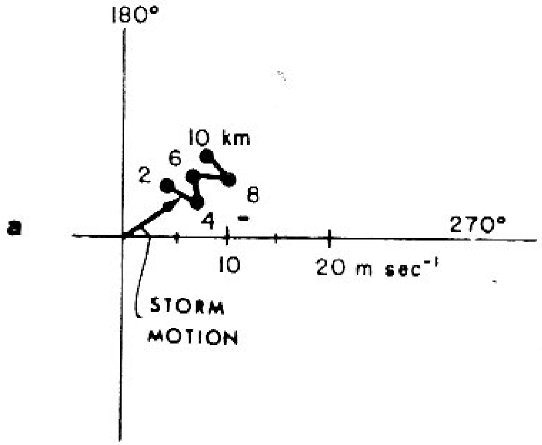
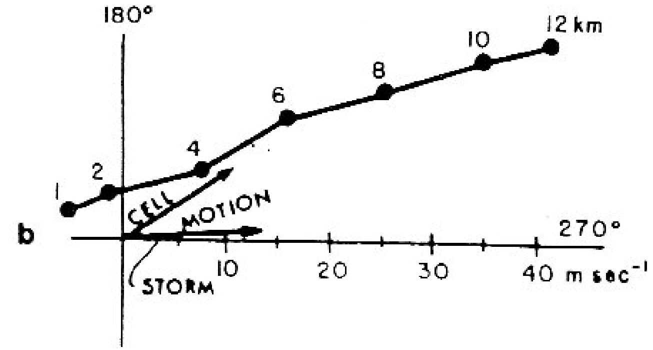
Typical Hodographs Associated with Various Storm Types

"Single Cell"



Multicell



Supercell

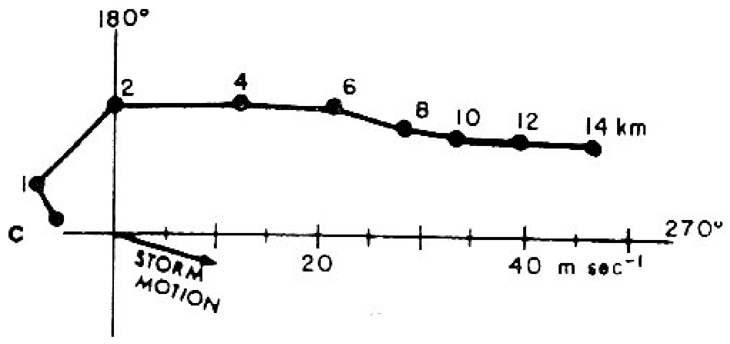


Figure 15.13. Typical wind hodographs for (a) single cell, (b) multicell, and (c) supercell storms observed during the Alberta Hail Studies project. (From Chisholm and Renick, 1972.)

Weisman and Klemp (1986)

Role of the Gust Front/Cold Pool in Multicell Convection

- from numerical simulations

If the amount of shear is just right to balance the cold pool, then gust front/cold pool circulation may allow air parcels to reach LFC and form new convection → multicell propagation.

NO shear (i.e., not enough.)

Shear just right.

Too much Shear.

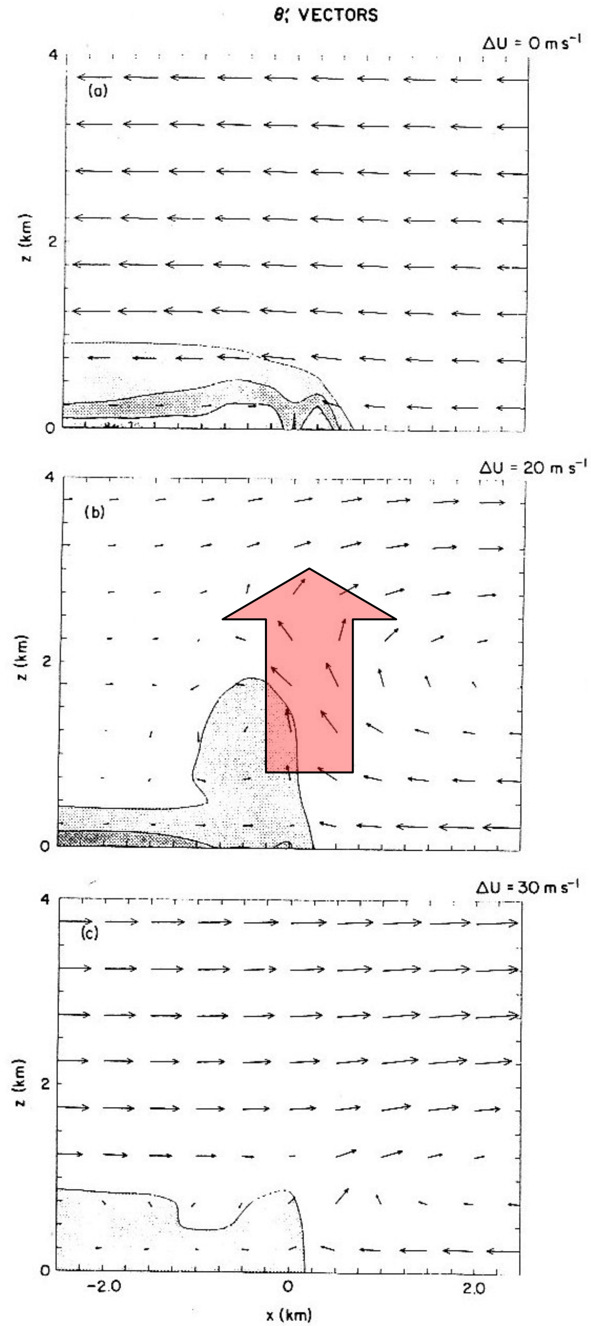


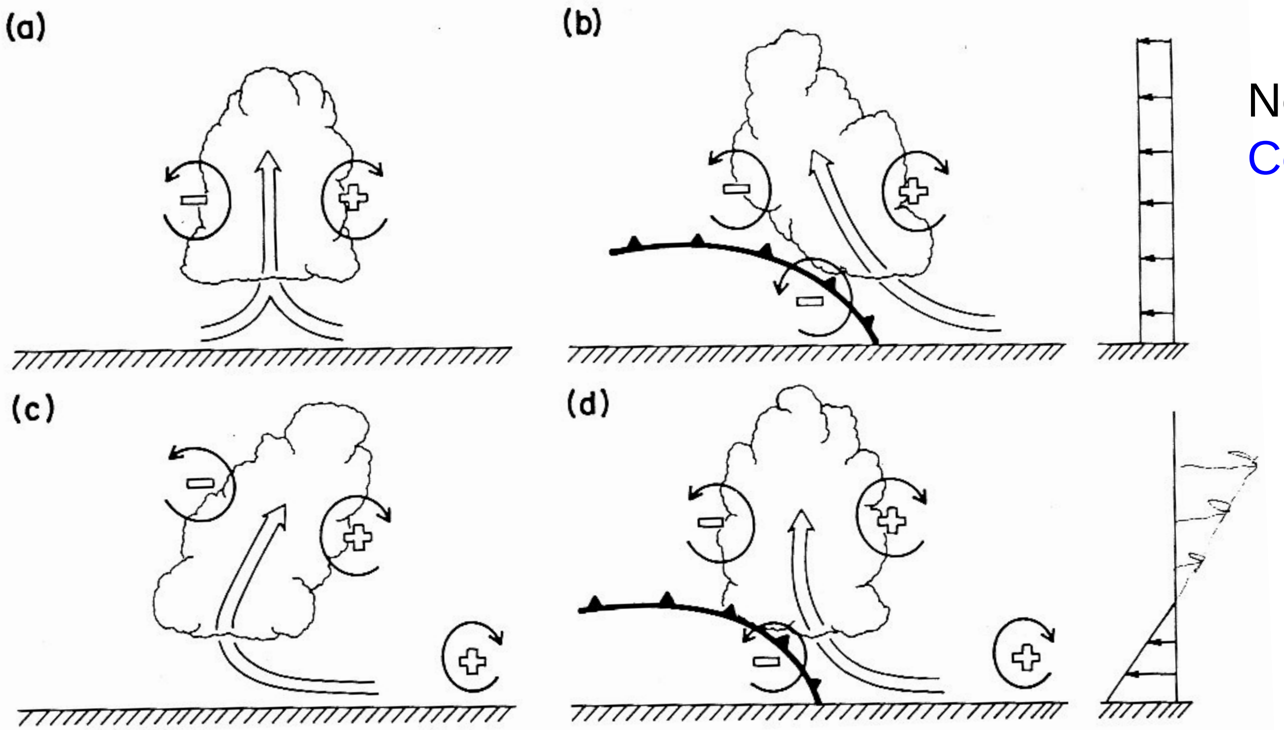
Figure 3.18 The behavior of a spreading cold pool at the ground in a numerically simulated thunderstorm for (a) no vertical shear in the lowest 2 km, (b) 20 m s^{-1} shear in the lowest 2 km, and (c) 30 m s^{-1} shear in the lowest 2 km. In (a)–(c) cold-pool-relative vectors plotted every other grid point (2 grid lengths represents 15 m s^{-1}). Negative potential temperature perturbations shaded at 2 K intervals, beginning at −1 K (from Rotunno et al., 1988). (Courtesy of the American Meteorological Society)

Bluestein (1993)

Vorticity balance concept for cold pool/shear interaction.

No Shear
No Cold pool

No Shear
Cold Pool



Shear
No Cold Pool

Shear
Cold pool

Figure 3.19 Schematic diagram showing how a buoyant updraft may be influenced by vertical wind shear and/or a cold pool. (a) With no vertical wind shear and no cold pool, the axis of the updraft (thick arrow) produced by the thermally created, symmetric vorticity (sense of rotation indicated by thin arrows and plus and minus signs) distribution is vertical. (b) With a cold pool (underneath cold-front symbol) and no shear, the distribution is biased by the negative vorticity of the underlying cold pool and causes the updraft to lean as shown. (c) With shear and no cold pool, the distribution is biased toward positive vorticity, and this causes the updraft to lean as shown. (d) With both a cold pool and shear, the two effects may negate each other, and allow an erect updraft. Environmental wind profile indicated at the right for (a) and (b) (top) and for (c) and (d) (bottom) (from Rotunno et al., 1988). (Courtesy of the American Meteorological Society)

Bluestein (1993)

Vorticity balance in the case of two colliding gust fronts

If the vorticity of each approaching cold pool is comparable, then vorticity balance upon collision is achieved and air parcel moves upward at intersection, possibly reaching LFC and forming new convection.

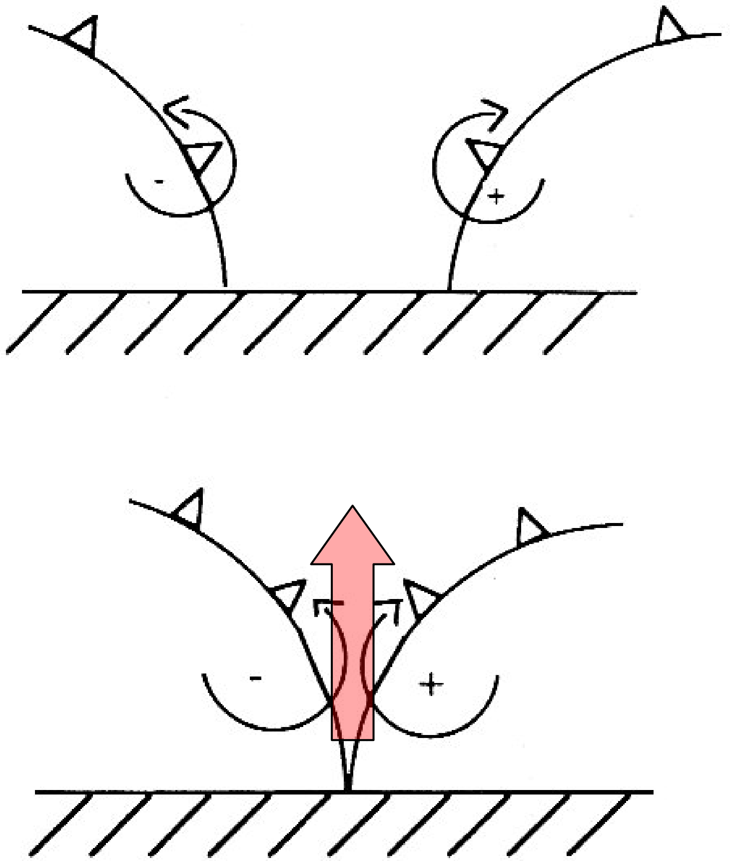
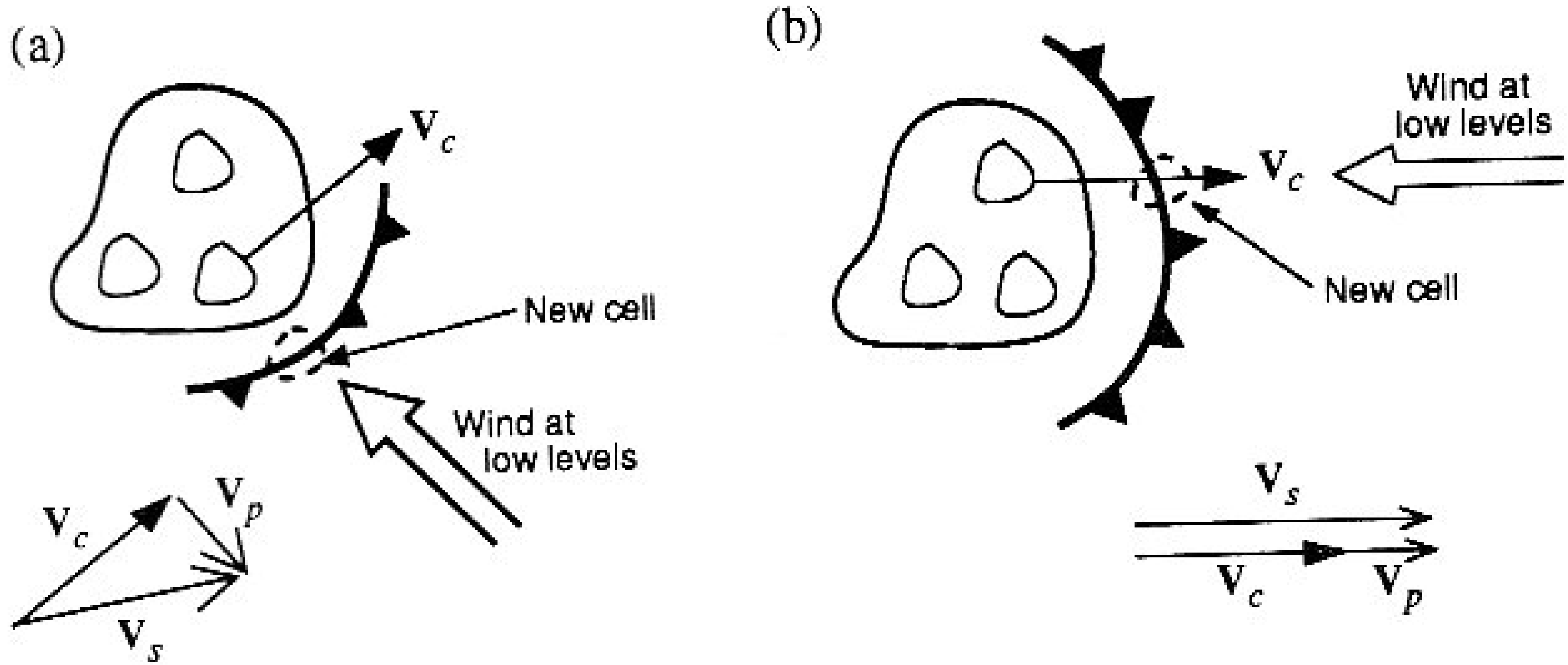


Figure 3.20 Effect of two colliding outflow boundaries (underneath cold-front symbols) on horizontal vorticity (sense of rotation indicated by thin arrows and plusses and minuses). (top) Before collision, (bottom) after collision.

Bluestein (1993)

Schematic showing storm motion as combination of cell motion and new cell development



V_c: cell motion vector
V_p: propagation vector (new cell growth)
V_s: storm system vector

Figure 8.8 Houze (1993)

$$V_s = V_c + V_p$$

Figure 8.8 Possible horizontal arrangements of cells in multicell thunderstorms. Solid contours indicate radar echoes of two different intensities. Frontal symbol denotes gust-front location. Vectors indicate the velocity of an individual cell ($\mathbf{V}_c$), storm propagation velocity resulting from new cell development ($\mathbf{V}_p$), and velocity of the storm as a whole ($\mathbf{V}_s$).

a. Unidirectional Shear Case

Interaction of an updraft with the environmental shear in a supercell, Part I

- **Linear** pressure perturbations and associated vertical motions
- Explains dominant right/left movers associated with clockwise/counter-clockwise shear

b. Clockwise Curved Shear Case

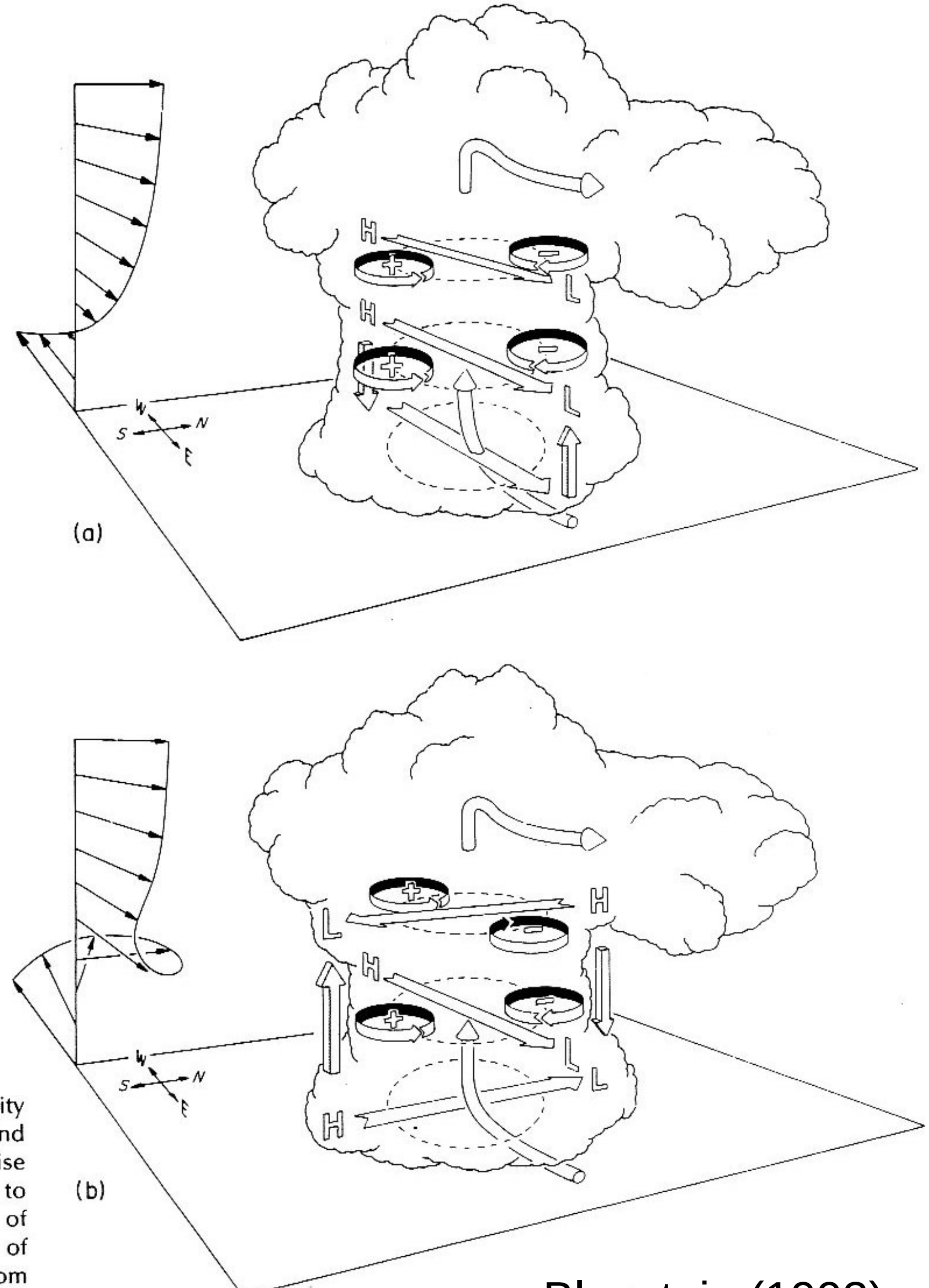


Figure 3.21 Schematic diagram illustrating the pressure and vertical vorticity perturbations arising as an updraft interacts with an environmental vertical wind shear vector that (a) does not change direction with height and (b) turns clockwise with height. The high (H) to low (L) horizontal pressure-gradient forces parallel to the shear vectors (flat arrows) are labeled along with the preferred location of cyclonic (+) and anticyclonic (−) vorticity. Shaded arrows depict orientation of resulting vertical pressure-gradient forces (from Klemp, 1987; adapted from Rotunno and Klemp, 1982). (Courtesy of the American Meteorological Society)

Bluestein (1993)

Classic example of
a splitting thunderstorm
and right-moving supercell.

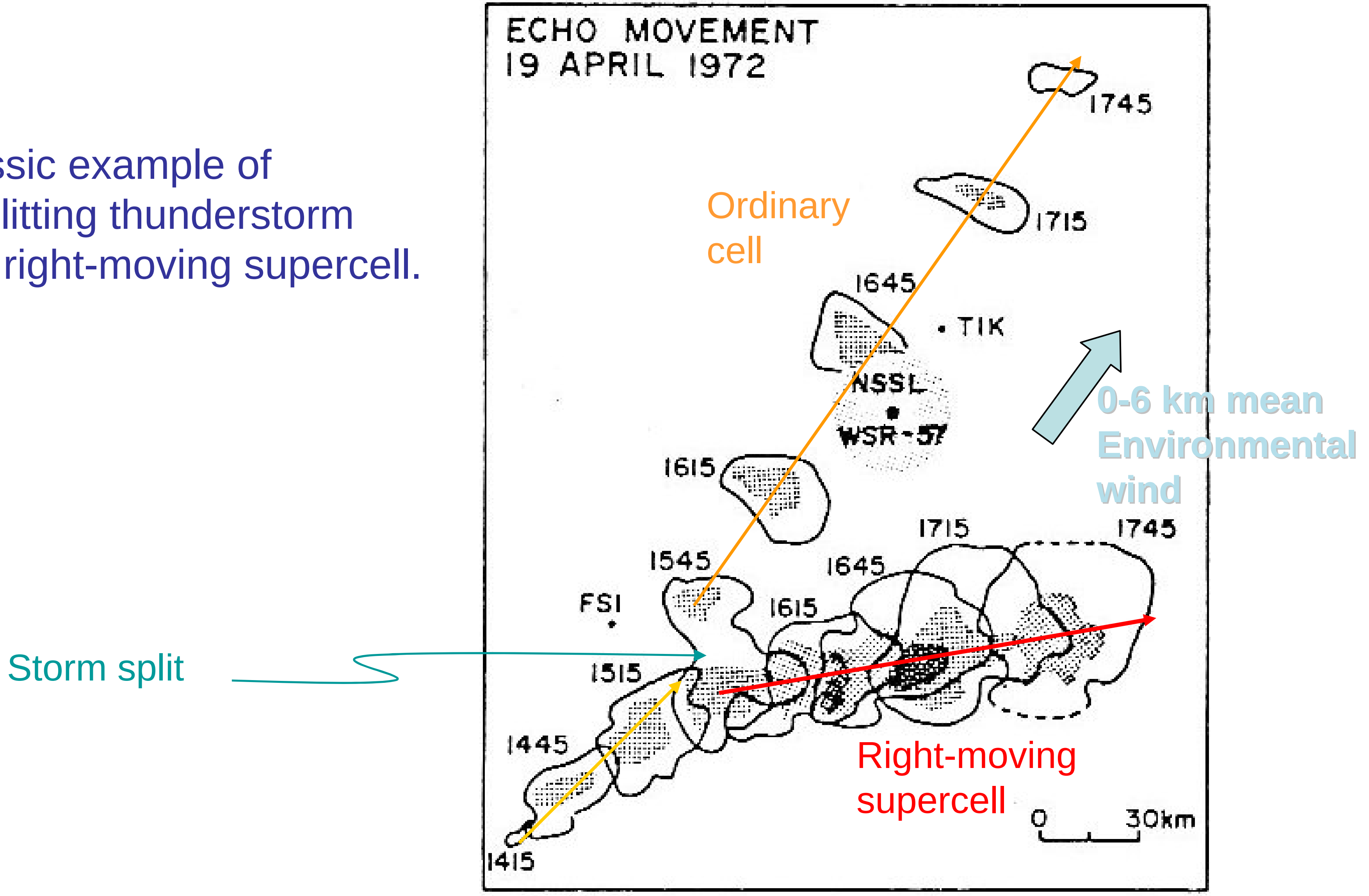


Figure 3.25 (Top) Radar-echo history of a splitting storm observed in south-central Oklahoma. Radar reflectivity of 10 dBZ (solid lines); radar reflectivity in excess of 40 dBZ (stippled regions). Times adjacent to each outline are CST. (Bottom)

Bluestein (1993)
Figure 3.25 (top)

a. Initial Stage

Interaction of an updraft with the environmental shear in a supercell
Part II

- Implications of rotation
- **Non-Linear** pressure perturbations and associated vertical motions
- Helps explain storm splitting

b. Splitting Stage

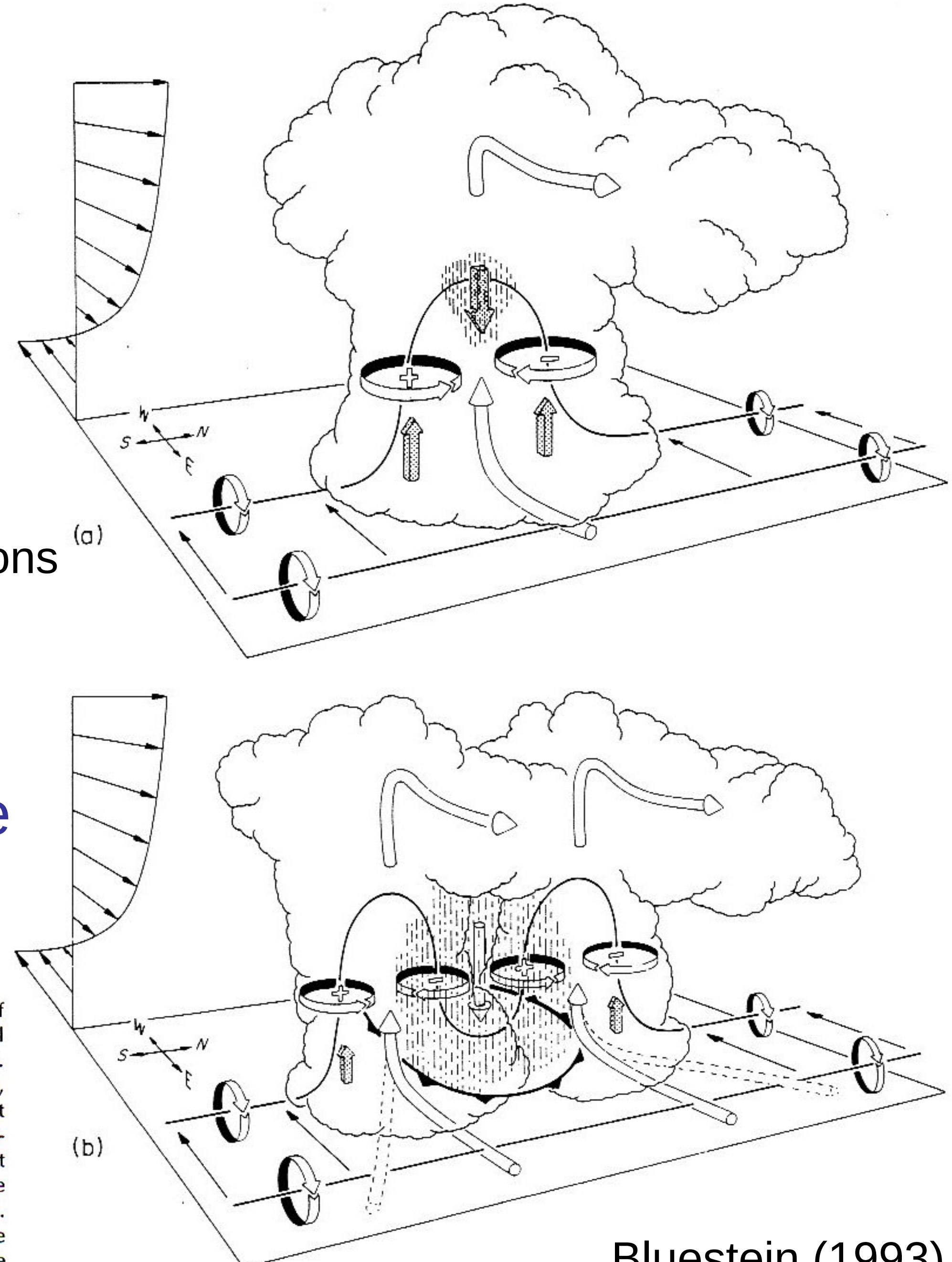
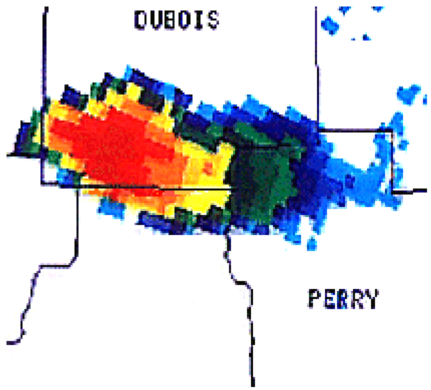


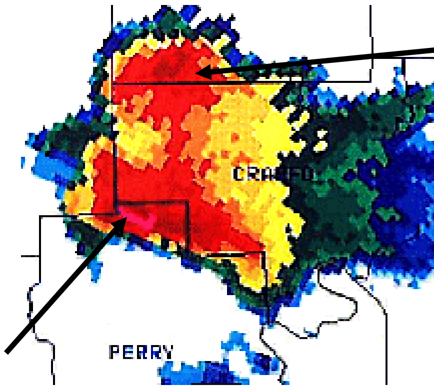
Figure 3.23 Schematic diagram depicting how a typical vortex line (streamline of three-dimensional vorticity vector) contained within (westerly) environmental shear is deformed as it interacts with a convective cell (viewed from the southeast). Direction of cloud-relative airflow (cylindrical arrows); 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)

Bluestein (1993)

WSR-88D reflectivity evolution of splitting supercells



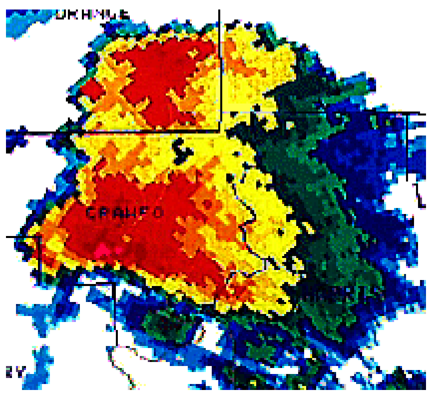
Time = T



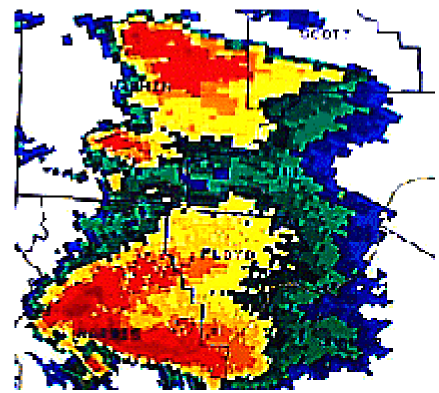
Left-mover

Right-mover

T + 20 min



T + 30 min



T + 50 min

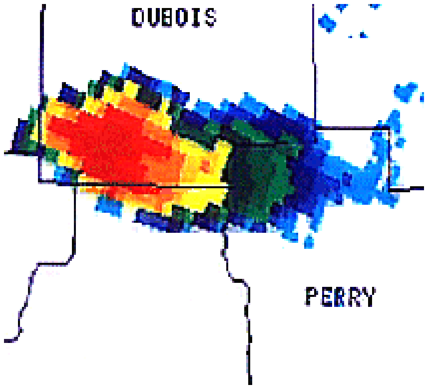
“(nearly) mirror image”

Right mover bit more dominant here.

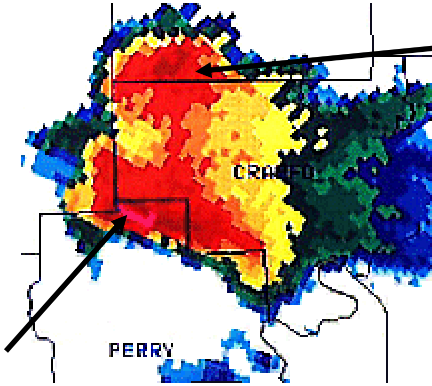
May 28 1996
South-central Indiana

Source: http://www.crh.noaa.gov/lmk/soo/88dimg/52896_evt.php

WSR-88D reflectivity evolution of splitting supercells



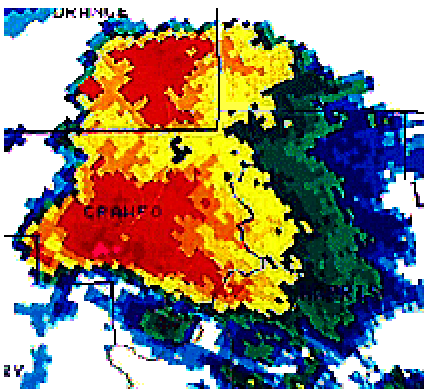
Time = T



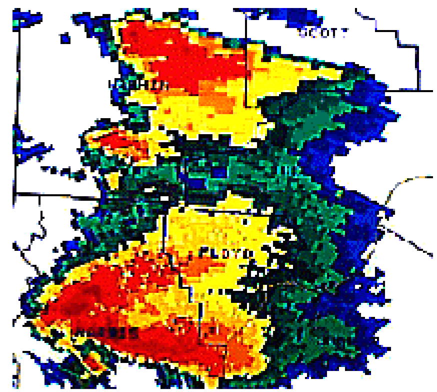
Left-mover

Right-mover

T + 20 min



T + 30 min

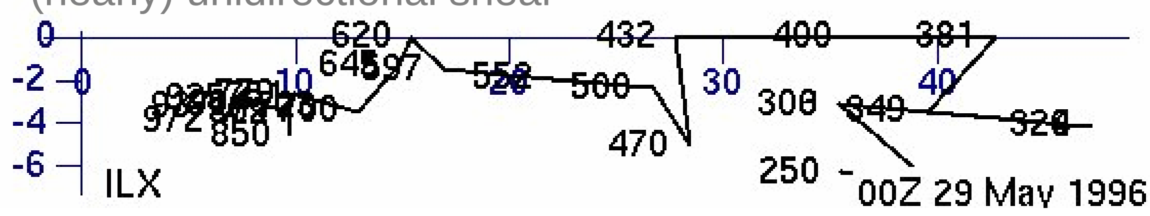


T + 50 min

"(nearly) mirror image"

Right mover bit more dominant here.

(nearly) unidirectional shear



May 28 1996
South-central Indiana

Schematic summarizing the role of shear in the development of multicell and supercell storms.

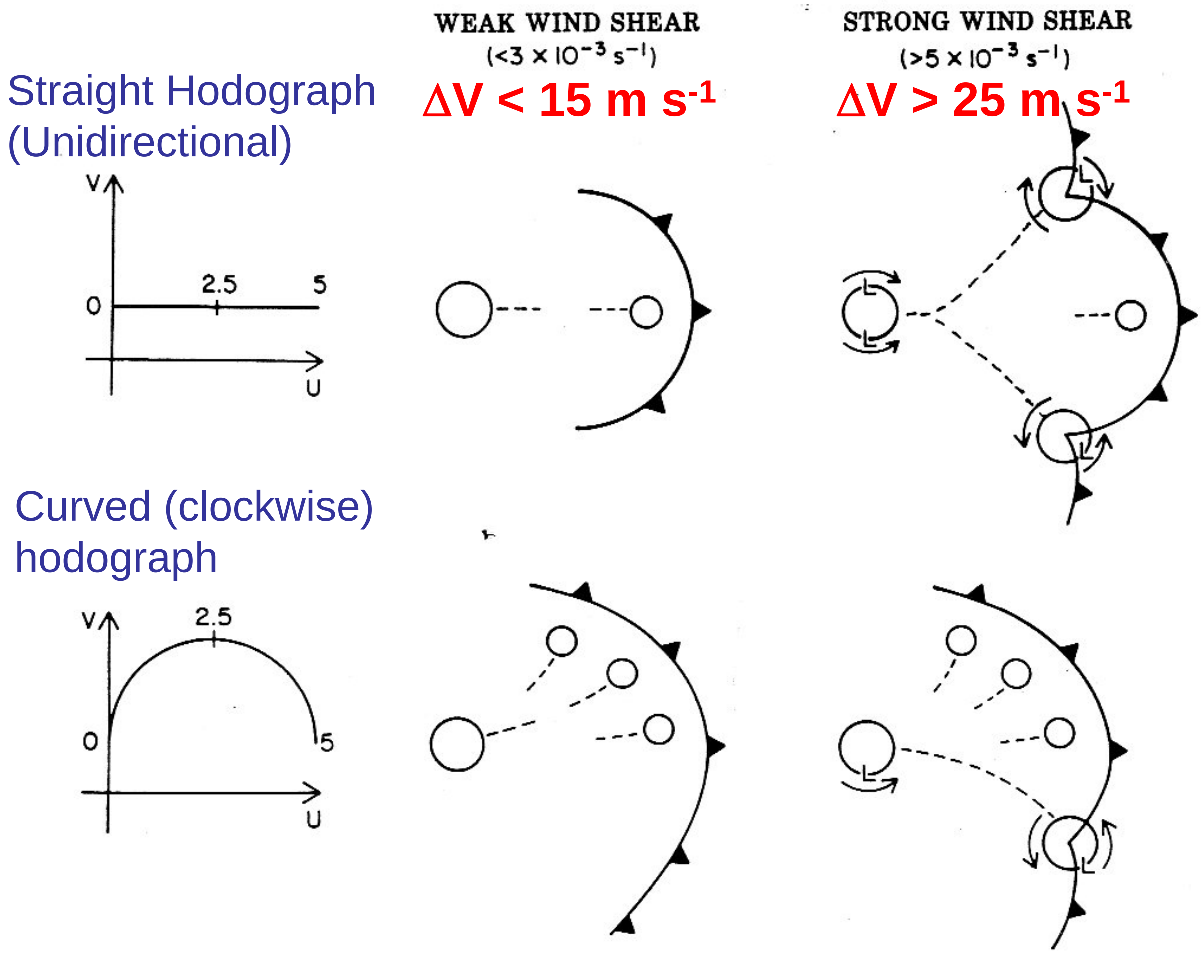


Figure 15.15. Updraft evolution in weak and strong wind shear conditions for unidirectional and clockwise-curved wind shear profiles. Hodographs on the left define the wind shear type; 0, 2.5, and 5 km levels are indicated. Large and small circles represent relatively strong and weak updrafts, respectively; the path of each updraft cell is indicated by a dotted line. Updraft structure is depicted at the early and mature phases of each storm; surface gust fronts (barbed lines) are included at the mature phase. L is the approximate position of significant middle-level mesolow features. The direction of the updraft rotation (if any) is indicated by arrows.

Weisman and Klemp (1986)

A. Short-lived multi-cell

Numerical model simulations of wind shear and updraft redevelopment (Runs A-F)

B. Supercell on the south side of a multicell line.

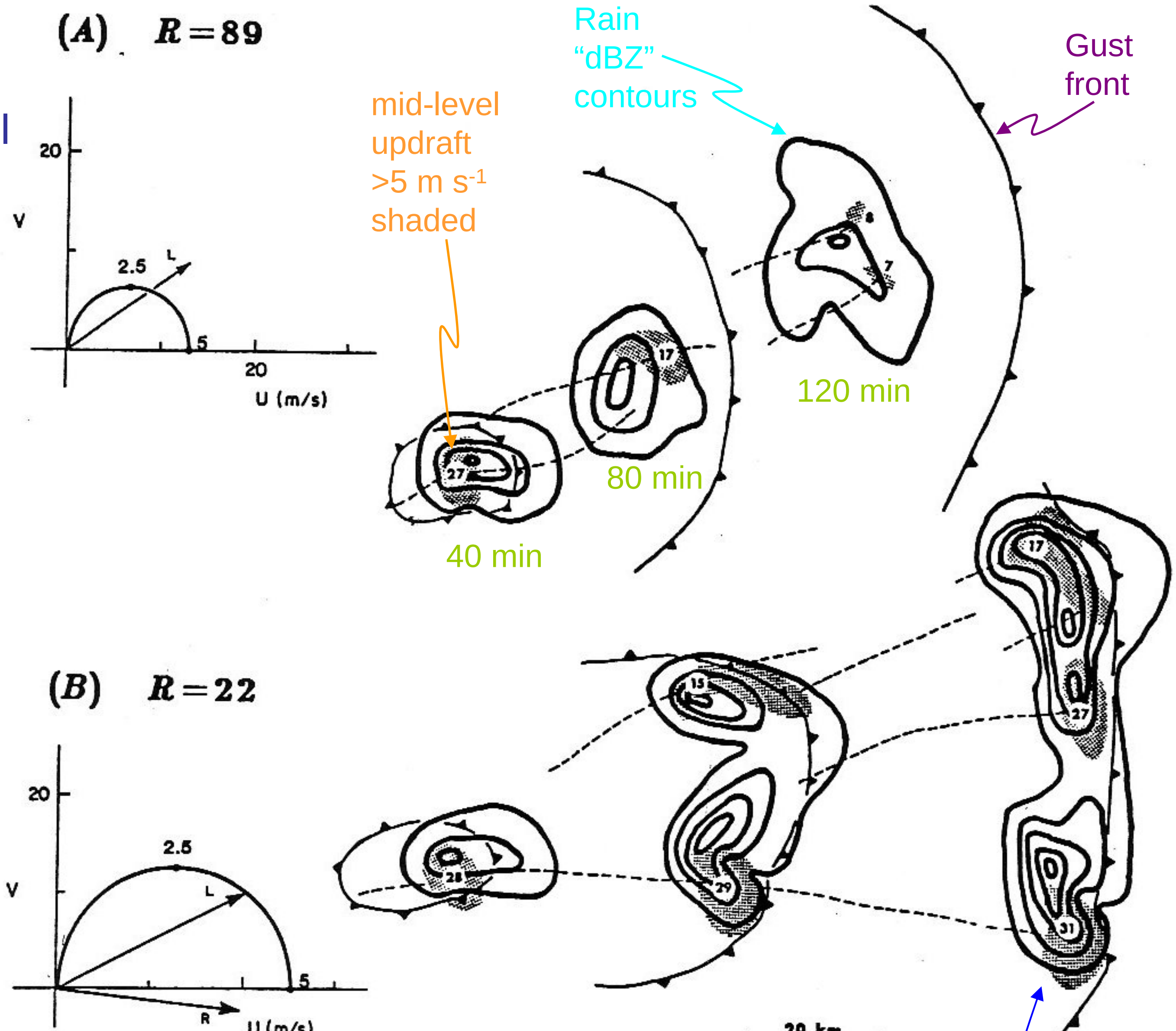
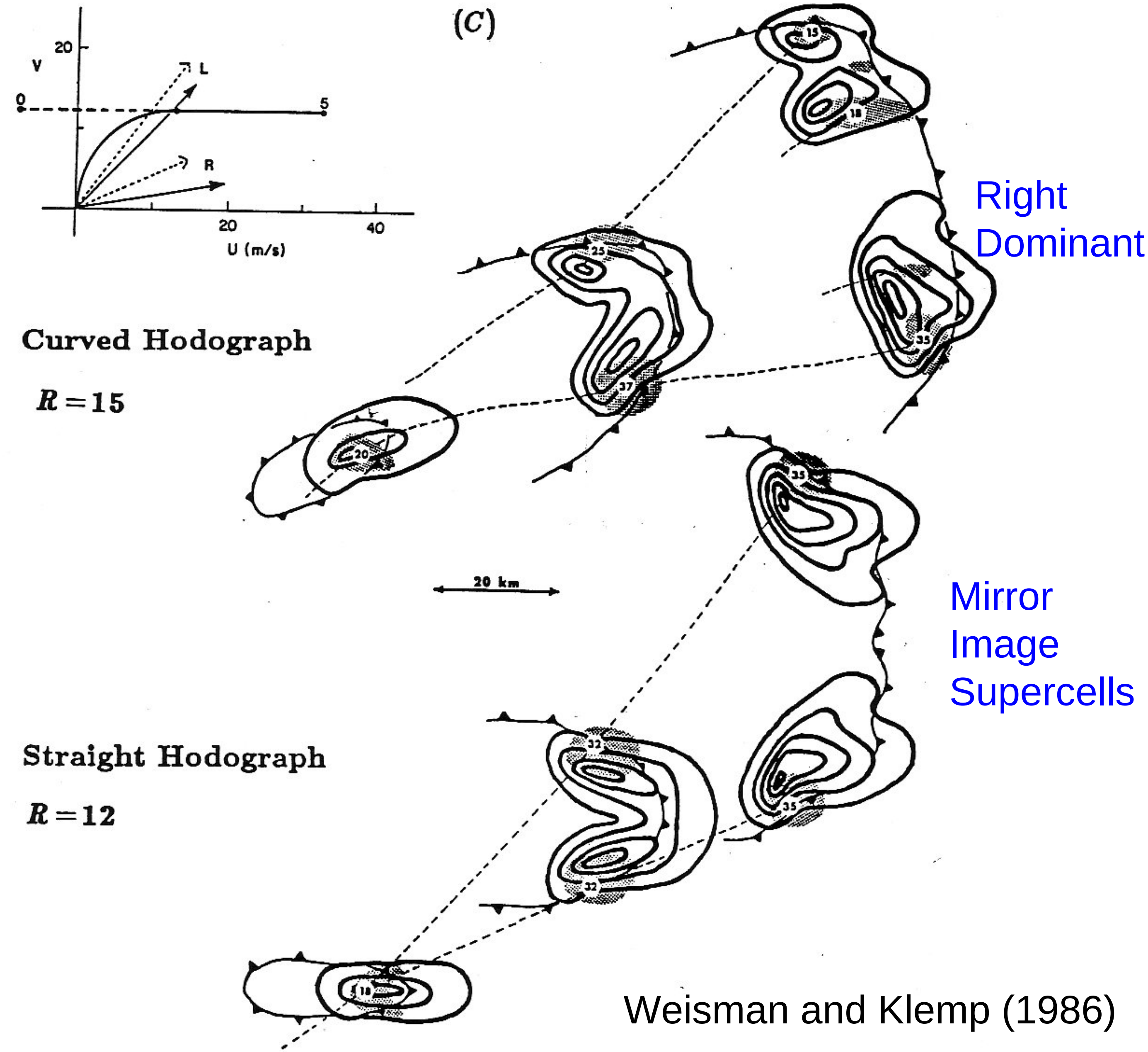


Figure 15.17. Hodograph and storm structures at 40, 80, and 120 min for cases A–F described in text. Storm positions are relative to the ground; dashed lines represent updraft cell path. Low-level (1.8 km) rainwater fields (similar to radar reflectivity) are contoured at 2 g kg^{-1} inervals. Regions in which the middle-level updraft (4.6 km) exceeds 5 m s^{-1} are shaded. Surface gust fronts are defined by the −1°C perturbation surface isotherm. Numbers at the updraft centers represent maximum vertical velocity (m s^{-1}) at the time. On hodographs, heights are labeled in km agl and arrows indicate the mean storm motion between 80 and 120 min. R = bulk Richardson number as discussed in Sec. 15.5.1. Cases A and B, multi-cell and supercell storms.

Weisman and Klemp (1986)

C. Right-flank Supercell split from weaker left flank storm.



Weisman and Klemp (1986)

Figure 15.17. Continued. Case C, splitting supercell storms.

D. Right-flank supercell

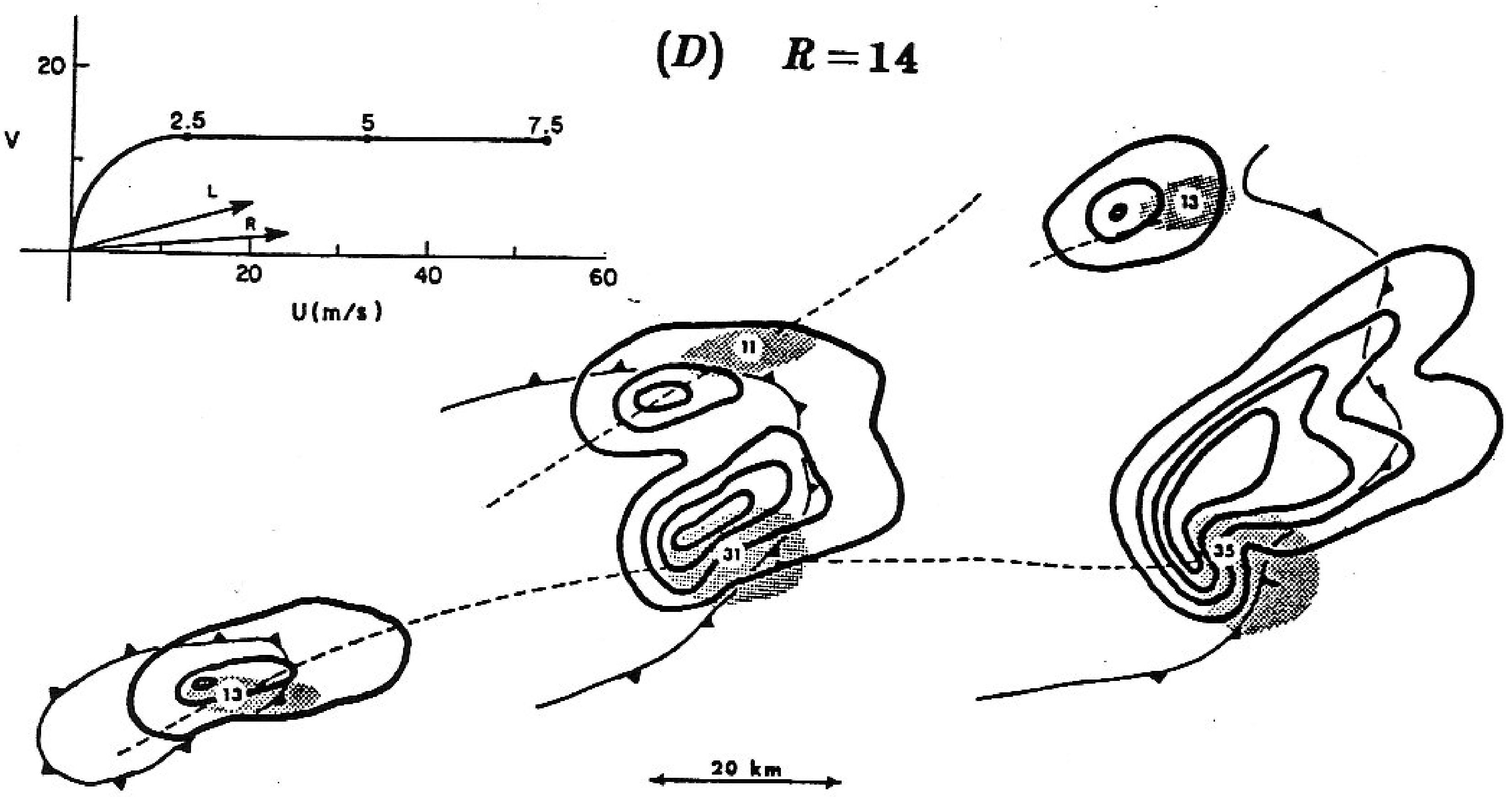


Figure 15.17. Continued. Case D, right-flank supercell.

Weisman and Klemp (1986)

E. Weak squall line

F. Squall line with bow-echo

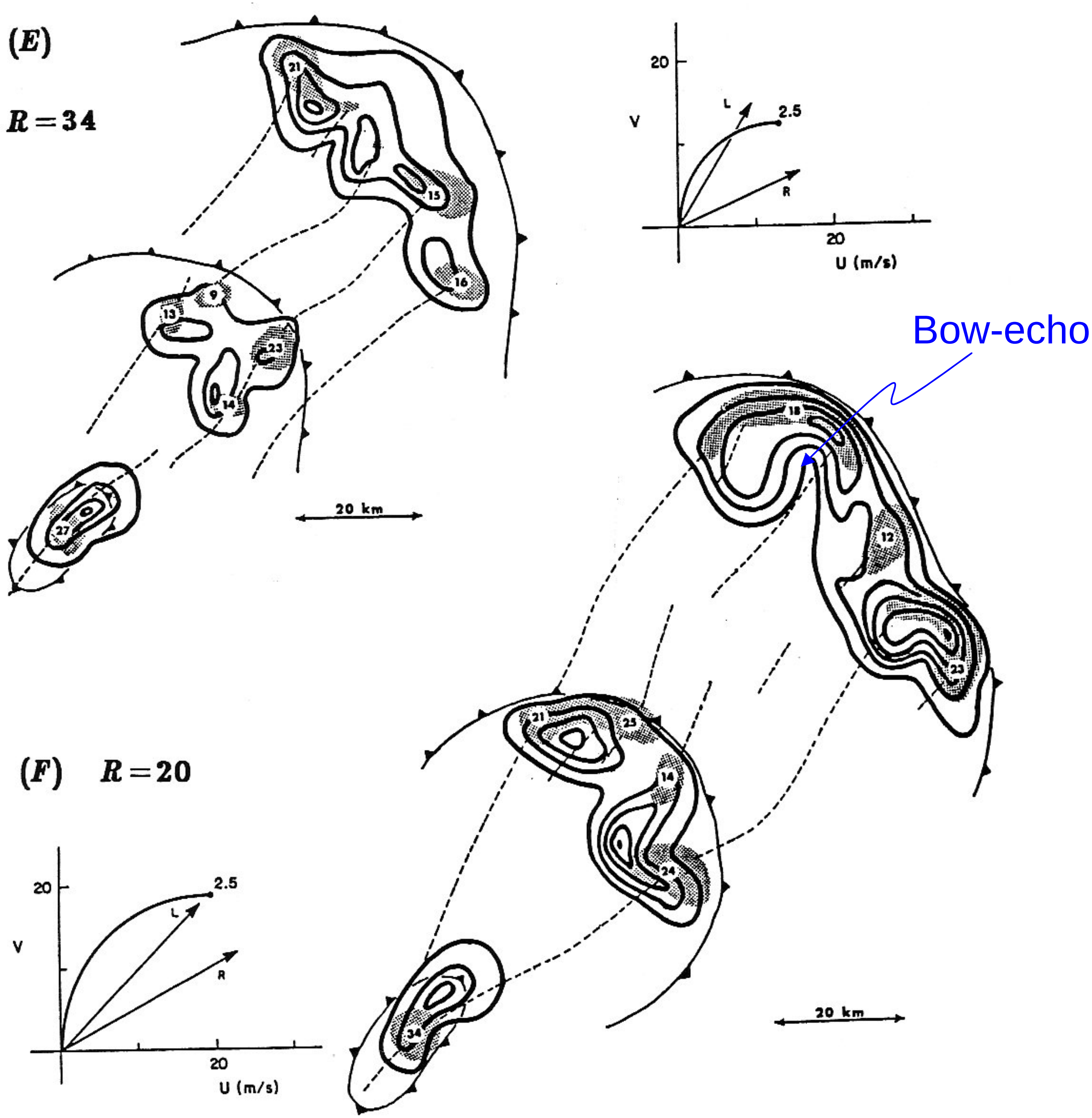


Figure 15.17. Continued. Cases E and F, multi-cellular squall lines.

Weisman and Klemp (1986)

Storm type as a function of vertical shear and CAPE

Shear

Table 3.2 Storm type as a function of vertical shear and CAPE

Vertical shear[a] CAPE	Weak $\lesssim 15$ m s^{-1}	Moderate ~15–25 m s^{-1}	Strong $\gtrsim 25$ m s^{-1}
Low (500–1000 J kg^{-1})	Ordinary cell	Ordinary cell/supercell	Ordinary cell/supercell
Moderate (~1000–2500 J kg^{-1})	Ordinary cell	Ordinary cell/supercell[b]	Supercell[b]
High ($\gtrsim 2500$ J kg^{-1})	Ordinary cell[b]	Ordinary cell[b]/supercell[b]	Supercell[b]

CAPE

[a] Over lowest 6 km.

[b] Storms in which severe weather is likely. Vertical shear is measured by the length of the hodograph of the environmental winds from the surface to 6 km AGL (small-scale curves and loops are not counted). Supercells can occur even in environments of low CAPE if there is low CIN and if the environment is so moist that entrainment of environmental air does not weaken the updraft significantly. Severe weather is likely in storms produced in an environment of moderate–high CAPE regardless of storm type because the updrafts can be strong (based upon numerical simulations by M. Weisman, NCAR).

Bluestein (1993)

Storm type as a function of Bulk Richardson Number (R).

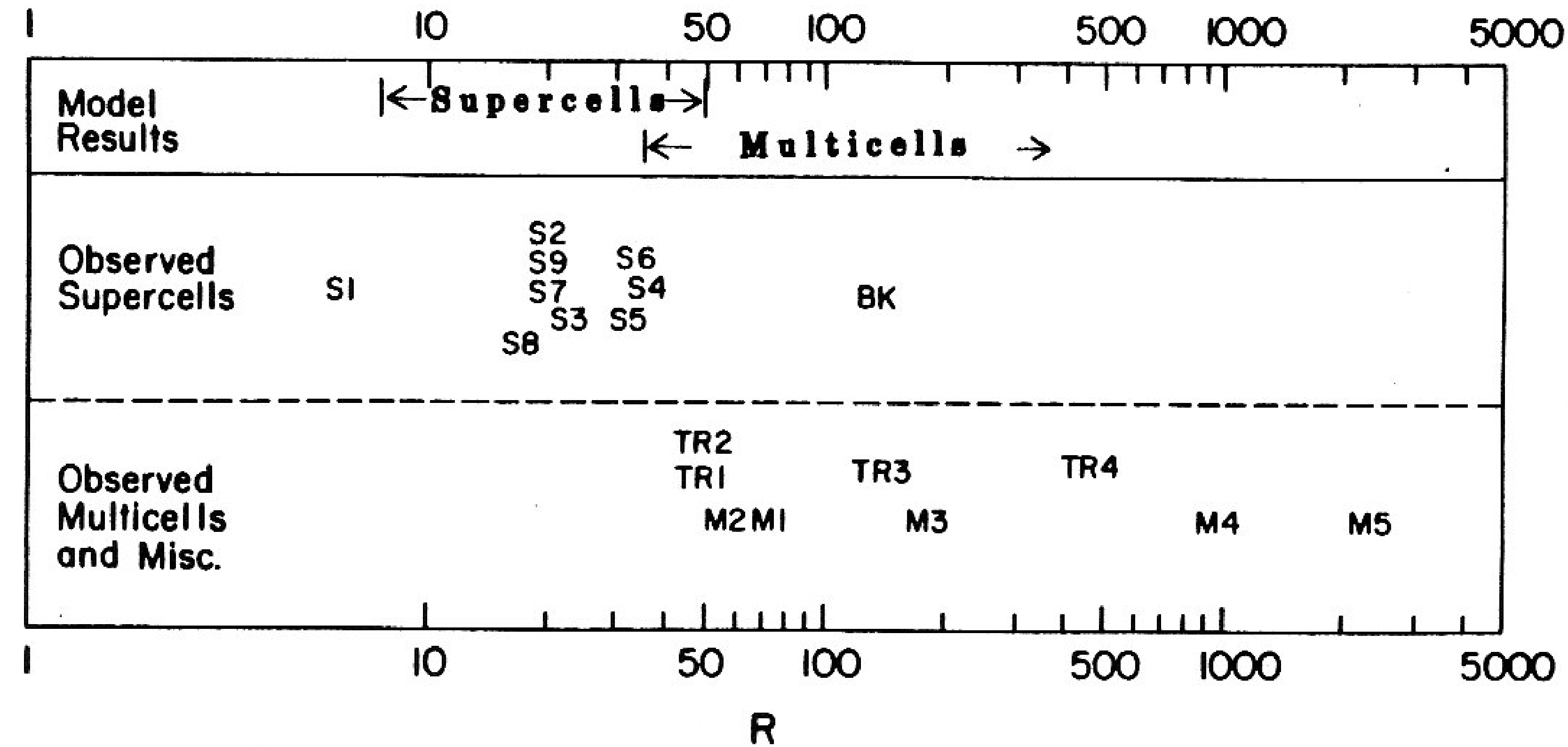


Figure 15.18. Richardson number R as calculated for a series of documented storms. Model results are summarized at the top of the figure. S1, S2,...,S9 represent supercell storms; M1, M2,...,M5 represent multicell storms; TR1, TR2,...,TR4 represent tropical cases. (Adapted from Weisman and Klemp, 1982.)

Weisman and Klemp (1986)