Supercell Tornadogenesis

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Learning Goals

- Understand the history of tornado science, and the iterative process between forecasting, collecting observations, and running models
- Understand the current state of tornado science
- Understand the the role of downdrafts in tornadogenesis
- Understand the importance of strong low-level updrafts in tornadogenesis

Disclaimer!

- I do not yet qualify as an expert (thesis in progress)!
- Even if I was an expert, a lot of this knowledge is evolving and new
- The papers referenced are a great resource for more depth
- The papers referenced are only a subset of a rich history of literature on the matter, and there are differing schools of thought
- Some of this contains opinion and work that has not been published. Always refer to published work before taking anything as “truth”
- The atmosphere cares not for our conceptual models

The First Successful Tornado Forecast: 1948
Ernest J Fawbush & Robert C Miller

- Major Ernest J Fawbush and Colonel Robert C Miller were meteorologists stationed at Tinker Air Force Base
- March 20th, 1948: A tornado strikes Tinker AFB, causing significant damage to base infrastructure and aircraft
- March 22-24th: Fawbush and Miller analyzed the surface and upper-air charts for the 20th, as well as other outbreaks of tornadoes that had recently occurred.
- March 25th, 1948: Only 5 days after the Tinker tornado, they noticed the pattern was incredibly similar to the 20th and their list of criteria for tornado outbreaks.
  - They were pressured by the base commander to issue a forecast. Eventually, they issued the forecast for tornado development, believing it to be career suicide.

Miller and Crisp (1999)

The First Successful Tornado Forecast: 1948
Ernest J Fawbush & Robert C Miller

- Shortly after 6:00 PM on March 25th, Tinker AFB was struck by a tornado. It caused extensive damage, but because of the early warning, losses were minimized.

NOAA

- The forecast of Fawbush and Miller kickstarted events that would eventually break a half-century ban on forecasting tornadoes, out of fear of mass hysteria.

- In 1951, the Severe Storms Forecast Center at Tinker AFB was established. It would go through many renamings and relocations (Severe Local Storm [SELS] unit, National Severe Storms Forecast Center [NSSFC]), but would eventually become the NOAA Storm Prediction center.

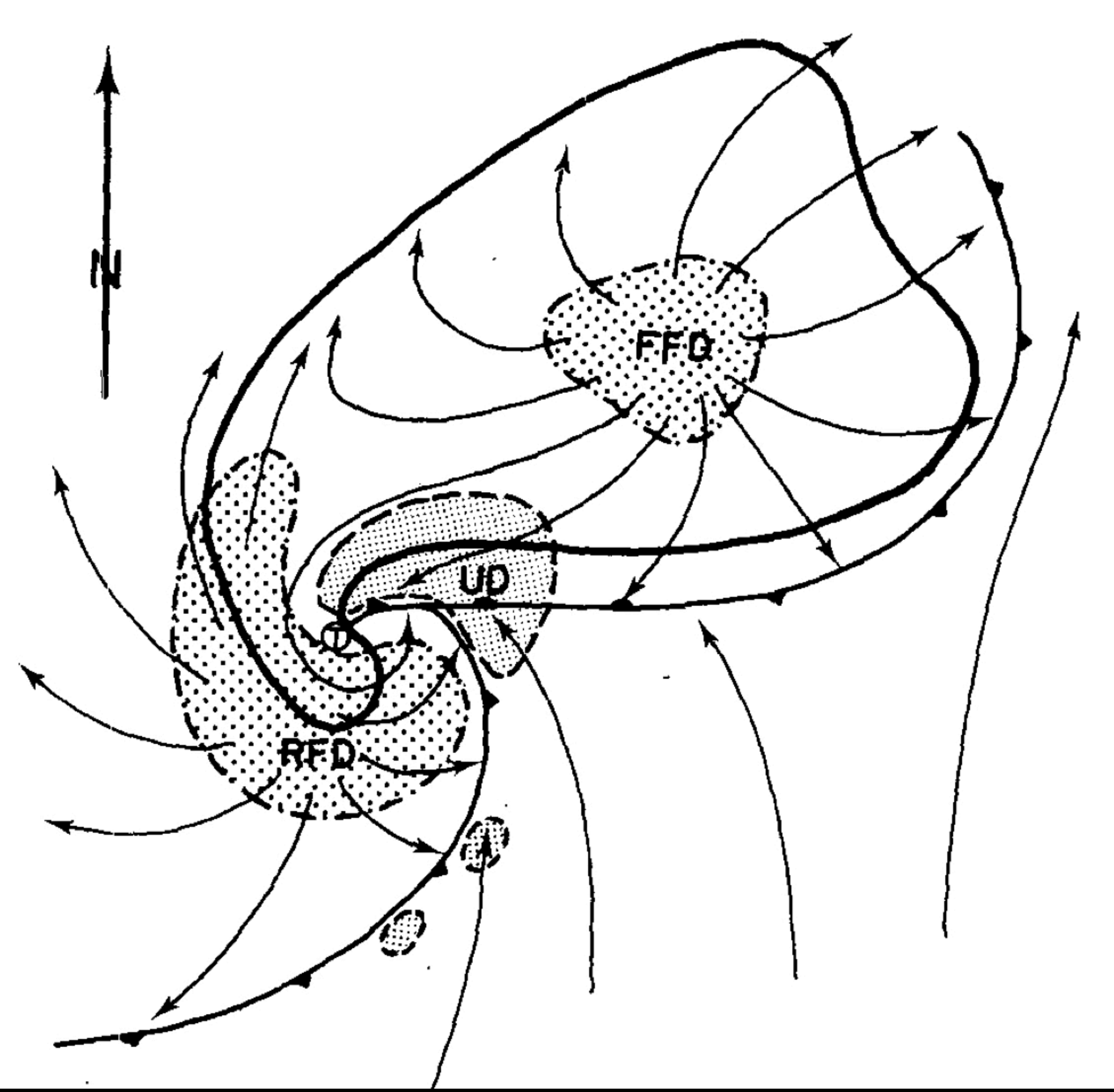
- In 1955, the National Severe Storms Project (NSSP) was established, later renamed the National Severe Storms Laboratory (NSSL) and moved to Norman, OK in 1964.

The First Tornadogenesis Theory Tied to the Supercell Thunderstorm Model

Based on observations of supercells and tornadoes using doppler radar, limited surface observations, and storm-chaser photography/videography

Theories of Supercell Tornadogenesis: Lemon and Doswell 1979

- Prior theories about tornadogenesis had been proposed, but none incorporated the observations of supercells and tornadoes collected from Doppler radar.
- Les Lemon and Charles Doswell of the NSSFC proposed a modified conceptual model of supercell thunderstorms, but more importantly, used the collected observations to limit the proposed theories of tornadogenesis
- Their additions to the supercell model of Browning (1964) included the Rear Flank Downdraft (RFD), which they also propose as being responsible for tornadogenesis

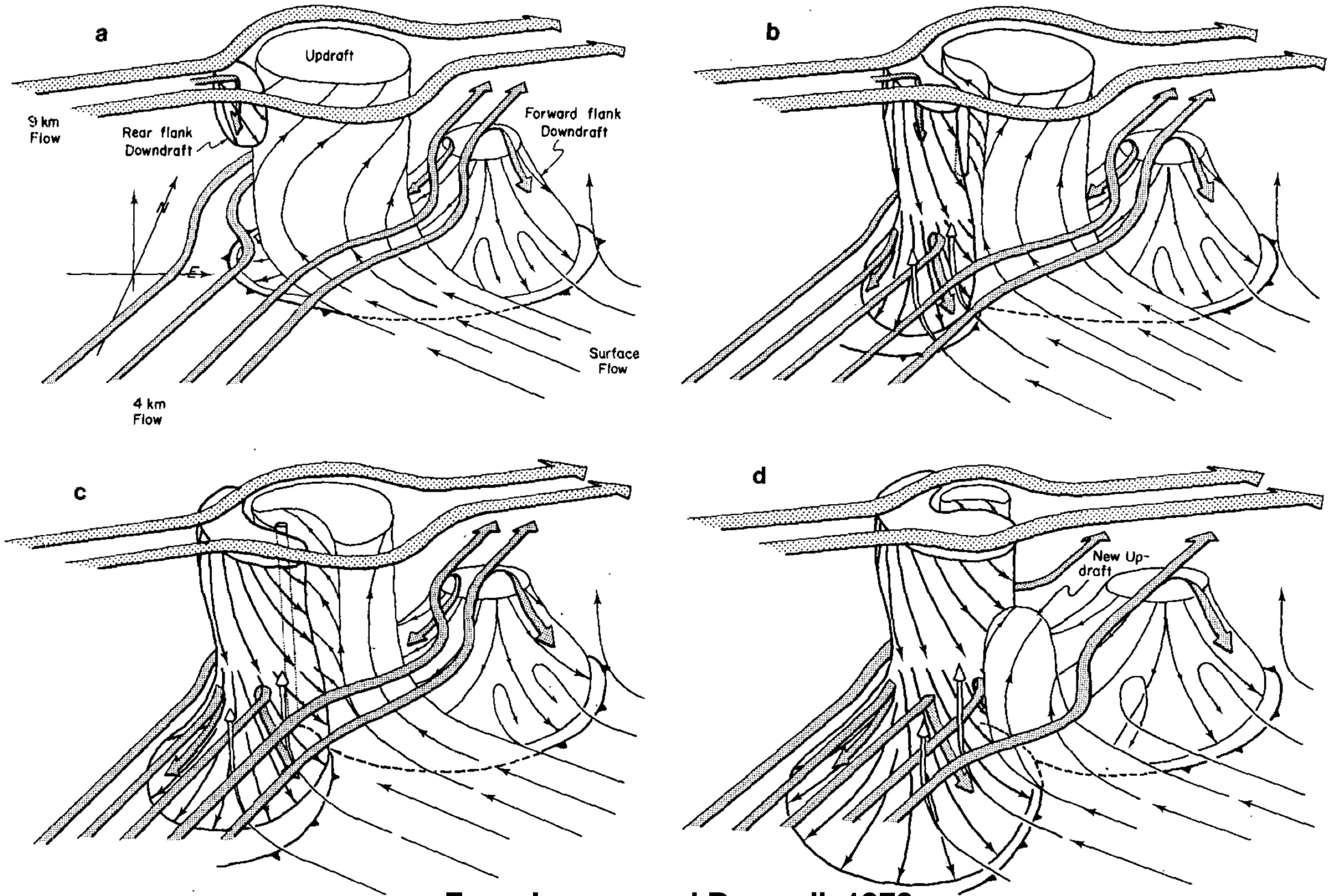


Prior Theories of Tornadogenesis

- Convergence of existing vertical vorticity was considered questionable due to tornadogenesis being associated with updraft weakening in radar observations (Lemon 1977; Lemon et al. 1978).
- The low-level gust front along the forward flank was suggested as a formation mechanism. It was proposed that the roll-up of shear vortices along a vertical vortex sheet could supply the vertical vorticity (Barcilon and Darzin 1971; Brandes 1977).
  - Lemon and Doswell eliminated this due to Doppler observations of elevated tornado vortex signatures.
- Scale analysis was used to reason that vortex tilting and stretching were both likely candidates for generating vertical vorticity.
- Baroclinic (solenoidal) vorticity generation was hypothesized to be important, but few thermodynamic observations near supercells existed.

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\Delta v}{\Delta x}\right) = \underbrace{-v\frac{\partial f}{\partial y}}_{\text{(Coriolis)}} \underbrace{- fD - \frac{\Delta v}{\Delta x}D}_{\text{(stretching)}} \underbrace{- \frac{\Delta w}{\Delta x}\frac{\partial v}{\partial z}}_{\text{(tilting)}} \underbrace{- \frac{\Delta \alpha}{\Delta x}\frac{\partial p}{\partial y}}_{\text{(solenoidal)}},$$

$$\frac{D\zeta}{Dt} = \underbrace{-\zeta\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)}_{\substack{\text{A} \\ \textbf{Vortex Stretching}}} + \underbrace{\left(\xi\frac{\partial w}{\partial x}+\eta\frac{\partial w}{\partial y}\right)}_{\substack{\text{B} \\ \textbf{Vortex Tilting}}} - \underbrace{\left(\frac{\partial \alpha}{\partial x}\frac{\partial p}{\partial y}-\frac{\partial \alpha}{\partial y}\frac{\partial p}{\partial x}\right)}_{\substack{\text{C} \\ \textbf{Baroclinic Generation}}} + \underbrace{\left(\frac{\partial F_y}{\partial x}-\frac{\partial F_x}{\partial y}\right)}_{\substack{\text{D} \\ \textbf{Turbulence/Friction}}}.$$



From Lemon and Doswell, 1979

FIG. 9. Schematic three-dimensional depiction of evolution of the drafts, tornado and mesocyclone in an evolving supercell storm. The stippled flow line suggesting descent of air from the 9 km stagnation point has been omitted from (c) and (d), for simplicity. Fine stippling denotes the TVS. Flow lines throughout the figure are storm relative and conceptual only, not intended to represent flux, streamlines, or trajectories. Conventional frontal symbols are used to denote outflow boundaries at the surface, as in Fig. 7. Salient features are labeled on the figure.

Example of RFD
13 April, 2022 in Iowa

Courtesy of Isaac Schluesche

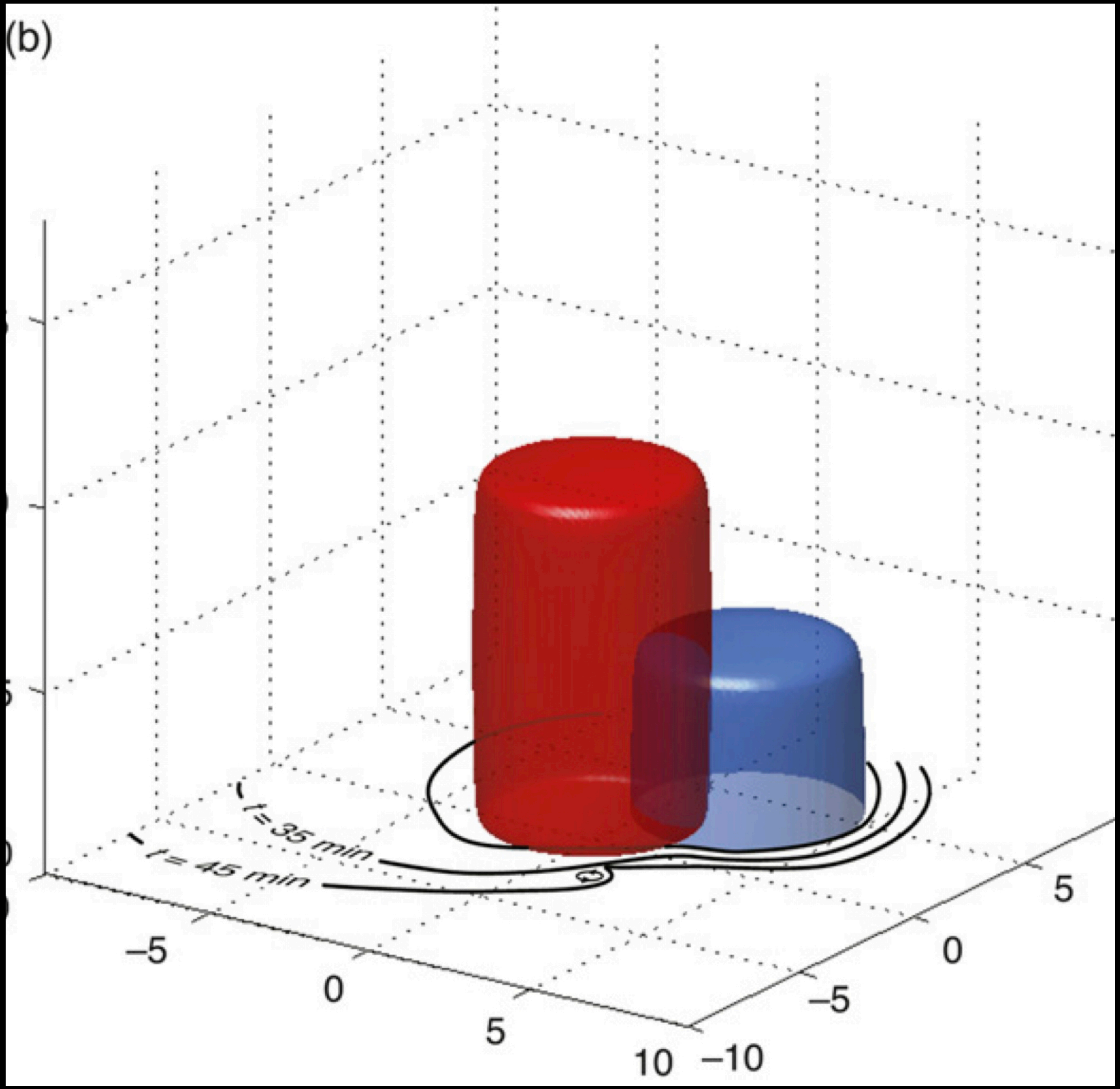
Summary of Lemon and Doswell 1979

- Supercell conceptual model updated to include the Rear Flank Downdraft (RFD), based primarily on Doppler radar observations
- Vortex tilting/stretching believed to be the primary source of vertical vorticity
- Baroclinic vorticity generation not ruled out, but they lacked observations to support this theory
- Shear vortices along the forward-flank gust front ruled out due to radar indicated elevated tornado vortex signatures. *It is pretty well agreed in current literature that the tornado vortex forms in the lower portions of the storm*.
- They proposed the tornado vortex forms aloft, in the vertical velocity gradient between the updraft/mid-level mesocyclone and the rear-flank downdraft
- The rear-flank downdraft descends, bringing the elevated vortex towards the surface


Supercell Tornadogenesis in the Modern Era
Theories derived from numerical simulations of supercell thunderstorms that produce significant near-surface vertical vorticity

Theories of Tornadogenesis: Markowski and Richardson 2014

- Used simulated "pseudo-storms" to quantify the effects of low-level wind shear and cold-pool buoyancy on tornadogenesis
  - Used a dry heat source as a proxy for the updraft, and a thermodynamic heat-sync to represent the downdraft and to create a cold-pool
  - No moist processes (no latent heating, no hydrometeors) to reduce degrees of freedom.



Theories of Tornadogenesis: Markowski and Richardson 2014

- Low-level horizontal vorticity is primarily generated by the baroclinic mechanism

- Strong low-level environmental shear results in stronger mid-level mesocyclones, and therefore stronger dynamic lifting by the mesocyclone

- The combination of strong dynamic lifting and weak negative buoyancy provides the best combination of factors leading to tornadogenesis

- **Downdraft is critical for re-orienting baroclinicly generated horizontal vorticity into the vertical, and then is stretched and amplified underneath low-level mesocyclone**

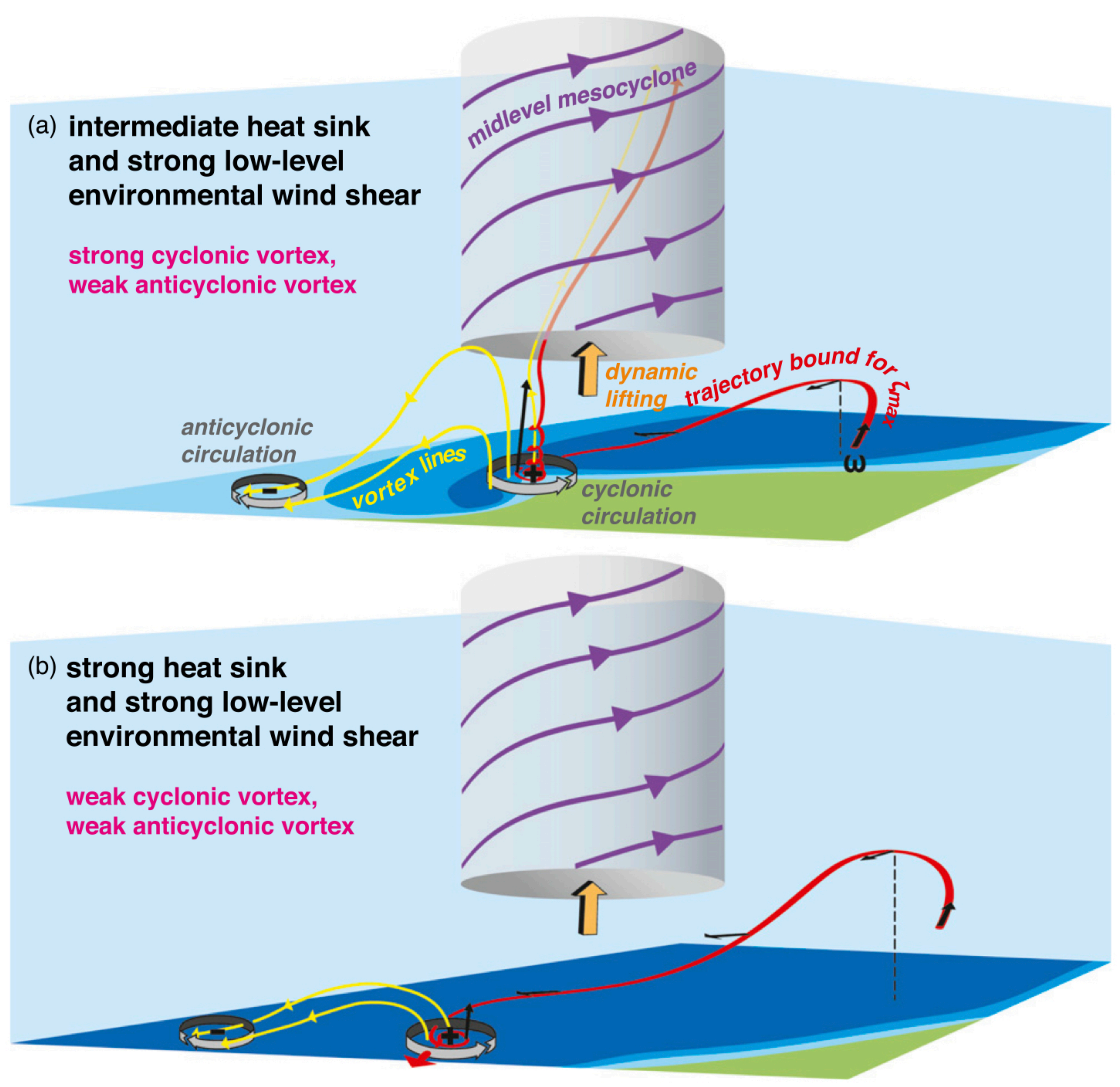


FIG. 25. Schematic summarizing the simulation outcomes: (a) the baseline simulation in which a strong cyclonic vortex develops (Sc8m8), the simulations in which (b) the heat sink is either too strong (results in colder outflow, i.e., Sc16m8) or (c) the environmental wind shear is too weak (results in a weaker dynamic VPPGF, i.e., Sc8m2), and (d) the simulation in which the heat sink is excessively weak (i.e., Sc4m8). A schematic trajectory bound for ζ_{min} (and evolution of $\boldsymbol{\omega}$ along this trajectory) is shown in (d) only (the anticyclonic vortex is dominant in this simulation), but the generalized trajectory and vorticity evolution also applies to trajectories approaching ζ_{min} in (a)–(c).

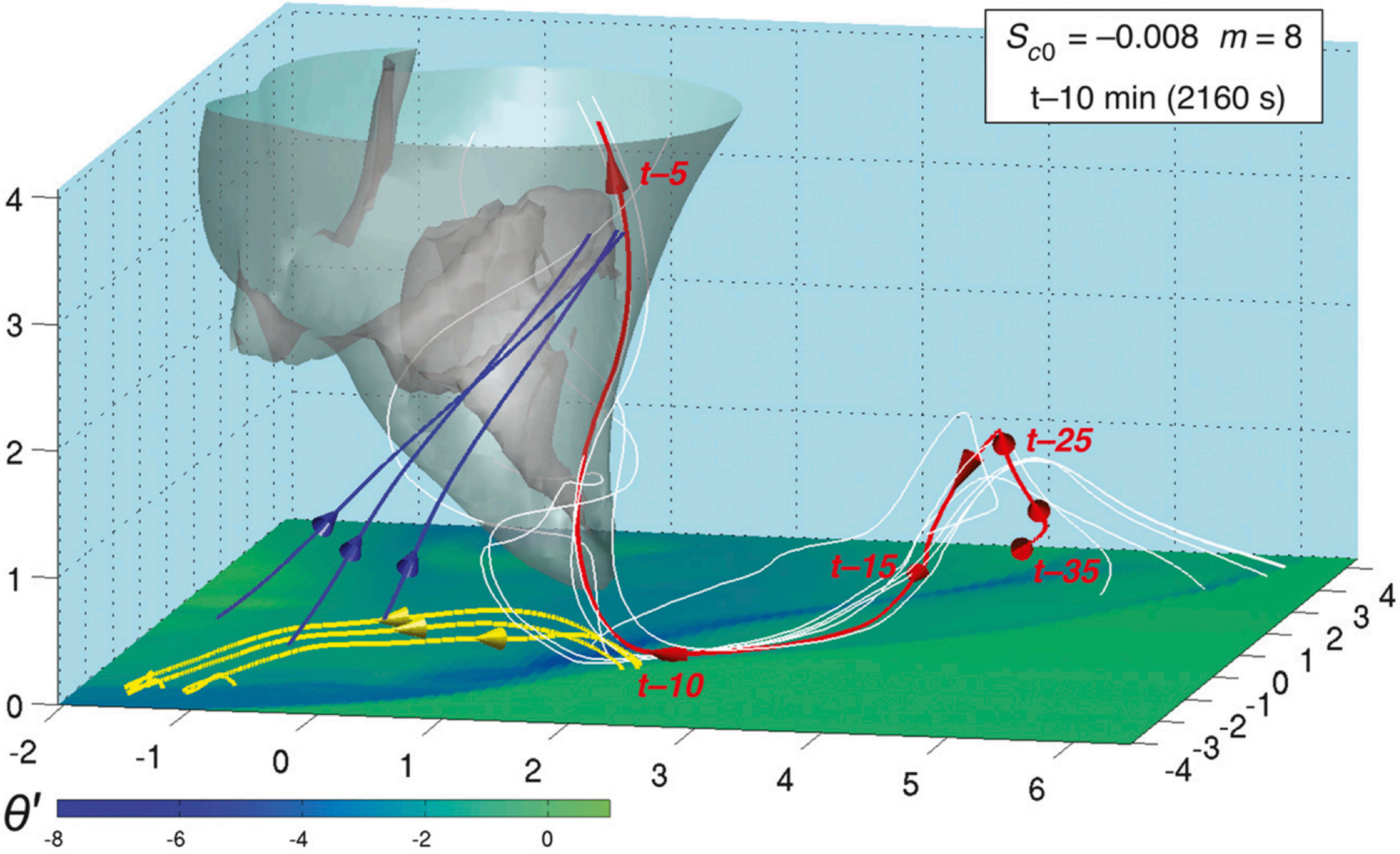


FIG. 6. Three-dimensional view of the midlevel updraft, near-surface θ' field, and key vortex lines and trajectories at $t - 10$ min (2160 s) in the Sc8m8 simulation. The view is from the south–southeast. Axes are in kilometers. The $w = 15\,\mathrm{m\,s^{-1}}$ isosurface is gray. The near-surface θ' field is color shaded (see legend). The yellow lines are vortex lines (their direction is indicated with arrows) that pass within 200 m of $\zeta_{\max}$ at the lowest scalar level ($z = 50$ m). The blue lines are vortex lines that pass within 500 m of $\zeta_{\max}$ at $z = 3$ km. The white lines are forward-integrated trajectories that pass within 500 m of $\zeta_{\max}$ at $t - 10$ min and have $\zeta \geq 0.008\,\mathrm{s^{-1}}$ in the lowest 75 m. The trajectory that passes nearest to the cyclonic vorticity maximum at $t - 10$ min is red. Arrows are placed along it at 5-min intervals.

From Markowski and Richardson, 2014

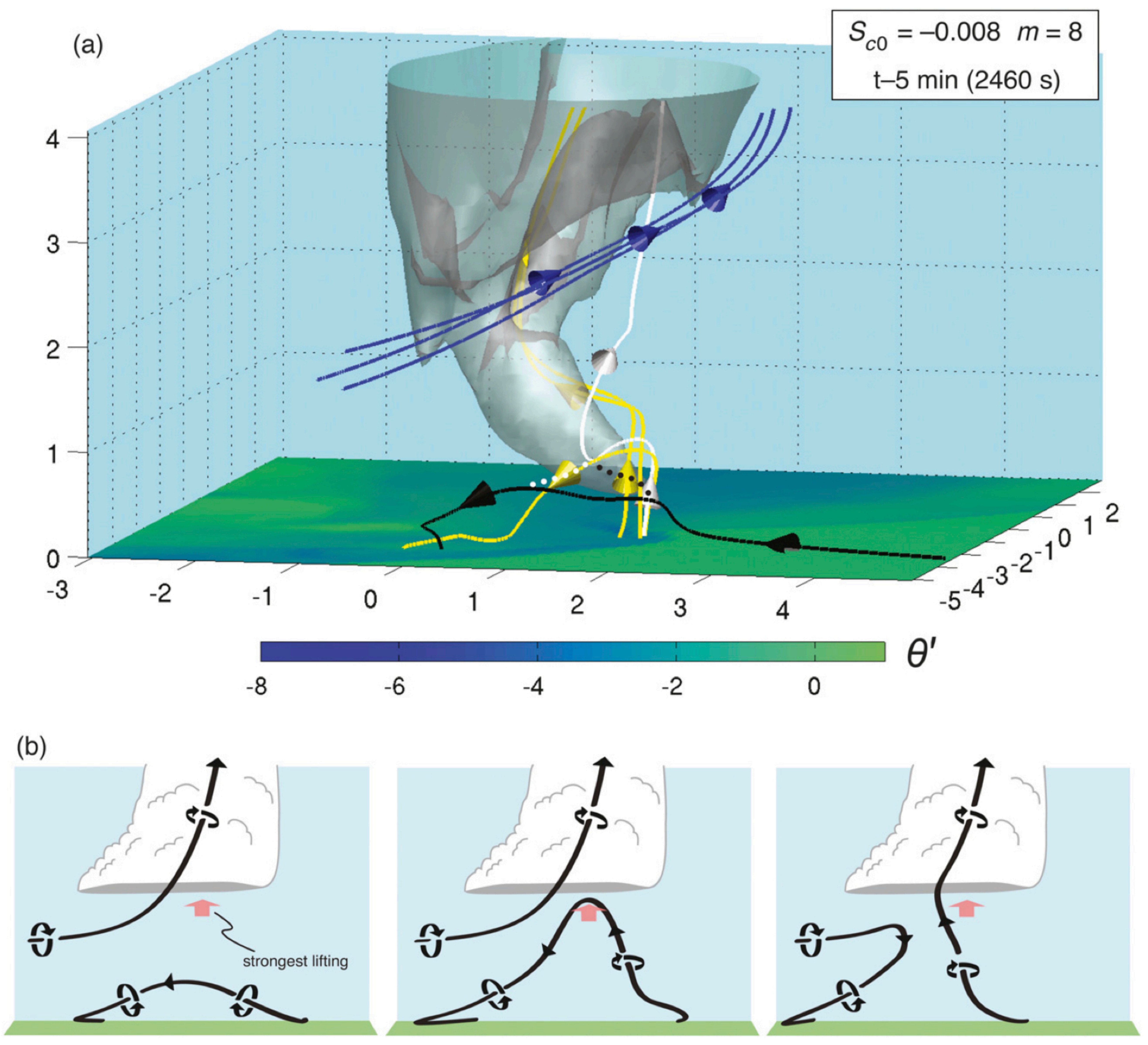


FIG. 7. (a) As in Fig. 6, but at $t - 5$ min (2460 s) in the Sc8m8 simulation. Trajectories have been omitted. The black and white lines are additional vortex lines; the black one originates in the environment and descends through anticyclonic vorticity in the cold pool. The purple vortex lines originate within the low-level cyclonic vortex and arches toward the anticyclonic vorticity before turning upright and passing into the midlevel updraft and mesocyclone. The dotted white and black lines suggest, respectively, plausible connections between the anticyclonic and cyclonic vortices in the cold pool and between the environmental vortex lines and vortex lines entering the midlevel mesocyclone. See text for further details. (b) Schematic evolution (left to right) of ''vortex-line surgery'' that joins a vortex line arching upward out of the cold pool with an environmental vortex line that enters the midlevel mesocyclone. The view is from the east–northeast.

From Markowski and Richardson, 2014

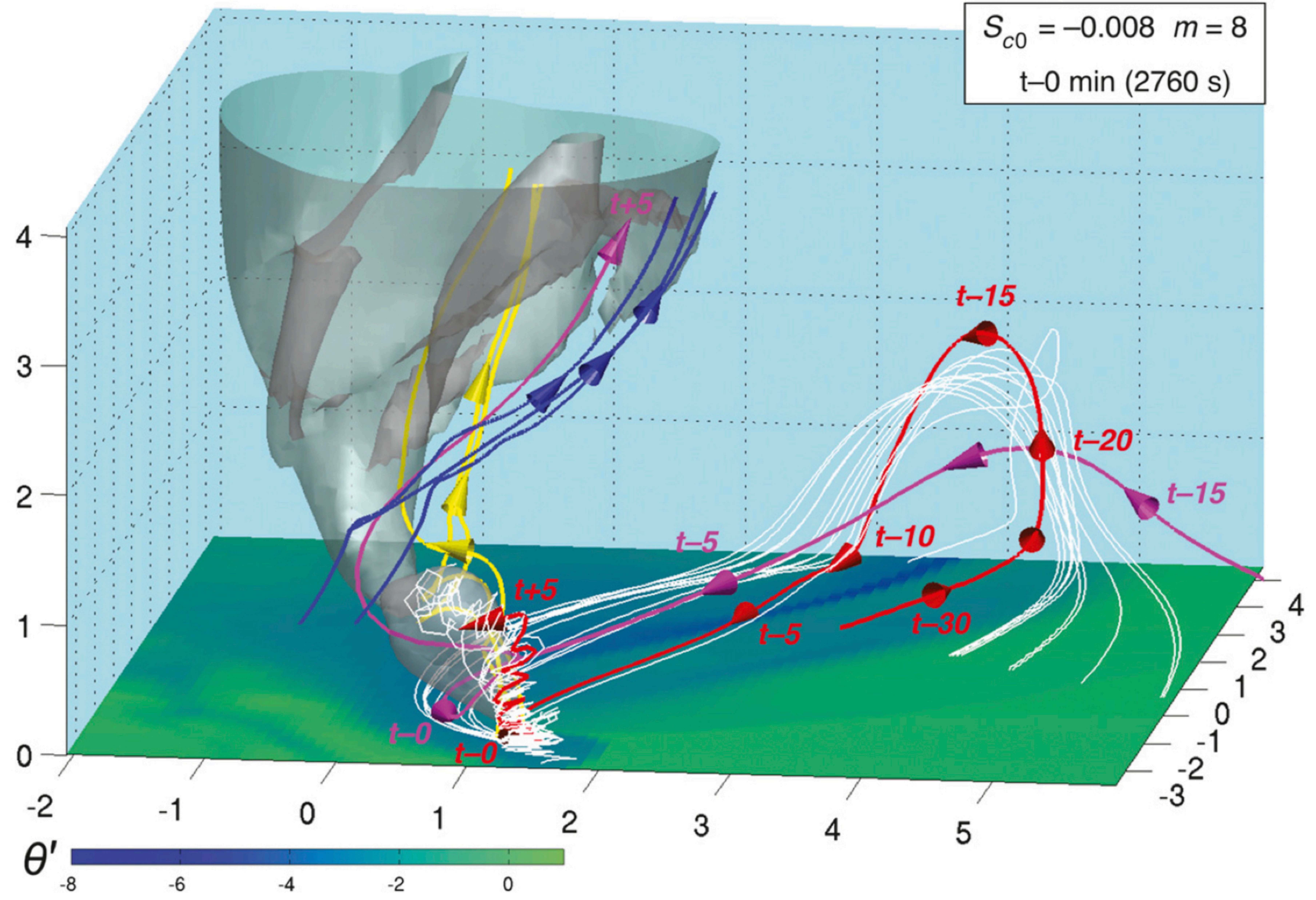
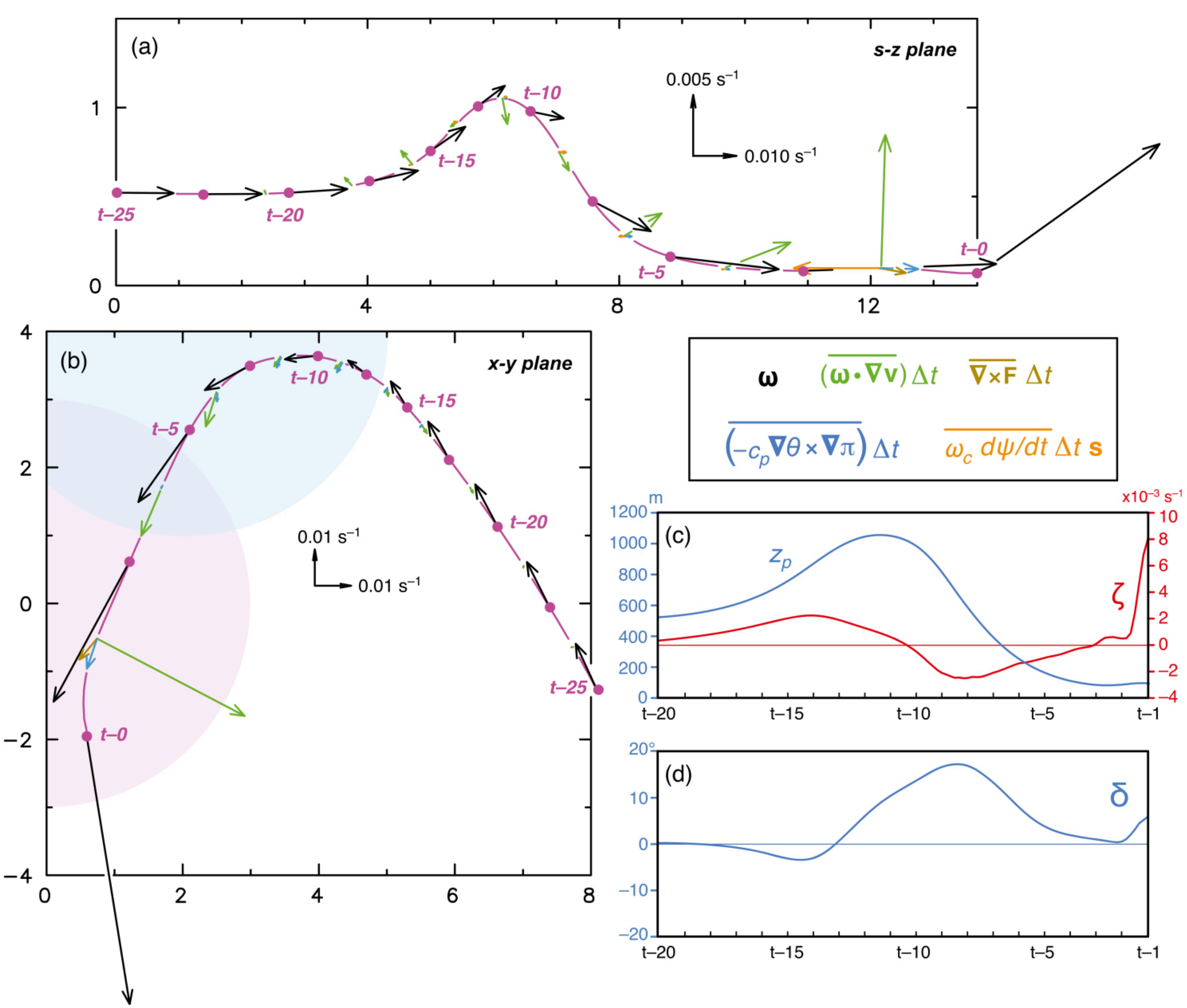


FIG. 8. As in Fig. 6, but at $t - 0$ min (2760 s) in the Sc8m8 simulation. The trajectories pass within 200 m of ζ_{max}, within 75 m of the surface, at $t - 0$ min. The trajectory that passes nearest to cyclonic vorticity maximum at $t - 0$ min is red. The magenta trajectory nears the lowest scalar level approximately 1 km west of ζ_{max} at $t - 0$ [see section 3a(3) and Fig. 11 for details]. The view is from the south–southeast.

From Markowski and Richardson, 2014



From Markowski and Richardson, 2014

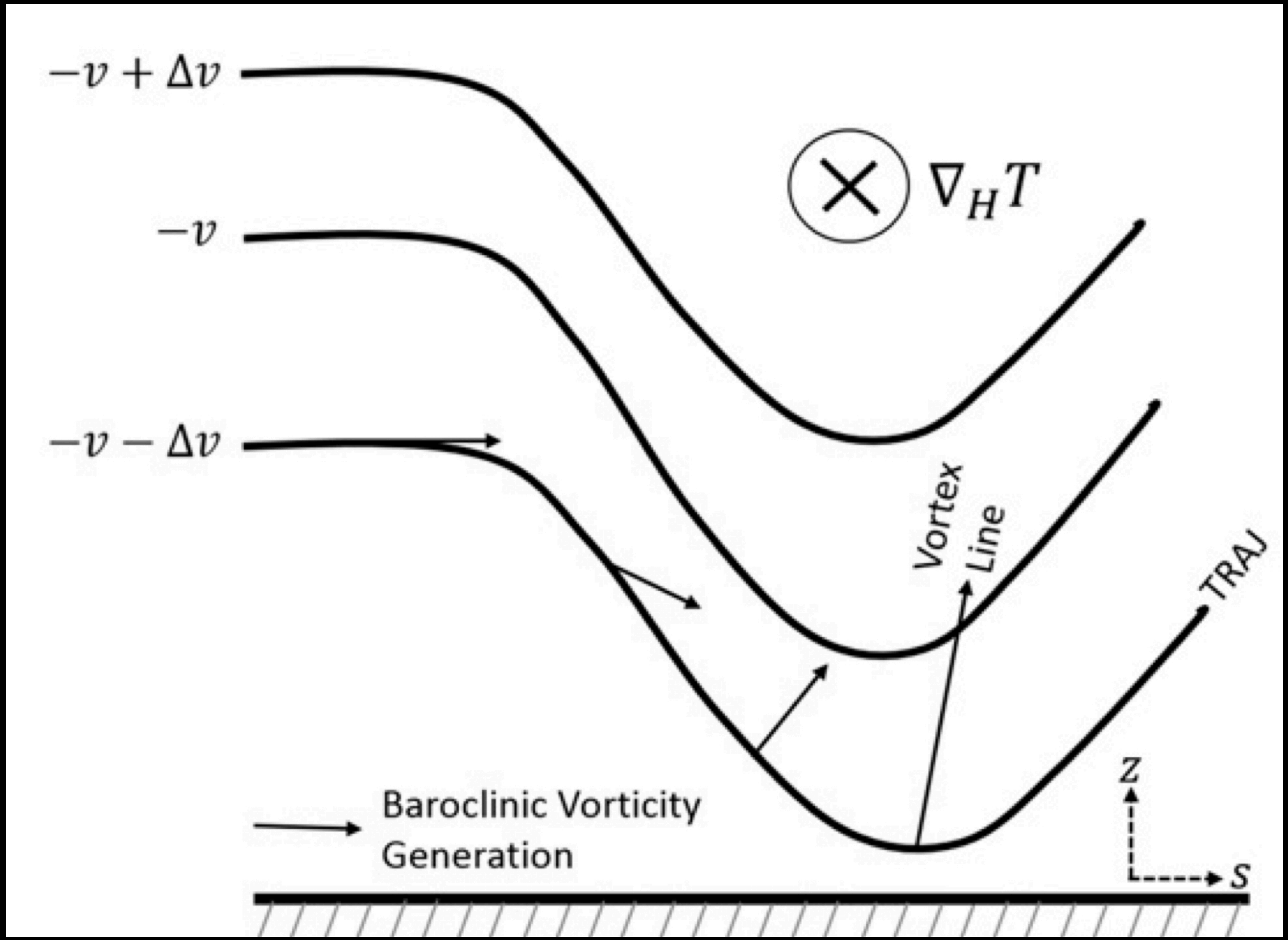
Summary of Markowski and Richardson 2014

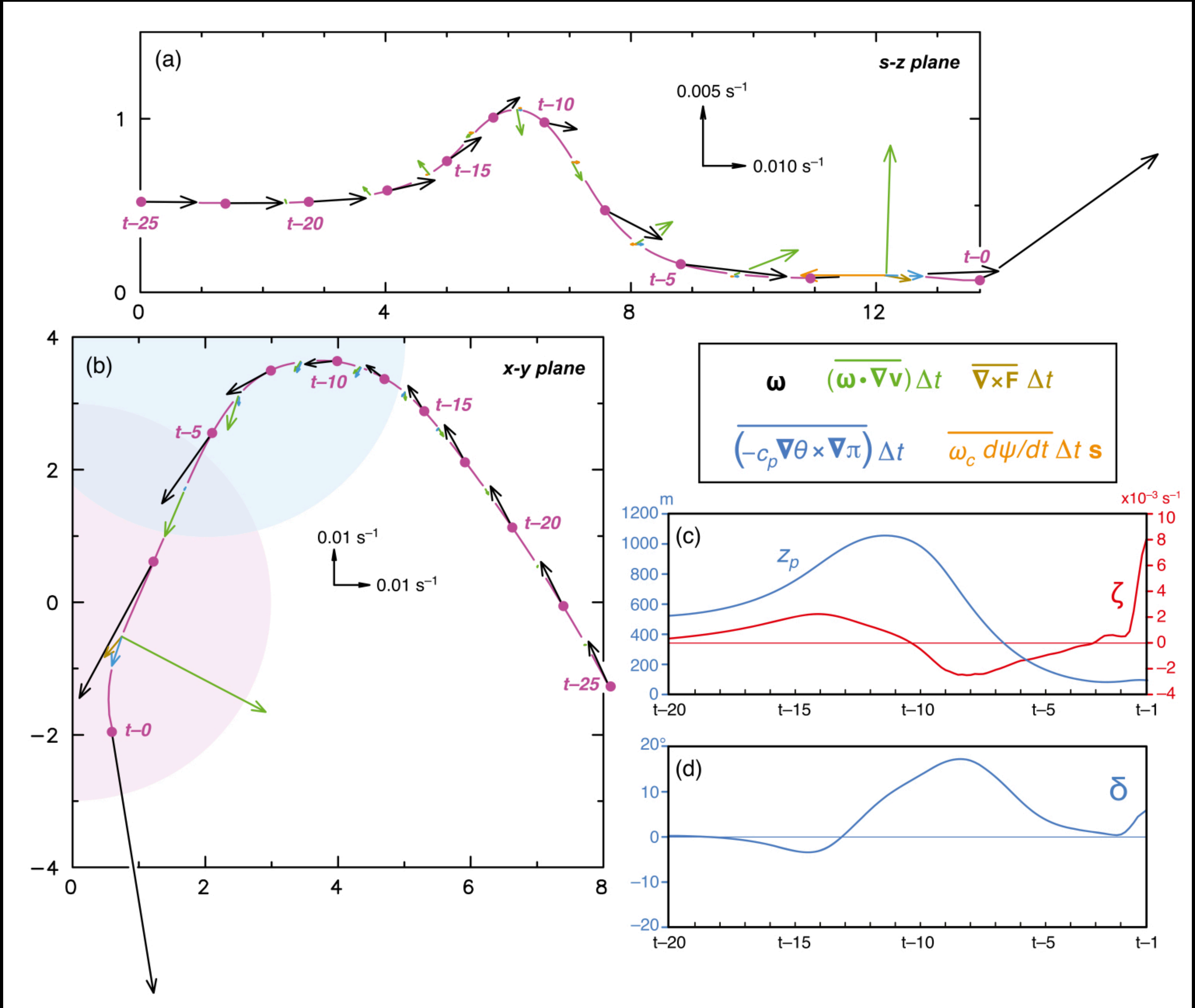
- Environments with large amounts of streamwise vorticity (strong wind shear in the low-levels) result in stronger mesocyclones closer to the surface.
- This provides strong dynamic lifting through the VPPGF
- **Baroclinic generation of horizontal vorticity and downdrafts are crucial for generating near-surface vertical vorticity**
- Strong negative buoyancy in the thunderstorm outflow results in a stronger circulation, but it is unable to be lifted by the mesocyclone
- Weak negative buoyancy does not develop strong enough near-surface circulation
- **Intermediate negative buoyancy is required to generate enough circulation for tornadogenesis while not being so negatively buoyant it cannot be lifted by the mesocyclone**

Summary of Current Theories on the Generation of Near-Surface Vertical Vorticity

Davies-Jones and Brooks (1993) Mechanism

- Using idealized simulation, the study describes how initially horizontal vorticity interacts with a downdraft, reorienting it into vertical vorticity
- Horizontal vorticity is continually generated along a trajectory via the baroclinic mechanism
- The vorticity vector is initially tilted downward by the downdraft, but continuous baroclinic generation of horizontal vorticity results in a mismatch between the velocity and vorticity vector
- This "slippage" means that by the time a parcel reaches the bottom of its descent, it acquires upward (or vertically) oriented vorticity
- This vorticity is then stretched underneath a low-level updraft and amplified into a tornadic vortex
- **Markowski and Richardson (2014) claimed this as the mechanism in their simulations**





From Markowski and Richardson, 2014

Rotunno et al. (2017) Mechanism

- The DJB mechanism requires that a parcel have positive vertical vorticity by the time I teaches it's maximum descent, or nadir.

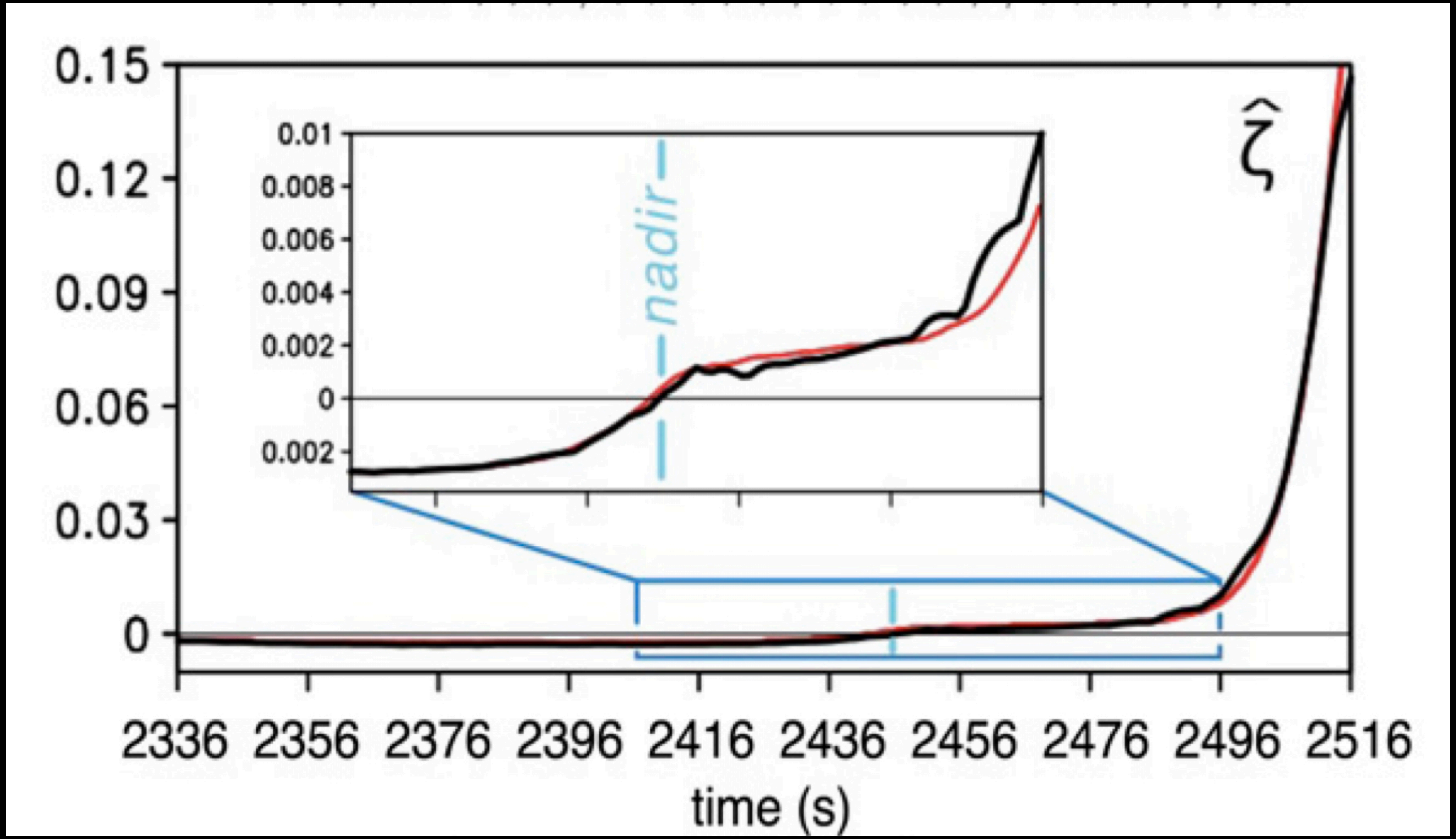
- This study demonstrates that while the vortex tilting described by DJB occurs, it need not have positive vertical vorticity at the nadir.

- The downdraft is responsible for generating near-surface horizontal vorticity through the baroclinic mechanism.

- The parcel's vertical vorticity can be zero at the nadir, and then tilting and stretching of horizontal vorticity into the vertical is responsible for significant vertical vorticity.

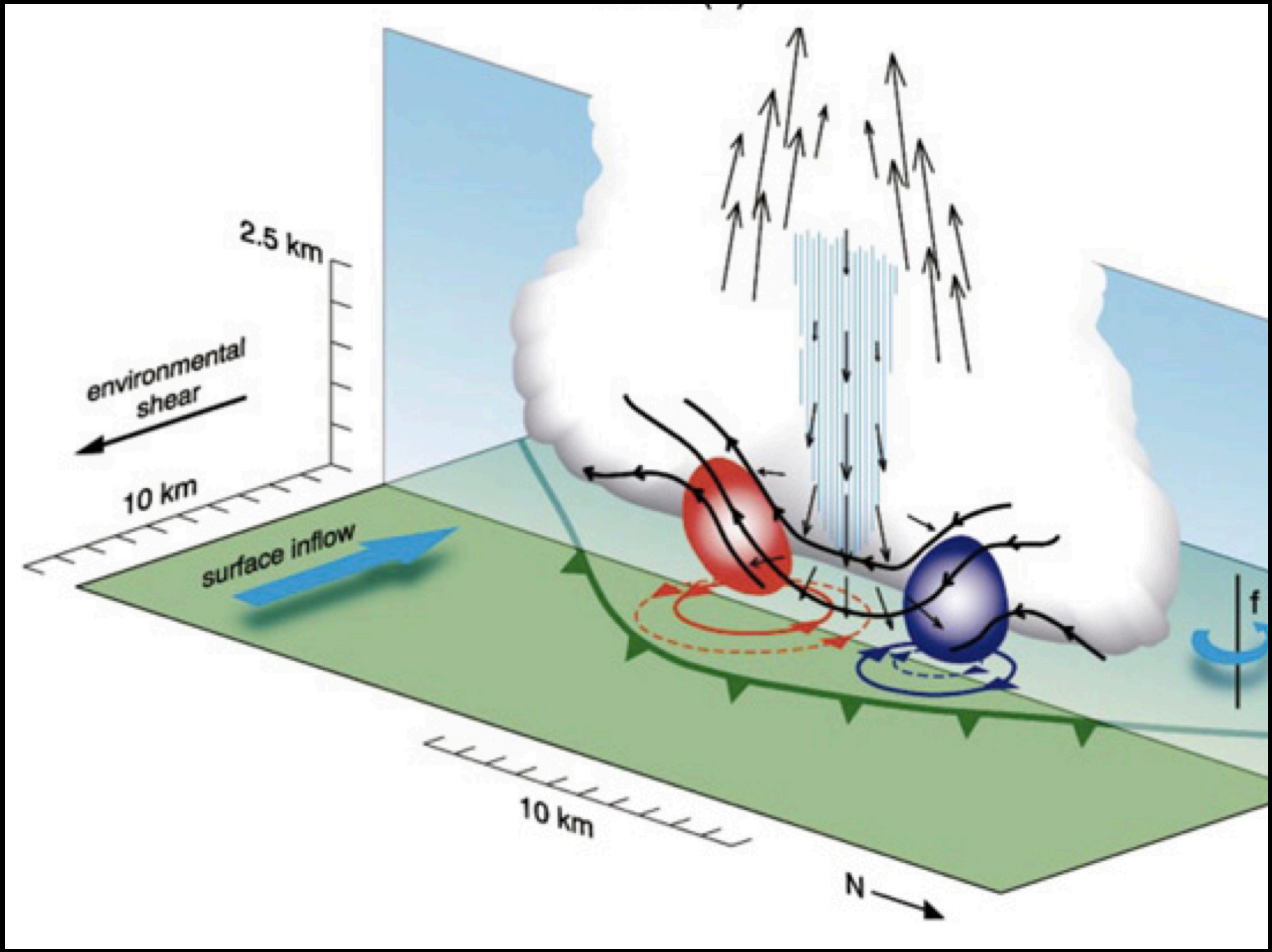
- **Vertical vorticity need not be present near the surface for tornadogenesis - purely horizontal vorticity is sufficient.**

- **This is effectively a revision of the DJB mechanism**



Trapp and Weisman (2003) Mechanism

- Proposed for Quasi-Linear-Convective-System (QLCS) tornadogenesis by Trapp and Weisman (2003); Dahl (2015) found it to be present in simulated supercells as well.
- Thunderstorm downdrafts depress horizontal vortex lines towards the surface, creating a pair of counter-rotating vortices.
- In simulations, the cyclonic vortex forms to the south, and the anti cyclonic vortex forms towards the north.
- The updraft then stretches and amplifies the cyclonic vertical vortex.



So Which Is It?

- **All of these mechanisms have been found to be present in simulations of supercell thunderstorms.**
- Boyer and Dahl (2020) sought to find out which is more important for maintaining near-surface vortices.
- They found that the tilting of vortex lines into the updraft (the Rotunno mechanism) was the most relevant, with the DJB and Trapp/Weisman mechanisms not apparent or present.

Caveats

- Many of these simulations have a sufficient resolution for resolving supercells, but not tornadoes. These vortices are called “tornado-like”, but are not tornadoes.

- All of these simulations are “free-slip” - the impacts of friction are completely unaccounted for.

    - Roberts et al. 2016 and 2017 evaluate the role of friction in tornadogenesis, and they find it to be a leading factor even above the baroclinic mechanism. Tornadogenesis often occurs before the establishment of a cold-pool in these simulations.

    - Physical and numerical chamber model studies show friction is important for radial convergence and corner-flow within the tornado,

    - However, it has been shown by Markowski and Bryan (2016) that our current understanding of the surface-layer in thunderstorm outflow is severely lacking, and standard boundary layer application of friction in cloud models is highly erroneous.

    - The true magnitude and role of friction in supercell tornadogenesis is an unknown and ongoing research topic.

What About Non-Supercell Tornadoes?

- These tornadoes are not associated with a rotating updraft
- Colloquially known as landspouts and water spouts
- Processes are driven entirely by the stretching of preexisting vertical vorticity:
  - Pre-existing boundaries
  - Horizontal shear instabilities
- Requires weakly sheared environments that allow for an updraft to reside over the vorticity source for longer periods.

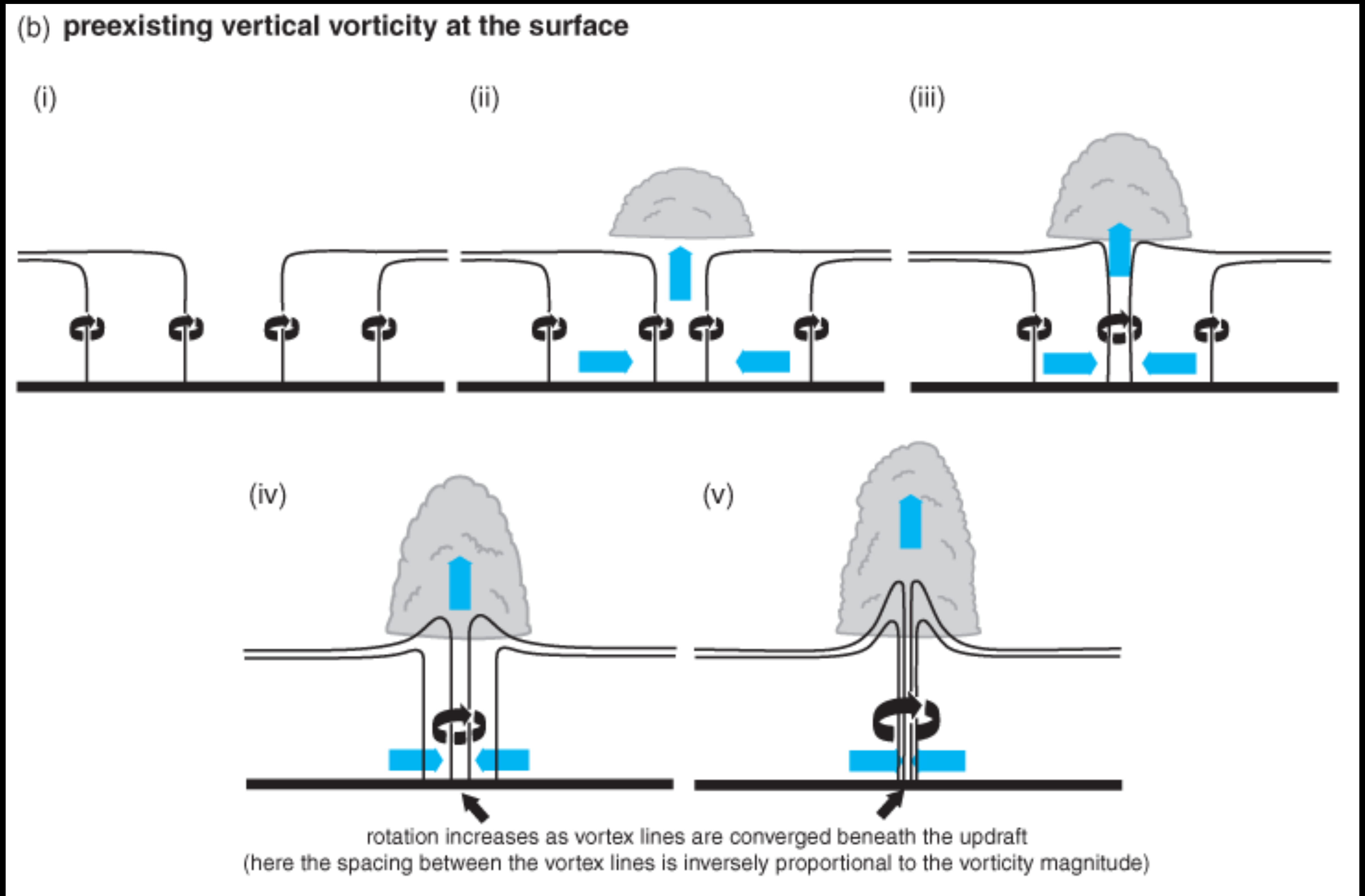


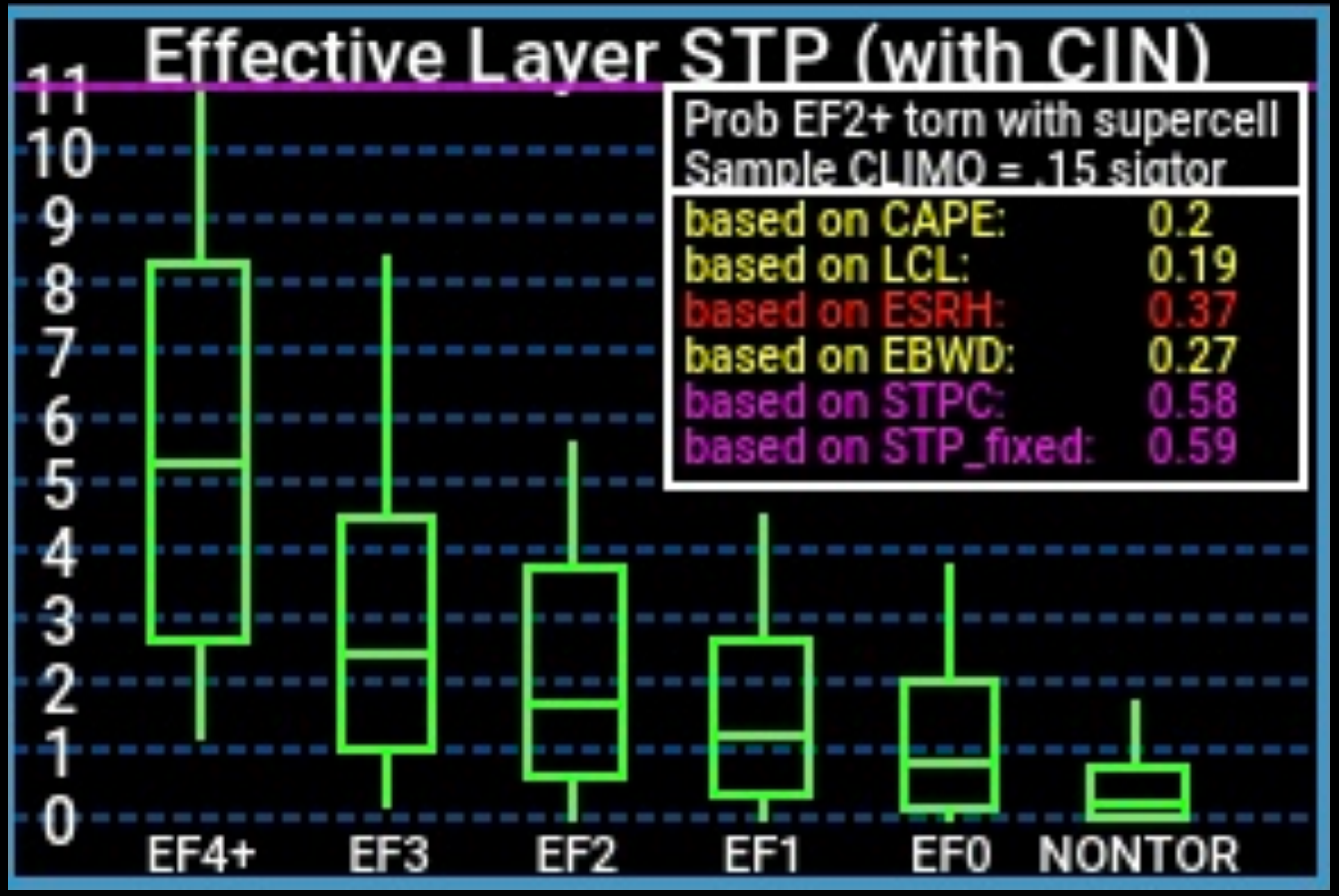
Figure 10.3 (Continued)
(b) Simple vortex line demonstration of how a tornado can arise from convergence alone, in the absence of a downdraft, when preexisting vertical vorticity is present at the ground.

Source: MR (2010)

How do we use any of this to predict the formation of tornadoes?

- Thompson et al. 2003 (revised by Thompson et al. 2007) created the Significant Tornado Parameter (STP)
  - Mixed-layer CAPE used to assess buoyancy for thunderstorm development
  - The mixed-layer lifted condensation level (LCL) is used as a proxy for cold pool buoyancy. Lowe LCLs are indicative of higher boundary layer relative humidity, which means less evaporation of hydrometeors.
  - The mixed layer CIN is included to allow for the presence of some inhibition, reflecting the mesocyclone's ability to lift stable air
  - The bulk wind difference (wind shear) is used to discriminate supercell potential
  - Storm Relative Helicity is used to asses low-level shear (and subsequently mesocyclone strength)
- Recent work by Coffer et al. 2019 suggests that using the surface-500 meter storm relative helicity may be an even better discriminator than what is currently used in STP

$$\mathrm{STP} = \frac{\mathrm{MLCAPE}}{1500\,\mathrm{J\,kg^{-1}}} \times \frac{2000 - \mathrm{MLLCL}}{1000\,\mathrm{m}} \times \frac{200 + \mathrm{MLCIN}}{150\,\mathrm{J\,kg^{-1}}} \times \frac{\mathrm{EBWD}}{20\,\mathrm{m\,s^{-1}}} \times \frac{\mathrm{ESRH}}{150\,\mathrm{m^2\,s^{-2}}}, \qquad (1)$$



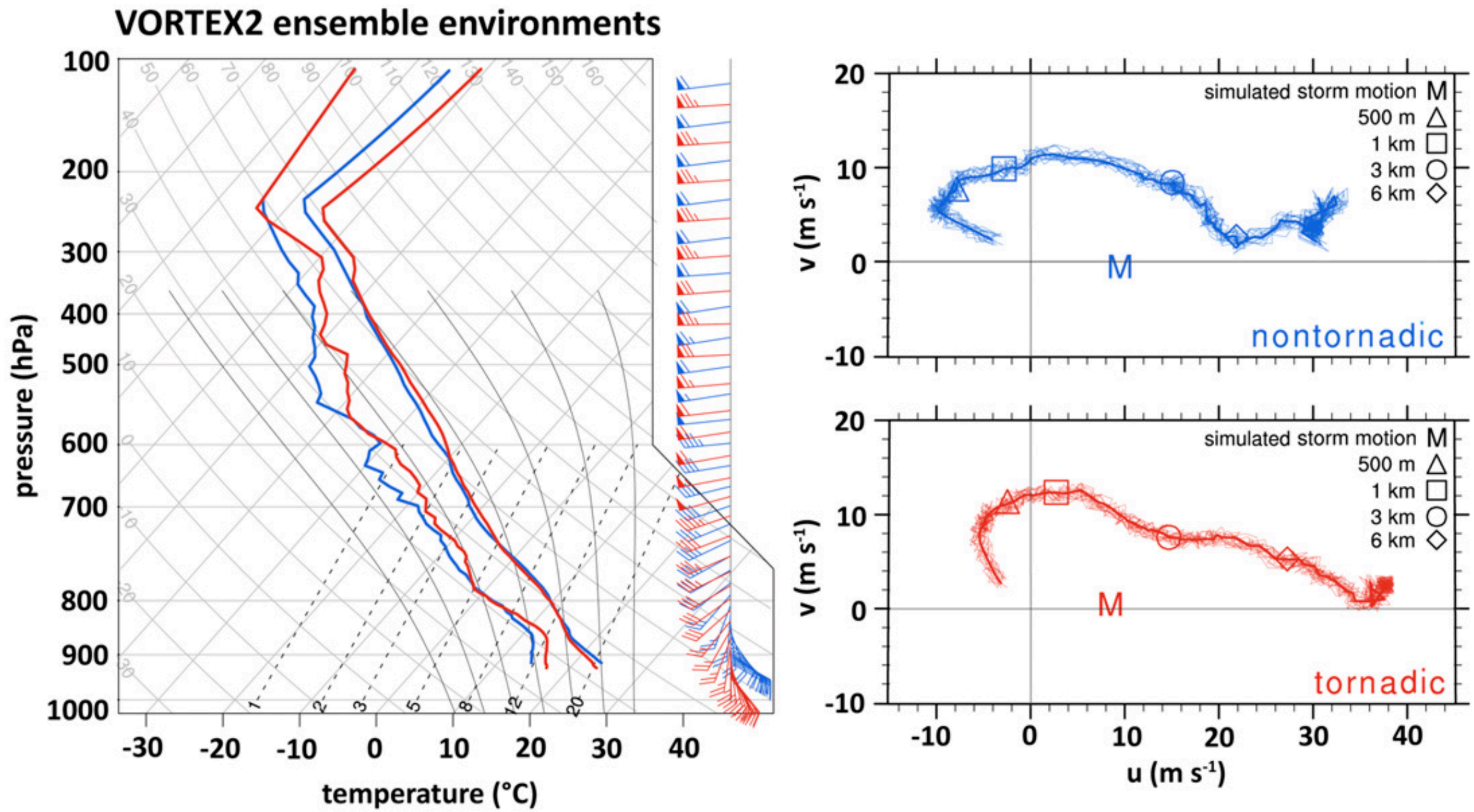


FIG. 1. (left) Skew *T*–log*p* diagram and (right) hodographs showing the (top) nontornadic (blue) and (bottom) tornadic (red) VORTEX2 near-inflow composite soundings. The wind profiles for the 14 ensemble members are overlaid on the control wind profile (boldface) for both the nontornadic and tornadic hodographs. The simulated storm motion is indicated on the hodograph by the M. Markers on the hodograph represent 500 m (triangle), 1 km (square), 3 km (circle), and 6 km (diamond) AGL. The wind barbs on the skew *T*–log*p* plot are displayed in kt (1 kt = 0.5144 m s^{-1}). See Parker (2014) for more discussion on the generation and interpretation of the VORTEX2 composite environments.

From Coffer et al. 2017

Crank Up The Resolution

Analysis of a High Resolution Simulation of a Supercell Thunderstorm Which Produces a Violent Tornado

(AKA video slideshow time)

Streamwise Vorticity Currents in the Wild

Ka-band radar RHIs of supercell outflow

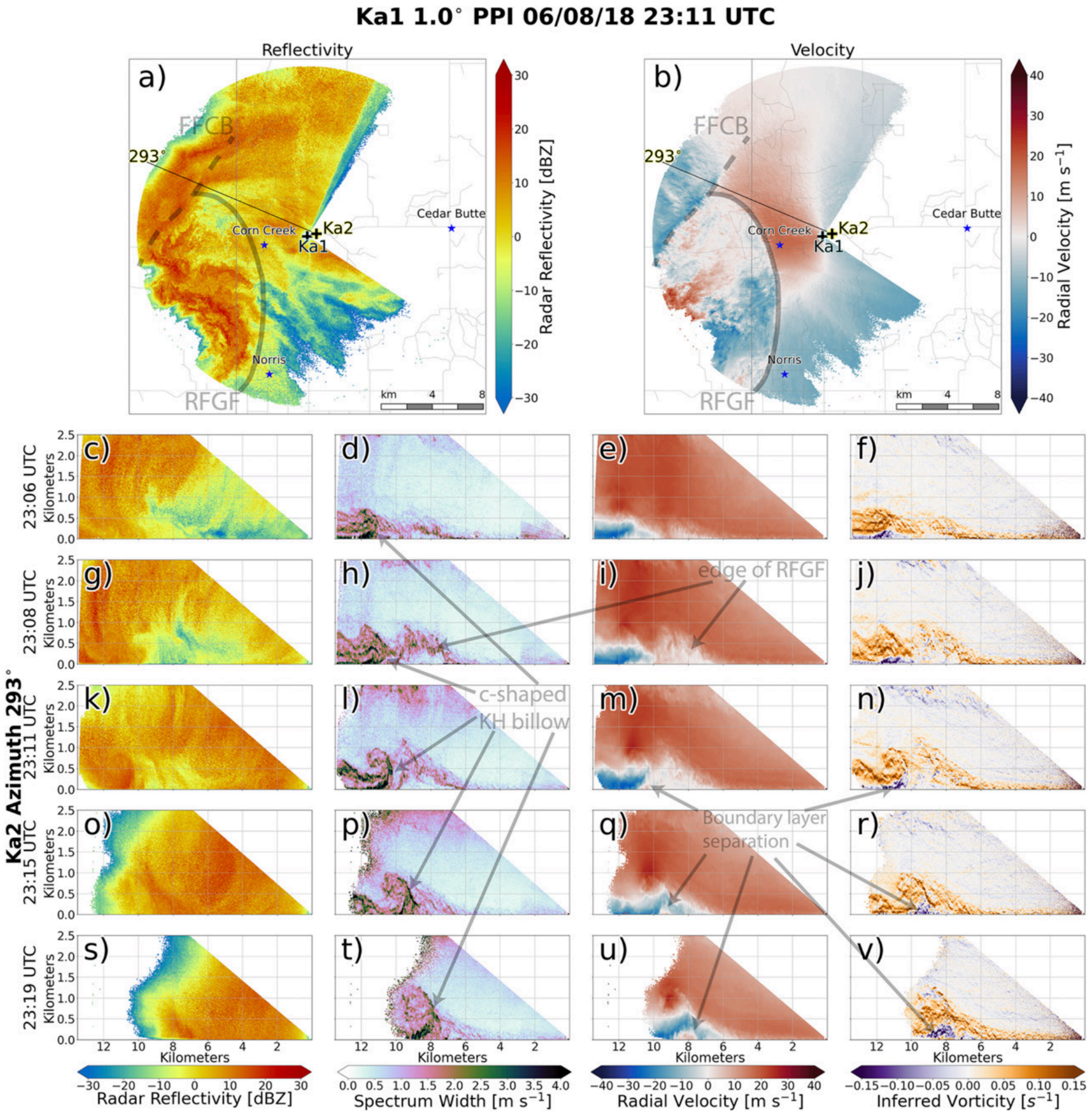


FIG. 9. A PPI scan of (a) reflectivity (dBZ, shaded) and (b) radial velocity (m s^{-1}, shaded) from TTUKa1 gathered at 2311 UTC 8 Jun 2018 at 1° elevation. The RFGF and FFCB are annotated. (c)–(v) A series of five RHIs (rows) over a duration of 780 s from TTUKa2 at a constant azimuth 293°. The columns in (c)–(v) are (left to right) reflectivity (dBZ, shaded), spectrum width (m s^{-1}, shaded), radial velocity (m s^{-1}, shaded), and inferred vorticity (s^{-1}, shaded).

Check Your Understanding

- What did Lemon and Doswell contribute to the conceptual model of the Supercell thunderstorm?
- How does the strength of low-level environmental shear affect dynamic lifting?
- How does the strength of the negative buoyancy in the cold-pool relate to the generation of horizontal vorticity? What kind of cold pools are most conducive for tornadogenesis?
- What is the difference between the DJB and Rotunno mechanisms for generating vertical vorticity near the surface?
- How do the individual terms of the Significant Tornado Parameter pertain to the processes of tornadogenesis?