

Tornado Dynamics

Readings:

Klemp (1987) Dynamics of Tornadic Thunderstorms (handout)

Bluestein Vol II. Section 3.4.8.

Rotunno, R., 1986: Tornadoes and tornadogenesis. In: P. Ray (Editor), *Mesoscale Meteorology and Forecasting*. AMS, Boston, 414-436.

Davie-Jones, Robert, R. J. Trapp, and H. B. Bluestein, 2001, Tornadoes and Tornadic Storms, In: C. A. Doswell (Editor), *Severe Convective Storms*, AMS, 167-222.

Houze Sections 8.6-8.

Definition: tornado, n. A rotating column of air usually accompanied by a funnel-shaped downward extension of a cumulonimbus cloud and having, ..[winds] whirling destructively at speeds of up to 300 miles per hour. (American Heritage Dictionary of the English Language)

This definition reflects a fundamental property of the tornado: it occurs in association with a thunderstorm.

Tornado Climatology in the US

Tornadoes in the United States are reported most frequently in a band stretching from West and North Texas through Oklahoma, central and eastern Kansas, and into eastern Nebraska. This region is referred to as **tornado alley**.

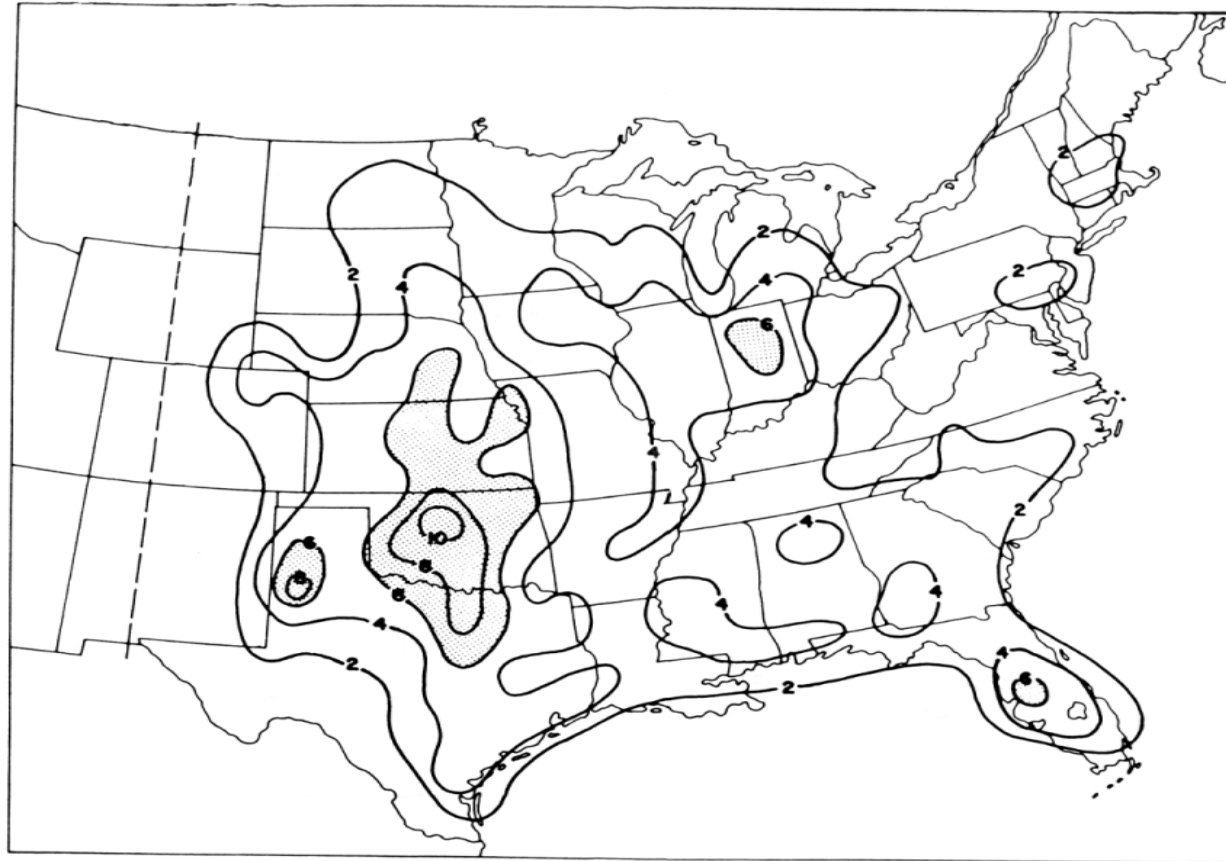


Figure 3.68 Frequency distribution of tornadoes (1950–1976) in the United States. Tornadoes per 2° latitude–longitude overlapping quadrilateral, normalized to 10,000 nm² area, per year (from Doswell, 1985; adapted from Kelly et al., 1978). (Courtesy of the American Meteorological Society)

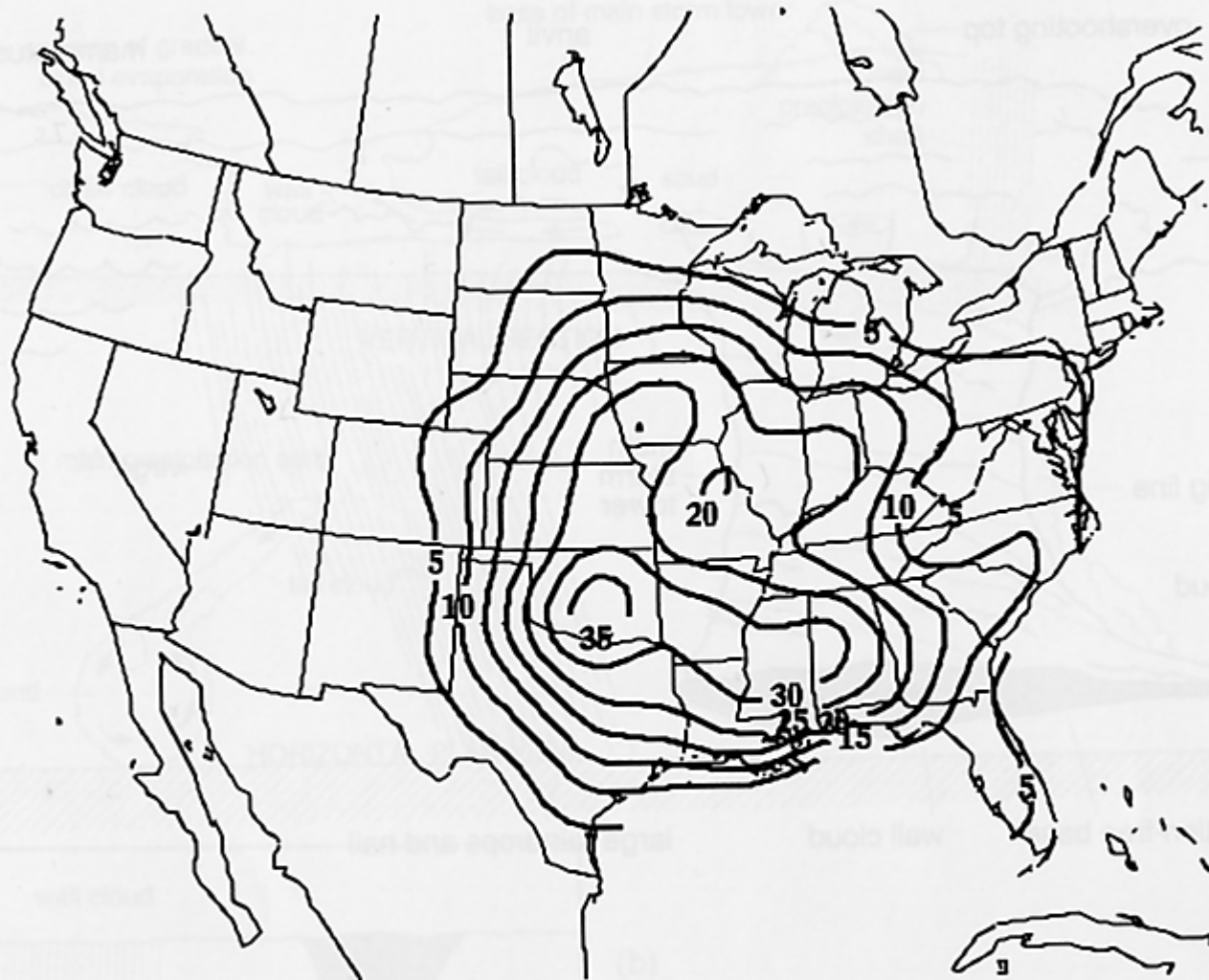


FIG. 5.5. Based on data from 1921 to 1995, the mean number of days per century of F2 intensity or greater tornado occurrence within 40km of a point in the United States (Concannon et al. 2000). Contour interval is 5 days, with minimum level equal to 5.

The **elevated terrain** to the west and southwest of the Great Plains and the Gulf of Mexico play important roles in producing soundings having high amounts of CAPE.

The sloping terrain is partially responsible for the **lee trough and low-level jet**, the latter which **advects the Gulf marine layer northward**, while warm dry air caps the moist layer.

The ubiquitous **dryline and fronts approaching from the north and northwest** are frequent locations of storm formation.

Most tornadoes occur during the **late afternoon and evening hours** in the late spring. This suggests that **solar heating plays an important role** in producing a potentially unstable environment for tornadic storm formation during the afternoon.

Major outbreaks occur primarily during the spring, when strong disturbances in the middle and upper troposphere promote regions of strong **lifting** and an environment of strong **vertical shear** and high values of **CAPE**.

Tornadic **activity begins along the Gulf States in late winter, and migrates northward**, so that summer activity is highest in the Northern Plains.

Environments for tornado outbreaks in the United States have been produced **as far east as the East Coast**.

Tornado outbreaks in late spring and early summer are often associated with short waves moving through northwesterly flow aloft, as a ridge is built up to the west and a trough is ensconced to the east.

In spring, outbreaks usually occur in southwesterly flow aloft, downstream from major troughs.

Relation of tornadoes to supercell storms

Although not all supercell storms produce tornadoes, most of the intense tornadoes are generated by them.

In a radar study of Oklahoma storms during 1971-1975, for example, Burgess (1976) found that 62% of the 37 storms that exhibited strong storm-scale rotation developed tornadoes while none occurred in storms which did not rotate.

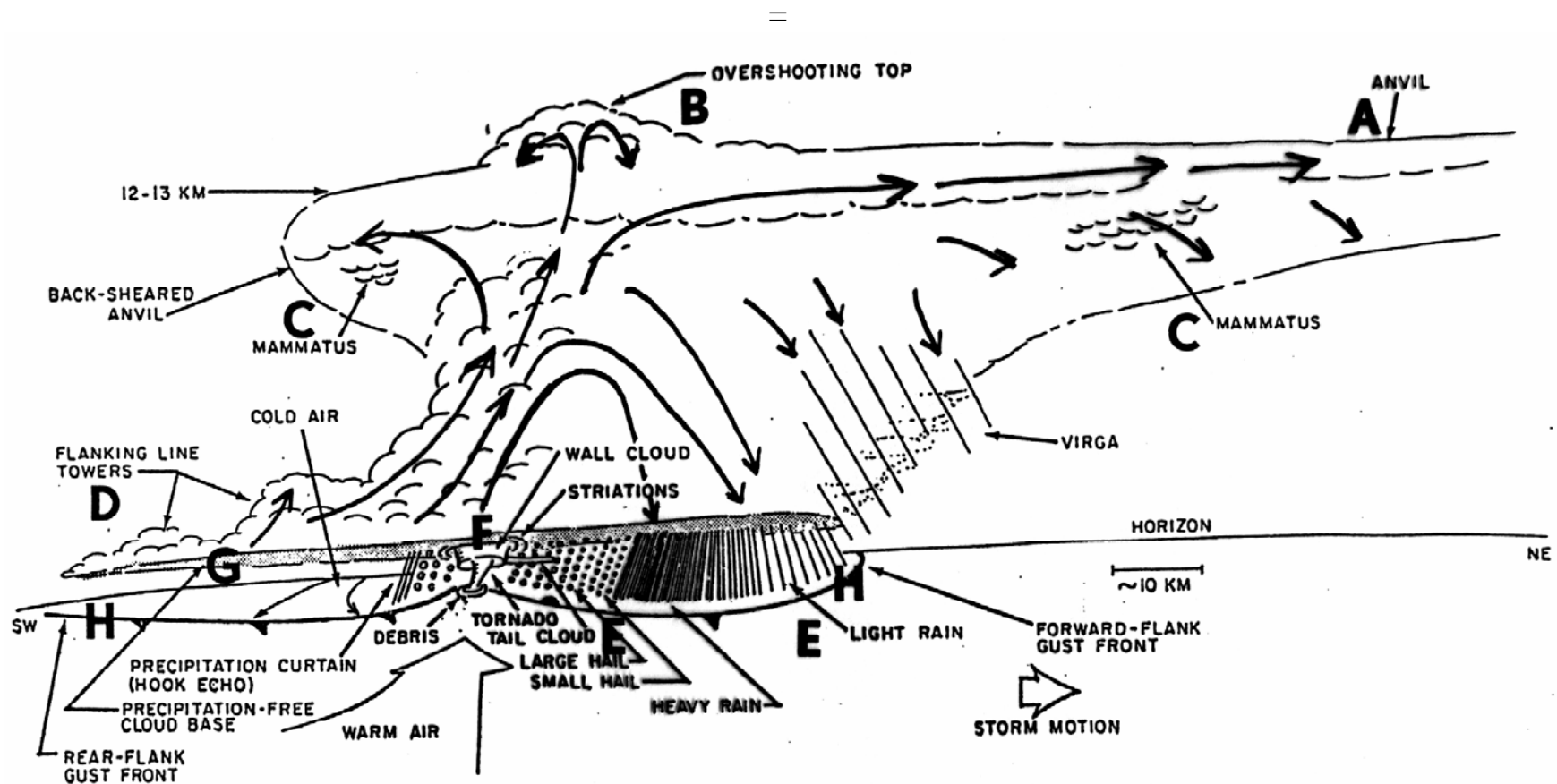




FIG. 5.1. Tornado at Osnabrock, North Dakota, on 24 July 1978 as seen looking NE. The eastward-moving tornado passed one-half mile to the north of the photographer. Note the cloud band spiralling inward and cyclonically around the tornado from the east. Copyright photo by Edi Ann Otto, permission granted for scientific use.

Transition of storms into their tornado phase

When a storm does move into its tornadic phase, significant alteration of the storm-scale structure occurs that disrupts the nearly steady configuration.

These changes include

- a rapid increase in low-level rotation,
- a decrease in updraft intensity,
- a small-scale downdraft forming behind the updraft, and
- a flow at low levels in which cold-outflow and warm-inflow air spiral around the center of circulation.

As the downdraft (labeled RFD) adjacent to the updraft intensifies, **downdraft outflow progresses cyclonically around the center of rotation** (marked by the northern encircled T), which is the likely location for tornado formation.

As this outflow pushes into the path of the oncoming moist inflow, a new updraft and center of rotation may also develop tornadic intensity (denoted by the southern encircled T in Figure 11). At the same time, the spreading downdraft outflow cuts off the supply of warm moist air to the original circulation center (called occlusion), causing the original updraft to weaken.

Although a supercell storm may persist in a nearly steady configuration for up to several hours, the **transition to the tornadic phase illustrated in the figure may take place in less than about 10 min.**

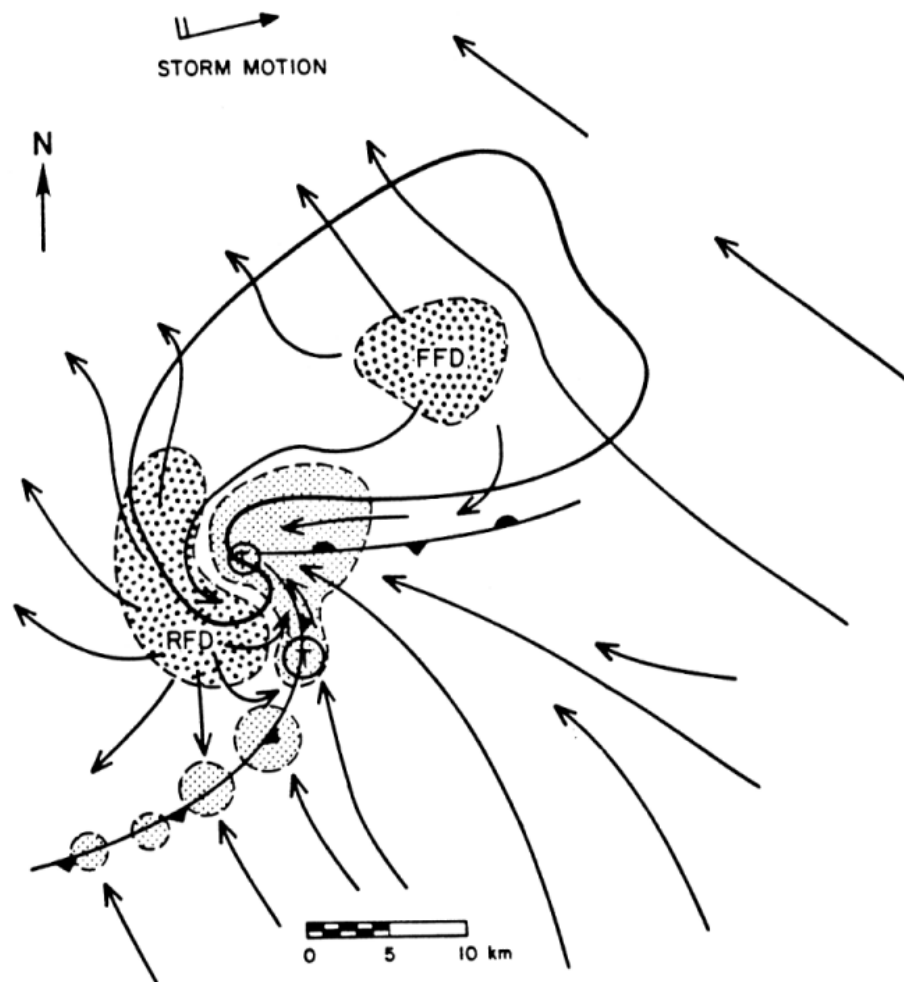


Figure 11 Schematic plan view of a tornadic thunderstorm near the surface. The thick line encompasses the radar echo. The barbed line denotes the boundary between the warm inflow and cold outflow and illustrates the occluding gust front. Low-level position of the updraft is finely stippled, while the forward-flank (FFD) and rear-flank (RFD) downdrafts are coarsely stippled. Storm-relative surface flow is shown along with the likely location of tornadoes (encircled T's). (From Lemon & Doswell 1979, as adapted by Davies-Jones 1985.)

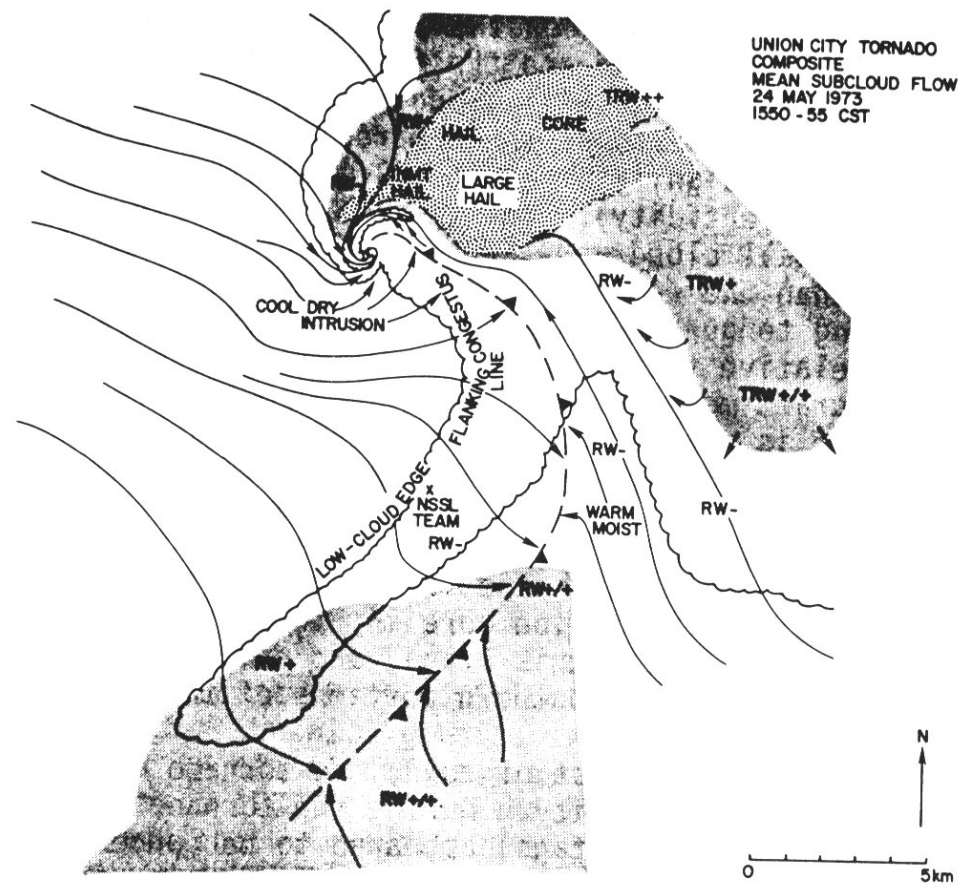


Figure 18.3. Schematic plan view of a tornadic thunderstorm from the surface observations of Golden and Purcell (1978a), showing the location of the surface gust front, major low-level cloud boundaries, and precipitation types and intensities. Note the flanking-line cloud base relative to surface gust front, stream flow, and tornado.

Figure 12 illustrates schematically the flow structure within a numerically simulated supercell evolving in a unidirectional wind shear at a time when the low-level rotation is intensifying rapidly, but prior to the formation of the occluded gust front shown in Figure 11.

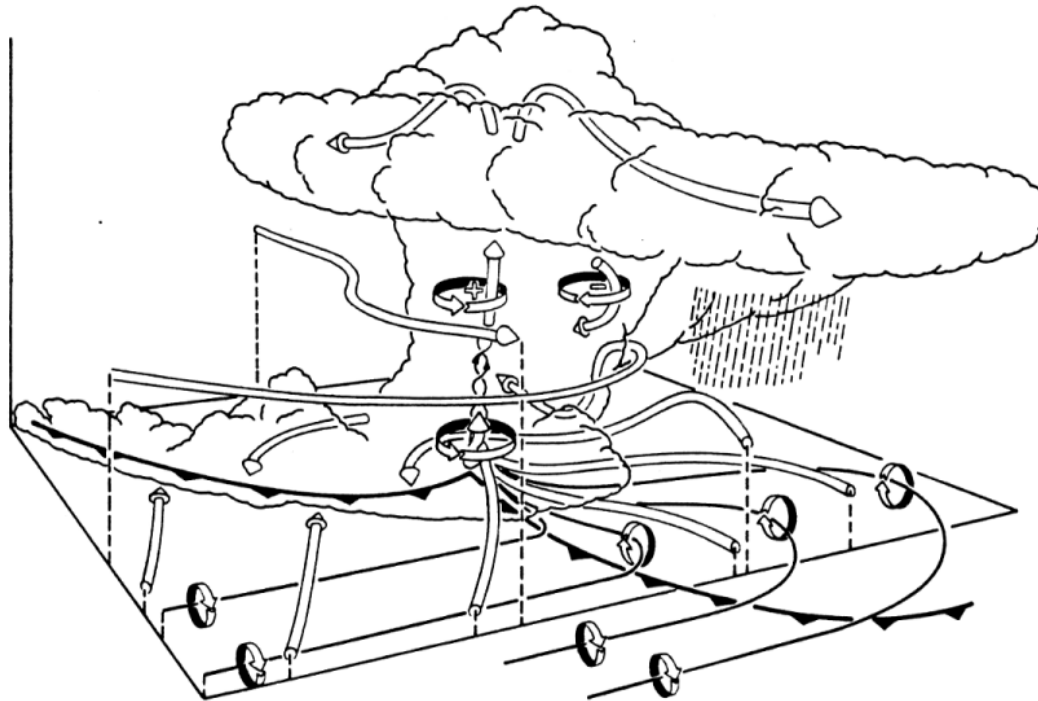


Figure 12 Three-dimensional schematic view of a numerically simulated supercell thunderstorm at a stage when the low-level rotation is intensifying. The storm is evolving in westerly environmental wind shear and is viewed from the southeast. The cylindrical arrows depict the flow in and around the storm. The thin lines show the low-level vortex lines, with the sense of rotation indicated by the circular-ribbon arrows. The heavy barbed line marks the boundary of the cold air beneath the storm.

Figure 12

Barnes (1978) and Lemon and Doswell (1979) have **suggested that this transition is initiated by the rear-flank downdraft** (see Figure 11), which forms at midlevels, descends to the surface, and then intensifies the low-level rotation by producing strong shear (Barnes) or temperature gradients (Lemon & Doswell) between this downdraft and the updraft.

The **numerical storm simulations** of Klemp & Rotunno (1983), Rotunno & Klemp (1985) **and observational studies** (Brandes 1984a,b) **indicate a reverse sequence of events**; the low-level rotation intensifies, followed by formation of the rear flank downdraft.

Klemp & Rotunno (1983) proposed that the rear-flank **downdraft** that promotes this occlusion is, in fact, **dynamically induced** as strong low-level rotation lowers the pressure locally and draws down air from above.

By decomposing the pressure field at a time when the simulated rear-flank downdraft was intensifying, they demonstrated that the fluid shear term was responsible for virtually the entire adverse vertical pressure gradient near the ground.

Since the intensifying rotation is largest near the ground, a downward- directed pressure gradient results, which in turn promotes the downdraft.

The retarding influence of rotation has been called the **vortex valve effect**; Lemon et al. (1975) suggested that as the rotation increases within the storm, **this effect may be responsible for its collapse**.

In the numerical simulation just described, the maximum low-level vertical vorticity remained less than one half the maximum at mid-levels for over an hour, and then in less than 10 min it intensified to double the midlevel maximum.

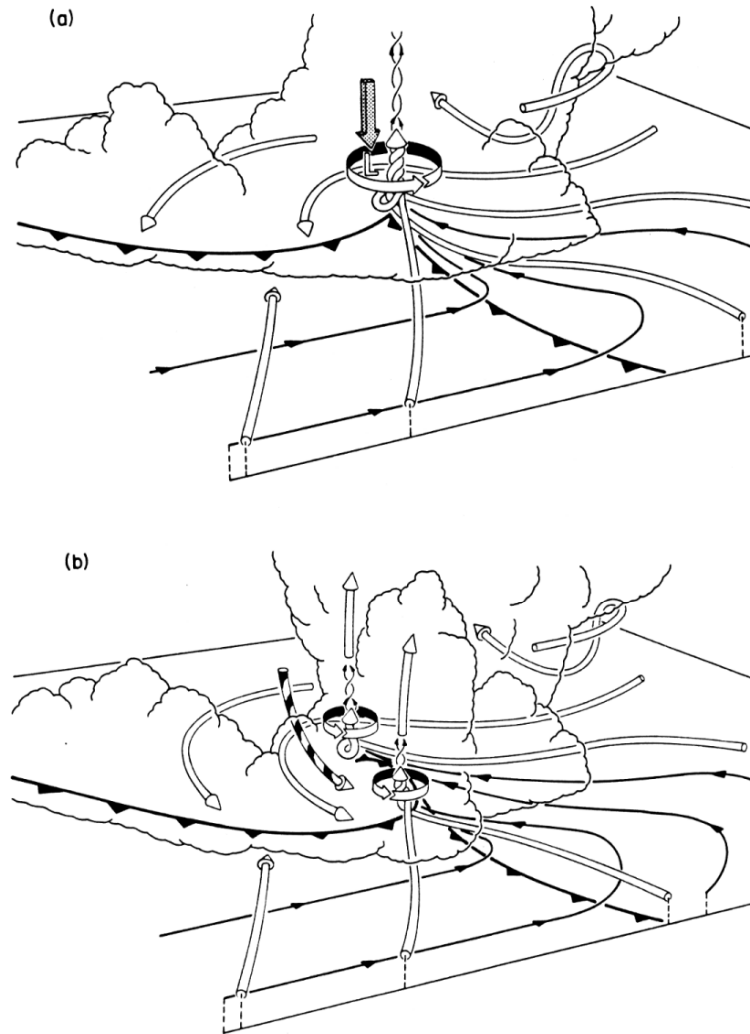


Figure 13 Expanded three-dimensional perspective, viewed from the southeast, of the low-level flow (a) at the time depicted in Figure 12, and (b) about 10 min later after the rear-flank downdraft has intensified. Features are drawn as described in Figure 12 except that the vector direction of vortex lines are indicated by arrows along the lines. The shaded arrow in (a) represents the rotationally induced vertical pressure gradient, and the striped arrow in (b) denotes the rear-flank downdraft.

Figure 13

Factors responsible for rapid amplification of the low-level rotation

Analyses of the storm simulations demonstrate clearly that the intensification is stimulated by the **baroclinic generation of strong horizontal vorticity along the low-level boundary** of the cold air pool forming beneath the storm (Klemp and Rotunno 1983, Rotunno and Klemp 1985).

$$\text{Remember } \frac{d\eta}{dt} = -\frac{\partial B}{\partial x}.$$

This **horizontal vorticity is then tilted into the vertical** and strongly stretched as the inflow enters the low-level updraft.

To see how this situation arises, notice that in the evolving storm, precipitation is swept around to the northern side of the cyclonically rotating storm. As it falls to the north and northeast of the updraft, evaporation cools the low-level air. With time, this cold pool of air advances progressively into the path of the low-level inflow to the storm. **A significant portion of the inflow can be approaching along the boundary of this cold air pool.** The horizontal temperature gradients thus baroclinically generate horizontal vorticity that is nearly parallel to the inflowing streamlines. This process generates horizontal vorticity that is several times the magnitude of the mean shear vorticity and that is more favorably oriented to be tilted into vertical cyclonic vorticity.

This same mechanism may also be responsible for tornadoes that form occasionally in non-supercellular storms. If a storm encounters a pre-existing cold front or an outflow boundary from another storm, strong horizontal vorticity (baroclinically generated along that boundary) may be swept into the storm and amplified.

The low-level vortex lines depicted in Figures 12 and 13 further illustrate the baroclinic vorticity generation mechanism.

Since the environmental shear is westerly, the horizontal vortex lines embedded in the shear are oriented south-north with the sense of rotation as indicated in the undisturbed region southeast of the storm in Figure 12. As these vortex lines penetrate the low-level pool of cold air, they turn rapidly toward the center of convergence and are swept into the updraft.

At this stage, the low-level updraft is located along the boundary between the warm and cold air, and it intertwines the warm and cold flow in the rising air.

As the rear-flank downdraft intensifies, this baroclinic generation supports the rapid intensification of rotation in the secondary updraft forming farther to the east along the gust front in Figure 13b.

Theory of rotation near ground

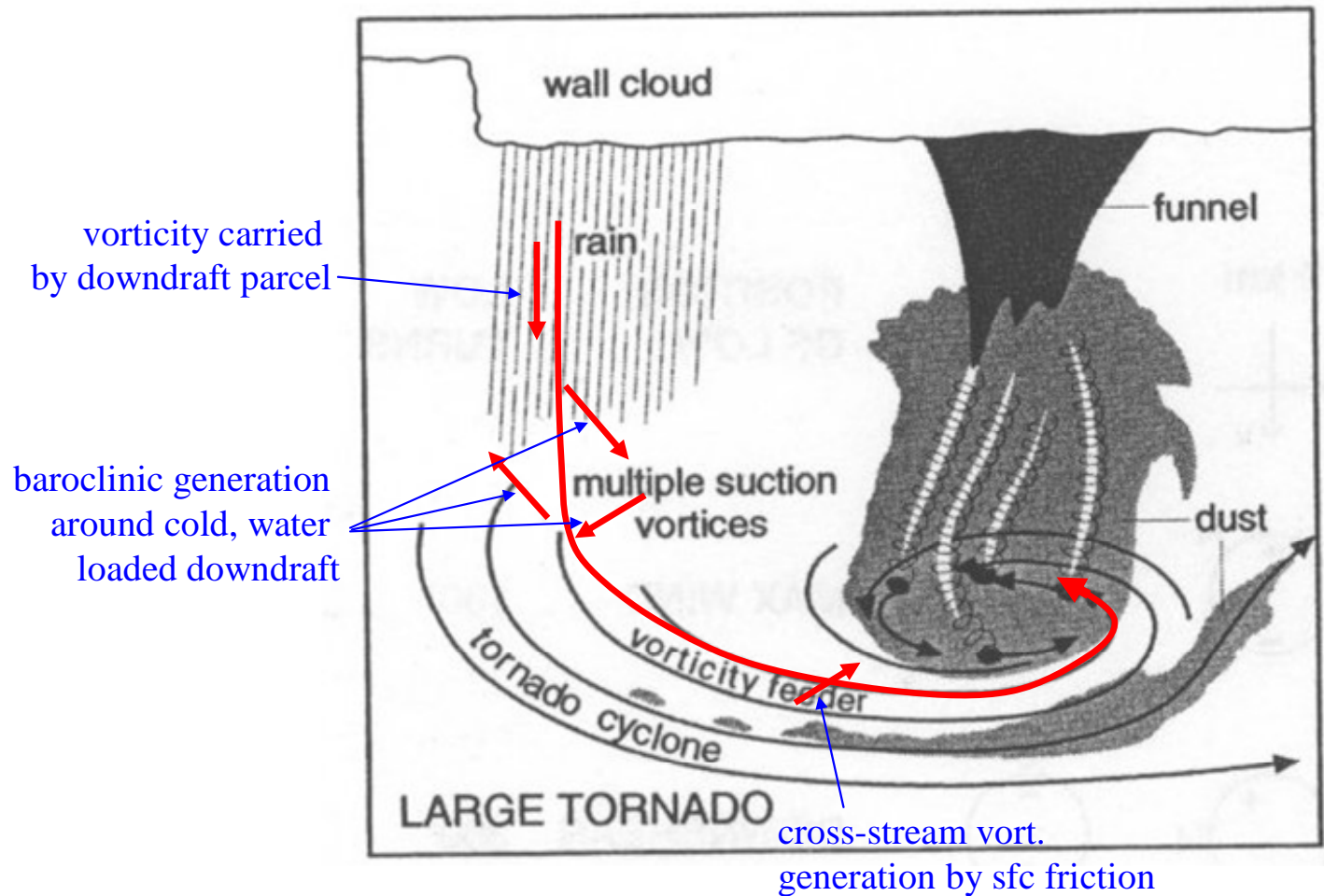
Davis-Jones points out that the tilting of horizontal vorticity into the vertical and the subsequent intensification of rotation due to stretching cannot explain the intensification of rotation near ground, because the tilted vortex tubes cannot intercept the ground and the vertical stretching is strongest above the ground (see Davis-Jones et al 2001).

Davis-Jones points to the importance of the presence of rainy downdraft. Three roles are identified of the downdraft:

1. A negatively buoyancy downdraft can impact the ground with considerable force and spring out rapidly.
2. A downdraft may transport high-momentum air down to the surface. In the presence of mid-level mesocyclone, this would transport the angular momentum associated with the mid-level mesocyclone downward and inward. This provides vertical vorticity to the near ground levels to be concentrated and intensified.
3. Cool downdraft enhances baroclinic boundaries therefore cause more generation of horizontal vorticity that can be tilted into vertical direction.

Pages 184-186 of Davis-Jones et al (2001) provides a very good synthesis of our current understanding of the typical processes involved with the intensification of low-level rotation within a supercell.

Downward Transport of Mid-level Mesocyclone Angular Momentum by Rainy Downdraft (Davis-Jones 2001, 2002)



After the original updraft is cut off from the warm inflow, it begins to dissipate while the new updraft continues to strengthen.

The strong rotation may then cause a new downdraft that spreads out at the surface, cuts off the inflow to this updraft, and promotes yet another convergence center farther east. (In Figure 13, visualize the eastern circulation center in 13b becoming the center shown in 13b, and then repeating the cycle.)

Such **cyclical redevelopments** or **tornadogenesis**, accompanied by successive tornadoes, are not uncommon in tornadic storms (Burgess et al. 1982). See next example.

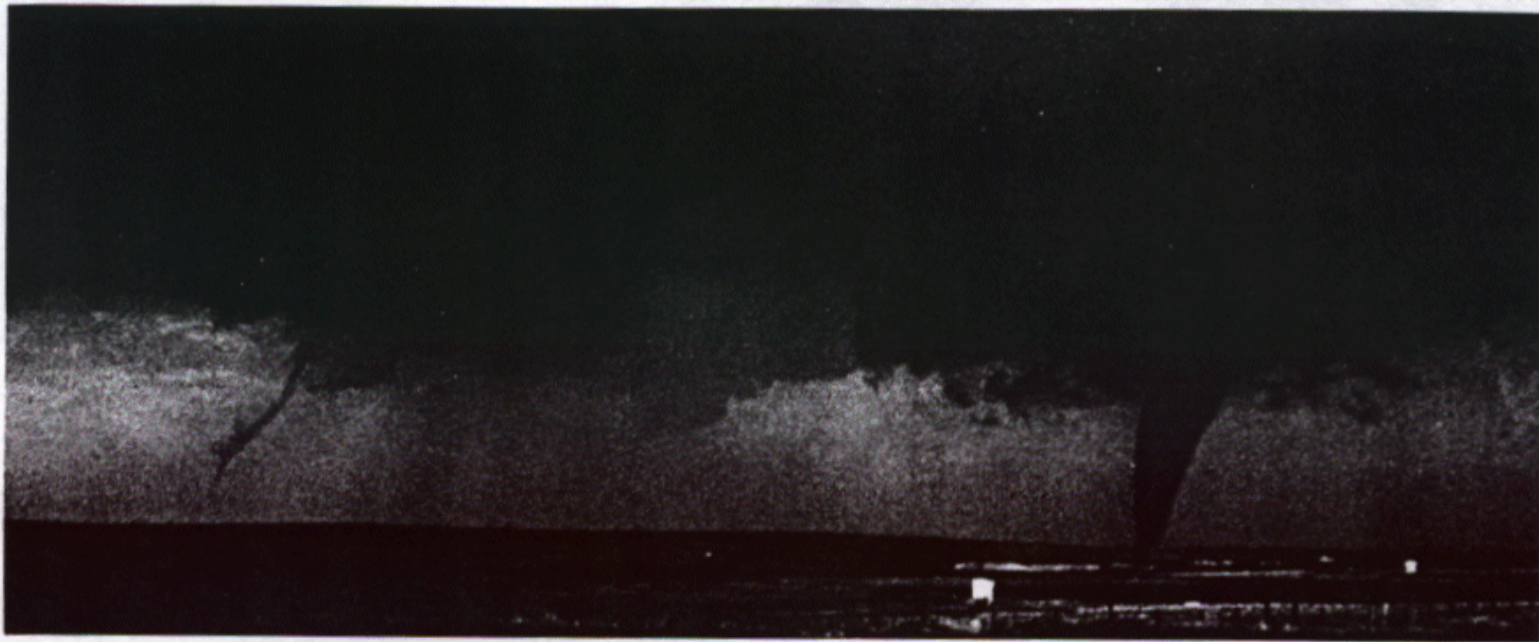


Figure 3.45 Example of cyclical tornado production. Rope stage of the second tornado in a series and its wall cloud (left), and mature stage of the next tornado (right) and its wall cloud. Looking to the northwest from a position 12.2 km south of Canadian, Texas, 2236 UTC, May 7, 1986 (photograph by H. Bluestein). (Courtesy of the American Meteorological Society)

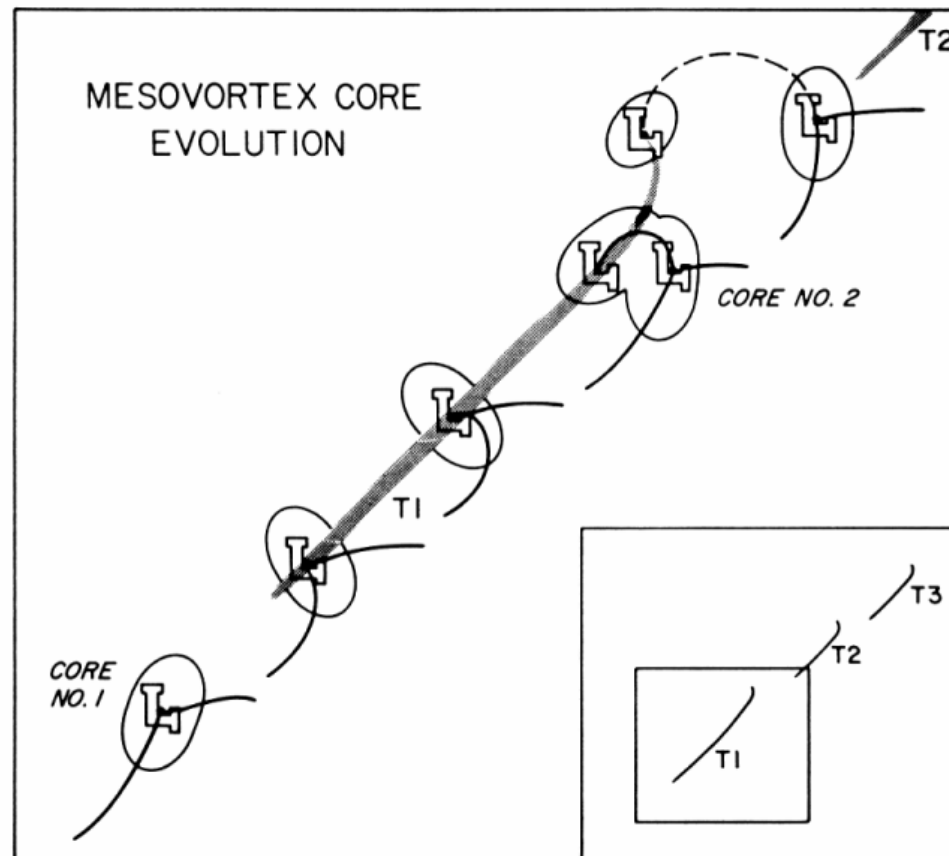


Figure 3.44 Conceptual model of mesocyclone core evolution. Low-level wind discontinuities (thick lines) and tornado tracks (shaded). Inset shows the tracks of the tornado family and the small square is the region expanded in the figure (from Burgess et al., 1982). (Courtesy of the American Meteorological Society)

In summary, the typical sequence of events of tornadogenesis (see good summary in Houze section 8.6):

- Storm-scale circulation and development creates the forward flank downdraft and gust front;
- The gust front creates intense horizontal vorticity that can be significant stronger than the environmental horizontal vorticity;
- this vorticity gets advected into the center of storm and updraft, and is tilted into vertical and stretched to intensify the vertical rotation;
- This process is believed to be responsible for the intensification of rotation at the low levels (but may not be at the ground), the lower end of the mesocyclone while the tilting of environmental vorticity is primarily responsible for the mid-level rotation/cyclone;
- The downdraft can also transport significant amount of vertical vorticity in the mid-level mesocyclone down to the surface. When this vorticity gets concentrated towards the low-level circulation center, it intensifies due to angular momentum conservation. This is believed to be at least one of the sources of ground level rotation in tornado.
- The increased low-level rotation creates pressure minimum at the low levels and downward PGF, which promotes the RFD and weakens the original downdraft;
- The advection of cold air from RFD by the rotating circulation at the low levels cuts off warm air supply to the original updraft and causes occlusion of FF and RF gust fronts and the demise of tornado at the occlusion the tip of gust front wedge, and
- New tornadoes often form again at the occlusion point.

- However, there are cases where tornado forms and remains inside the cold air, behind the gust front. Such tornadoes are less connected to/affected by the occlusion process.
- In some cases during Vortex field experiment, surface mobile network failed to find significant surface temperature gradient. The tornadogenesis problem remains unsolved, at least not fully.

Typical Tornado Life Cycles from Observational Perspective

Read Houze section 8.8.

The tornado frequently **first becomes visible as a dust whirl on the ground under the wall cloud.**

The **condensation funnel** soon appears aloft.

Late in life, it may bend at the ground while it stretches in length and narrows in width. This final decaying stage in the tornado's life history is called the **rope stage** owing to the ropelike appearance of the condensation funnel.

The gust front associated with the RFD may tilt the tornado so that it becomes nearly horizontal.

The tornado life cycle of 10-30 min is common, but not exclusive.

For example, tornadoes sometimes occur in the absence of any condensation funnel, always look like a rope, or never go through a rope stage. Some long damage paths are associated with tornadoes that last much longer than 30 min.

Most tornadoes in supercells are cyclonic. Anticyclonic tornadoes are rare. They have been documented, however, along the RFD gust front away from the mesocyclone.

Therefore the **life cycle** can be divided into:

- **Organizing** stage – visible funnel touching ground intermittently
- **mature** stage - tornado reaches its full strength and damage more severe
- **shrinking** – the funnel decreases to a thin column
- **decay** stage – funnel becomes fragments, contorted and still destructive

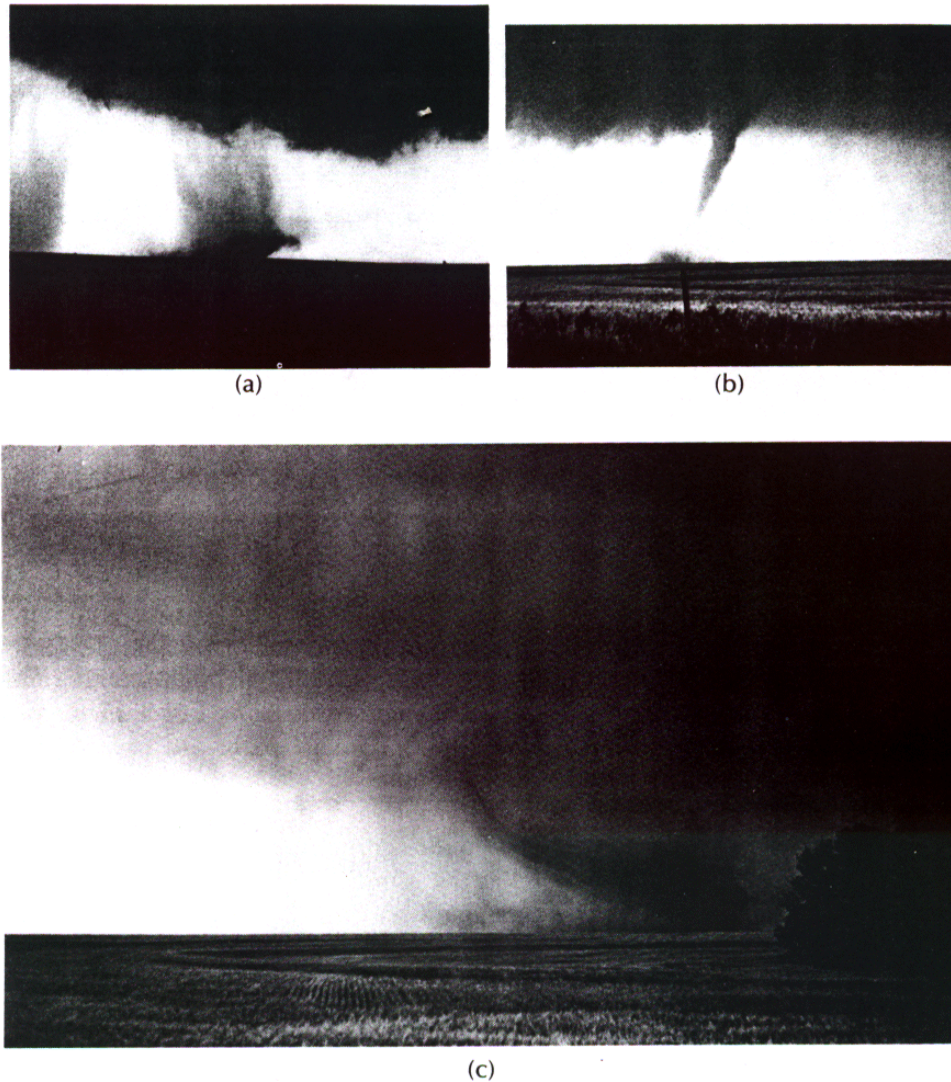


Figure 3.46 A series of photographs depicting the life cycle of a tornado: (a) a dust whirl appears near the ground, underneath the wall cloud; (b) a condensation funnel builds downward from cloud base; (c) the tornado becomes tilted and stretches out just before it dissipates (from Bluestein, 1983). This tornado occurred near Cordell, Oklahoma on May 22, 1981 (photographs copyright H. Bluestein). [(c) courtesy of the American Meteorological Society]

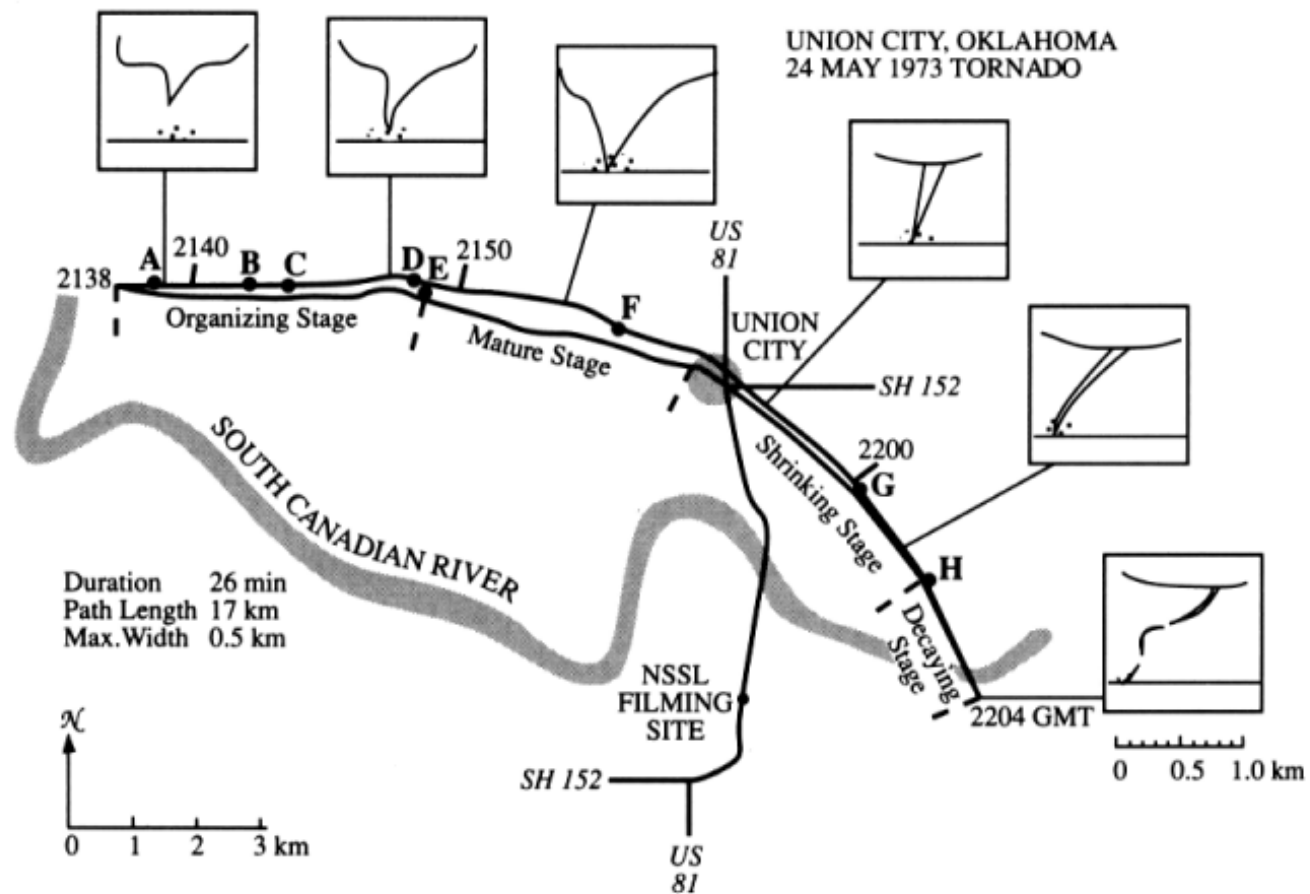


Figure. Structure of a tornado observed at several stages of its life cycle. Sketches show funnel cloud and associated debris.

Multi-vortex tornadoes

Although tornadoes frequently consist of a single vortex, they occasionally exist as two or more smaller "**suction vortices**" that rotate around the center of the wall cloud.

Laboratory model and numerical model evidence suggests that **multiple vortices are associated with high "swirl ratio,"** that is, relatively large azimuthal flow compared to radial flow.

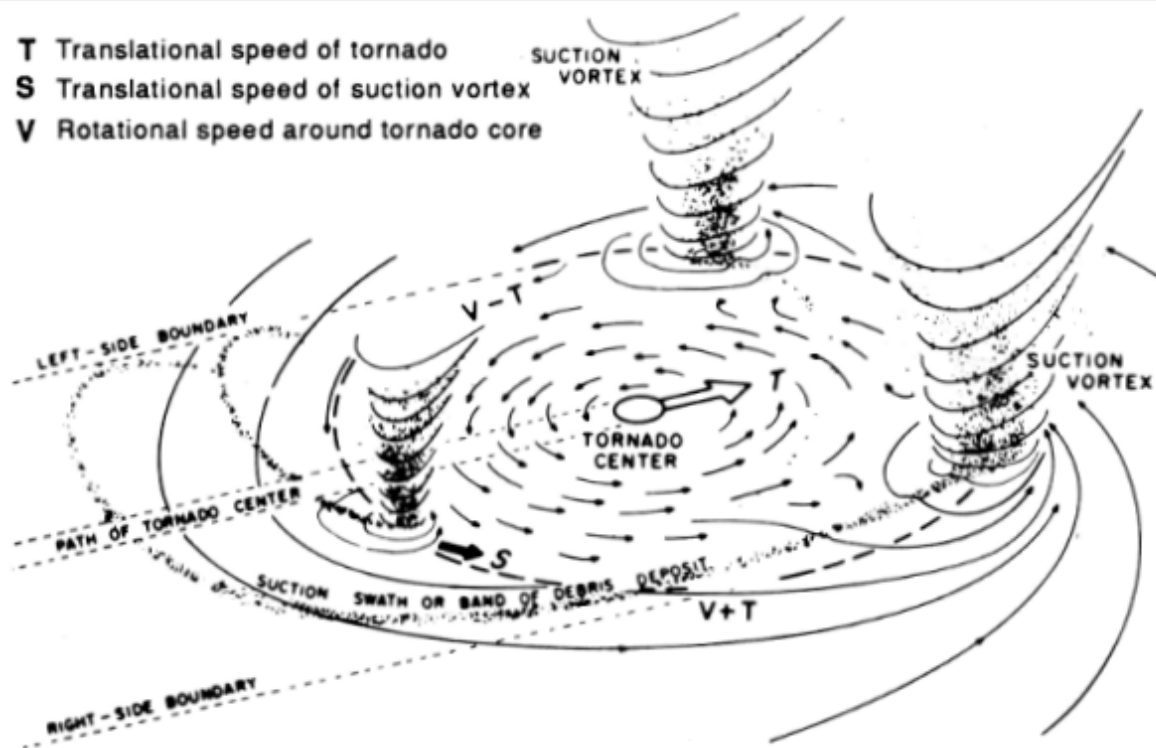
Suction vortices often have a lifetime of only one revolution around the wall cloud; new ones form and dissipate in the identical location relative to the mesocyclone.

Sometimes **multiple-vortex tornadoes evolve into single-vortex tornadoes, and vice versa.**

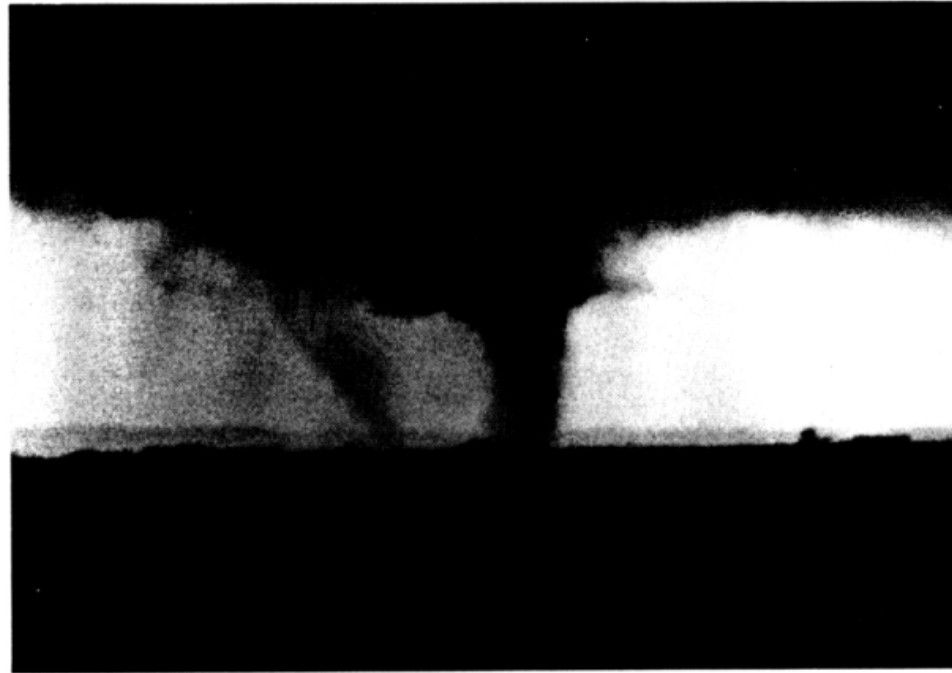
Some suction vortices extend all the way to cloud base; others are visible only near the ground underneath a broader rotating cloud base.

The multiple-vortex phenomenon was first postulated by T. Fujita on the basis of cycloidal damage swaths.

The "**suction vortices**" **create greater maximum wind speed** inside the tornadoes vortex because the effect due to the smaller and larger vortices are additive. They are observed to be particularly dangerous and damaging.



(a)



(b)

Figure 3.48 (a) Model of tornado with multiple vortices (from Fujita, 1981; proposed by Fujita in 1971). (b) Photograph of a multiple-vortex tornado; view to the south on May 2, 1979, in north-central Oklahoma near Orienta, (photograph taken by H. Bluestein for NSSL). Also see the multiple-vortex tornado in Vol. I, Fig. 1.6. [(a) courtesy of the American Meteorological Society]

Nonsupercell tornadoes and Gustnadoes

Read Houze section 8.7.

Tornadoes don't occur exclusively in supercells.

Non-supercell tornadoes can occur along a low-level convergence line underneath growing cumulus clouds.

Preexisting vortices along the line get stretched in the vertical by updraft of the growing cumulus cloud and intensify to form usually relative weak tornadoes.

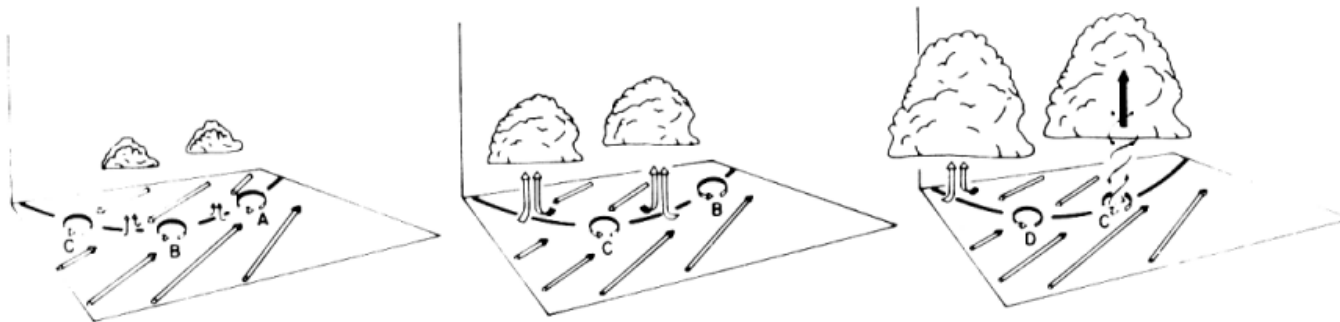


Figure 3.49 Schematic model of the life cycle of the nonsupercell tornado. The black line is the radar detectable convergence boundary. Low-level vortices are labeled with letters. At the left, clouds begin to form over the convergence zone, along which there are pre-existing vortices. In the middle, strong updrafts develop beneath the growing cumulus congestus clouds. At the right, a strong updraft becomes superimposed on one of the pre-existing vortices, and a tornado forms. The tornado dissipates when precipitation falls out of the updraft and the cell collapses (from Wakimoto and Wilson, 1989). (Courtesy of the American Meteorological Society)

Lee and Wilhelmson (1997) present a very nice numerical study on nonsupercell tornadogenesis. The following figure is taken from the paper:

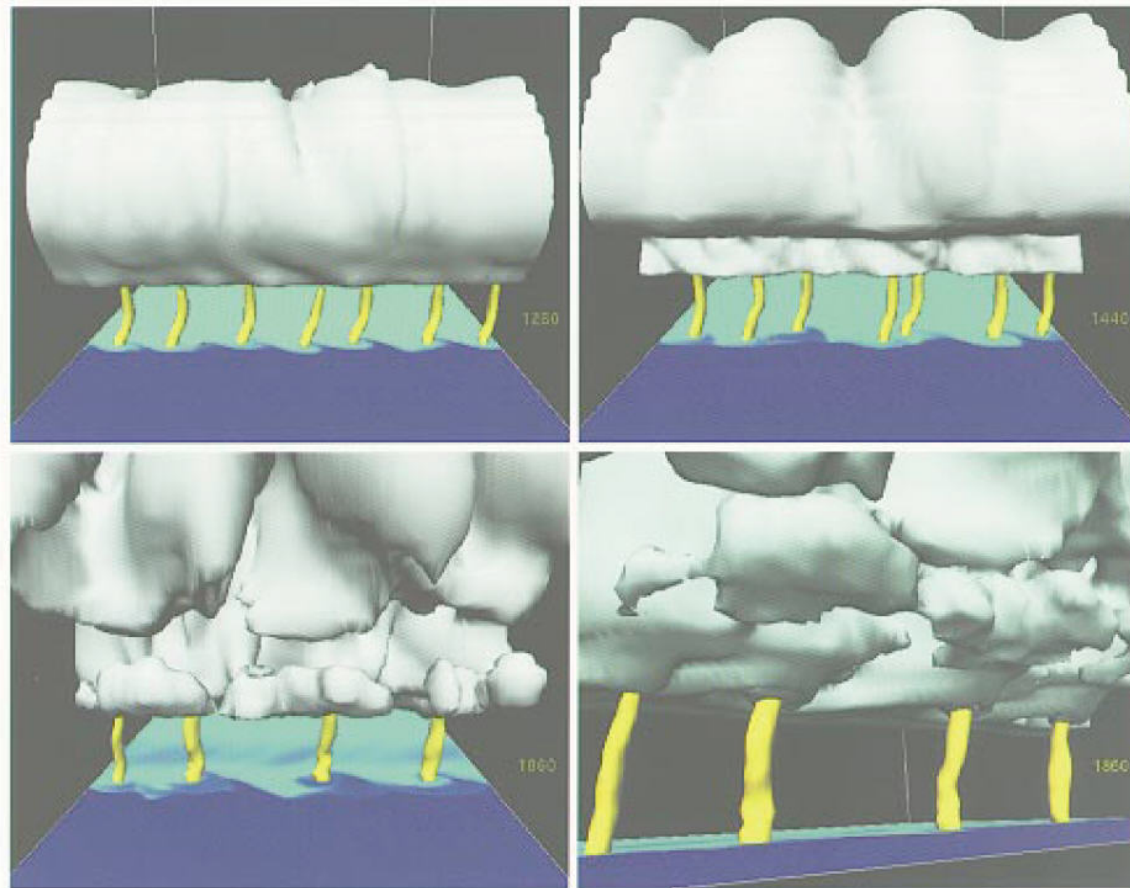


FIG. 4. Three-dimensional model renderings of the evolving ensemble of leading edge vortices, storm, and outflow boundary for 1260, 1440, and 1860 s. At the domain base the blue color spectrum delineates the outflow boundary (darker = colder). The yellow vertical vortex tubes are representative of vertical vorticity greater than 0.1 s^{-1} . The gray-scaled cloud isosurface represents cloud water greater than 0.2 g kg^{-1} . Viewing perspective in the first three panels is from an elevated position looking east, while the viewing position in the fourth panel is surface-based, looking southeast.

Reference: Lee, B. D. and R. B. Wilhelmson, 1997: The Numerical Simulation of Nonsupercell Tornadogenesis. Part II: Evolution of a Family of Tornadoes along a Weak Outflow Boundary. *J. Atmos. Sci.*, **54**, 2387-2415.

Low-level convergence helps concentrate the vertical vorticity.

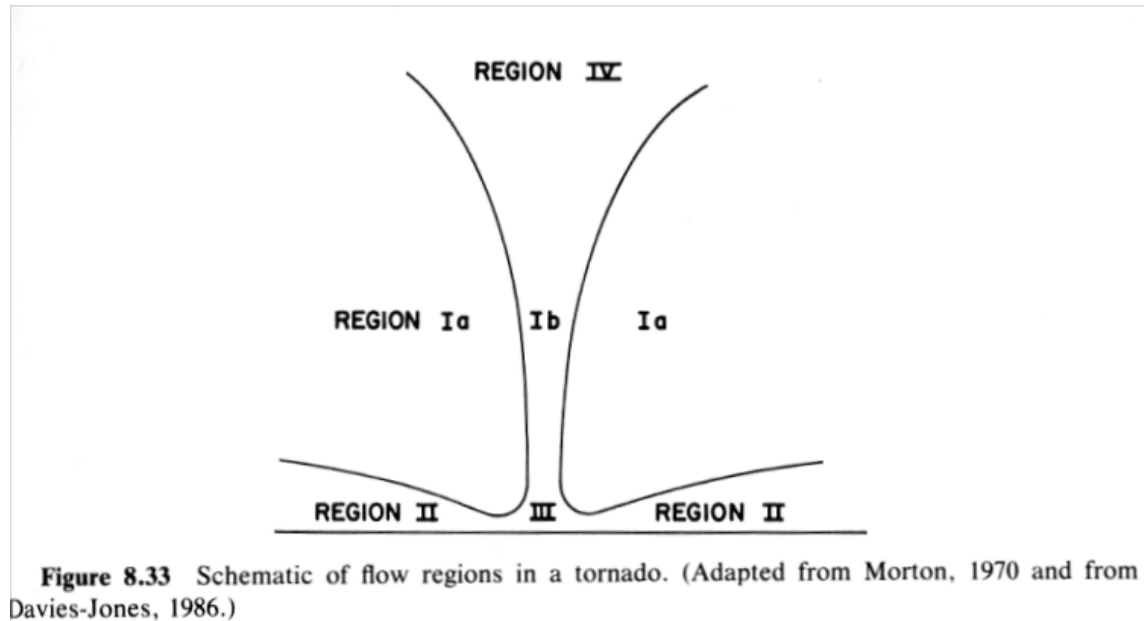
The vortex intensification can be further aided by rotation in the convective updraft.

Gustnadoes are short lived vortices occurring along preexisting gust fronts, coming into existence mainly due to horizontal shear instability.

Waterspouts: Vortices forming over water often along outflow boundaries of nearby shower. The processes involved are similar to the land-based non-supercell tornadoes forming along a gust front.

Flow structure inside tornadoes

The following schematic shows flow regions inside a tornado.



- Region I is in cyclonostrophic balance
- Ia is called the outer flow region – region of converging flow where angular momentum is conserved
- Ib is the core – in a state of solid body rotation – the angular velocity is constant and the core is stable against radial displacement
- The boundary between Ia and Ib is where max tangential velocity lies
- Flow along the core axis can be either up or down and there is little mixing with outside air

- II is region of turbulent boundary layer where cyclostrophy is upset by friction
- Strong radial inflow exists in II towards III because of net inward force (centrifugal force is weaker due to frictional reduction in wind speed)
- III is called the corner region where inflow turns into core region Ib.
- Region IV is the region of buoyant updraft

Wind Speed inside tornadoes

Horizontal wind speeds in tornadoes can be as high as **100-150 m/s**.

There is some theoretical evidence that **even stronger upward vertical velocities** can occur near center of a tornado, near the ground.

The **maximum possible tornadic wind speed** is a function not only of the **hydrostatic-pressure deficit** owing to latent-heat release in the updraft, which is a function of the CAPE, but also to the **dynamic-pressure deficit**, which is a function of the character of the wind field itself, especially in the surface boundary layer.

The Fujita Scale of Tornado Intensity

F-Scale Number	Intensity Phrase	Wind Speed	Type of Damage Done
F0	Gale tornado	40-72 mph (18-32m/s)	Some damage to chimneys; breaks branches off trees; pushes over shallow-rooted trees; damages sign boards.
F1	Moderate tornado	73-112 mph (33-50m/s)	The lower limit is the beginning of hurricane wind speed; peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos pushed off the roads; attached garages may be destroyed.
F2	Significant tornado	113-157 mph (51-71m/s)	Considerable damage. Roofs torn off frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light object missiles generated.
F3	Severe tornado	158-206 mph (72-93m/s)	Roof and some walls torn off well constructed houses; trains overturned; most trees in forest uprooted
F4	Devastating tornado	207-260 mph (94-117m/s)	Well-constructed houses leveled; structures with weak foundations blown off some distance; cars thrown and large missiles generated.
F5	Incredible tornado	261-318 mph (118-143m/s)	Strong frame houses lifted off foundations and carried considerable distances to disintegrate; automobile sized missiles fly through the air in excess of 100 meters; trees debarked; steel reinforced concrete structures badly damaged.
F6	Inconceivable tornado	319-379 mph (144-170m/s)	These winds are very unlikely. The small area of damage they might produce would probably not be recognizable along with the mess produced by F4 and F5 wind that would surround the F6 winds. Missiles, such as cars and refrigerators would do serious secondary damage that could not be directly identified as F6 damage. If this level is ever achieved, evidence for it might only be found in some manner of ground swirl pattern, for it may never be identifiable through engineering studies

