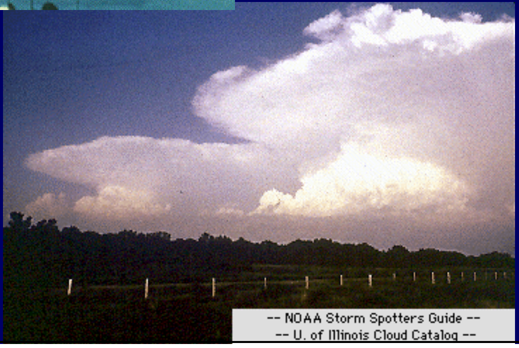
Chapter 3
Convective Dynamics
Part VI. Supercell Storms

Photographs © Todd Lindley

(This part contains materials taken from UCAR MCS training module)



-- NOAA Storm Spotters Guide --
-- U. of Illinois Cloud Catalog --

Introduction

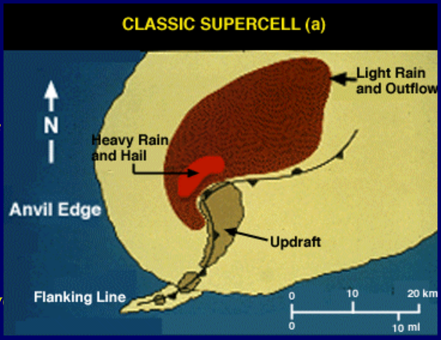
- **A supercel storm is defined as a thunderstorm with a deep rotating updraft.**
- **Supercell thunderstorms are perhaps the most violent of all thunderstorm types, and are capable of producing damaging winds, large hail, and weak-to-violent tornadoes.**
- **They are most common during the spring across the central United States when moderate-to-strong atmospheric wind fields, vertical wind shear and instability are present.**
- **The degree and vertical distribution of moisture, instability, lift, and especially wind shear have a profound influence on convective storm type.**
- **Once thunderstorms form, small/convective-scale interactions also influence storm type and evolution. There are variations of supercells, including "classic," "miniature," "high precipitation (HP)," and "low precipitation (LP)" storms.**
- **In general, however, the supercell class of storms is defined by a persistent rotating updraft (i.e., mesocyclone) which promotes storm organization, maintenance, and severity.**

Supercell Characteristics

- The supercell storm is an unusually long-lasting convective event that tends to be self-perpetuating.
- It is characterized by
  - A single (or dominant) updraft that can be quasi-steady in time
  - A separate dowdraft
  - Propagate to the right of mean tropospheric wind
  - Well-defined updraft rotation about a vertical axis within the updraft
  - A high tendency to produce tornadoes
  - A hook lie apprendage in the rain or reflectivity field

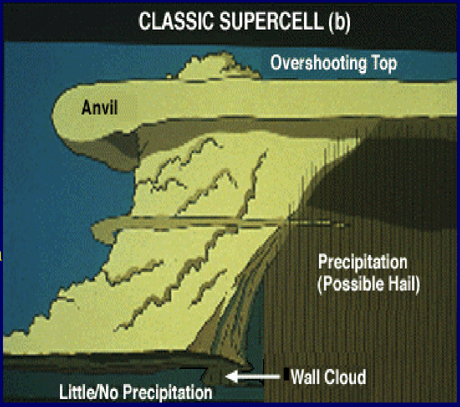
Structure of Classic Supercell Storm – Horizontal cross-section

- A horizontal, low-level cross-section of a "classic" supercell.
- The storm is characterized by a large precipitation area on radar, and a pendant or hook-shaped echo wrapping cyclonically around the updraft area. Note the position of the updraft and the gust front wave. The intense updraft suspends precipitation particles above it, with rain and hail eventually blown off of the updraft summit and downwind by the strong winds aloft.
- Updraft rotation results in the gust front wav pattern, with warm surface air supplying a continual feed of moisture to the storm.



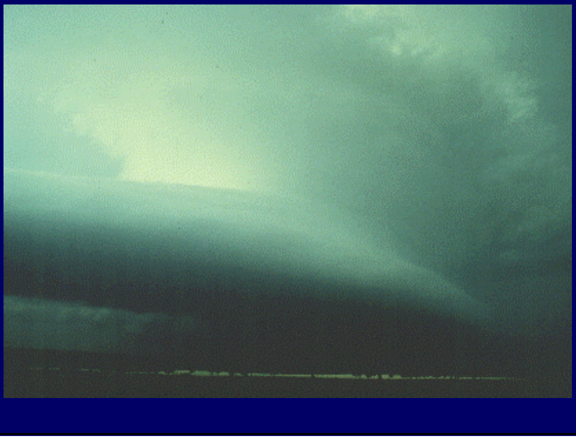
Structure of Classic Supercell Storm - Side view

- A westward view of the classic supercell reveals the wall cloud beneath the intense updraft core and an inflow tail cloud on the rainy downdraft side of the wall cloud. Wall clouds tend to develop beneath the north side of the supercell rain-free base, although other configurations occur.
- Observe the nearly vertical, "vaulted" appearance of the cloud boundary on the north side of the Cb and adjacent to the visible precipitation area. A sharp boundary between downdraft and rotating updraft results in this appearance.
- Note the anvil overhang on the upwind (southwest) side of the storm and the overshooting top, both visual clues as to the intensity of the updraft.



Rotating Updrafts - Visual Clue

- The circular mid-level cloud bands and the smooth, cylindrical Cb strongly hint of updraft rotation. Above the mid-level cloud band, an extremely hard Cb top is barely visible (upper right) towering into the anvil.
- Note the smooth, "laminar" flanking line on the extreme left. A strong, "capping" temperature inversion in the low levels probably accounted for the laminar appearance of the flank.



Wall Clouds - a lowering cloud base

- It is believed that wall clouds develop when some rain-cooled air is pulled upward, along with the more buoyant air.
- The rain-cooled air is very humid, and upon being lifted it quickly saturates to form the lowered cloud base.
- Thus, the wall cloud probably develop sometime after an intense storm begins to precipitate.

Basic structure

- The distinquishing feature of supercells is that the updraft and downdraft remain separated such that they feed on each other. Also the storm in highly three dimensional.

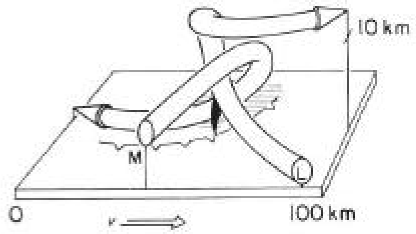


Figure 3.38 Browning's conceptual model for a right-moving supercell (SR). (a) Wind plot illustrating low- (L), middle- (M), and high- (H) level winds relative to the ground (solid arrows) and relative to the storm (dashed arrows). Motion of the SR storm is shown with an open arrow. The motion and relative wind vectors for a possible left-moving supercell (SL) are also shown. (b) Airflow trajectories at selected starting points at low (L) and middle levels (M) (from Klemp, 1987; adapted from Browning, 1964). (Courtesy of the American Meteorological Society)

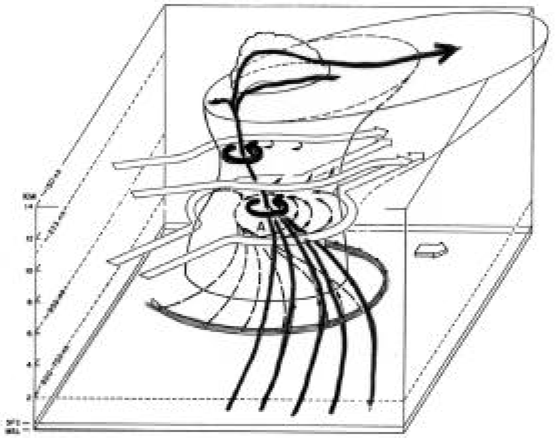


Figure 3a.--Three-dimensional interpretation of interacting external and internal airflow associated with individual persistent Great Plains cumulonimbus. The thin, solid inflowing and ascending streamlines represent the history of moist air originating in low levels (surface to ~750 mb). The heavy dashed streamlines trace the entry and descent of potentially cold and dry middle-level (700- to 400-mb) air feeding downrushing and diverging downdraft. The surface boundary between the inflow and downdraft is shown as a barbed band. The internal circular bands signify net updraft rotation. The shape and orientation of the dividing external bands represent typical vertical shear and character of ambient relative horizontal airflow at middle (~500 mb) and upper (~225 mb) levels. The approximate pressure-height relationship is shown on the left forward corner of the perspective box. The broad flat arrow on the right represents direction of travel (after Fankhauser, 1971).

Radar echo with moderate updraft

In a storm with moderate updraft, the radar echo is quasi-symmetric and erect.

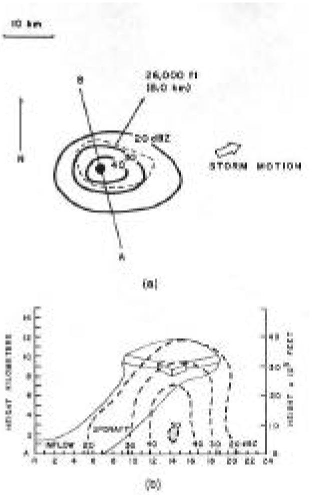


Figure 3.30 (a) Schematic diagram of a thunderstorm having a moderate updraft as seen on a radar PPI during a tilt sequence. Solid lines are low-level reflectivity contours. Dashed line outlines the echo in excess of 20 dBZ derived from the mid-level scan. Black dot is the location of the maximum echo top from the high-level scan. (b) Schematic diagram of vertical cross section (through line AB in (a)): range-height indicator (RHI) radar display of a thunderstorm with the low-level inflow, a moderate updraft, and outflow aloft (solid lines) superimposed. Radar reflectivity (dashed lines) with reflectivities greater than 50 dBZ stippled (from Lemon, 1977).

Radar echo with strong updraft

In the strong updraft of a supercell storm, howver, precipiatation does not have enough time to form until air has reached relatively high levels. On a radar PPI (plan position indicator) display there is therefore a 'weak-echo' region or "valt" at low and middle levels.

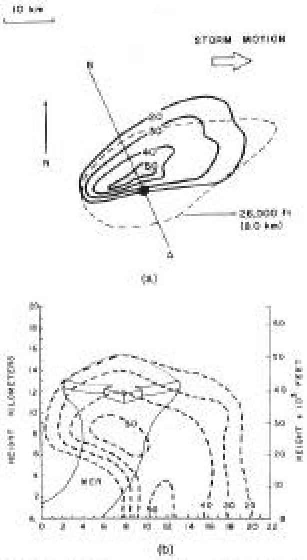


Figure 3.31 (a) As in Fig. 3.30(a), except that the updraft of the storm is strong. (b) As in Fig. 3.30(b), except that the updraft is strong. The WER is the weak-echo region. The cross section is along the line AB shown in (a) (from Lemon, 1977).

Radar echo with intense updraft

When the updraft is really intense, the valt can extend further to the higher level, forming a "bounded weak-each region (BWER)". Precipitation particles may flow around the updraft to produce a V-shape to the reflectivity pattern at the high levels.

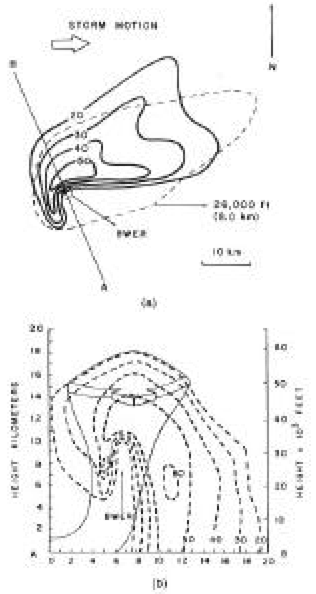


Figure 3.32 (a) As in Fig. 3.30(a), except that the updraft of the storm is intense. BWER is the location of the bounded weak-echo region. (b) As in Fig. 3.30(b), except that the updraft is intense. The cross section is along the line AB shown in (a) (from Lemon, 1977).

3D flow and Echo pattern in a supercell storm

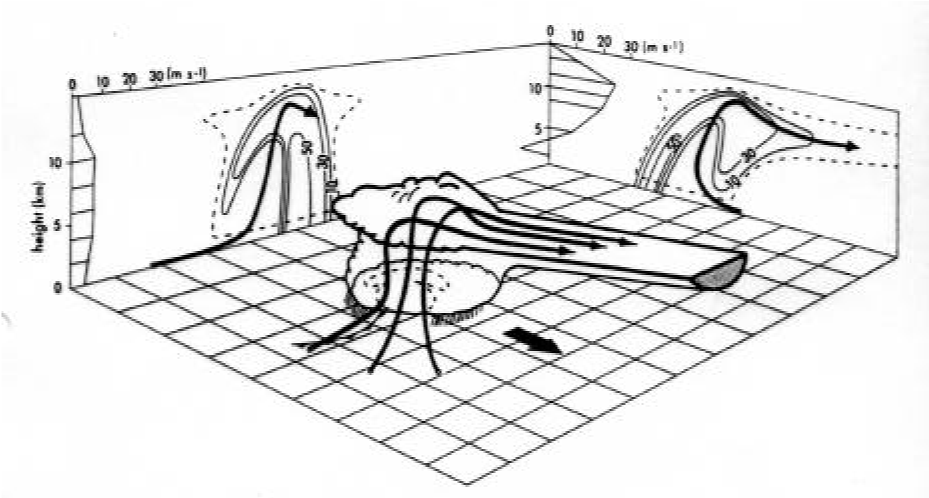
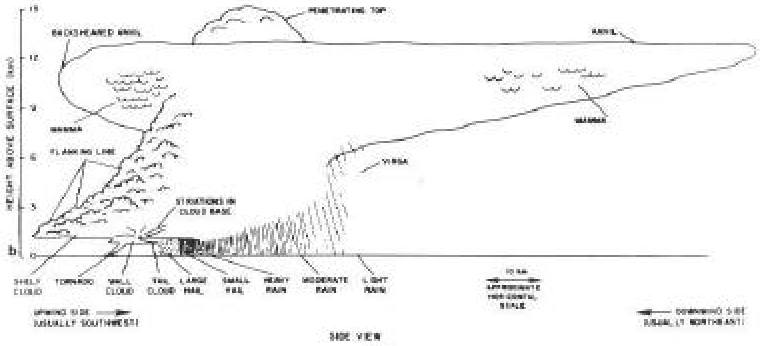
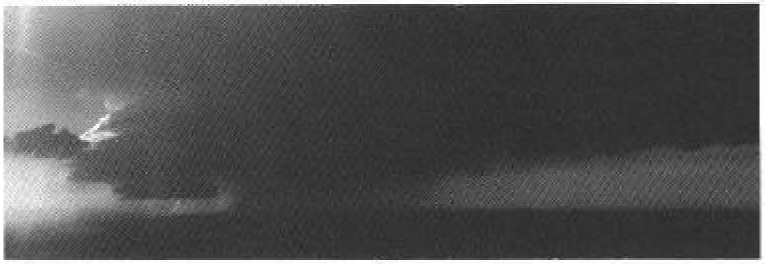


FIG. 133. Schematic three-dimensional view of a supercell storm depicting relative airflow and reflectivity. (After Chisholm and Renick, 1972.)

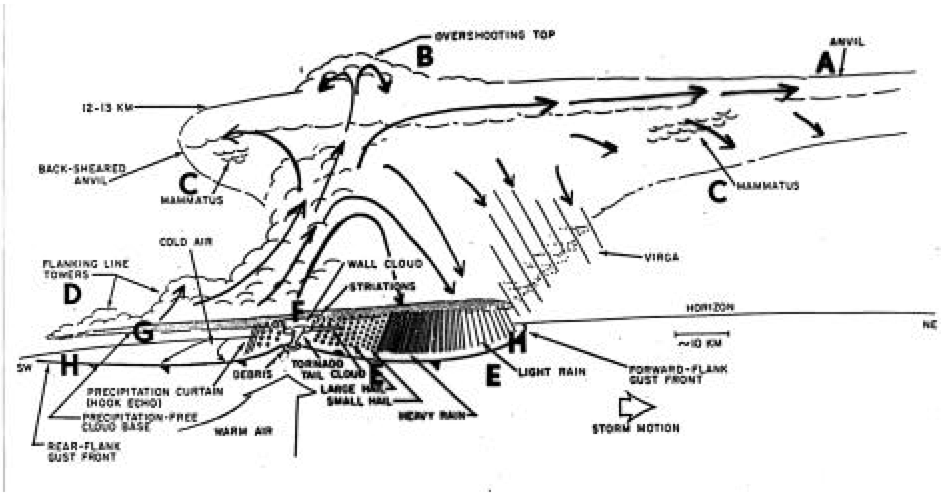


(a)



(b)

Tornadic Supercell Storm Conceptual Model



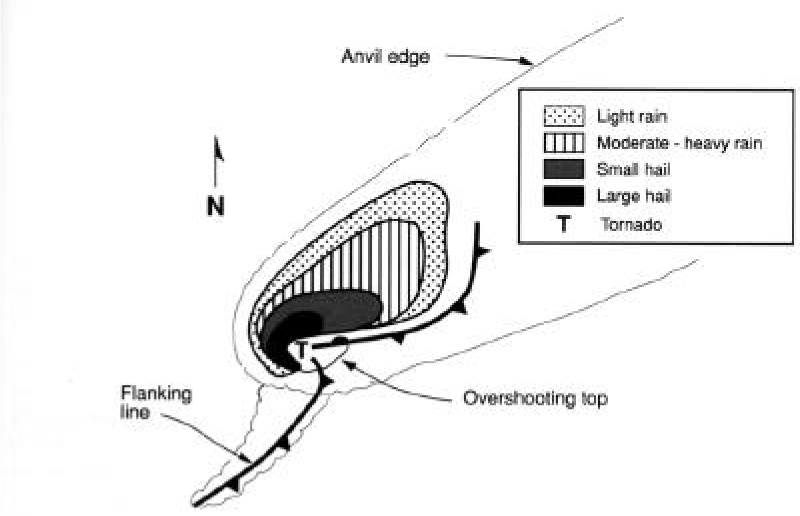


Figure 8.10 Idealized plan view of a supercell thunderstorm as it would appear in a satellite picture and in the low-level precipitation pattern that would be detected by a horizontally scanning radar. Cloud features seen by satellite include the flanking line, the edge of the anvil cloud, and the overshooting cloud top. Positions of the gust front (given by frontal symbols) and tornado are also shown. (Based on U.S. National Severe Storms Laboratory publications.)

Mesocyclone and Hook Echo

Precipitation can be advected away from and around the precipitation core by the mesocyclone to form a "hook" echo.

Mesocyclone is a small scale vortex with positive vorticity associated with a rotating updraft in a supercell storm.

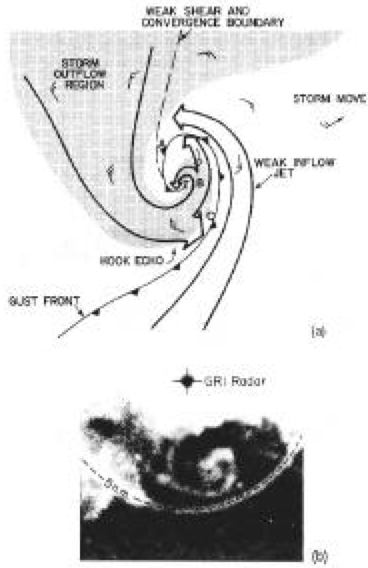


Figure 3.33 (a) Idealized illustration of the low-level mesocyclone characteristics during the tornadic phase of a supercell. Key features include the tornado (T), principal updraft and region of primary tornadogenesis (A), downdraft within the mesocyclone core (B), and possible genesis region of gust front tornadoes (C). A full wind barb is 10 m s^{-1}. Stippled area represents radar echo/precipitation (from Brandes, 1978). (b) Spiral-shaped hook echo in a tornadic supercell in Nebraska (from Fujita, 1981). [(a) and (b) courtesy of the American Meteorological Society]

Supercell Storm Dynamics

- Environmental Conditions and Storm Types
- Early Development of Rotation
- Storm Splitting
- Helicity
- Tornadic Phase of Supercell Storms

Effect of Environment on Storm Types

- CAPE and Vertical Environmental Wind Shear are the two most important factors in determining the storm types
- Numerical models have been very effective tools to understand such effects
- In general, single cell storms occur in environment with little vertical shear
- Multicell storms occur in environment with moderate vertical shear
- Supercell storms occur in environment with strong vertical shear

Numerical Experiments of Weisman and Klemp (1982)

Vertical wind profiles with unidirectional shear of different magnitudes

Time series of max w for 5 experiments

Supercell behavior is observed with u_s =25, 35 and 45m/s cases – quasi-steady updraft is found

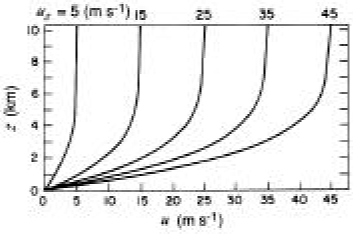


Figure 8.15 Profiles of wind speed u used in three-dimensional model simulations of multicell and supercell thunderstorms. Profiles becomes asymptotic to u_s. (From Weisman and Klemp, 1982. Reprinted with permission from the American Meteorological Society.)

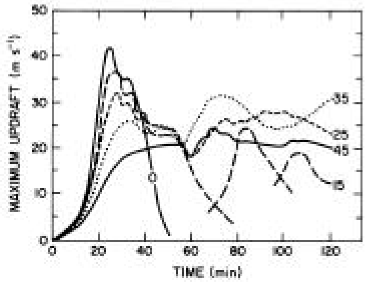


Figure 8.16 Results of three-dimensional model simulations of thunderstorms under different amounts of wind shear. The quantity plotted is the maximum vertical velocity as a function of time for different values of the wind-shear parameter u_s(m s^{-1}), which is the number plotted next to each curve. (From Weisman and Klemp, 1982. Reprinted with permission from the American Meteorological Society.)

Results from u = 15m/s and 35 m/s cases

- **Multicell case (left) with u =15 m/s and supercell case (right) with u = 35m/s.**
- **One the southern half of the computational domain is shown because the fields are symmetric about the central E-W axis**
- **The splitting of the initial storm into two (only the southern member is shown).**
- **The storm splitting is a result of rotational storm dynamics (more later). The member that moves to the right of vertical shear vector is called right mover, and the other the left mover.**
- **When the shear is not unidirectional, i.e., when shear changes direction with height, one of the member will be favored, again due to rotational storm dynamics**

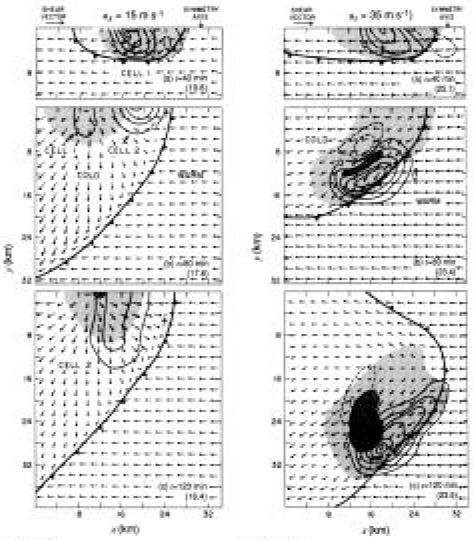


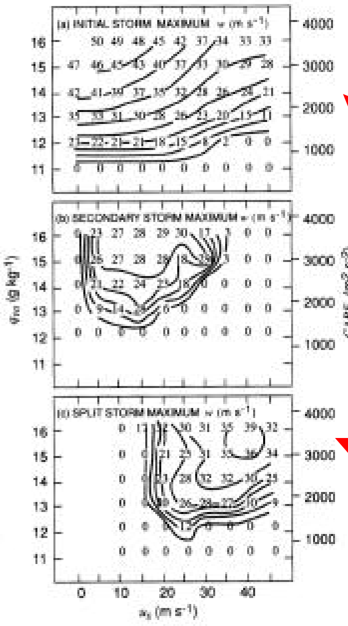
Figure 8.17 **Figure 8.18**

Figure 8.17 Results of a model simulation showing a multicell thunderstorm occurring under conditions of moderate environmental wind shear (u_s = 15 m s^{-1}). Fields are shown for three times during the simulation. Vectors represent storm-relative wind at an altitude of 178 m. The maximum vector magnitude (m s^{-1}) is shown in parentheses in the lower right corner of each plot. The surface rain field is indicated by stippling. The surface gust front is denoted by the frontal symbol and corresponds to the −0.5°C temperature perturbation contour. The midlevel (4.6 km) vertical velocity field is contoured every 5 m s^{-1} for positive values and 2 m s^{-1} for negative values. The zero contours outside the main region of storm activity have been deleted. Plus and minus signs represent the location of the low-level (178 m) vertical velocity maximum and minimum, respectively. Only the southern half of the model domain is shown. The fields in the northern half are mirror images. (From Weisman and Klemp, 1982. Reprinted with permission from the American Meteorological Society.)

Figure 8.18 Results of a model simulation showing a supercell thunderstorm occurring under conditions of strong environmental wind shear (u_s = 35 m s^{-1}). Format same as Fig. 8.17. (From Weisman and Klemp, 1982. Reprinted with permission from the American Meteorological Society.)

Maximum w as a function of CAPE and shear

- The vertical axis is the low-level qv – higher value corresponds to higher CAPE
- First cell intensity increases with CAPE and decreases with shear
- Second cell occurs only with moderate shear.
- Supercell storm occurs in stronger vertical shear.
- Strong updraft can survive in supercells because of the support of pressure perturbations associated with vertical rotation which initially comes from horizontal vorcitity in the environment via tilting.



Multicell case

Supercell case

Figure 8.19 Maximum vertical velocity of model thunderstorms as a function of CAPE and wind-shear parameter u_s. Panels (a) and (b) refer to multicell cases; panel (c) refers to supercell cases. (From Weisman and Klemp, 1982. Reprinted with permission from the American Meteorological Society.)

Generation of vertical vorticity via tilting

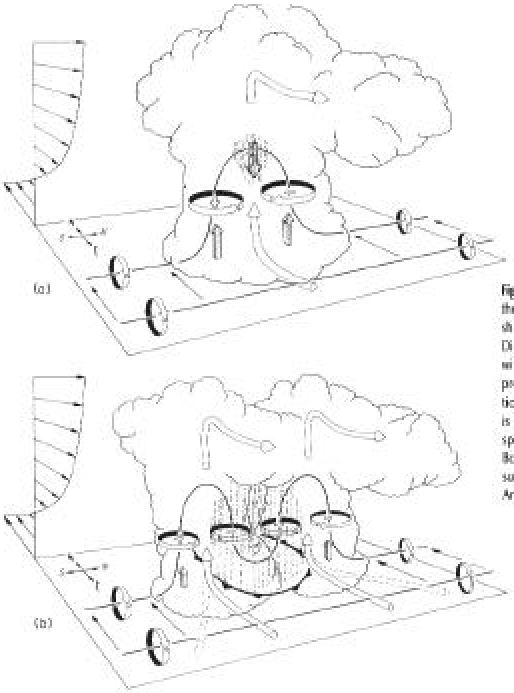


Figure 3.33 Schematic diagram depicting how a typical vortex line (streamline of three-dimensional vorticity vector) contained within (westerly) environmental shear is deformed as it interacts with a convective cell (viewed from the southeast). Direction of cloud-relative airflow (cylindrical arrows); vortex lines (solid lines), with the sense of rotation indicated by circular arrows; the forcing influences that promote new updraft and downdraft growth (shaded arrows); regions of precipitation (vertical dashed lines). (a) Initial stage: Vortex line loops into the vertical as it is swept into the updraft. (b) Splitting stage: Downdraft forming between the splitting updraft cells tilts vortex line downward, producing two vortex pairs. Boundary of the cold air spreading out beneath the storm (cold-front symbol at the surface) (from Klemp, 1987; adapted from Rotunno, 1981). (Courtesy of the American Meteorological Society)