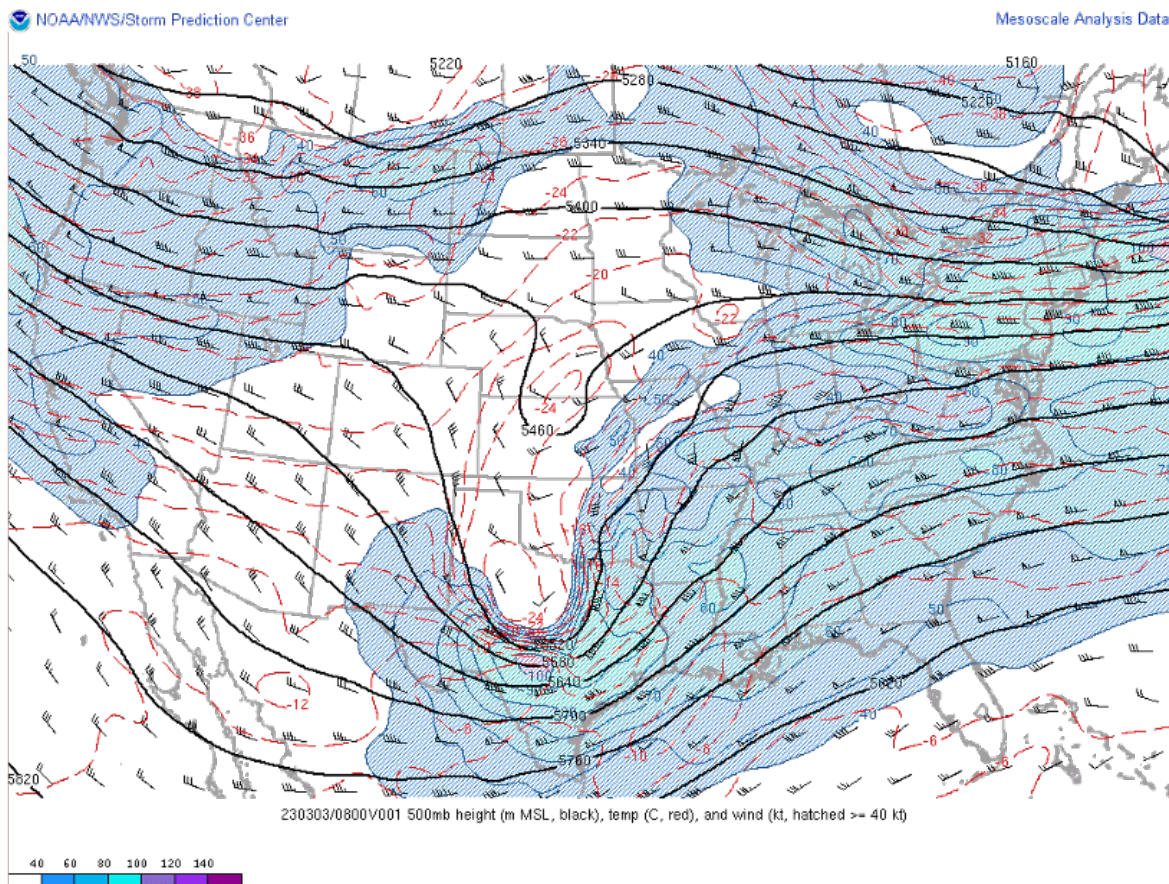


Figure 3.2: 500-hPa geopotential heights (black lines), temperature (dashed red lines), and winds (barbs and shaded) from SPC mesoanalysis valid at 0800 UTC 3 March 2023. Image from Storm Prediction Center archive.

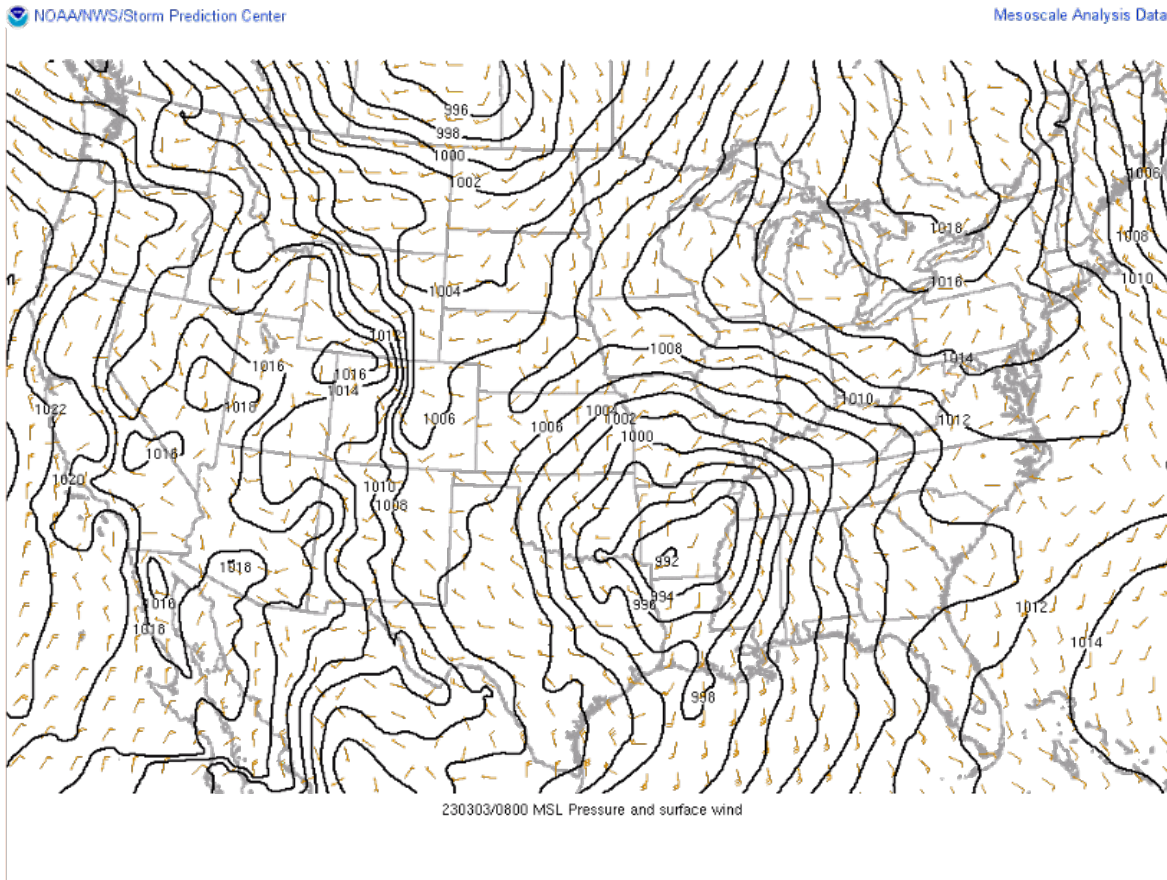


Figure 3.3: Mean sea-level pressure (black lines) and winds (barbs) from SPC meso-analysis valid at 0800 UTC 3 March 2023. Image from Storm Prediction Center archive.

Isolated supercells initiated in west Texas in the late morning and early afternoon of 2 March and began growing upscale in the mid-afternoon. By 2230 UTC, a tornadic QLCS stretched across central Texas while more supercells began to initiate within the warm sector ahead of the line. The QLCS continued to intensify overnight into 3 March in response to an approaching shortwave trough, which contributed to enhancement of 0–6 km bulk wind shear and low-level storm-relative helicity (SRH), erosion of convective inhibition (CIN), and development of a surface-based effective inflow layer (Fig. 3.5) in the mid-Delta region. IOP operations began at 0500 UTC on 3 March as the QLCS approached the Clarksdale, Mississippi subdomain (see Kosiba et al. 2024, their Figs. 2 and 3), where the evolving high-shear, low-CAPE (HSLC) environment

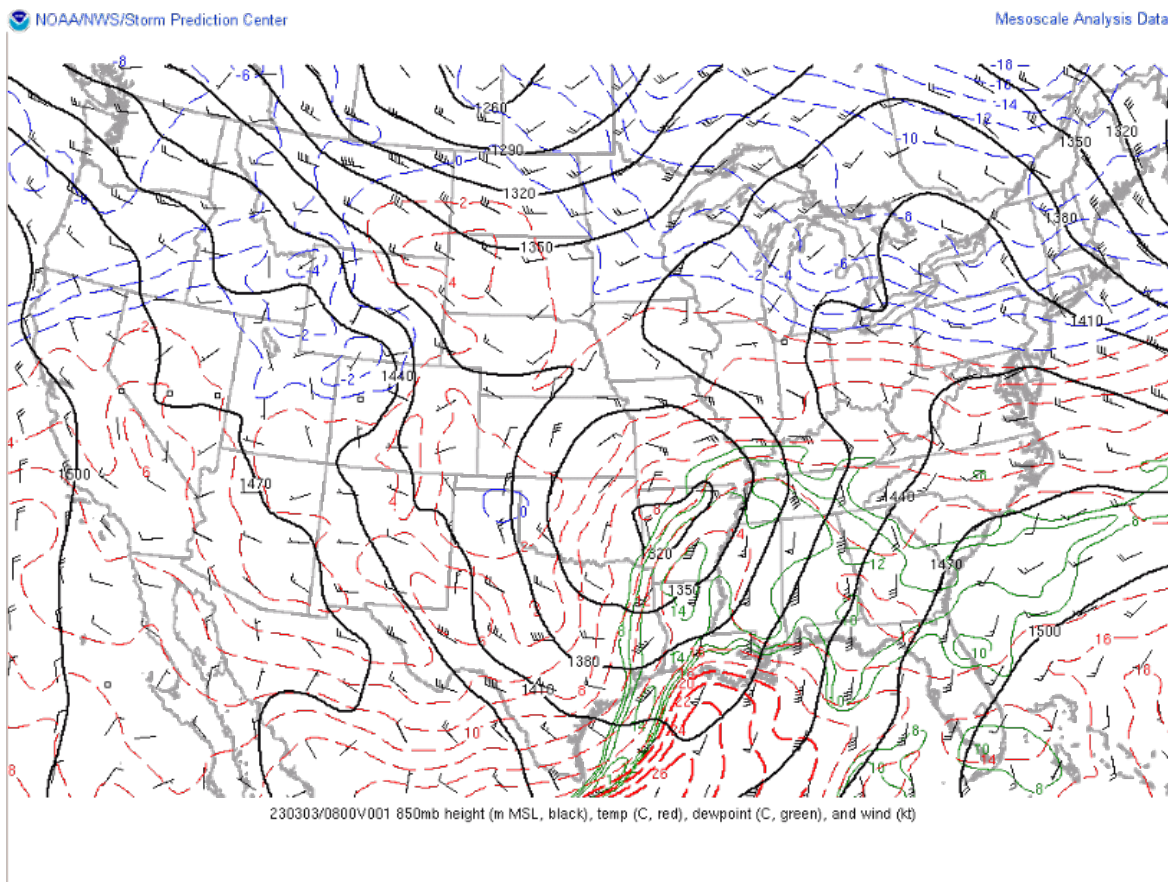


Figure 3.4: 850-hPa geopotential heights (black lines), temperature (dashed red and blue lines), dewpoint (green lines), and winds (barbs) from SPC mesoanalysis valid at 0800 UTC 3 March 2023. Image from Storm Prediction Center archive.

was becoming increasingly supportive of severe linear convection. Low-level SRH in eastern Arkansas continued to increase dramatically after 0600 UTC, reaching values of 0–1 km SRH $>600 \text{ m}^2 \text{ s}^{-2}$ and 0–3 km SRH $>700 \text{ m}^2 \text{ s}^{-2}$ by 0800 UTC (Fig. 3.5). In response to real-time data from PERiLS radiosondes and surface observing networks during the IOP, the Storm Prediction Center issued a mesoscale discussion MCD 0241 for enhanced tornado potential in southeastern AR and the ArkLaMiss area at 0626 UTC. Over the next two hours, the QLCS produced multiple strong low-level mesovortices and an EF0 tornado within range of the PERiLS observing network.

Operations ended shortly after 0900 UTC as the line weakened and moved out of Arkansas.

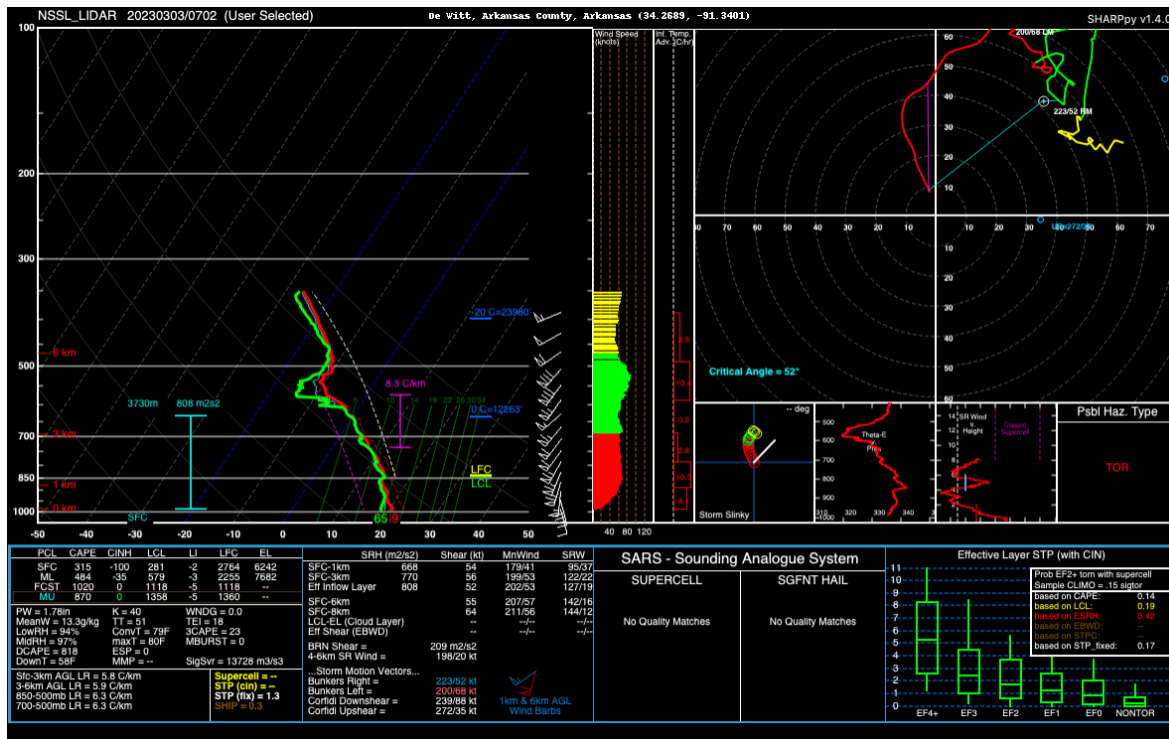


Figure 3.5: Skew T - $\log p$ diagram and hodograph of the observed vertical thermodynamic and wind profiles from an upper-air sounding from the NSSL Lidar and mobile sounding system at 0702 UTC, along with calculated and derived environmental and convective parameters. Image from the Earth Observing Laboratory PERiLS 2023 field catalog.

3.4 Results

3.4.1 Nontornadic vortex evolution

Between 0740–0840 UTC, two low-level mesovortices developed within the target QLCS near the PERiLS observing network. Both of these mesovortices were observed by the C-band On Wheels (COW) mobile radar as they formed approximately 50 km apart and reached their peak intensity within 30 min of each other (Fig. 3.6). However,

despite occurring in similar environments around the same time, only one mesovortex was tornadic. The earlier northern mesovortex produced a brief EF-0 tornado at 0757 UTC near Jefferson, Arkansas, while the later southern mesovortex reached its peak intensity between 0820–0825 UTC but never produced a tornado. The differences in the evolution of these two nearby mesovortices suggest that their tornado potential was likely influenced by local storm-scale features and processes. The nontornadic mesovortex was sampled by RaXPol at very close range, and these observations offer more detail on the fine-scale processes occurring in the lowest levels of the QLCS near the mesovortex.

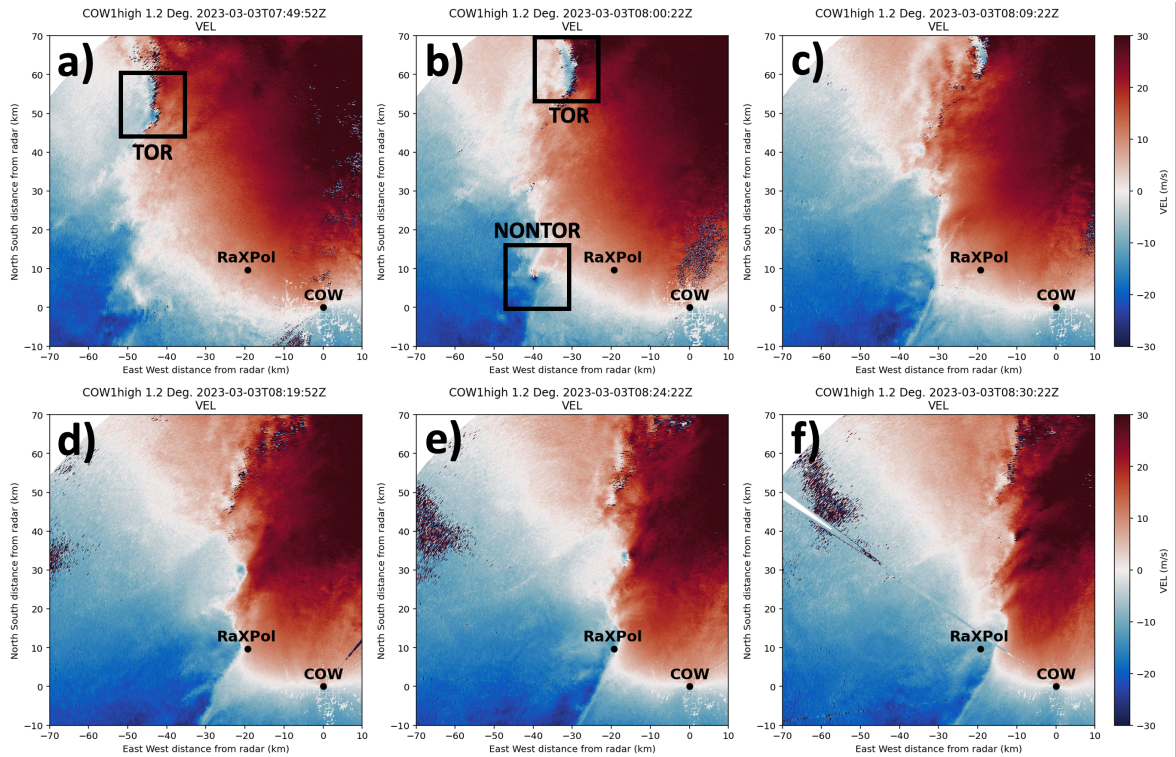


Figure 3.6: COW Doppler velocity observations at the 1.2° tilt at (a) 0749:52 UTC, (b) 0800:22 UTC, (c) 0809:22 UTC, (d) 0819:52 UTC, (e) 0824:22 UTC, and (f) 0830:22 UTC. The black squares show the location of the tornadic and nontornadic mesovortices. Data: (Wurman and Kosiba 2023).

The nontornadic mesovortex develops at the northern end of a prominent bow echo and associated outflow surge (Fig. 3.6d–e, Fig. 3.7a–e). Bow echoes and outflow surges are a known preferential location for QLCS mesovortex and tornado genesis due to the development of line-end vortices as well as enhanced low-level convergence, which leads to locally stronger updrafts and vertical vorticity stretching (e.g., Weisman and Trapp 2003; Trapp and Weisman 2003; Wakimoto et al. 2006b,a; Atkins et al. 2004; Atkins and St. Laurent 2009a,b). RaXPol was positioned within 6 km of the mesovortex for a 5-min time period between 0820–0825 UTC, and the low-level reflectivity and radial velocity fields in Figs. 3.7–3.8 show a variety of fine-scale heterogeneities and storm features along the bow echo. Between 0820–0821 UTC, wave-like streaks of reflectivity are present ahead of the convective precipitation along the bow echo and near the mesovortex (Fig. 3.7a–c). These reflectivity streaks merge back into the main convective line by 0821:30 UTC (Fig. 3.7d). Many local, small-scale heterogeneities are also apparent along the leading edge. For example, a hook echo-like structure is visible in Fig. 3.7c along the northern end of the bow echo. This apparent hook echo is collocated with weak rotation and a region of locally stronger inbound radial velocities in Fig. 3.8c, suggesting the development of a local outflow surge south of the hook echo feature, potentially similar to a rear-flank downdraft internal surge in a supercell. In the low-level environmental wind field, thin line-parallel streaks of enhanced outbound velocities are present ahead of the mesovortex between 0820–0821:30 UTC (Figs. 3.8a–d). A full discussion of all of these features is outside the scope of this study, but their presence illustrates the fine level of detail that can be resolved in the RaXPol observational datasets.

Radial velocity and derived pseudovorticity fields reveal the presence of transient tornado-scale circulations within the low-level mesovortex between 0820–0825 UTC. These nontornadic tornado-scale vortices (NTVs) are associated with clear maxima in

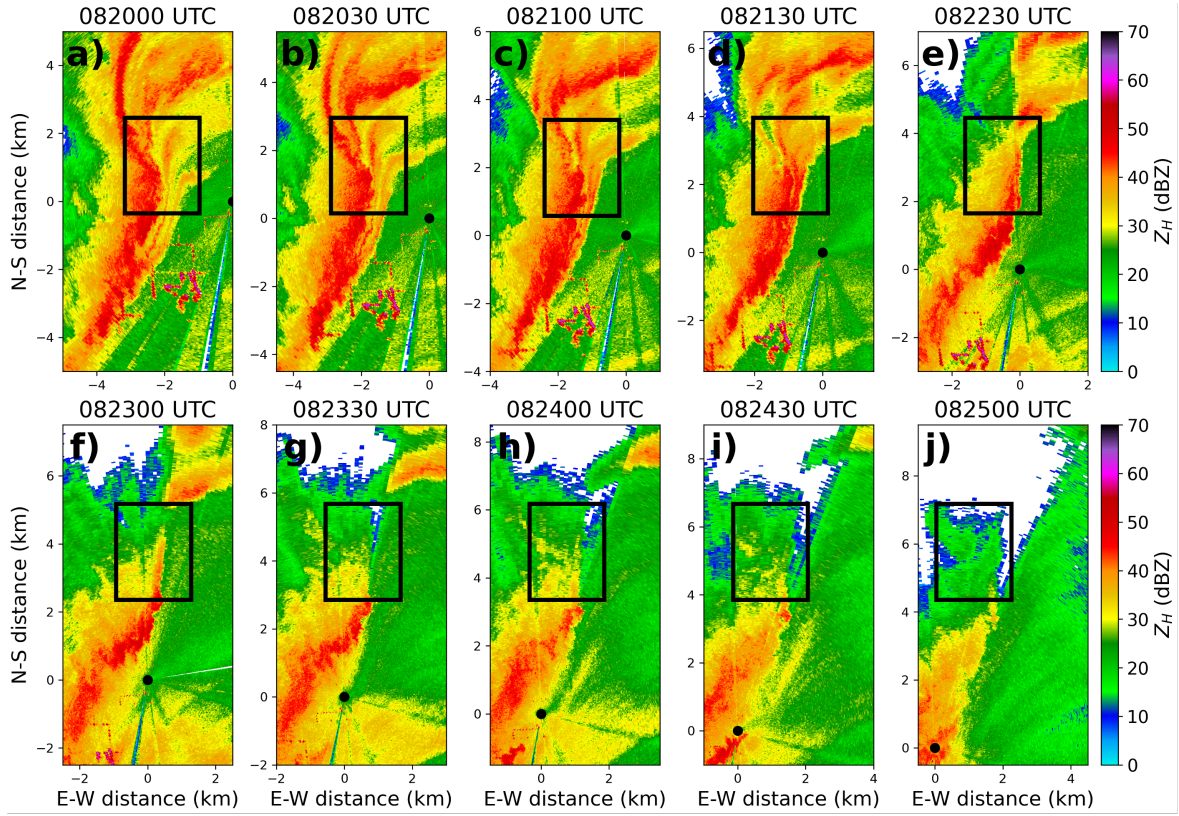


Figure 3.7: RaXPOL radar reflectivity factor PPIs at 2.4° elevation from volumes at: (a) 0820:00 UTC, (b) 0820:30 UTC, (c) 0821:00 UTC, (d) 0821:30 UTC, (e) 0822:30 UTC, (f) 0823 UTC, (g) 0823:30 UTC, (h) 0824:00 UTC, (i) 0824:30 UTC, and (j) 0825:00 UTC. (Note: there is no 0822:00 UTC volume due to brief transceiver malfunctions.)

derived ζ' fields (as in Fig. 3.9a) and weak horizontally oriented couplets in reconstructed velocity RHIs (as in Fig. 3.9c). The NTVs develop quasi-cyclically along the gust front, then rapidly advect backward into the convective precipitation before dissipating. The most intense and persistent NTV forms around 0820:30 UTC (Fig. 3.8b) and is associated with the visible velocity couplet that develops in the velocity field after 0822:30 UTC (Fig. 3.8e) and persists through at least 0825 UTC. This main NTV (hereafter simply referred to as “the NTV”) is the primary focus for the analyses in this work.

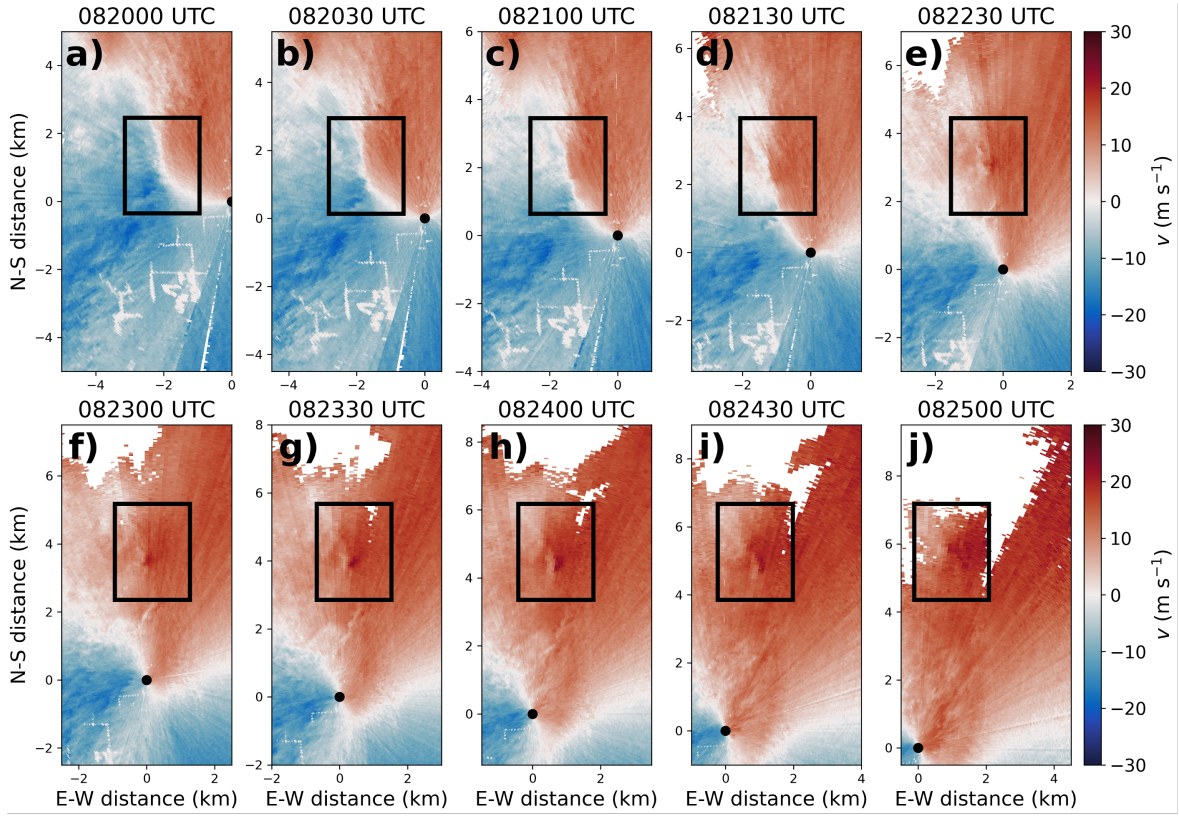


Figure 3.8: As in Fig. 3.7, but for radial velocity (m s^{-1}).

The NTV first forms at 0820:30 UTC as part of a cluster of weak, transient tornado-scale vortices (Figs. 3.9a and 3.10a). While most of the vortices rapidly dissipate within 1–2 min of genesis, the NTV persists for several minutes longer than the rest of the vortex cluster. The ζ' maxima associated with the NTV are used to track the center of rotation through the depth of the radar volume. The vertical structure of the NTV can then be inferred from vertical cross sections of ζ' through the radar volume along the center of rotation (as in Fig. 3.9b). The ζ' cross sections shown in Figs. 3.9–3.13 are reconstructed from the advection-corrected gridded volumes, and encompass the the genesis of the NTV at 0820:30 UTC through the beginning of its demise at 0823:00 UTC. Reconstructing the composite vertical structure of the NTV allows the intensity and evolution of its rotation to be examined in greater detail.

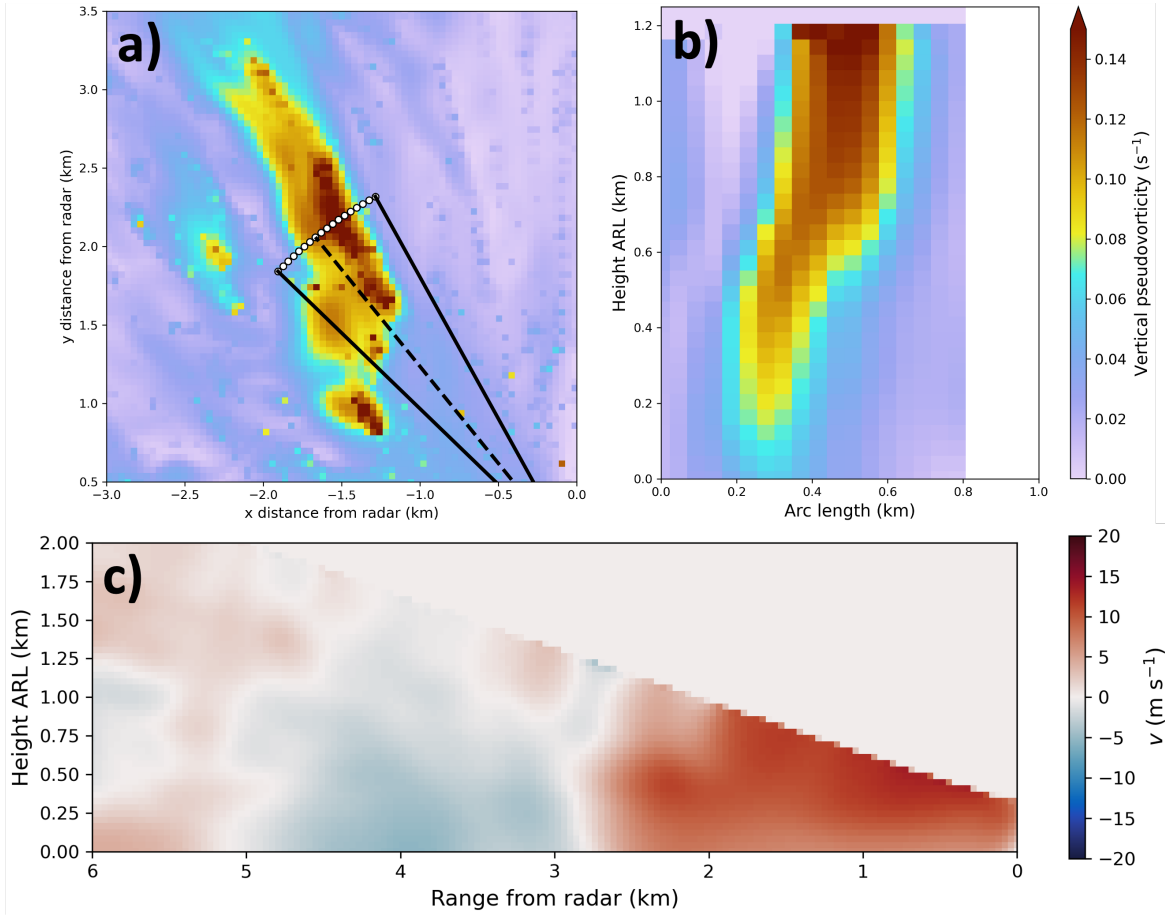


Figure 3.9: From the RaXPoI volume at 0820:30 UTC: (a) PPI of column-maximum ζ' (s^{-1}) with white markers showing the trace of a cross section through the NTV. Lines surrounding the overhead trace of the NTV (solid black) and the azimuth of the reconstructed RHI (dashed black) are overlaid. (b) Composite vertical cross-section of ζ' magnitude (s^{-1}) along the NTV trace between the solid black lines in (a). (c) Reconstructed RHI of radial velocity (m s^{-1}) along the dashed black line in (a).

During genesis, rotation in the NTV initially develops above the lowest 150 m (Fig. 3.9a–b) before quickly extending downward closer to the surface (Figs. 3.10a–b, 3.11a–b). At this point, the NTV is not yet associated with a prominent velocity couplet, and its characteristics are generally similar to the other vortices in the cluster during the first minute after their genesis. The evolution of the NTV becomes increasingly distinct from the other vortices around 0822:30–0823:00 UTC, at which point the NTV is the

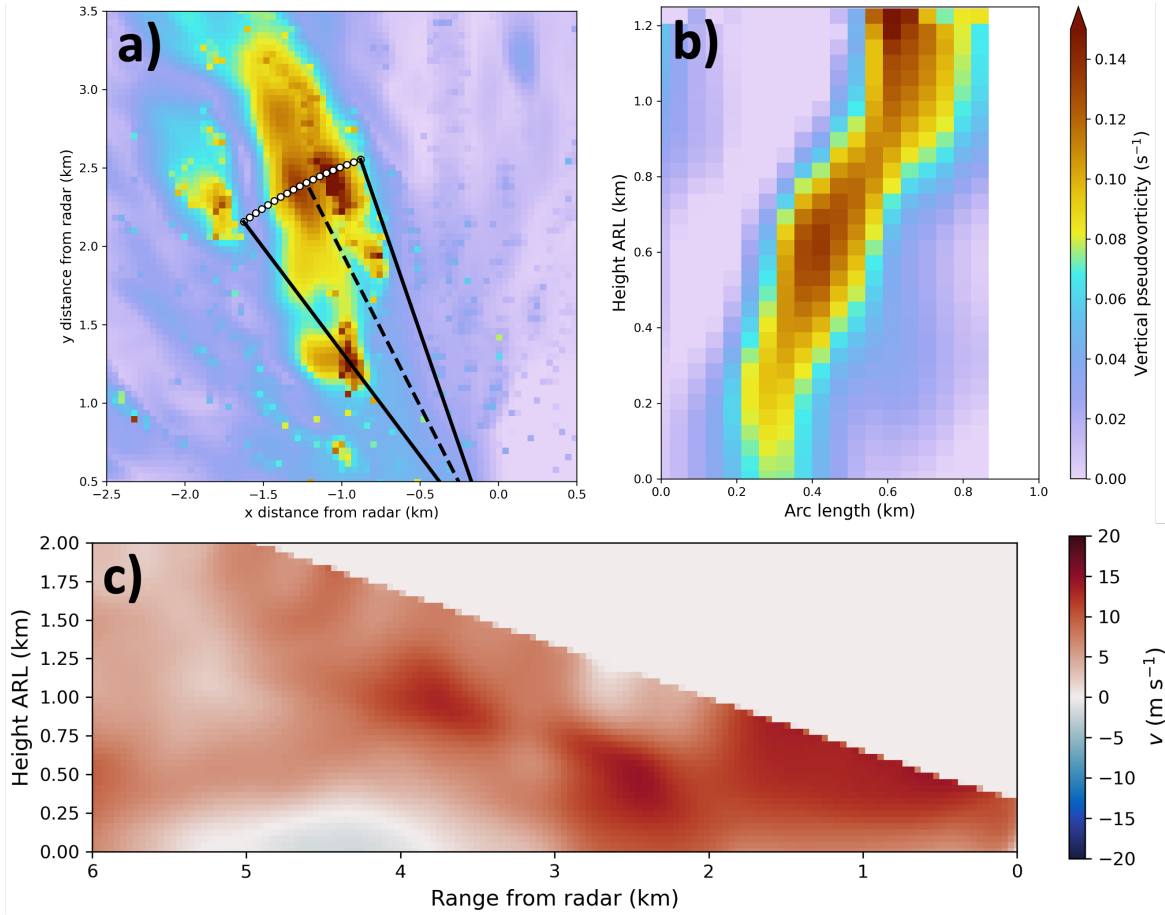


Figure 3.10: As in Fig. 3.9, but at 0821:00 UTC.

only remaining vortex and the prominent velocity couplet appears in the radial velocity fields. The NTV exhibits considerably stronger rotation and persists for a much longer time (>5 min) compared to the other vortices ($\sim 1\text{--}2$ min). Before 08210:30 UTC, other small patches of ζ' maxima are located very close to the NTV within a larger elongated region of maximum ζ' (Figs. 3.9a–3.11a). After 0822:30 UTC, the NTV is the only remaining ζ' patch, and an elongated ζ' region is no longer apparent (Figs. 3.12a–3.13a). Although this is mostly speculative, this could indicate a possible merging of nearby subtornadic vortex patches or contraction of the larger ζ' maximum between 0821:30 and 0822:30 UTC, which could have influenced on the enhanced intensity and lifespan of the NTV. This could be reminiscent of the role of vortex patch roll-up in

tornadogenesis, where regions of surface vertical vorticity coalesce and contract into a coherent surface vortex via self-organization (e.g., Dahl 2020; Parker 2023). In this case, the merging of the two vortices or roll-up of the elongated ζ' maximum may have resulted in the contraction and intensification of the NTV through a similar self-organization mechanism. There may be other processes that contributed to the formation and evolution of the NTV, which will be addressed in a later section.

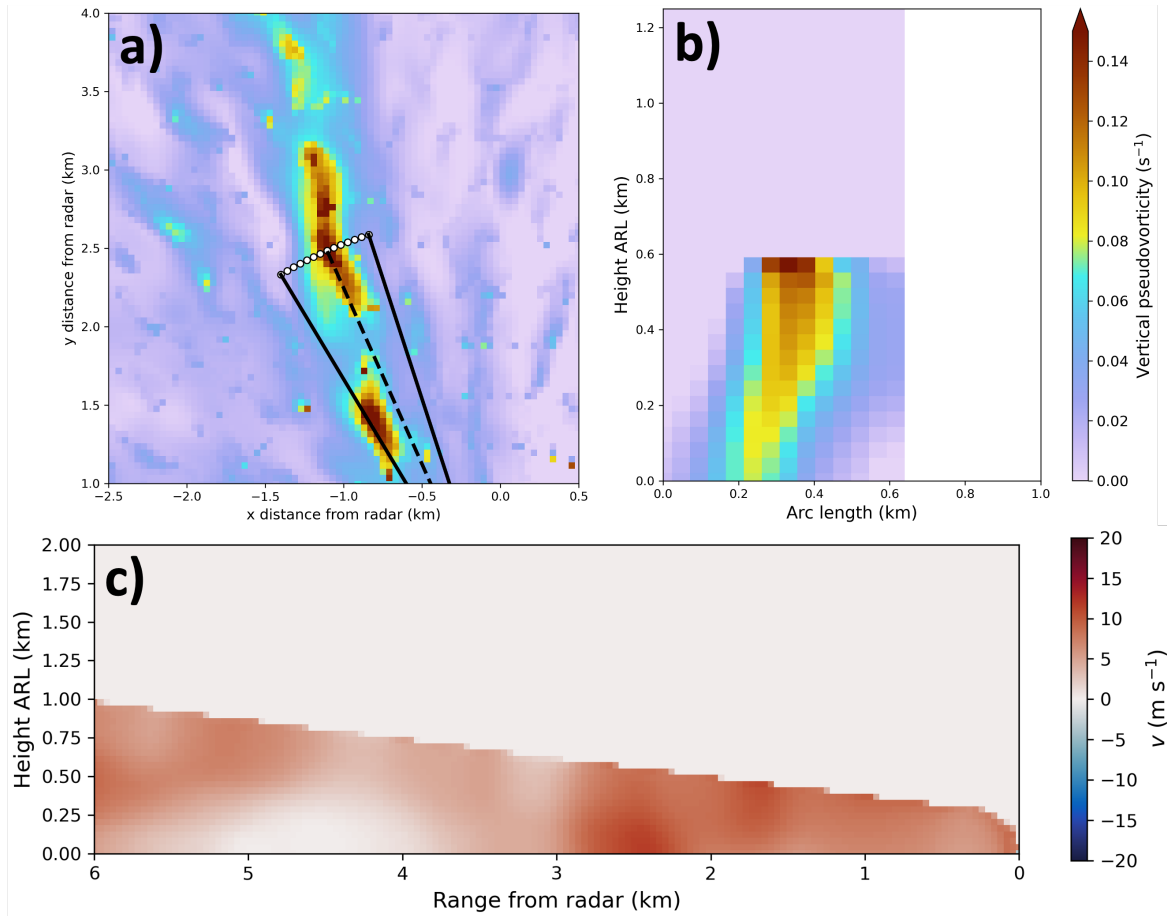


Figure 3.11: As in Fig. 3.9, but at 0821:30 UTC. Note that this volume is shallower than the others due to missing sweeps at higher tilts.

To begin to identify processes that could have inhibited tornadogenesis, two key characteristics of the NTV's vertical structure are identified and examined in greater detail: (1) its tilt, and (2) its lack of strong near-surface vorticity. These characteristics

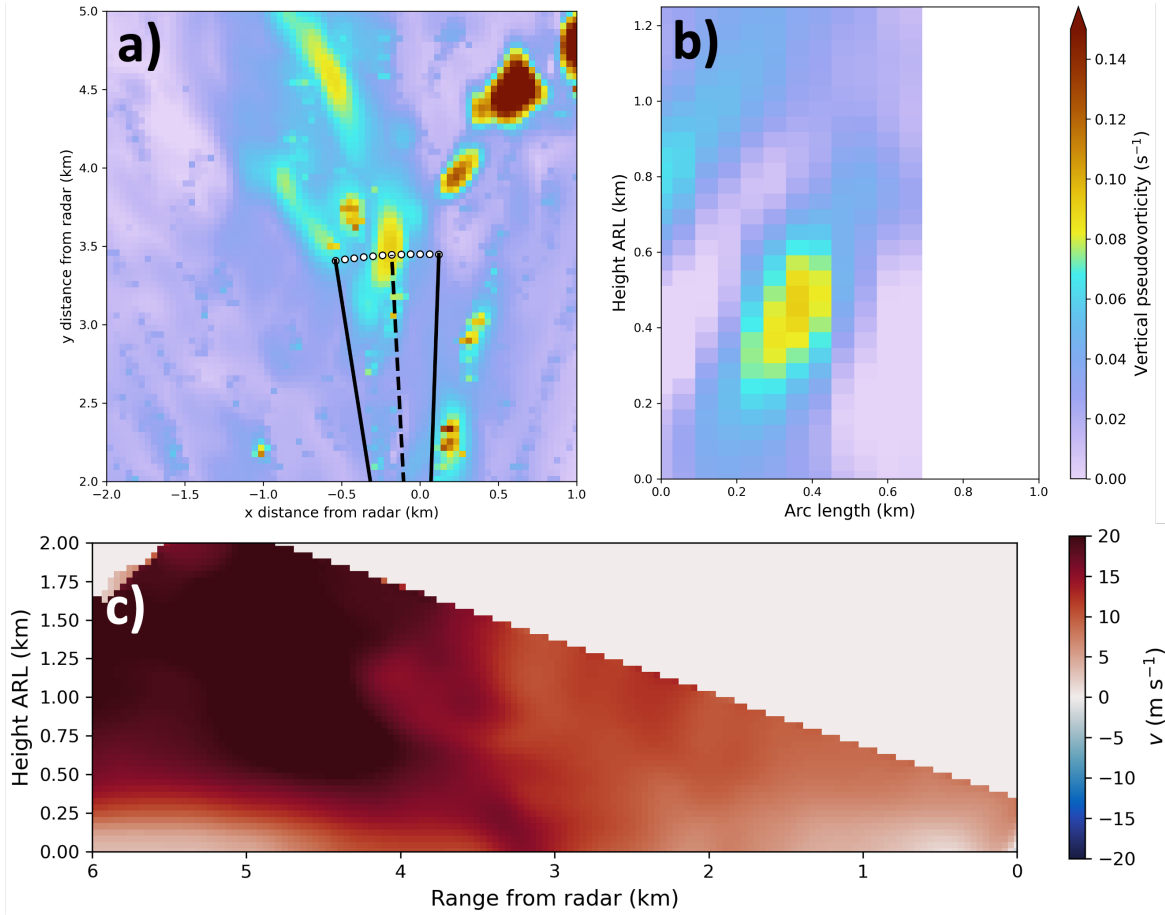


Figure 3.12: As in Fig. 3.9, but at 0822:30 UTC.

are hypothesized to reflect mechanisms that could have contributed to tornadogenesis failure, and they are present throughout the entire observed lifespan of the NTV. In all cross sections (Figs. 3.9b–3.13b), the axis of rotation exhibits some vertical tilt toward the leading edge of the convective line, with the layer of maximum tilt located aloft—generally between 300–400 m ARL and 800–1000 m ARL. This tilt is also illustrated by the presence of weak horizontal velocity couplets in the reconstructed RHIs through the NTV (Figs. 3.9c–3.13c). Comparisons between the NTV orientation and RaXPOL’s reflectivity fields indicate that the center of rotation near the surface is located farther back within the cold pool (storm-relative rearward), while the center of rotation aloft tends to remain closer to the leading edge of the convective line. In addition to the

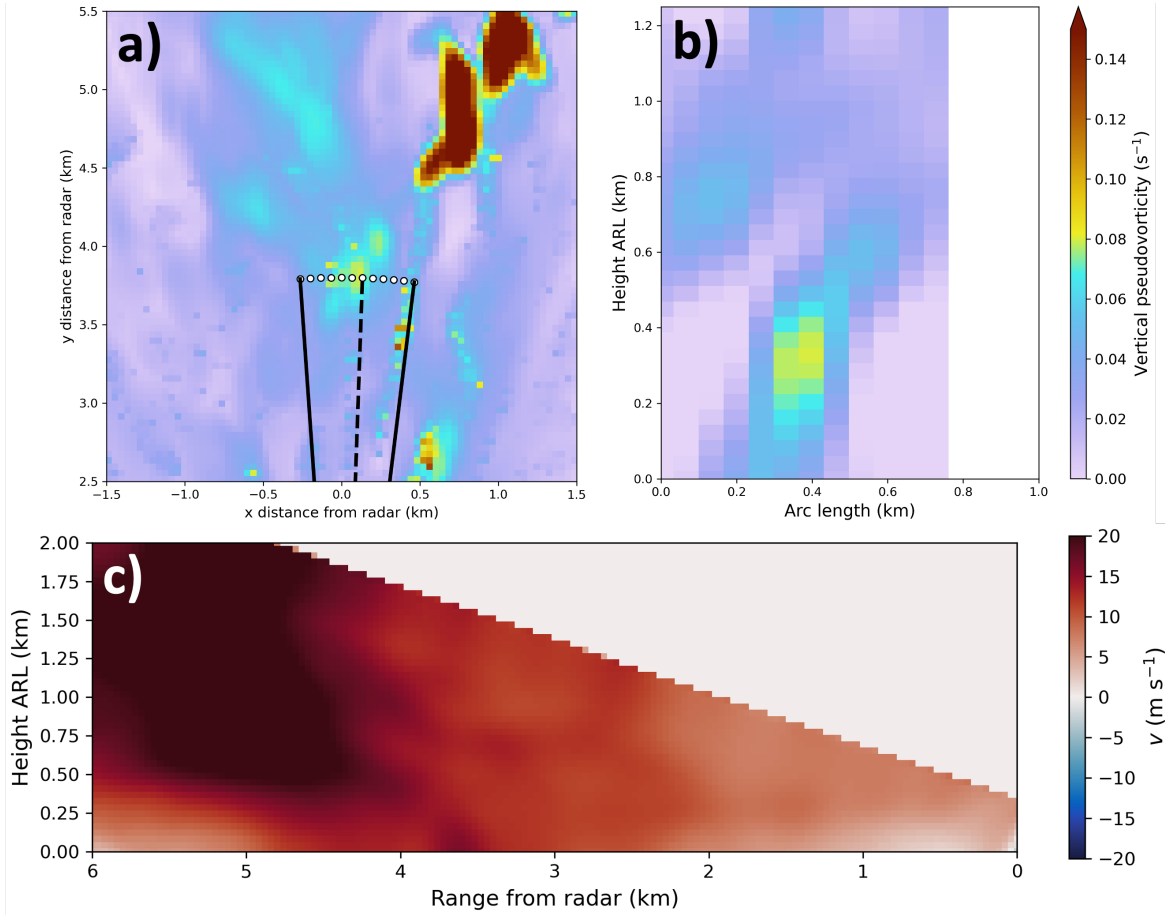


Figure 3.13: As in Fig. 3.9, but at 0823:00 UTC.

rearward displacement of near-surface rotation into the cold pool, the lowest levels of the NTV never achieve ζ' magnitudes comparable to those aloft.

Time-heights of maximum ζ' and gate-to-gate rotational velocity (V_{rot}) profiles in Figs. 3.14 and 3.15 illustrate how the vertical structure of the NTV evolves throughout the analysis period. Because ζ' inherently decreases as the NTV moves away from the radar due to its dependence on $\frac{1}{r}$, profiles of V_{rot} are also included to provide a less range-dependent representation of the vertical structure of rotation in the NTV. However, V_{rot} is still somewhat range-dependent due to increasing gate width with distance, which impacts the ability to resolve fine-scale rotation farther from the radar. A potential alternative to using V_{rot} or ζ' could be to evaluate linear least-squares

derivative estimates of azimuthal shear (AzShear), which is normalized to mitigate range dependence and could allow for more quantitative analyses of NTV rotational intensity.

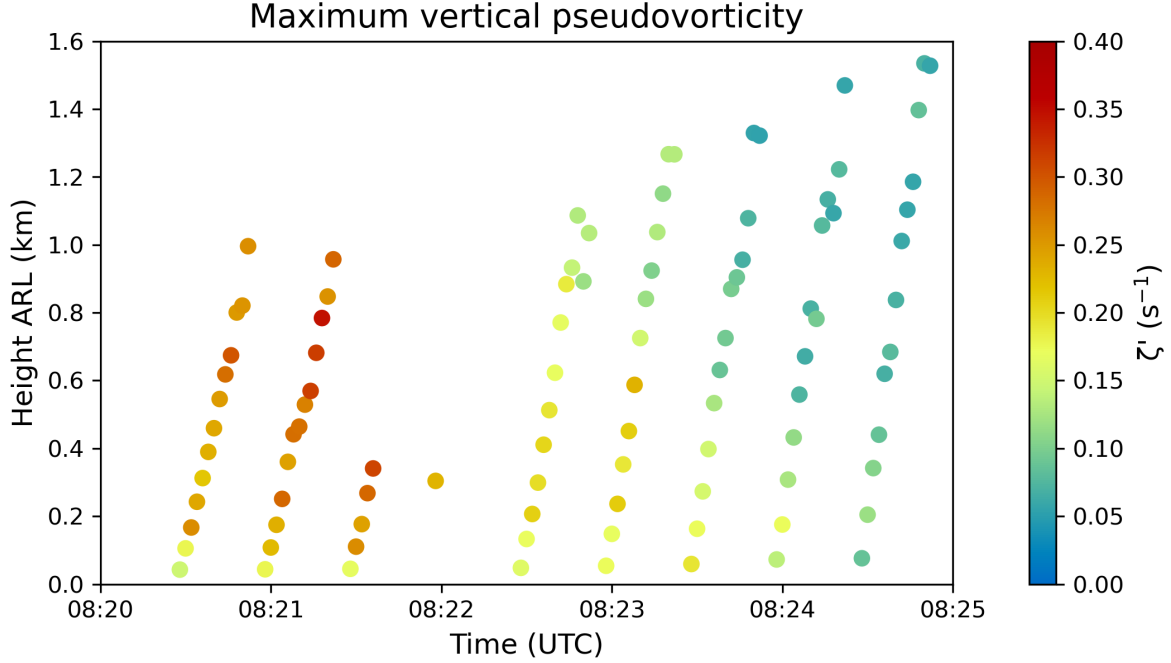


Figure 3.14: Time-height plot showing vertical profiles of maximum ζ' within the NTV between 0820:00–0825:00 UTC.

These time-height analyses further confirm that the strongest rotational intensity in the NTV is located aloft, while rotation near the surface remains comparatively weak. During the entire 5-min analysis period, V_{rot} magnitudes are almost entirely subornadic through the depth of the profile, with magnitudes $<10 \text{ m s}^{-1}$ (equivalent to the $20 \text{ m s}^{-1} \Delta V_{max}$ threshold used by Houser et al. 2015). While the overall strongest V_{rot} magnitudes are generally confined to within the lowest 500 m, the V_{rot} maxima tend to be around 100–200 m ARL and nearly always located above the lowest tilt. However, the decrease in V_{rot} and ζ' magnitudes after 0822:00 UTC may be at least partially an artifact of the NTV moving away from RaXPOL, which limits the analysis of their evolution to a primarily qualitative evaluation.

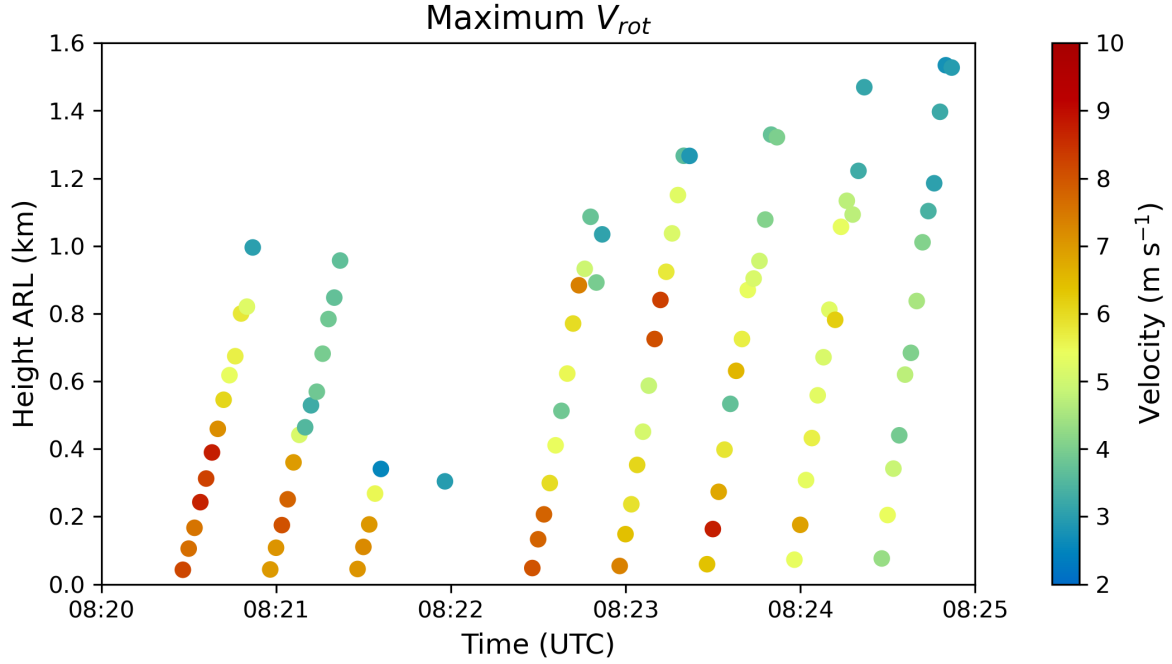


Figure 3.15: As in Fig. 3.14, but for V_{rot} .

These analyses also illustrate a third key feature that may be related to tornadogenesis failure mechanisms: the directionality of vortex dissipation. In Fig. 3.15, the NTV shows periods of weakening between 0820:30–0821:30 UTC and again after 0824:00 UTC, with a brief period of reintensification below 1 km ARL around 0823:00 UTC (Note: because of the range dependence of ζ' , the directionality of vortex weakening is primarily determined using V_{rot}). During the first weakening period, the NTV decays in a top-down manner almost immediately after it forms at 0820:30 UTC, with V_{rot} rapidly decreasing throughout the profile except in the lowest 100 m. Figs. 3.9b and 3.10b show that from 0820:30 to 0821:00 UTC, rotation weakens most rapidly within the layer of maximum tilt between 800–1000 m ARL. The second weakening period after 0824:00 also shows dissipation happening more rapidly aloft than near the surface, although the overall magnitudes of V_{rot} weaken simultaneously throughout the full profile. Moreover, in Figs. 3.12b and 3.13b, the NTV appears shallower overall

after 0822:30 UTC, with the depth of positive ζ' only extending to ~ 600 m AGL—coincident with the layer of maximum tilt during the first weakening period. As the V_{rot} maximum is in the lowest few hundred meters throughout the entire time period, and both V_{rot} and ζ' tend to weaken more rapidly aloft during periods of vortex weakening, top-down dissipation appears to be the dominant mode of decay for the NTV, and dissipation initiates in the layer of greatest tilt. Processes potentially related to this NTV decay mode and tornadogenesis failure are discussed further in the following section.

3.4.2 The role of the cold pool

Cold pool processes are important to storm- and tornado-scale processes in QLCSs just as they are in supercells. The important NTV features discussed in the previous section—vortex tilt, lack of surface vorticity, and top-down weakening—may all be connected to the characteristics of the cold pool. In combination with the radar evolution of the NTV and its vertical structure, the surface observations collected by the mobile mesonets around the mesovortex can provide further insight into processes that may have impeded tornadogenesis. Since it is hypothesized that the role of the cold pool in inhibiting tornadogenesis is substantial, this analysis focuses on identifying mechanisms by which the cold pool could have contributed to tornadogenesis failure.

Fig. 3.16 shows mobile mesonet measurements of temperature deficits (θ'_v) and surface winds collected around the circuit, with vortex-relative locations determined using the time-space conversion described in Section 3.2.2. Overall, these observations reveal an extremely weak cold pool surrounding the mesovortex and the NTV. At the start of the circuit (Fig. 3.16a), Probe 2 immediately enters the cold pool north of the mesovortex, while Probe 1 transects through the near-inflow environment directly ahead of the mesovortex. The θ'_v gradient measured by Probe 2 is extremely weak

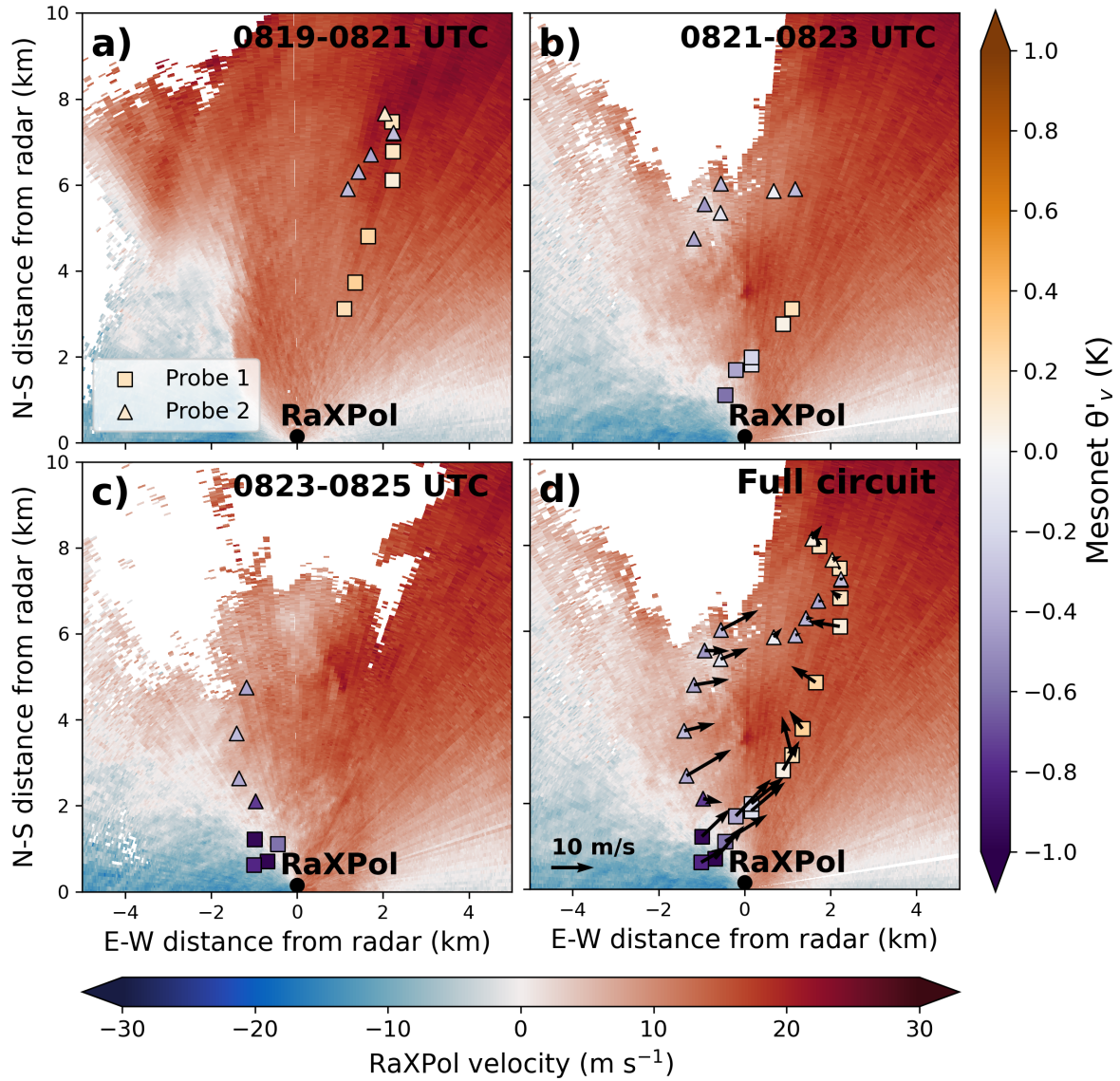


Figure 3.16: Radial velocity PPIs at the 2.4° tilt with 2-min subsets of the time-space converted mobile mesonet circuit (square and triangle markers), shaded by derived θ'_v (K). (a) Radial velocity at 0821 UTC with θ'_v between 0819–0821 UTC. (b) Radial velocity at 0823 UTC with θ'_v between 0821–0823 UTC. (c) Radial velocity at 0824:30 UTC with θ'_v between 0823–0825 UTC. (d) Radial velocity at 0823 UTC with mobile mesonet θ'_v and wind vectors from the full circuit.

in this portion of the circuit, with cold pool temperature deficits of only $\approx -0.4^\circ\text{C}$. Probe 1 observed slightly warmer temperatures in the near-inflow compared to the

ambient environment—however, these differences largely fall within the instrument error of $\pm 0.3^\circ\text{C}$, so this may not be meaningful.

During the north and south legs in the middle of the circuit (Fig. 3.16b), Probe 1 crosses the gust front and both probes continue into the cold pool as the mesovortex passes between them. Both mesonets display a continued decrease in θ'_v . However, Probe 1 shows a slightly more rapid decrease in temperatures across the gust front than Probe 2 did, indicating a slightly stronger θ'_v gradient to the south of the mesovortex. During the final transect of the circuit (Fig. 3.16c), θ'_v continues to decrease in the cold pool behind and to the south of the mesovortex. Around the full closed circuit in Fig. 3.16d, the measured winds indicate surface convergence surrounding the mesovortex and NTV. As with cold pool strength, convergence is also strongest south of the mesovortex, where the near-surface inflow wind speeds are strongest as measured by Probe 1.

Although the cold pool temperature gradient is slightly larger to the south of the mesovortex, it is important to note that the largest measured temperature deficits during the transect are only around -1.1°C . The cold pool surrounding the mesovortex is extremely weak, which may be a result of the nearly saturated environmental profile seen in Fig. 3.5. The strongest mass convergence in Fig. 3.16d is also focused more to the south of the mesovortex, rather than directly near it, and the maximum surface wind speeds are around 12 m s^{-1} . The weakness of the cold pool may have contributed to possibly weak surface convergence by limiting the cold pool outflow strength and propagation speeds.

3.4.3 Inferred processes contributing to tornadogenesis failure

The key NTV characteristics identified in the previous sections—lack of strong surface rotation, vortex tilt, and top-down dissipation mode—could all plausibly be explained

by the weakness of the cold pool. While tornadogenesis failure in supercells is typically associated with stronger cold pools, this relationship may not be completely applicable to QLCSs, which feature more dominant cold pool processes. Baroclinic generation of horizontal vorticity along the cold pool leading edge has been shown to contribute to both tornadogenesis and mesovortexgenesis in QLCSs (Flournoy and Coniglio 2019; McDonald and Weiss 2021). Stronger cold pools also generate stronger surface convergence along the gust front, which is known to be important for amplifying near-surface vertical vorticity during tornadogenesis (e.g., Marquis et al. 2012). Baroclinity and surface convergence may be weak in this case, which would have inhibited both the production and amplification of near-surface vorticity needed for tornadogenesis.

In addition to inhibiting the production of surface rotation, the cold pool could also have contributed to the transience of the nontornadic vortices, or the storm’s inability to maintain a tornado-strength vortex. Alignment with the parent updraft is known to be important to tornado maintenance (e.g., Wicker and Wilhelmson 1995; Dowell and Bluestein 2002; Lee et al. 2012; Marquis et al. 2012, 2016; McKeown et al. 2020). The storm updraft provides the upward vertical perturbation pressure gradient acceleration (VPPGA) necessary for a tornado to sustain itself; if the tornado becomes displaced from this source, the VPPGA instead becomes directed downward due to the nonlinear dynamic effect of the strong rotation, and the tornado dissipates. Displacement from the updraft also advects the tornado away from the zone of surface convergence beneath the updraft, disrupting the amplification of strong surface vertical vorticity to tornado intensity. A balance between outflow and inflow strength is important to maintaining this alignment—if outflow is too strong (e.g., Wicker and Wilhelmson 1995; Lee et al. 2012; Murdzek et al. 2020) or too weak (e.g. Dowell and Bluestein 2002), the tornado is advected away from the updraft. The cold pool in this QLCS was extremely weak

and the NTV displayed substantial tilt above the lowest few hundred m, suggesting misalignment of the surface vortex with the leading edge updraft.

The top-down mode of dissipation of the main NTV is also consistent with the loss of upward VPPGA due to displacement from the leading updraft, as well as the observed vortex tilt. Top-down dissipation of tornadoes in supercells has been seen in previous rapid-scan radar observations of tornado dissipation by French et al. (2014) and Griffin et al. (2019), which also found that the tornadoes began to dissipate first within the layer of maximum vortex tilt. Houser et al. (2015) found that while dissipation of tornado-strength rotation happened simultaneously through the depth of the tornado, dissipation of *subtornadic* rotation occurred in a top-down manner. Between these studies, it can be concluded that tornado dissipation is partially related to displacement from the parent updraft, while the top-down mode of dissipation may be related to vortex tilt and the decoupling of the surface vortex from the vortex aloft. The dissipation behavior of the NTV in this case study is consistent with all of these previous studies and their conclusions. Once the NTV became separated from the leading updraft, its rotation would first dissipate aloft, as a remnant upward VPPGA would still exist at the lower levels of the tornado due to nonlinear dynamic effects of the rotation in the layers above.

These processes are reminiscent of known mechanisms for occluding supercell tornado dissipation, as in Dowell and Bluestein (2002). We hypothesize that those same processes had a crucial role in QLCS tornadogenesis failure in this case, and more broadly that tornado dissipation and tornadogenesis failure may have similar mechanisms. The location of the low-level rotation in the NTVs within the cold pool is consistent with this process. Via this mechanism, the too-weak outflow would have allowed the inflow to advect the NTVs into or above the cold pool, thereby (1) displacing them from the parent updraft, (2) removing them from the zone of surface

convergence, and (3) isolating them from buoyant inflow air. Because these processes happened almost immediately after the genesis of the NTV, they could have inhibited the development and amplification of rotation to tornado intensity. While the role of tornado dissipation processes in tornadogenesis failure has not been definitively studied, similar implications have been suggested in past work. Sherburn and Parker (2019) and Lovell and Parker (2022) found that most transient subtornadic vortices in simulated QLCSs lacked either surface vorticity or a strong low-level updraft, and hypothesized that the tilting and stretching process was too brief to fully generate and consolidate a tornadic surface vortex as a result. While the findings of this research are somewhat speculative as well, our observations are interpreted in the context of several past studies that offer supporting insight into the processes underlying tornadogenesis failure in this case.

3.4.4 Vorticity worms

While the primary focus of this work is the physical mechanisms of tornadogenesis failure, there are some features worth discussing that may be related to the genesis of the nontornadic vortices. Typically, the genesis of clusters of tornado-scale vortices in a QLCS is attributed to horizontal shearing instability (HSI) release along the leading edge of the gust front (e.g., Forbes and Wakimoto 1983; Przybylinski 1995; Wheatley and Trapp 2008; Conrad and Knupp 2019). However, the theory of HSI release predicts that the wavelength between shearing instabilities should be 7–8 times the width of the vortex sheet, or on the order of ~ 10 km. The spacing between the nontornadic vortices in this work, by contrast, is on the order of 0.1–1 km, which is far too small to be explained by HSI release.

As speculated previously, the persistence of the main NTV appears to be associated with a potential contraction of several nearby ζ' patches and an elongated region of

large cyclonic ζ' , which could reflect processes similar to tornadogenesis via vortex patch roll-up. However, this does not address the initial genesis of the cluster of NTVs. As briefly mentioned at the beginning of Section 3.4.1, the low-level RaXPol velocity fields in Fig. 3.8 feature thin line-parallel streaks of enhanced outbound velocities in the near environmental inflow between 0820–0821:30 UTC. In ζ' fields at the lowest tilt, the velocity streaks correspond to similarly oriented streaks of local ζ' maxima (Fig. 3.17). Such streaks of enhanced near-surface vertical vorticity, or “vorticity worms,” have been seen in the near inflow ahead of observed and simulated tornadic supercells, and are speculated to have some role in tornadogenesis or the tornadic potential of supercell (Coniglio et al. 2024; Markowski 2024; Fischer et al. 2024). Vorticity worms are organized vertical vorticity anomalies in supercell near-inflow environments, and are located on the descending branch of coherent turbulent structures that are well-known to occur in surface layers. These streaks are aligned with the mean flow and oriented perpendicular to the environmental shear-generated vortex lines.

At 0820 UTC, the worms develop within the inflow approximately 2 km east of the leading edge of the QLCS, and only one nontornadic vortex has formed at this point (Fig. 3.17a). By 0820:30 UTC, the worms are much closer to the leading edge of the QLCS, and they remain just ahead of the leading edge through 0821:30 UTC (Fig. 3.17b–d). The advection of the worms to the leading edge of the QLCS coincides with the formation of three more nontornadic vortices in the cluster, which suggests that the worms could have had a role in their genesis. The worms are no longer visible in the near inflow by 0822:30 UTC (not shown), and their disappearance coincides with the demise of the vortices except for the main NTV after 0823. These results suggest that vorticity worms could have been an important source of low-level vorticity for both the genesis and maintenance of the vortex cluster, and their disappearance may have contributed to their transience. Their presence could reflect the strong environmental

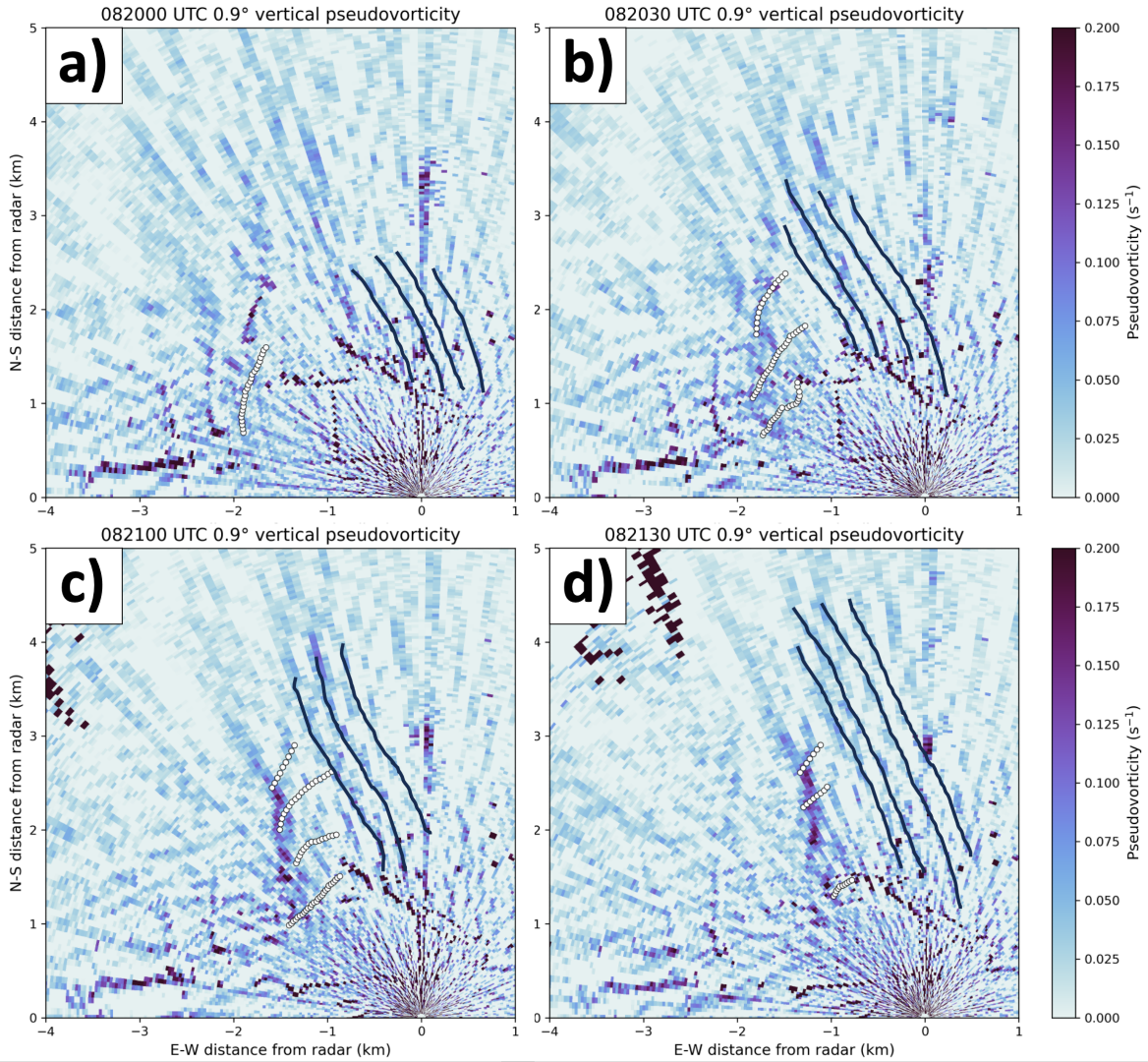


Figure 3.17: PPIs of ζ' at the 0.9° tilt at (a) 0820 UTC, (b) 0820:30 UTC, (c) 0821 UTC, and (d) 0821:30 UTC. Ground traces of all NTVs in the initial vortex cluster are denoted by white circle markers. Vorticity worms are annotated by the black lines.

horizontal vorticity that is then tilted by the gust front, which may have additionally contributed to the tilt and orientation of the vortices. Vorticity worms have so far only been identified, observed, and studied in supercell near-inflow environments, so the vorticity worms sampled by RaXPol would be the first instance of worms in a nocturnal QLCS environment. Vorticity worms are a novel feature identified in simulated and

observed convective inflow environments, so the degree to which they influence low-level and surface vortex evolution is still generally uncertain, especially for QLCSs with more dominant cold pool processes.

3.5 Conclusions

This work was motivated by the need for targeted observations of QLCSs to better understand the genesis and evolution of QLCS mesovortices and tornadoes in the Southeast. The observations collected by RaXPol and the mobile mesonets during PERiLS comprise a highly novel dataset of high-resolution, close-range mobile radar observations and a closed circuit of surface observations specifically targeting low-level and near-surface processes occurring in mesovortices. RaXPol observations of a non-tornadic mesovortex reveal the cyclic formation and dissipation of multiple transient subtornadic NTVs over a 5-min analysis period. The characteristics and evolution of the strongest, longest-lived NTV were analyzed in detail to investigate the potential influence of storm-scale features on tornadogenesis failure in a previously tornadic QLCS.

RaXPol velocity observations and derived pseudovorticity fields were used to evaluate the intensity, structure, and evolution of the NTV. Three key characteristics for inferring mechanisms of tornadogenesis failure were identified from the vertical structure and evolution of the NTV: vortex tilt, top-down dissipation, and lack of surface vorticity. Composite cross sections of ζ' through the NTV reveal notable vertical tilt in the axis of rotation aloft, with the lowest-level rotation located storm-relative rearward from the rotation aloft. This vortex orientation indicates differential advection of the near-surface vortex away from the leading edge and into the cold pool. In vertical profiles of ζ' and V_{rot} , the maximum rotational intensity is consistently located above

the lowest tilts, suggesting an inability of the storm to generate and amplify surface rotation. The evolution of these vertical profiles shows that during periods of NTV weakening, (1) ζ' and V_{rot} magnitudes tend to decrease more rapidly aloft than near the surface, resulting in top-down dissipation similar to previous tornado studies (e.g., French et al. 2014; Griffin et al. 2019), and (2) the NTV appears to dissipate first in the layer of maximum tilt and last near the surface.

Cold pool characteristics are known to modulate tornadic potential and tornado evolution in both supercells and QLCSs. Mobile mesonet observations offer further insight into the processes underlying tornadogenesis failure and the role of the cold pool characteristics in inhibiting tornado formation. While many past studies have concluded that nontornadic storms have relatively stronger cold pools than tornadic storms (e.g., Wicker and Wilhelmson 1995; Markowski et al. 2002; Grzych et al. 2007; Hirth et al. 2008; Lee et al. 2012; French et al. 2015; Flournoy et al. 2020; Murdzek et al. 2020), there are also been studies that found nontornadic storms to be associated with weaker cold pools (e.g., Naylor and Gilmore 2014; McDonald and Weiss 2021). In this case study, the cold pool surrounding the mesovortex was extremely weak, with a temperature deficit of only $\theta'_v \approx -1.1$ K behind the leading edge. The notable weakness of the cold pool is hypothesized to have had multiple roles in tornadogenesis failure: (1) Inhibiting the storm’s ability to *generate* strong rotation, especially at the surface; and (2) Inhibiting the storm’s ability to *sustain* strong rotation long enough for a vortex to reach tornadic intensity.

Inability to generate rotation: The extremely small temperature deficit would have resulted in a lack of baroclinity and surface convergence along the gust front, preventing the production and amplification of near-surface vorticity.

Inability to sustain rotation: The weakness of the outflow would have allowed the inflow to advect the NTV into the cold pool. This would have disrupted the NTV’s

access to upward VPPGA from the leading updraft, surface convergence, and buoyant inflow air. The top-down weakening and observed vortex tilt could also reflect this process. Vortex tilt would similarly interrupt intensification by decoupling near-surface rotation from the vortex aloft.

The processes that impede a storm’s ability to sustain strong rotation are reminiscent of known mechanisms for tornado dissipation in supercells. However, we hypothesize that these processes could potentially also serve to inhibit tornadogenesis by interrupting the initial amplification of vorticity before the developing vortex could reach tornadic strength in the first place, which was also proposed by Sherburn and Parker (2019) and Lovell and Parker (2022) to explain the evolution of transient subtornadic vortices in simulated HSLC QLCSs. One implication of this is that tornado dissipation and tornadogenesis failure may result from similar processes. Another larger implication arising from these results is that conventionally “supercell-like” mechanisms for the genesis, maintenance, and interruption of tornado-scale vortices may occur in QLCSs alongside (and potentially simultaneously with) linear mode-specific processes like horizontal shearing instability release and cold pool-driven dynamics. The potential overlap between supercell and QLCS processes is evident in the similarities between the hypothesized QLCS tornadogenesis failure modes and known supercell tornado dissipation mechanisms, as well as in the apparent presence of vorticity worms in the QLCS near-inflow and their potential influence on tornado-scale processes.

Chapter 4

Conclusions and Future Work

The impacts of severe storms and tornadoes are uniquely compounded in the Southeastern United States in part due to the frequency of QLCS tornadoes, which are associated with lower probability of detection and higher false alarm rates. Much progress has been made in recent years toward understanding Southeast QLCSs and their environments, dynamics, and impacts. However, there are still many unanswered questions about how and why QLCS mesovortices and tornadoes form and what makes a QLCS tornadic. These remaining questions culminated in the PERiLS field campaign in 2022–2023, which was the first large field project to specifically target severe QLCSs in the Southeast. Because of their substantial human impacts, this work has focused on understanding the processes involved in the formation and evolution of mesovortices and tornadoes in Southeast QLCSs using both idealized simulations and high-resolution observations. This work has shown similarities between the physical processes occurring in QLCSs and those known to occur in supercells, which are much better understood from decades of supercell-focused research. The outcomes from this work can hopefully be used to improve the detection of potentially tornadic mesovortices and ultimately improve tornado warning lead times in Southeastern QLCSs.

The overarching objectives of this research were to evaluate the nature of physical processes involving both *storm-scale* and *tornado-scale* rotation in potentially tornadic QLCSs. This work was carried out using a combination of high-resolution idealized simulations and novel observational datasets of high-resolution radar observations and

coordinated mobile mesonet surface measurements from PERiLS. From these analyses, the following conclusions are presented:

1. Storm-scale processes in an embedded mesocyclone in a QLCS-supercell merger:

- Low-level rotation in the mesocyclone originates partially in parcels from a mid-level environment inflow source, which has been seen in both supercells and mesoscale convective systems.
- Low-level vertical vorticity is produced via tilting by both the downdraft and updraft through a combination of the Davies-Jones and Brooks (1993) downdraft mechanism and the Boyer and Dahl (2020) in-and-up mechanism.
- Low-level crosswise horizontal vorticity is produced via baroclinity within the downdraft and amplified before entering the mesocyclone via stretching in a low-level horizontal rotor.
- *The mechanisms for vertical vorticity generation are supercell-like, while the mechanisms for crosswise horizontal vorticity generation are more uniquely QLCS-like.*

2. Tornado-scale processes in an observed nontornadic QLCS mesovortex:

- The weak cold pool allowed nontornadic vortices to be advected away from the leading updraft, preventing them from intensifying to tornadic strength.
- Development of strong surface rotation was inhibited by the weak cold pool. Baroclinic horizontal vorticity production and surface vertical vorticity organization were likely limited by the weak buoyancy gradient and possibly weak surface convergence.

- Vorticity worms in the near inflow of the mesovortex may have contributed to the formation of the nontornadic vortices. Vorticity worms have previously been found in the near inflow of tornadic supercells.
- *Cold pool weakness contributed to tornadogenesis failure via multiple mechanisms, and these processes may be similar to tornado dissipation processes.* The processes preventing vortex intensification are similar to supercell tornado dissipation processes, while the processes inhibiting surface vortex development are both supercell-like and QLCS-like in nature.

The various physical mechanisms involved in storm-scale mesocyclone rotation and tornadogenesis failure in these analyses are comprised of a combination of supercell-like processes and uniquely QLCS-like processes. In the simulated QLCS-supercell merger, the downdraft and in-and-up mechanisms for generation of low-level vertical vorticity were first identified in studies of supercell mesocyclones, and have since also been found in QLCSs by previous work. However, the mechanisms for horizontal vorticity generation via baroclinity and stretching in a rotor are more uniquely related to the linear morphology of the QLCS. Likewise, tornadogenesis failure in the observed QLCS mesovortex was attributed in part to the displacement of the nontornadic vortices from the updraft before they could reach tornadic intensity due to the weakness of the cold pool, which is a mechanism known to contribute to supercell tornado dissipation. Strong surface rotation was inhibited by potentially weak surface convergence and a probable lack of baroclinic horizontal vorticity production by the weak buoyancy gradient, which are also important to supercell tornadogenesis. Vorticity worms have only been found near supercells so far, and have never been observed in association with a QLCS before these high-resolution radar analyses. These outcomes ultimately imply that the mechanisms for mesocyclone/mesovortex formation and tornadogenesis in supercells and QLCSs may not be as distinct as has been traditionally assumed.

There are a wide range of potential avenues for future work stemming from these results. Integrated vorticity budgets and pressure perturbation analysis for the simulated merger in Chapter 2 may provide more insight into the forcing mechanisms and vorticity generation processes in the downdraft and how these processes evolve. These simulations could also be extended to study the influence of mergers on tornado production and the nature of tornadogenesis mechanisms in a merger. More work is needed to address the influence of an approaching QLCS on supercell evolution. In our simulations, the pre-merger supercell featured a more rapidly strengthening low-level mesocyclone than the isolated supercell, implying that a QLCS meaningfully modifies the near-storm ambient environment ahead of it, which is consistent with previous work on this topic (e.g., French 2014). Ensemble simulation studies would be useful to determine a range of outcomes of QLCS-supercell mergers and their intrinsic predictability. These outcomes may vary with different thermodynamic environments, different low-level wind shear vector, or the maturity of the supercell or QLCS. Any simulation work will benefit from observations to corroborate findings—for example, a windsonde launched into a tornadic QLCS mesovortex in Holly Pond, AL, followed a similar trajectory to the up-down trajectories of the mid-level parcels in our simulations (A. Lyza, personal communication 2024).

The outcomes from the radar and surface analysis in Chapter 3 motivate further examination of existing PERiLS datasets to better understand the range of QLCS tornadogenesis failure modes. More observations of potentially tornadic mesovortices in varying Southeast convective environments are needed to better gauge a range of outcomes for QLCS tornadogenesis and failure, and their relationship to the cold pool. The convective environment is known to influence cold pool strength, and it may also have a role in modulating how the cold pool influences a storm’s tornadic potential. A limitation of this study is the lack of a tornadic case for comparison. The nearby

tornadic mesovortex was not observed by either RaXPol or the mobile mesonets, so it is unknown whether the cold pool characteristics were meaningfully different near the tornadic mesovortex compared to the nontornadic mesovortex. Many open questions remain about the mechanisms for tornadogenesis in QLCSs, and more observational datasets of both tornadic and nontornadic mesovortices will enable more comprehensive analyses of the processes involved in QLCS tornado formation and failure. These efforts would greatly benefit from phased array radar technology, which will facilitate rapid volumetric observations of these difficult-to-observe phenomena.

The overarching implication of this work is that Southeast QLCSs can feature a combination of both supercell-like and QLCS-like processes for storm-scale and tornado-scale rotation. These results raise larger questions that warrant future study. What modulates how supercell-like a QLCS mesovortex or tornado is? For example, are there relationships to the thermodynamic and kinematic environment, cold pool characteristics, storm interactions, or other factors? How often do the supercell-like processes found in this work occur in QLCS mesovortices and tornadoes? Do these processes also occur in QLCSs in higher-CAPE environments? Finally, are conventionally “supercell-like” and “QLCS-like” processes truly distinct from each other, or can any of these processes occur in any rotating updraft? Future research in these areas will continue to clarify the small-scale processes important to QLCS tornado production and identify possible ways to detect them in real time using current and future observing technologies, ultimately improving forecasts of QLCS tornadoes.

Reference List

- Anderson-Frey, A. K., Y. P. Richardson, A. R. Dean, R. L. Thompson, and B. T. Smith, 2016: Investigation of near-storm environments for tornado events and warnings. *Wea. Forecasting*, **31**, 1771–1790, <https://doi.org/10.1175/WAF-D-16-0046.1>.
- Anderson-Frey, A. K., Y. P. Richardson, A. R. Dean, R. L. Thompson, and B. T. Smith, 2019: Characteristics of tornado events and warnings in the Southeastern United States. *Wea. Forecasting*, **34**, 1017–1034, <https://doi.org/10.1175/WAF-D-18-0211.1>.
- Ashley, W. S., 2007: Spatial and temporal analysis of tornado fatalities in the United States: 1880–2005. *Wea. Forecasting*, **22**, 1214–1228, <https://doi.org/10.1175/2007WAF2007004.1>.
- Ashley, W. S., A. M. Haberlie, and J. Strohm, 2019: A climatology of quasi-linear convective systems and their hazards in the United States. *Wea. Forecasting*, **34**, 1605–1631, <https://doi.org/10.1175/WAF-D-19-0014.1>.
- Atkins, N. T., J. M. Arnott, R. W. Przybylinski, R. A. Wolf, and B. D. Ketcham, 2004: Vortex structure and evolution within bow echoes. Part I: Single-Doppler and damage analysis of the 29 June 1998 derecho. *Mon. Wea. Rev.*, **132**, 2224–2242, [https://doi.org/10.1175/1520-0493\(2004\)132<2224:VSAEWB>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<2224:VSAEWB>2.0.CO;2).
- Atkins, N. T., C. S. Bouchard, R. W. Przybylinski, R. J. Trapp, and G. Schmocker, 2005: Damaging surface wind mechanisms within the 10 June 2003 Saint Louis bow echo during BAMEX. *Mon. Wea. Rev.*, **133**, 2275–2296, <https://doi.org/10.1175/MWR2973.1>.
- Atkins, N. T., and M. St. Laurent, 2009a: Bow echo mesovortices. Part I: Processes that influence their damaging potential. *Mon. Wea. Rev.*, **137**, 1497–1513, <https://doi.org/10.1175/2008MWR2649.1>.
- Atkins, N. T., and M. St. Laurent, 2009b: Bow echo mesovortices. Part II: Their genesis. *Mon. Wea. Rev.*, **137**, 1514–1532, <https://doi.org/10.1175/2008MWR2650.1>.
- Bernardet, L. R., and W. R. Cotton, 1998: Multiscale evolution of a derecho-producing mesoscale convective system. *Mon. Wea. Rev.*, **126**, 2991–3015, [https://doi.org/10.1175/1520-0493\(1998\)126<2991:MEOADP>2.0.CO;2](https://doi.org/10.1175/1520-0493(1998)126<2991:MEOADP>2.0.CO;2).
- Blind-Doskocil, L. M., 2023: Radar and model-based studies of mesovortices in cool-season quasi-linear convective systems. M.S. thesis, Dept. of Atmospheric Sciences, University of Illinois Urbana–Champaign, 81 pp., URL <https://hdl.handle.net/2142/121541>.

- Bluestein, H. B., M. M. French, R. L. Tanamachi, S. Frasier, K. Hardwick, F. Junyent, and A. L. Pazmany, 2007: Close-range observations of tornadoes in supercells made with a dual-polarization, X-band, mobile Doppler radar. *Mon. Wea. Rev.*, **135**, 1522–1543, <https://doi.org/10.1175/MWR3349.1>.
- Bluestein, H. B., W.-C. Lee, M. Bell, C. C. Weiss, and A. L. Pazmany, 2003a: Mobile Doppler radar observations of a tornado in a supercell near Bassett, Nebraska, on 5 June 1999. Part I: Tornado-vortex structure. *Mon. Wea. Rev.*, **131**, 2968–2984, [https://doi.org/10.1175/1520-0493\(2003\)131<2968:MDROOA>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<2968:MDROOA>2.0.CO;2).
- Bluestein, H. B., K. J. Thiem, J. C. Snyder, and J. B. Houser, 2018: The multiple-vortex structure of the El Reno, Oklahoma, tornado on 31 May 2013. *Mon. Wea. Rev.*, **146**, 2483–2502, <https://doi.org/10.1175/MWR-D-18-0073.1>.
- Bluestein, H. B., K. J. Thiem, J. C. Snyder, and J. B. Houser, 2019: Tornadogenesis and early tornado evolution in the El Reno, Oklahoma, supercell on 31 May 2013. *Mon. Wea. Rev.*, **147**, 2045–2066, <https://doi.org/10.1175/MWR-D-18-0338.1>.
- Bluestein, H. B., C. C. Weiss, and A. L. Pazmany, 2003b: Mobile Doppler radar observations of a tornado in a supercell near Bassett, Nebraska, on 5 June 1999. Part I: Tornadogenesis. *Mon. Wea. Rev.*, **131**, 2954–2967, [https://doi.org/10.1175/1520-0493\(2003\)131<2954:MDROOA>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<2954:MDROOA>2.0.CO;2).
- Bluestein, H. B., C. C. Weiss, and A. L. Pazmany, 2004: The vertical structure of a tornado near Happy, Texas, on 5 May 2002: High-resolution, mobile, W-band, Doppler radar observations. *Mon. Wea. Rev.*, **132**, 2325–2337, [https://doi.org/10.1175/1520-0493\(2004\)132<2325:TVSOAT>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<2325:TVSOAT>2.0.CO;2).
- Boyer, C. H., and J. M. L. Dahl, 2020: The mechanisms responsible for large near-surface vertical vorticity within simulated supercells and quasi-linear storms. *Mon. Wea. Rev.*, **148**, 4281–4297, <https://doi.org/10.1175/MWR-D-20-0082.1>.
- Brotzge, J. A., S. E. Nelson, R. L. Thompson, and B. T. Smith, 2013: Tornado probability of detection and lead time as a function of convective mode and environmental parameters. *Wea. Forecasting*, **28**, 1261–1276, <https://doi.org/10.1175/WAF-D-12-00119.1>.
- Bryan, G. H., J. C. Wyngaard, and J. M. Fritsch, 2003: Resolution requirements for the simulation of deep moist convection. *Mon. Wea. Rev.*, **131**, 2394–2416, [https://doi.org/10.1175/1520-0493\(2003\)131<2394:RRFTSO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<2394:RRFTSO>2.0.CO;2).
- Calianese, E. J., J. K. Jordan, E. B. Curran, A. R. Moller, and G. Woodall, 2002: The Mayfest high-precipitation supercell of 5 May 1995: A case study. *21st Conf. on Severe Local Storms*, Amer. Meteor. Soc., San Antonio, TX, P3.4, https://ams.confex.com/ams/SLS_WAF_NWP/techprogram/paper_47099.htm.

- Coffer, B. E., and M. D. Parker, 2017: Simulated supercells in nontornadic and tornadic VORTEX2 environments. *Mon. Wea. Rev.*, **145**, 149–180, <https://doi.org/10.1175/MWR-D-16-0226.1>.
- Coffer, B. E., M. D. Parker, J. M. Peters, and A. R. Wade, 2023: Supercell low-level mesocyclones: Origins of inflow and vorticity. *Mon. Wea. Rev.*, **151**, 2205–2232, <https://doi.org/10.1175/MWR-D-22-0269.1>.
- Coniglio, M. C., J. Gebauer, R. A. Saba, T. M. Bell, R. M. Frost, and M. Diedrichsen, 2024: In search of vortex patches and vorticity worms: Observations of near-ground flow underneath supercells using a Doppler wind lidar. *31st Conf. on Severe Local Storms*, Amer. Meteor. Soc., Virginia Beach, VA, 5.1, URL <https://ams.confex.com/ams/31SLS/meetingapp.cgi/Paper/444940>.
- Conrad, D. M., and K. R. Knupp, 2019: Doppler radar observations of horizontal shearing instability in quasi-linear convective systems. *Mon. Wea. Rev.*, **147**, 1297–1318, <https://doi.org/10.1175/MWR-D-18-0257.1>.
- Dahl, J. M. L., 2015: Near-ground rotation in simulated supercells. *Mon. Wea. Rev.*, **143**, 4929–4942, <https://doi.org/10.1175/MWR-D-15-0115.1>.
- Dahl, J. M. L., 2017: Tilting of horizontal shear vorticity and the development of updraft rotation in supercell thunderstorms. *J. Atmos. Sci.*, **74**, 2997–3020, <https://doi.org/10.1175/JAS-D-17-0091.1>.
- Dahl, J. M. L., 2020: Near-surface vortex formation in supercells from the perspective of vortex patch dynamics. *Mon. Wea. Rev.*, **148**, 3533–3547, <https://doi.org/10.1175/MWR-D-20-0080.1>.
- Dahl, J. M. L., M. D. Parker, and L. J. Wicker, 2014: Imported and storm-generated near-ground vertical vorticity in a simulated supercell. *J. Atmos. Sci.*, **71**, 3027–3051, <https://doi.org/10.1175/JAS-D-13-0123.1>.
- Davies-Jones, R., 1984: Streamwise vorticity: The origin of updraft rotation in supercell storms. *J. Atmos. Sci.*, **41**, 2991–3006, [https://doi.org/10.1175/1520-0469\(1984\)041<2991:SVTOOU>2.0.CO;2](https://doi.org/10.1175/1520-0469(1984)041<2991:SVTOOU>2.0.CO;2).
- Davies-Jones, R., 2015: A review of supercell and tornado dynamics. *Atmos. Res.*, **158–159**, 274–291, <https://doi.org/10.1016/j.atmosres.2014.04.007>.
- Davies-Jones, R., and H. E. Brooks, 1993: Mesocyclone from a theoretical perspective. *The tornado: Its Structure, Dynamics, Prediction, and Hazards*, *Geophys. Monogr.*, Vol. 79, Amer. Geophys. Union, 105–114.
- Davies-Jones, R., J. R. Trapp, and H. B. Bluestein, 2001: Tornadoes and tornadic storms. *Severe Convective Storms*, *Meteor. Monogr.*, Vol. 50, Amer. Meteor. Soc., 167–221.

- Davis, J. M., and M. D. Parker, 2014: Radar climatology of tornadic and nontornadic vortices in high-shear, low-CAPE environments in the Mid-Atlantic and Southeastern United States. *Wea. Forecasting*, **29**, 828–853, <https://doi.org/10.1175/WAF-D-13-00127.1>.
- Deardorff, J. W., 1980: Stratocumulus-capped mixed layers derived from a three-dimensional model. *Bound. -Layer Meteor.*, **18**, 495–527, <https://doi.org/10.1007/BF00119502>.
- Doswell, C. A., and D. W. Burgess, 1993: Tornadoes and tornadic storms: A review of conceptual models. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards, Geophys. Monogr.*, Vol. 79, Amer. Geophys. Union, 161–172.
- Dowell, D. C., and H. B. Bluestein, 2002: The 8 June 1995 McLean, Texas, storm. Part II: Cyclic tornado formation, maintenance, and dissipation. *Mon. Wea. Rev.*, **130**, 2649–2670, [https://doi.org/10.1175/1520-0493\(2002\)130<2649:TJMTSP>2.0.CO;2](https://doi.org/10.1175/1520-0493(2002)130<2649:TJMTSP>2.0.CO;2).
- Finley, C. A., M. Elmore, L. Orf, and B. D. Lee, 2023: Impact of the streamwise vorticity current on low-level mesocyclone development in a simulated supercell. *Geophys. Res. Lett.*, **50**, e2022GL100005, <https://doi.org/10.1029/2022GL100005>.
- Fischer, J., and J. M. L. Dahl, 2022: Transition of near-ground vorticity dynamics during tornadogenesis. *J. Atmos. Sci.*, **79**, 467–483, <https://doi.org/10.1175/JAS-D-21-0181.1>.
- Fischer, J., and J. M. L. Dahl, 2023: Supercell-external storms and boundaries acting as catalysts for tornadogenesis. *Mon. Wea. Rev.*, **151**, 23–38, <https://doi.org/10.1175/MWR-D-22-0026.1>.
- Fischer, J., J. M. L. Dahl, B. E. Coffey, J. L. Houser, P. M. Markowski, M. D. Parker, C. C. Weiss, and A. Schueth, 2024: Supercell tornadogenesis: Recent progress in our state of understanding. *Bull. Amer. Meteor. Soc.*, **105**, E1084–E1097, <https://doi.org/10.1175/BAMS-D-23-0031.1>.
- Fischer, J., M. D. Flournoy, and A. W. Lyza, 2023: Comments on “A climatology of cell mergers with supercells and their association with mesocyclone evolution” and “The influence of cell mergers on supercell characteristics and tornado evolution on 27–28 April 2011”. *Mon. Wea. Rev.*, **151**, 2541–2545, <https://doi.org/10.1175/MWR-D-23-0120.1>.
- Flournoy, M. D., and M. C. Coniglio, 2019: Origins of vorticity in a simulated tornadic mesovortex observed during PECAN on 6 July 2015. *Mon. Wea. Rev.*, **147**, 107–134, <https://doi.org/10.1175/MWR-D-18-0221.1>.
- Flournoy, M. D., M. C. Coniglio, E. N. Rasmussen, J. C. Furtado, and B. E. Coffey, 2020: Modes of storm-scale variability and tornado potential in VORTEX2 near- and

- far-field tornadic environments. *Mon. Wea. Rev.*, **148**, 4185–4207, <https://doi.org/10.1175/MWR-D-20-0147.1>.
- Flournoy, M. D., A. W. Lyza, M. A. Satrio, M. R. Diedrichsen, M. C. Coniglio, and S. Waugh, 2022: A climatology of cell mergers with supercells and their association with mesocyclone evolution. *Mon. Wea. Rev.*, **150**, 451–461, <https://doi.org/10.1175/MWR-D-21-0204.1>.
- Flournoy, M. D., and E. N. Rasmussen, 2023: The influence of convection initiation strength on subsequent simulated supercell evolution. *Mon. Wea. Rev.*, **151**, 2179–2203, <https://doi.org/10.1175/MWR-D-22-0069.1>.
- Forbes, G. S., and R. M. Wakimoto, 1983: A concentrated outbreak of tornadoes, downbursts and microbursts, and implications regarding vortex classification. *Mon. Wea. Rev.*, **111**, 220–236, [https://doi.org/10.1175/1520-0493\(1983\)111<0220:ACOOTD>2.0.CO;2](https://doi.org/10.1175/1520-0493(1983)111<0220:ACOOTD>2.0.CO;2).
- French, A. J., 2014: The response of a simulated supercell to environmental perturbations induced by an approaching squall line. *27th Conf. on Severe Local Storms*, Amer. Meteor. Soc., Madison, WI, 15B.5, <https://ams.confex.com/ams/27SLS/webprogram/Paper253982.html>.
- French, A. J., 2017: A tale of two mergers: Comparing examples of tornado-producing and non-tornado-producing QLCS-supercell mergers in western South Dakota. *Special Symp. on Severe Local Storm, 97th Annual Mtg.*, Amer. Meteor. Soc., Seattle, WA, 943, <https://ams.confex.com/ams/97Annual/webprogram/Paper312636.html>.
- French, A. J., and M. D. Parker, 2012a: Idealized simulations of mergers between squall lines and isolated supercell thunderstorms. *26th Conf. on Severe Local Storms*, Amer. Meteor. Soc., Nashville, TN, 148, <https://ams.confex.com/ams/26SLS/webprogram/Paper211312.html>.
- French, A. J., and M. D. Parker, 2012b: Observations of mergers between squall lines and isolated supercell thunderstorms. *Wea. Forecasting*, **27**, 255–278, <https://doi.org/10.1175/WAF-D-11-00058.1>.
- French, A. J., and M. D. Parker, 2014: Numerical simulations of bow echo formation following a squall line-supercell merger. *Mon. Wea. Rev.*, **142**, 4791–4822, <https://doi.org/10.1175/MWR-D-13-00356.1>.
- French, M. M., H. B. Bluestein, I. PopStefanija, C. A. Baldi, and R. T. Bluth, 2014: Mobile, phased-array, Doppler radar observations of tornadoes at X-band. *Mon. Wea. Rev.*, **142**, 1010–1036, <https://doi.org/10.1175/MWR-D-13-00101.1>.
- French, M. M., D. W. Burgess, E. R. Mansell, and L. J. Wicker, 2015: Bulk hook echo raindrop sizes retrieved using mobile, polarimetric Doppler radar observations. *J. Appl. Meteor. Climatol.*, **54**, 423–450, <https://doi.org/10.1175/JAMC-D-14-0171.1>.

- Fujita, T. T., 1978: Manual of downburst identification for project NIMROD. SMRP Res. Pap. 117, University of Chicago, 104 pp.
- Gallus, W. A., N. A. Snook, and E. V. Johnson, 2008: Spring and summer severe weather reports over the Midwest as a function of convective mode: A preliminary study. *Wea. Forecasting*, **23**, 101–113, <https://doi.org/10.1175/2007WAF2006120.1>.
- Gibbs, J. G., and B. R. Bowers, 2019: Techniques and thresholds of significance for using WSR-88D velocity data to anticipate significant tornadoes. *J. Operational Meteor.*, **7**, 117–137, <https://doi.org/10.15191/nwajom.2019.0709>.
- Goodman, S. J., and K. R. Knupp, 1993: Tornadogenesis via squall line and supercell interaction: The November 15, 1989, Huntsville, Alabama, tornado. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards, Geophys. Monogr.*, **79**, 183–199, <https://doi.org/10.1029/GM079p0183>.
- Griffin, C. B., D. J. Bodine, J. M. Kurdzo, A. Mahre, and R. D. Palmer, 2019: High-temporal resolution observations of the 27 May 2015 Canadian, Texas, tornado using the Atmospheric Imaging Radar. *Mon. Wea. Rev.*, **147**, 873–891, <https://doi.org/10.1175/MWR-D-18-0297.1>.
- Grzych, M. L., B. D. Lee, and C. A. Finley, 2007: Thermodynamic analysis of supercell rear-flank downdrafts from Project ANSWERS. *Mon. Wea. Rev.*, **135**, 240–246, <https://doi.org/10.1175/MWR3288.1>.
- Hastings, R., and Y. Richardson, 2016: Long-term morphological changes in simulated supercells following mergers with nascent supercells in directionally varying shear. *Mon. Wea. Rev.*, **144**, 471–499, <https://doi.org/10.1175/MWR-D-15-0193.1>.
- Helmus, J. J., and S. M. Collis, 2016: The Python ARM Radar Toolkit (Py-ART), a library for working with weather radar data in the Python programming language. *J. Open Res. Software*, **4**, e25, <https://doi.org/10.5334/jors.119>.
- Hirth, B. D., J. L. Schroeder, and C. C. Weiss, 2008: Surface analysis of the rear-flank downdraft outflow in two tornadic supercells. *Mon. Wea. Rev.*, **136**, 2344–2363, <https://doi.org/10.1175/2007MWR2285.1>.
- Houser, J. L., H. B. Bluestein, and J. C. Snyder, 2015: Rapid-scan, polarimetric, Doppler radar observations of tornadogenesis and tornado dissipation in a tornadic supercell: The “El Reno, Oklahoma” storm of 24 May 2011. *Mon. Wea. Rev.*, **143**, 2685–2710, <https://doi.org/10.1175/MWR-D-14-00253.1>.
- Houser, J. L., H. B. Bluestein, and J. C. Snyder, 2016: A finescale radar examination of the tornadic debris signature and weak-echo reflectivity band associated with a large, violent tornado. *Mon. Wea. Rev.*, **144**, 4101–4130, <https://doi.org/10.1175/MWR-D-15-0408.1>.

- Houser, J. L., H. B. Bluestein, K. Thiem, J. Snyder, D. Reif, and Z. Wienhoff, 2022: Additional evaluation of the spatiotemporal evolution of rotation during tornadogenesis using rapid-scan mobile radar observations. *Mon. Wea. Rev.*, **150**, 1639–1666, <https://doi.org/10.1175/MWR-D-21-0227.1>.
- Kis, A. K., and J. M. Straka, 2010: Nocturnal tornado climatology. *Wea. Forecasting*, **25**, 545–561, <https://doi.org/10.1175/2009WAF2222294.1>.
- Kosiba, K., and J. Wurman, 2010: The three-dimensional axisymmetric wind field structure of the Spencer, South Dakota, 1998 tornado. *J. Atmos. Sci.*, **67**, 3074–3083, <https://doi.org/10.1175/2010JAS3416.1>.
- Kosiba, K., J. Wurman, Y. Richardson, P. Markowski, P. Robinson, and J. Marquis, 2013: Genesis of the Goshen County, Wyoming, tornado on 5 June 2009 during VORTEX2. *Mon. Wea. Rev.*, **141**, 1157–1181, <https://doi.org/10.1175/MWR-D-12-00056.1>.
- Kosiba, K. A., R. J. Trapp, and J. Wurman, 2008: An analysis of the axisymmetric three-dimensional low level wind field in a tornado using mobile radar observations. *Geophys. Res. Lett.*, **35**, L05 805, <https://doi.org/10.1029/2007GL031851>.
- Kosiba, K. A., and J. Wurman, 2013: The three-dimensional structure and evolution of a tornado boundary layer. *Wea. Forecasting*, **28**, 1552–1561, <https://doi.org/10.1175/WAF-D-13-00070.1>.
- Kosiba, K. A., and Coauthors, 2024: The Propagation, Evolution, and Rotation in Linear Storms (PERiLS) Project. *Bull. Amer. Meteor. Soc.*, E1768–E1799, <https://doi.org/10.1175/BAMS-D-22-0064.1>.
- Kuster, C. M., K. D. Sherburn, V. N. Mahale, T. J. Schuur, O. F. McCauley, and J. S. Schaumann, 2024: Radar signatures associated with quasi-linear convective system mesovortices. *Wea. Forecasting*, **39**, 1143–1161, <https://doi.org/10.1175/WAF-D-23-0144.1>.
- Lee, B. D., C. A. Finley, and C. D. Karstens, 2012: The Bowdle, South Dakota, cyclic tornadic supercell of 22 May 2010: Surface analysis or rear-flank downdraft evolution and multiple internal surges. *Mon. Wea. Rev.*, **140**, 3419–3441, <https://doi.org/10.1175/MWR-D-11-00351.1>.
- Lee, B. D., and R. B. Wilhelmson, 1997a: The numerical simulation of non-supercell tornadogenesis. Part I: Initiation and evolution of pretornadic mesocyclone circulations along a dry outflow boundary. *J. Atmos. Sci.*, **54**, 32–60, [https://doi.org/10.1175/1520-0469\(1997\)054<0032:TNSONS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1997)054<0032:TNSONS>2.0.CO;2).
- Lee, B. D., and R. B. Wilhelmson, 1997b: The numerical simulation of non-supercell tornadogenesis. Part II: Evolution of a family of tornadoes along a weak outflow

- boundary. *J. Atmos. Sci.*, **54**, 2387–2415, [https://doi.org/10.1175/1520-0469\(1997\)054<2387:TNSONT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1997)054<2387:TNSONT>2.0.CO;2).
- Lovell, L. T., and M. D. Parker, 2022: Simulated QLCS vortices in a high-shear, low-CAPE environment. *Wea. Forecasting*, **37**, 989–1012, <https://doi.org/10.1175/WAF-D-21-0133.1>.
- Lyza, A. W., A. W. Clayton, K. R. Knupp, E. Lenning, M. T. Friedlein, R. Castro, and E. S. Bentley, 2017: Analysis of mesovortex characteristics, behavior, and interactions during the second 30 June–1 July 2014 Midwestern derecho event. *Electron. J. Severe Storms Meteor.*, **12**, 1–33.
- Lyza, A. W., and M. D. Flournoy, 2023: The influence of cell mergers on supercell characteristics and tornado evolution on 27–28 April 2011. *Mon. Wea. Rev.*, **151**, 1551–1569, <https://doi.org/10.1175/MWR-D-22-0189.1>.
- MacIntosh, C. W., and M. D. Parker, 2017: The 6 May 2010 elevated supercell during VORTEX2. *Mon. Wea. Rev.*, **145**, 2635–2657, <https://doi.org/10.1175/MWR-D-16-0329.1>.
- Mahale, V. N., J. A. Brotzge, and H. B. Bluestein, 2012: An analysis of vortices embedded within a quasi-linear convective system using an X-band polarimetric radar. *Wea. Forecasting*, **27**, 1520–1537, <https://doi.org/10.1175/WAF-D-11-00135.1>.
- Mahre, A., J. M. Kurdzo, D. J. Bodine, C. B. Griffin, R. D. Palmer, and T.-Y. Yu, 2018: Analysis of the 16 May 2015 Tipton, Oklahoma, EF-3 tornado at high spatiotemporal resolution using the Atmospheric Imaging Radar. *Mon. Wea. Rev.*, **146**, 2103–2124, <https://doi.org/10.1175/MWR-D-17-0256.1>.
- Mansell, E. R., 2010: On sedimentation and advection in multimoment bulk microphysics. *J. Atmos. Sci.*, **67**, 3084–3094, <https://doi.org/10.1175/2010JAS3341.1>.
- Mansell, E. R., C. L. Ziegler, , and E. C. Bruning, 2010: Simulated electrification of a small thunderstorm with two-moment bulk microphysics. *J. Atmos. Sci.*, **67**, 171–194, <https://doi.org/10.1175/2009JAS2965.1>.
- Markowski, P. M., 2024: A new pathway for tornadogenesis exposed by numerical simulations of supercells in turbulent environments. *J. Atmos. Sci.*, **81**, 481–518, <https://doi.org/10.1175/JAS-D-23-0161.1>.
- Markowski, P. M., and Y. P. Richardson, 2009: Tornadogenesis: Our current understanding, forecasting considerations, and questions to guide future research. *Atmos. Res.*, **93**, 3–10, <https://doi.org/10.1016/j.atmosres.2008.09.015>.

- Markowski, P. M., J. M. Straka, and E. N. Rasmussen, 2002: Direct surface thermodynamic observations within the rear-flank downdrafts of nontornadic and tornadic supercells. *Mon. Wea. Rev.*, **130**, 1692–1721, [https://doi.org/10.1175/1520-0493\(2002\)130<1692:DSTOWT>2.0.CO;2](https://doi.org/10.1175/1520-0493(2002)130<1692:DSTOWT>2.0.CO;2).
- Marquis, J., Y. Richardson, P. Markowski, D. Dowell, and J. Wurman, 2012: Tornado maintenance investigated with high-resolution dual-Doppler and EnKF analysis. *Mon. Wea. Rev.*, **140**, 3–27, <https://doi.org/10.1175/MWR-D-11-00025.1>.
- Marquis, J., Y. Richardson, P. Markowski, J. Wurman, K. Kosiba, and P. Robinson, 2016: An investigation of the Goshen County, Wyoming, tornadic supercell of 5 June 2009 using EnKF assimilation of mobile mesonet and radar observations collected during VORTEX2. Part II: Mesocyclone-scale processes affecting tornado formation, maintenance, and decay. *Mon. Wea. Rev.*, **144**, 3441–3463, <https://doi.org/10.1175/MWR-D-15-0411.1>.
- McDonald, J. M., and C. C. Weiss, 2021: Cold pool characteristics of tornadic quasi-linear convective systems and other convective modes observed during VORTEX-SE. *Mon. Wea. Rev.*, **149**, 821–840, <https://doi.org/10.1175/MWR-D-20-0226.1>.
- McKeown, K. E., M. M. French, K. S. Tuftedal, D. M. Kingfield, H. B. Bluestein, D. W. Reif, and Z. B. Wienhoff, 2020: Rapid-scan and polarimetric radar observations of the dissipation of a violent tornado on 9 May 2016 near Sulphur, Oklahoma. *Mon. Wea. Rev.*, **148**, 3951–3971, <https://doi.org/10.1175/MWR-D-20-0033.1>.
- Murdzek, S. S., P. M. Markowski, Y. P. Richardson, and R. L. Tanamachi, 2020: Processes preventing the development of a significant tornado in a Colorado supercell on 26 May 2010. *Mon. Wea. Rev.*, **148**, 1753–1778, <https://doi.org/10.1175/MWR-D-19-0288.1>.
- Naylor, J., and M. S. Gilmore, 2014: Vorticity evolution leading to tornadogenesis and tornadogenesis failure in simulated supercells. *J. Atmos. Sci.*, **71**, 1201–1217, <https://doi.org/10.1175/JAS-D-13-0219.1>.
- Newman, J. F., and P. L. Heinselman, 2012: Evolution of a quasi-linear convective system sampled by phased array radar. *Mon. Wea. Rev.*, **140**, 3467–3486, <https://doi.org/10.1175/MWR-D-12-00003.1>.
- Nixon, C. J., J. T. Allen, M. B. Wilson, M. J. Bunkers, and M. Taszarek, 2024: Cell mergers, boundary interactions, and convective systems in cases of significant tornadoes and hail. *Wea. Forecasting*, <https://doi.org/inpress>.
- Okubo, A., 1970: Horizontal dispersion of floatable particles in the vicinity of velocity singularities such as convergences. *Deep-Sea Res.*, **17**, 445–454, [https://doi.org/10.1016/0011-7471\(70\)90059-8](https://doi.org/10.1016/0011-7471(70)90059-8).

- Orf, L., R. Wilhelmson, B. Lee, C. Finley, and A. Houston, 2017: Evolution of a long-track violent tornado within a simulated supercell. *Bull. Amer. Meteor. Soc.*, **98**, 45–68, <https://doi.org/10.1175/BAMS-D-15-00073.1>.
- Pardun, T. J., A. E. Reinhart, C. C. Weiss, E. N. Rasmussen, S. M. Waugh, and A. L. Houston, 2025: The observed and simulated analysis of supercellular demise from 15 June 2019. *In prep.*
- Parker, M. D., 2023: How well must surface vorticity be organized for tornadogenesis? *J. Atmos. Sci.*, **80**, 1433–1448, <https://doi.org/10.1175/JAS-D-22-0195.1>.
- Parker, M. D., and J. M. Dahl, 2015: Production of near-surface vertical vorticity by idealized downdrafts. *Mon. Wea. Rev.*, **143**, 2795–2816, <https://doi.org/10.1175/MWR-D-14-00310.1>.
- Pazmany, A. L., J. B. Mead, H. B. Bluestein, J. C. Snyder, and J. B. Houser, 2013: A mobile rapid-scanning X-band polarimetric (RaXPo) Doppler radar system. *J. Atmos. Oceanic Technol.*, **30**, 1398–1413, <https://doi.org/10.1175/JTECH-D-12-00166.1>.
- Przybylinski, R. H., 1995: The bow echo: Observations, numerical simulations, and severe weather detection methods. *Wea. Forecasting*, **10**, 203–218, [https://doi.org/10.1175/1520-0434\(1995\)010<0203:TBEONS>2.0.CO;2](https://doi.org/10.1175/1520-0434(1995)010<0203:TBEONS>2.0.CO;2).
- Richter, H., J. Peter, and S. Collis, 2014: Analysis of a destructive wind storm on 16 November 2008 in Brisbane, Australia. *Mon. Wea. Rev.*, **142**, 3038–3060, <https://doi.org/10.1175/MWR-D-13-00405.1>.
- Roberts, B., and M. Xue, 2017: The role of surface drag in mesocyclone intensification leading to tornadogenesis within an idealized supercell simulation. *J. Atmos. Sci.*, **74**, 3055–3077, <https://doi.org/10.1175/JAS-D-16-0364.1>.
- Rotunno, R., 1981: On the evolution of thunderstorm rotation. *Mon. Wea. Rev.*, **109**, 577–586, [https://doi.org/10.1175/1520-0493\(1981\)109<0577:OTEOTR>2.0.CO;2](https://doi.org/10.1175/1520-0493(1981)109<0577:OTEOTR>2.0.CO;2).
- Rotunno, R., and J. B. Klemp, 1985: On the rotation and propagation of simulated supercell thunderstorms. *J. Atmos. Sci.*, **42**, 271–292, [https://doi.org/10.1175/1520-0469\(1985\)042<0271:OTRAPO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1985)042<0271:OTRAPO>2.0.CO;2).
- Rotunno, R., P. M. Markowski, and G. H. Bryan, 2017: “Near ground” vertical vorticity in supercell thunderstorm models. *J. Atmos. Sci.*, **74**, 1757–1766, <https://doi.org/10.1175/JAS-D-16-0288.1>.
- Sabones, M., E. M. Agee, and M. Akridge, 1996: The Pulaski county and West Lafayette, Indiana, tornadoes, 26–27 April 1994: A case of supercell (mesocyclone) and squall line bow-echo interaction. *18th Conf. on Severe Local Storms*, Amer. Meteor. Soc., San Francisco, CA, 746–750.

- Schenkman, A. D., M. Xue, and M. Hu, 2014: Tornadogenesis in a high-resolution simulation of the 8 May 2003 Oklahoma City supercell. *J. Atmos. Sci.*, **71**, 130–154, <https://doi.org/10.1175/JAS-D-13-073.1>.
- Schenkman, A. D., M. Xue, and A. Shapiro, 2012: Tornadogenesis in a simulated mesovortex within a mesoscale convective system. *J. Atmos. Sci.*, **69**, 3372–3390, <https://doi.org/10.1175/JAS-D-12-038.1>.
- Schenkman, A. D., M. Xue, A. Shapiro, K. Brewster, and J. Gao, 2011: Impact of CASA radar and Oklahoma Mesonet data assimilation on the analysis and prediction of tornadic mesovortices in an MCS. *Mon. Wea. Rev.*, **139**, 3422–3445, <https://doi.org/10.1175/MWR-D-10-05051.1>.
- Schneider, R. S., A. R. Dean, S. J. Weiss, and P. D. Bothwell, 2006: Analysis of estimated environments for 2004 and 2005 severe convective storm reports. *23rd Conf. on Severe Local Storms*, Amer. Meteor. Soc., St. Louis, MO, 3.5, https://ams.confex.com/ams/23SLS/techprogram/paper_115246.htm.
- Schueth, A., C. Weiss, and J. M. L. Dahl, 2021: Comparing observations and simulations of the streamwise vorticity current and the forward-flank convergence boundary in a supercell storm. *Mon. Wea. Rev.*, **149**, 1651–1671, <https://doi.org/10.1175/MWR-D-20-0251.1>.
- Sessa, M. F., and R. J. Trapp, 2020: Observed relationship between tornado intensity and pretornadic mesocyclone characteristics. *Wea. Forecasting*, **35**, 1243–1261, <https://doi.org/10.1175/WAF-D-19-0099.1>.
- Sherburn, K. D., and M. D. Parker, 2014: Climatology and ingredients of significant severe convection in high-shear, low-CAPE environments. *Wea. Forecasting*, **29**, 854–877, <https://doi.org/10.1175/WAF-D-13-00041.1>.
- Sherburn, K. D., and M. D. Parker, 2019: The development of severe vortices within simulated high-shear, low-CAPE convection. *Mon. Wea. Rev.*, **147**, 2189–2216, <https://doi.org/10.1175/MWR-D-18-0246.1>.
- Sherburn, K. D., M. D. Parker, J. R. King, and G. M. Lackmann, 2016: Composite environments of severe and nonsevere high-shear, low-CAPE convective events. *Wea. Forecasting*, **31**, 1899–1927, <https://doi.org/10.1175/WAF-D-16-0086.1>.
- Sieveking, J. E., and R. W. Przybylinski, 2004: The interaction of a HP supercell thunderstorm and bow echo to produce a prolonged severe wind event in east central Missouri. *22nd Conf. on Severe Local Storms*, Amer. Meteor. Soc., Hyannis, MA, 7A.5, <https://ams.confex.com/ams/11aram22sls/webprogram/Paper81818.html>.
- Smith, B. T., R. L. Thompson, J. S. Grams, C. Broyles, and H. E. Brooks, 2012: Convective modes for significant severe thunderstorms in the contiguous United

- States. Part I: Storm classification and climatology. *Wea. Forecasting*, **27**, 1114–1135, <https://doi.org/10.1175/WAF-D-11-00115.1>.
- Straka, J. M., E. N. Rasmussen, and S. E. Fredrickson, 1996: A mobile mesonet for finescale meteorological observations. *J. Atmos. Oceanic Technol.*, **13**, 921–936, [https://doi.org/10.1175/1520-0426\(1996\)013<0921:AMMFFM>2.0.CO;2](https://doi.org/10.1175/1520-0426(1996)013<0921:AMMFFM>2.0.CO;2).
- Tanamachi, R. L., H. B. Bluestein, J. B. Houser, S. J. Frasier, and K. M. Hardwick, 2012: Mobile, X-band, polarimetric Doppler radar observations of the 4 May 2007 Greensburg, Kansas, tornadic supercell. *Mon. Wea. Rev.*, **140**, 2103–2125, <https://doi.org/10.1175/MWR-D-11-00142.1>.
- Tanamachi, R. L., H. B. Bluestein, M. Xue, W.-C. Lee, K. A. Orzel, S. J. Frasier, and R. M. Wakimoto, 2013: Near-surface vortex structure in a tornado and in a sub-tornado-strength convective-storm vortex observed by a mobile, W-band radar during VORTEX2. *Mon. Wea. Rev.*, **141**, 3661–3690, <https://doi.org/10.1175/MWR-D-12-00331.1>.
- Taylor, G. I., 1938: The spectrum of turbulence. *Proc. Roy. Soc.*, **164**, 476–490, <https://doi.org/10.1098/rspa.1938.0032>.
- Thompson, R. L., B. T. Smith, J. S. Grams, A. R. Dean, and C. Broyles, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part II: Supercell and QLCS tornado environments. *Wea. Forecasting*, **27**, 1136–1154, <https://doi.org/10.1175/WAF-D-11-00116.1>.
- Tochimoto, E., and H. Niino, 2022: Tornadogenesis in a quasi-linear convective system over Kanto Plain in Japan: A numerical case study. *Mon. Wea. Rev.*, **150**, 259–282, <https://doi.org/10.1175/MWR-D-20-0402.1>.
- Trapp, R. J., E. D. Mitchell, G. A. Tipton, D. W. Effertz, A. I. Watson, D. L. A. Jr., and M. A. Magsig, 1999: Descending and nondescending tornadic vortex signatures detected by WSR-88Ds. *Wea. Forecasting*, **14**, 625–639, [https://doi.org/10.1175/1520-0434\(1999\)014<0625:DANTVS>2.0.CO;2](https://doi.org/10.1175/1520-0434(1999)014<0625:DANTVS>2.0.CO;2).
- Trapp, R. J., S. A. Tessendorf, E. S. Godfrey, and H. E. Brooks, 2005: Tornadoes from squall lines and bow echoes. Part I: Climatological distribution. *Wea. Forecasting*, **20**, 23–34, <https://doi.org/10.1175/WAF-835.1>.
- Trapp, R. J., and M. L. Weisman, 2003: Low-level mesovortices within squall lines and bow echoes. Part II: Their genesis and implications. *Mon. Wea. Rev.*, **131**, 2804–2823, [https://doi.org/10.1175/1520-0493\(2003\)131<2804:LMWSLA>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<2804:LMWSLA>2.0.CO;2).
- Wakimoto, R. M., 2001: Convectively driven high wind events. *Severe Convective Storms, Meteor. Monogr.*, Vol. 50, Amer. Meteor. Soc., 255–298.

- Wakimoto, R. M., N. T. Atkins, K. M. Butler, H. B. Bluestein, K. Thiem, J. Snyder, and J. Houser, 2015: Photogrammetric analysis of the 2013 El Reno tornado combined with mobile X-band polarimetric radar data. *Mon. Wea. Rev.*, **143**, 2657–2683, <https://doi.org/10.1175/MWR-D-15-0034.1>.
- Wakimoto, R. M., N. T. Atkins, and J. Wurman, 2011: The LaGrange tornado during VORTEX2. Part I: Photogrammetric analysis of the tornado combined with single-Doppler radar data. *Mon. Wea. Rev.*, **139**, 2233–2258, <https://doi.org/10.1175/2010MWR3568.1>.
- Wakimoto, R. M., H. V. Murphey, C. A. Davis, and N. T. Atkins, 2006a: High winds generated by bow echoes. Part II: The relationship between the mesovortices and damaging straight-line winds. *Mon. Wea. Rev.*, **134**, 2813–2829, <https://doi.org/10.1175/MWR3216.1>.
- Wakimoto, R. M., H. V. Murphey, A. Nester, D. P. Jorgensen, and N. T. Atkins, 2006b: High winds generated by bow echoes. Part I: Overview of the Omaha bow echo 5 July 2003 storm during BAMEX. *Mon. Wea. Rev.*, **134**, 2793–2812, <https://doi.org/10.1175/MWR3215.1>.
- Wakimoto, R. M., P. Stauffer, W.-C. Lee, N. T. Atkins, and J. Wurman, 2012: Finescale structure of the LaGrange, Wyoming, tornado during VORTEX2: GBVTD and photogrammetric analyses. *Mon. Wea. Rev.*, **140**, 397–3418, <https://doi.org/10.1175/MWR-D-12-00036.1>.
- Wakimoto, R. M., Z. Wienhoff, H. B. Bluestein, D. J. Bodine, and J. M. Kurdzo, 2020: Mobile radar observations of the evolving debris field compared with a damage survey of the Shawnee, Oklahoma, tornado of 19 May 2013. *Mon. Wea. Rev.*, **148**, 1779–1803, <https://doi.org/10.1175/MWR-D-19-0215.1>.
- Wakimoto, R. M., Z. Wienhoff, D. Reif, H. B. Bluestein, and D. C. Lewellen, 2022: The Dodge City tornadoes on 24 May 2016: Understanding cycloidal marks in surface damage tracks and further analysis of the debris cloud. *Mon. Wea. Rev.*, **150**, 1233–1246, <https://doi.org/10.1175/MWR-D-21-0262.1>.
- Waugh, S., 2023: PERiLS_2022: NSSL Mobile Radiosonde Data, version 1.0. UCAR/NCAR - Earth Observing Laboratory, <https://doi.org/10.26023/S0SK-WHS3-CC00>.
- Waugh, S. M., 2012: The “U-tube”: An improved aspirated temperature system for mobile meteorological observations, especially in severe weather. M.S. thesis, School of Meteorology, University of Oklahoma, 76 pp., URL <http://hdl.handle.net/11244/24679>.
- Weisman, M. L., and R. J. Trapp, 2003: Low-level mesovortices within squall lines and bow echoes. Part I: Overview and dependence on environmental shear. *Mon.*

- Wea. Rev.*, **131**, 2779–2803, [https://doi.org/10.1175/1520-0493\(2003\)131<2779:LMWSLA>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<2779:LMWSLA>2.0.CO;2).
- Weiss, J., 1991: The dynamics of enstrophy transfer in two-dimensional hydrodynamics. *Physica D*, **48**, 273–294, [https://doi.org/10.1016/0167-2789\(91\)90088-Q](https://doi.org/10.1016/0167-2789(91)90088-Q).
- Wheatley, D. M., and R. J. Trapp, 2008: The effect of mesoscale heterogeneity on the genesis and structure of mesovortices within quasi-linear convective systems. *Mon. Wea. Rev.*, **136**, 4220–4241, <https://doi.org/10.1175/2008MWR2294.1>.
- Wicker, L. J., and R. B. Wilhelmson, 1995: Simulation and analysis of tornado development and decay within a three-dimensional supercell thunderstorm. *J. Atmos. Sci.*, **52**, 2675–2703, [https://doi.org/10.1175/1520-0469\(1995\)052<2675:SAAOTD>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<2675:SAAOTD>2.0.CO;2).
- Wolf, P. L., 1998: WSR-88D radar depiction of supercell–bow echo interaction: Unexpected evolution of a large, tornadic “comma-shaped” supercell over eastern Oklahoma. *Wea. Forecasting*, **13**, 492–504, [https://doi.org/10.1175/1520-0434\(1998\)013<0492:WRDOSB>2.0.CO;2](https://doi.org/10.1175/1520-0434(1998)013<0492:WRDOSB>2.0.CO;2).
- Wolf, R., R. Przybylinski, and P. Berg, 1996: Observations of a merging bowing segment and supercell. *18th Conf. on Severe Local Storms*, Amer. Meteor. Soc., San Francisco, CA, 16.2.
- Wurman, J., and K. Kosiba, 2013: Finescale radar observations of tornado and mesocyclone structures. *Wea. Forecasting*, **28**, 1157–1174, <https://doi.org/10.1175/WAF-D-12-00127.1>.
- Wurman, J., and K. Kosiba, 2023: PERILS 2023 radar data (Version 1) [Data set]. Flexible Array of Radars and Mesonets (FARM), University of Illinois, <https://doi.org/10.48514/K7WX-NP56>.
- Wurman, J., K. Kosiba, P. Markowski, Y. Richardson, D. Dowell, and P. Robinson, 2010: Finescale single- and dual-Doppler analysis of tornado intensification, maintenance, and dissipation in the Orleans, Nebraska, supercell. *Mon. Wea. Rev.*, **138**, 4439–4455, <https://doi.org/10.1175/2010MWR3330.1>.
- Wurman, J., Y. Richardson, C. Alexander, S. Weygandt, and P. F. Zheng, 2007: Dual-Doppler and single-Doppler analysis of a tornadic storm undergoing mergers and repeated tornadogenesis. *Mon. Wea. Rev.*, **135**, 736–758, <https://doi.org/10.1175/MWR3276.1>.
- Wurman, J., and Coauthors, 2021: The Flexible Array of Radars and Mesonets (FARM). *Bull. Amer. Meteor. Soc.*, **102**, E1499–E1525, <https://doi.org/10.1175/BAMS-D-20-0285.1>.

- Wurman, J. M., and S. Gill, 2000: Finescale radar observations of the Dimmitt, Texas (2 June 1995), tornado. *Mon. Wea. Rev.*, **128**, 2135–2164, [https://doi.org/10.1175/1520-0493\(2000\)128<2135:FROOTD>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<2135:FROOTD>2.0.CO;2).
- Xu, X., M. Xue, and Y. Wang, 2015: The genesis of mesovortices within a real-data simulation of a bow echo system. *J. Atmos. Sci.*, **72**, 1963–1986, <https://doi.org/10.1175/JAS-D-14-0209.1>.
- Ziegler, C. L., 1985: Retrieval of thermal and microphysical variables in observed convective storms. Part I: Model development and preliminary testing. *J. Atmos. Sci.*, **42**, 1487–1509, [https://doi.org/10.1175/1520-0469\(1985\)042<1487:ROTAMV>2.0.CO;2](https://doi.org/10.1175/1520-0469(1985)042<1487:ROTAMV>2.0.CO;2).