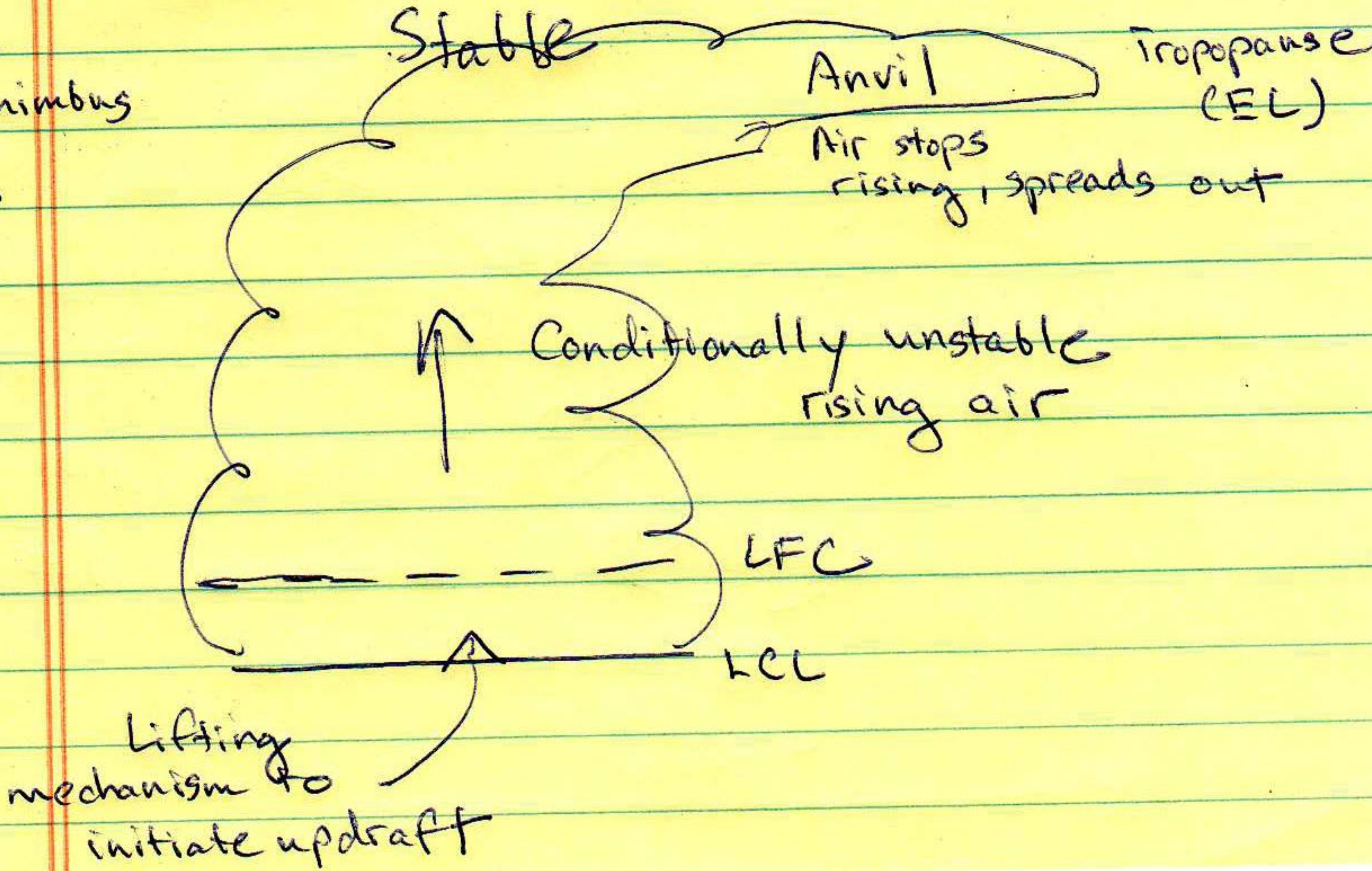
Introduction to mid-latitude deep convection

Typical cumulonimbus cloud

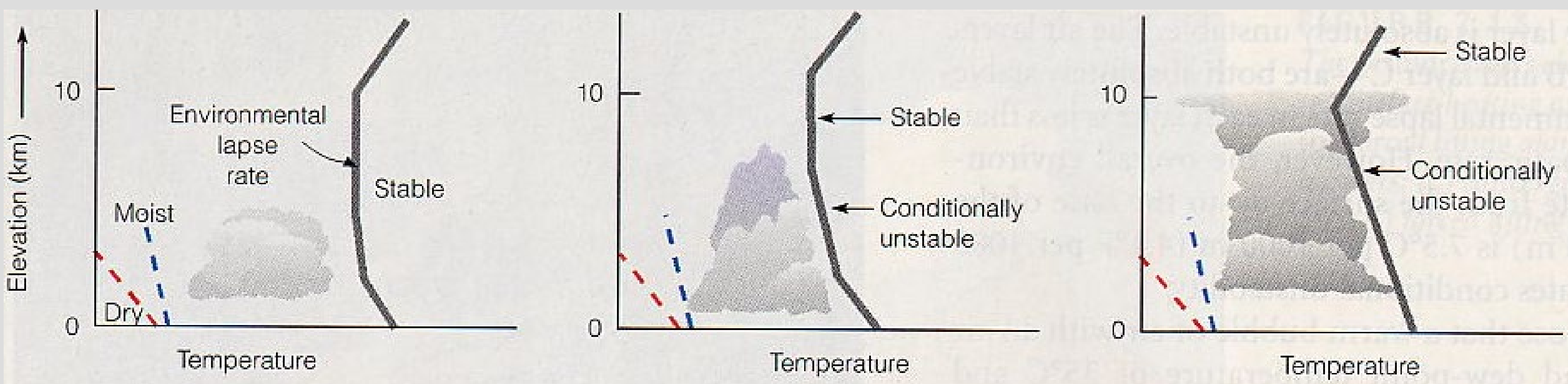


How deep convection is depends on how far up the instability goes in the atmosphere

Cumulus humilis

Cumulus congestus

Cumulonimbus



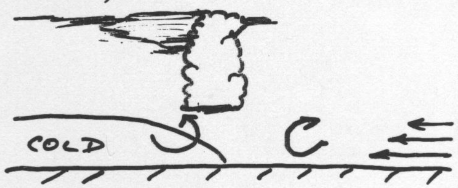
Conditionally unstable in a shallow layer

Conditionally unstable about midway through troposphere

Conditionally unstable nearly to the tropopause

Why does convection organize on the mesoscale?

Mesoscale organization is common when the low-level shear is moderate or greater. The shear provides ample moisture supply to promote extended growth of the convection. System propagation and/or upper-level shear encourages spreading of ice (anvil cloud) aloft. Both processes enable development to larger scales.



Rotunno et al. (1988)

Other factors

- *midlatitude baroclinic systems*
- *convergence lines*

  gust fronts (outflow boundaries)

  drylines

  sea/land breezes
- *gravity waves*
- *upper-level jet streaks*
- *low-level jets*
- *topographic effects*
- *others*

(e.g., boundary-layer circulations)

In the absence of surface gradients, principal facilitating mechanism for convective initiation is an air mass boundary (e.g. front, dryline)

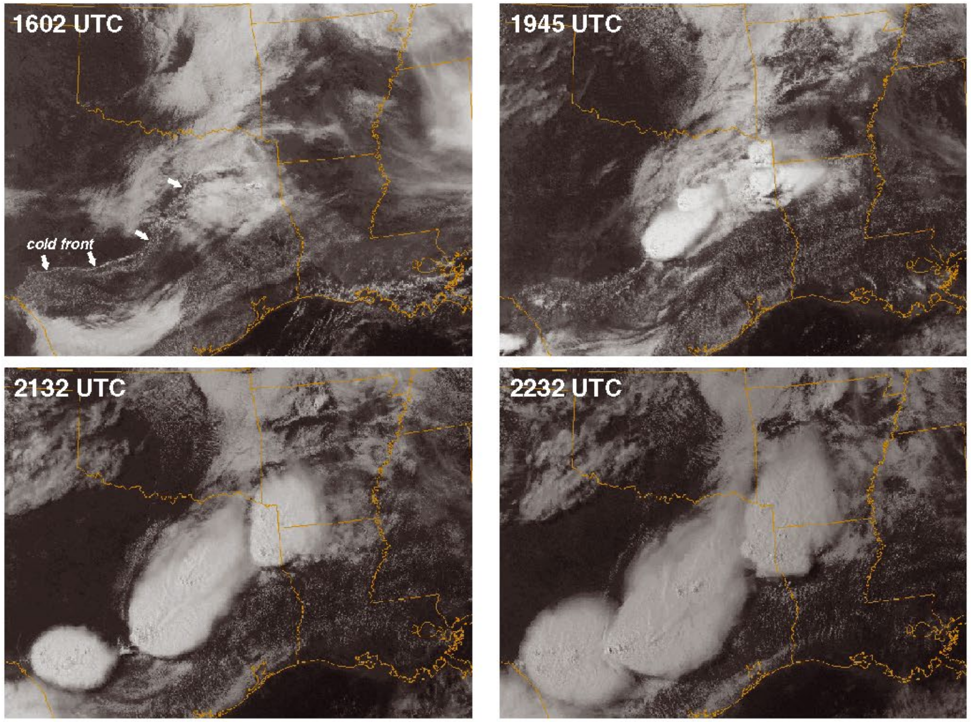


Figure 7.2 In the absence of favored topographic features that act as elevated buoyancy sources, DMC tends to be initiated along air mass boundaries, which are usually accompanied by a wind shift and convergence. This allows forecasters to enjoy at least modest predictability with regard to anticipating the location of convection initiation, for such boundaries are fairly easily observable in routinely available synoptic surface observations and radar and satellite data. The sequence of visible satellite images shows the development of a line of severe thunderstorms along a cold front on 27 May 1997. The town of Jarrell, TX, was devastated by a tornado during this event.

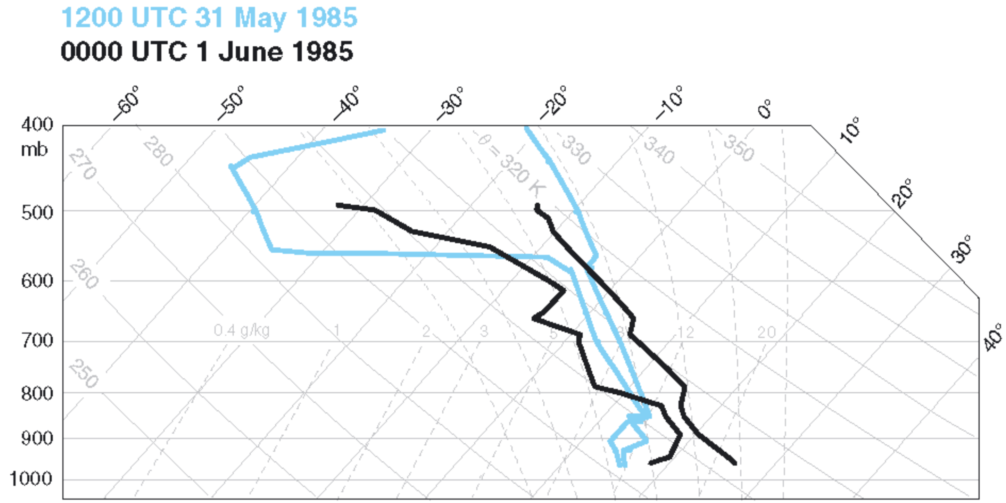


Figure 7.3 Soundings from Pittsburgh, PA, at 1200 UTC 31 May 1985 (blue) and 0000 UTC 1 June 1985 (black). Between 1200 and 0000 UTC, the mean tropospheric lapse rate has undergone significant changes, probably as the result of a number of large-scale processes acting in unison (e.g., insolation, lapse rate advection/differential temperature advection, stretching effect, etc.). The low-level moisture also increased by several g kg^{-1} during the same 12 h period, primarily as a result of moisture advection. The increase in lapse rate and low-level moisture between 1200 and 0000 UTC led to the development of large CAPE (the lifted index decreased from +3 to −7; the lifted index is the temperature difference between the environmental 500 mb temperature and the temperature of an air parcel that has been lifted to 500 mb from the surface, with negative indices indicating that the lifted parcel is warmer than the environment at 500 mb). (Large vertical wind shear also accompanied the large instability; the worst tornado outbreak in the history of Pennsylvania was in progress not far from Pittsburgh at 0000 UTC.)

Changing synoptic conditions can affect potential for deep convection from one day to the next, for example:

Low level moisture, theta-e
Temperature, lapse-rates
Vertical wind profile, wind shear

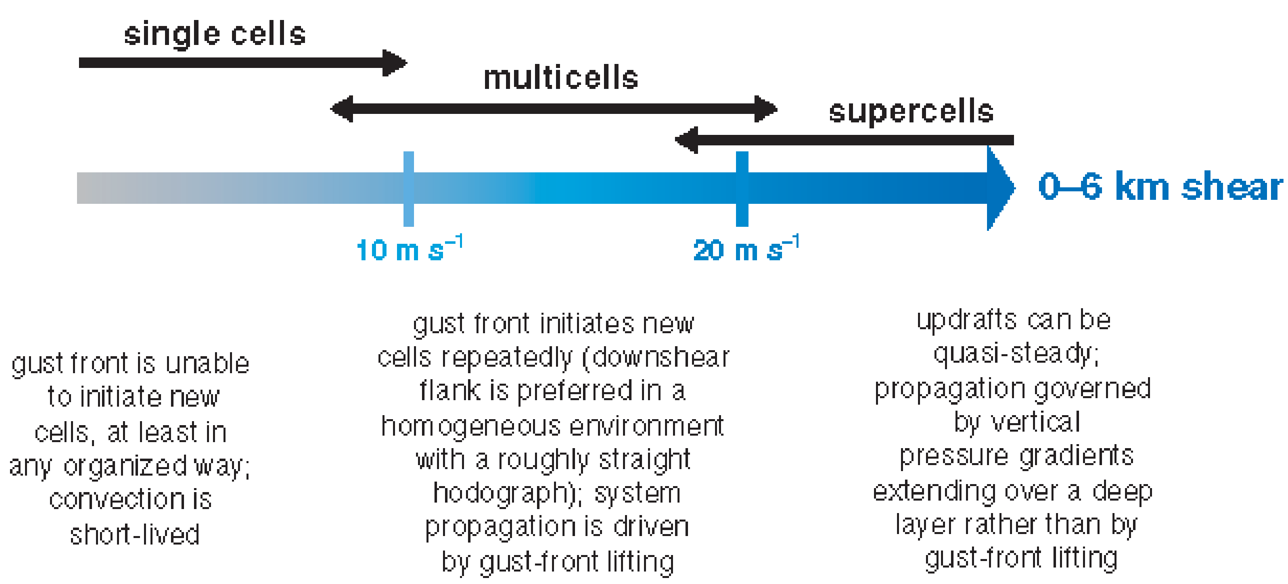


Figure 8.5 Spectrum of storm types as a function of vertical wind shear. Although the vertical shear exerts the greatest influence on storm type, other secondary factors can also affect the mode of convection (e.g., vertical distribution of buoyancy, moisture, and shear, as well as the means by which storms are initiated); thus, some overlap among storm types exists in this simple single-parameter depiction. The relationship between vertical wind shear magnitudes and the nature of cell regeneration/propagation is also shown.

Convection purely thermodynamically driven

Convection organizes by mostly linear dynamic pressure effects

Convection organizes by <u>both</u> linear and non-linear dynamic pressure effects

Air-mass type thunderstorms: Isolated, symmetric

Multi-cellular type thunderstorms: Larger, more asymmetric

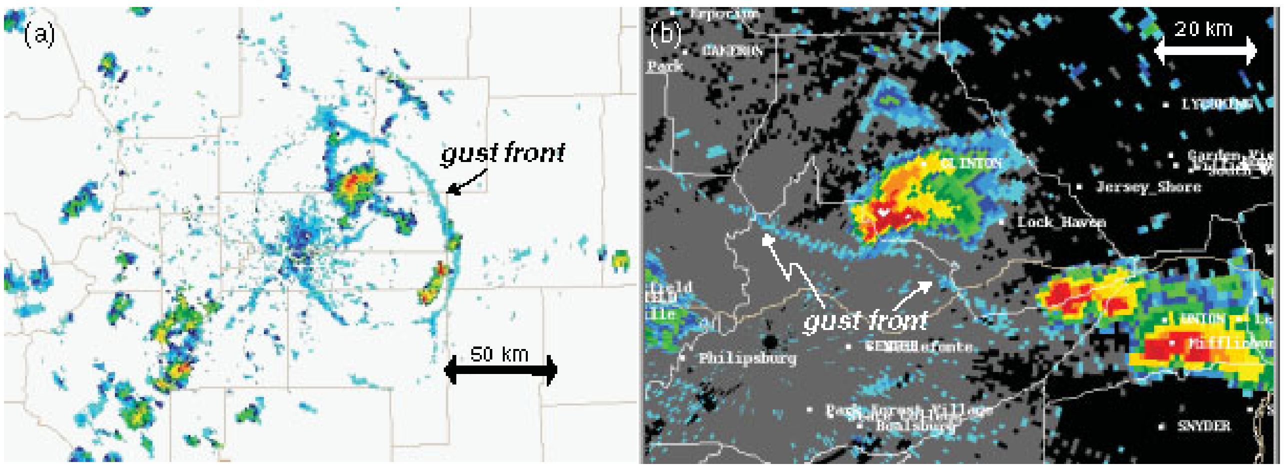


Figure 8.4 Radar reflectivity comparison of gust fronts associated with convection in (a) weak shear and (b) strong shear. In environments containing weak vertical wind shear, the gust front moves well beyond the radar echo (and the updraft that produces the precipitation that is responsible for the echo). Conversely, in environments containing strong vertical wind shear, the gust front tends to be closely attached to the echo, indicating that the updrafts are not being undercut by outflow. Also refer to Figure 8.3b, d.

Air mass thunderstorm life cycle

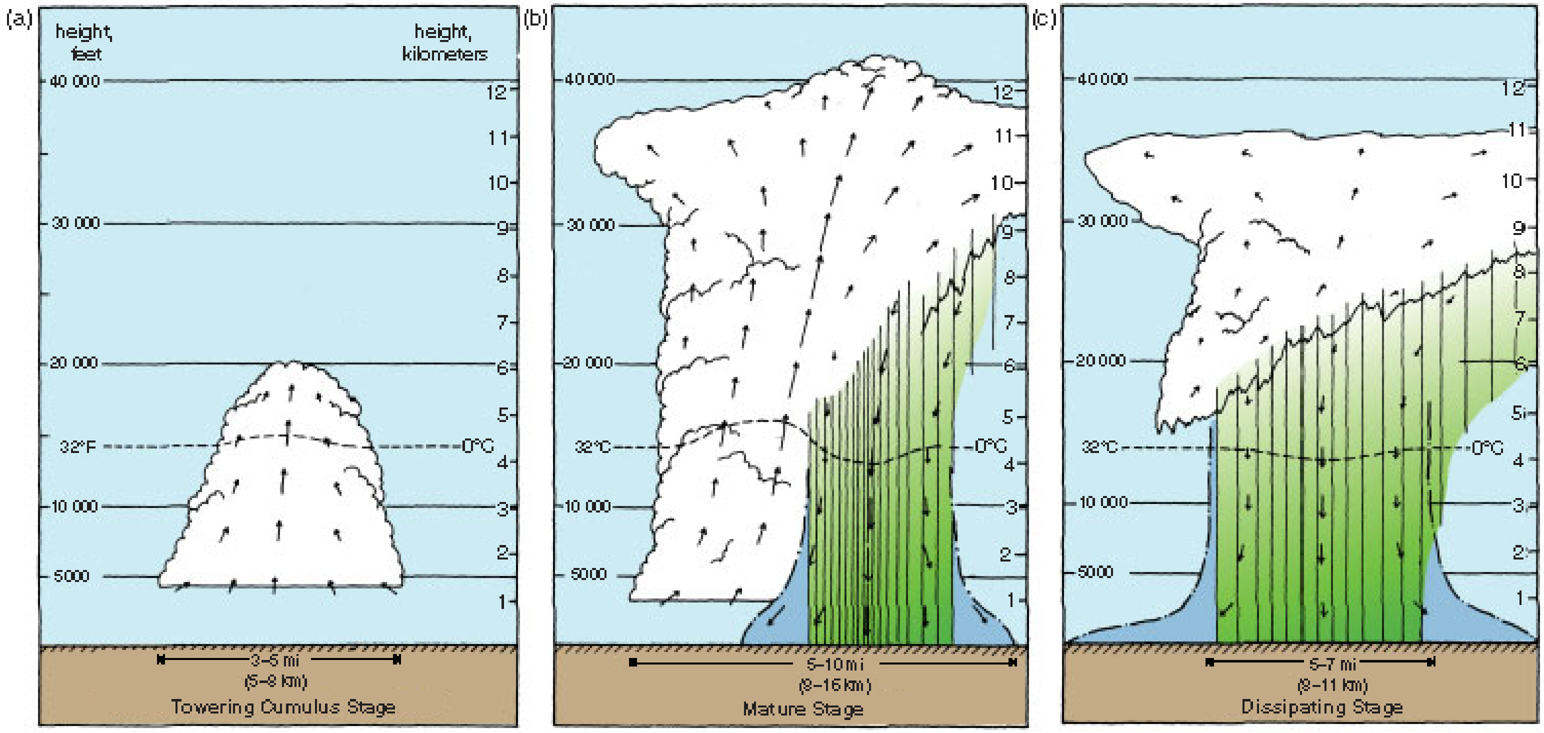
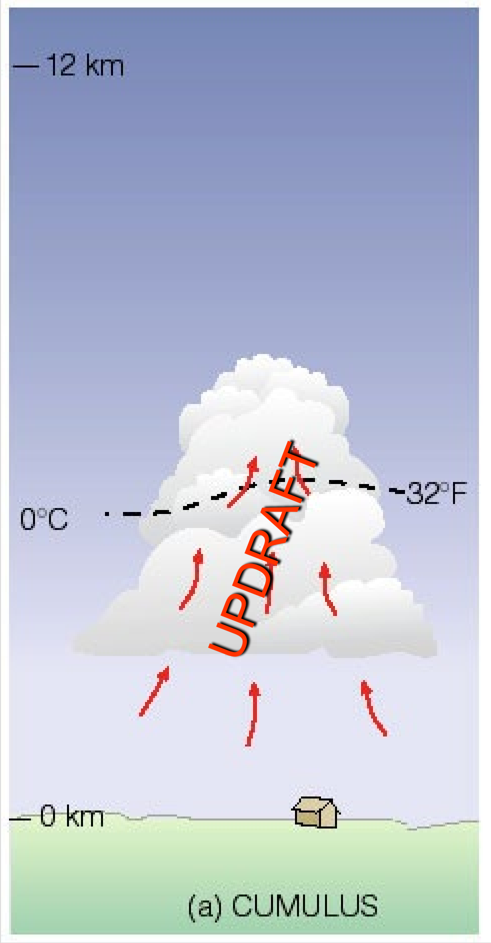


Figure 8.8 The three stages of an ordinary cell: (a) towering cumulus stage, (b) mature stage, and (c) dissipating stage. (Adapted from Byers and Braham [1949] and Doswell [1985].)

Air mass Thunderstorm *Cumulus Stage*



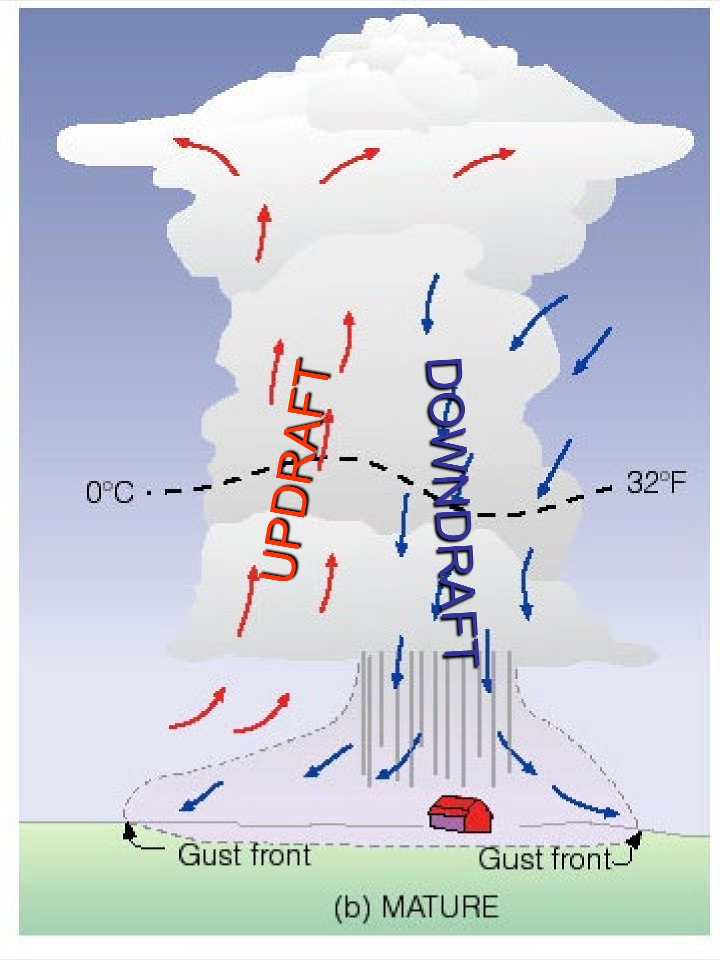
A parcel of air is lifted from surface (updraft)

As the parcel rises, it reaches the lifting condensation level and forms a cumulus cloud. Air continues to rise because condensation occurs.

Lifting mechanisms include:

- Mountain-valley circulations
- Sea-breeze front
- Thermals arising from the land surface.

Air mass Thunderstorm *Mature Stage*



Cumulonimbus with anvil.

Cloud liquid and ice particles grow larger, eventually falling to the ground as rain.

Process draws in drier air surrounding the cloud to create a downdraft.

Leading edge of the downdraft is *gust front*.

Mature air mass thunderstorm with gust front

Gust front can provide a lifting mechanism to get other storms going.

Monsoon Thunderstorms in Arizona

Monsoon thunderstorms at Kitt Peak at mature stage with gust fronts.

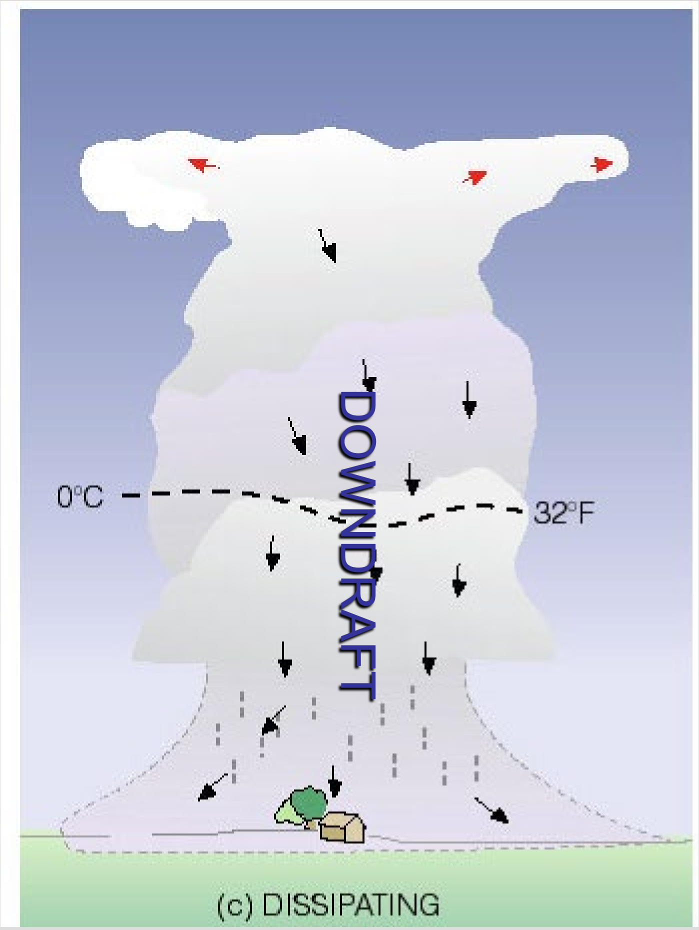
Forced by the diurnal mountain valley circulation

Form over the mountains during late morning to early afternoon

Reach mature stage by about mid-afternoon.

(*Photo taken around 3pm)*

Air mass Thunderstorm *Dissipating Stage*



Gust front moves far enough away from the storm to “choke off” the updraft.

Once this supply of warm, moist air is from the updraft is cut off, the storm begins to weaken either by evaporation and/or by raining itself out.

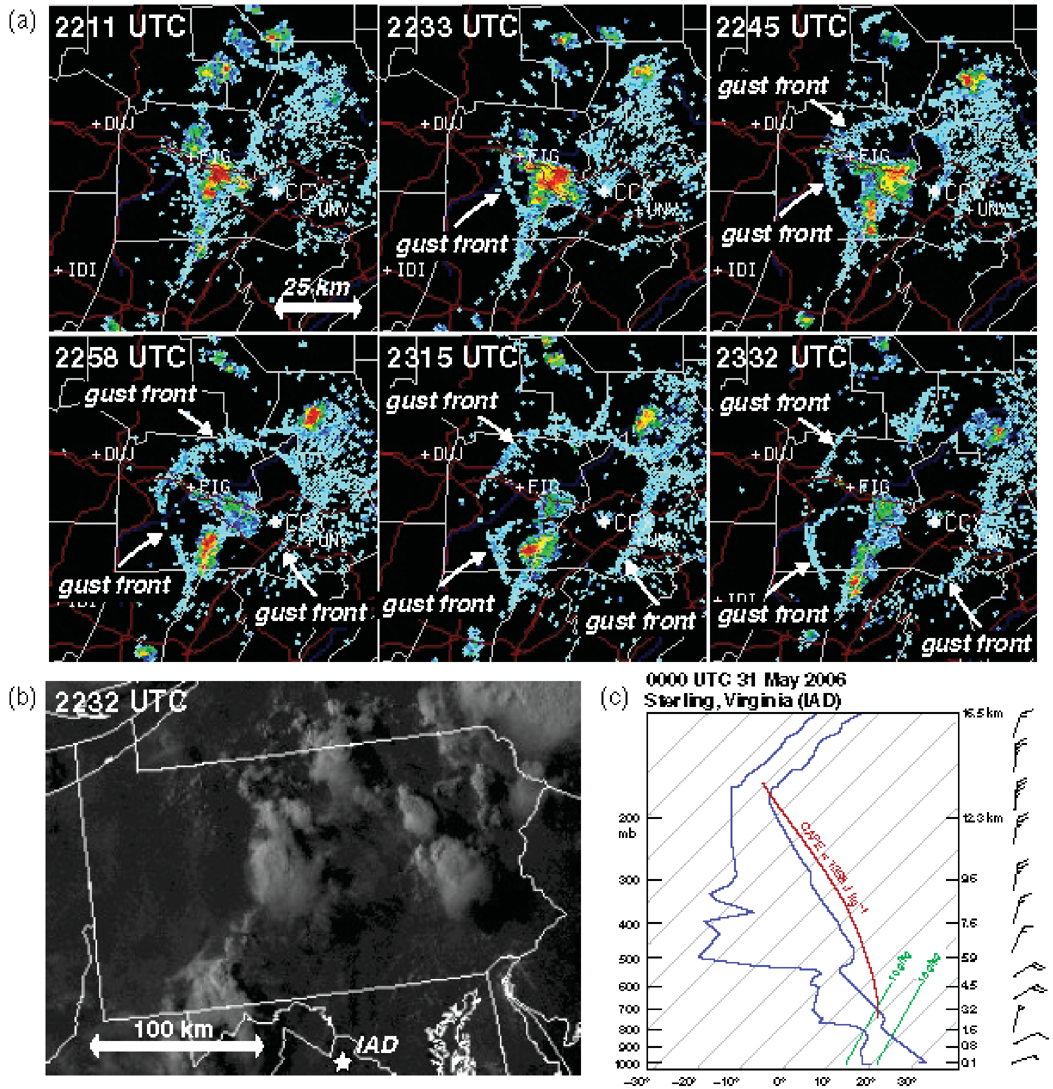


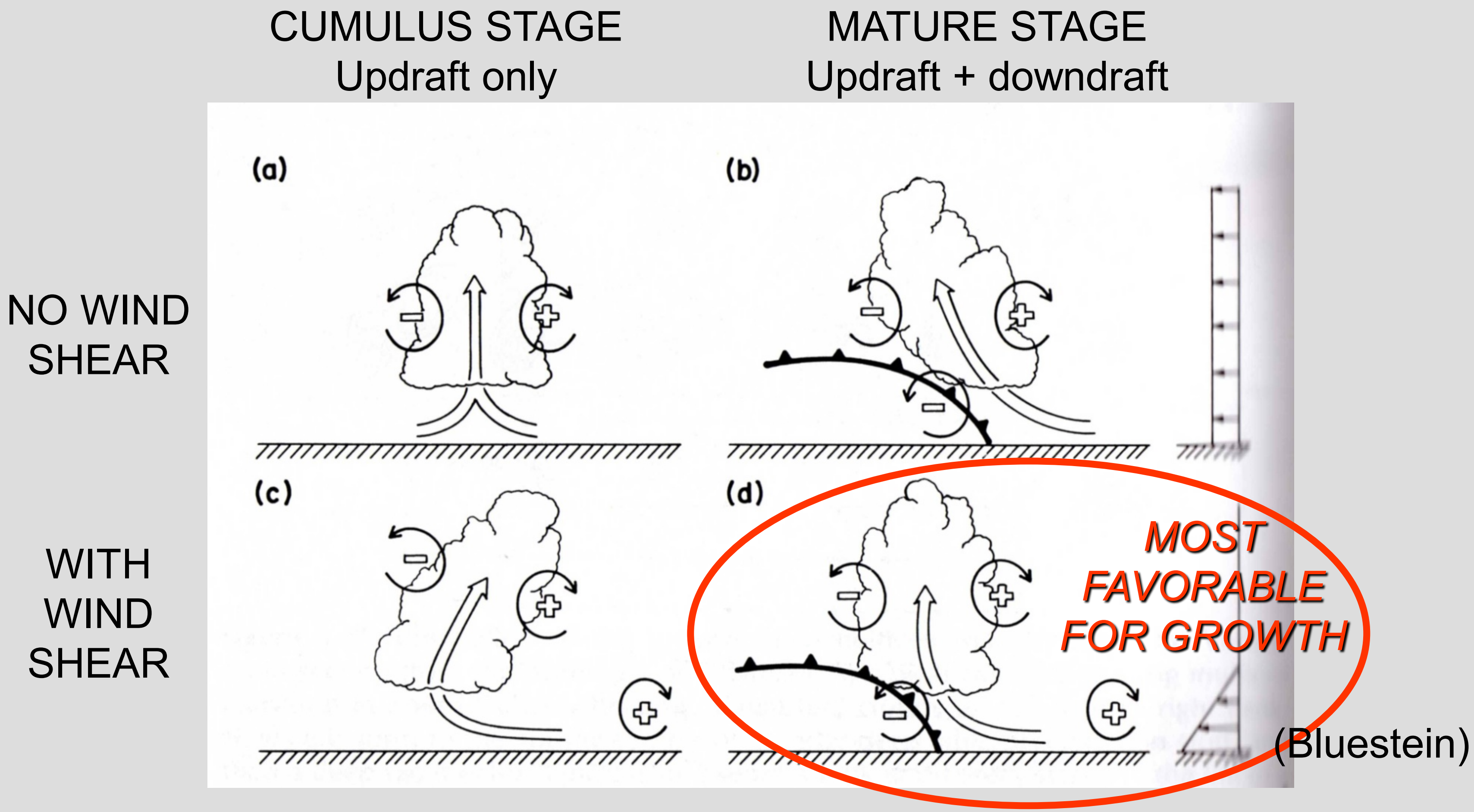
Figure 8.7 (a) Sequence of radar reflectivity images (0.5° elevation angle) from the State College, PA, WSR-88D on 30 May 2006 from 2211 to 2332 UTC showing the evolution of single-celled convection (*disorganized convection* would perhaps be more appropriate terminology in this case). (b) Visible satellite image at 2232 UTC. (c) Sounding from Sterling, VA (IAD; the location is indicated with a star in [b]) at 0000 UTC 31 May 2006. Note the weak vertical wind shear (the magnitude of the 0–6 km vector wind difference is approximately 5 m s^{-1}).

Incorporation of vertical wind profile in diagnosing potential for convection

Idea: In addition to thermodynamic instability (CAPE), wind changing speed and direction with height to facilitate convective organization.

Why that is we'll talk about later, by further analysis of how the shear affects growth from a dynamical standpoint, but point is to become familiar with basic convective types, structures now.

Why is wind shear a necessary ingredient for severe thunderstorms?



Wind shear allows the updraft to be maintained in the cloud and not get choked off by the downdraft—so the thunderstorm keeps receiving the warm, moist air it needs to keep growing.

Multicell Thunderstorms

In moderate shear, thunderstorms can get a bit more organized (meso-β, meso-α scales), numerous and have longer lifetimes.

Note the tilted structure of the anvil with respect to the cloud base—this indicates wind shear.

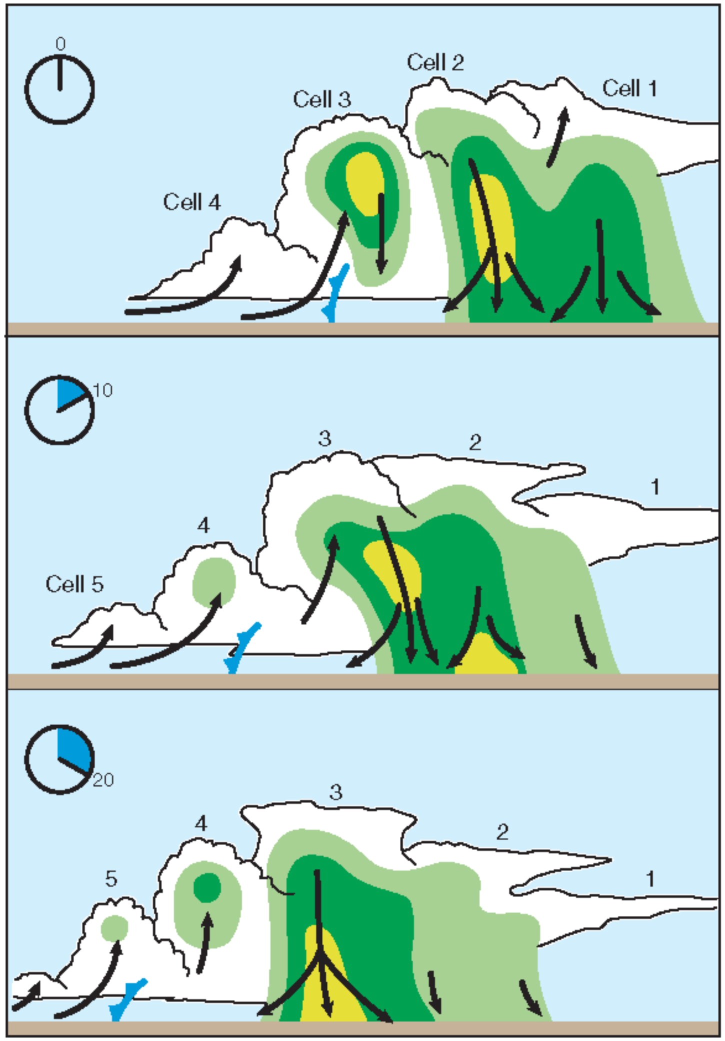


Figure 8.11 Schematic of the evolution of multicellular convection. Refer to the text for details. (Adapted from Doswell [1985].)

Repeated development of new convection along the gust front, on downshear flank of outflow

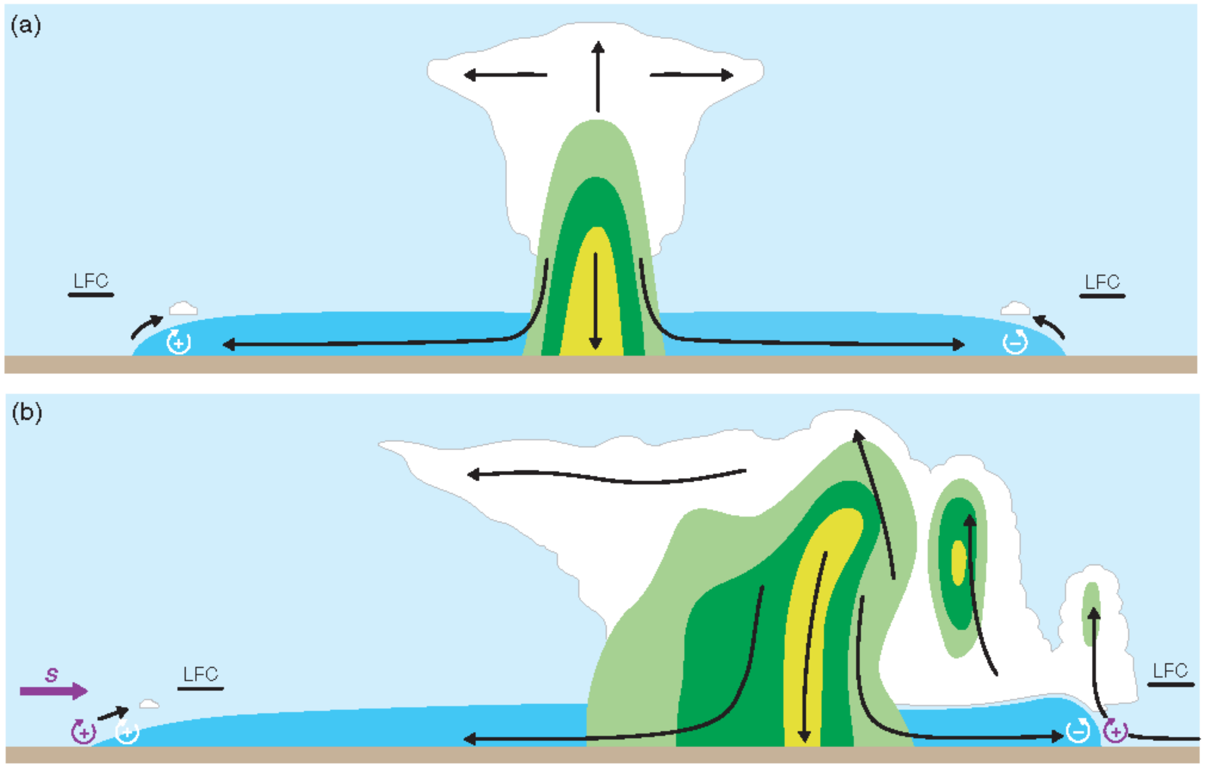
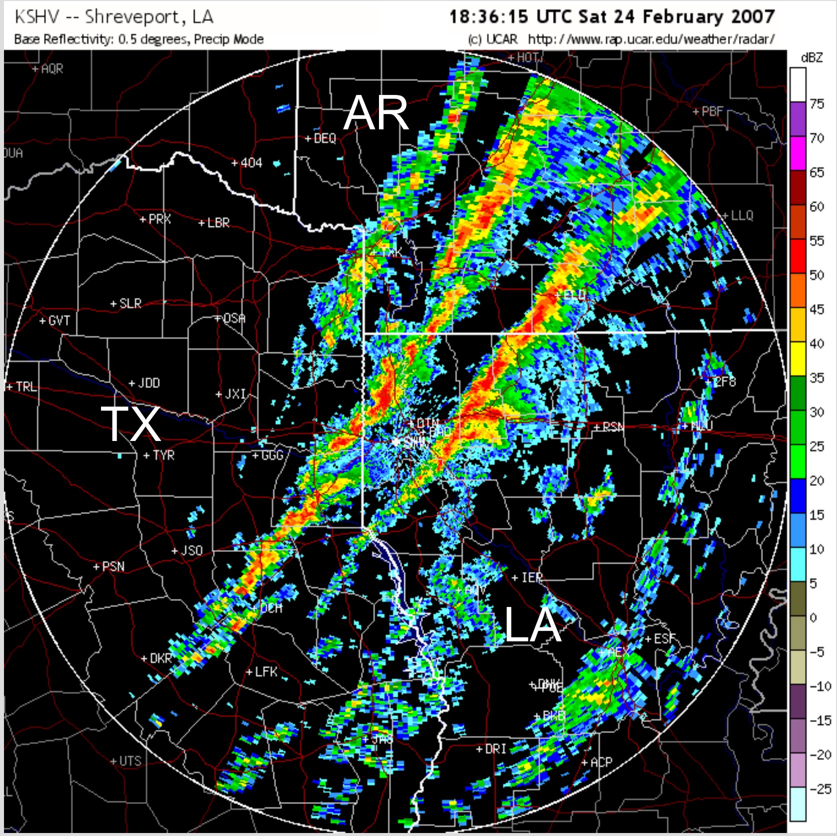


Figure 8.12 Comparison of lifting by the gust front in (a) a no-shear, single-cell environment and (b) a moderate-shear, multicell environment (the shear is westerly). Rain and hail are schematically indicated by the green and yellow shading. Evaporatively cooled outflow is shaded dark blue. Cloud is white. Some select storm-relative streamlines are shown as black arrows. The LFC is also indicated. The sense of the horizontal vorticity induced by the cold pools is indicated with white circular arrows. In (b), the sense of the horizontal vorticity associated with the environmental vertical wind shear is indicated with purple circular arrows. Moreover, the modification of the depth and slope of the leading portions of the cold pool by its interaction with the environmental shear, along with the effect on the nature of the lifting along the gust front, is also reflected in (b). Compare the depths of the western and eastern outflow heads in (b) to each other, as well as to those drawn in (a).

Squall Line



Squall lines on radar image in the warm sector of Colorado low.
(February 2007 Case)

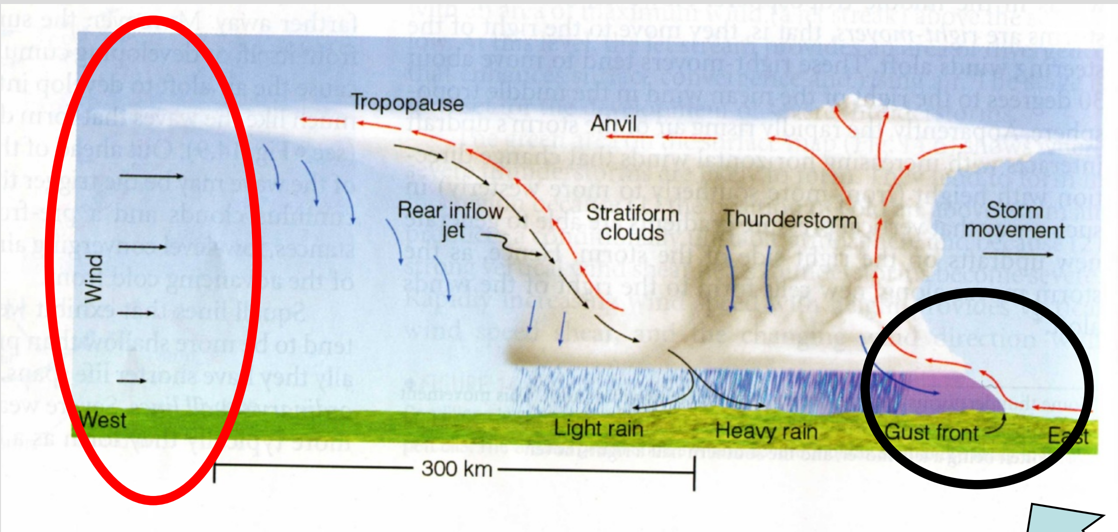
Line of thunderstorms that can be hundreds of miles long.

Form along the cold front or ahead of it in the warm sector

Heavy precipitation on the leading edge and then light rain behind.

Multiple lines may form, with the leading line being the most severe.

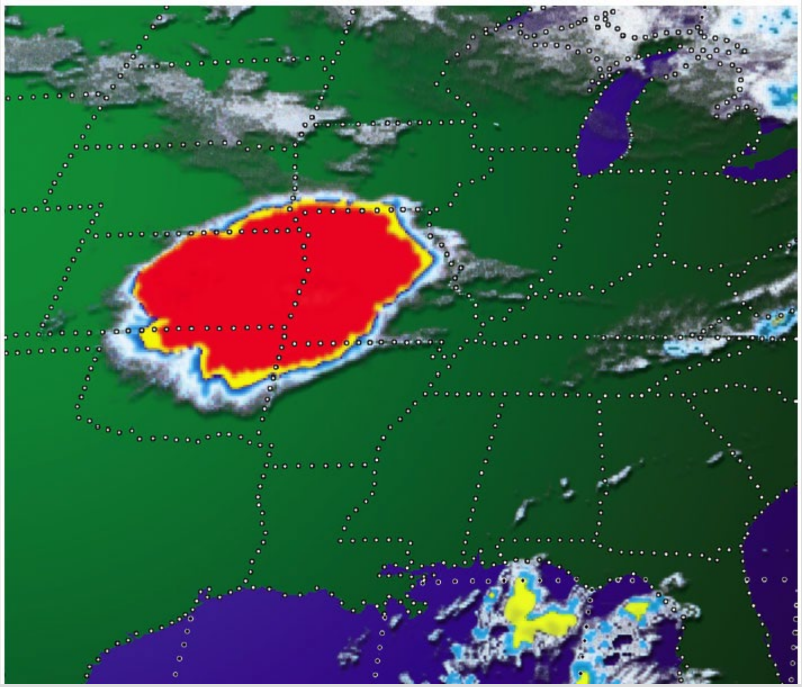
Idealized squall line thunderstorm structure



Note the wind shear profile

Shelf cloud at leading edge of squall line

Mesoscale Convective System (MCS)



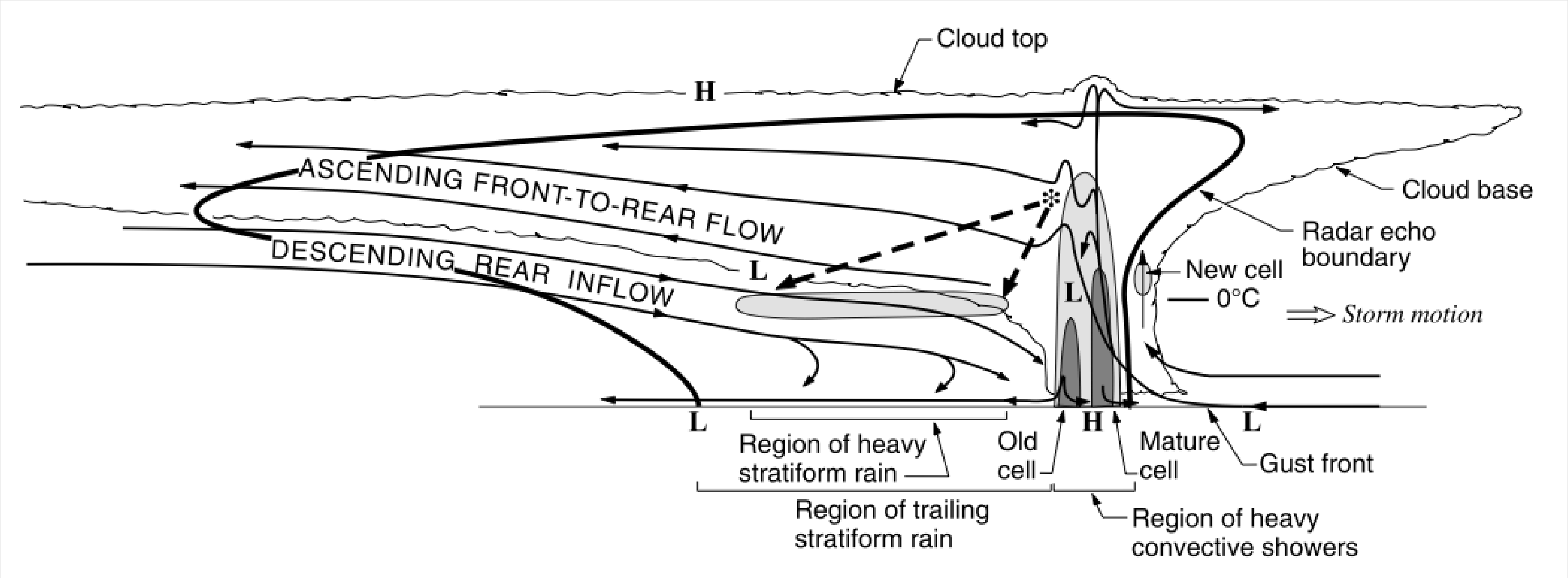
A number of individual thunderstorms cluster together to form a giant circular convective weather system.

Can be the size of an entire state!

Most common in summer, originating from convection which forms over mountains (the Rockies in the case of U.S.)

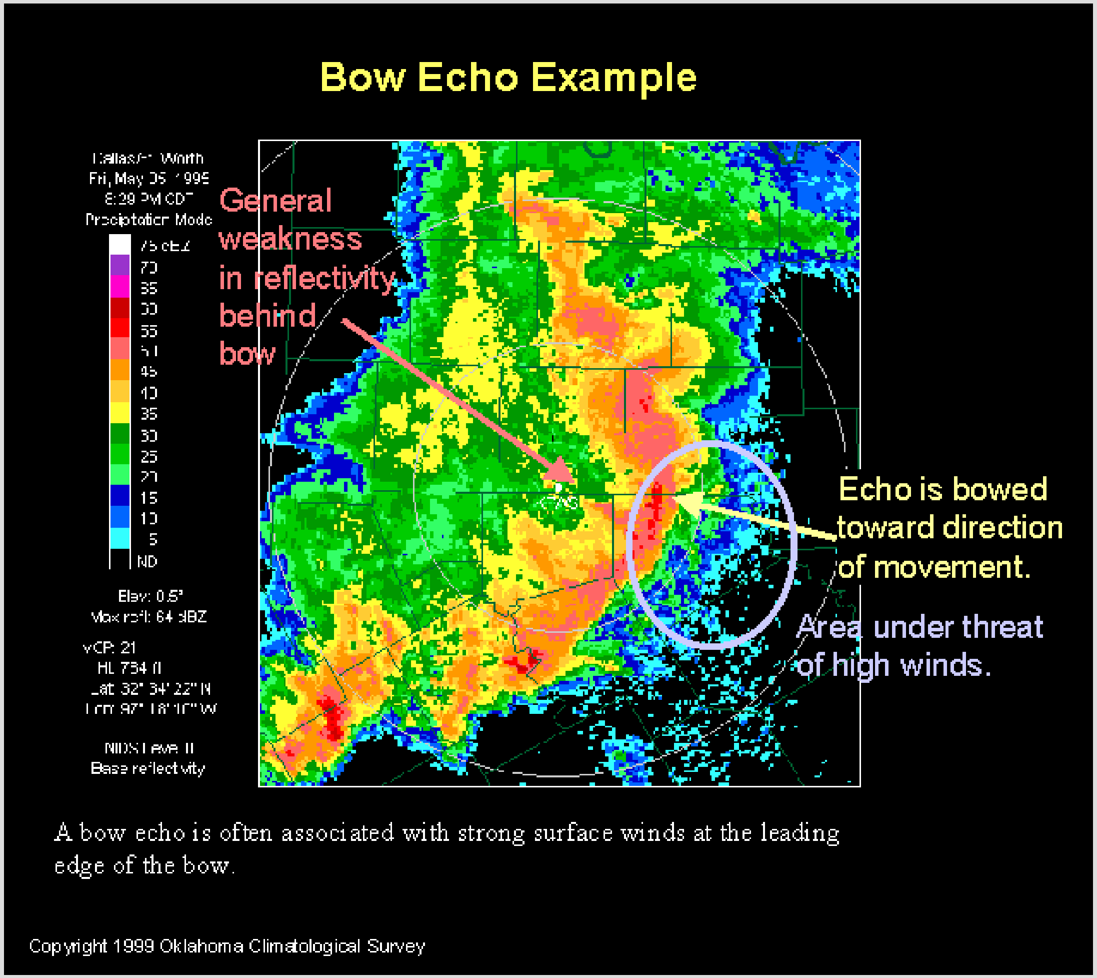
Sometime referred to as ‘quasi-linear’ convective systems (QCLS)

Idealized structure of a mature mesoscale convective system



Houze (1993)

Derecho or Straight Line Wind



Bow echoes are typically found in well developed mesoscale convective complexes.

These produces very strong (straight line) winds which can potentially exceed hurricane force
(75 mph).

Called a derecho
(*Spanish = straight ahead*)

Ingredients for a supercell

INGREDIENT 1: HIGH "CAPE"

Make the atmosphere more conditionally unstable by:

- Warming and moistening near the surface
- Cooling and drying aloft

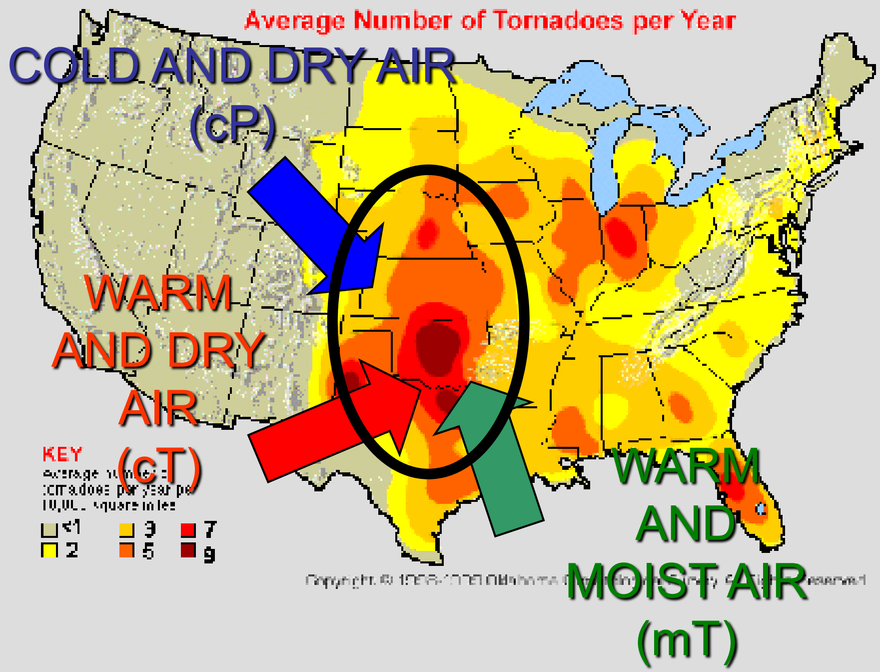
INGREDIENT 2: LARGE HELICITY

Helicity is essentially the integrated *directional wind shear*, or change in horizontal wind speed and direction, through a vertical depth.
NECESSARY FOR THE STORM TO ROTATE!

INGREDIENT 3: A CAPPING INVERSION

An inversion that occurs near about 800-mb. Only a few strong updrafts break through the cap and utilize the enormous amount of convective available potential energy

Tornadoes occur where three different air masses clash



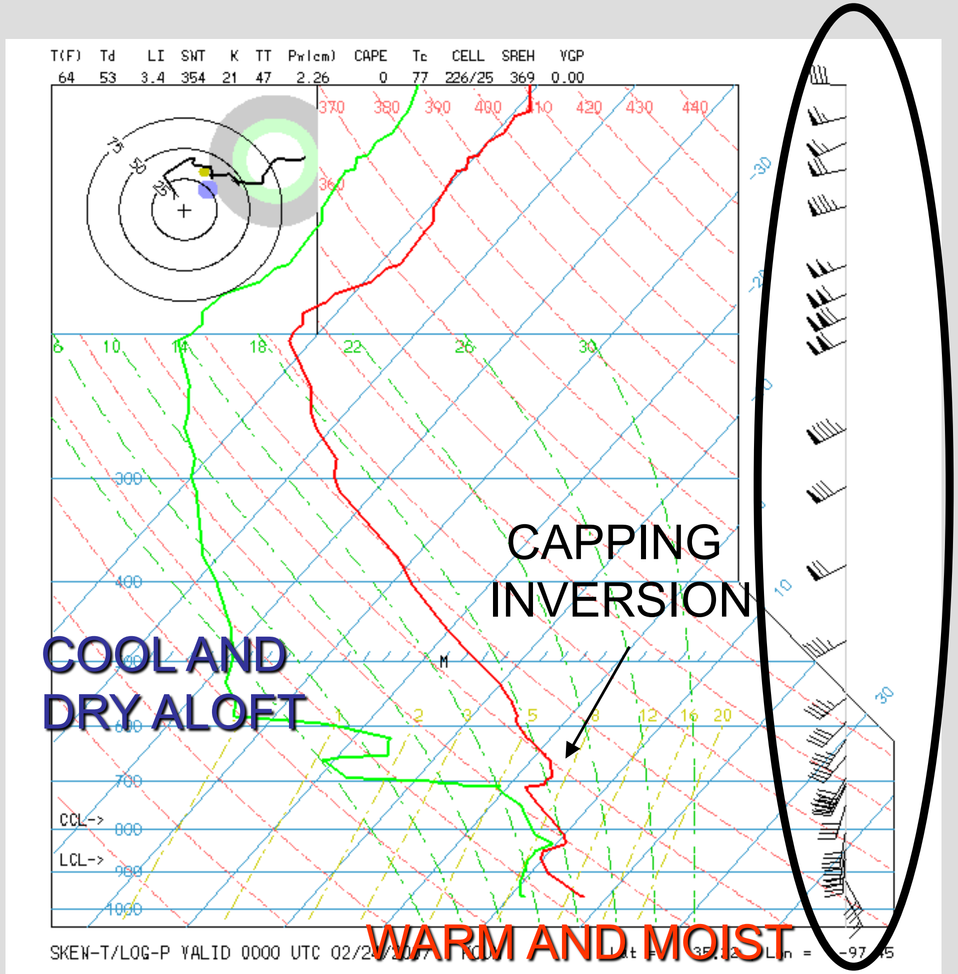
Tornadoes (and the supercell thunderstorms that spawn them) are most prevalent in “tornado alley” in the central U.S.

Some of the most severe weather on Earth!

Tornado Alley: A unique clash of air masses like no where else on Earth

AIRMASS	WINDS	CHARACTER	WHAT IT DOES
cP	Westerly above about 700 mb	Cold and dry.	CREATES INSTABILITY ALOFT
cT	Southwesterly at about 800 mb	Warm and dry.	PROVIDES CAPPING INVERSION
mT	Southerly to Southeasterly near surface	Warm and moist	CREATES INSTABILITY NEAR SURFACE AND PROVIDES FUEL FOR STORMS

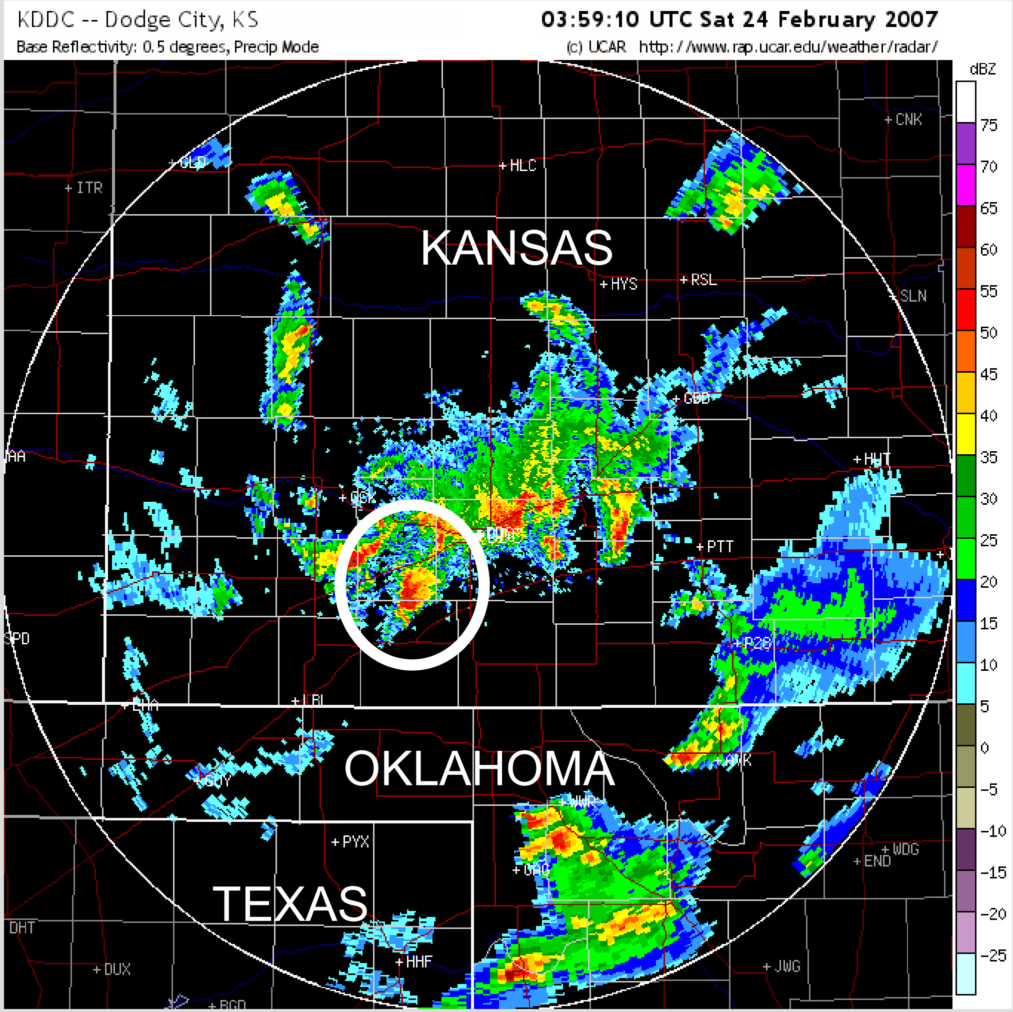
THE "LOADED GUN" SOUNDING
THE SIGNATURE FOR SUPERCELLS



NEAR SURFACE

WIND DRASTICALLY CHANGES IN SPEED AND DIRECTION WITH HEIGHT

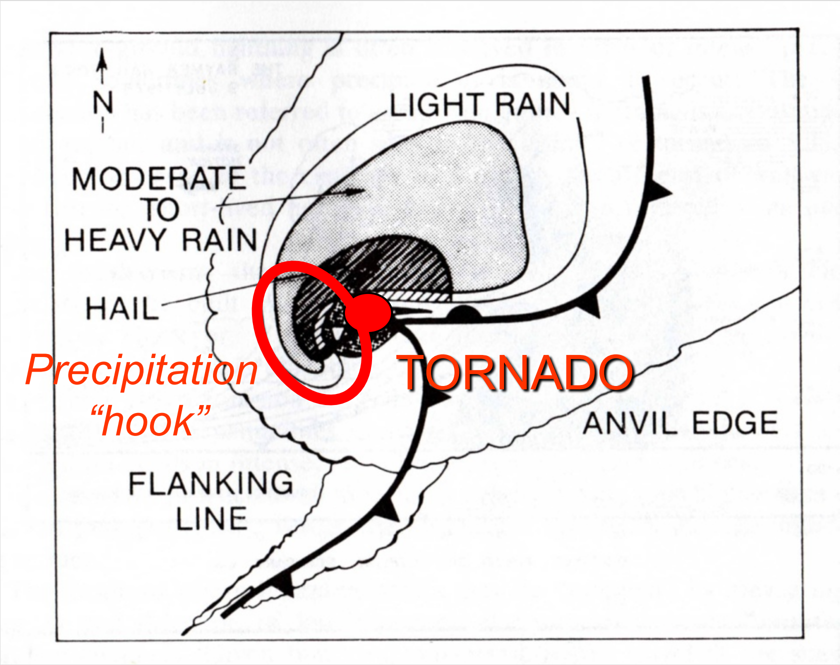
Supercells on radar

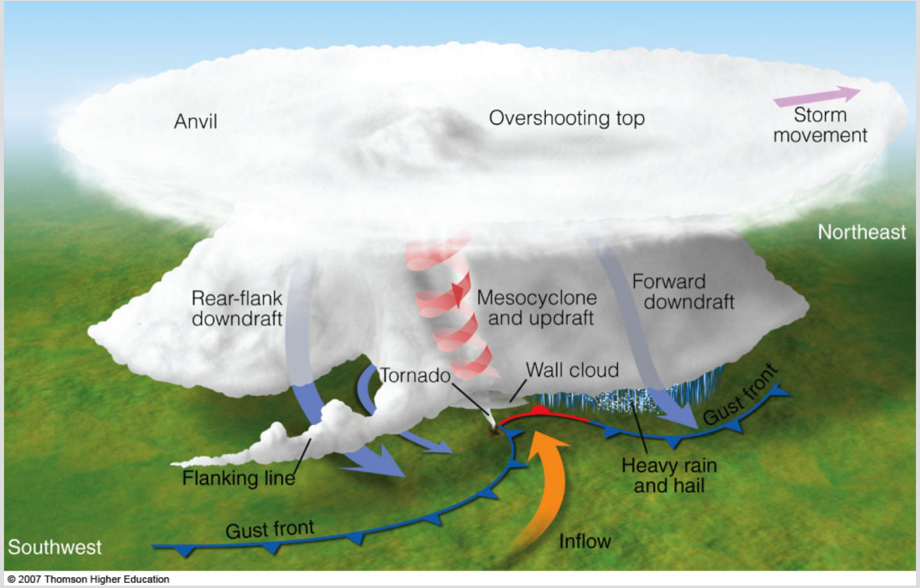


NOT big long squall lines.

Get compact and isolated rotating cells.

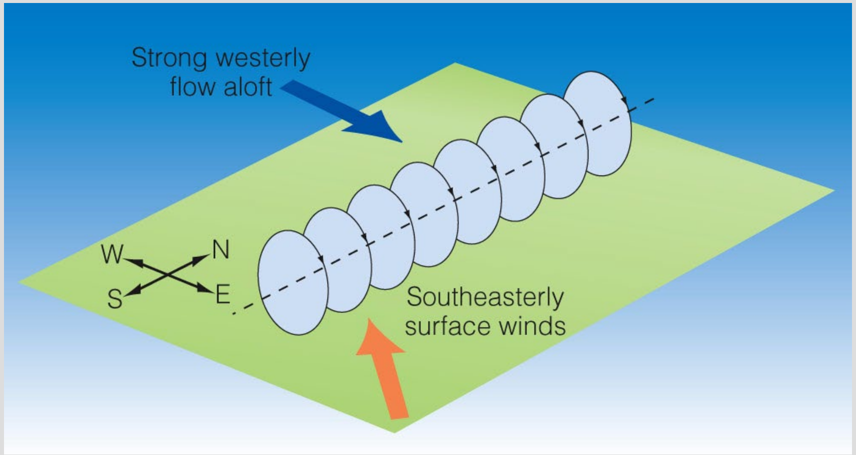
Horizontal structure of a tornadic supercell

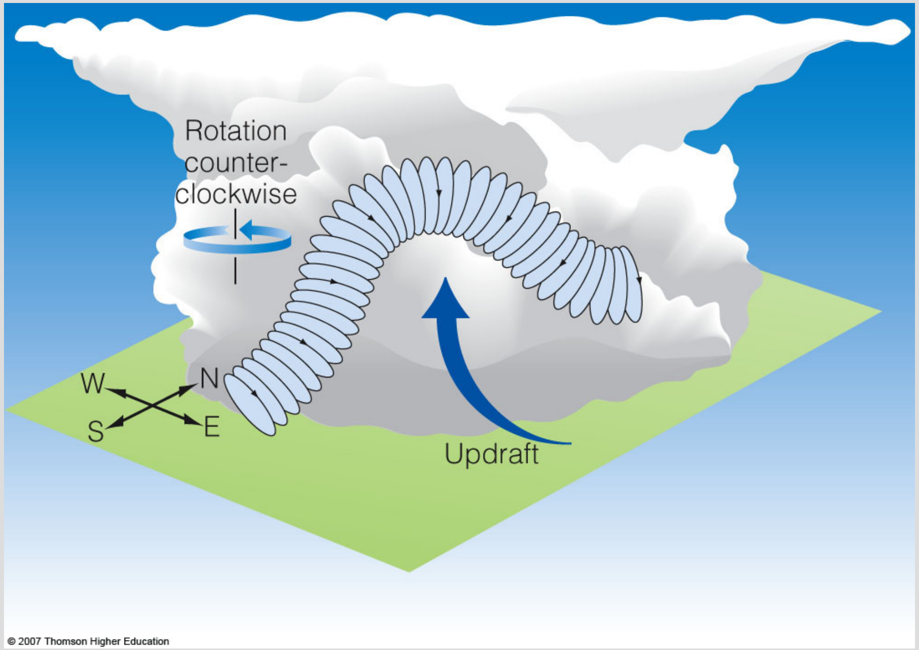




The tornado is located in front of the precipitation "hook" which defines the area of hail and rain curving around the mesocyclone.

Formation of a rotating updraft in a supercell



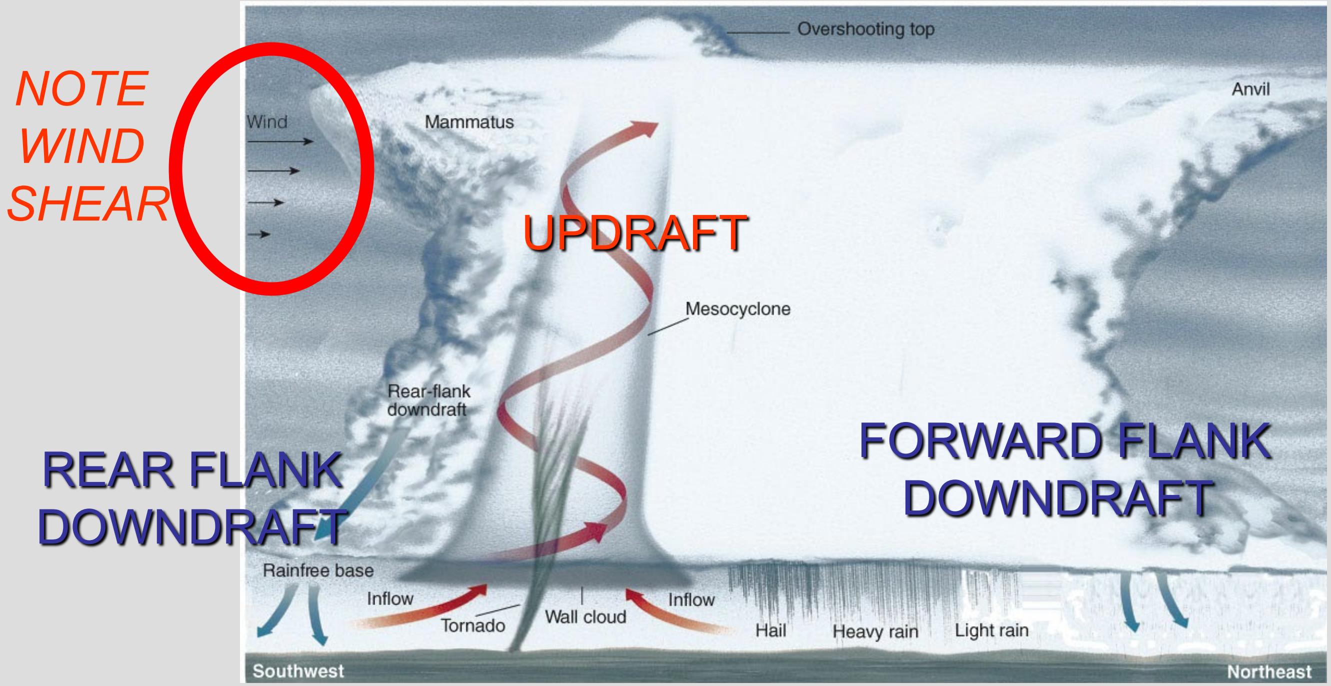


Wind shear caused by a change in wind speed and direction with height causes rotation in the horizontal.

Updraft in a thunderstorm tilts horizontal rotation into vertical rotation.

Net result is a relatively small, supercell rotating about a mesocyclone.

Vertical structure of tornadic supercell



REAR FLANK DOWNDRAFT: Downdraft at the base of the supercell, right before the wall cloud.

UPDRAFT: Tornado forms at the base of the updraft is the extension of the mesocyclone, defined by a *wall cloud*.

FORWARD FLANK DOWNDRAFT: Precipitation falls in the form of (possibly large) hail and heavy rain.

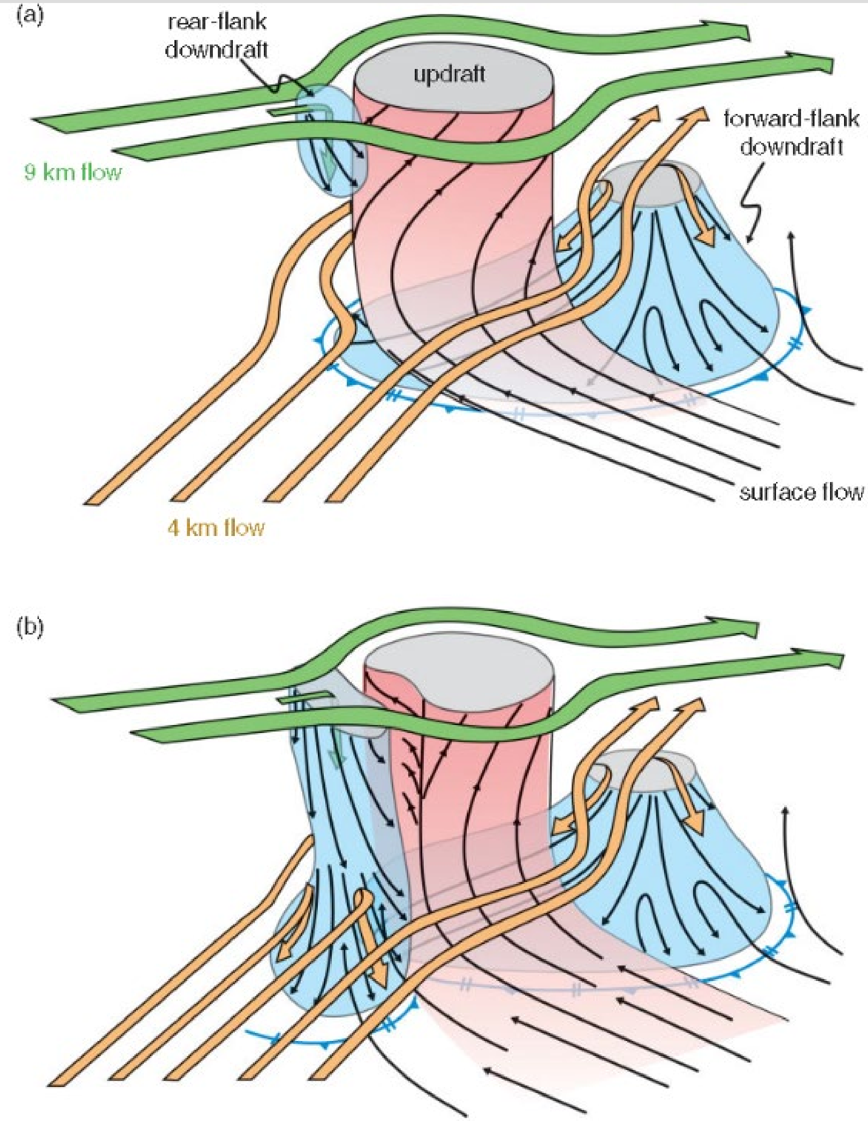


Figure 8.20 Schematic three-dimensional depiction of updraft and downdraft structure in a supercell storm (a) early in the lifetime and (b) during the mature stage, as proposed by Lemon and Doswell (1979). One aspect of this conceptual model that should probably not be taken too literally is the implied descent of air from high altitudes all the way to the surface. (The original figure caption by Lemon and Doswell in fact warns against literal interpretation of the arrows as actual streamlines or trajectories.) (Adapted from Lemon and Doswell [1979].)

Wall cloud in rotating mesocyclone

Figure 8.17 A midlevel mesocyclone is the defining visual characteristic of a supercell storm. Little imagination is needed to sense the cyclonic vertical vorticity associated with the storm updraft. Photograph by Herb Stein (the Dopper On Wheels radar is in the foreground).

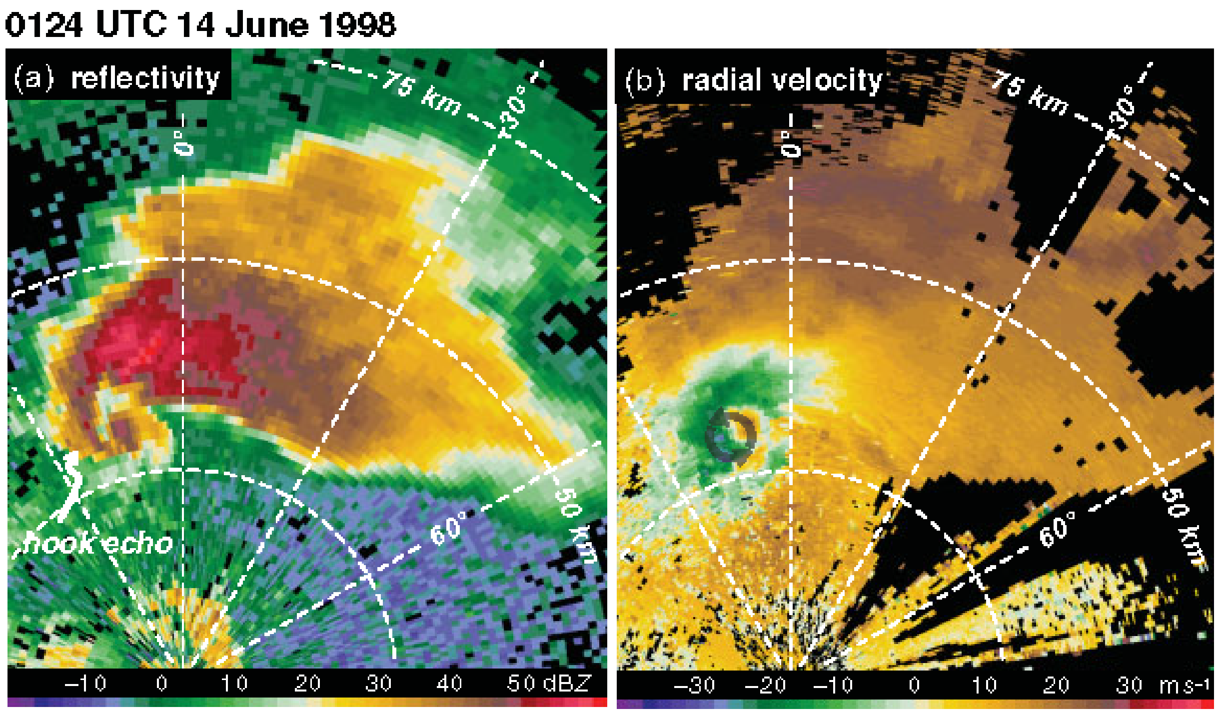


Figure 8.18 A hook echo in reflectivity data and an inbound–outbound couplet in radial velocity data are the defining radar characteristics of supercells in low-altitude radar scans. The images are (a) reflectivity and (b) radial velocity from the Oklahoma City, OK, radar at 0124 UTC 14 June 1998. The inbound–outbound radial velocity couplet is oriented such that the zero contour is approximately parallel to the radials, with inbound (outbound) velocities to the west (east), thereby implying cyclonic vertical vorticity.

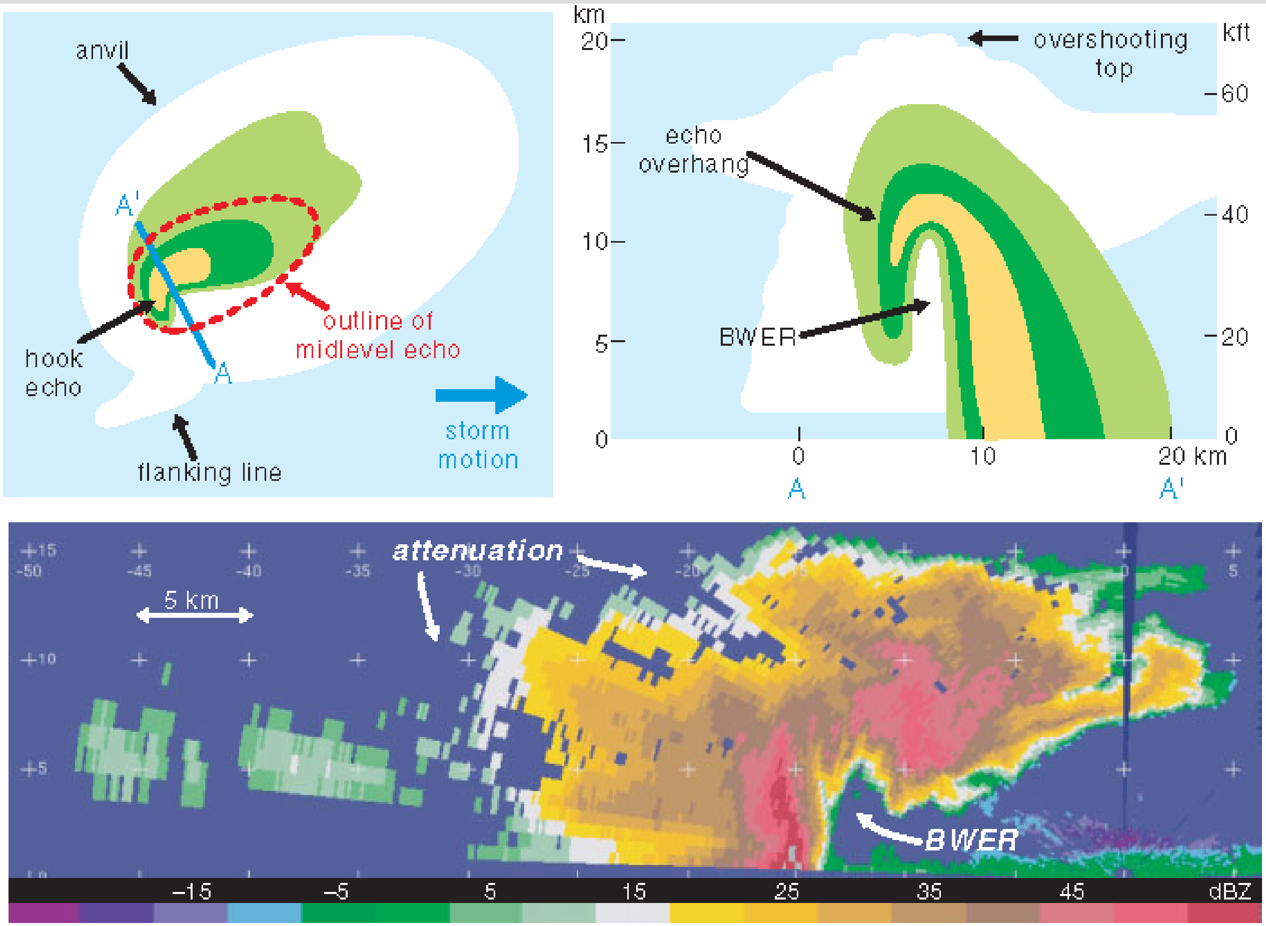


Figure 8.21 Top, schematic of the reflectivity structure of a supercell, showing the relationship between the bounded weak echo region (BWER), overshooting top, and hook echo. The green and yellow shading indicates weak, moderate, and high radar reflectivity visible at low levels (top left) and in a vertical cross-section (top right). Bottom, actual quasi-vertical cross-section of radar reflectivity factor in a supercell thunderstorm obtained from a helically scanning radar mounted in the tail of an aircraft at 2306 UTC 16 May 1995 during the Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX).

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 ($\sim$1000–2500 J kg^{-1})	Ordinary cell	Ordinary cell/supercell[b]	Supercell[b]
High ($\gtrsim$2500 J kg^{-1})	Ordinary cell[b]	Ordinary cell[b]/supercell[b]	Supercell[b]

[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).

Bulk Richardson number (R)

Since storm strength is dependent on BOTH instability and shear, can define a bulk Richardson number (R).

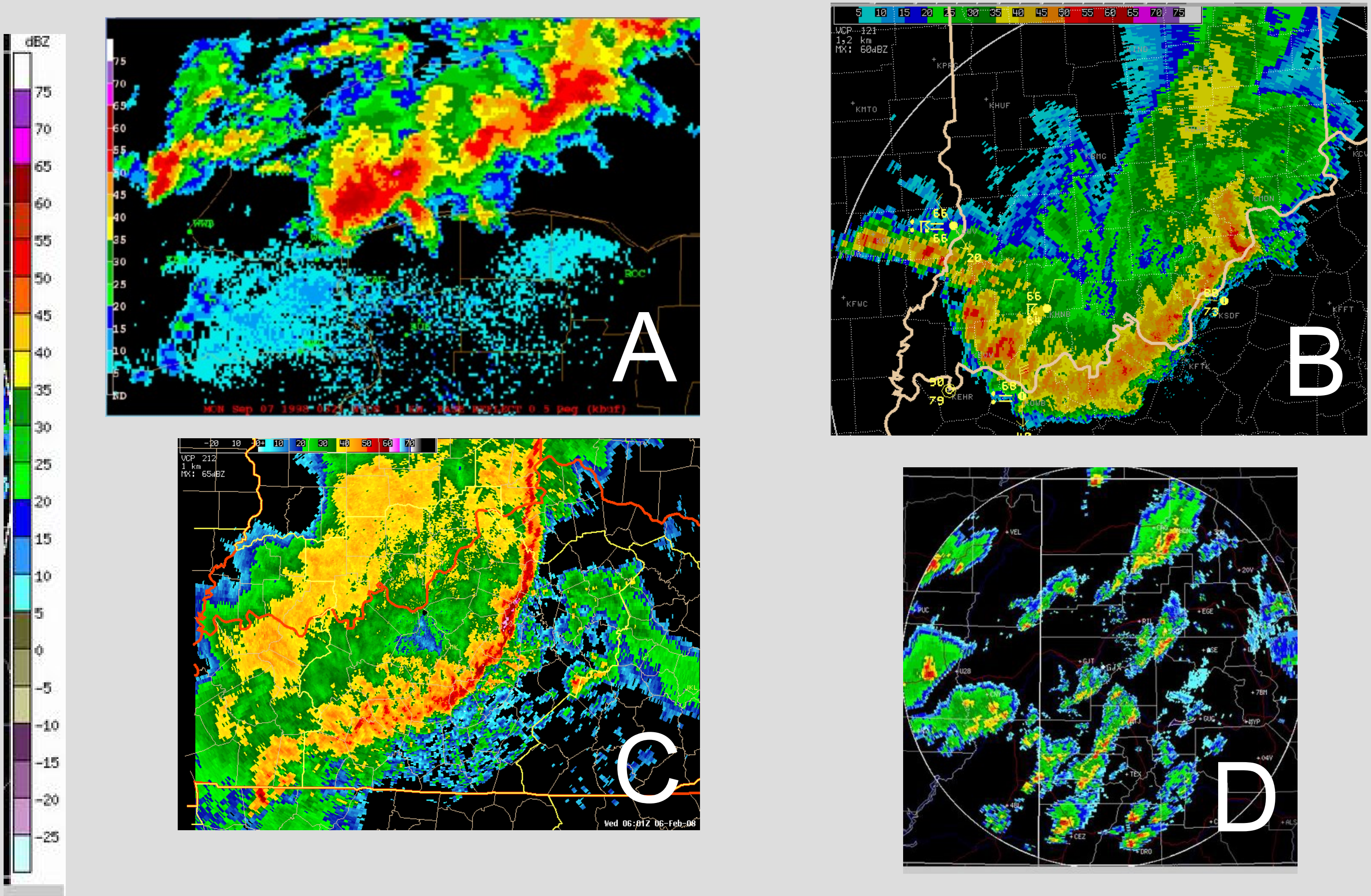
$R = CAPE/S^2$

$S^2 = ½ (u_{6km} – u_{500m})^2$

This measure gives some indication of the potential for organized convection.

Supercell (tornadic) thunderstorms tend to form with $10 < R <40$. So need some sort of optimal balance of CAPE vs. shear to get most intense kinds of thunderstorms.

REFLECTIVITY



Johnson & Mapes (1997)

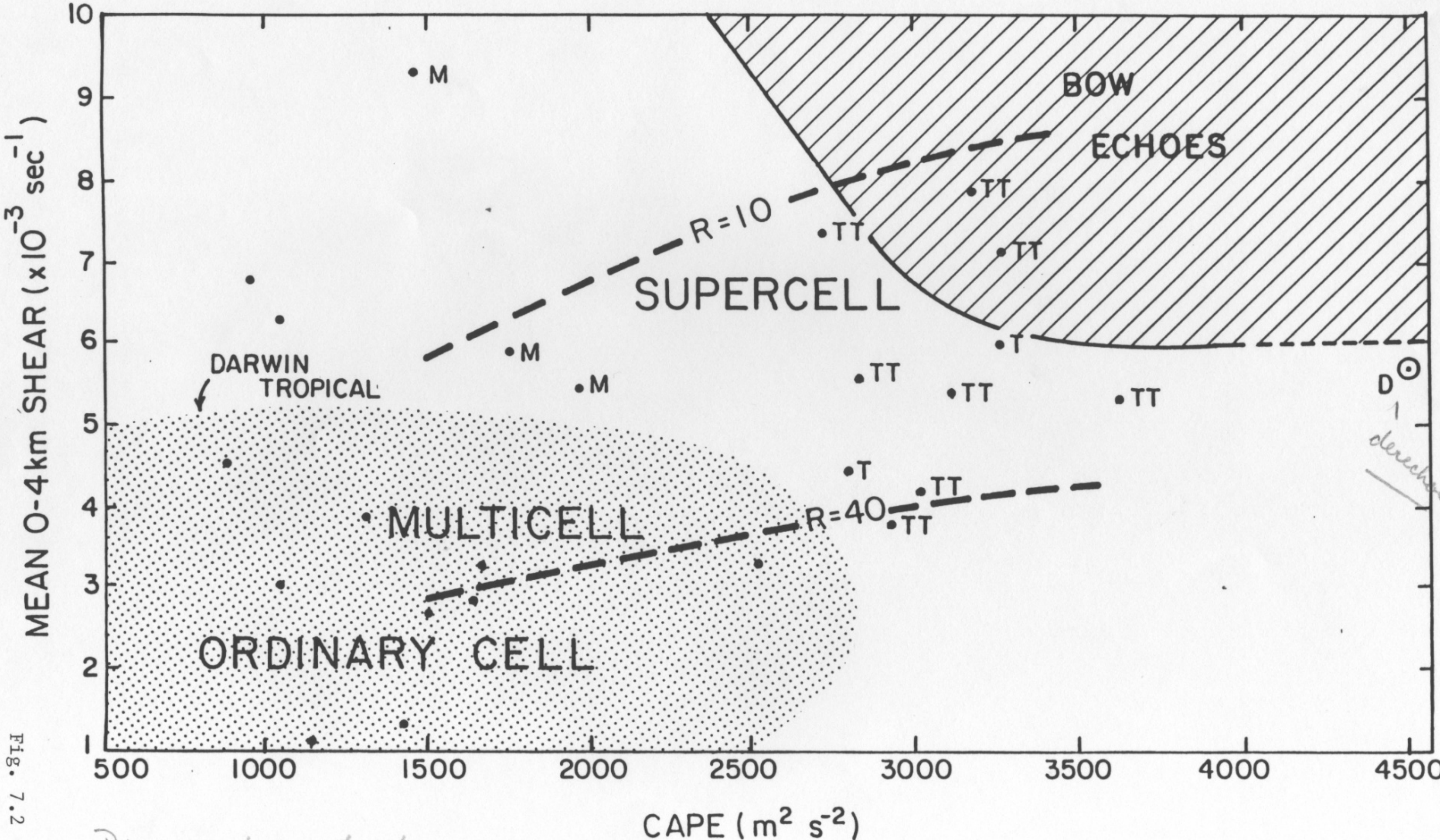
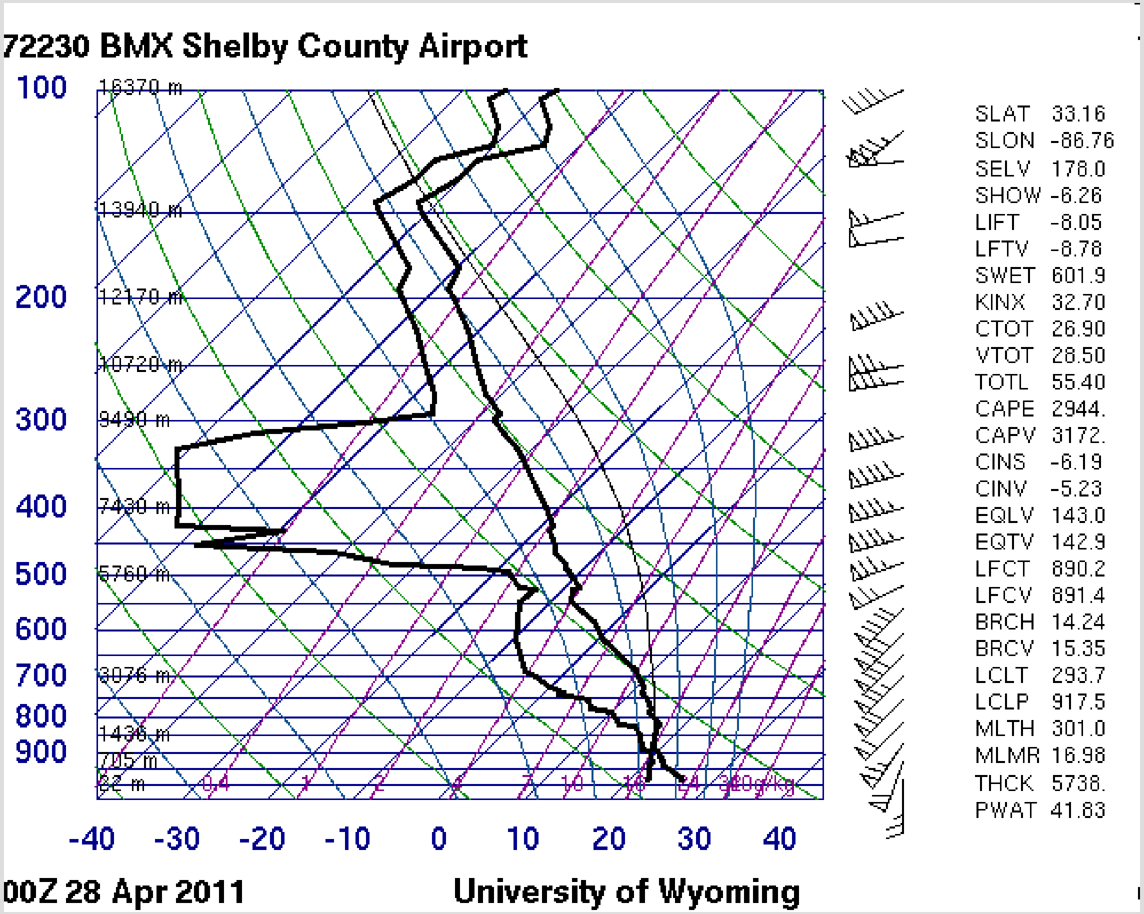


Fig. 7.2

Diagram does not show turning of the shear vector

T = tornado
M = mesocyclone

Sounding for Alabama tornado outbreak in late April 2011



http://www.srh.noaa.gov/images/bmx/significant_events/2011/042711/Radar/ref_80.gif