Why does the atmosphere produce deep columnar convective vortices?

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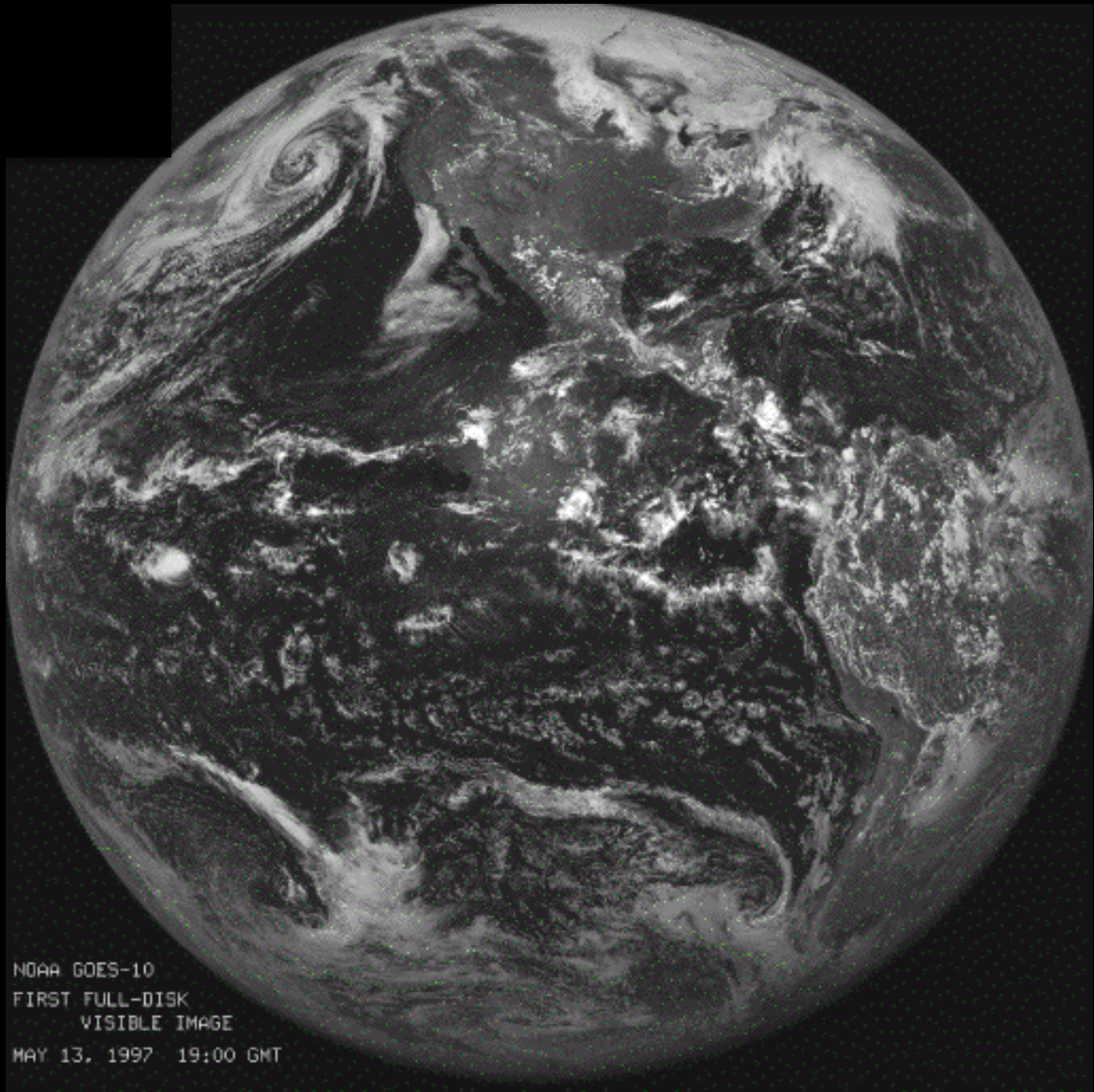
A fundamental assumption

- In the physical world (*not* at the quantum scale!), <u>nothing</u> happens
  - Randomly
  - For no physical purpose
- Atmospheric processes – examples
  - Extratropical cyclones
  - Deep, moist convective storms
  - Tropical cyclones
  - Gravity waves
  - … etc. …

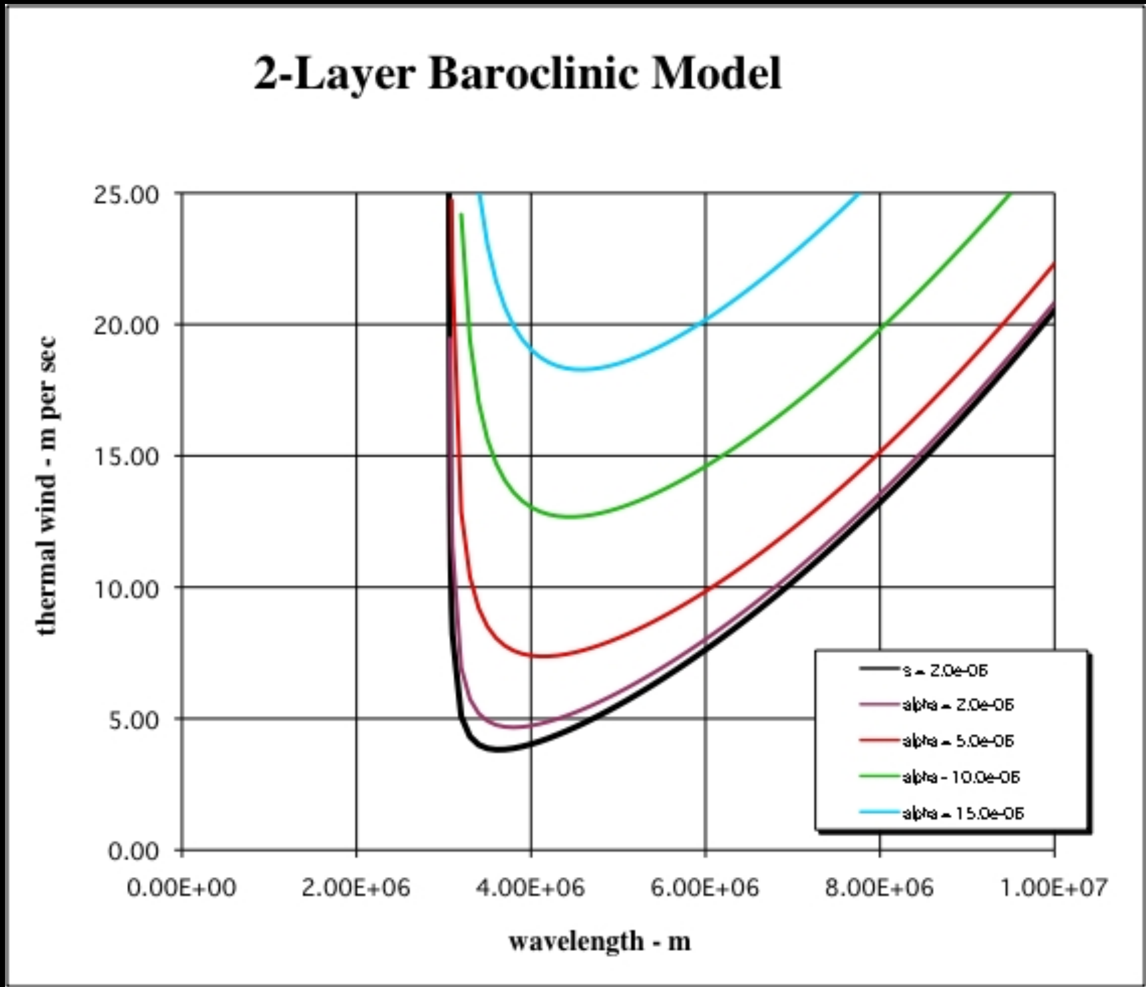
ETCs - always present



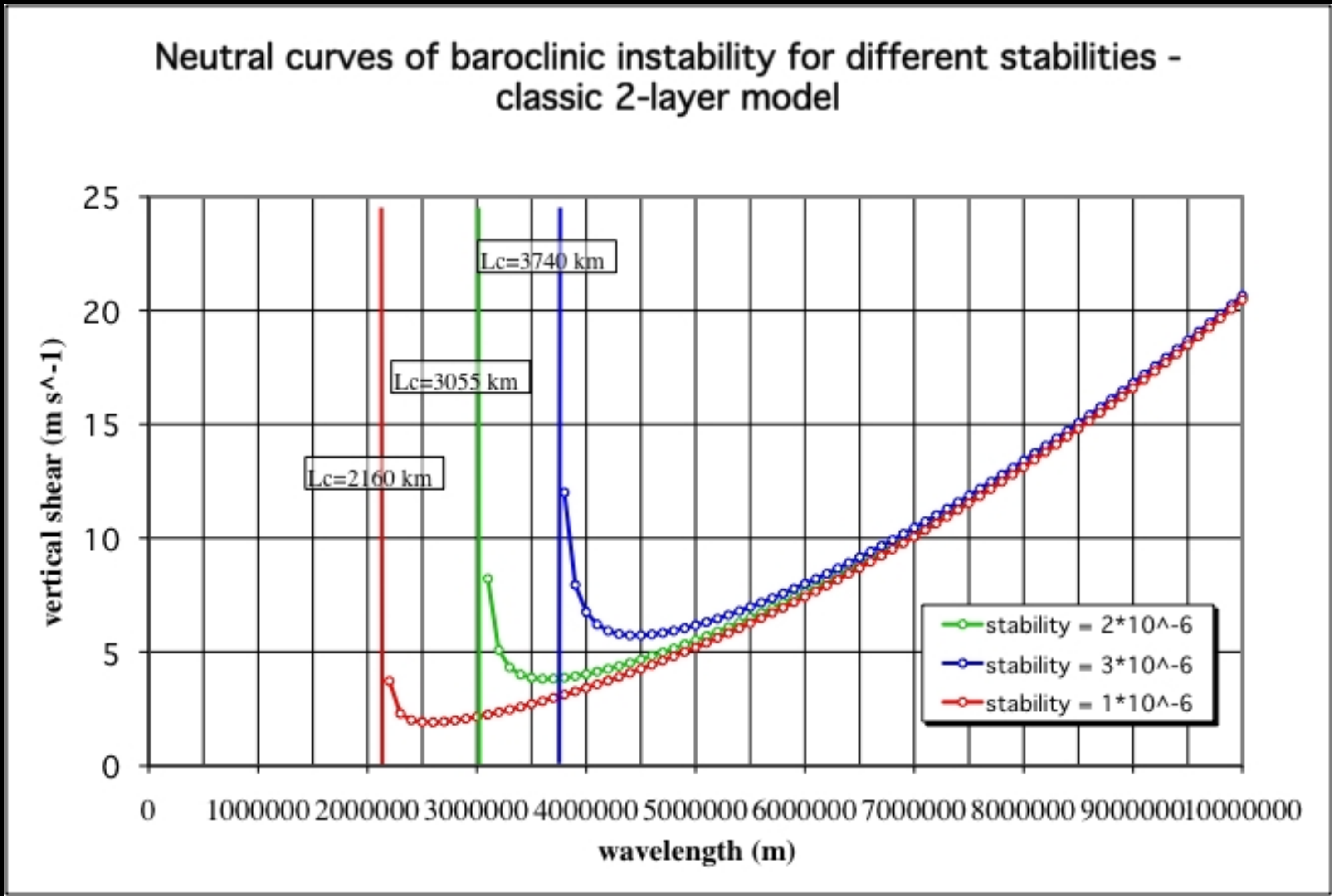
What are ETCs for?

- Baroclinic instability (Charney/Eady theory)
  - Available potential energy (APE)
  - Meridional temperature gradient / vertical shear
  - Static stability is a factor
- Kinetic energy of disturbance drawn from APE
  - "Self-development" early in the life cycle
  - Redistributes solar heat input so as to reduce the meridional temperature gradient
  - Vertical motion leads to increasing static stability

Neutral Stability Curve



Varying Static Stability



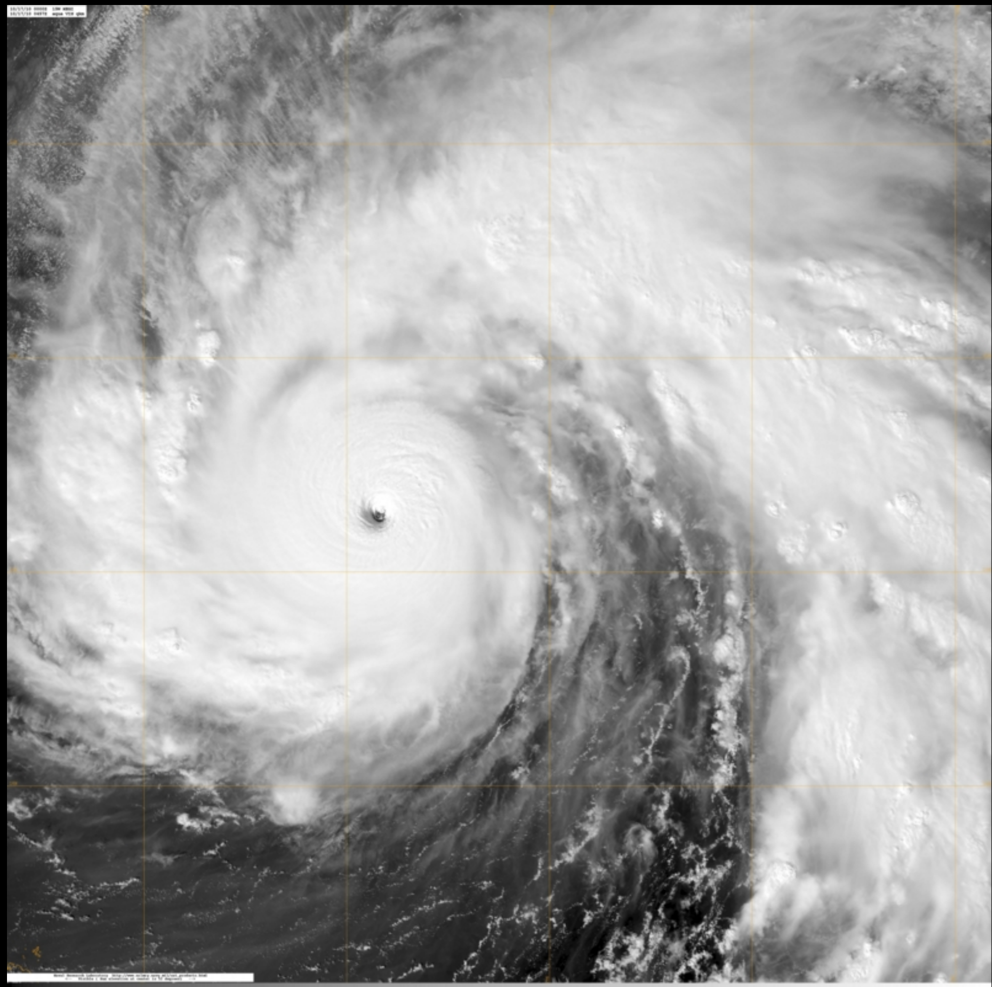
Deep, moist convection (DMC)

What is DMC for?

- Buoyant instability – Parcel theory
  - Convective available potential energy (CAPE)
  - Vertical gradients of temperature and moisture
- Kinetic energy of disturbance drawn from CAPE
  - Redistributes heat and moisture vertically
- Intermittent – only when needed (ingredients)

Tropical Cyclones

- Basically, a heat engine
- Involves DMC
- Transfers heat from the oceans into the atmosphere



Supercells – why?

- Obviously, also associated with CAPE and buoyant instability
- Definition of a supercell:
  - Deep, persistent mesocyclone
    - Significant fraction of vertical depth of DMC
    - Persists $\geq$ convective time scale, τ_c
    - Vorticity ~ 1 x 10^{-2} s^{-1}
- A helical flow – *begins* as a rotating updraft

A supercell

Supercell characteristics

- Only about 20-25% of supercells are tornadic
- Most DMC storms are <u>not</u> supercells
  – Supercell rotation is a result of pre-existing (environmental) horizontal vorticity being tilted into the vertical by vertical drafts - updraft becomes helical
- Supercells have a significant contribution to their vertical motion from a *non-buoyant* source: updraft/vertical shear interactions

Buoyancy and perturbation pressure

- Parcel theory:

$$\left.\frac{dw}{dt}\right|_B = g\frac{T_v - \bar{T}_v}{\bar{T}_v} \equiv B$$

Doswell and Markowski (2004)

$$\frac{dw}{dt} = -\frac{1}{\rho}\left[\frac{\partial p'_b}{\partial z} + \frac{\partial p'_d}{\partial z}\right] + B$$

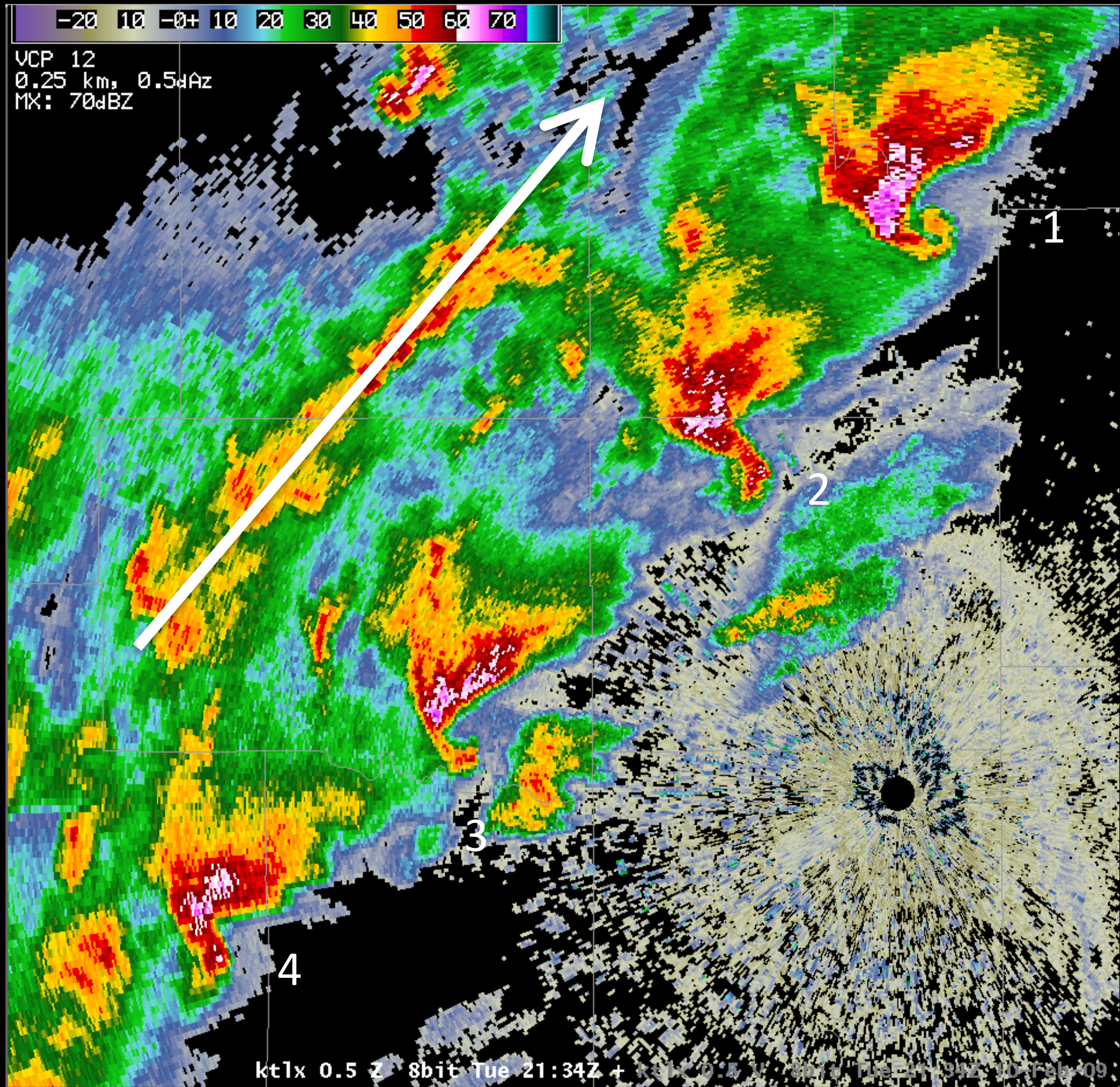
$$= \underbrace{-\frac{1}{\rho}\frac{\partial p'_d}{\partial z}}_{i} + \underbrace{\left[\frac{-1}{\rho}\frac{\partial p'_b}{\partial z} + B\right]}_{ii},$$

What do supercells do?

- Mitigating CAPE is <u>not</u> the only answer
  - Multiple passages of tornadic supercells over nearly the same track
  - "Clearing" squall lines often signal the end of storm activity
  - If that's *all* that supercells are doing, it would fail to explain what supercells do that ordinary DMC does not do
  - The key is <u>helicity</u> and the fact that a supercell is dominated by a rotating, helical updraft

Classic supercells and buoyancy

10 Feb 2009
KTLC radar



What are supercells for?

- *Some* energy of the supercell is drawn from a reservoir of CAPE
- Helicity, H, can be interpreted as a form of *potential* energy – owing to the distribution of airflow – units of energy per unit mass (J kg^{-1} or m^{2} s^{-2}) – integrand is *streamwise vorticity*

$$H(z) = -\int_{z_0}^{z} \left[\left(\mathbf{V}_h - \mathbf{C} \right) \bullet \mathbf{k} \times \frac{\partial \mathbf{V}_h}{\partial z} \right] dz$$

Helical flows can be unstable

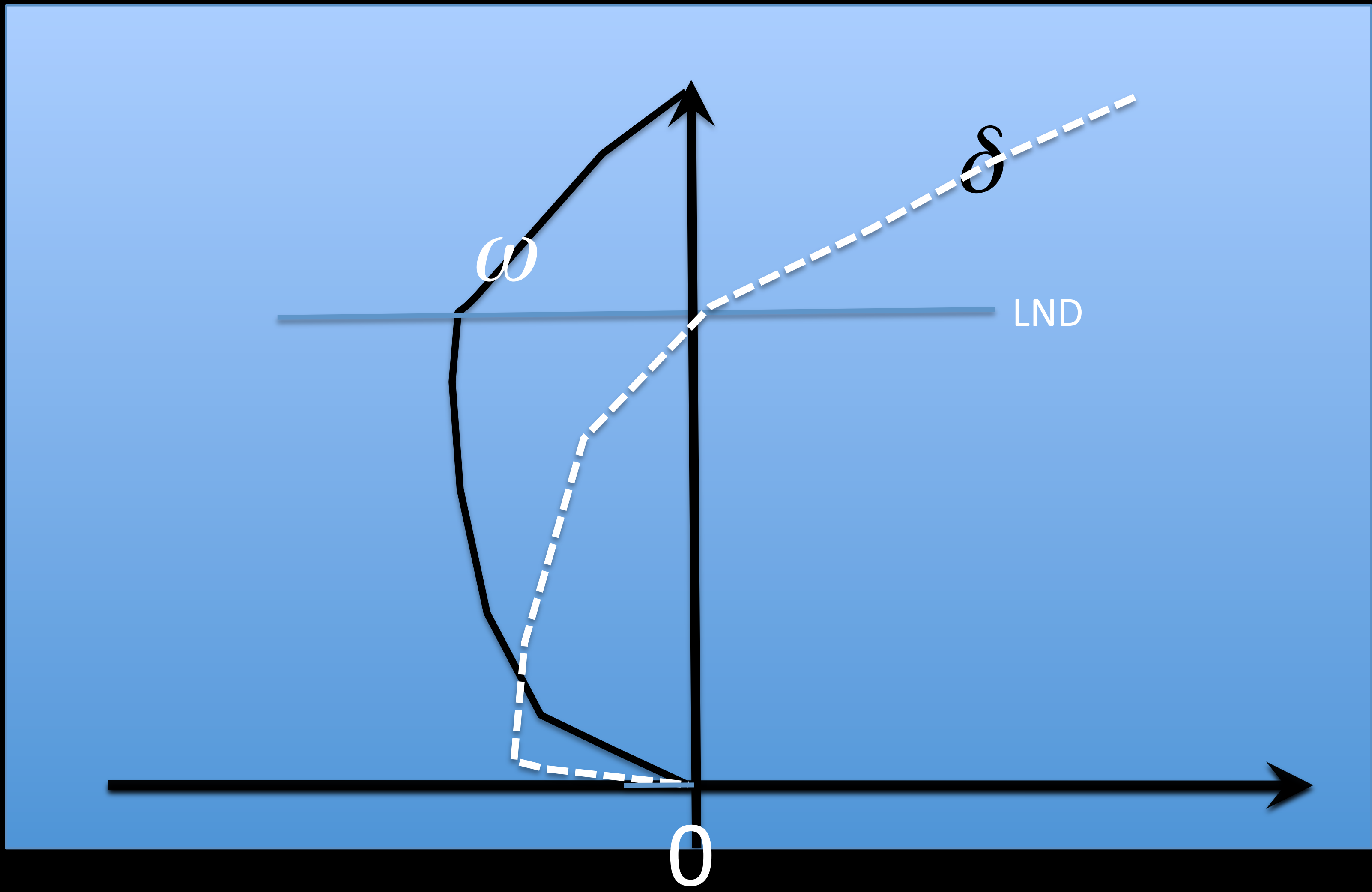
- "Stretching" term in the vorticity (ζ) equation, when divergence ($\delta < 0$) – i.e., conservation of angular momentum

$$\frac{d\zeta}{dt} = -\delta\zeta \quad \Rightarrow \quad \zeta(t) = \zeta_0 \exp(-\delta t)$$

- Exponential growth = classical indicator of an instability

$$\frac{\partial \omega}{\partial p} = -\delta = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

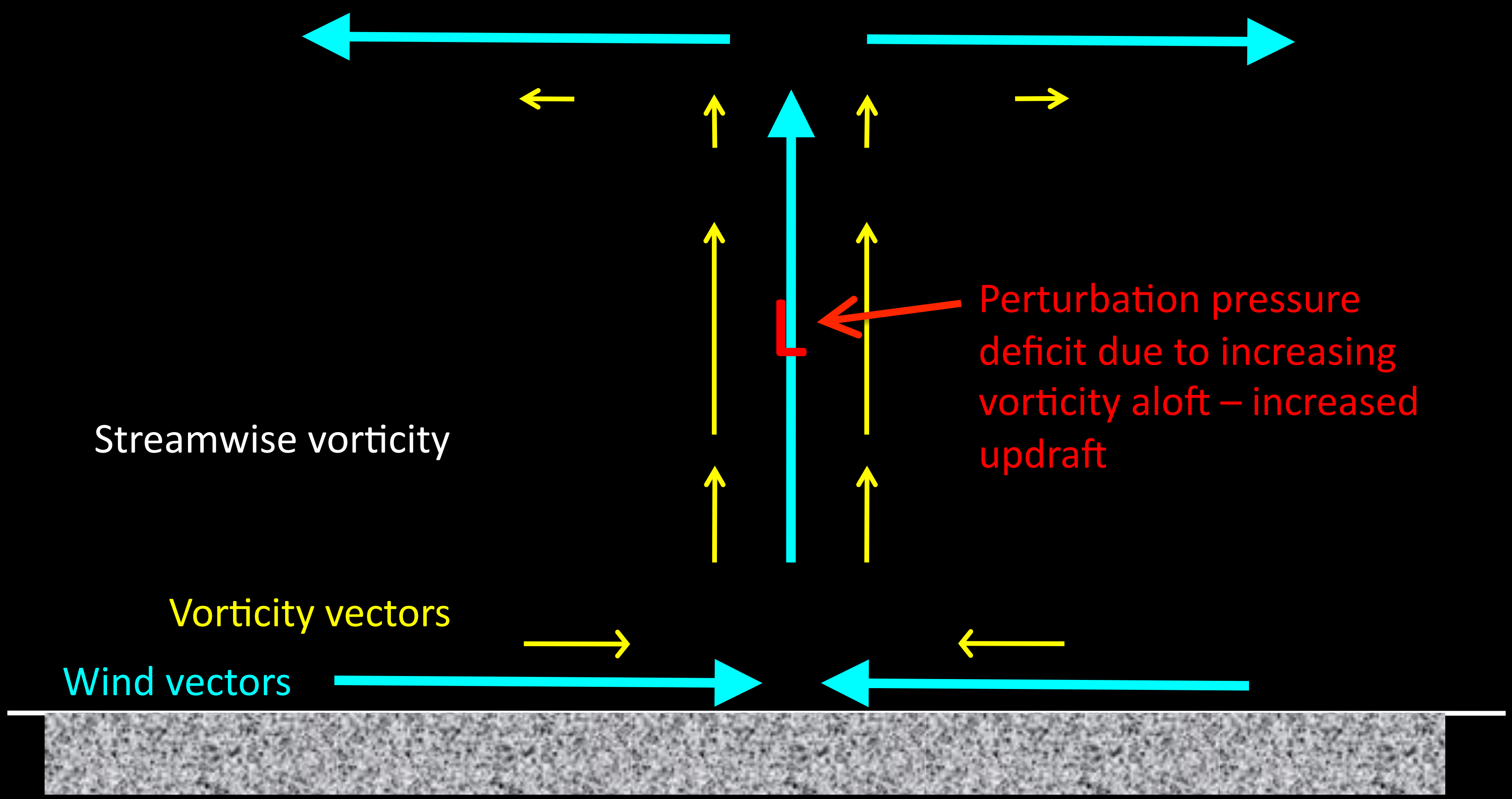
Schematic supercell vertical motion (ω)/divergence (δ)



What are supercells for? - cont'd

- *Both* buoyant instability and "helicity instability" are involved – a *synergy*
  – No buoyancy => no DMC
  – No helicity => nonsupercellular DMC
- All DMC mitigates buoyant instability
- Supercells also mitigate 'helicity instability'
  – Updraft ingests streamwise vorticity
  – Vorticity is amplified by stretching (to LND)
  – Vorticity is deamplified by storm top divergence

Updraft-shear/helicity interaction

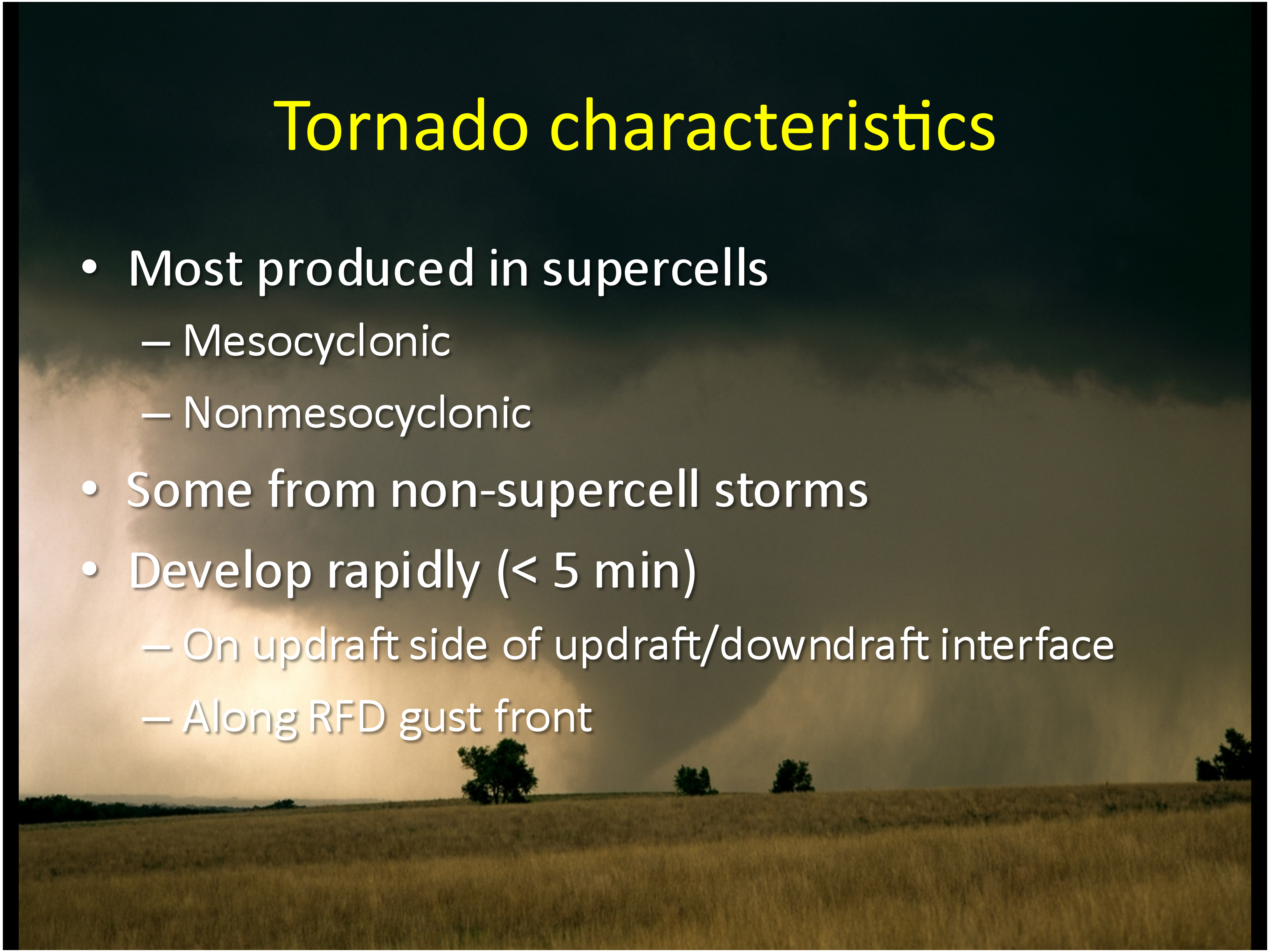


Summary for supercells

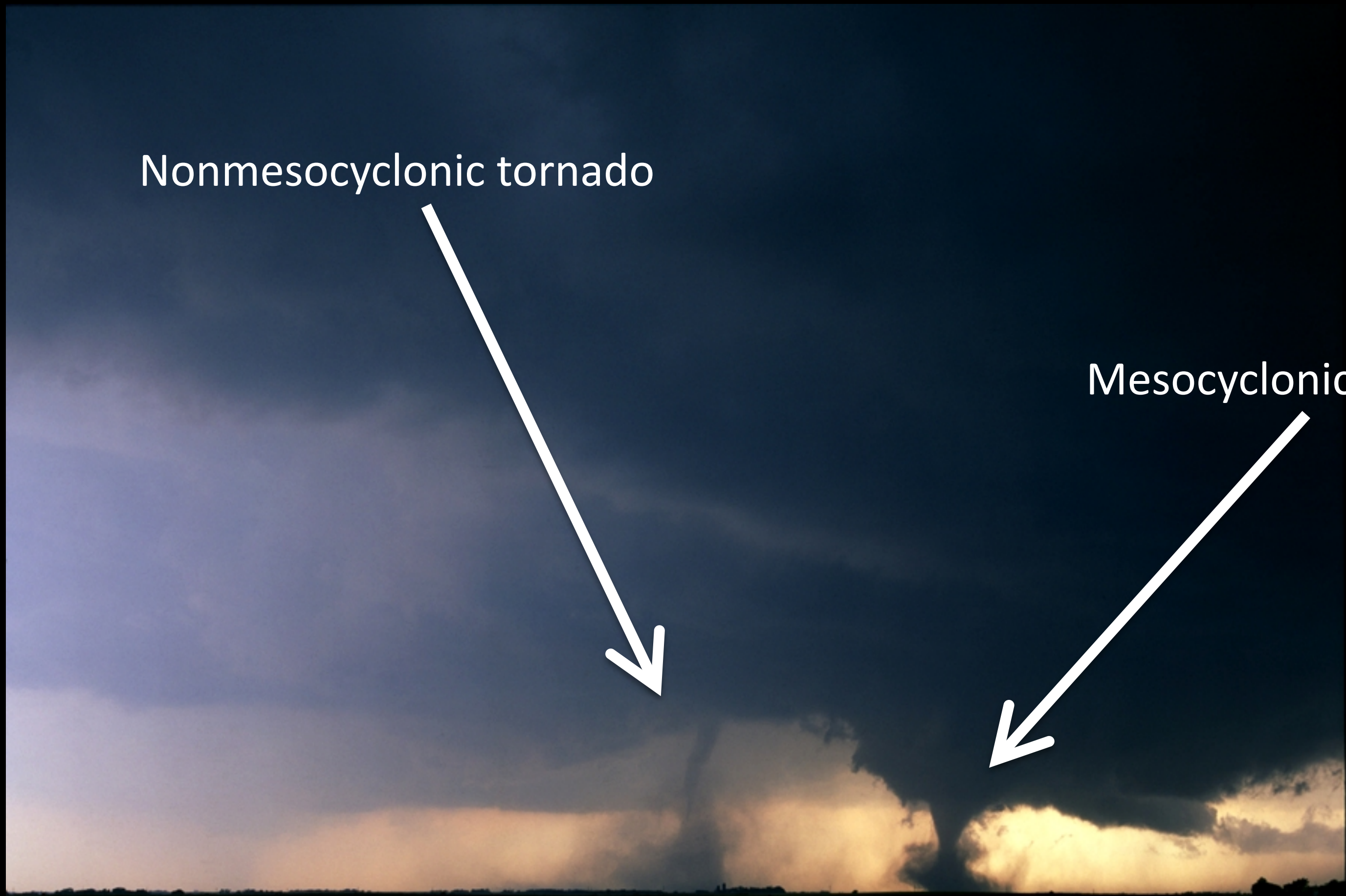
- Supercells have *both* buoyant and nonbuoyant potential energy available
- Tornadic supercells, in particular, can be inefficient at producing pools of stable air at low levels but will "consume" reservoirs of CAPE and helicity
- Supercell consumes helicity by first spinning it up and then spinning it down even more

Tornado characteristics

- Most produced in supercells
  - Mesocyclonic
  - Nonmesocyclonic
- Some from non-supercell storms
- Develop rapidly (< 5 min)
  - On updraft side of updraft/downdraft interface
  - Along RFD gust front



Two tornadoes – one supercell



Tornado characeristics (cont'd)

- Some tornadoes develop first aloft and develop downward (dynamic pipe)
- Some tornadoes develop first near the surface and develop upward (nonmesocyclonic)
- Some tornadoes form through a deep layer at about the same time
- Some tornado-like vortices come close to, but never develop surface-based tornadic intensity ("funnel clouds", TVSs aloft)

Tornadogenesis research

- Seeks to explain what makes a supercell storm tornadic
  - *Deep layer* shear/helicity (e.g., 0-6 km) is associated with supercells
  - *Empirical* observations – tornadoes are more likely whenever:
    - *Near-surface* (e.g., 0-1 km) shear/helicity is large
    - Near-surface LCLs are low (r.h. Is high)
- Tornadoes from non-supercells

Energy source for tornadoes

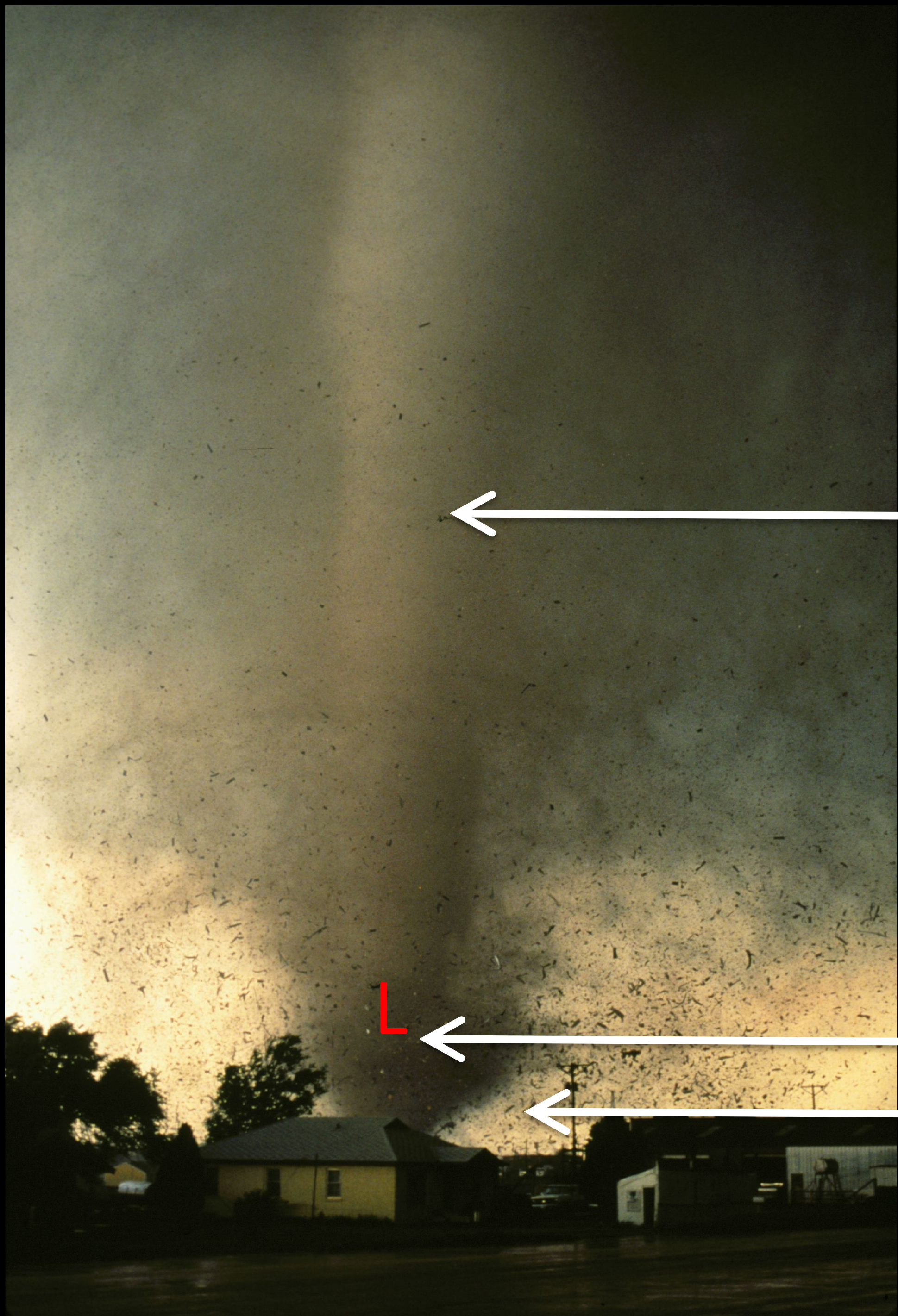
- CAPE has been proposed
  - Tornado would be a "parasite"
  - How much buoyant energy is released by the vortex itself? – tiny compared to updraft
  - Some tornadoes have no visible condensation funnel below cloud base
  - Thermodynamic "speed limit"?

What do tornadoes do?

- Vorticity is an efficient *mixing* mechanism on all scales
  - What is being mixed?
    - Not mitigating CAPE!
    - 'Helicity instability' is likely involved (e.g., short time scale of tornado development)
  - What determines the scale of a tornado?
    - Is it simply contraction and, therefore, amplification of stormscale vorticity?
    - Shear instabilities within mesocyclonic vortex flow?

Empirical evidence

- The most relevant shear/helicity for discriminating tornadic from non-tornadic storms is that very near the surface
- Studies of tornadoes suggest greatest perturbation pressure drop is above, but very near the surface – upward accelerations > 1 g!
- Again suggestive of 'helicity instability' in the 'corner flow' region of the vortex



"spin down" occurs much higher up

Upward vorticity advection

Extreme upward acceleration

Intense radial inflow

Tornado-like vortices aloft

- Presumably, some form of ‘helicity instability’ first develops aloft
- Kinematics – vortex lines don’t end at the sfc
- Conditions near the surface don’t permit the vortex to interact strongly with the surface boundary layer
  - Too negatively buoyant
  - Not enough helicity within the surface boundary layer to intensify the near-surface vortex

Nonmesocyclonic tornadoes

- Pre-existing maxima in low-level vertical vorticity ("misocyclones")
- Flow becomes helical when an updraft moves over a low-level vorticity maximum
- Helicity instability again operates, rapidly creating a deep vortex that begins near the surface
- Low-level mesoscale boundaries (fronts, dry lines, gust fronts) can have considerable vertical vorticity ($\zeta \sim 10^{-3}$ s^{-1})

Thank you!! Questions? Contact:

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