Supercell Tornadogenesis

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Disclaimer!

- I do not possess the credentialed letters of an “expert”, but I have spent the better of 8 years in the weeds of tornado research.
- 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 is plenty of ongoing and recently published research not referenced.
- 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 in Oklahoma
- 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 would break over a half-century ban on tornado forecasting

- In 1951, They established the Severe Storms Forecast Center at Tinker AFB. 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 Norman, Oklahoma.

- 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 NSSL now shares a building with the NOAA SPC.

The First Tornadogenesis Theory Tied to the Supercell Thunderstorm Model

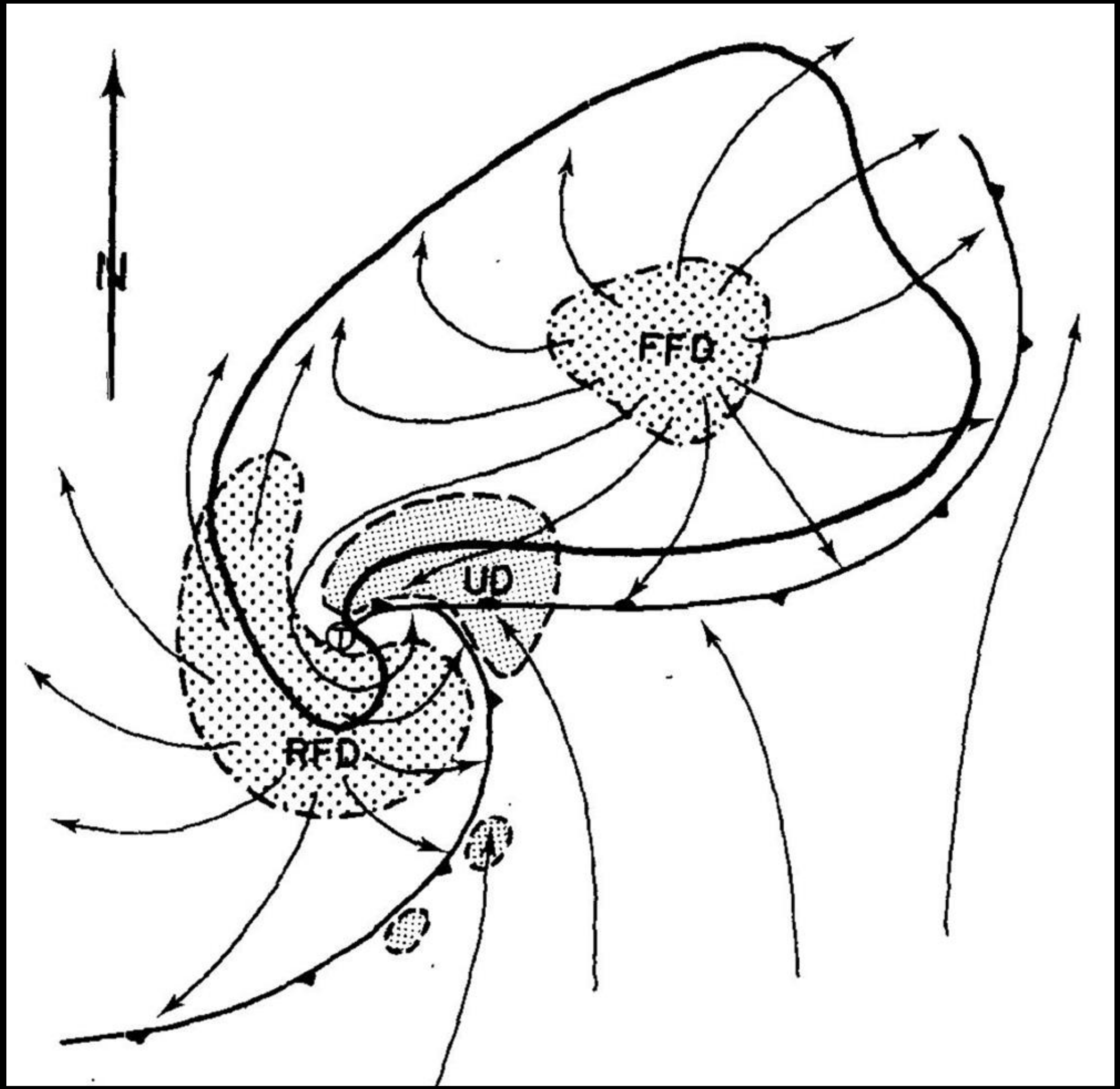
Based on observations of supercells and tornadoes using doppler radar, limited surface observations, and storm-chaser photography/videography

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) includes 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.

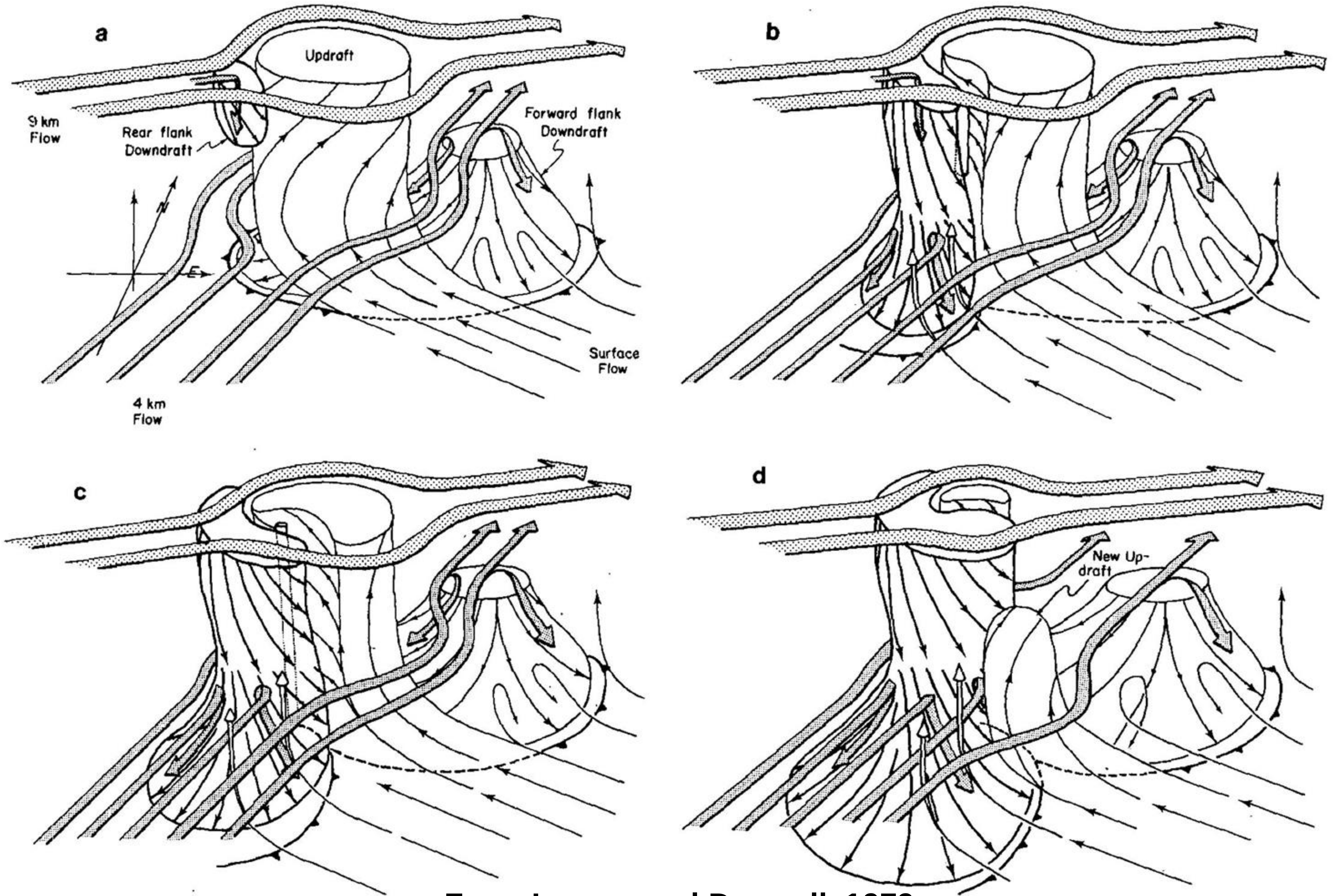
$$\frac{d}{dt}\left(\frac{\Delta v}{\Delta x}\right) = -v\frac{\partial f}{\partial y} - fD - \frac{\Delta v}{\Delta x}D - \frac{\Delta w}{\Delta x}\frac{\partial v}{\partial z} - \frac{\Delta \alpha}{\Delta x}\frac{\partial p}{\partial y},$$

(Coriolis) (stretching) (tilting) (solenoidal)

$$\frac{D\zeta}{Dt} = \underbrace{-\zeta\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)}_{A} + \underbrace{\left(\xi\frac{\partial w}{\partial x}+\eta\frac{\partial w}{\partial y}\right)}_{B} - \underbrace{\left(\frac{\partial \alpha}{\partial x}\frac{\partial p}{\partial y}-\frac{\partial \alpha}{\partial y}\frac{\partial p}{\partial x}\right)}_{C} + \underbrace{\left(\frac{\partial F_y}{\partial x}-\frac{\partial F_x}{\partial y}\right)}_{D}.$$

Vortex Stretching (A) **Vortex Tilting** (B)

Baroclinic Generation (C) **Turbulence/Friction** (D)



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

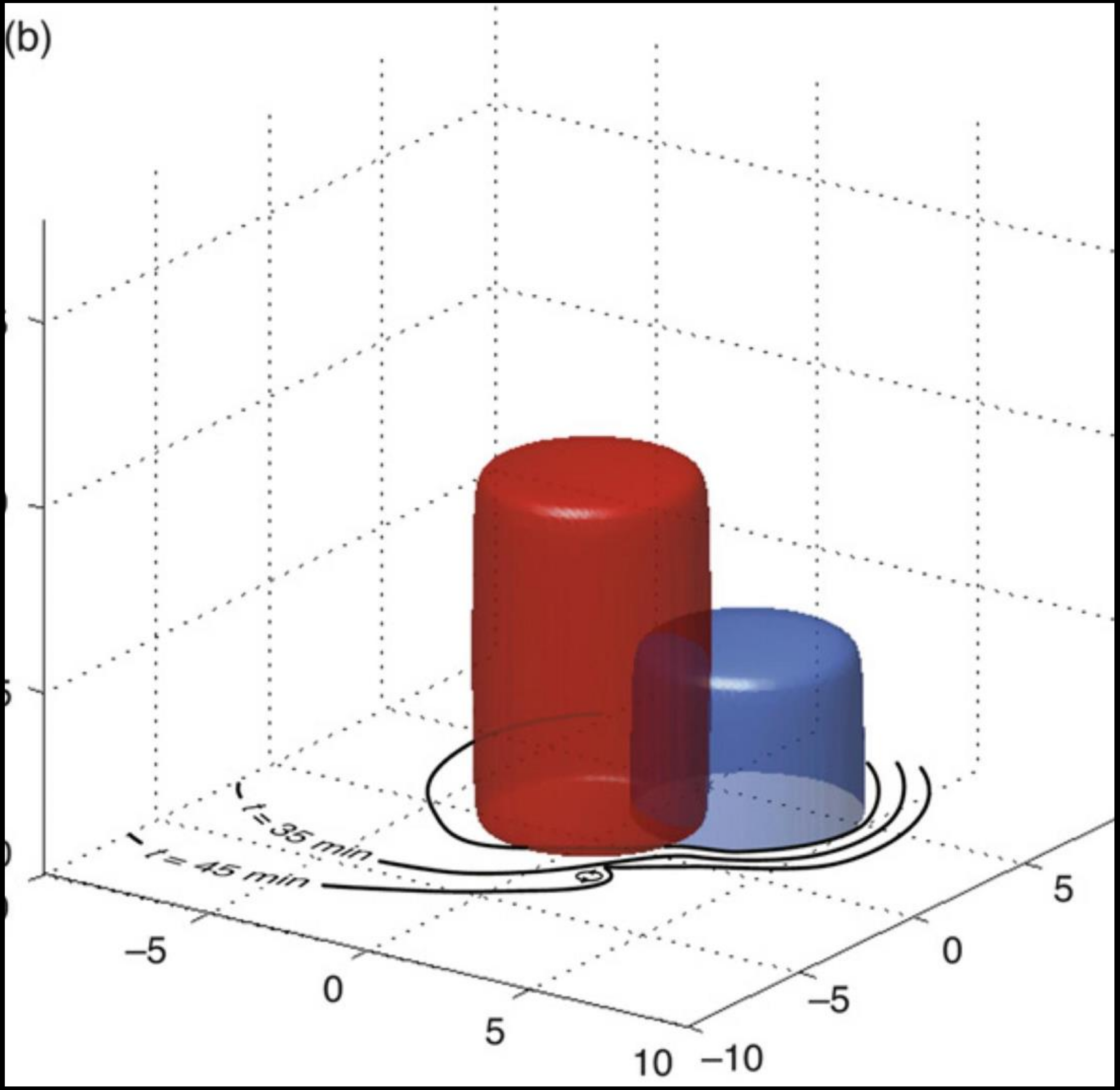
- Supercell conceptual model updated to include the Rear Flank Downdraft (RFD), based primarily on Doppler radar observations
- Vortex tilting/stretching believed to be the primary source of vertical vorticity
- Baroclinic vorticity generation not ruled out, but they lacked observations to support this 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 tornadoes form from below, not above*.
- 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**

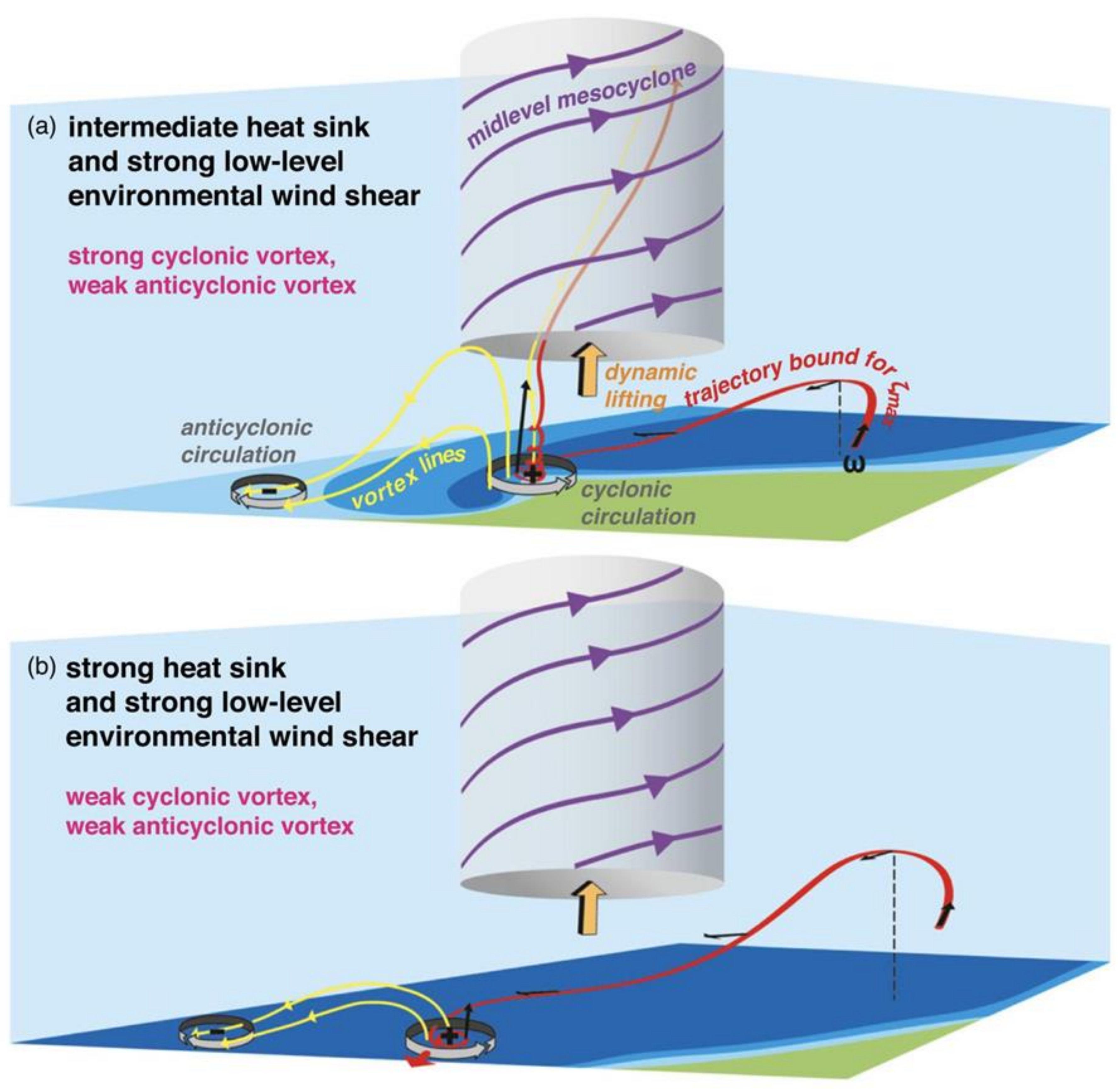


FIG. 25. Schematic summarizing the simulation outcomes: (a) the baseline simulation in which a strong cyclonic vortex develops (Sc8m8), the simulations in which (b) the heat sink is either too strong (results in colder outflow, i.e., Sc16m8) or (c) the environmental wind shear is too weak (results in 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).

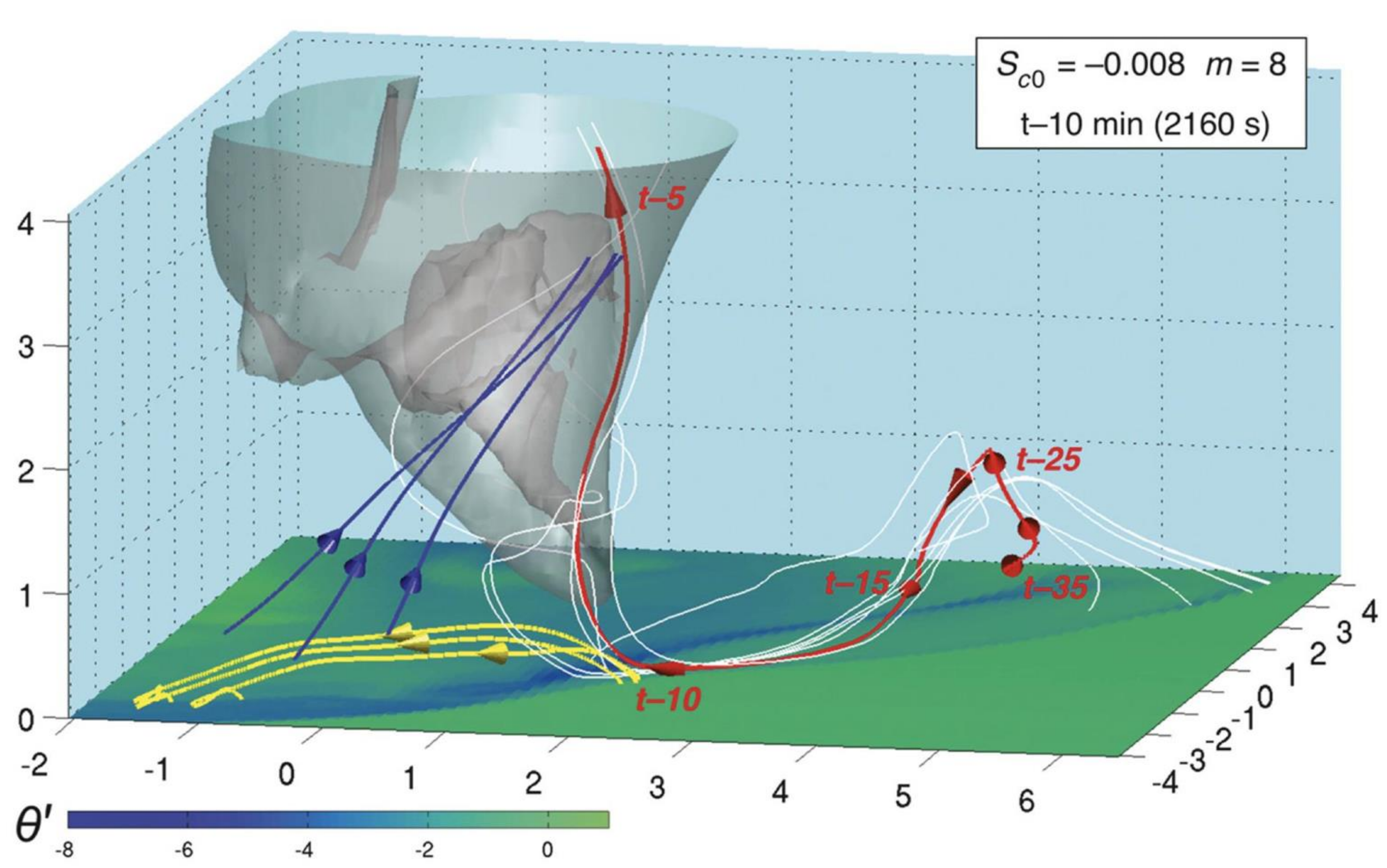


FIG. 6. Three-dimensional view of the midlevel updraft, near-surface θ' field, and key vortex lines and trajectories at $t - 10$ min (2160 s) in the Sc8m8 simulation. The view is from the south–southeast. Axes are in kilometers. The $w = 15\,\mathrm{m\,s^{-1}}$ isosurface is gray. The near-surface θ' 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

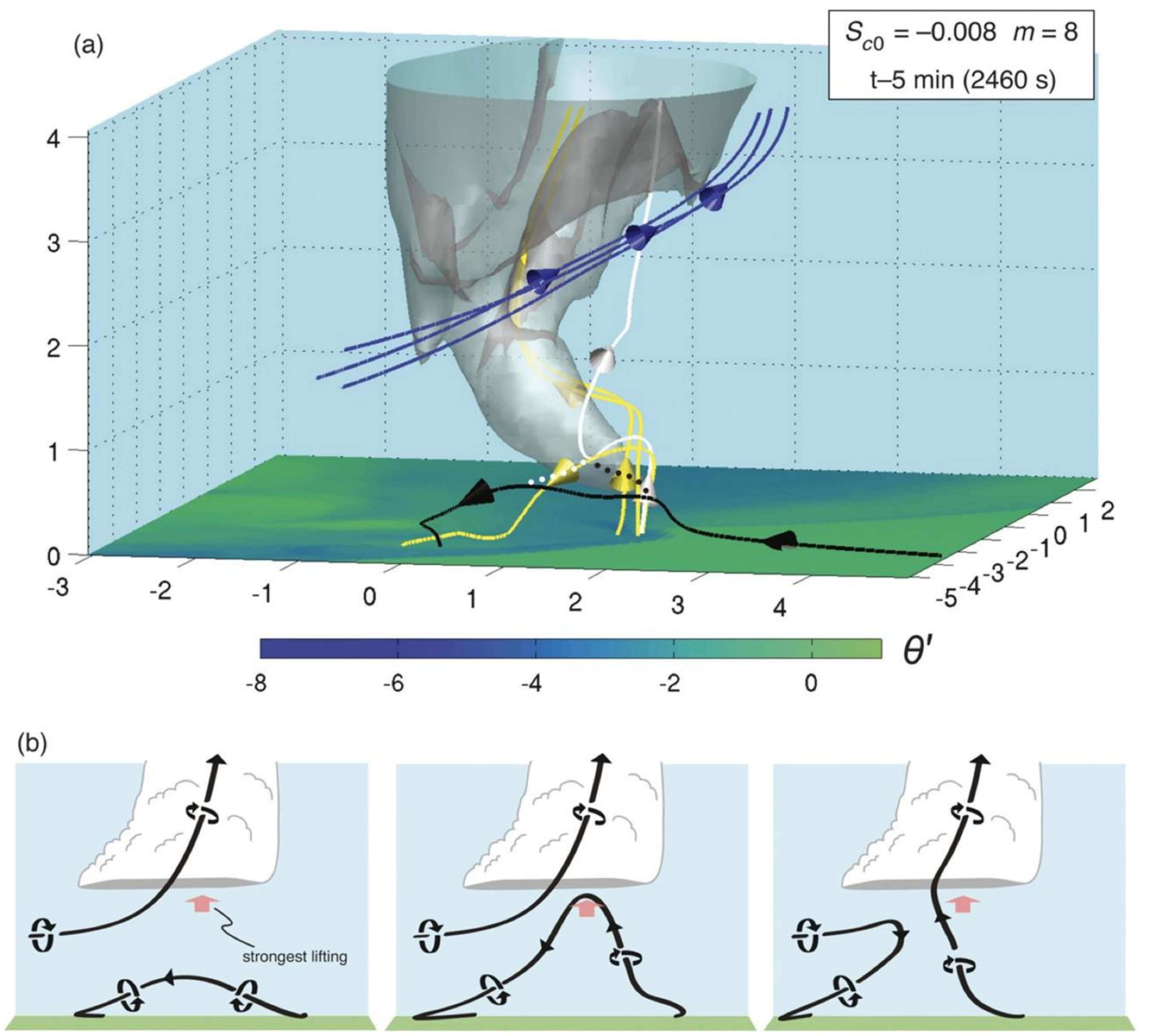


FIG. 7. (a) As in Fig. 6, but at $t - 5$ min (2460 s) in the Sc8m8 simulation. Trajectories have been omitted. The black and white lines are additional vortex lines; the black one originates in the environment and descends through anticyclonic vorticity in the cold pool. The purple vortex lines originate 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

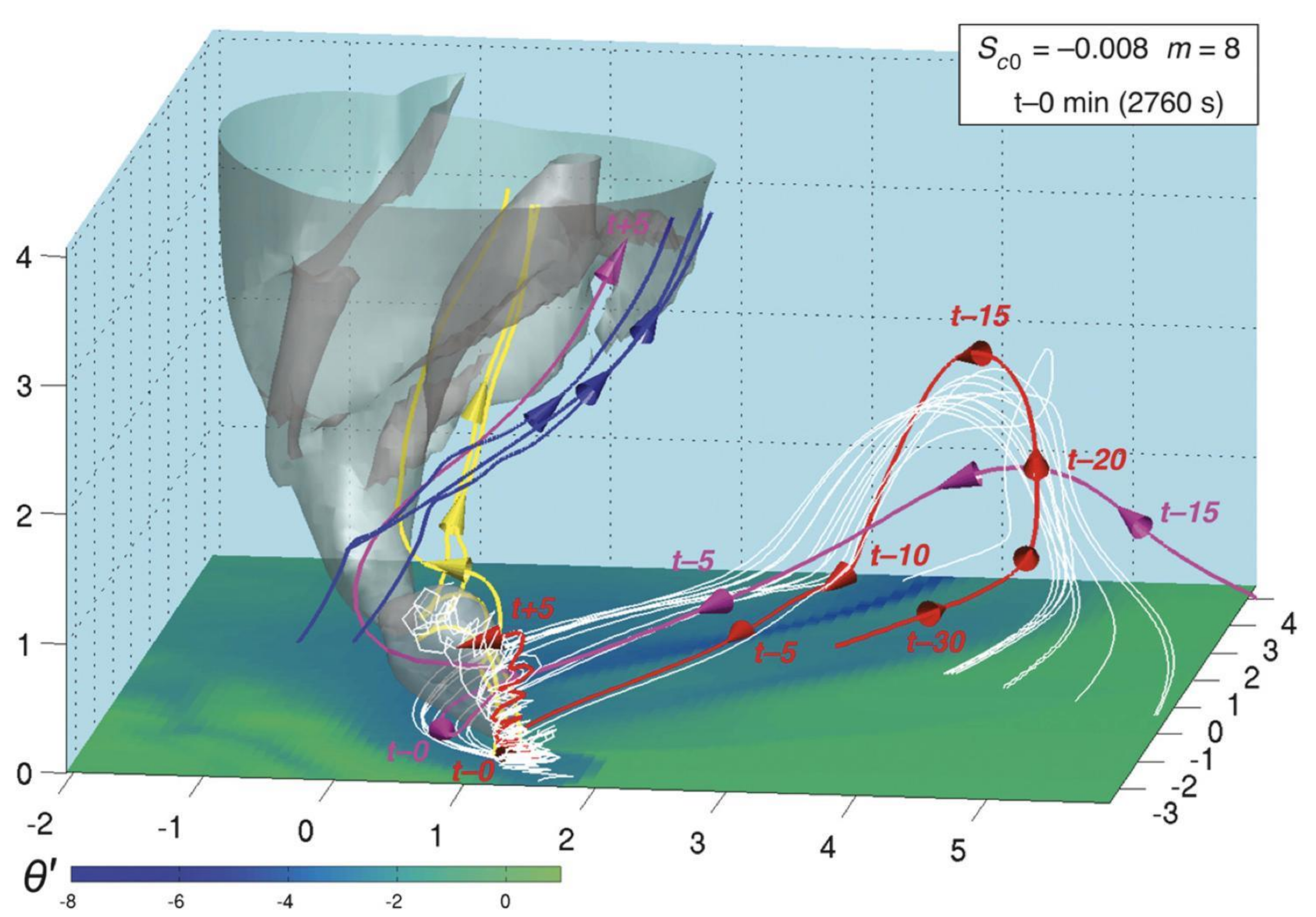


FIG. 8. As in Fig. 6, but at $t - 0$ min (2760 s) in the Sc8m8 simulation. The trajectories pass within 200 m of $\zeta_{\max}$, within 75 m of the surface, at $t - 0$ min. The trajectory that passes nearest to cyclonic vorticity maximum at $t - 0$ min is red. The magenta trajectory nears the lowest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

From Markowski and Richardson, 2014

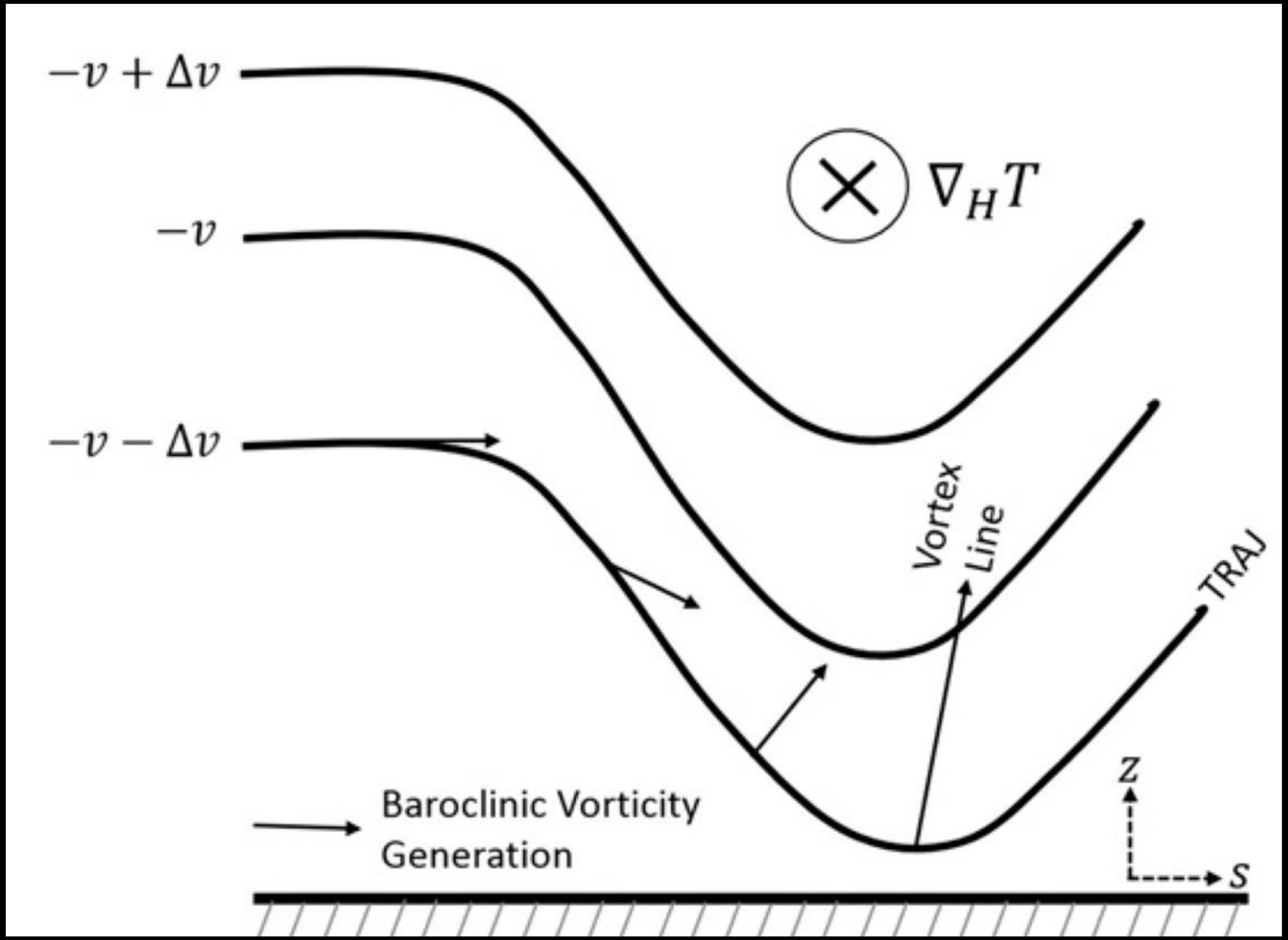
Summary of Markowski and Richardson 2014

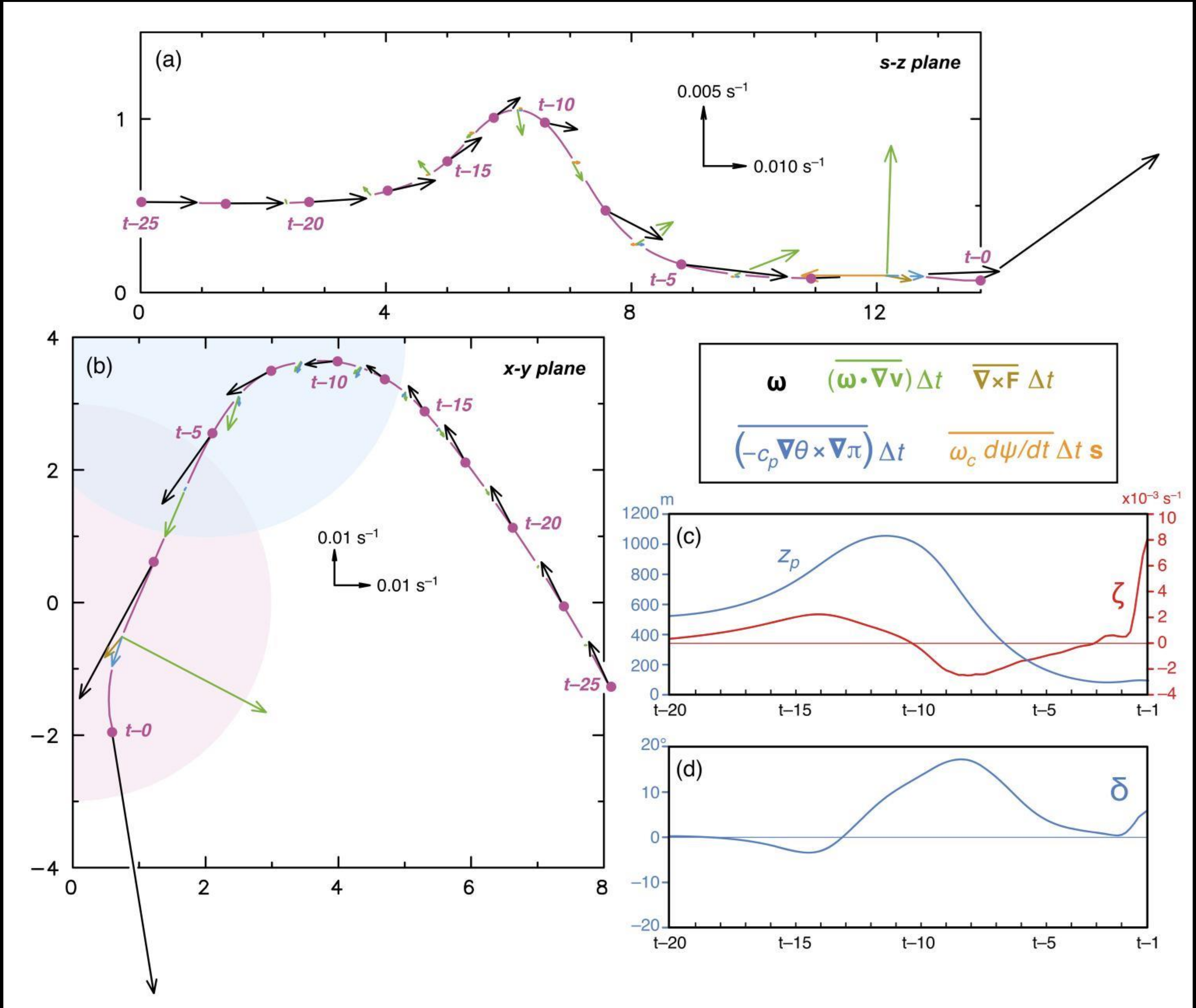
- Environments with large amounts of streamwise vorticity (strong SRH in the low-levels) result in stronger mesocyclones closer to the surface.
- This provides strong dynamic lifting through the VPPGF
- **Baroclinic generation of horizontal vorticity and downdrafts are crucial for generating near-surface 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.

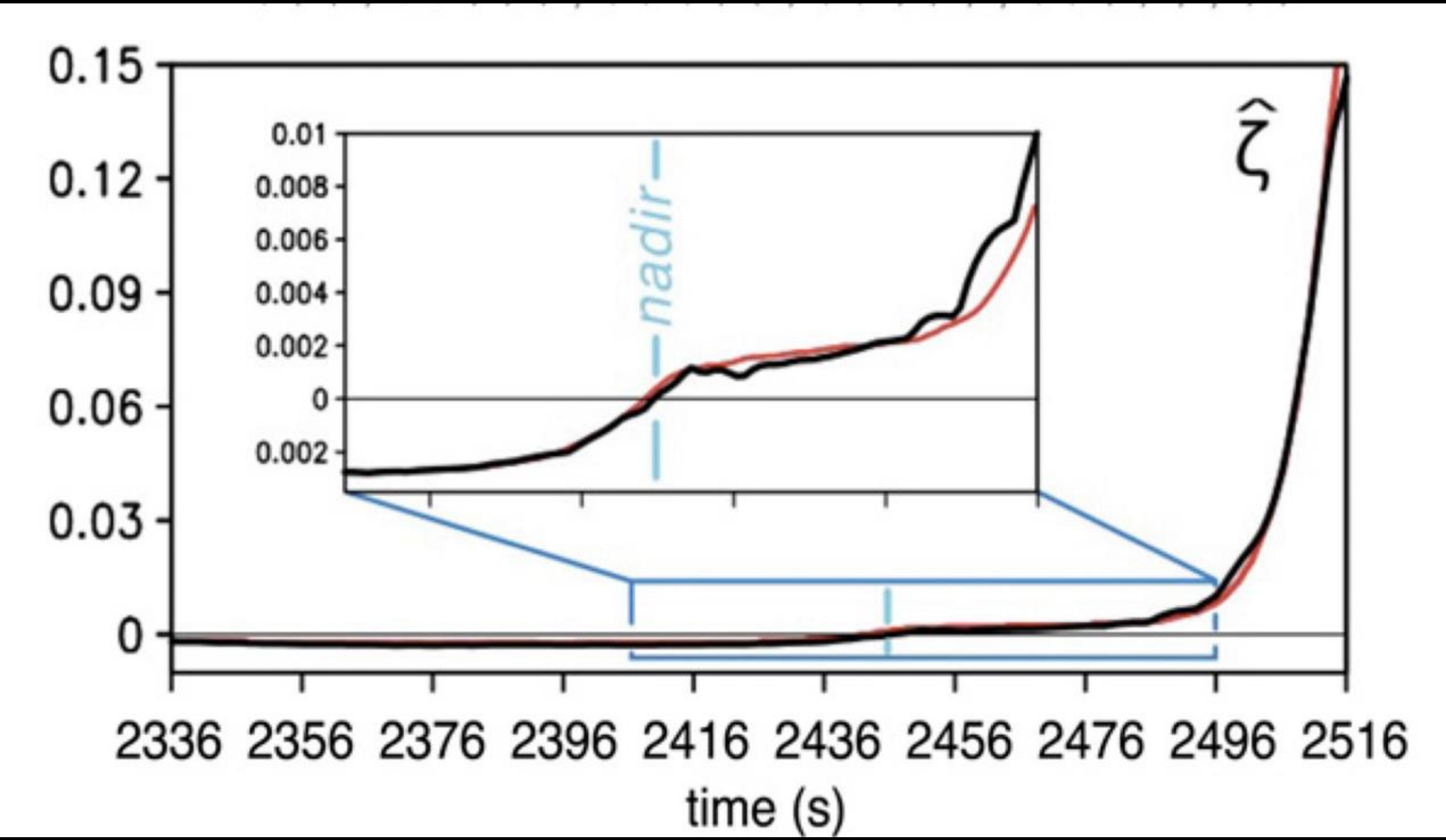
- This study demonstrates that while the vortex tilting described by DJB occurs, it need not have positive vertical vorticity at the nadir.

- 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.

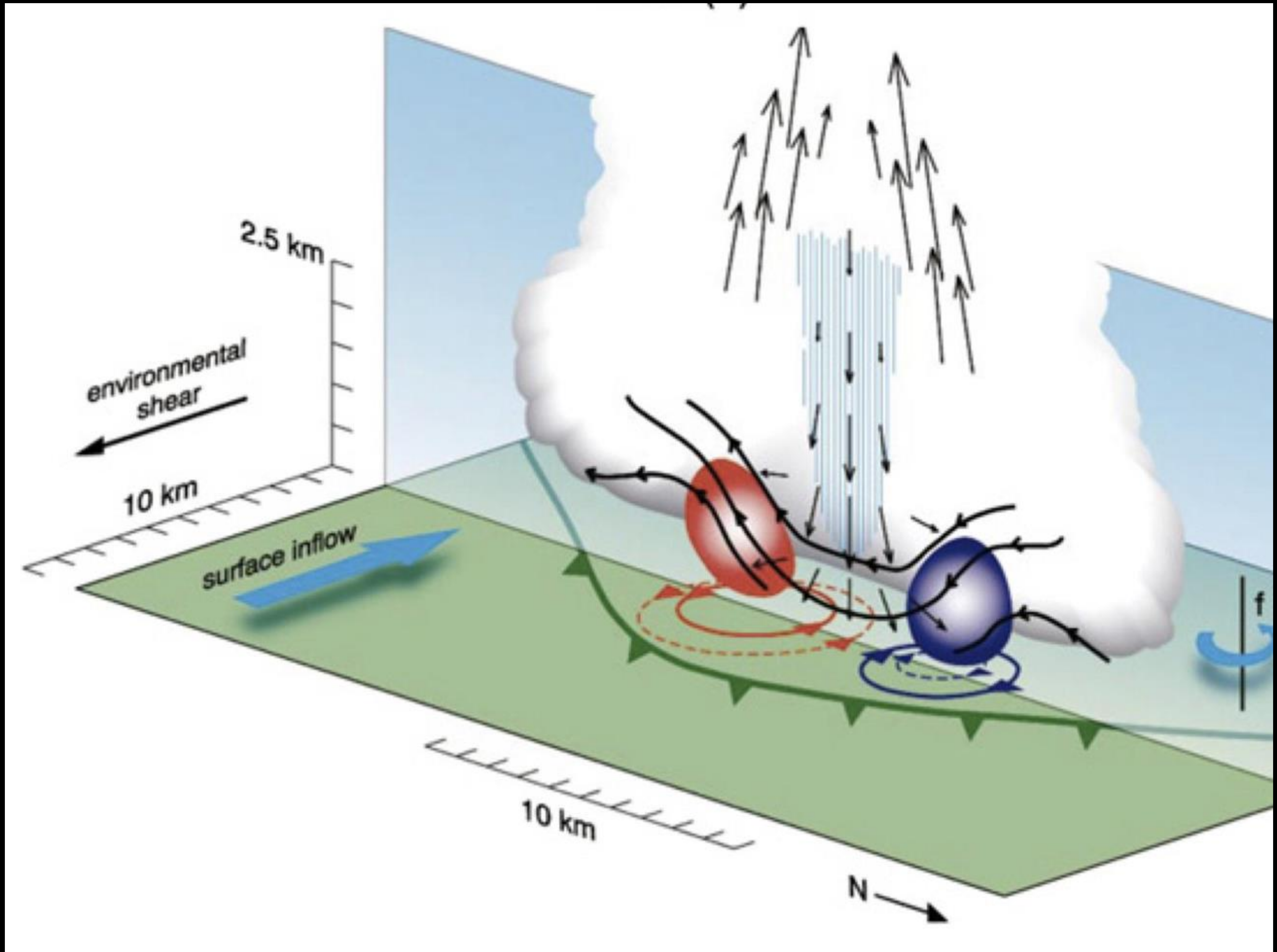
- **Vertical vorticity need not be present near the surface for tornadogenesis - purely horizontal vorticity is sufficient.**

- **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.



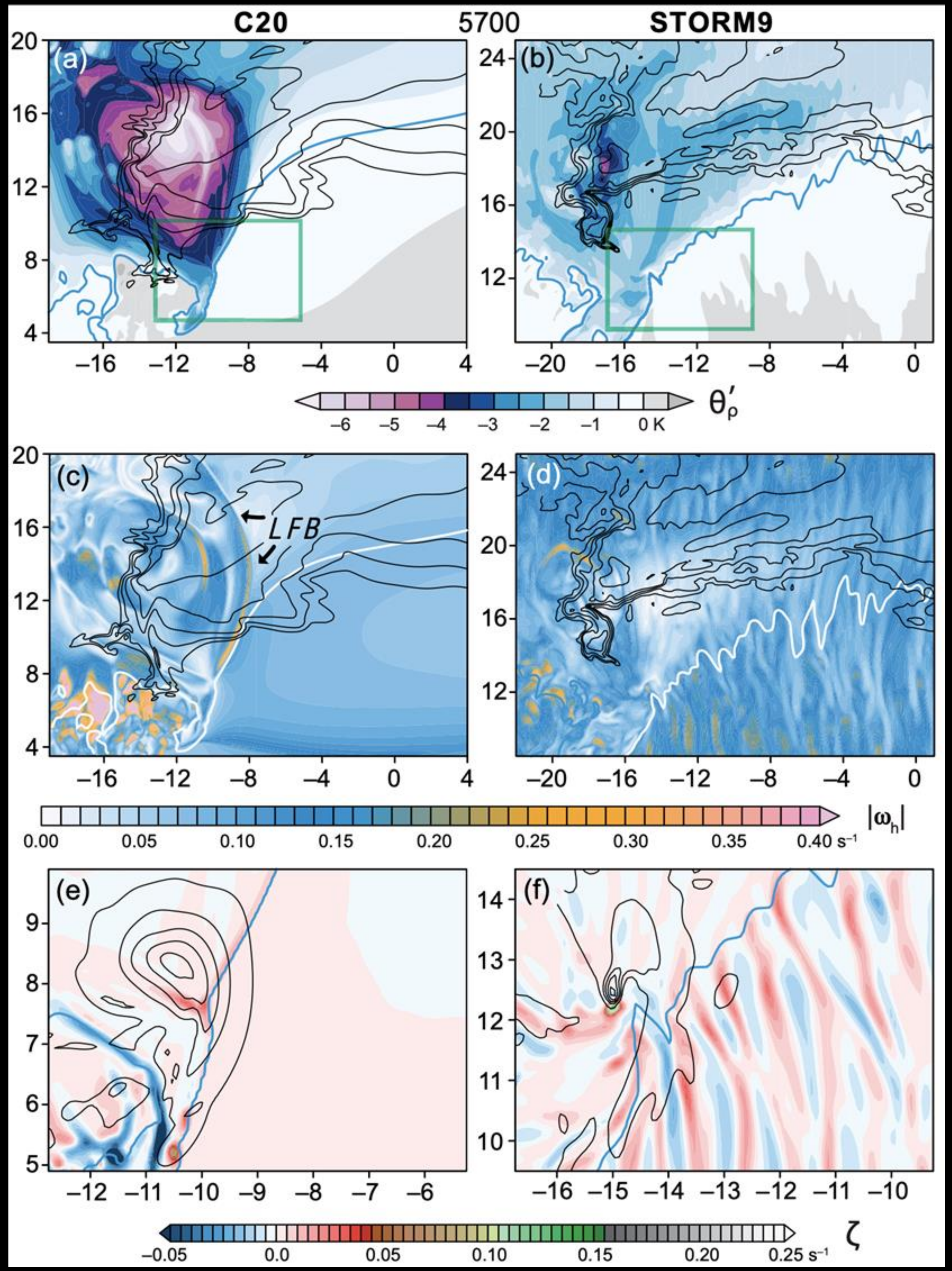
Markowski 2024: Turbulence, Turbulence, and More Turbulence!

- Most prior (20th century; C20) simulations are laminar-flow simulations. The real atmosphere has turbulence! What happens when turbulence is included in the inflow and storm environment?

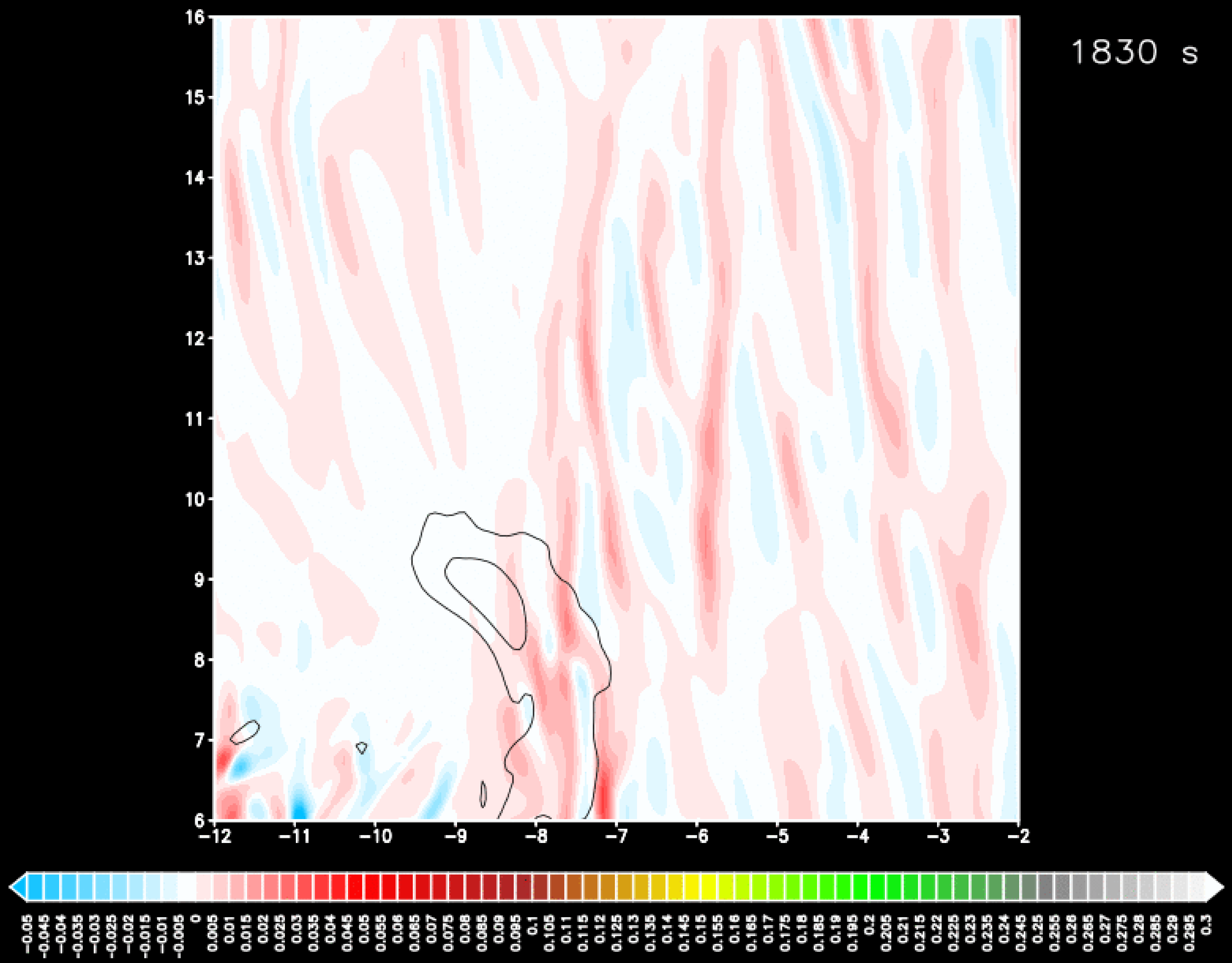
- Source of vorticity for initial TLV comes from surface-layer features (~0-50m AGL), instead of from baroclinically generated/amplified sources.

- The proximity of the updraft to the surface, and subsequently, dw/dz, is of great importance for drawing up these surface-layer features into the updraft.

- Per trajectory analysis, baroclinic vorticity generation is not a leading source of vorticity for the TLV at any point in its lifecycle.



Markowski 2024: Turbulence, Turbulence, and More Turbulence!



So Which Is It?

- **All of these mechanisms have been found to be present in simulations of supercell thunderstorms.**
- **All of these mechanisms and studies have flaws and caveats, whether it's the lack of turbulence, poor surface-layer and turbulence closure schemes/assumptions, or parameterized microphysics.**
- **It is entirely possible that tornadoes form via many (or all) of these methods in nature.**

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.

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

  - Recent studies (e.g. Roberts et al. 2016 & 2017, Markowski 2020 & 2024) have looked at semi-slip boundary conditions in simulations of supercells and TLVs. Often, with the inclusion of friction and turbulence, it comes out with first-order importance relative to baroclinic mechanisms.

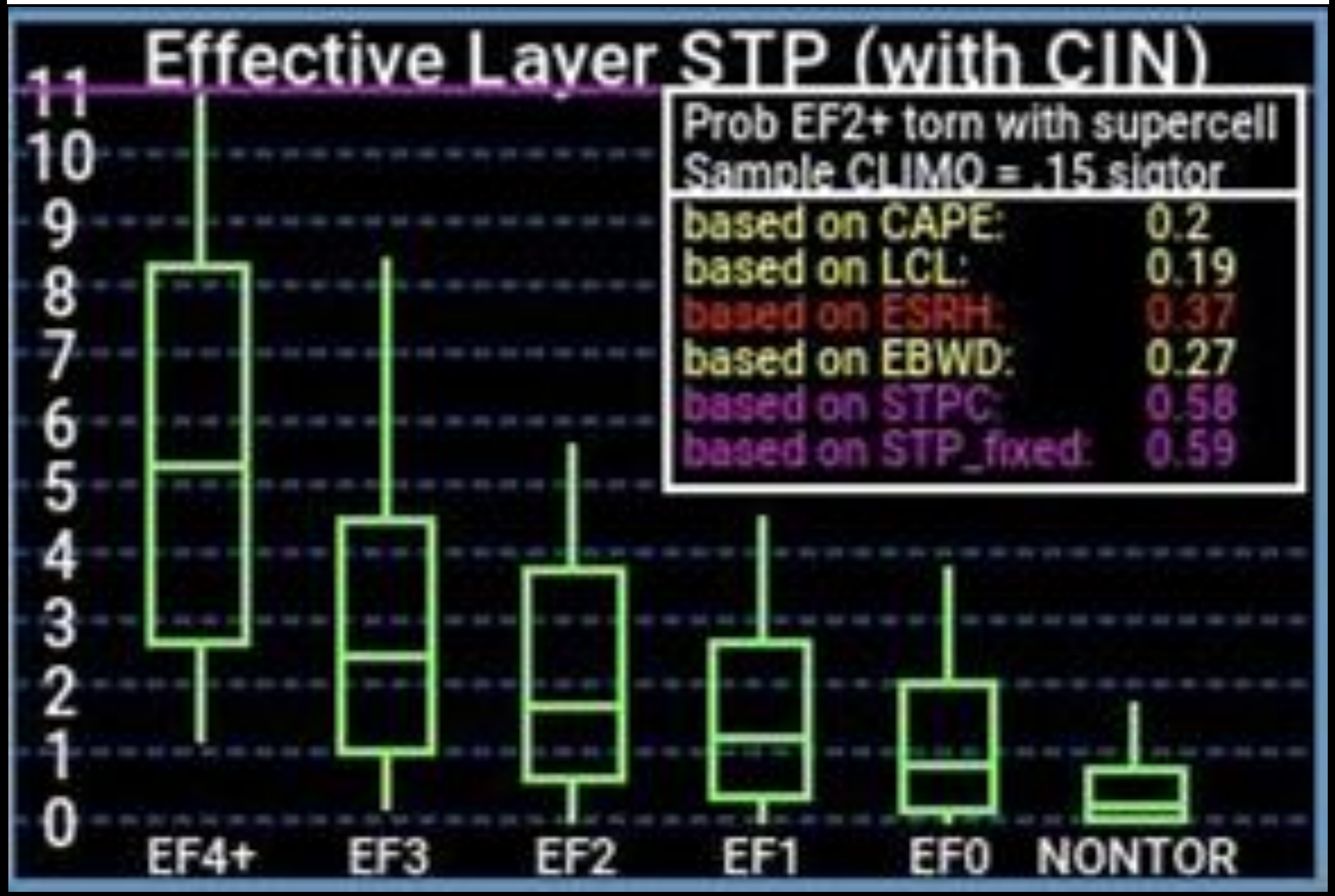
  - However, it has been shown by Markowski and Bryan (2016) that our current understanding of the surface-layer in thunderstorm outflow is severely lacking, and standard boundary layer application of friction in cloud models is erroneous.

  - The true role of friction and the surface-layer in tornadogenesis is an unknown and ongoing research topic.

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 (i.e. nocturnal tornadoes)
  - 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

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



Congratulations! You are all now tornadogenesis experts!

- **I’ll try to answer any questions the best I can!**
- Email: kelton.halbert@noaa.gov
- BlueSky: @stormscale.io