Numerical Simulation of a Supercell with an Embedded Long-Track EF5 Tornado

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Overview

The "Calumet–El Reno–Piedmont–Guthrie" tornado swept through the northern outskirts of metropolitan Oklahoma City on May 24, 2011. The tornado, rated EF5 based upon University of Oklahoma mobile Doppler radar, left a damage path of 65 miles.

As part of an ongoing numerical study on supercell tornadogenesis and tornado maintenance utilizing the Blue Waters supercomputer, we explored using the May 24, 2011 storm environment in an idealized simulation utilizing the CM1 numerical model. The resulting supercell is intensely strong and long-lived, and produces a long-track (65 miles at by 3 hours model time) EF5 tornado. The simulated storm bears some surprising similarities to the observed storm including track length, direction, intensity, and tornado morphology, based upon storm chaser footage and utilizing volume rendering techniques to visualize the cloud and rain fields. To the best of our knowledge, this is the first time a supercell producing a long-track EF5 tornado has ever been simulated.

The simulated tornado reaches EF5 strength approximately 98 minutes into the model simulation. The tornado maximum surface winds remain consistently at or well above EF5 strength for a continuous period of 40 minutes, where a maximum instantaneous surface wind 143.2 m s^{-1} (320 mph) occurs at t=6580 s.

The model is run out to 3 hr simulation time. At this time, the simulated tornado has been on the ground for 95 minutes and has traveled 65 miles, at which point it is producing EF3-strength winds.

The simulation described herein was completed in January 2014, hence we are only able to present preliminary analysis at this time.

CM1 (version 16) model configuration

Domain size: 120 km×120 km×20 km (2200×2200×380 grid points)

Grid mesh: 30 meter isotropic horizontal grid spacing spanning 60 km×60 km×10 km, stretching upwards and laterally to boundaries outside this inner domain

Advection: 5th order

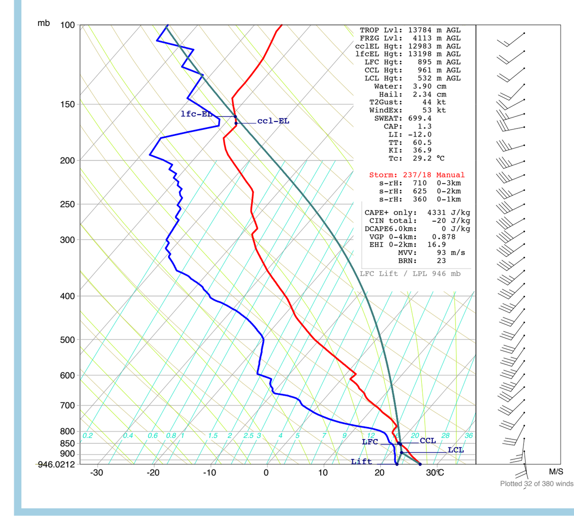
Surface boundary condition: free slip

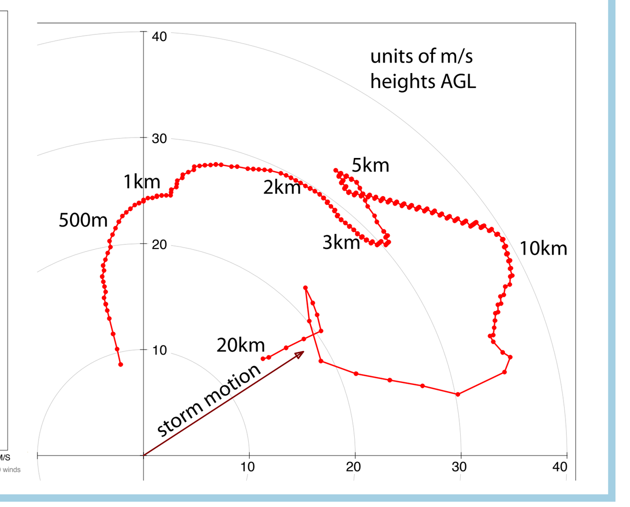
Physics options: Morrison two-moment microphysics, Smagorinky turbulence closure

Forcing: Supercell initiated using the updraft nudging technique of Naylor and Gilmore (2012)

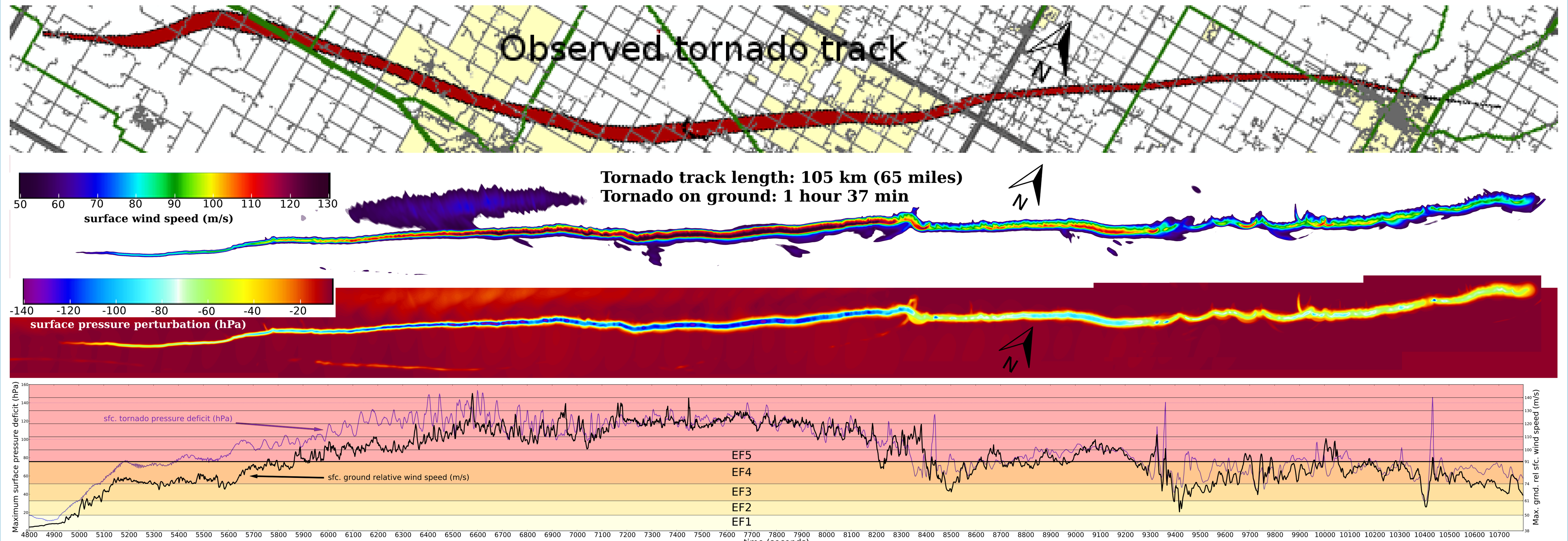
Environmental base state: Horizontally homogeneous, initialized from a 1 hour RUC forecast sounding located off the right flank of the Calumet-El Reno-Piedmont-Guthrie supercell of May 29, 2011.

Sounding and hodograph



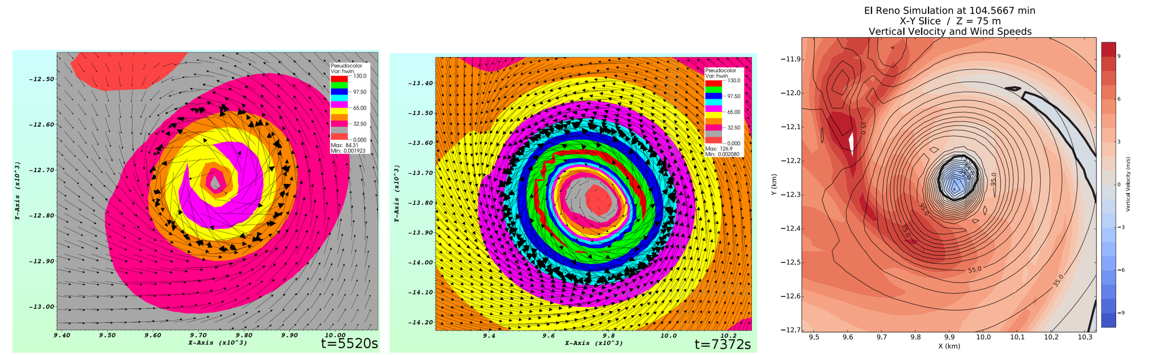


Observed and modeled tornado track and time series data

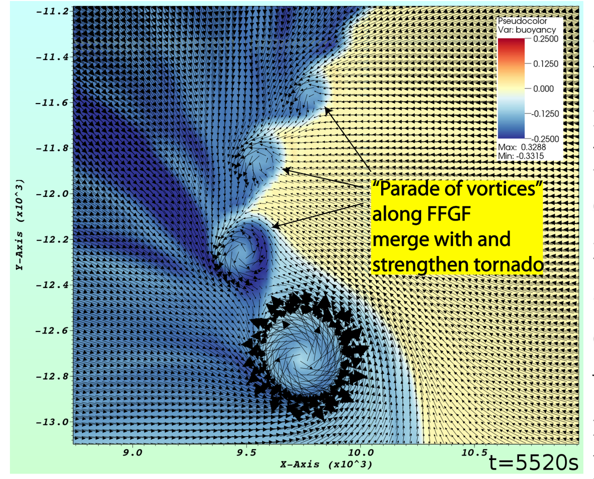


The observed tornado cut a 65 mile-long swath of damage (top). The center track is a history of the strongest surface wind speed indicating the path of the simulated tornado. Similarly, the bottom track is a history of the largest surface pressure deficit. Time series data shows both maximum surface wind and minimum pressure deficit centered on the location of the tornado. Cutoff values for the Enhanced Fujita scale are included for reference.

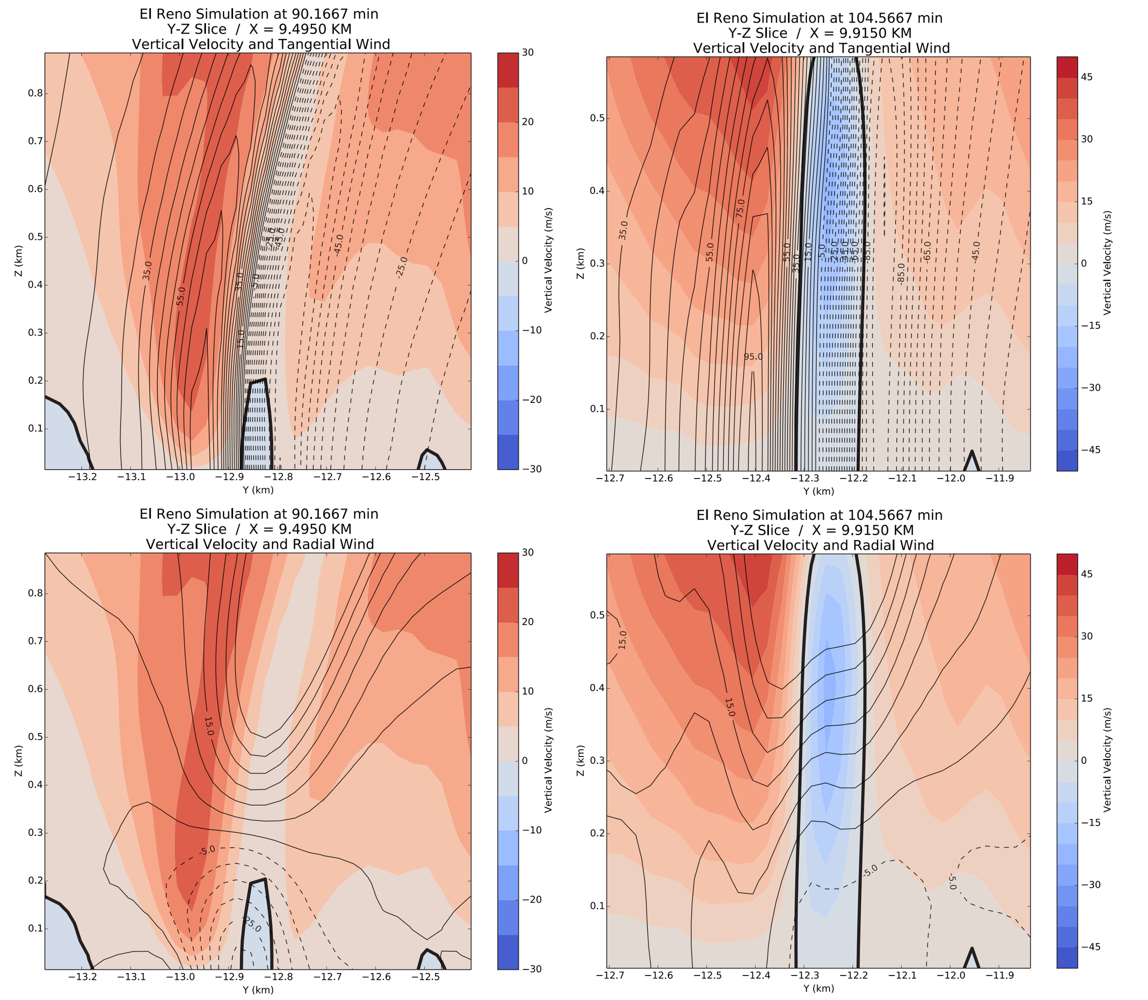
Tornado structure



Left: Surface wind vectors (drawn at each model gridpoint) and horizontal wind speed shortly following tornadogenesis (t=5520 s). **Center:** Same as left, 31 minutes later (note change of scale). **Right:** Vertical velocity (shaded, with solid $w = 0\,\mathrm{m\,s^{-1}}$ contour) and wind speed, t=6274 s, 75 m AGL.

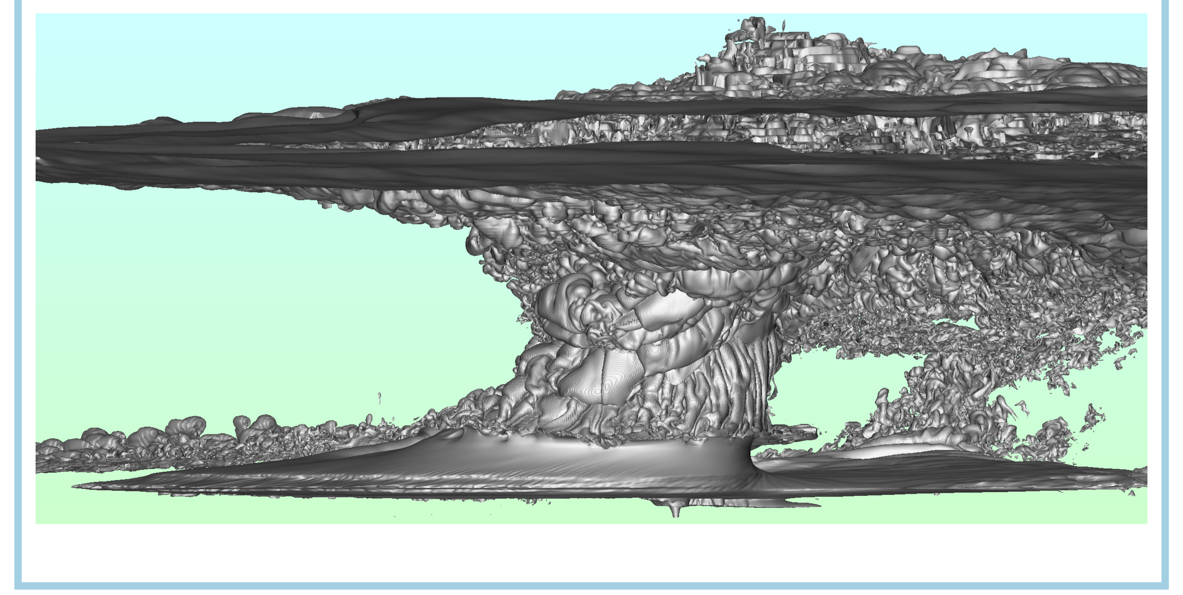


Above: A source of vertical vorticity during tornado genesis and maintenance is the forward flank gust front boundary. The buoyancy gradient across the FFGF tends to be sharp, and shear instabilities form and travel along the FFGF towards the tornado. Both cyclonic and anticyclonic vortices form along the FFGF; $+\zeta$ vortices are "absorbed" into the tornado circulation, while $-\zeta$ vortices are advected cyclonically around the tornado, often tilted horizontally and lifted, forming a horizontal ring encircling the tornado and acting to "shed" $+\zeta$ vorticity from the tornado.

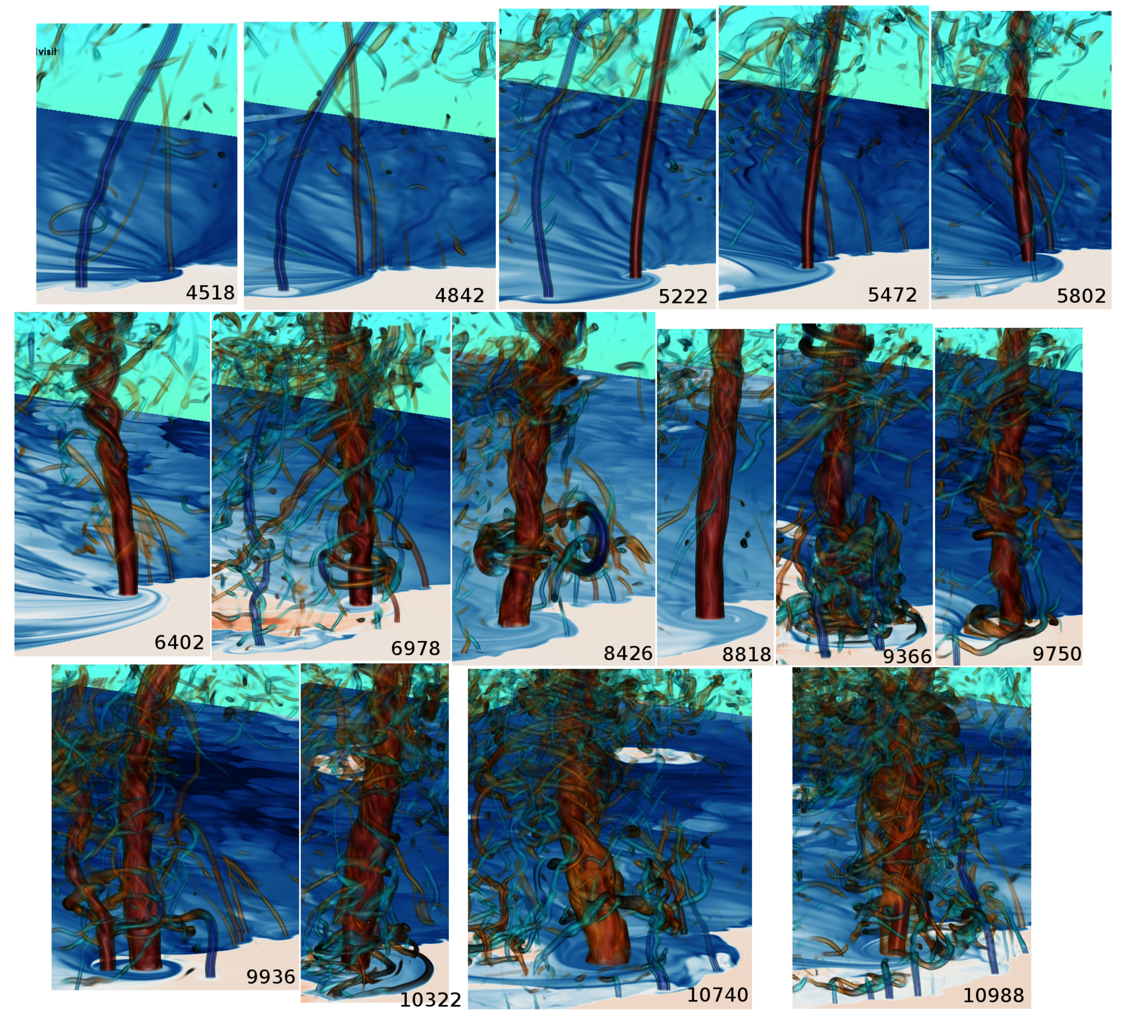


Left: Vertical cross section of tangential (top) and radial (bottom) winds through the tornado, t=5410 s. In both plots, vertical velocity is shaded, with a solid $w = 0\,\mathrm{m\,s^{-1}}$ contour. **Right:** Same as left, at t=6274 s. The two-celled tornado structure is clearly evident in both plots, with downward motion observed extending several km upwards in the center of the tornado during much of its life cycle.

View from south (cloud water+ice isosurface)

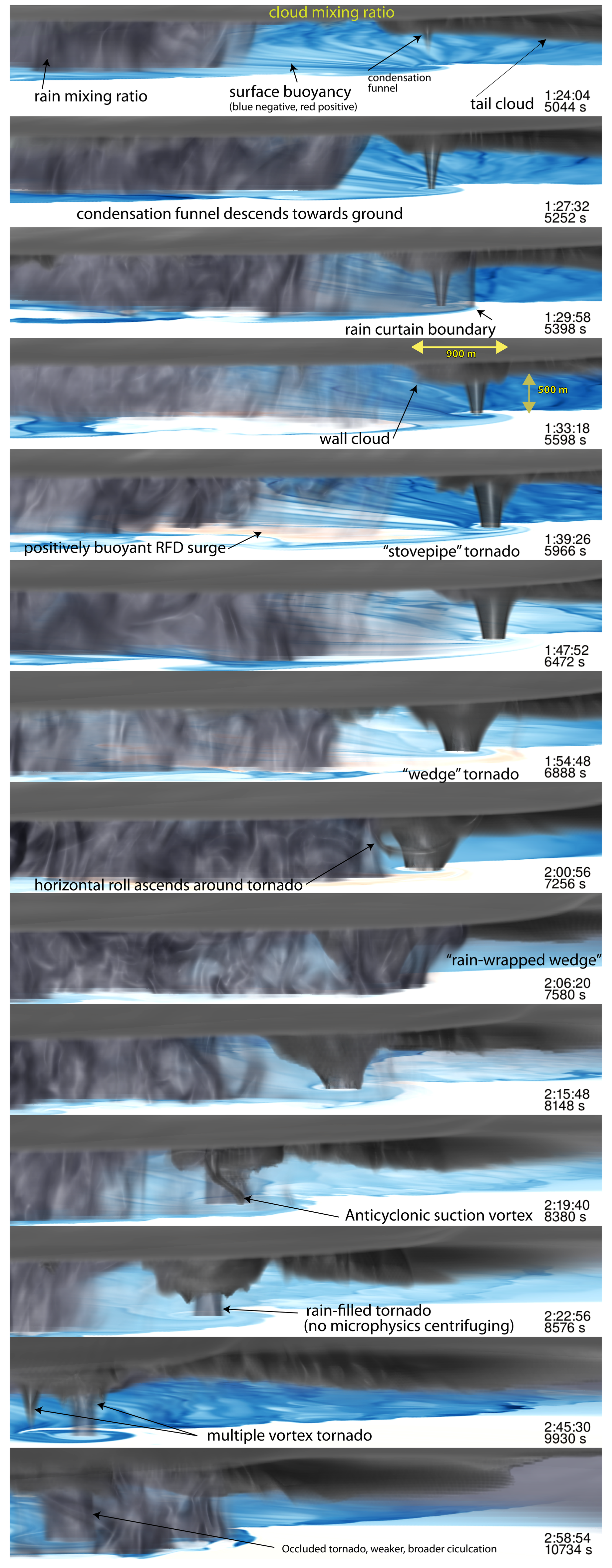


Vort. magnitude colored by ζ ($+\zeta$ red, $-\zeta$ blue)

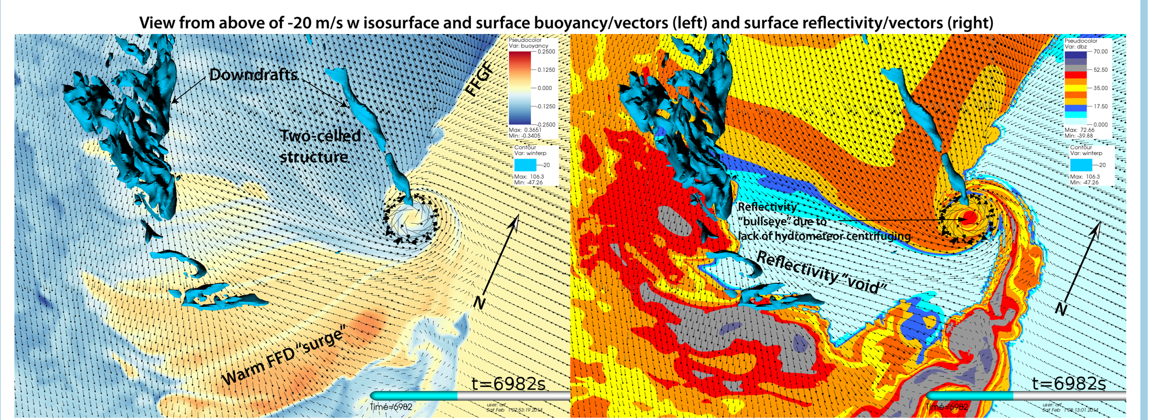


Above: Volume rendering of vorticity magnitude, $|\vec{\omega}| = \left|\vec{\nabla} \times \vec{V}\right|$, colored by ζ (the vertical component of the vorticity vector). The colored horizontal plane is buoyancy (units m s^{-2}) at the bottom-most model grid plane ($z = 15$ m), with red indicating positive buoyancy and blue indicating negative buoyancy. Numeric labels indicate model time in seconds. Red vortices contain a $+\zeta$ (cyclonic) component, blue contain a $-\zeta$ (anticyclonic) component. Thresholds were chosen to focus on vorticity magnitude exceeding 0.2 s^{-1}, which focuses on rotational flow. Several minutes prior to tornadogenesis, a tall, narrow $+\zeta$ vortex forms beneath a lowering in the cloud base (4518). This vortex first appears above the ground and appears to stretch upward beneath the supercell updraft. A series of $+\zeta$ vortices are observed to move rearward along the FFGF and merge with the nascent tornado vortex (4842–5802). What appears to be vortex breakdown begins to occur aloft (6402), coinciding with the beginning of the strongest period of the tornado's life cycle. Secondary RFD surges, sometimes positively buoyant, wrap around the tornado (6978), and $-\zeta$ vortices that move along the RFGF and FFGF interact with the tornado circulation in complex ways. Note: Persistent tornado-like anticyclonic circulations (e.g., 4518–5222) are evident throughout the simulation.

Vol. rendering of cloud and rain mixing ratios



Warm RFD surges



Throughout the simulation, a series of surges behind the rear-flank gust front occur. Some of these surges at the surface are positively buoyant and are sometimes associated with large regions containing little if any hydrometeor content, suggesting warm downdrafts exhibiting adiabatic compression. Further analysis is required to determine whether these warm RFD surges play a role in tornado maintenance.

Preliminary observations

- Tornadogenesis occurs several minutes after the formation of a persistent strenghtening cyclonic vortex, originating near the ground and stretching upwards
- Tornado condensation funnel is observed to originate at base of the wall cloud and descend downwards to the ground
- Tornado is strengthened by a train of cyclonic vortices which propagate rearward along the FFGF, merging into the main tornado circulation
- Anticyclonic vortices are also plentiful along FFGF and RFGF and are cyclonically advected around the edge of the tornado vortex, causing "destructive interference"
- Tornado structure appears primarily two-celled as evidenced by a persistent downdraft in the tornado core
- Volume rendered fields of cloud and rain bear striking resemblance to field observations of tornadic supercells, indicating features such as a wall cloud, tail cloud, and a tornado condensation funnel extending to the ground for an extended period

Future Work

- Determine whether the mode of tornadogenesis is consistent with current theory and observations
- Explore the near-tornado environment to analyze the "balance of forces" existing during its maintenance
- Include hydrometeor centrifuging
- Utilize a more sophisticated turbulence closure scheme
- Increase resolution and include the effects of surface friction and explore how it affects the tornado
- Compare simulation data to radar observations of actual storm

Acknowledgments

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