Practical Use of the Skew-T, log-p diagram for weather forecasting

Primer on organized convection

Outline

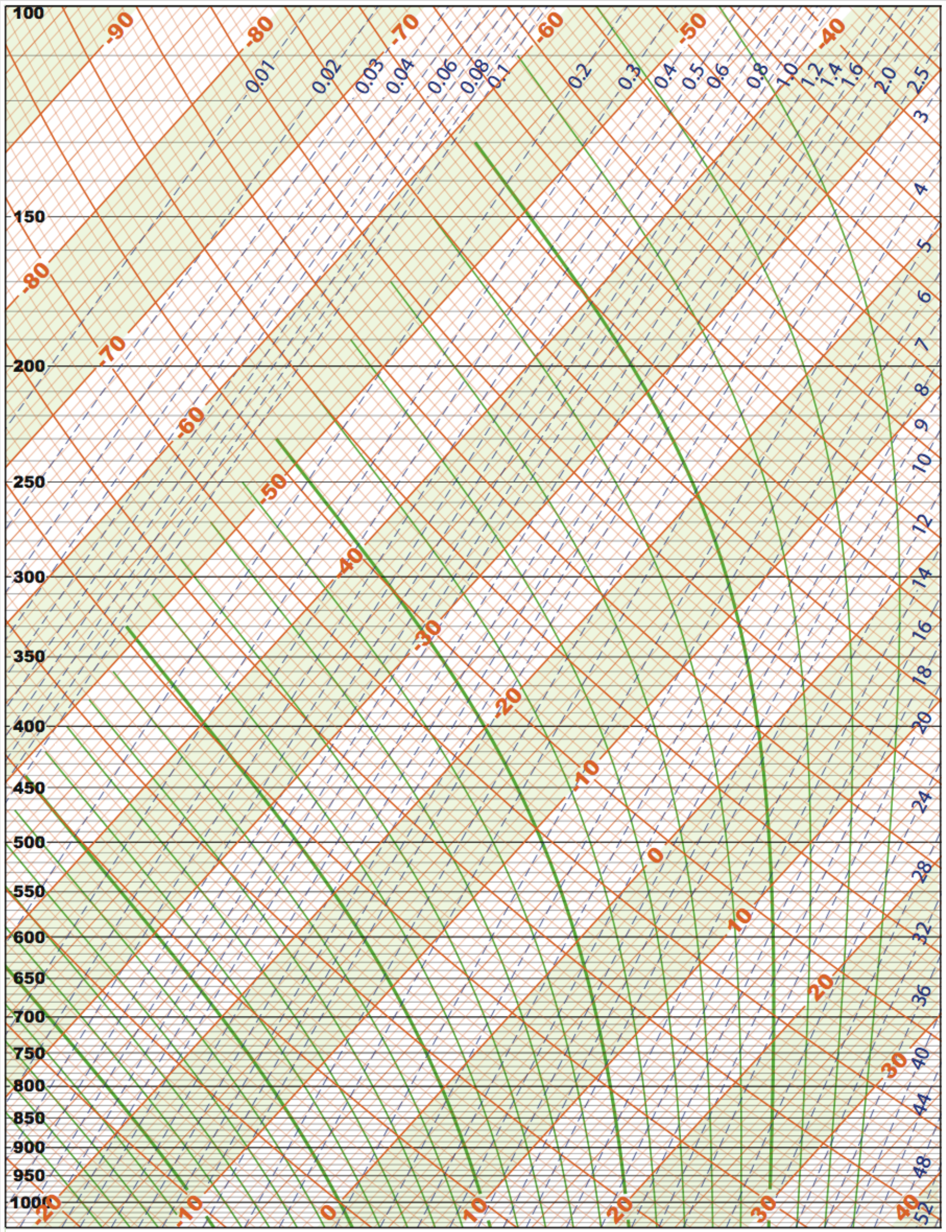
Rationale and format of the skew-T, log-P diagram

Some basic derived diagnostic measures

Characterizing the potential for convection

Accounting for dynamic effect of vertical wind profile

Introductory overview to organized convection

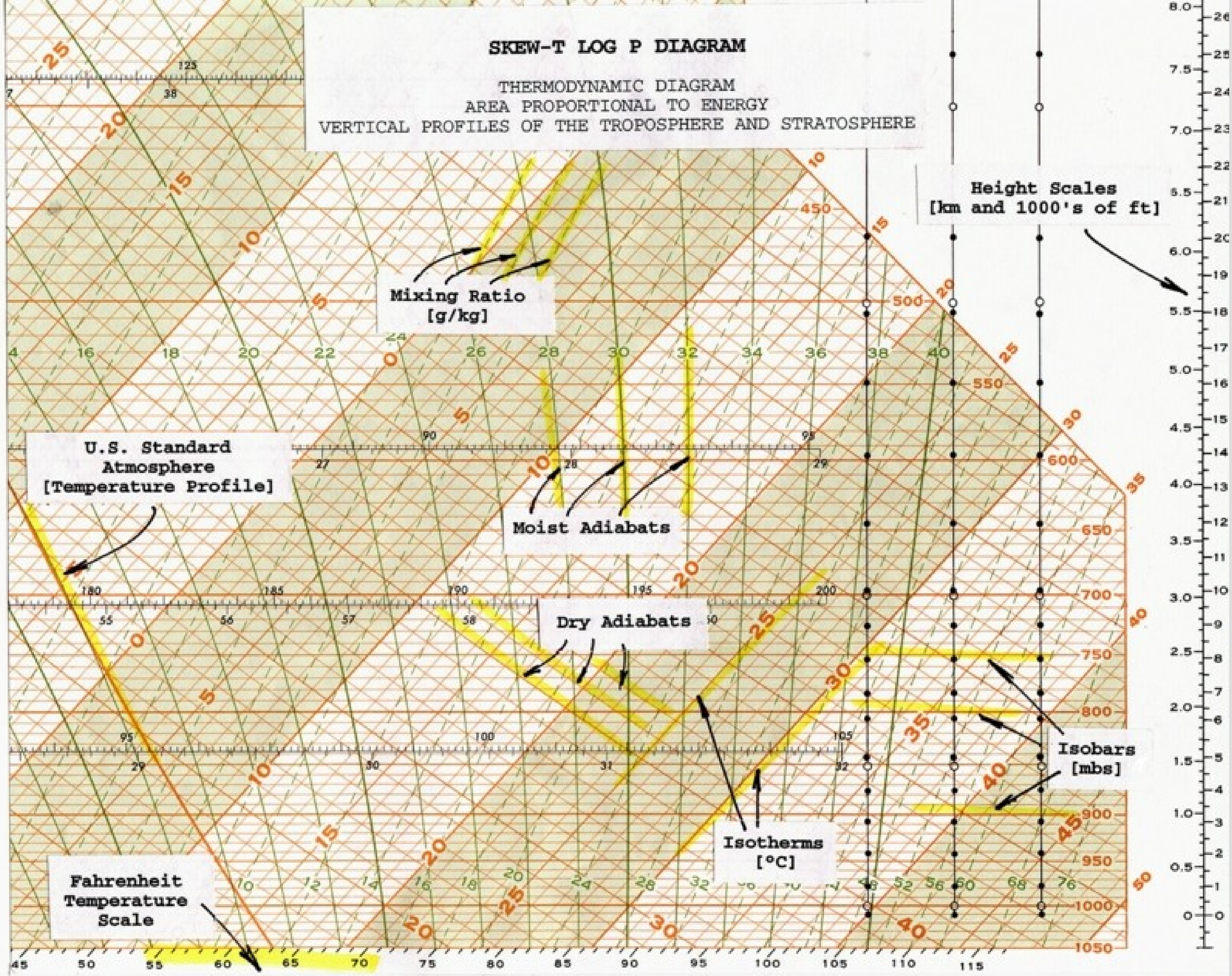


Rationales for the diagram

See the temperature and moisture (dew point) profiles of the observed atmosphere (as recorded from a radiosonde)

The diagram is, at its essence, a visual depiction of the first law of thermodynamics (dq=du+dw)

Can be used to derive diagnostic quantities associated with both dry and moist adiabatic processes. This can be quickly done graphically without the use of formulas, which can be quite complicated when atmosphere is behaving moist adiabatically.


SKEW-T LOG P DIAGRAM
THERMODYNAMIC DIAGRAM
AREA PROPORTIONAL TO ENERGY
VERTICAL PROFILES OF THE TROPOSPHERE AND STRATOSPHERE
Height Scales
[km and 1000's of ft]
Mixing Ratio
[g/kg]
U.S. Standard
Atmosphere
[Temperature Profile]
Moist Adiabats
Dry Adiabats
Isobars
[mbs]
Isotherms
[°C]
Fahrenheit
Temperature
Scale

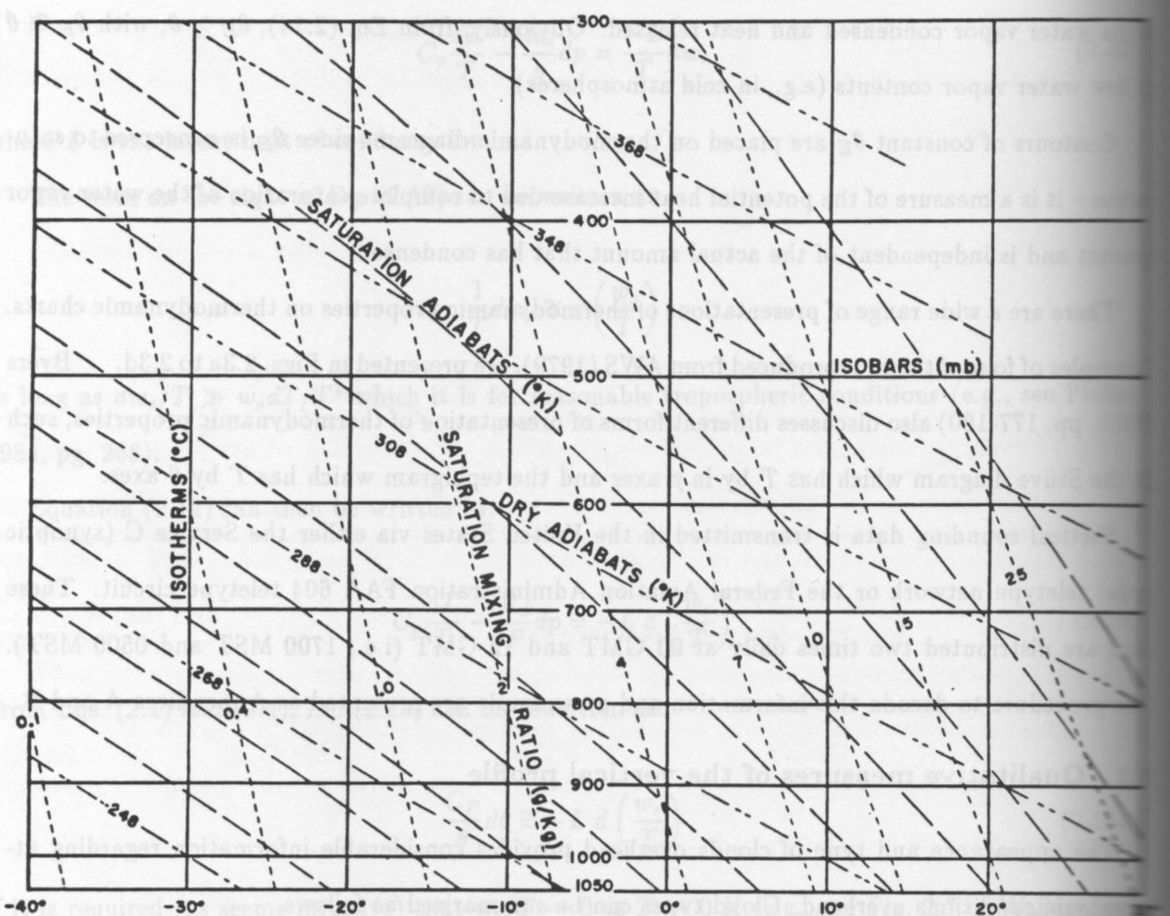


Figure 2.3: (a). Coordinate system of the emagram (from AWS, 1979).

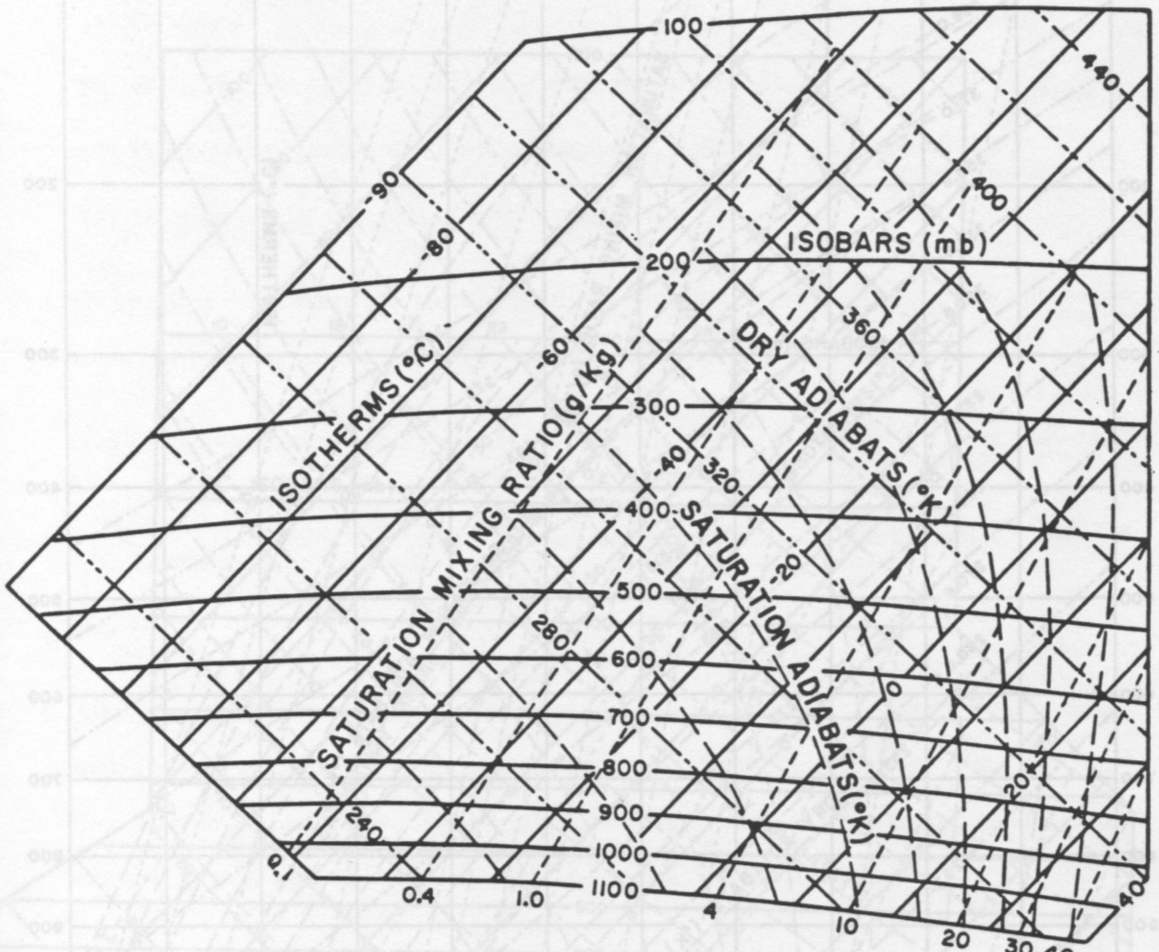


Figure 2.3: (b). Coordinate system of the tephigram (from AWS, 1979).

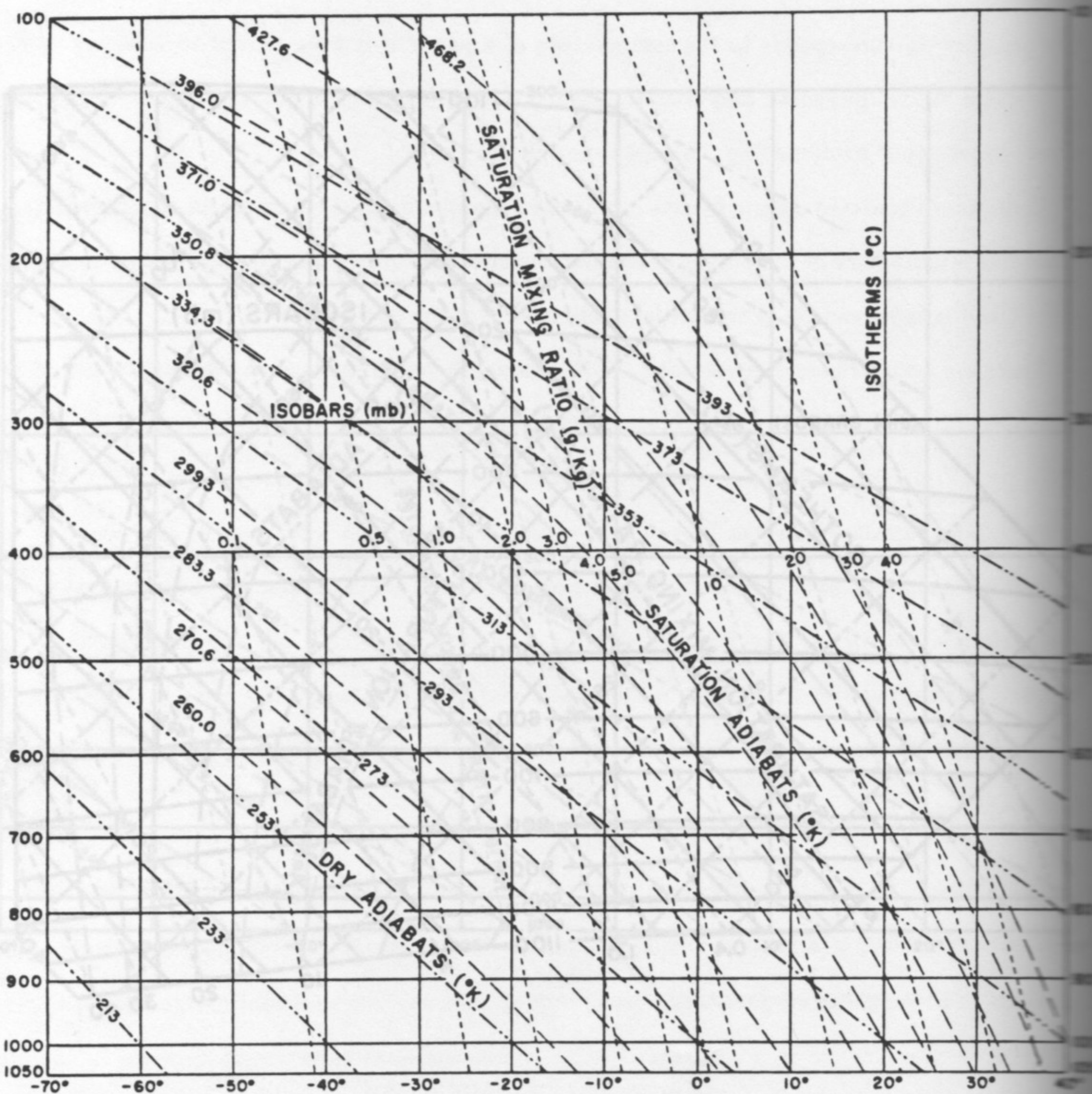
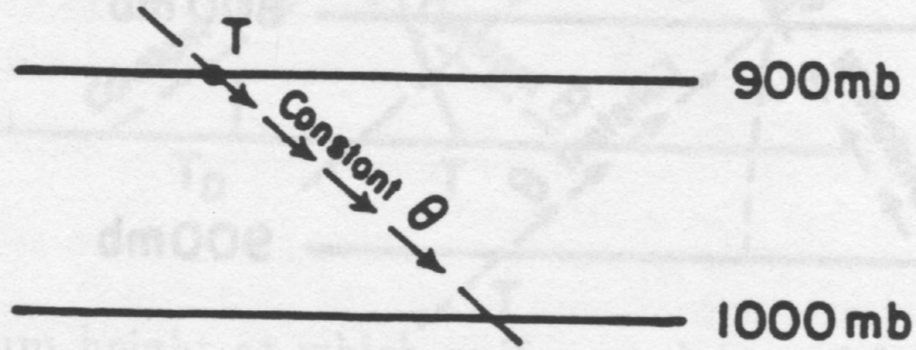


Figure 2.3: (c). Coordinate system of the Stüve ("pseudo-adiabatic) diagram (from AWS, 1979).

Some basic thermodynamically derived quantities

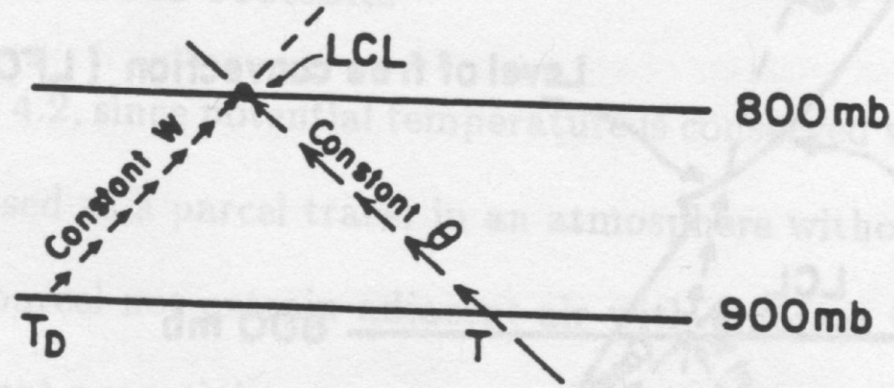
4.2.1 Potential temperature, (θ)



<u>Potential Temperature:</u> Temperature that a parcel of air would potentially have following a dry adiabat to the reference level of 1000-mb.

<u>Utility:</u> Absent any phase change of water, potential temperature will be conserved as a parcel moves vertically in the atmosphere.

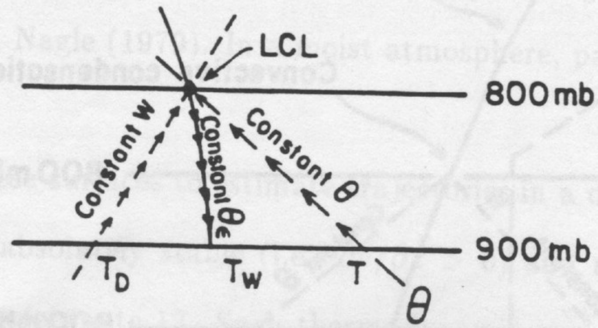
4.2.2 Lifted condensation level (LCL)



<u>Lifting condensation level:</u> Assuming dry adiabatic rise of a parcel with its mixing ratio conserved, defines the point at which the temperature of the parcel = dew point temperature and RH = 100%.

<u>Utility:</u> Defines where (the flat) cloud base is going to occur, especially for any cumuliform cloud. Also nominally defines the height of the planetary boundary layer, because potential temperature and mixing ratio nearly constant in PBL.

4.2.3 Wet bulb potential temperature (θ_W) and wet bulb temperature (T_W)



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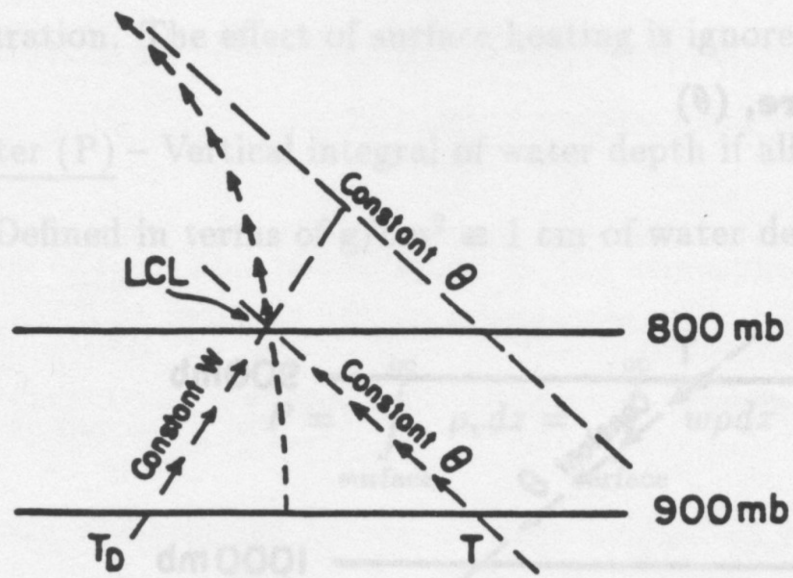
<u>Wet bulb temperature:</u> temperature a parcel of air would have if it were cooled to saturation (100% relative humidity) by the evaporation of water into it. Find by descending along a moist adiabat from LCL. Continue on to 1000-mb to find wet bulb potential temperature.

<u>Utility:</u> Wet-bulb temperature is one of the easiest manual measures of atmospheric moisture to calculate, via use of a sling psychrometer. Also relates to efficiency of evaporative cooling processes (e.g. swamp cooler)

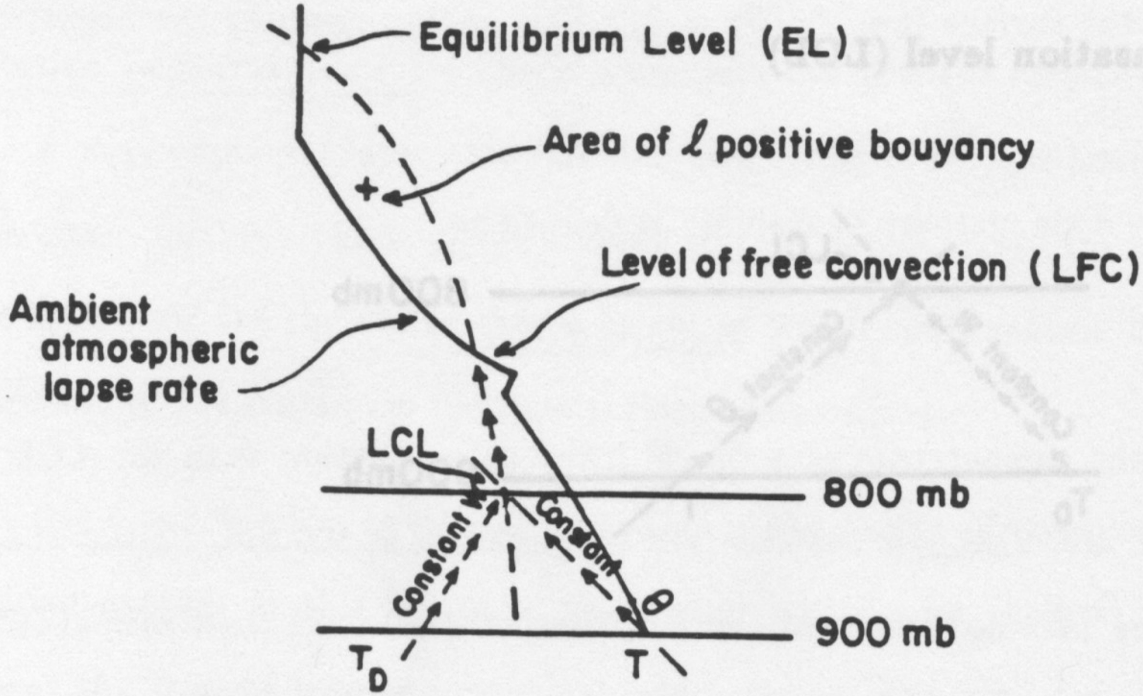
4.2.4 Equivalent potential temperature (θ_E)



<u>Equivalent potential temperature:</u> follow moist adiabat upward till all moisture is condensed out. Then descend along a dry adiabat to reference level of 1000-mb.

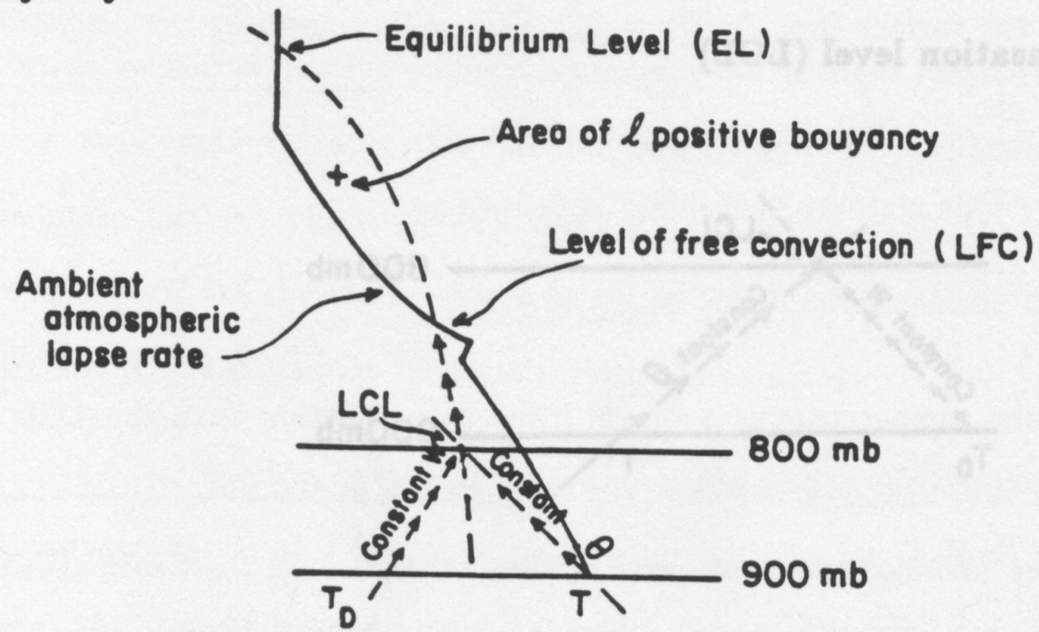
<u>Utility:</u> Potential temperature parcel of air would have if all its moisture were condensed out. Good as a combined metric of heat and moisture, which are requisite conditions in the lower atmosphere for convective initiation. Commonly used in reference to any convective processes (e.g. thundestorms, tropical cyclones), since saturated air moves along a moist adiabat

4.2.5 Level of free convection (LFC), equilibrium level (EL), and area of pos buoyancy



4.2.5 Level of free convection (LFC), equilibrium level (EL), and area of po

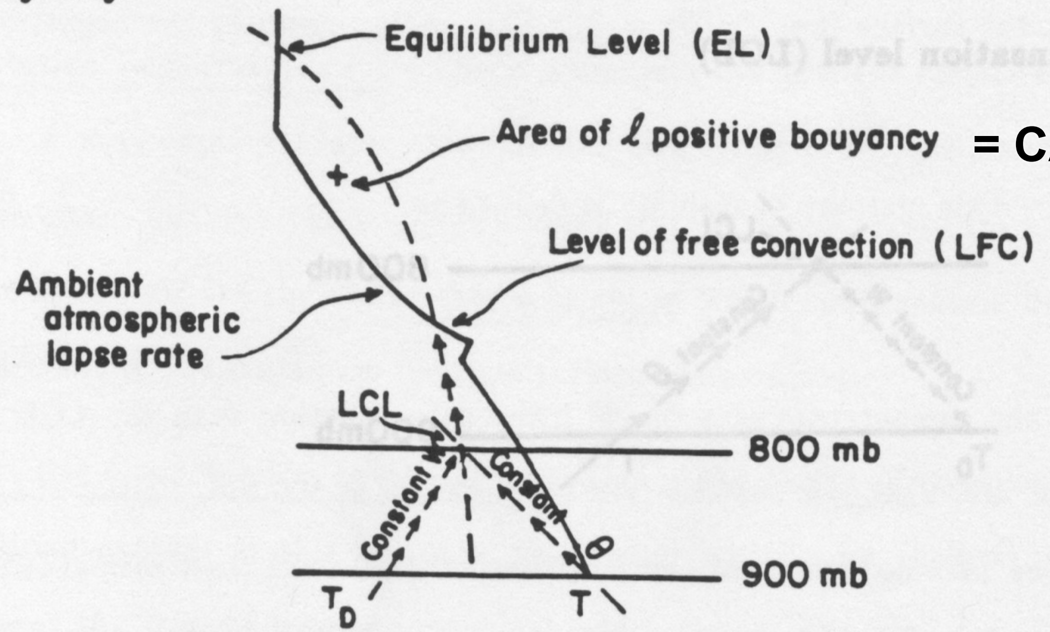
buoyancy



<u>Level of free convection (LFC):</u> Assuming moist adiabatic rise from LCL, defines point at which the temperature of the rising parcel > temperature of the environment. At this point the parcel is conditionally unstable and will spontaneously rise due to its positive buoyancy.

MUST reach this point to utilize any convective available potential energy present in the sounding. So some sort of forced lifting mechanism to trigger the convection on synoptic scale or mesoscale (e.g. a front, differential heating due to terrain, sea breeze circulation, mesoscale convective vortex, etc., etc.).

4.2.5 Level of free convection (LFC), equilibrium level (EL), and area of po buoyancy

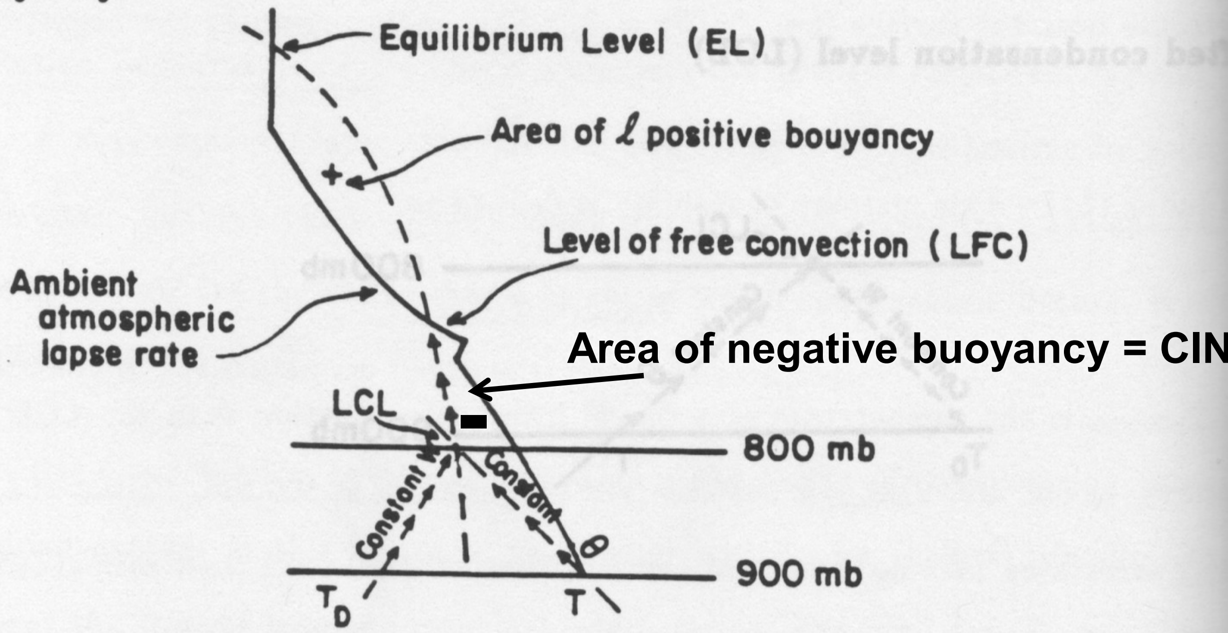


$$CAPE = g \int_{LFC}^{EL} \frac{\theta(z) - \bar{\theta}(z)}{\bar{\theta}(z)} \, dz$$

Convective available potential energy

Vertically integrated energy due to positive buoyancy in the cloud, calculated from the level of free convection to the equilibrium level. Units J kg^{-1} = m^2 s^{-2}

4.2.5 Level of free convection (LFC), equilibrium level (EL), and area of positive buoyancy

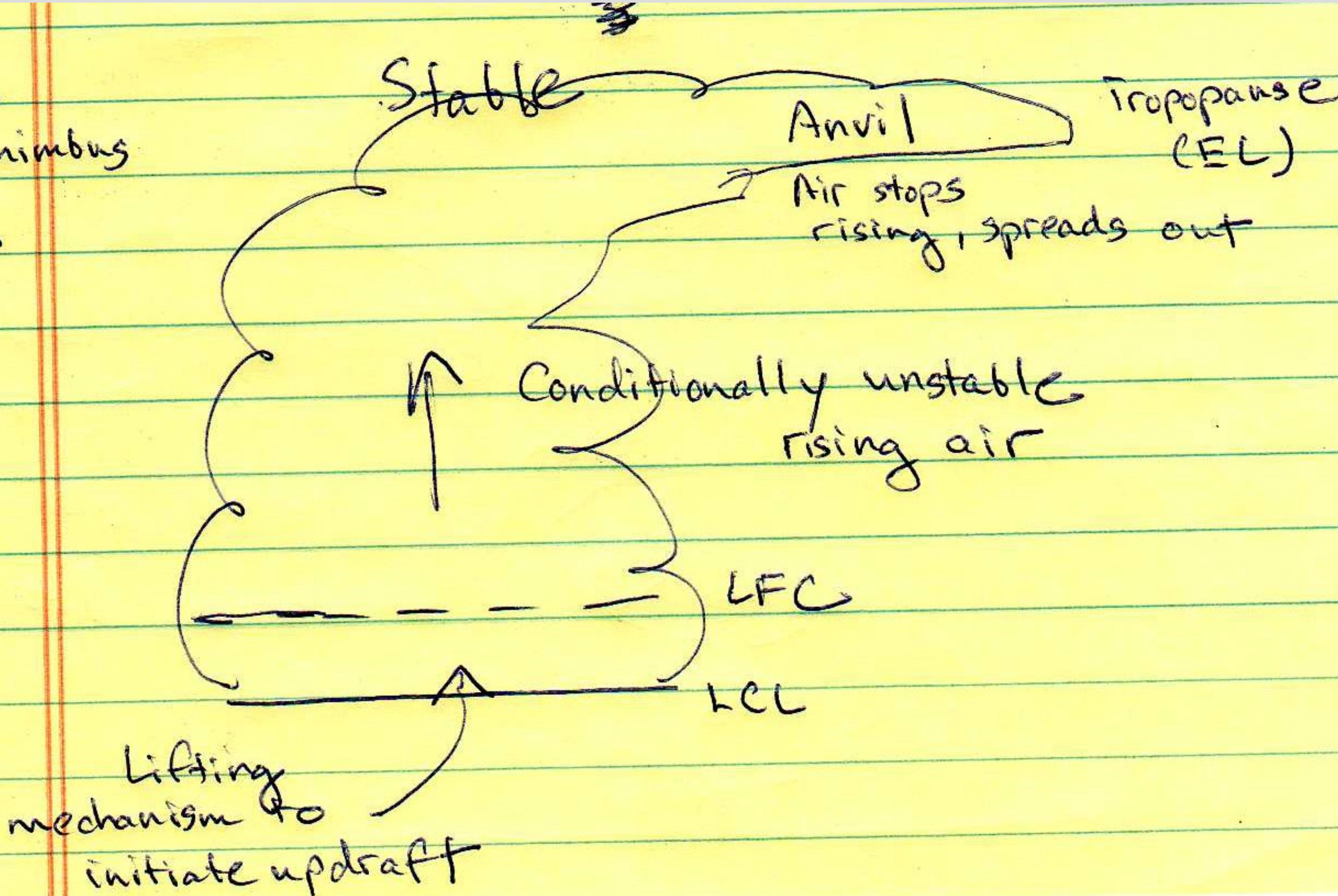


$$CIN = -g \int_{LCL}^{LFC} \frac{\theta(z) - \bar{\theta}(z)}{\bar{\theta}(z)} \, dz$$

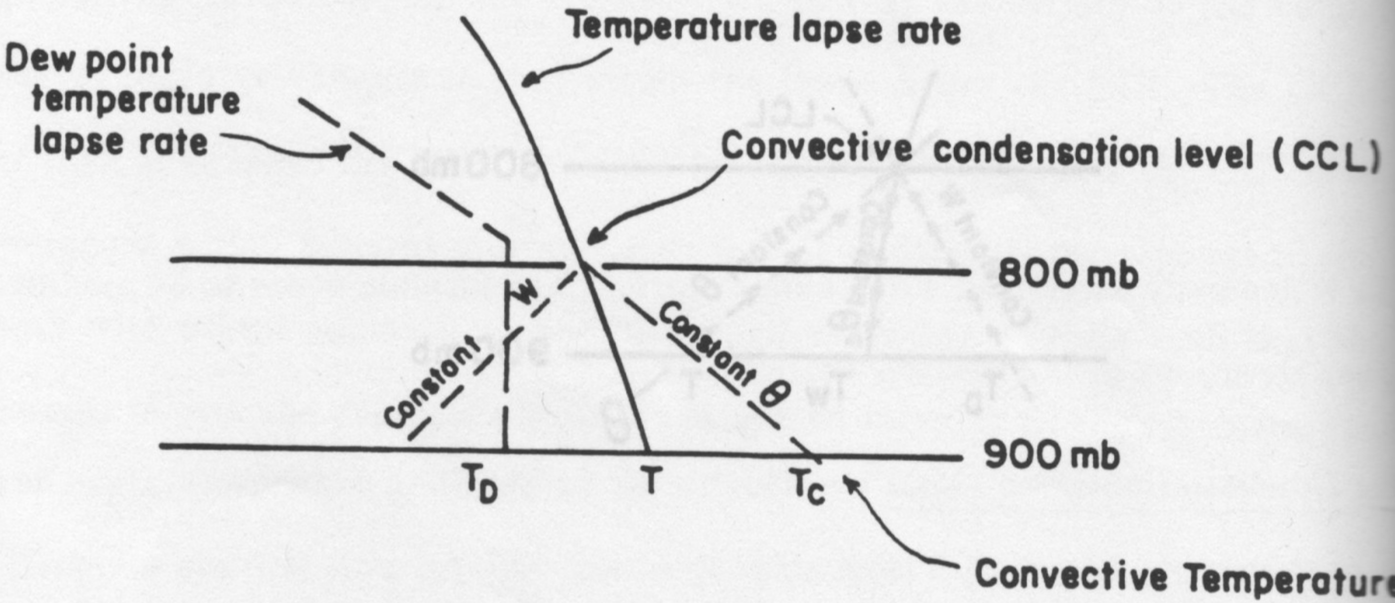
Convective inhibition.

Vertically integrated negative buoyancy in the cloud, calculated from the LCL to LFC. Initiating updraft must overcome this barrier for spontaneous convection. Some CIN is necessary for the most severe types of thunderstorms (e.g. supercells).

Typical cumulonimbus cloud



4.2.6 Convective temperature (T_c) and convective condensation level (CCL)



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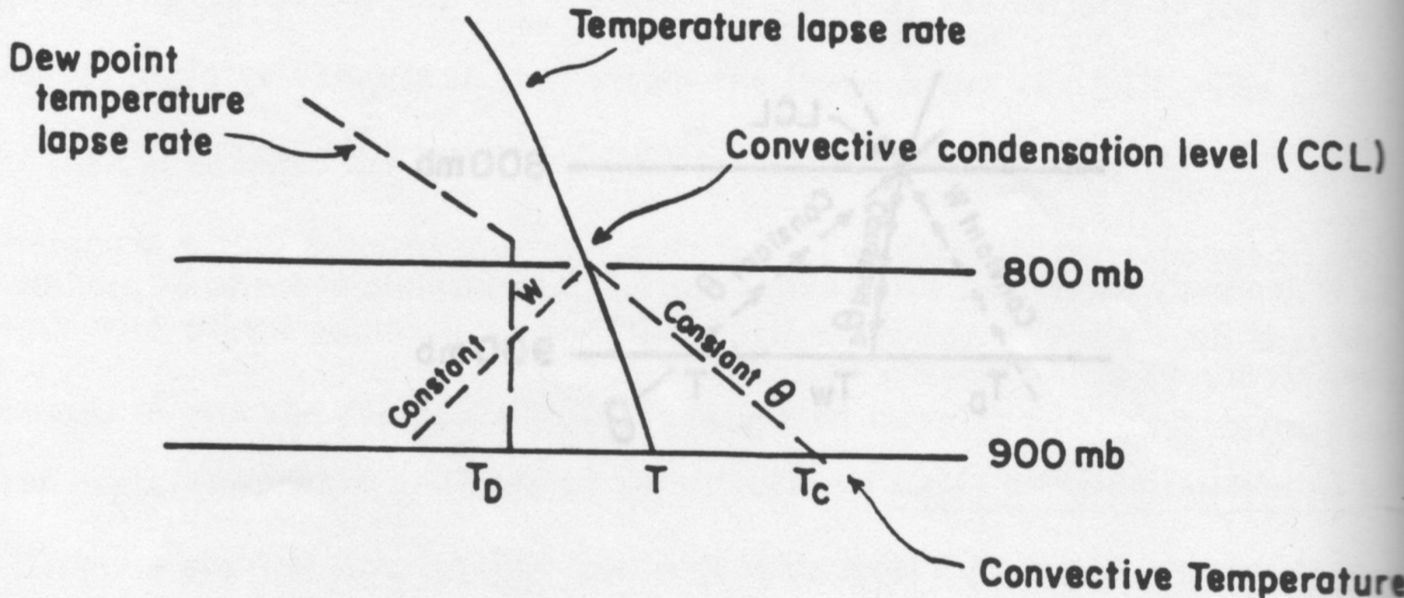
<u>Convective Temperature:</u> Temperature near the surface corresponding to a dry adiabatic lapse rate creating by heating and upward expansion of the boundary layer during the day. Closely matches maximum daytime temperature.

<u>Utility:</u> If considering a morning sounding, the convective temperature is what is more appropriate to consider as the surface temperature, as it will define the maximum height of the PBL.

4.2.6 Convective temperature (T_c) and convective condensation level (CCL)



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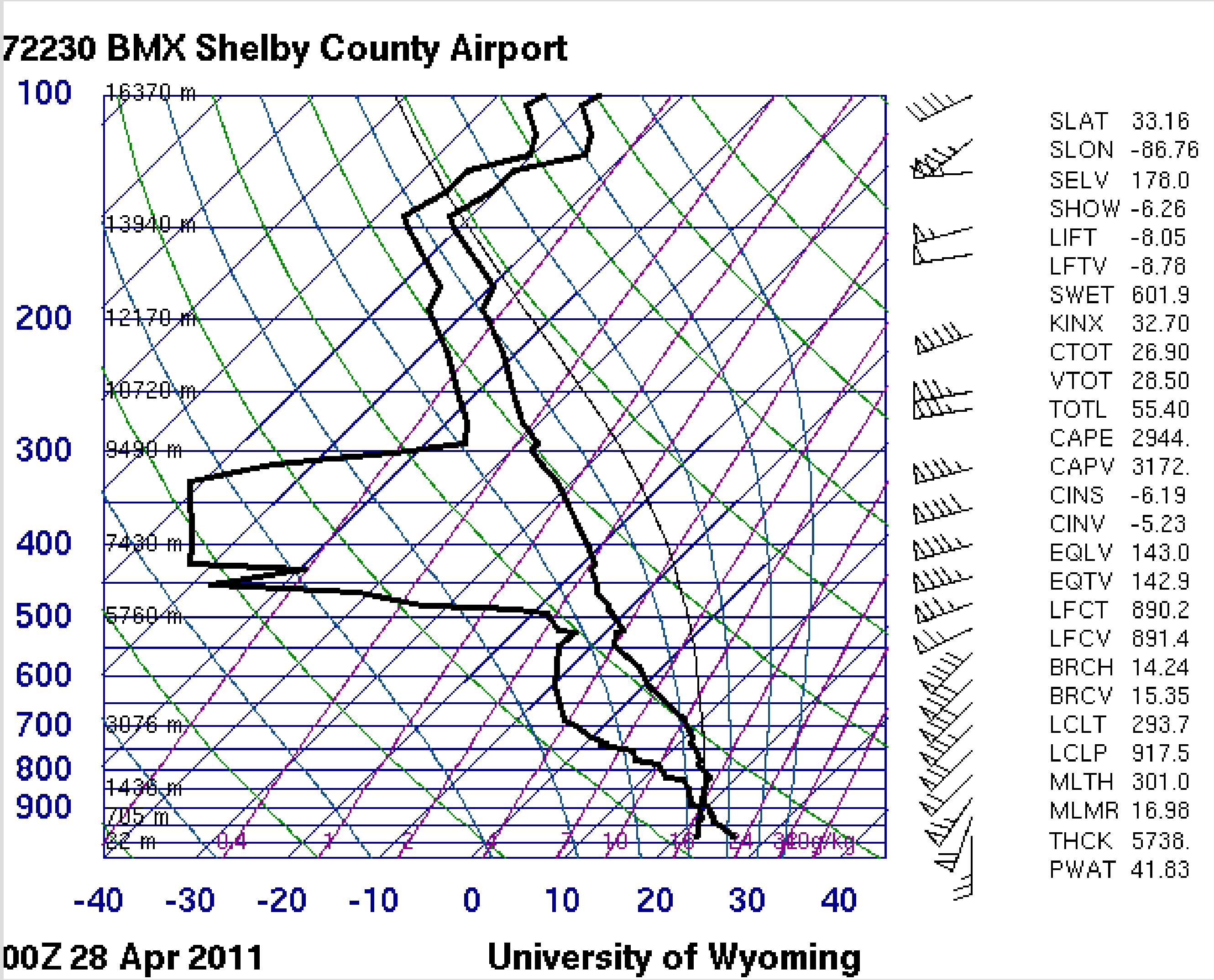
<u>Convective condensation level:</u> Estimate the average dewpoint within a well mixed boundary layer to define PBL-averaged mixing ratio. The intersection of the modified value of w and dry adiabat from the surface convective temperature.

<u>Utility:</u> Most accurate metric for cloud base height and height of the PBL during the day. BUT…its dependent on the particular forecaster!

Diagnosing potential for convection from CAPE and other indices

LOTS of potential indices…we'll just focus on most commonly used ones.



Which one of these do you use???

Whatever one you choose, I suggest look at CAPE and CIN first.

Those are the most fundamental metrics which have most firm basis in physics (my opinion).

No one "right" answer on indices…frankly depends on the preference of the forecaster. Lots of indices because there's a lot of regional, seasonal dependencies on how they perform.

Convective available potential energy. The acceleration induced by the buoyancy force in moist air, in the absence of liquid water or ice, is

$$B = g\,\frac{T_v(z) - \bar{T}_v(z)}{\bar{T}_v(z)}. \qquad (3.4.35)$$

The dynamical effect of B [Eq. (3.4.12)] alone when w is steady state and independent of x and y is as follows:

$$\frac{Dw}{Dt} = w\,\frac{dw}{dz} = \frac{d}{dz}\left(\tfrac{1}{2}w^2\right) = B. \qquad (3.4.36)$$

(We are not including here the effects of the vertical, perturbation pressure-gradient force, which opposes the buoyancy force.) Integrating Eq. (3.4.36) from the level of free convection (LFC) to the equilibrium level (EL), we find that if the air parcel is at rest at the LFC, and if the air parcel does not "entrain" any cooler, drier environmental air, then the updraft at the equilibrium level, the maximum vertical velocity (w_{max}), is

$$w_{max} = \sqrt{2\,\mathrm{CAPE}}, \qquad (3.4.37)$$

where CAPE, the *convective available potential energy* (also known as the *buoyant energy*), is given by

$$\mathrm{CAPE} = \int_{\mathrm{LFC}}^{\mathrm{EL}} g\,\frac{T_v(z) - \bar{T}_v(z)}{\bar{T}_v(z)}\,dz. \qquad (3.4.38)$$

Bluestein, Vol 2

Moderate to strong convection = CAPE of 1000 to 3000 J kg^{-1}

Yields a maximum vertical velocity of 70 ms^{-1} for CAPE = 2500 J kg^{-1}.
Close to what is actually observed!

Showalter Index

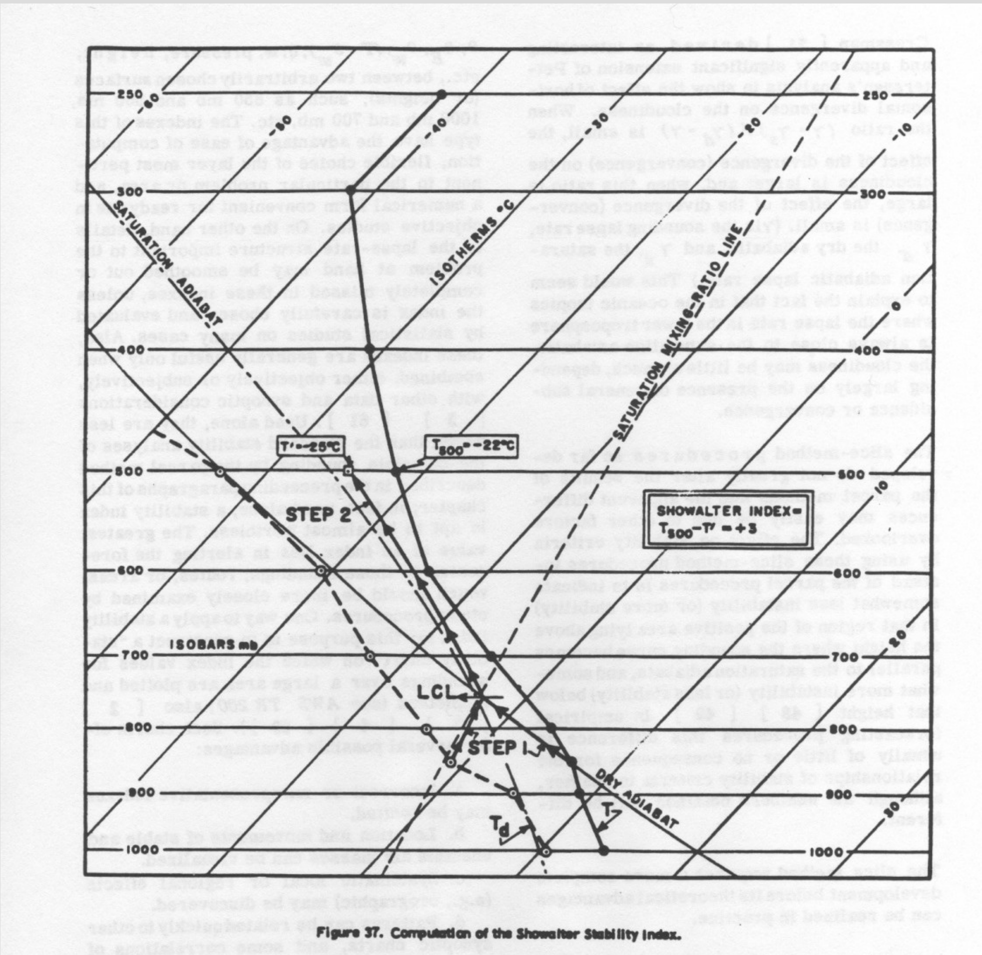


Figure 37. Computation of the Showalter Stability Index.

1. From 850-mb temperature, draw line parallel to dry adiabats upward to LCL
2. From LCL draw line parallel to moist adiabat upward to 500-mb. Call this value T'
3. Subtract T' from 500-mb environmental T to define index.

SHOWALTER INDEX (SI)[1]	Thunderstorm Indications
3 to 1	Thunderstorm possible--strong trigger needed
0 to -3	Unstable--thunderstorms probable
-4 to -6	Very unstable--good heavy thunderstorm potential
less than -6	Extremely unstable--good strong thunderstorm potential

Not very good for high based convection, when source air for convective clouds is above 850-mb

Lifted Index

Temperature excess at 500-mb of the environment, with respect to an air parcel in the PBL lifted to LCL and then lifted moist adiabatically to 500-mb

LIFTED INDEX (LI)[1]	Thunderstorm Indications
0 to -2	Thunderstorms possible--good trigger mechanism needed
-3 to -5	Unstable--thunderstorms probable
less than -5	Very unstable--heavy to strong thunderstorm potential

Similar to the idea of the convective temperature, need to forecast PBL characteristics in the afternoon from the morning sounding. Similar to Showalter index but more regionally adaptable.

“K” index

K = 850-mb temperature – 500-mb temperature
+ 850-mb dew point – 700-mb dew point depression

K INDEX West of Rockies[1]	K INDEX East of Rockies[2]	Airmass Thunderstorm Probability
less than 15	less than 20	None
15 to 20	20 to 25	Isolated thunderstorms
21 to 25	26 to 30	Widely scattered thunderstorms
26 to 30	31 to 35	Scattered thunderstorms
above 30	above 35	Numerous thunderstorms

Note: K value may not be representative of airmass if 850-mb level is near surface. Western U.S. values are forced to approximate area coverage used by George.[2]

Designed to capture the potential instability in the lower half of the atmosphere, availability of moisture in PBL, and reduction in buoyancy through dry air entrainment. Useful in the absence of strong synoptic-scale forcing.

Totals-Totals (TT) Index

TT= Sum of Vertical Totals (VT) and Cross Totals (CT)

VT = 850-mb temperature minus 500-mb temperature
→ lapse rate between two pressure surfaces

CT = 850-mb dew point minus 500-mb temperature
→ Combines measure of low-level moisture with temperature aloft

Does NOT involve the use of any dry or moist adiabatic lapse rates

WEST OF THE ROCKIES (with adequate moisture):

VERTICAL TOTALS (VT)	Expect:
<28	No thunderstorms
29 to 32	Few thunderstorms
>32	Scattered thunderstorms

WEST OF THE ROCKIES:

TOTAL TOTALS (TT)[1]	Expect:
48	Isolated or few thunderstorms
52	Scattered thunderstorms, few of moderate intensity
55	Scattered thunderstorms, few of moderate intensity, isolated severe
58	Scattered thunderstorms, few severe, isolated tornadoes
61	Scattered to numerous thunderstorms, few to scattered severe, few tornadoes
64	Numerous thunderstorms, scattered severe, scattered tornadoes

EAST OF THE ROCKIES[3] (Total Totals Most Important):

CROSS TOTALS	VERTICAL TOTALS	TOTAL TOTALS	Expect:
18-19*	26 or more*	44	Isolated or few thunderstorms
20-21	26 or more	46	Scattered thunderstorms
22-23	26 or more	48	Scattered thunderstorms, isolated severe thunderstorms
24-25	26 or more	50	Scattered thunderstorms, few severe thunderstorms, isolated tornadoes
26-29	26 or more	52	Scattered to numerous thunderstorms, few to scattered severe thunderstorms, few tornadoes
30	26 or more	56	Numerous thunderstorms, scattered severe thunderstorms, scattered tornadoes

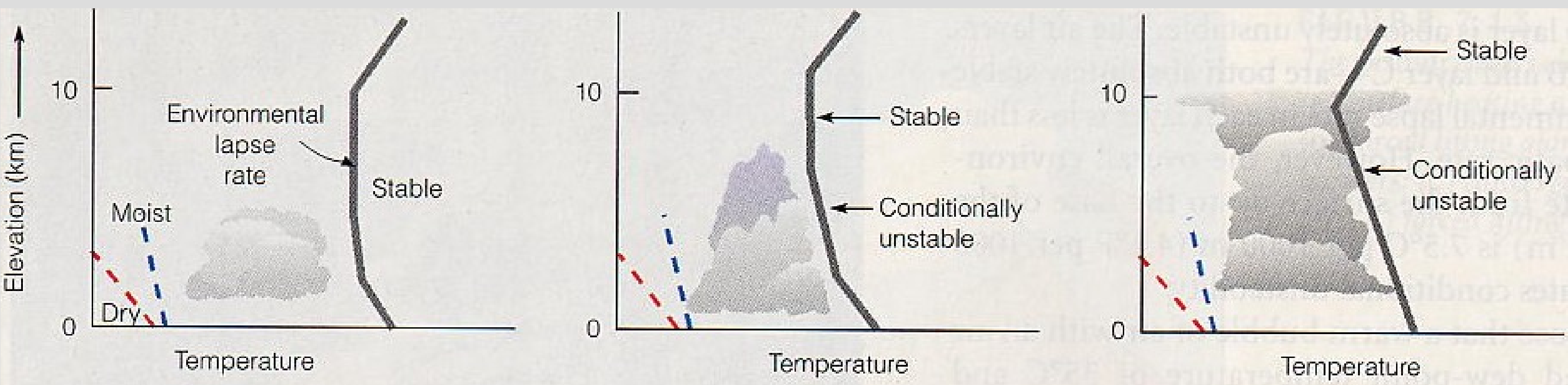
*Except along the immediate Gulf Coast and over the Gulf Stream, where the CT value is only 16 or more, and the VT value is only 23 or more.

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

Cumulus humilis

Cumulus congestus

Cumulonimbus

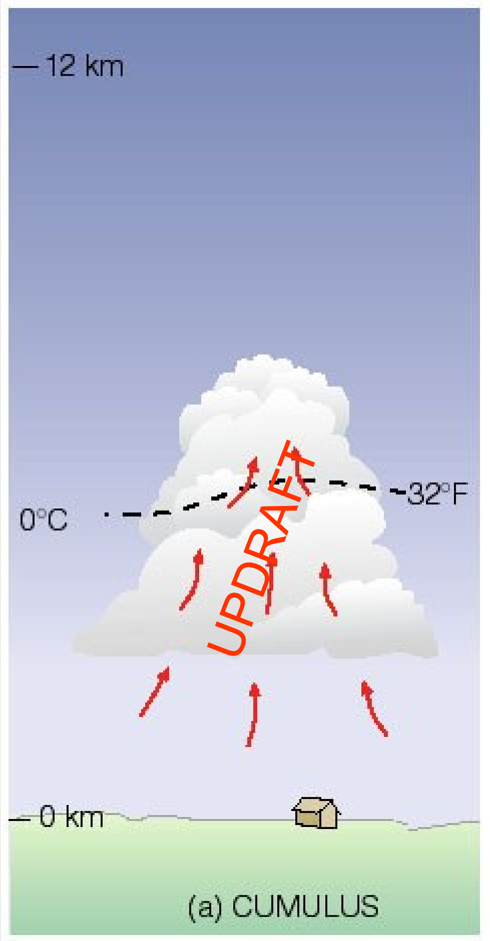


Conditionally unstable in a shallow layer

Conditionally unstable about midway through troposphere

Conditionally unstable nearly to the tropopause

Air mass Thunderstorm *Cumulus Stage*



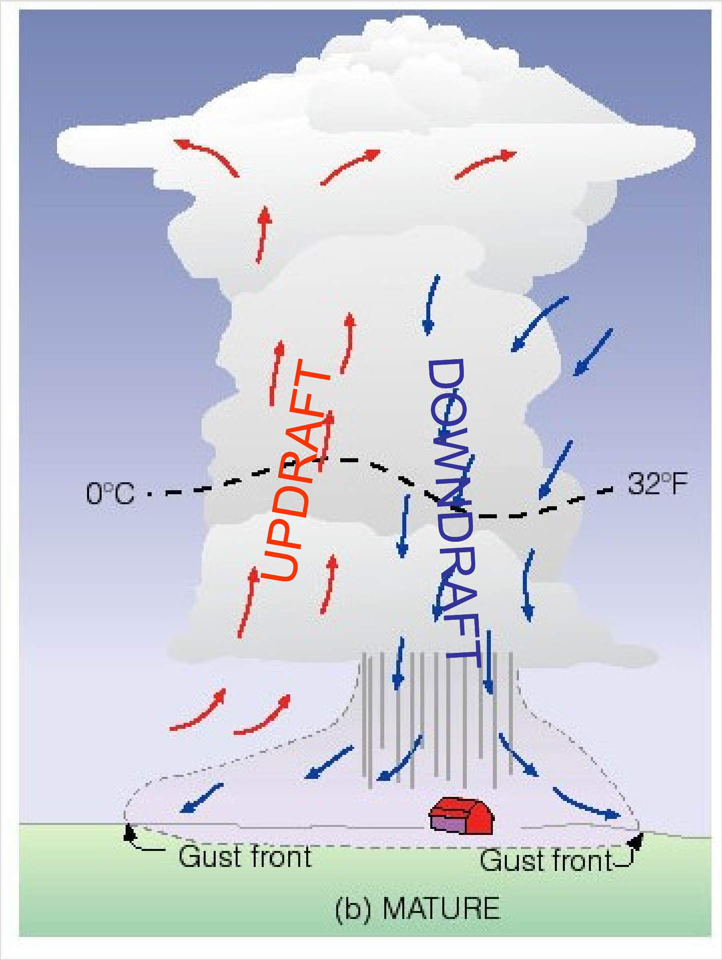
A parcel of air is lifted from surface (updraft)

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 could to create a downdraft.

Leading edge of the downdraft is called the *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.

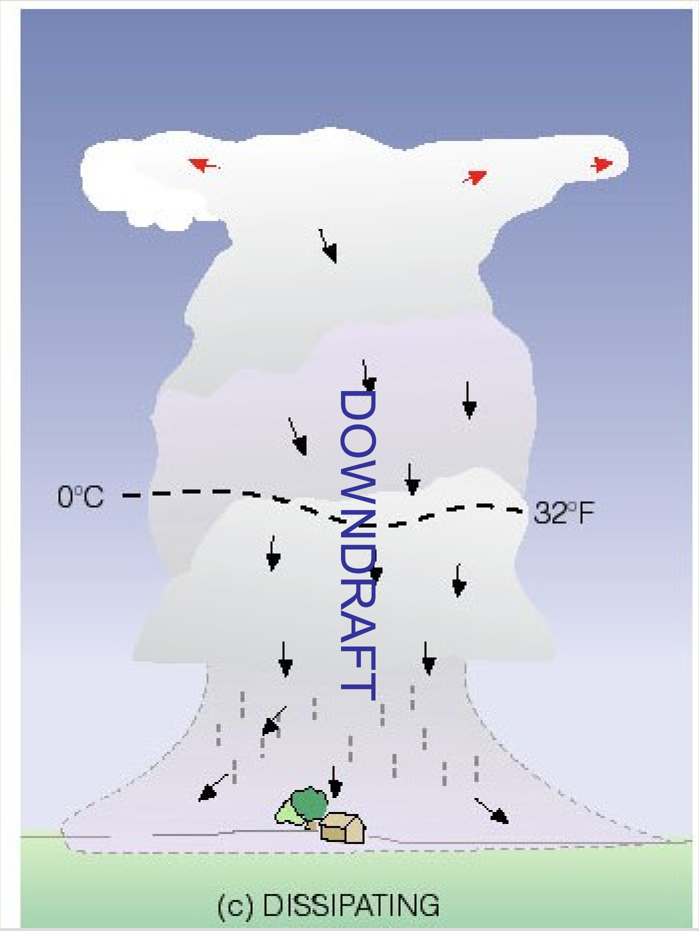
Forced by the diurnal mountain valley circulation

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.

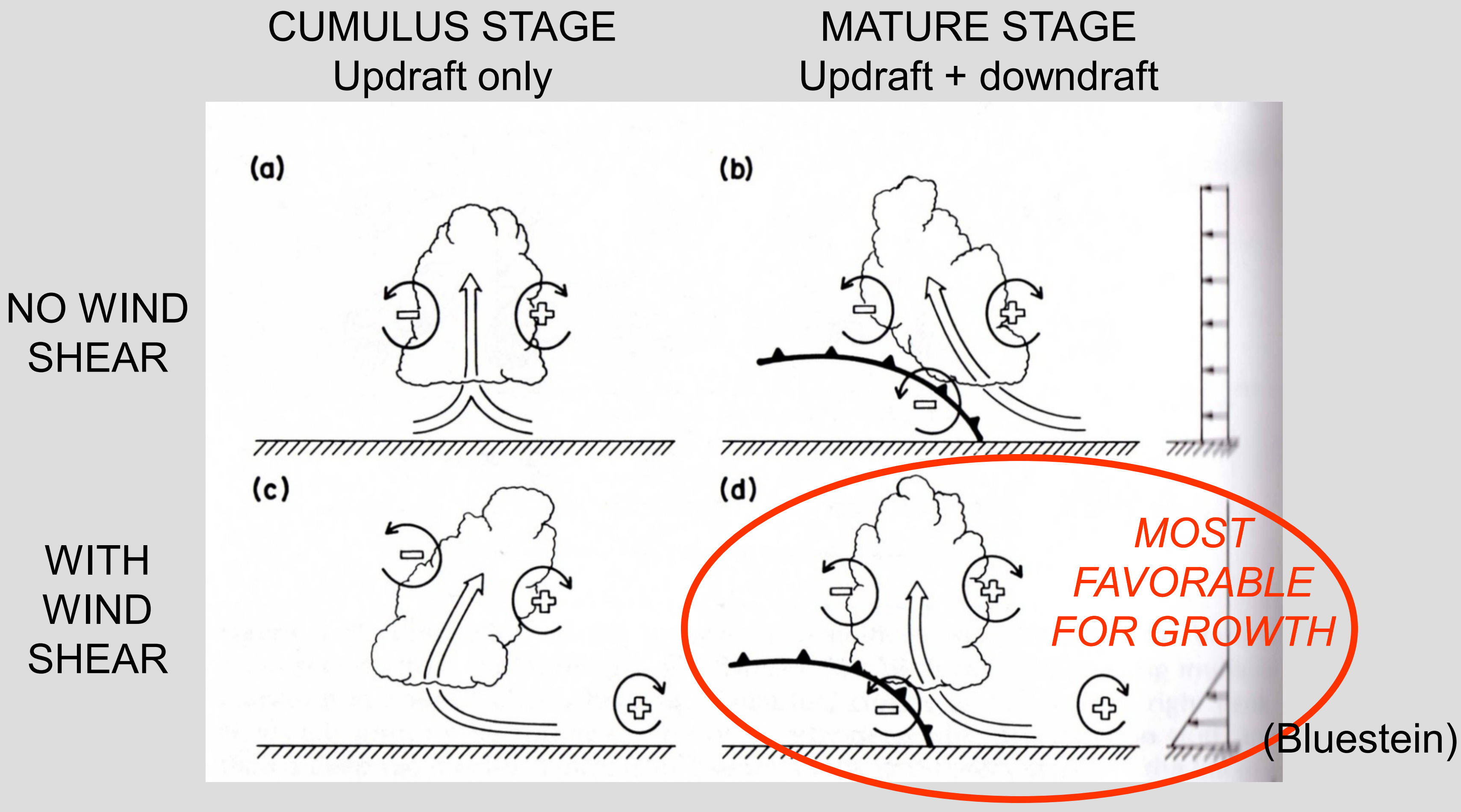
Once this supply of warm, moist air is from the updraft is cut off, the storm begins to weaken either by evaporation and/or by raining itself out.

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?



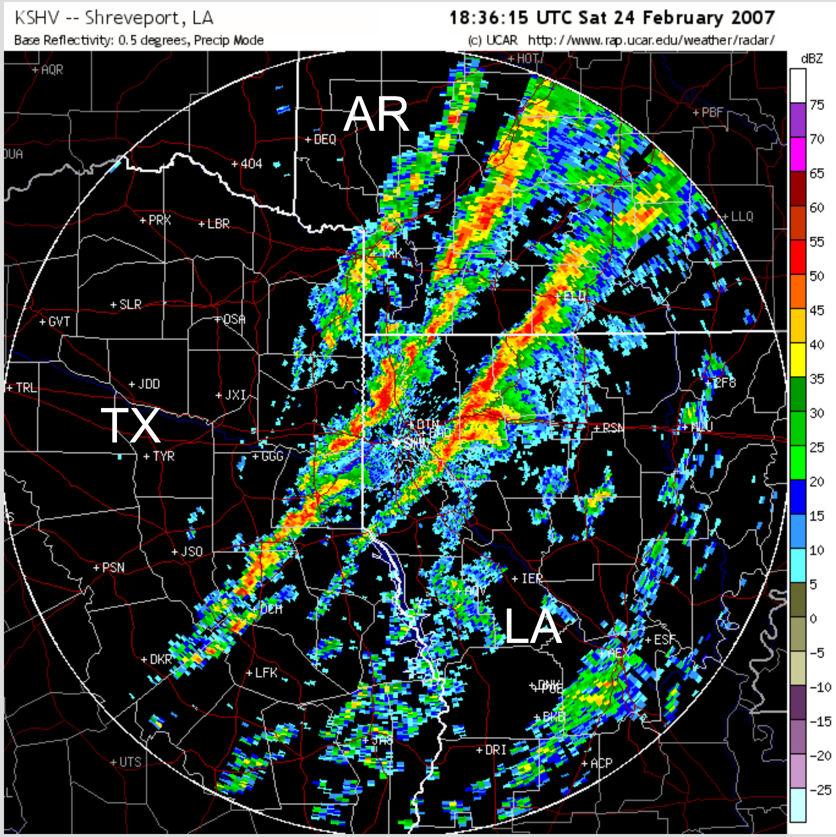
Wind shear allows the updraft to be maintained in the cloud and not get choked off by the downdraft—so the thunderstorm keeps receiving the warm, moist air it needs to keep growing.

Multicell Thunderstorms

In moderate shear, thunderstorms can get a bit more organized, numerous and have longer lifetimes.

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

Squall Line



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

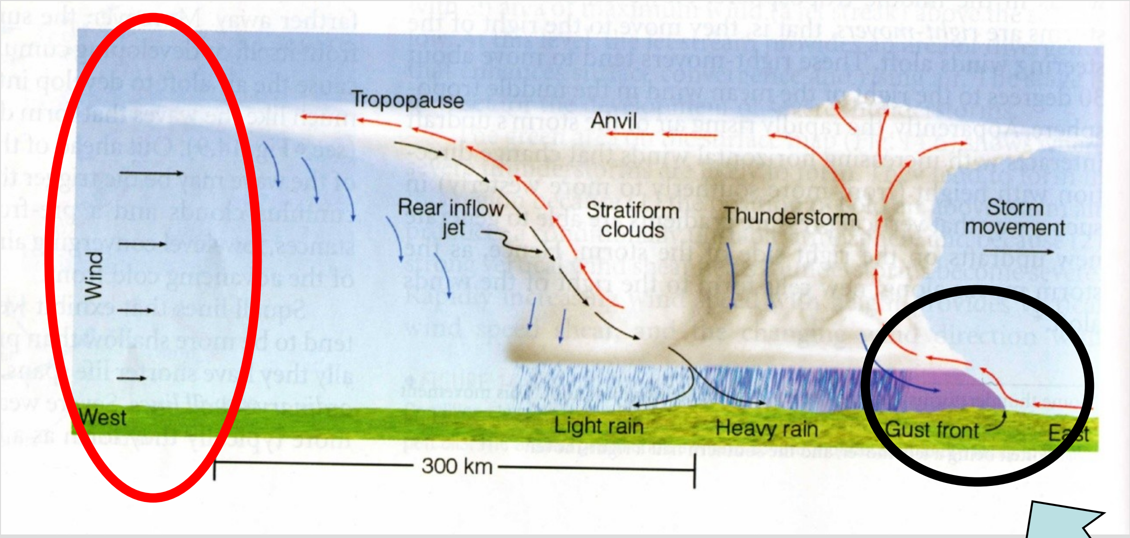
Line of thunderstorms that can be hundreds of miles long.

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.

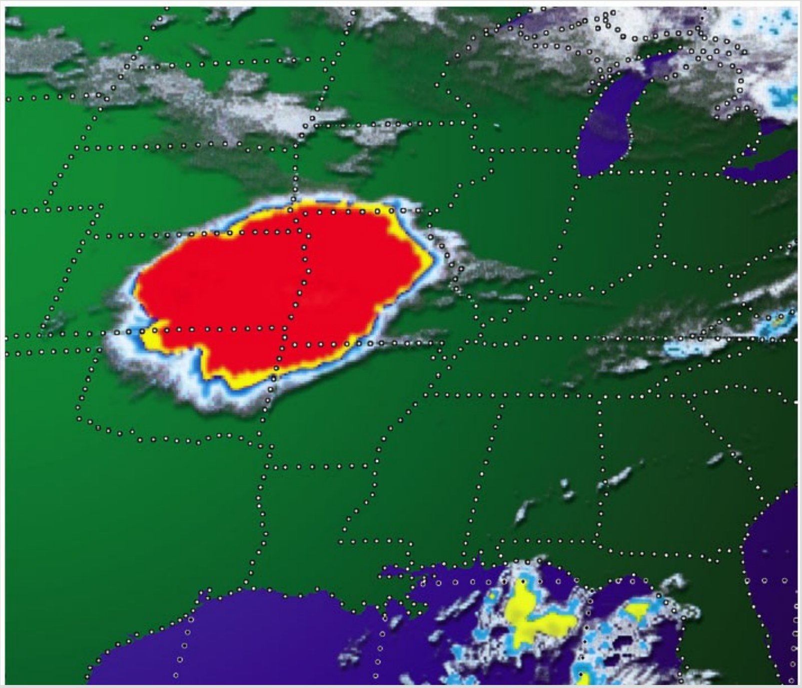
Idealized squall line thunderstorm structure



Note the wind shear profile

Shelf cloud at leading edge of squall line

Mesoscale Convective System (MCS)

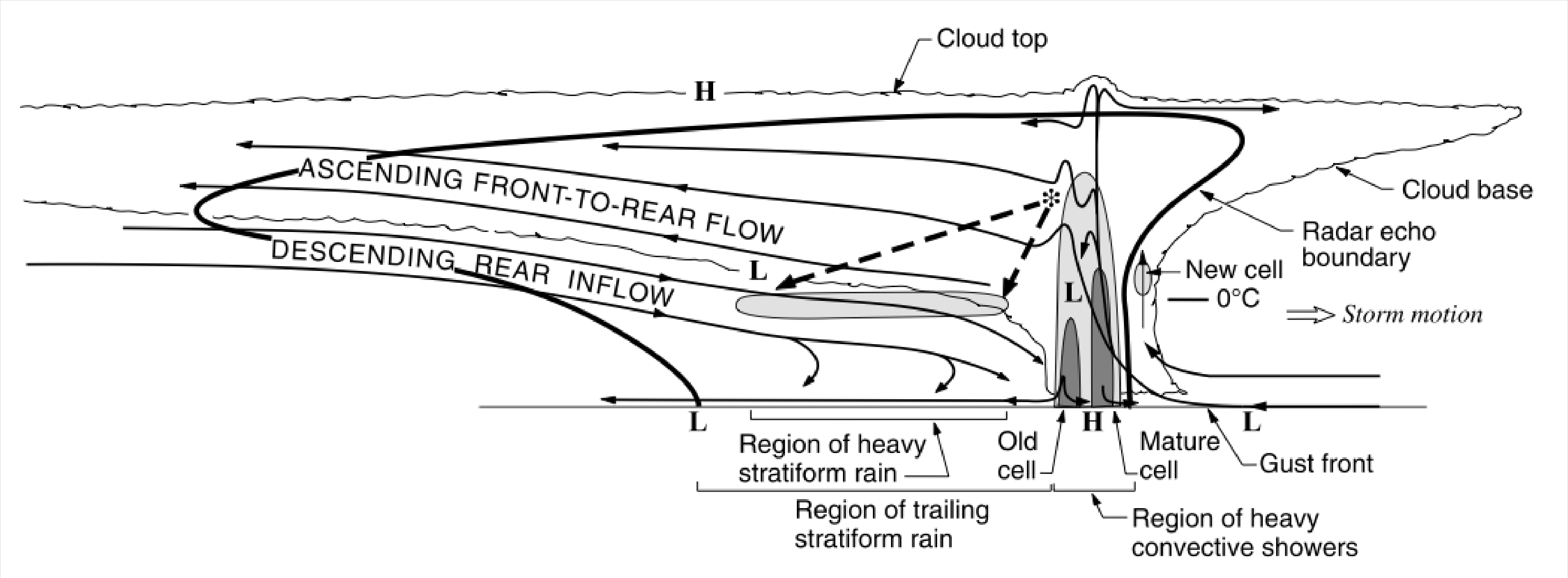


A number of individual thunderstorms cluster together to form a giant circular convective weather system.

Can be the size of an entire state!

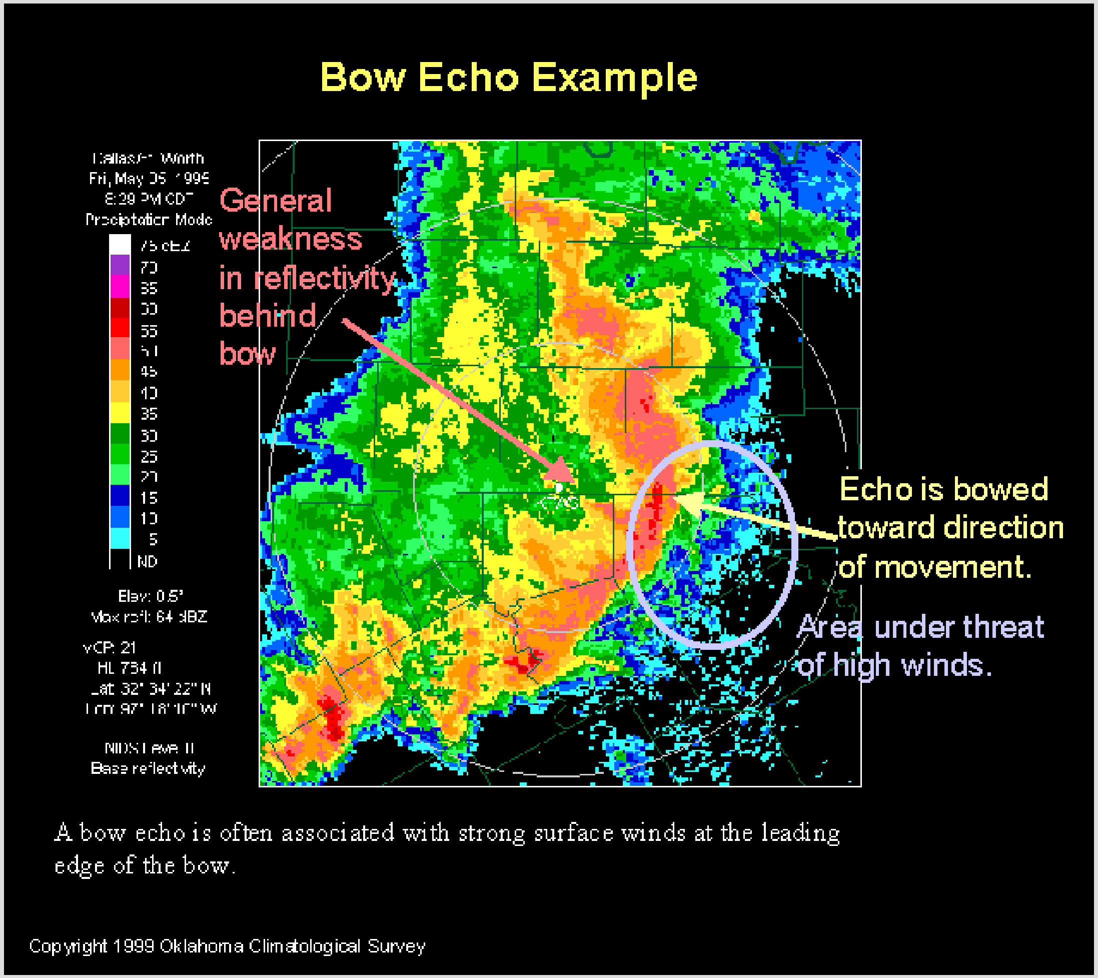
Most common in summer, originating from convection which forms over mountains (the Rockies in the case of U.S.)

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

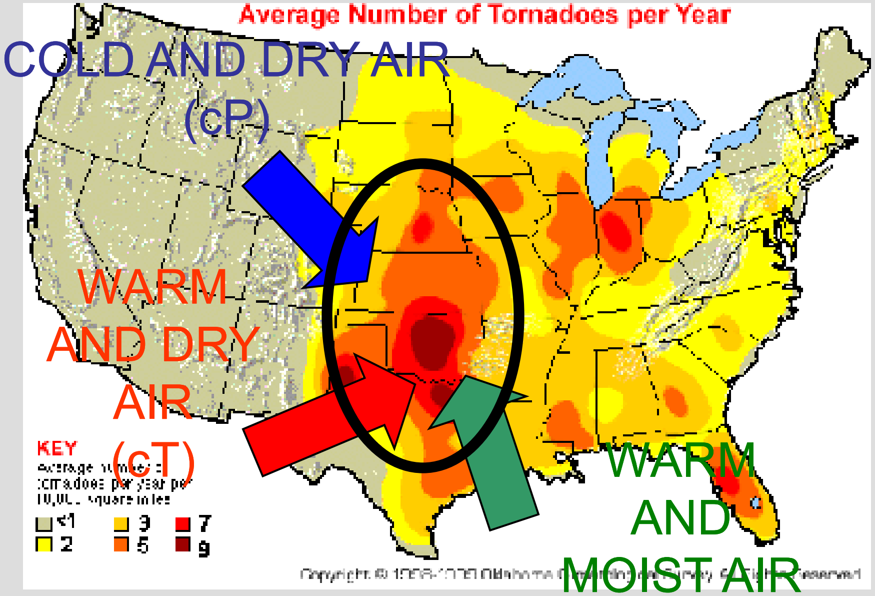
INGREDIENT 2: LARGE HELICITY

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

(NEW) 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



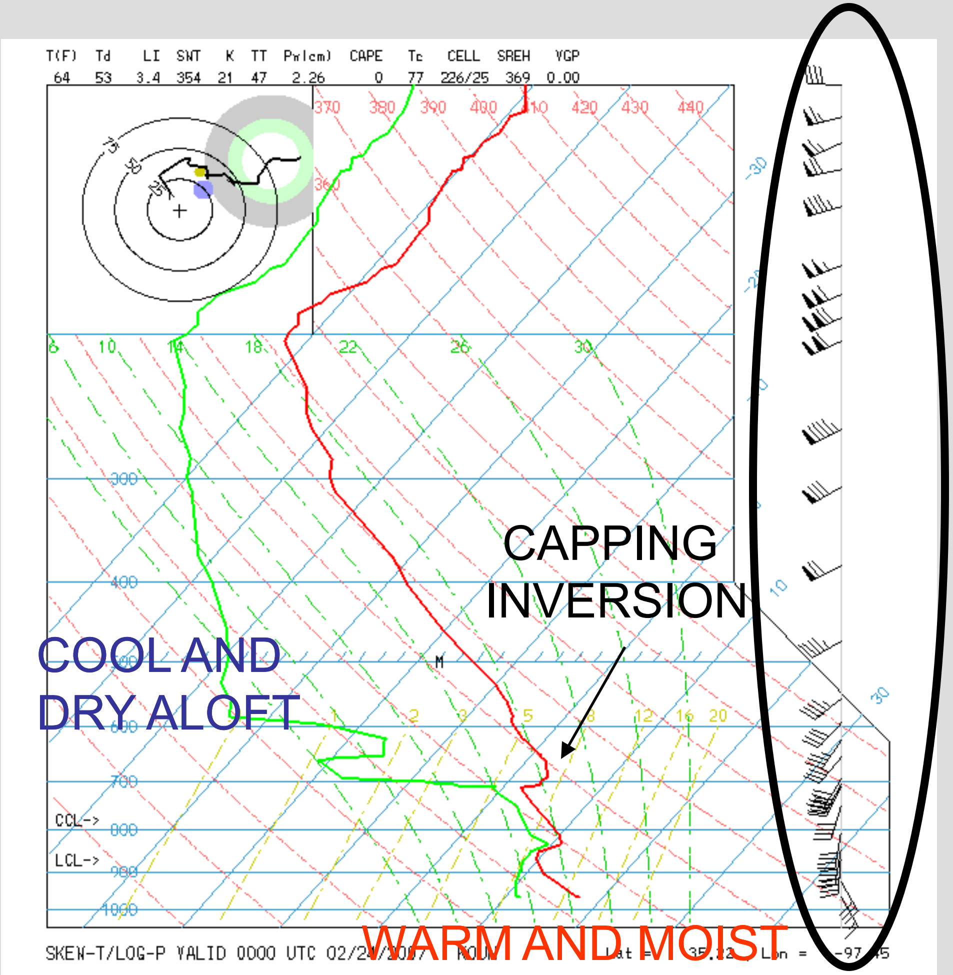
Tornadoes (and the supercell thunderstorms that spawn them) are most prevalent in “tornado alley” in the central U.S.

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

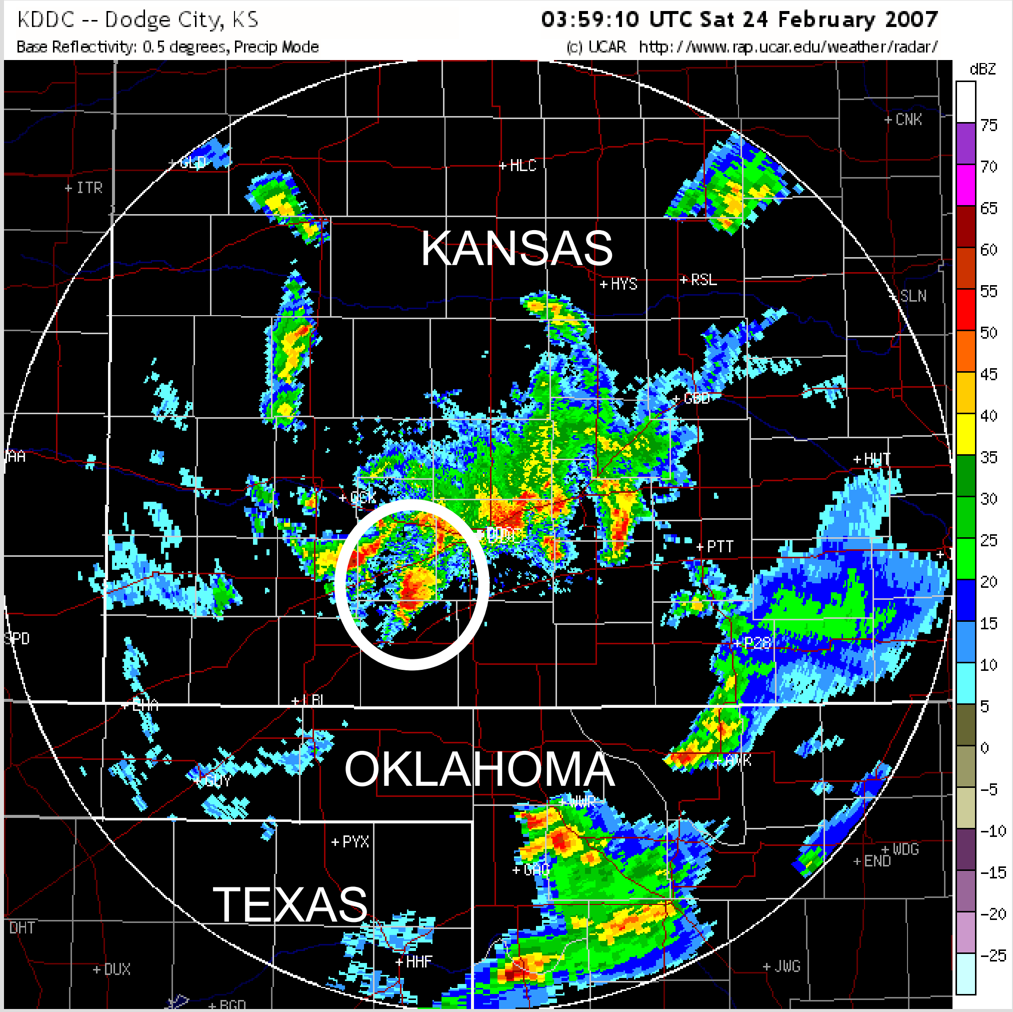
THE "LOADED GUN" SOUNDING
THE SIGNATURE FOR SUPERCELLS!



NEAR SURFACE

WIND DRASTICALLY CHANGES IN SPEED AND DIRECTION WITH HEIGHT

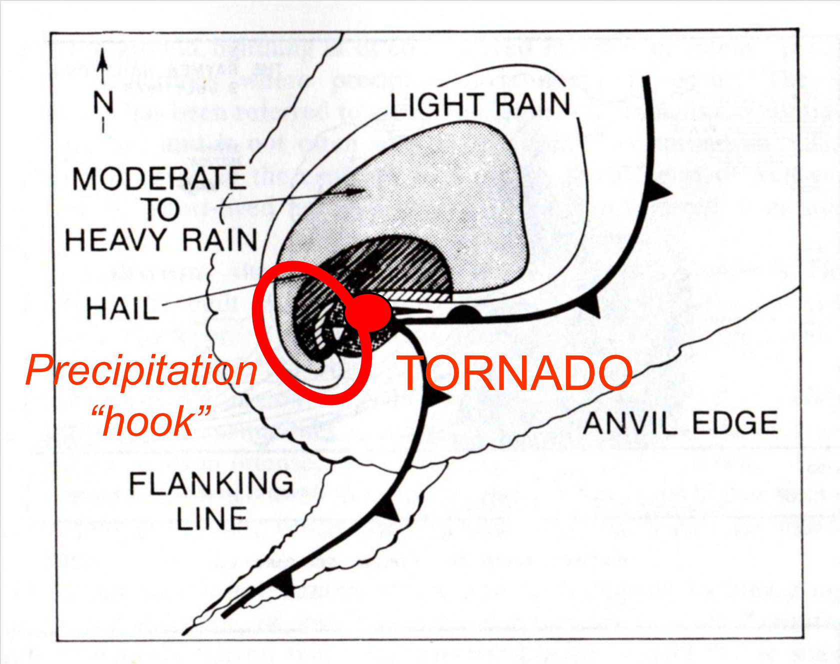
Supercells on radar

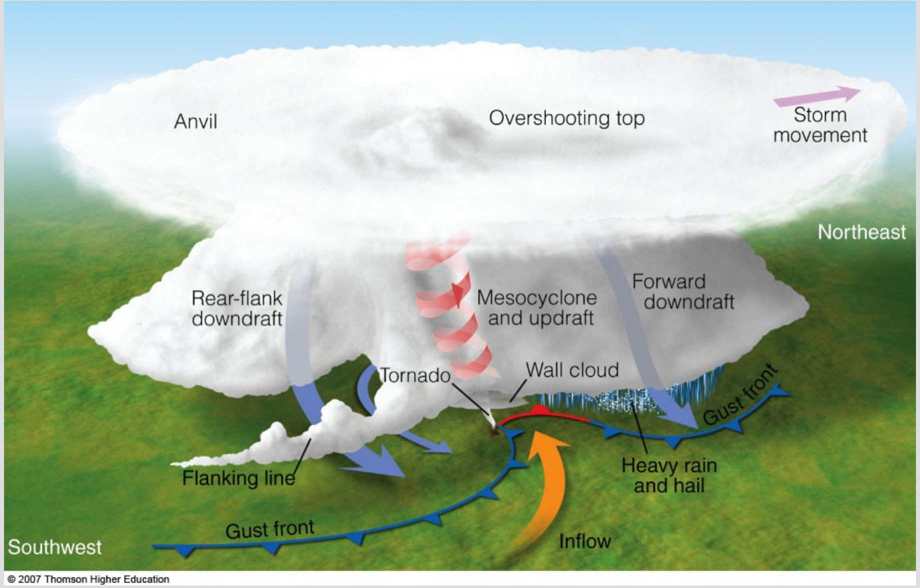


NOT big long squall lines!

Get compact and isolated rotating cells!

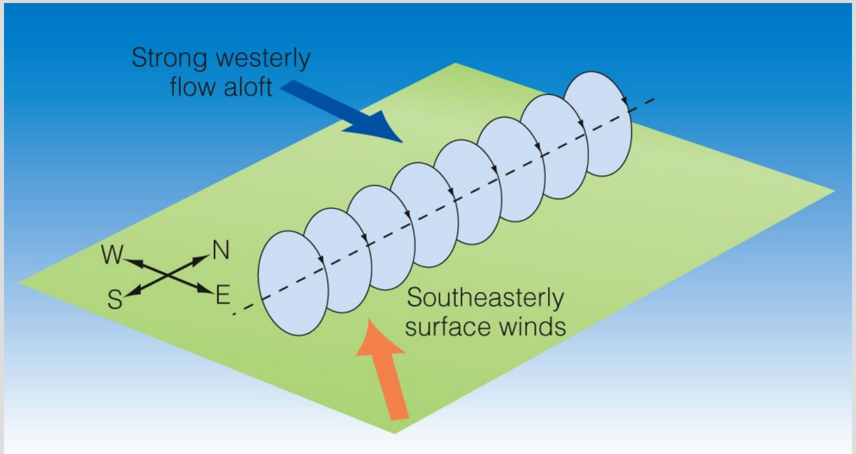
Horizontal structure of a tornadic supercell

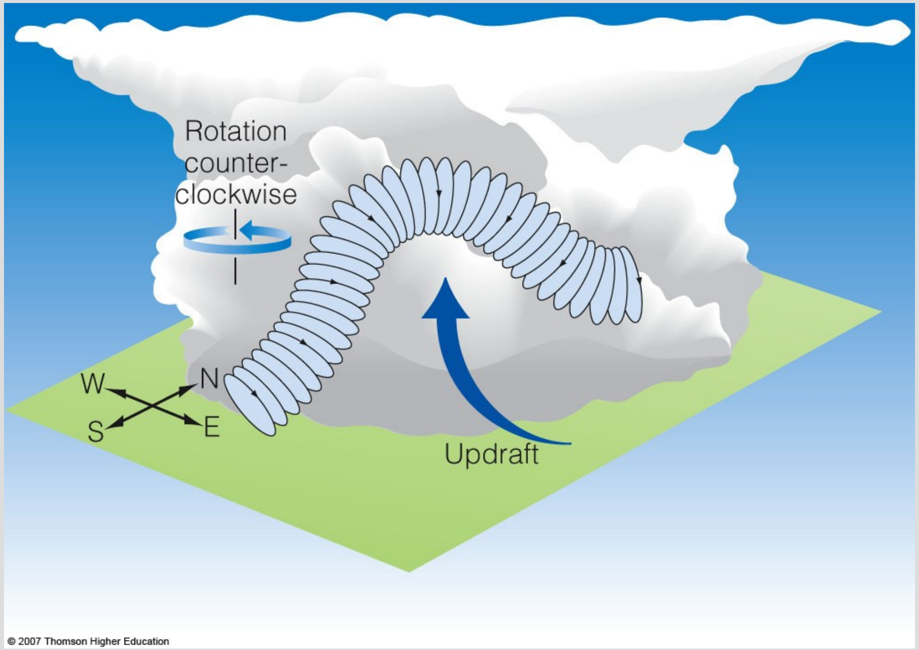




The tornado is located in front of the precipitation "hook" which defines the area of hail and rain curving around the mesocyclone.

Formation of a rotating updraft in a supercell



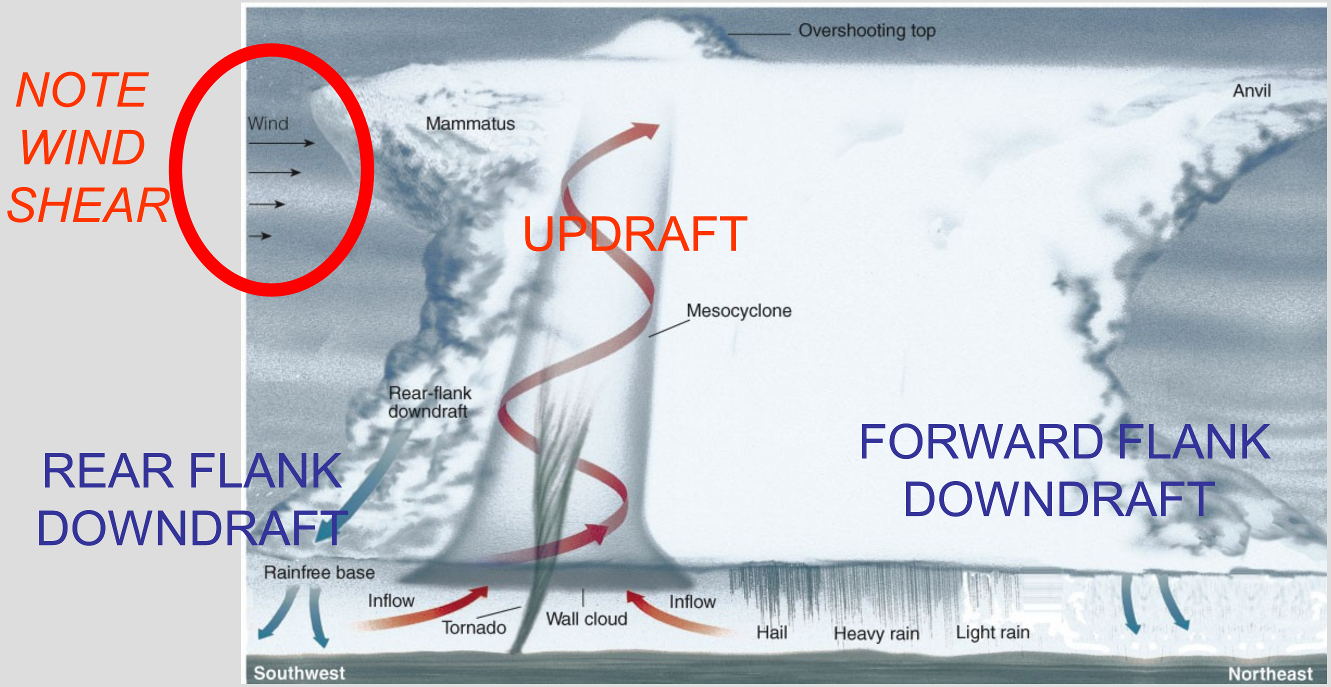


Wind shear caused by a change in wind speed and direction with height causes rotation in the horizontal.

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

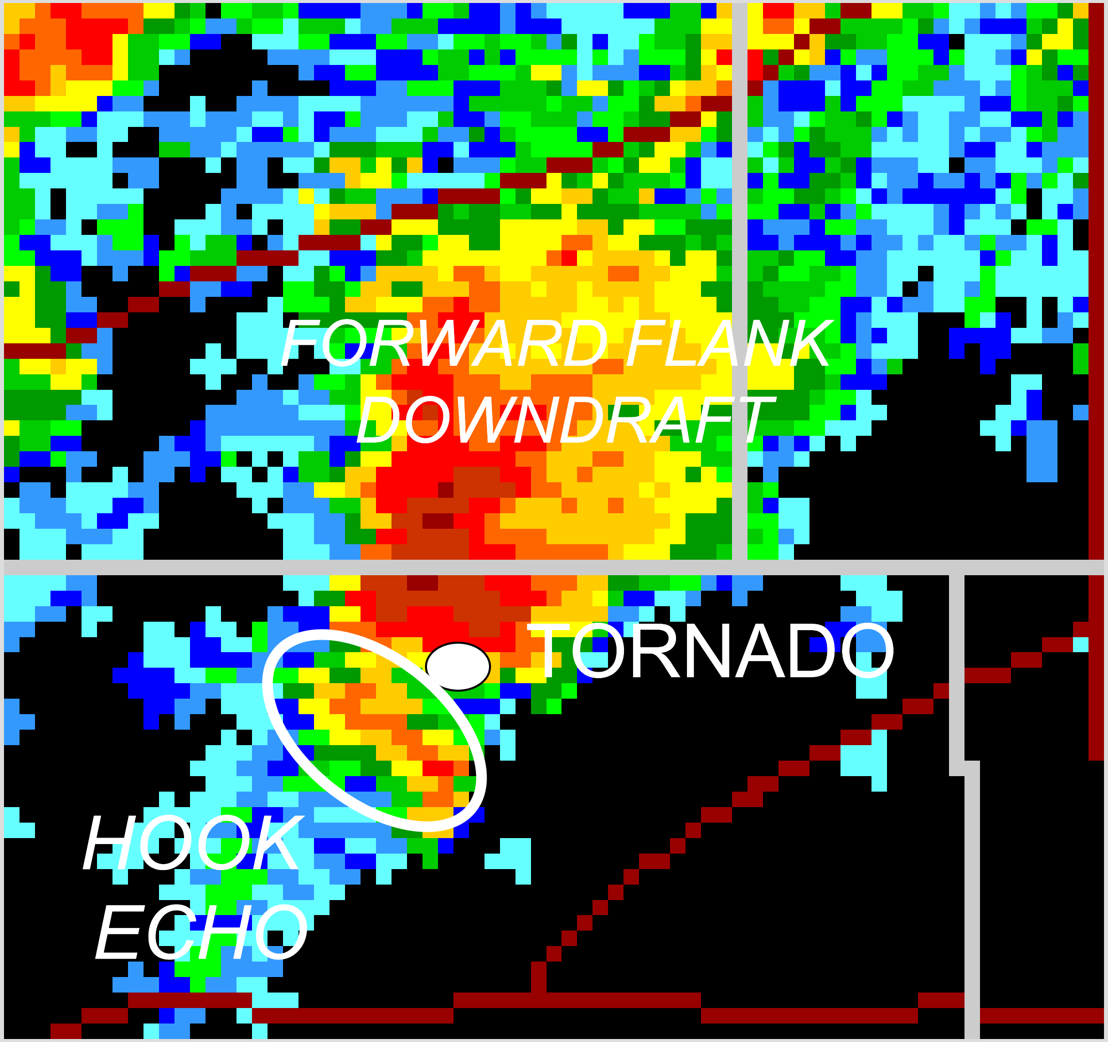


REAR FLANK DOWNDRAFT: Downdraft at the base of the supercell, right before the wall cloud.

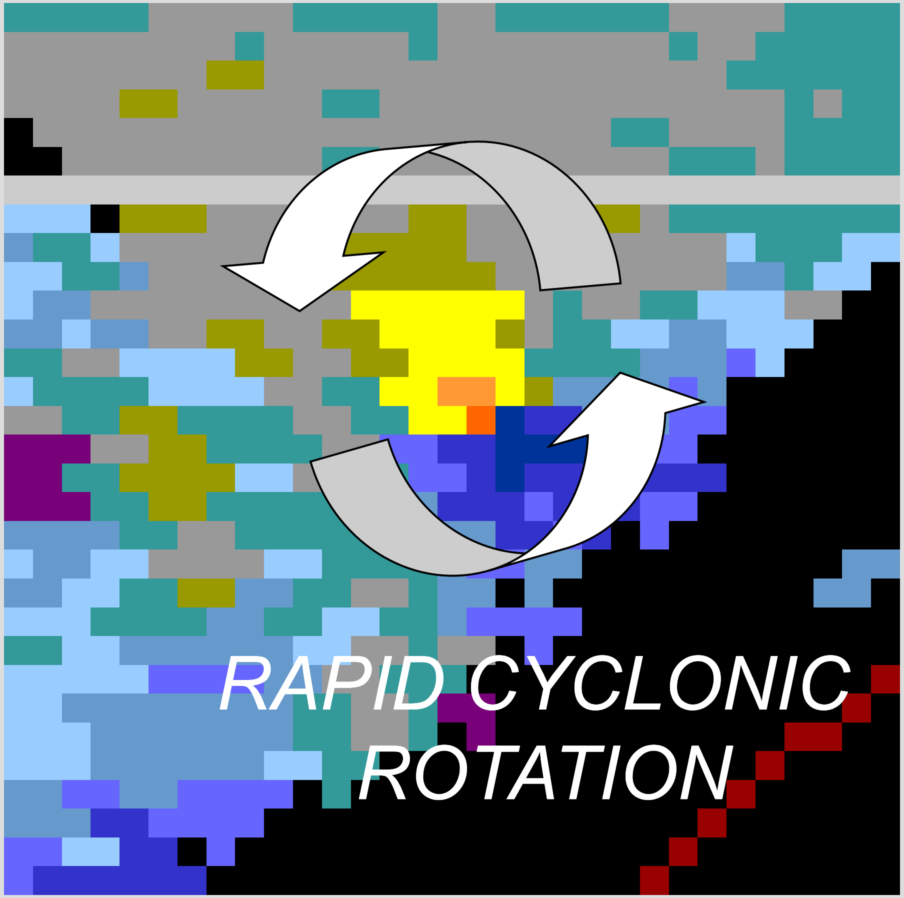
UPDRAFT: Tornado forms at the base of the updraft is the extension of the mesocyclone, defined by a *wall cloud*.

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

Radar signature of a tornadic supercell
Reflectivity



Radar signature of a tornadic supercell
Wind velocity



YELLOW = ECHOES TRAVELING AWAY FROM RADAR

BLUE = ECHOES TRAVELING TOWARD RADAR

NOTE: In Northern Hemisphere, tornadic supercells typically rotate counterclockwise due to the typical wind shear profile.

They can also rotate clockwise on rare occasions—since the vortex is in cyclostrophic balance.

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

CAPE \ Vertical shear[a]	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).

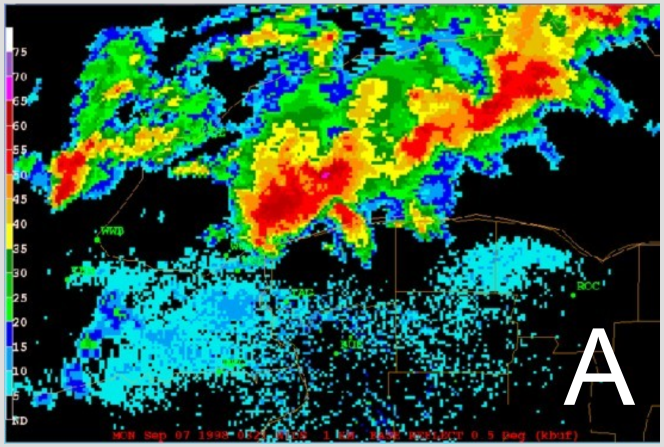
$R = CAPE/S^2$

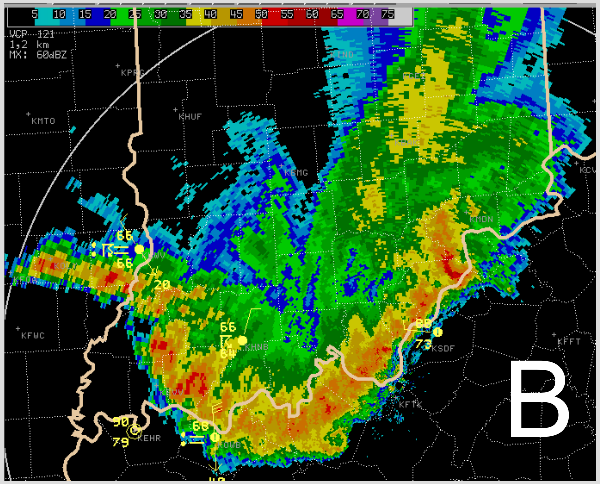
$S^2 = \frac{1}{2} (u_{6km} – u_{500m})^2$

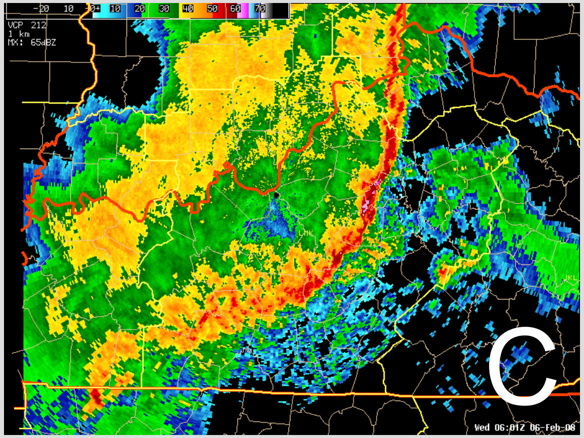
This measure gives some indication of the potential for organized convection.

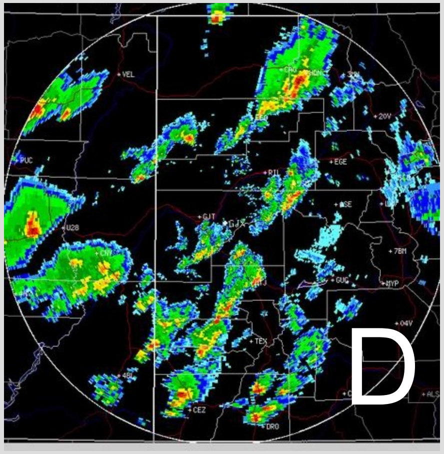
Supercell (tornadic) thunderstorms tend to form with $10 < R < 40$. So need some sort of optimal balance of CAPE vs. shear to get most intense kinds of thunderstorms.

REFLECTIVITY









WHICH RADAR IMAGERY INDICATES THE MOST DANGEROUS THUNDERSTORM?

CHOOSE E IF YOU THINK THEY'RE ALL EQUALLY DANGEROUS.

Johnson & Mapes (1997)

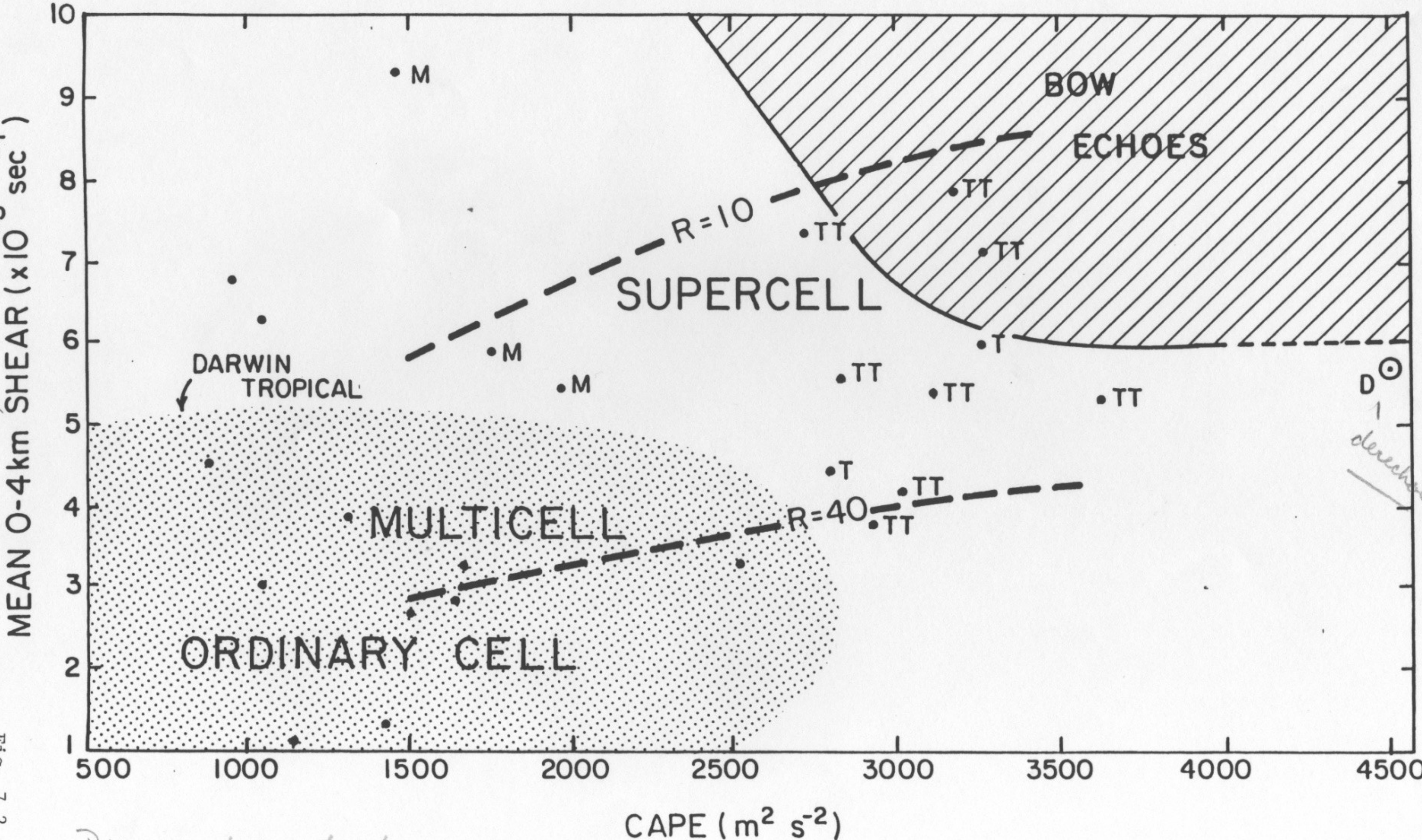
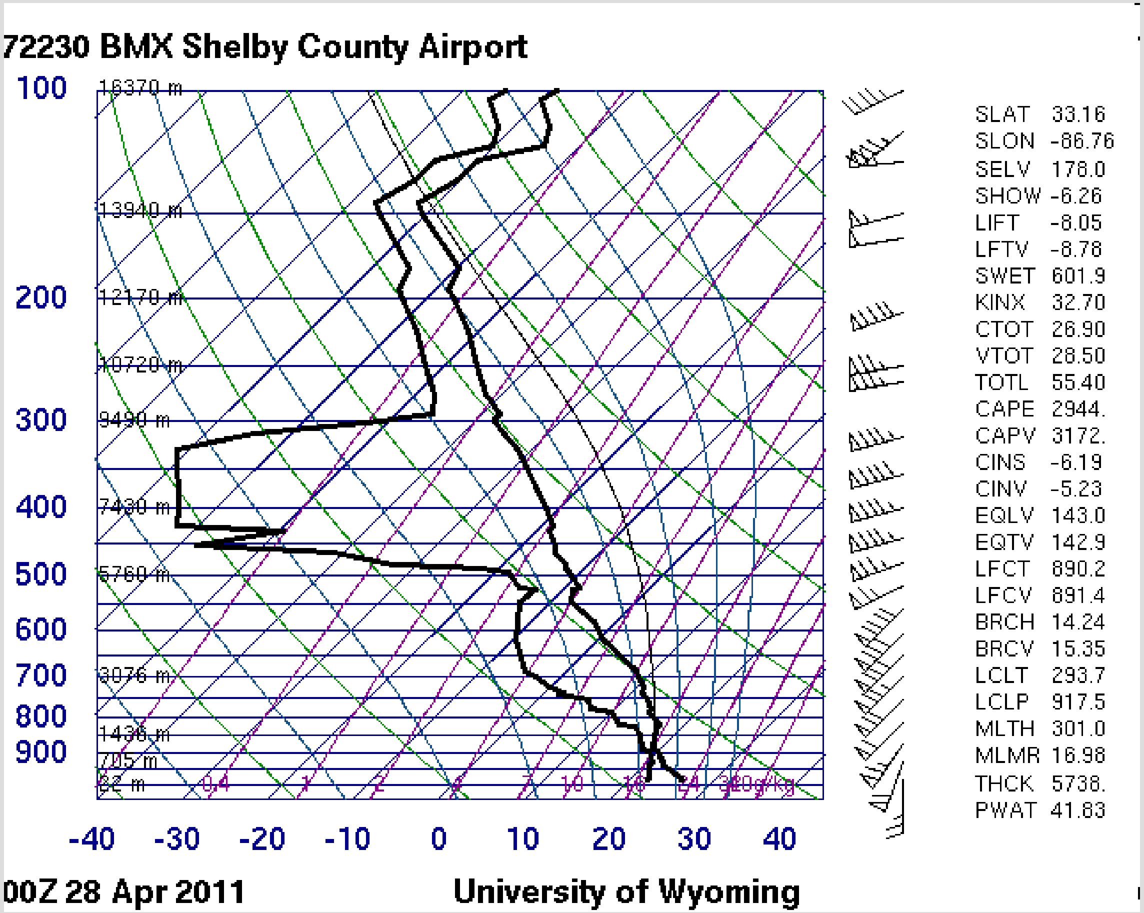


Fig. 7.2

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