Sensitivity of Supercell Behavior to Artificial Airmass Boundaries in High-Resolution CM1 Simulations

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12th European Conference on Severe Storms

17–21 November 2025, Utrecht, Netherlands

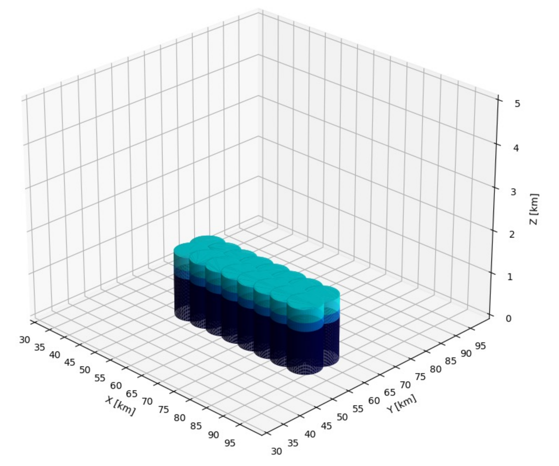
INTRODUCTION

Supercells are long-lived convective storms characterized by deep, persistent, rotating updrafts. They often produce large hail, damaging winds, and tornadoes, imposing significant economic impacts. Baroclinic boundaries are known to enhance horizontal and vertical vorticity, thereby promoting the strengthening of low-level rotation within updrafts. Observational studies have shown that the relative distance between a boundary and a supercell can influence which severe phenomenon is most likely to occur. In this study, we present results from Bryan Cloud Model (CM1) simulations in which an idealized supercell interacts with boundaries of varying distance, depth, and intensity, and we compare the most prolific hail-producing case with the one exhibiting the strongest tornado-like vortex.

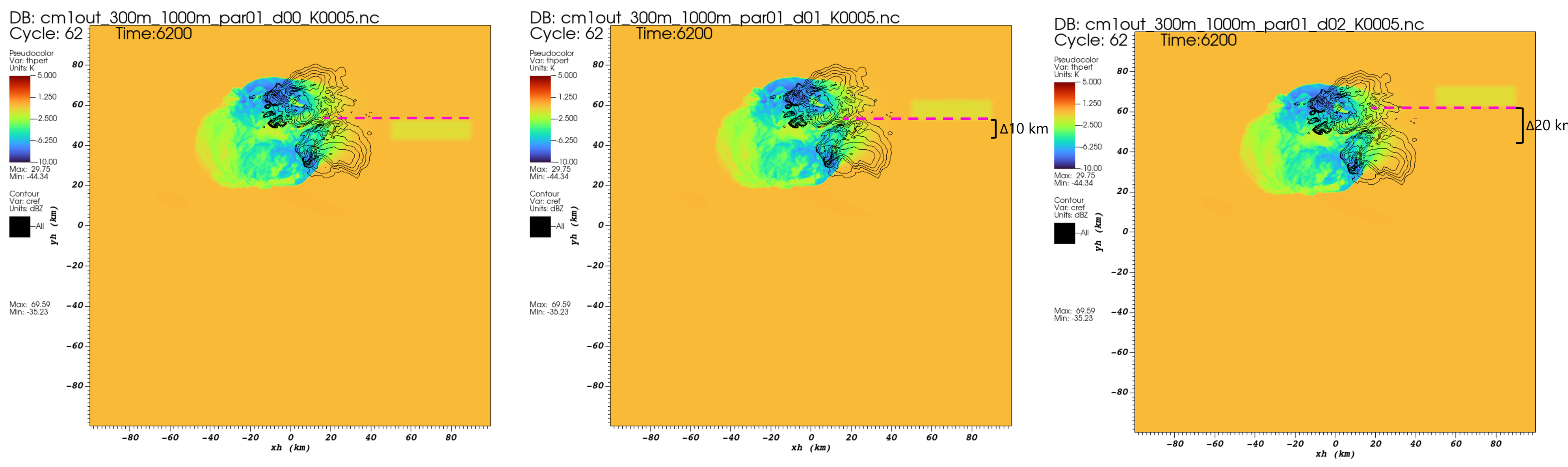
METHODOLOGY

Parameter	Configuration
Grid points	666 × 666 × 60
Horizontal grid spacing	300 m
Vertical grind spacing	100 m (stretching up to 500 m)
Number of vertical levels	60 levels
Model top	20 km
Time step	3.5 s
Simulation length	12 000 s (3 h 20 min)
Output frequency	every 100 s
Model setup	Large-Eddy Simulation (LES)
Initial perturbation	Warm bubble
Initial sounding	Weisman-Klemp Analytic sounding
Initial wind profile	Weisman-Klemp supercell profile
Cloud microphysics	Morrison double-moment scheme
Turbulence closure	Turbulent closure via 2D Smagorinsky
Numerical diffusion	6th-order
Upper level damping	Rayleigh damping above 15 km
Lateral boundary damping	Rayleigh damping within 30 km of boundaries
Parcels	1,800,000

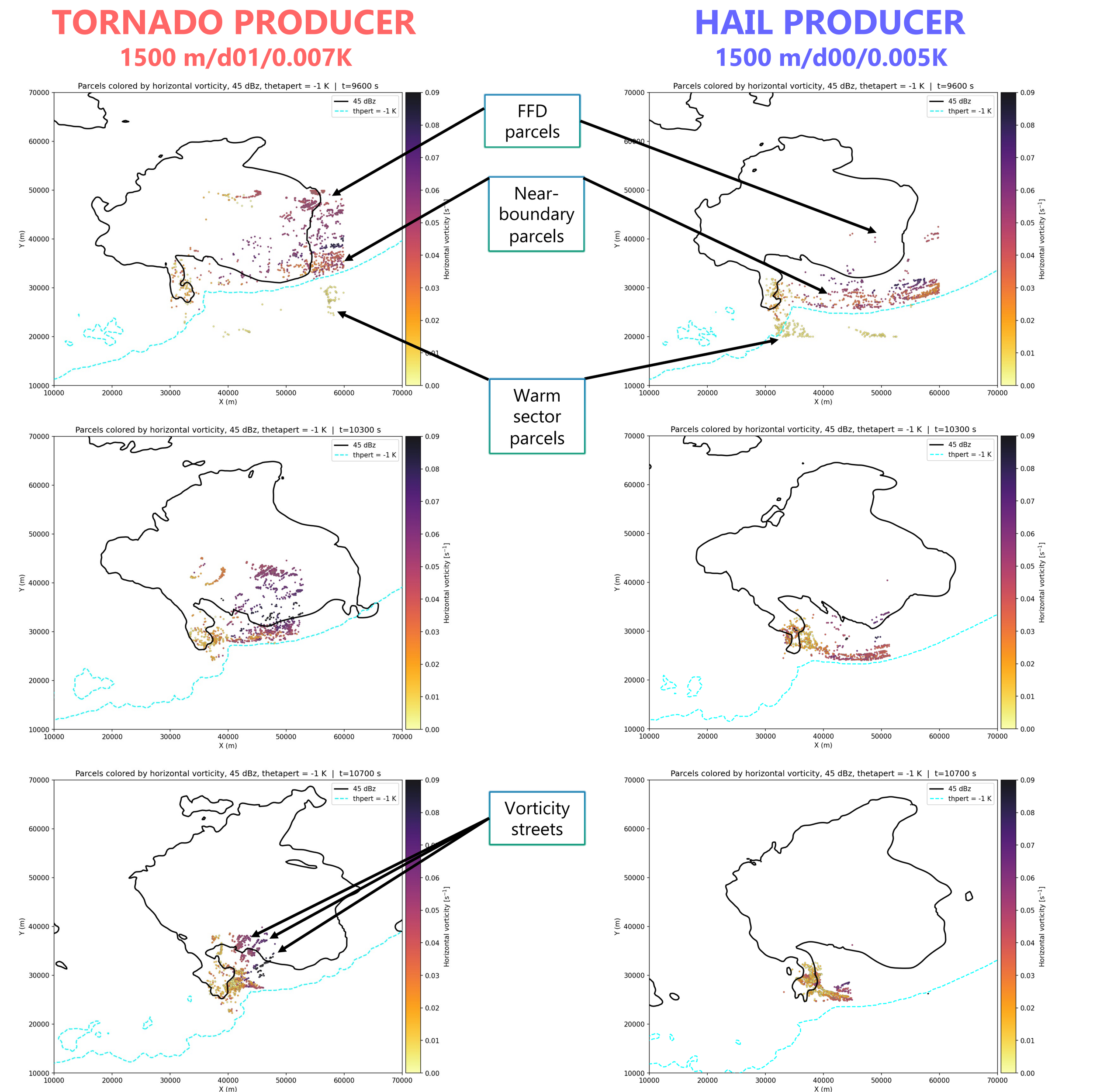
To simulate the boundary, a total of 16 heat sinks were placed in the model domain following the approach of Fischer and Dahl (2020, 2023), aligned parallel to the path of the right-moving supercell. The sinks were positioned in three locations: (1) along the northernmost tip of the right-moving supercell, (2) 10 km north of that point, and (3) 20 km north of it. Each heat sink had a radius of 4 km and varied in depth (1000, 1200, and 1500 m) and intensity (0.002, 0.005, and 0.007 K s^{-1}). The combination of these parameters resulted in 3 × 3 × 3 = 27 simulations. All heat sinks were activated at 6000 s, corresponding to the midpoint of the simulations.



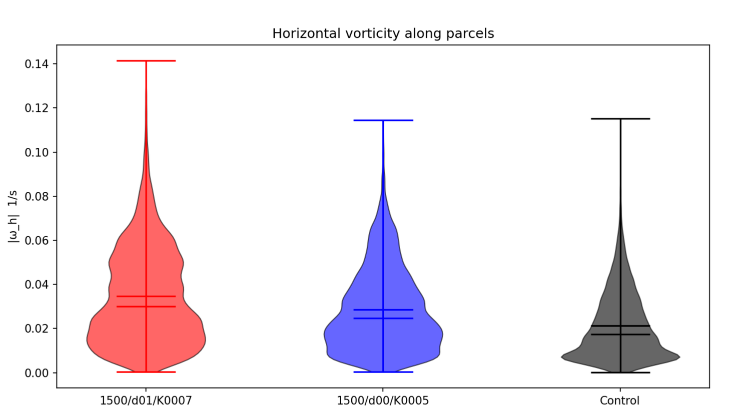
A parcel analysis was also performed by releasing 1,800,000 parcels within a 30 × 30 km region surrounding the supercell, initialized from the lowest 2 km layer.



PARCEL ANALYSIS

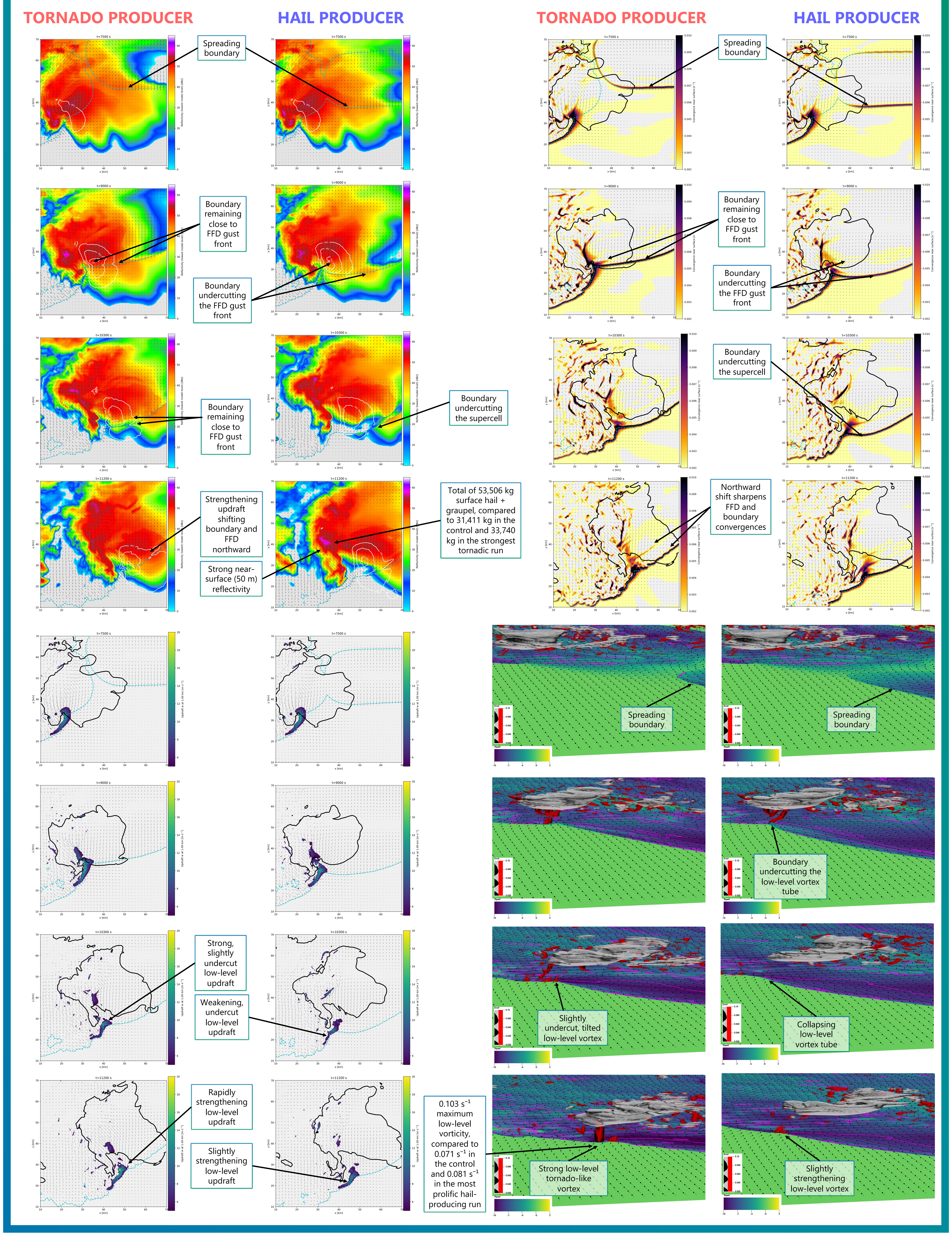


The stronger and less undercut low-level updraft was associated with a wider inflow area. As a result, the updraft was fed by parcels originating from the warm sector, the near-boundary environment, and the FFD region. Consequently, a larger amount of horizontal vorticity was ingested into the updraft.



The weaker, undercut low-level updraft was associated with a narrower inflow region, fed primarily by parcels from the warm sector and near-boundary environment. Consequently, the total horizontal vorticity entering the updraft was smaller than in the tornadic case, yet greater than in the control run.

FIELD ANALYSIS



CONCLUSIONS

CM1 simulations were conducted to examine the interaction between a supercell and an idealized thermal boundary. Out of 27 sensitivity tests, the strongest tornado-like vortex developed when the storm interacted with a 1500 m deep boundary positioned 10 km north of the storm track and with a cooling rate of 0.007 K s^{-1}. In this case, the boundary remained close to the forward-flank downdraft (FFD) gust front.

The most prolific hail-producing case occurred when the storm interacted with a 1500 m deep boundary collocated with the storm (0 km) and with a cooling rate of 0.005 K s^{-1}. In this simulation, the expanding boundary undercut the main updraft during its evolution, and the storm remained more persistently on the cool side.

The near-surface maximum vertical vorticity in the tornadic case was 39.4 % higher than in the hail-producing case and 46.6 % higher than in the control. Conversely, the hail-dominated cell produced 58.6 % more surface hail mass than the tornadic case and 70.3 % more than the control. Ongoing work aims to further analyze the dynamical processes governing these outcomes.

ACKNOWLEDGEMENTS

Kornél Komjáti, Hajnalka Breuer, and Kálmán Csirmaz were supported by the EKÖP-KDP-24 university excellence scholarship program cooperative doctoral program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund. Hajnalka Breuer was supported by the Hungarian Scientific Research Fund under the grant FK132014.