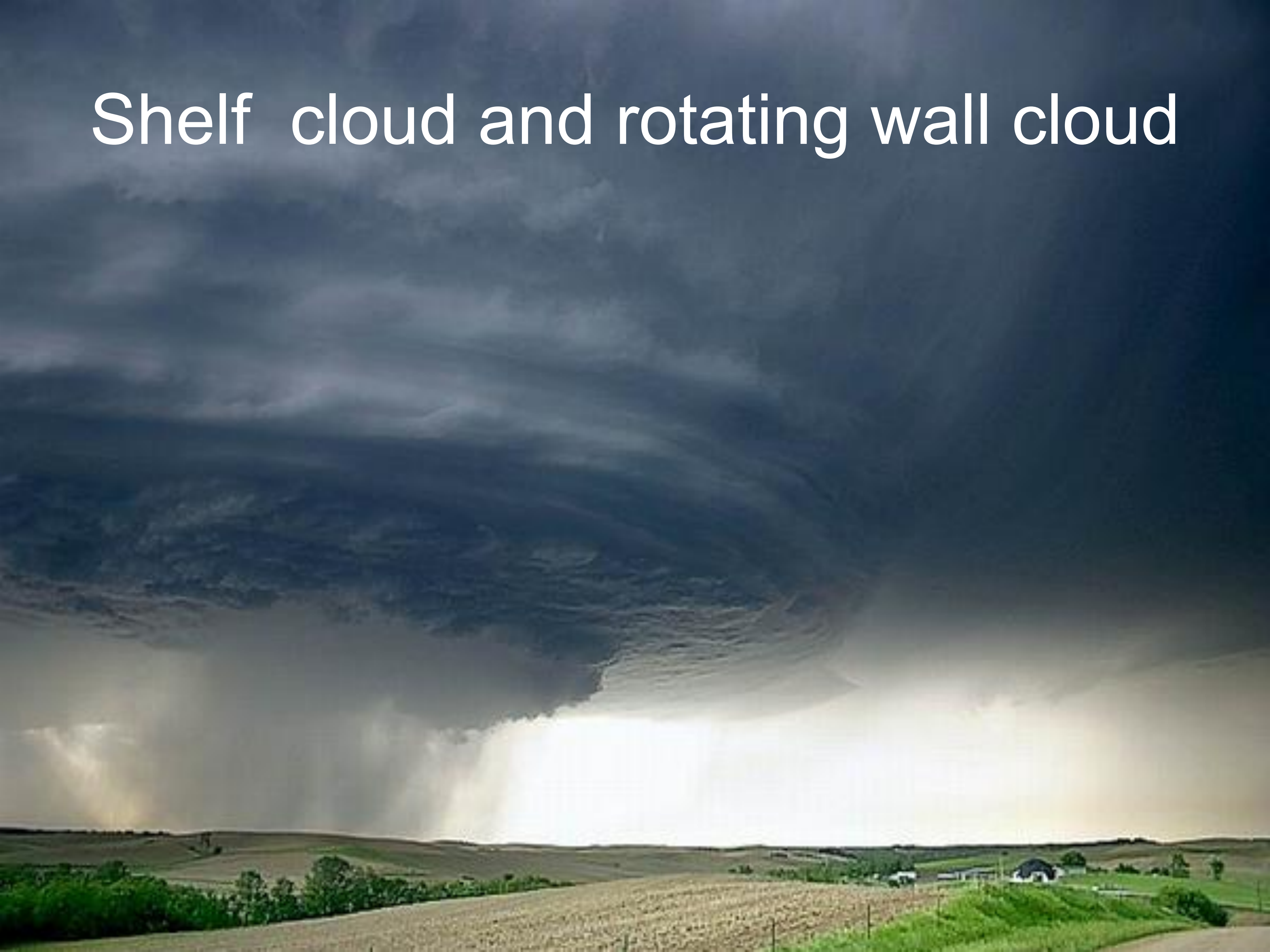
MET 4300

A Large Tornado approaches Lyndon, Kansas, on May 8, 2003

Giant tornado near Pilger, Nebraska, on 15 June 2014


Shelf cloud and rotating wall cloud

Outline

- Definition, life cycle
- Tornado formation within supercells (Type I)
- Tornado formation within non-supercell thunderstorms (Type II)
- Fujita scale
- Tornado statistics
- Historic cases
- Tornado detection, forecasting, and safety

TORNADOES

- Violently rotating columns of air that extend from a thunderstorm cloud to the ground.
- Appears as a condensation funnel or swirl of dust on the ground.
- A funnel that does not reach the ground is a ***Funnel Cloud***.
- A tornado over water is called a ***Water Spout***.
- Weaker dry vortex over land is called a ***Dust Devil***

TORNADOES

- **On average, over 1,000 tornadoes per year in US. An averge of about 56 people killed/975 injured during 2000-2009, but this increased to 110 killed/1207 injured during 2006-2015.**
- **Mainly develop within supercell T-storms, but also form in T-storms along squall lines, near the end of T-storm bow echoes, within land-falling hurricanes, and rarely within ordinary T-storms.**
- **Width: 50-800 m (record width: 2.6 miles OK May 31, 2013)**
- **Wind speed: 57 to over 174 knots (265 kts record high, same OK storm in May31, 2013)**
- **75% of all tornadoes occur in the US.**
- **Life time: mostly short-lived, lasting only minutes (up to 1 hr)**
- **Damage length: 30 miles**

Characteristics

- Maximum winds can be as strong as 125-140 m/s
- ***Type I*** Tornadoes
  - Form within the ***Mesocyclone*** of a supecell thunderstorm
  - Strongest tornadoes are Type I
- **Type II** Tornadoes
  - Form along stationary or slowly moving wind-shift lines (outflow boundaries) within non-supercell thunderstorms
  - Much weaker
- **Fujita Scale** (more later)
  - Weak F0-F1, Winds 40-112 mph
  - Strong F2-F3, Winds 113-206 mph
  - Violent F4-F5, Winds 207-318 mph
  - Enhanced Fujita Scale based upon 3-s gust to take effect in 2007

Tornado Life Cycle (5 stages)

- **1) Initial Stage: A funnel cloud** emerging from the wall cloud (not reaching the ground yet) or a rotating **dust swirl** on the ground.

A funnel cloud extending from a wall cloud near Canadian, Texas, on 27 May 2015.

Tornado Life Cycle (5 stages)

- **2) Organizing Stage**: the condensation funnel cloud descends to the ground as the vortex intensifies
  - Funnel may be condensation, or dust, or both

A well-developed tornado near Dodge City on 24 May 2016.

Tornado Life Cycle (5 stages)

- **2) Organizing Stage**: In larger tornadoes, the tornado funnel first widens above the ground, with the wider part expanding downward to the ground.

A tornado widening above the ground in Goshen County, Wyoming, on 5 June 2009.

Tornado Life Cycle (5 stages)

- **3) Mature Stage**: Following the organizing stage, some tornadoes grow substantially in width as the expanded region reaches the surface. The intensity of the vortex peaks during its mature stage. During this time, the tornado is at its largest size (could exceed 1 km in diameter) and is often nearly vertically erect.

A wide tornado near Bennington, Kansas, on 27 May 2013.

The same tornado after it evolved to become an extremely large multivortex tornado.

Tornado Life Cycle (5 stages)

- **4) Shrinking Stage**: the vortex tilts over more, often taking on a rope-like appearance.
- **5) Dissipating Stage**: Funnel becomes nearly horizontal and stretch into rope-like formations.

A tornado decaying to its rope stage near Russell, Kansas, on 25 May 2012.

Life cycle of the Cordell Oklahoma tornado of 22 May 1981


(A)


(D)


(B)


(E)


(C)

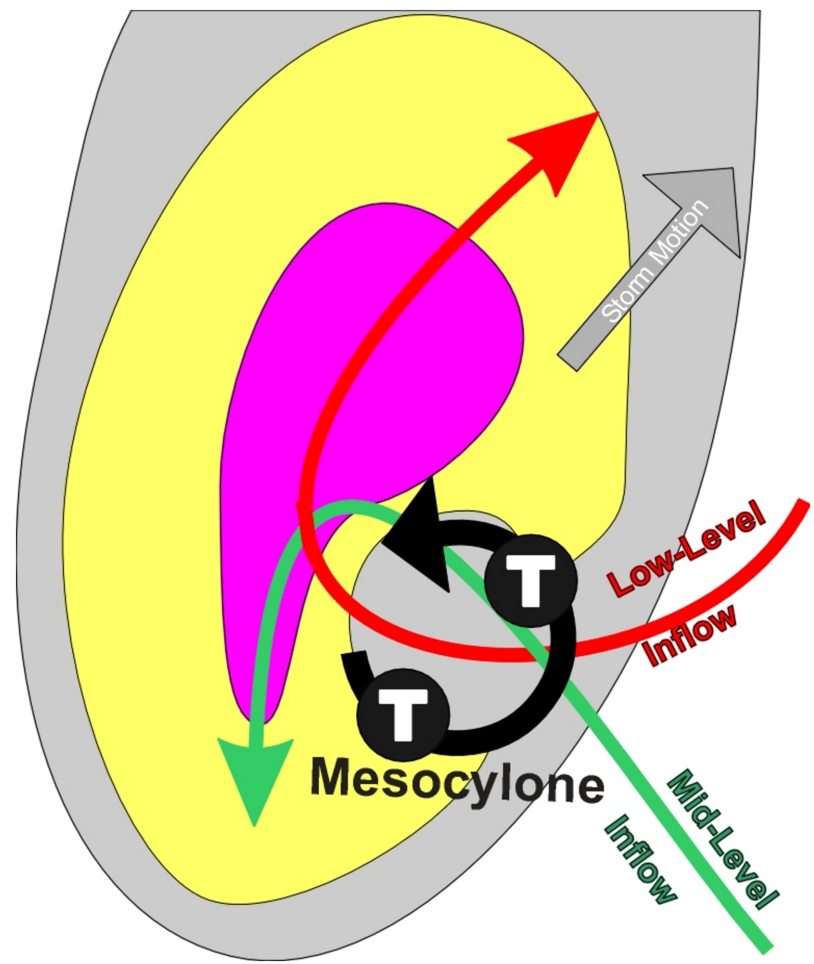

(F)

- **A: Initial Stage:** Dust became airborne underneath **a wall cloud** at 5:20pm.
- **B: Initial Stage:** A rotating dust column (**dust swir**l) formed under the wall cloud and obscured any existent condensation funnel at 5:22pm.
- **C: Organizing Stage:** At 5:26pm, a **narrow condensation funnel** was visible as the dust swirl disappeared, after the tornado had moved away from a recently plowed field.
- D: **Mature Stage:** a **dust swirl** again surrounding the funnel at 5:36pm.
- E: **Shrinking Stage:** At 5:28 pm, the tornado **roped out**
- F: **Dissipating Stage:** dissipated at 5:28pm (**rope cloud**)

Tornado formation within supercells

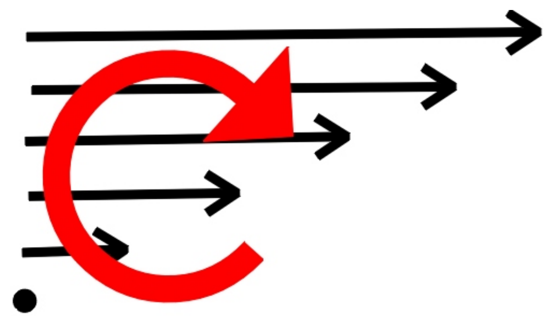
Supercells and Tornadoes

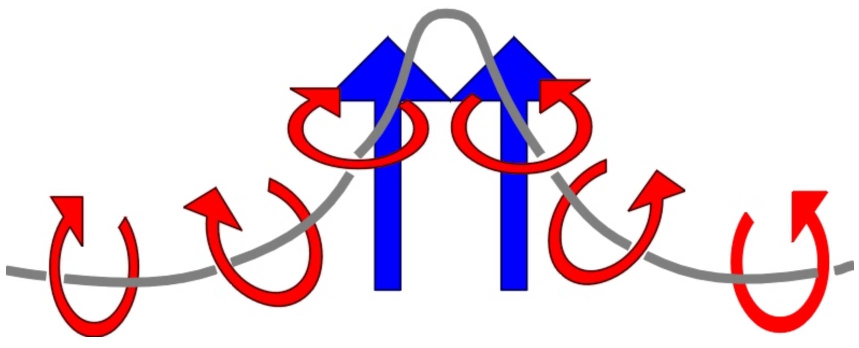
- Most F2-F5 tornadoes form in supercells
- Rotating updraft forms a mid-level mesocylone
- Tornadoes are generated within the mesocyclone
- Need to understand how the mesocyclone forms within a supercell and how tornadoes form within a mesocyclone



The mesocyclone rotation is generated by the vertical wind shear

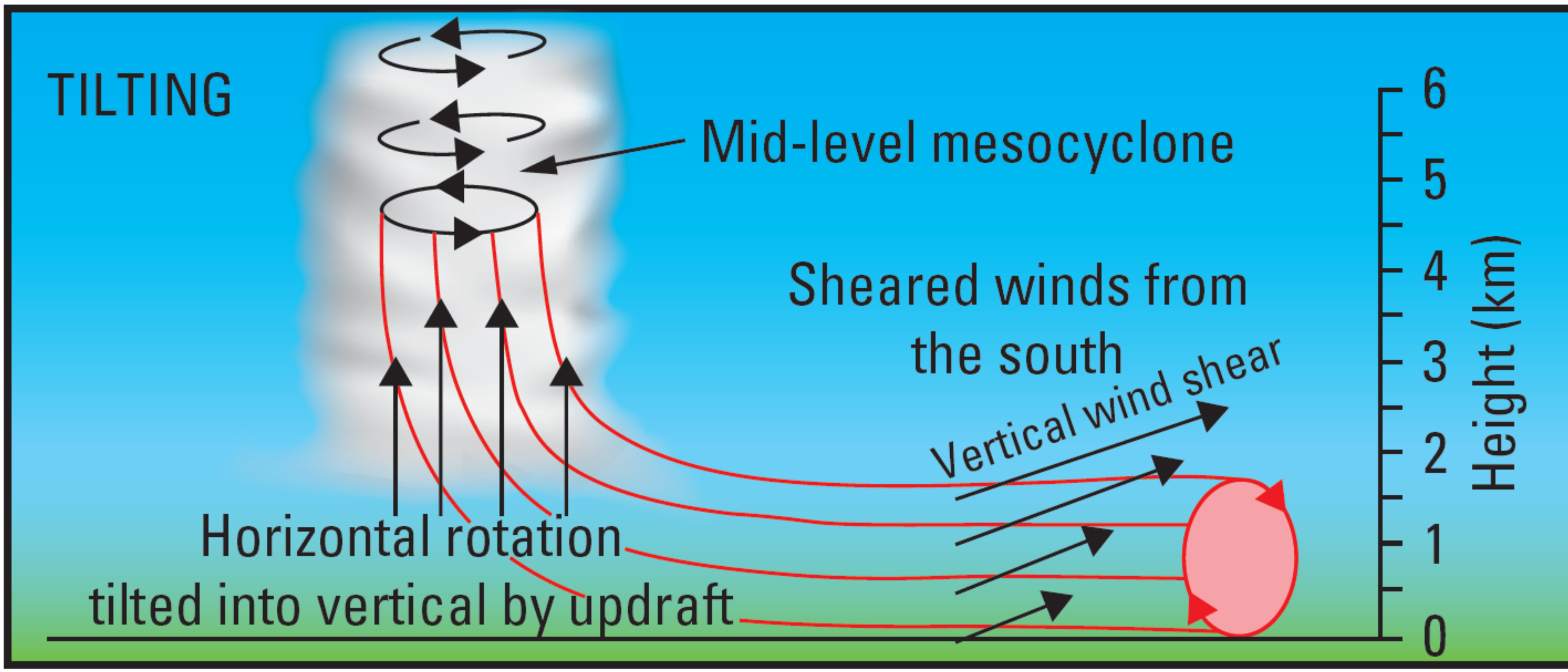
- **Shear** is a form of vorticity/rotation around a horizontal axis.
- The axis of the rotation is parallel to the ground.
- In a supercell, updrafts make the axis of rotation **<u>tilted</u>** into the vertical: **vortex tilting**
- Cells of opposite rotation on opposite flanks of the updraft
- In supercells the cyclonic rotation on the right side of the updraft causes low pressure and gives the inflow an extra kick





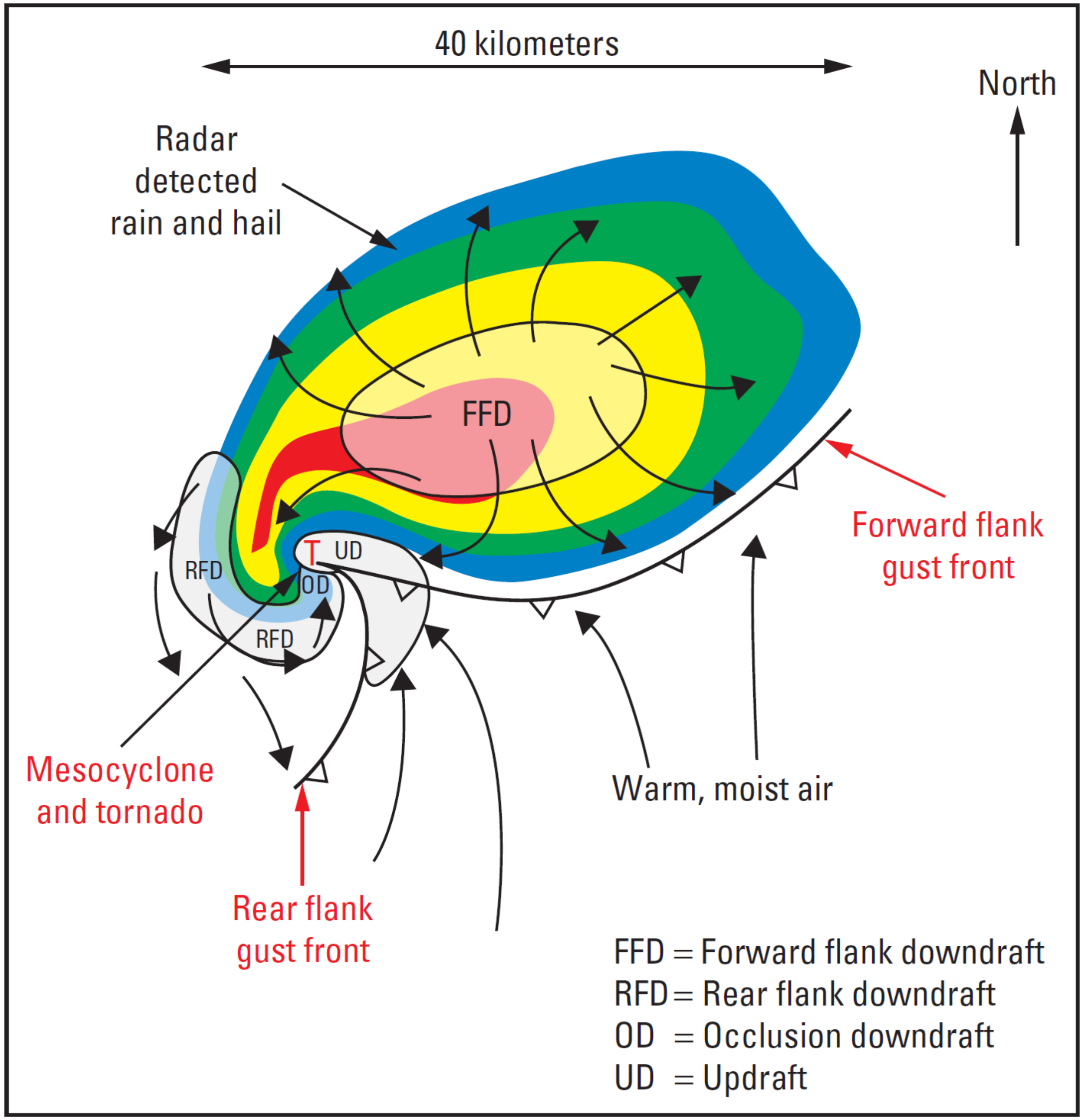
Supercell Tornadogenesis: Three Steps

- **Step 1**: Formation of **mid-level mesocyclone (typically between 2-10km in diameter)** due to the vortex tilting.



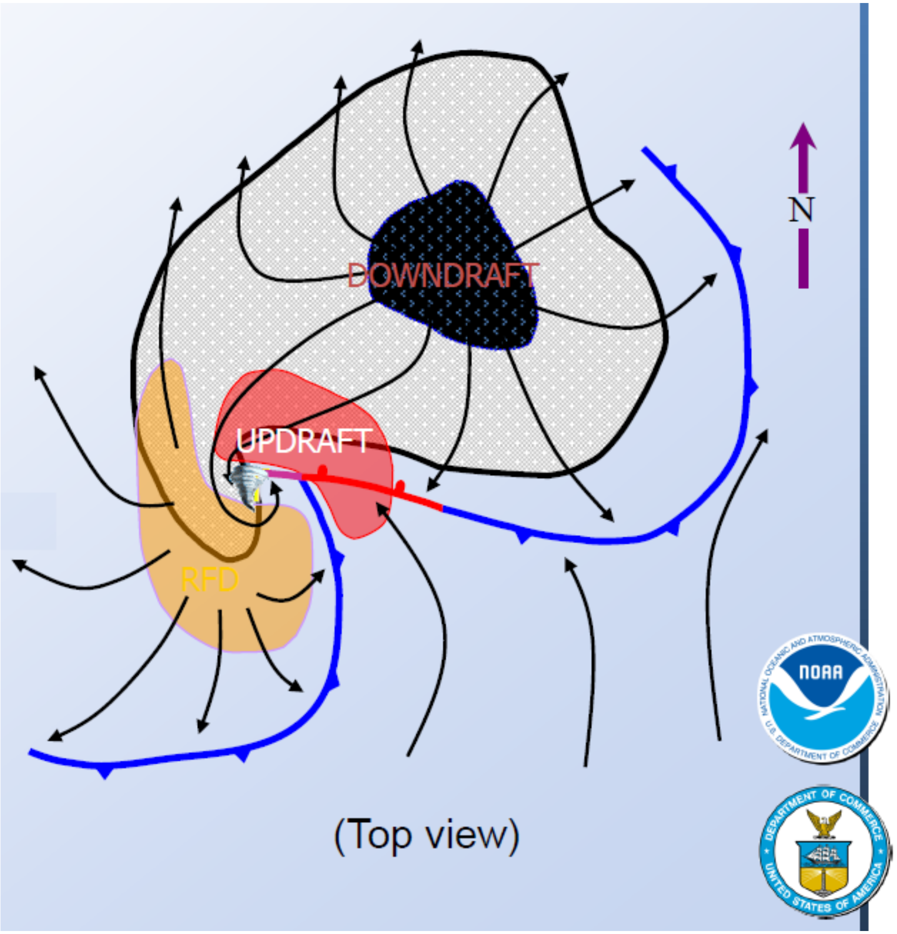
Location of the rotating updraft within supercells

- Mesocyclone: similar to an extratropical cyclone (EC)
- Low pressure center: co-located with the rotation center
- FFD gust front: ~ warm front of an EC
- RFD gust front: ~ cold front of an EC
- RFD gust front catches up to the FFD gust front & forms an occlusion (OD)
- Updraft is rapidly rising aloft above the OD.
- Mesocyclone size: 5-km (2-10 km)



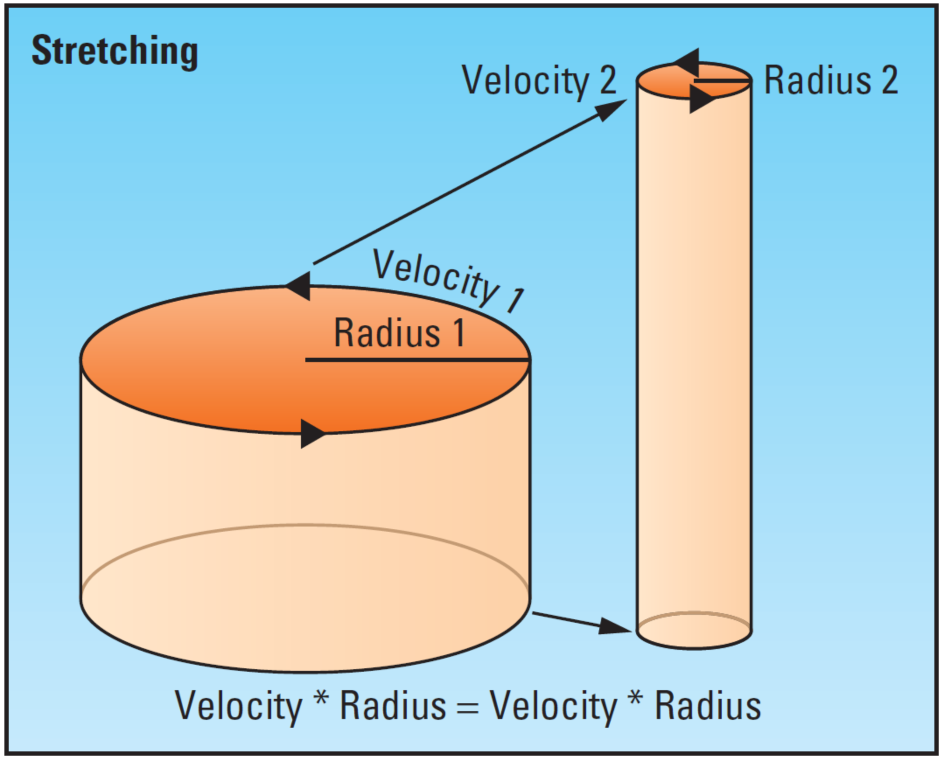
Supercell vs. Mid-Latitude Cyclone

- Tornadogenesis often occurs when the RFD reaches the FFD, assisting in vortex stretching



From mesocyclone to tornado: vortex stretching

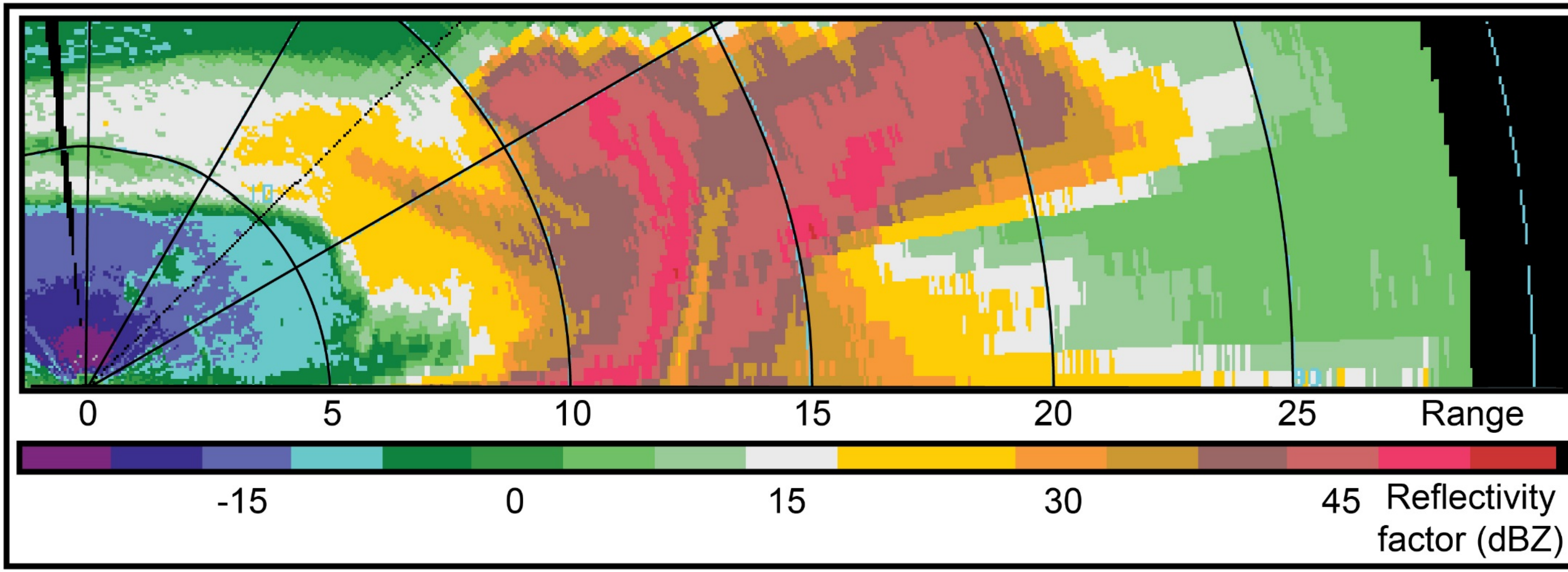
- **Conservation of angular momentum**: Air stretched in a narrower and narrower column will rotate faster and faster.
- Exactly how stretching proceeds and leads to the narrow tornado vortex is still uncertain.
- <30% of all supercells with a mesocyclone signature on radar actually produce a tornado.
- Very few supercells have been observed in sufficient detail to study tornadogenesis. Therefore, different mechanisms have emerged!



VORTEX Field Campaign (1994 & 1995)

- Dual Doppler ELDORA radar by NCAR
- Mobile ground-based radars, instruments on chaser cars.
- 8 tornadoes were examined at close range
- Best case: Garden City (Kansas) tornado in 16 May 1995; Roger Wakimoto’s study

Aircraft Radar Looks at a Tornado

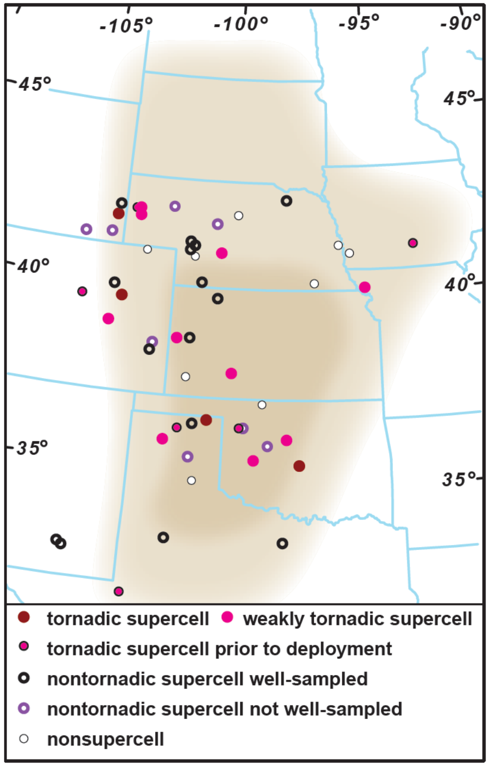


Remarkable tornado column that extends from cloud base to top: Vertical cross section of the radar reflectivity through a supercell thunderstorm and tornado near Friona, Texas, on 2 June 1995 measured by the ELDORA radar onboard the National Center for Atmospheric Research Electra aircraft. The data were collected during VORTEX field campaign.

VORTEX 2 (2009 & 2010)

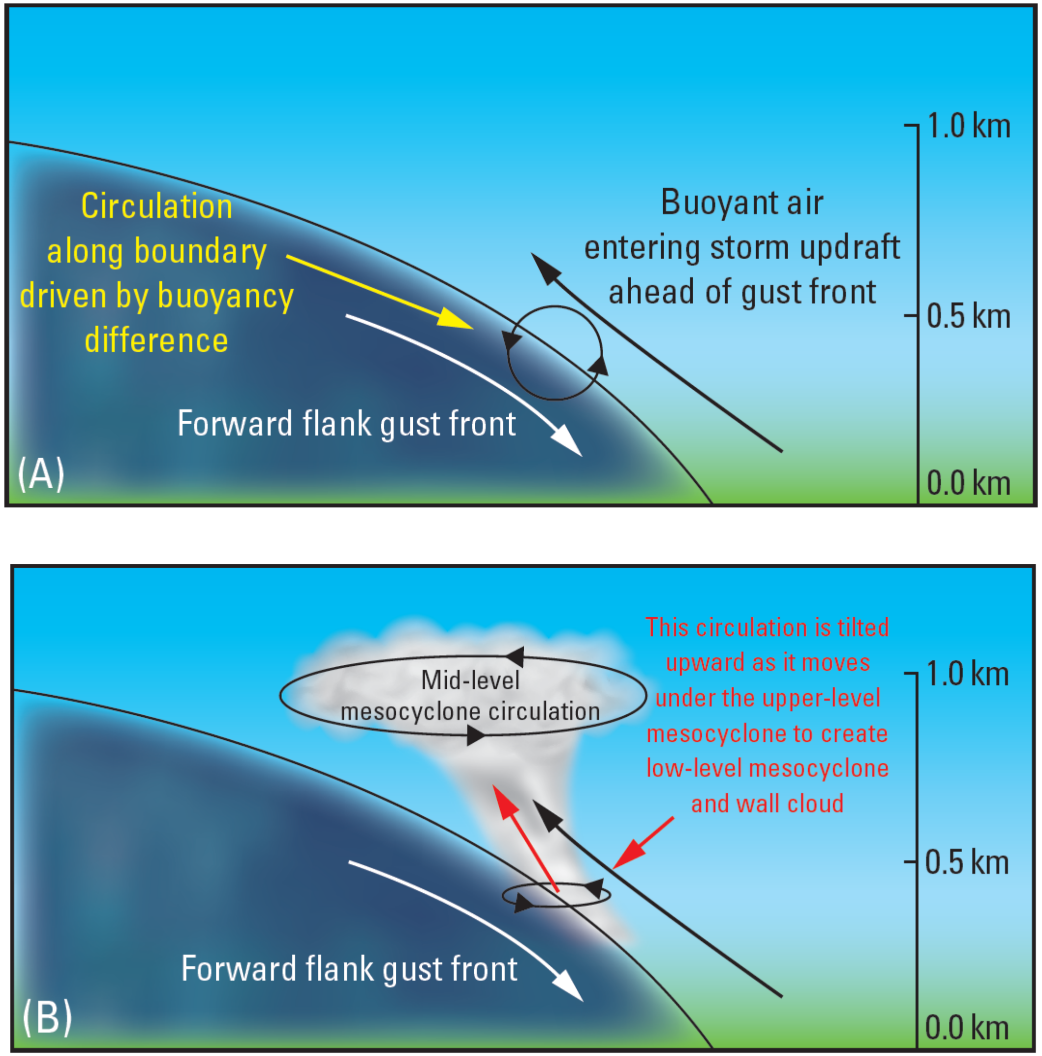
- 11 mobile Doppler radars
- Surface observing systems: sticknets, Mobile Mesonet, disdrometers
- Special soundings, special photography & a vast array of operational weather stations across the Great Plains
- 2009 season: very inactive, only one tornado observed.
- 2010 season: more tornadoes
- In total, 2 well-sampled and 2 partially sampled strong tornadoes (>= EF2), 10 weakly tornadic supercells (EF0-EF1), 22 non-tornadic supercells, and 9 non-supercell thunderstorms over 9 states.

VORTEX 2 armada of vehicles



VORTEX 2 Operational Area (9 states) and storm intercepts

Supercell Tornadogenesis: Step 2: Formation of low-level mesocyclone



- Behind the forward flank gust front, the air is negatively buoyant & descending
- The warm air adjacent to the gust front is positively buoyant and ascending.
- This leads to a rotation due to buoyancy difference.
- **The axis of rotation is initially horizontal, but is tilted to the vertical by the updraft**, creating the low-level mesocyclone.
- This low-level mesocyclone appears visually as the rotating wall cloud.
- However, the rotation at this point still **does not extend to the ground →**

Supercell Tornadogenesis: Step 3

- **Step 3:** The rotation reaches the ground. How does this happen?
- There are three mechanisms that have been proposed for how this process occurs.

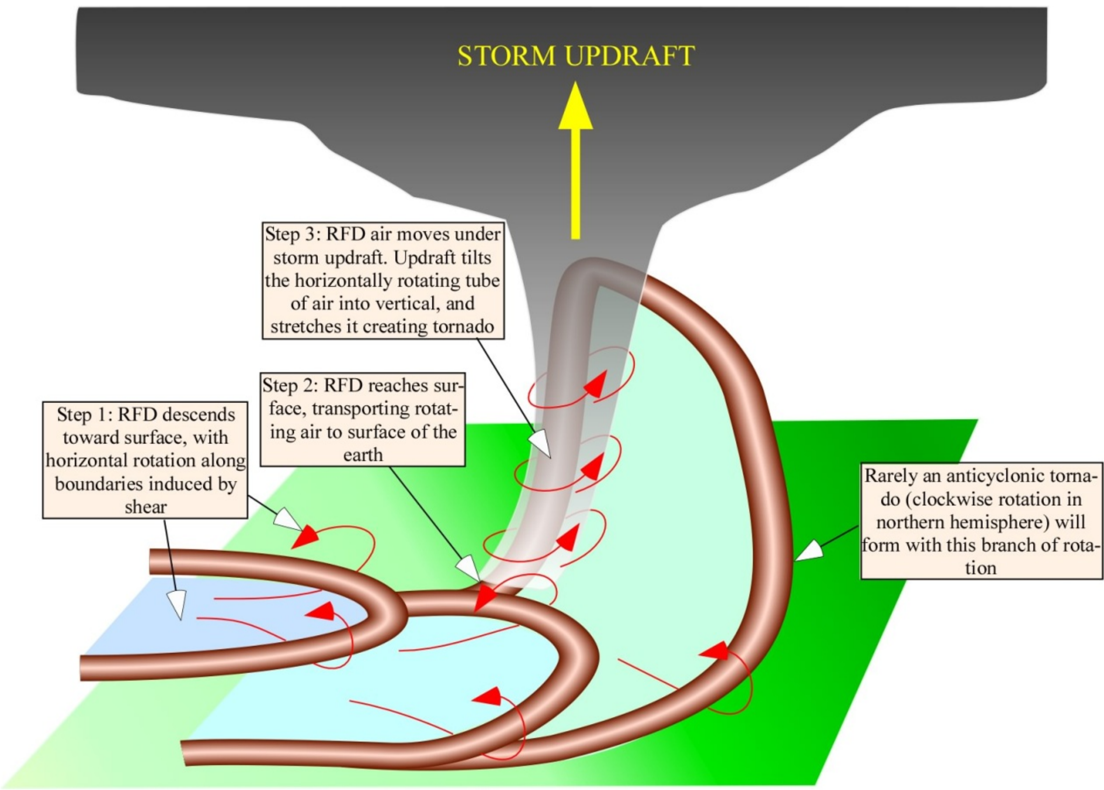
  Mechanism 1: Bottom-up process (this is believed to be the most common, based on the VORTEX field studies)

  Mechanism 2: top-down process (dynamic pipe effect)

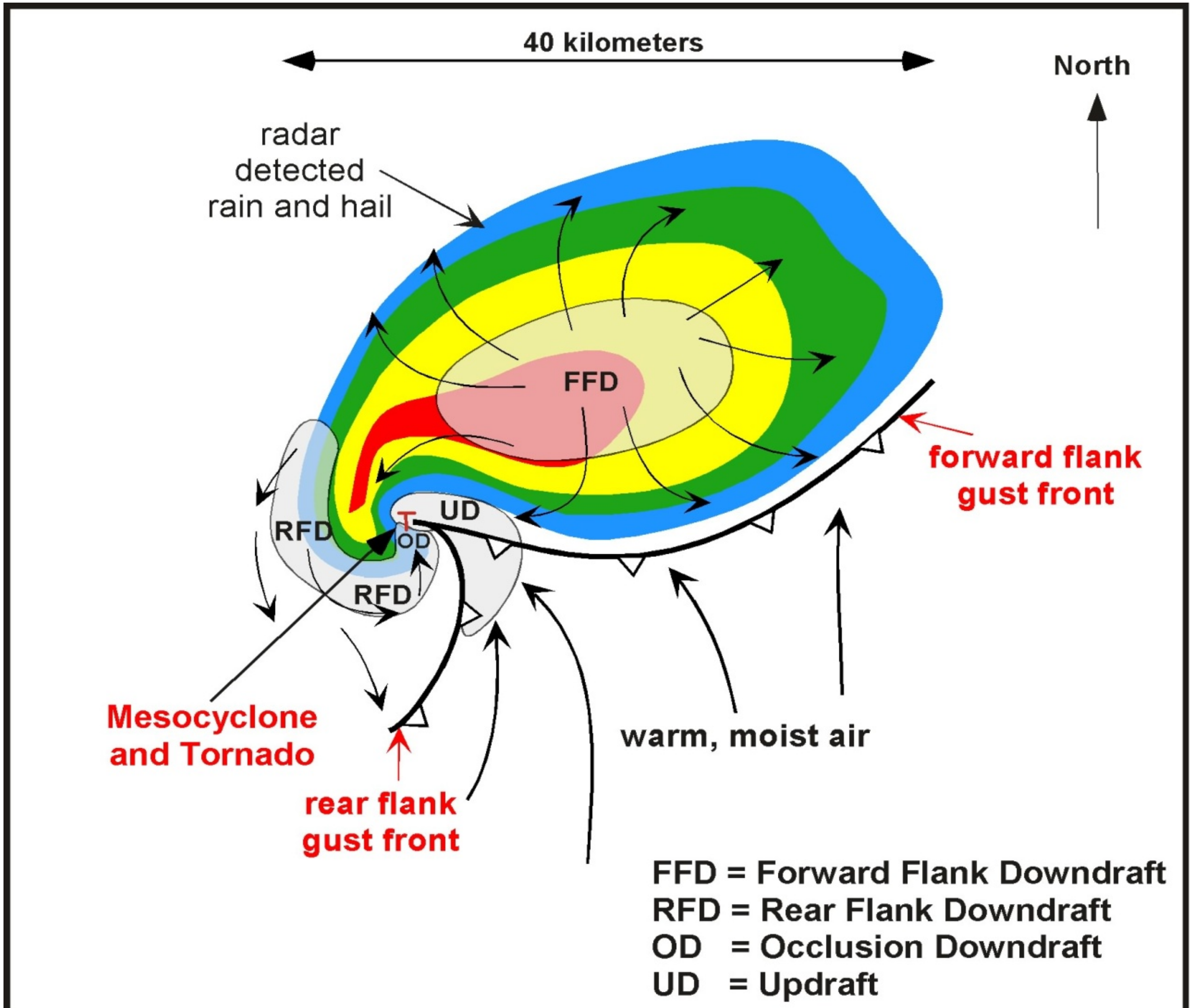
  Mechanism 3: Vortex breakdown, similar to the suction vortex formation mechanism (the Garden City tornado is the only tornado in which this mechanism has been observed. Whether this process is common or rare is unknown)

Mechanism 1: Bottom-up process

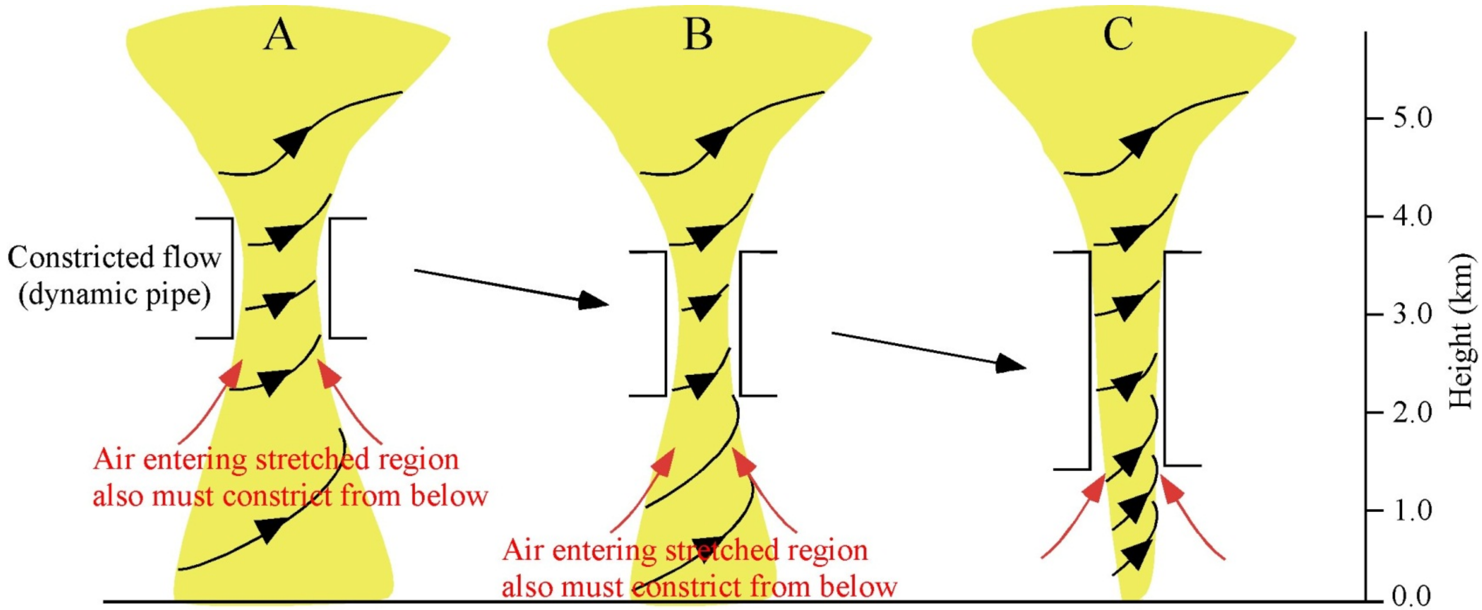
- **1**: Descending air within RFD generates **horizontal rotation** along its periphery (similar as the low-level mesocyclone generation process along the Front Flank Gust front)
- **2:** After the descending air reaches ground, the surface-based rotation at the gust front periphery **moves under the updraft.**
- **3: The rotation is tilted upward** by the updraft creating the tornado.
- On rare occasions, the clockwise-rotating branch of rotation on the opposite side of the RFD (south boundary of RFD) may be stretched upward into the updraft to form an anticyclonic tornado.
- **Air temperature** within the rear flank downdraft is crucial. Must not be too cold to form a tornado.



Location of the mesocyclone within supercells



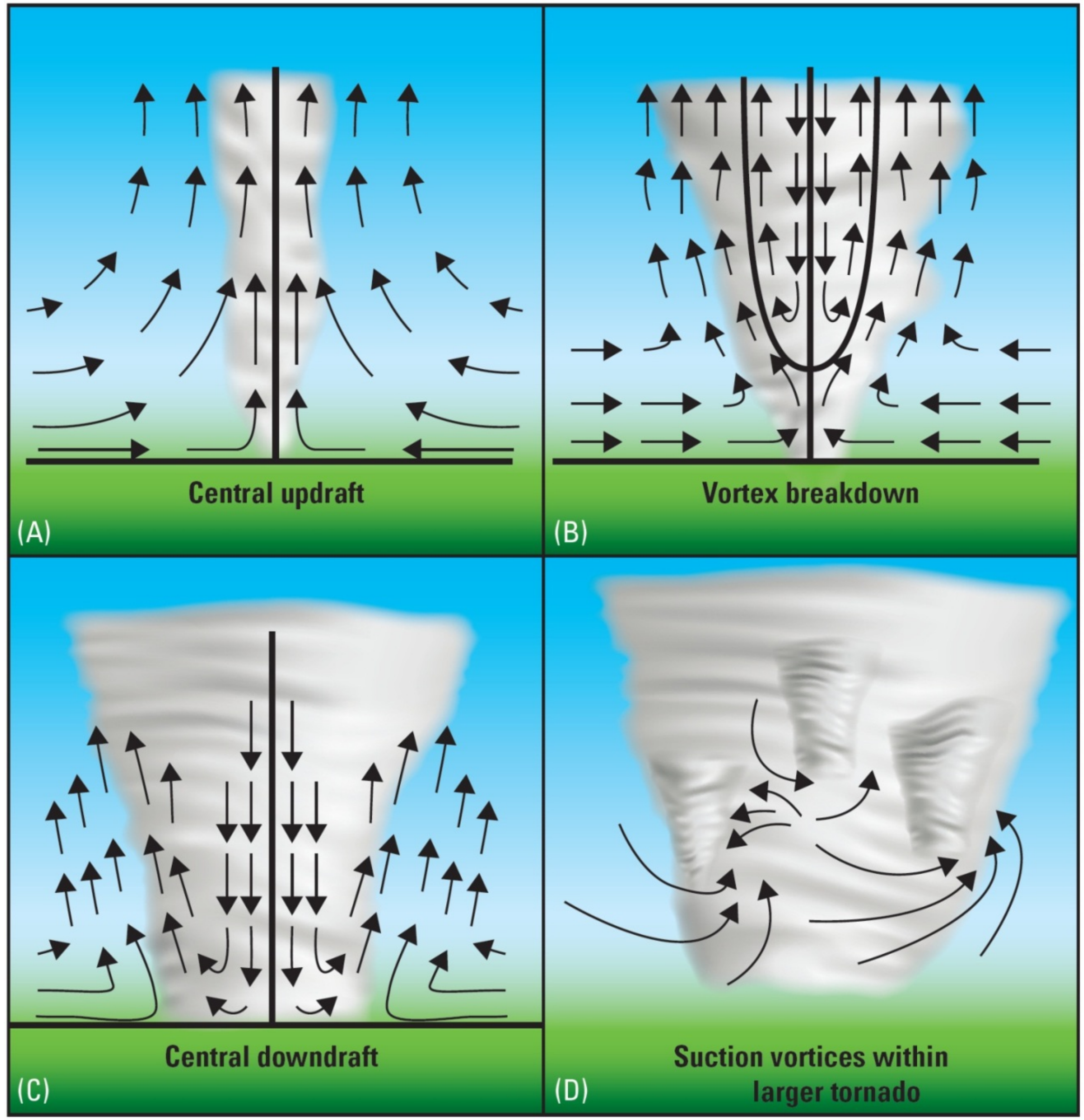
Mechanism 2: Top-down process (dynamic pipe effect)



- A narrowly constricted flow in the mid-level (which develops when the mid-level mesocyclone is stretched)
- Air rotating in the middle have two forces in balance: PGF inward and centrifugal force pointing outward.
- The stretched vortex in A causes **rotating air below it** to constrict its circulation, leading to a tighter vortex in B.
- The process proceeds earthward until the vortex is narrow at the ground in C, creating a tornado.

Vortex Breakdown (a large tornado forms from a small one)

- ***Vortex breakdown***: a downdraft develops at the center of the tornado vortex due to extremely low pressure (~100mb lower), just like in the eye of hurricanes.
- As the downdraft progresses toward surface, the tornado vortex expands, forming a large tornado.
- Large tornadoes (**multiple vortex tornadoes**) often develop smaller vortices, called ***suction vortices,*** as the central downdraft outflow merges with the rotating air outside the downdraft.
- Most violent parts of a tornado are the suction vortices (>250 kts).



Mechanism 3: Similar to Vortex Breakdown

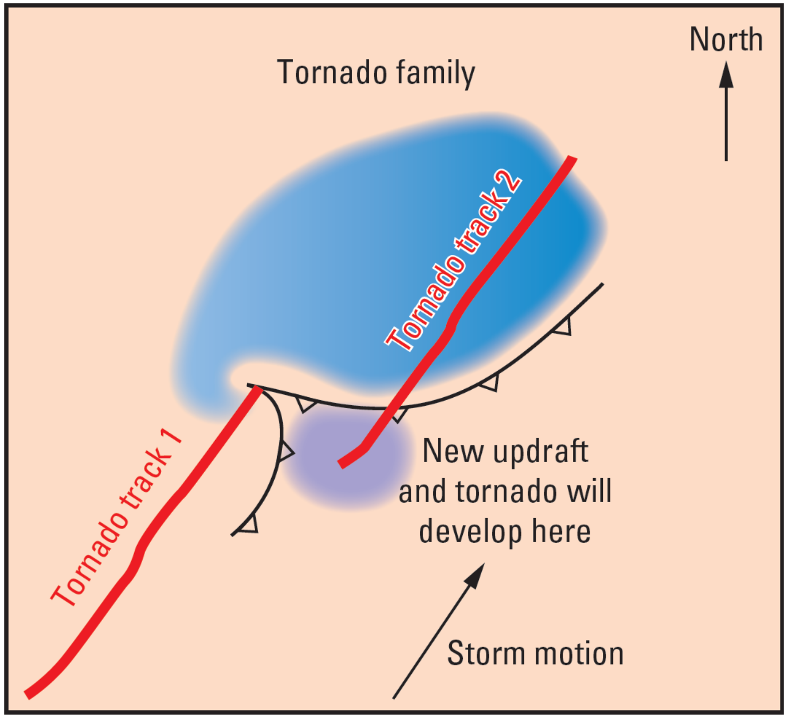
- The analysis of the Garden City tornado showed that a similar process occurred in the mesocyclone during tornadogenesis.

- In the Garden City case, a central downdraft occurred within the mesocyclone circulation. The tornado developed as the central downdraft within the mesocyclone merged with the rotating air in the outer part of the surface mesocyclone.

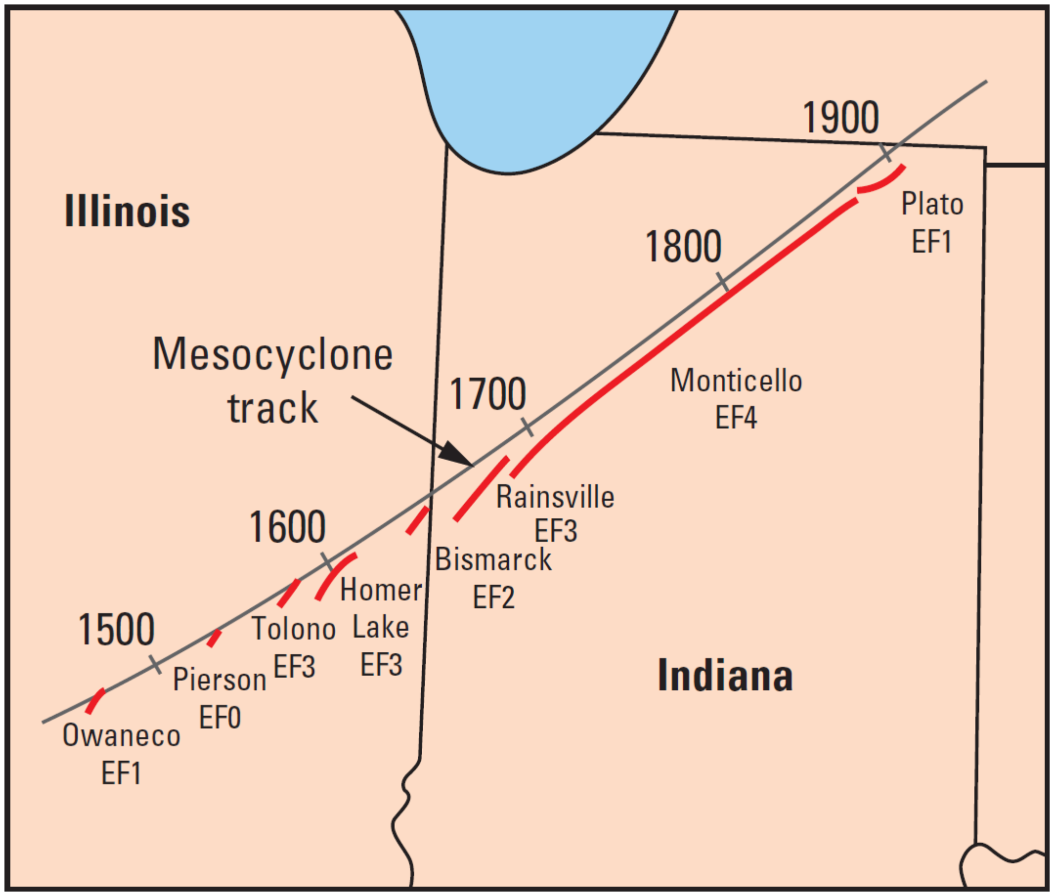
- In a similar manner to the suction vortex formation mechanism, one of the resulting vortices spun up to form the Garden City tornado.

Tornado Family within a supercell's lifetime

- The typical tornado lifecycle concludes as the RFD cuts off the updraft and the tornado begins to dissipate
- A new updraft will then form ahead of the old updraft and the process can repeat
- A tornadic supercell may pass through this sequence several times in its lifetime
- Cycle occurs about every 30 minutes
- Tornadoes emerging from the supercell over its lifetime constitue a **tornado family**.

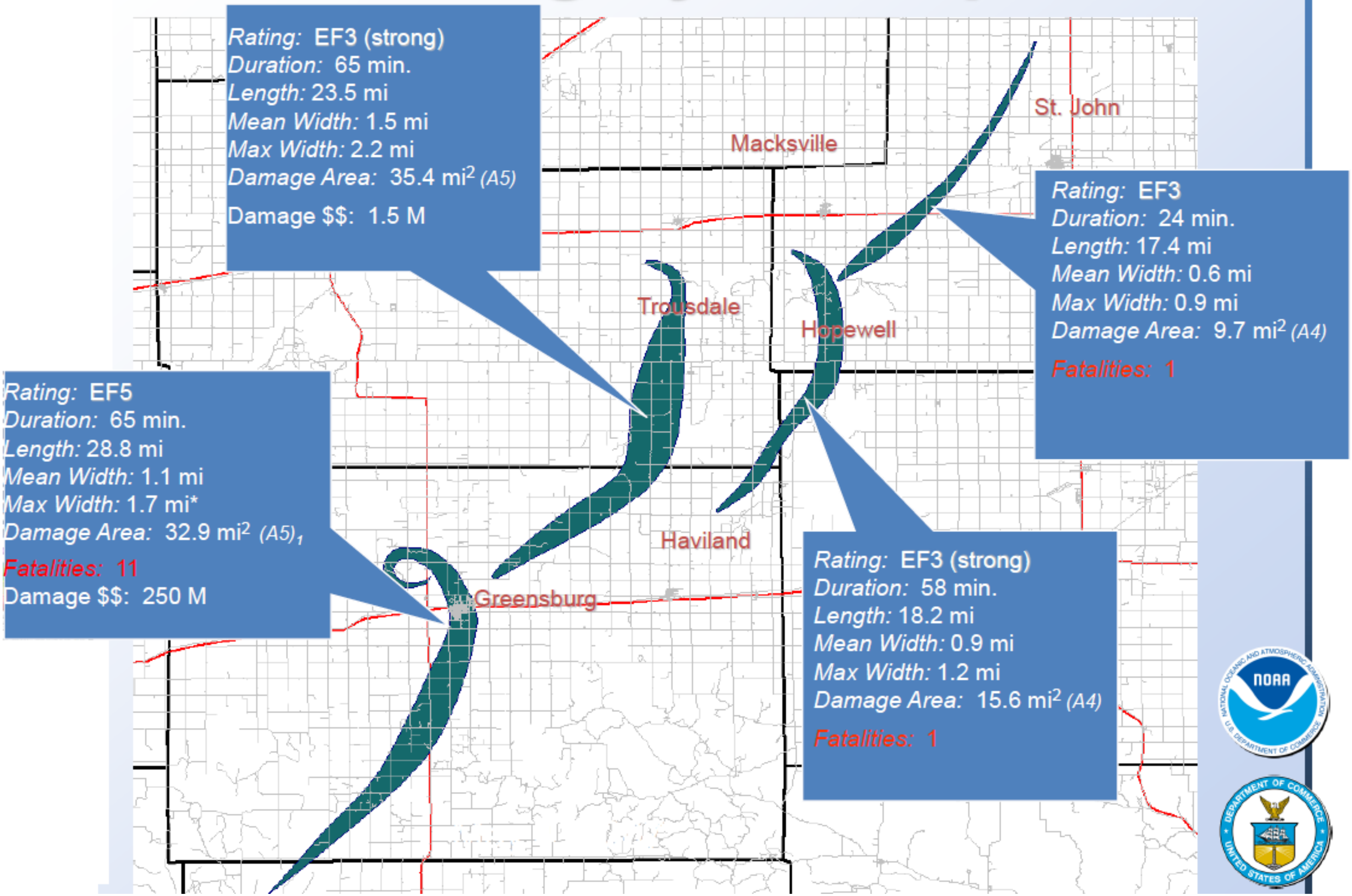


Tornado family generated by a supercell over Illinois & Indiana on 3 Apr. 1974



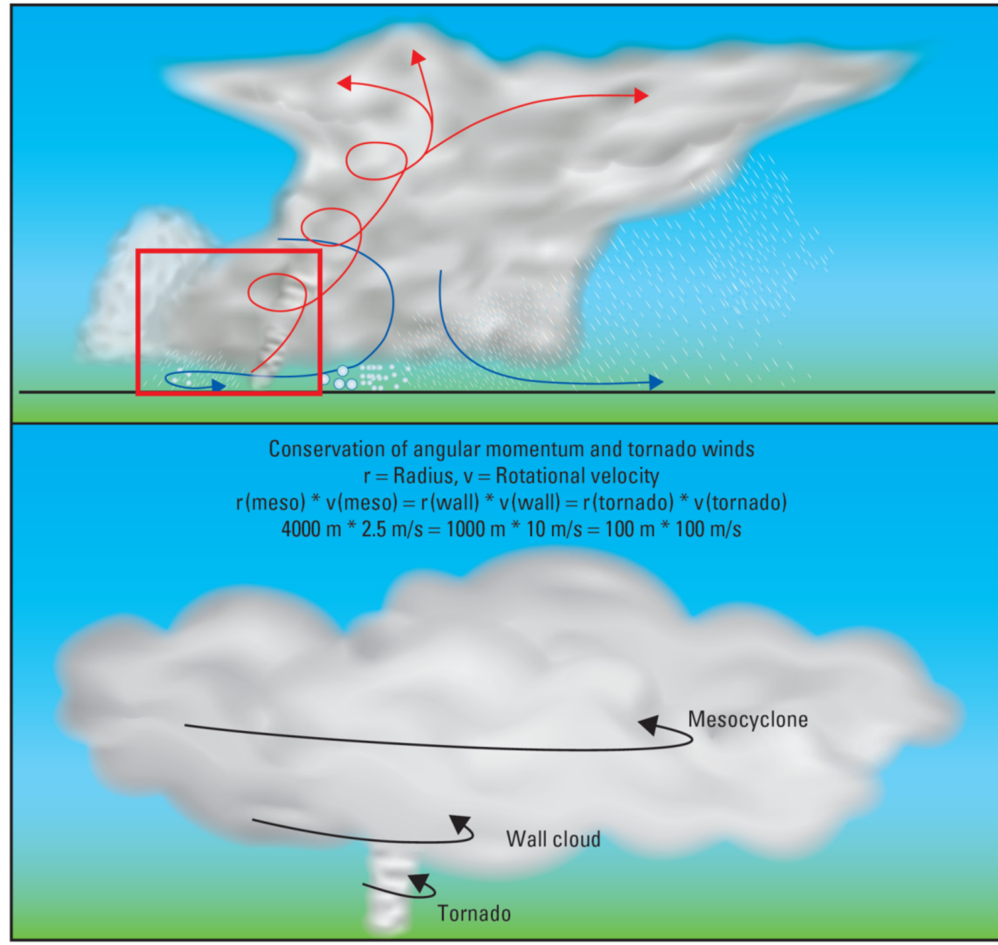
- The supercell produced 8 tornadoes within 5 hours.
- The light gray line is the mesocyclone track.
- Local time is labeled along the track.

Greensburg Cyclic Supercell



Tornado Winds

- Violent winds in a tornado are from the contraction of the mesocyclone.
- Conservation of Angular Momentum: The product of the rotating velocity (v) and the distance from the rotation center (r) is constant. r * v =constant
- In a mesocyclone: r=4000 m, and v=2.5 kts (5 m/s). r*v=10,000 m^2/s
- If the radius contracts to 100m, then v=10,000/100=100 m/s (200 kts)!



Conservation of Angular Momentum and Tornado Winds

Tornado Winds: variation by locations

- Total wind speed measured at the ground = the rotational velocity + forward (translational) velocity
- Winds are stronger on a tornado's right side than on its left side.
- For example, if a tornado's rotational velocity is 160 kts, and forward speed is 40 kts, then the total wind on the right would be 200 kts, while 120 kts on the left.
- Most violent winds are in the suction vortices.