# Clouds, Cloud Formation, Precipitation, Thunderstorms, and Tornados

## Clouds are Cloud Formation

Pages 169 – 189 of UWC

Pages 165 to 173 in MSE

## Types of Clouds
## Mechanisms of Formation

# The Cloud Genera

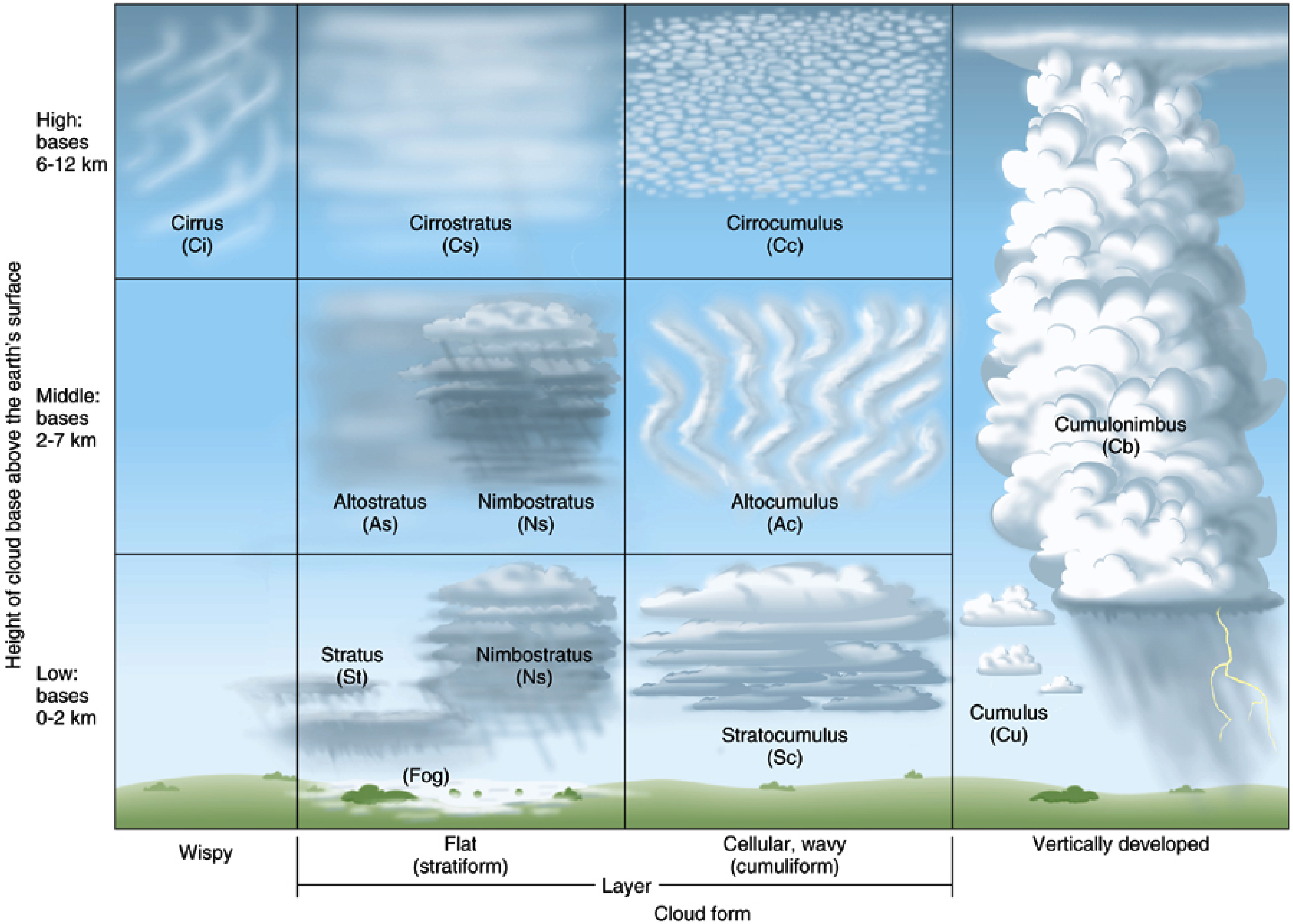



Figure from **Meteorology** by Danielson, Levin and Abrams

- Low, middle or High.
- Convective or stratus
- Potentially rainy (dark) or light.

# Cloud Classifications: Cloud Heights

- Low clouds are typically within 2000m (6500ft) of the surface.
  - Low clouds are usually composed of water droplets or supercooled water droplets, but not ice crystals.
  - Strongly influenced by surface characteristics (e.g., heating and topography).
- Middle clouds usually occur between 2000m and 7000m (6500 to 23000ft).
  - In the higher part of this height range, the temperatures are often below freezing, make the $H_20$ either supercooled droplets or ice crystals.
  - Prefix of alto in the names of these clouds.
  - Caused by large-scale circulation, fronts, and thunderstorms.
- High Clouds usually occur between 6000 and 12000m (20,000 to 40,000ft).
  - Composed of ice crystals.
  - Prefix of cirro (or cirrus).

# Cloud Classification: Shape

- The shape of a cloud is closely linked to the mechanisms that formed the cloud.
- Stratus Clouds
  - Stratus clouds are long and relatively shallow: their horizontal scale is much greater than their vertical scale.
  - They tend to be relatively flat bottomed and featureless.
  - These clouds tend to be advected (transported or blown) into a region, or formed by night time cooling.
- Convective Clouds
  - Formed (at least in part) by vertical motion
  - Suffix contains cumulus.

# Cloud Classification: Rain Producing

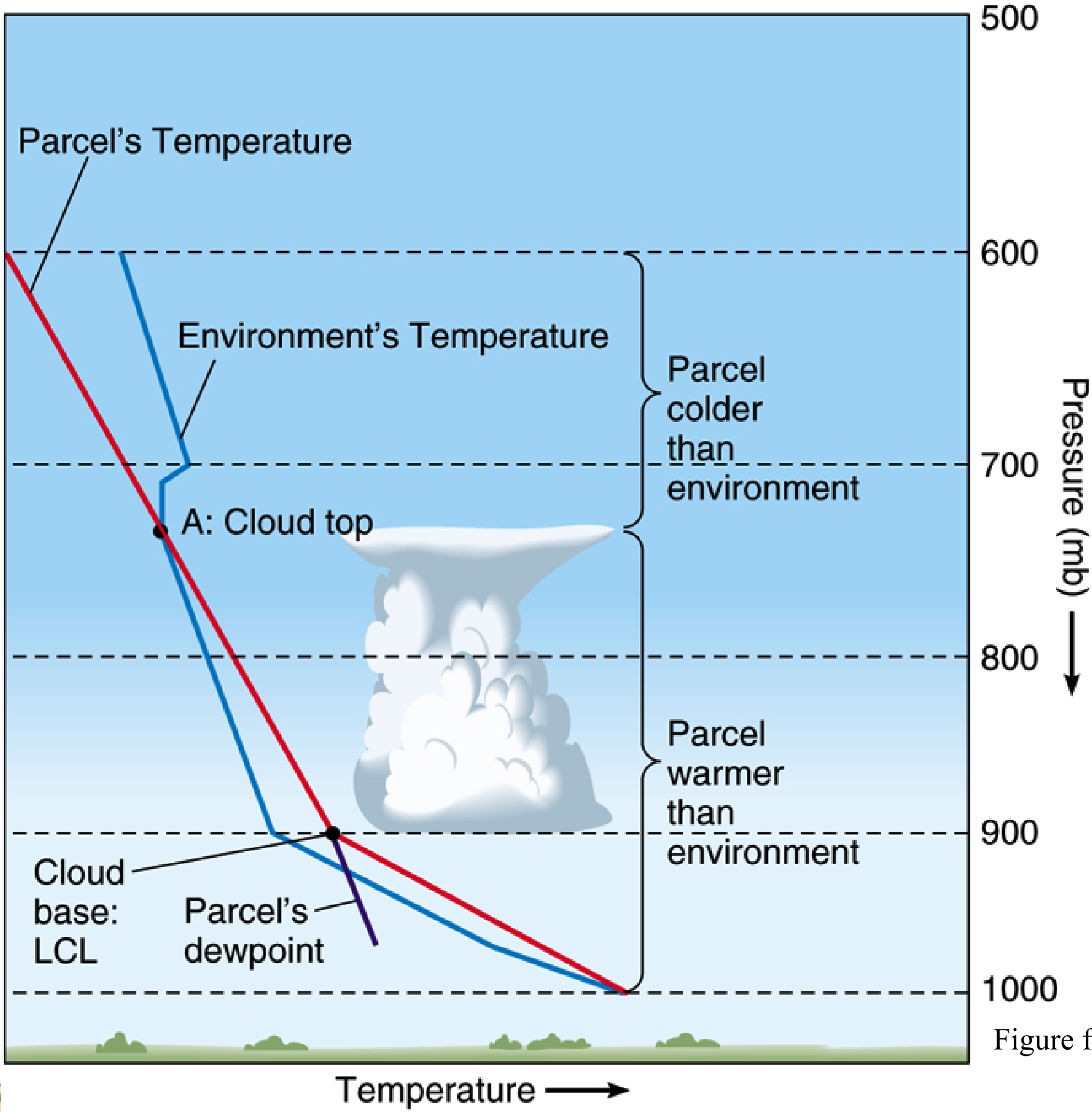
- Clouds that are darker, carrying more liquid water, are more likely to produce precipitation.
- The prefix nimbo or suffice nimbus is associated with these clouds.
- Examples:
  - Nimbostratus
    - Occurs at low and mid levels.
    - The low level version tend to produce greater rain rates
    - Can rain for long periods (hours)
  - Cumulonimbus
    - Massive clouds with great vertical scale (up to 16 km).
    - Anvil structure at the cloud top.
    - Can produce extremely high rain rates for short periods of time, as well as lightning and hail.

# Low Cloud Types

- Low cloud types are:
  - Stratus (St), which are flat and sheet-like, with much greater horizontal lengths than vertical lengths.
    - If the base of the stratus touches the surface, it is usually called fog.
  - Stratocumulus (Sc), a hybrid cloud type, formed by vertical motion.
    - Causing cloud bottoms to be at a similar height.
    - Vertical motion does not extend very far, resulting in a thin layer.
  - Nimbostratus (Ns), see previous page

- Mid-level cloud types are similarly characterized.

# Convective Cloud Formation




- Convective clouds are formed by rising air.
- The height of the cloud depends on the humidity and the environmental temperature profile.
- It will grow taller so long as the top parcel remains less dense than the surrounding air (and a little further).
- When the rising air cannot rise any further, it is forced to spread out and form an anvil.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Stability Ranges

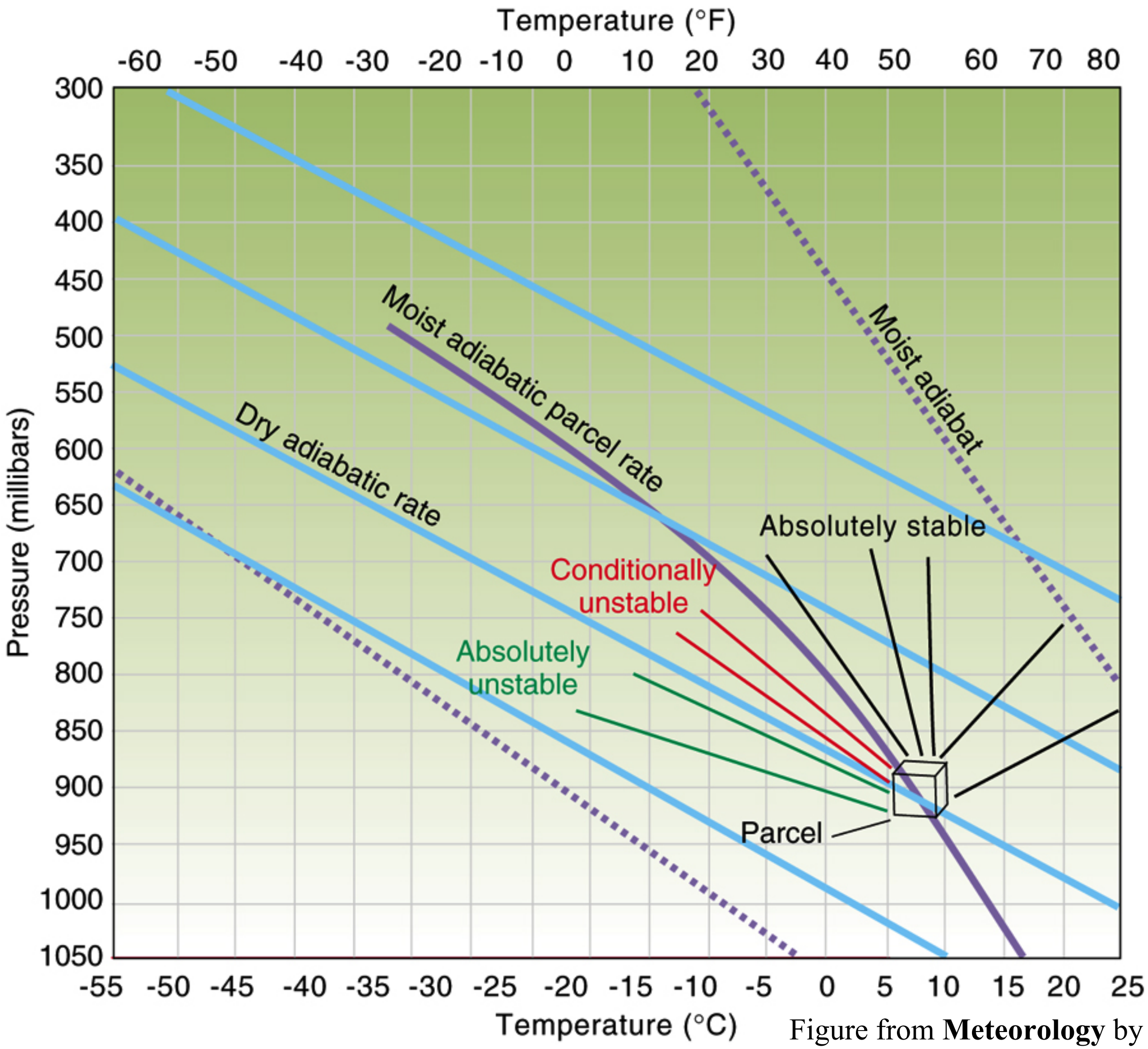
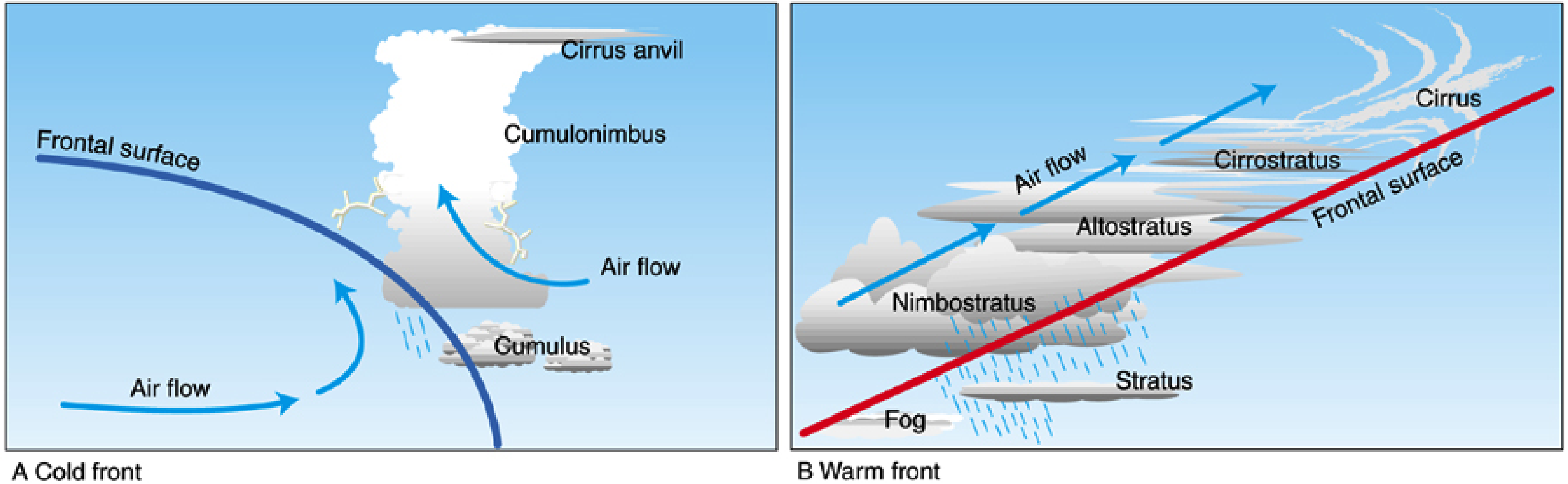



Figure from **Meteorology** by Danielson, Levin and Abrams

- An environmental lapse rate that is greater than the dry adiabatic lapse rate is absolutely (always) unstable.
- An environmental lapse rate that is less than the moist adiabatic lapse rate is absolutely (always) stable.
- A lapse rate between the dry and moist adiabatic lapse rates is conditionally (sometimes) unstable.

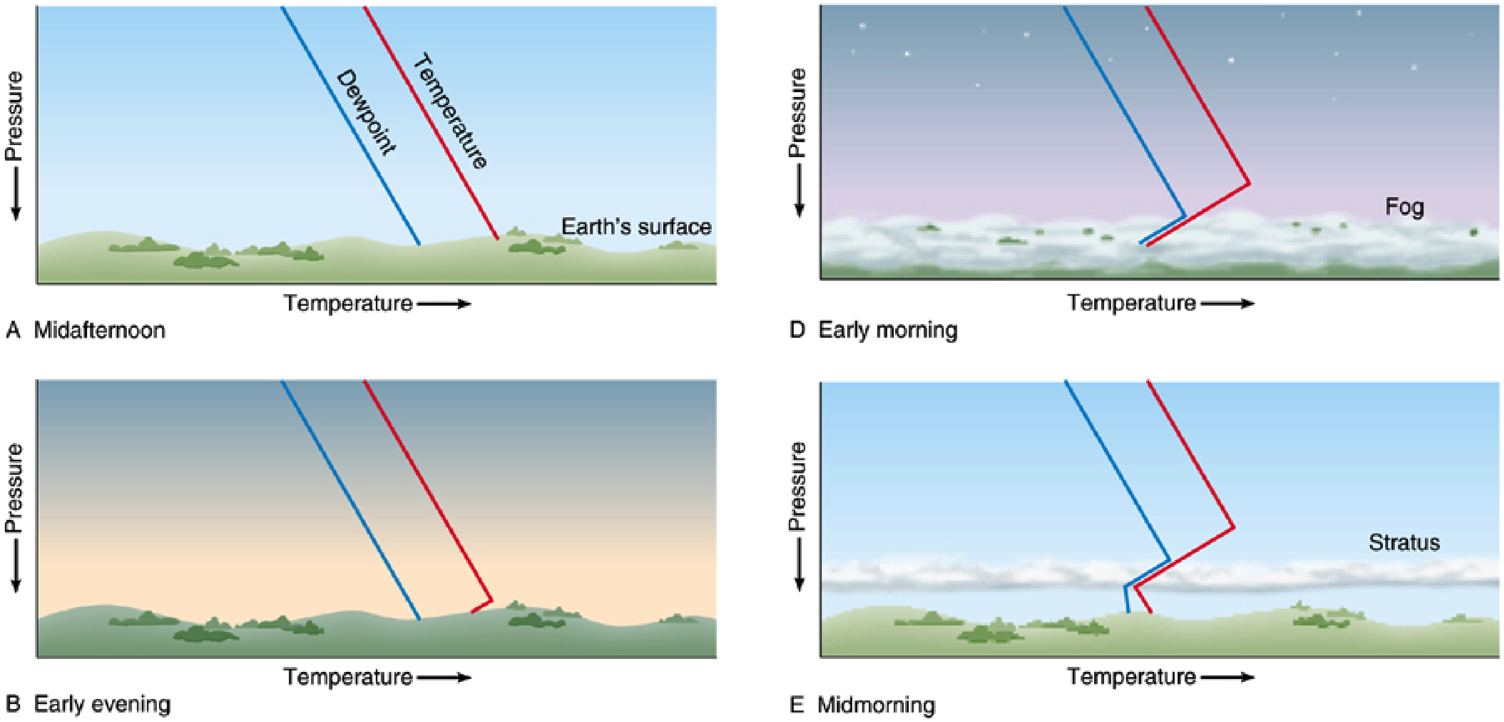
# Warm and Cold Front Cloud Types

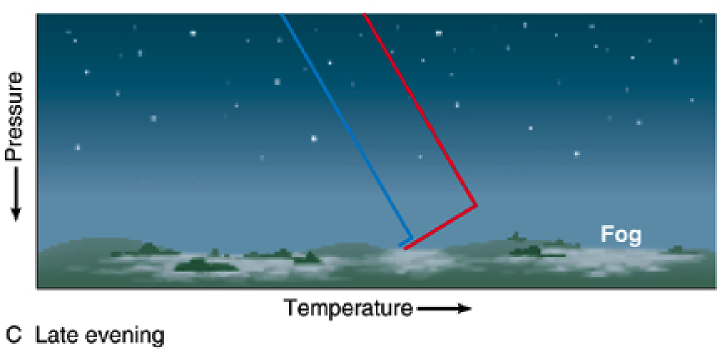



- Different types of clouds are associated with warm and cold fronts.
  - Rapid rising of air occurs at the leading edge of a cold front.
    - This motion creates convective clouds.
    - A rapidly moving cold front can produce a wall of cumulonimbus clouds.
  - The air along a warm front moves more slowly, creating a much more varied progression of cloud types.
- Watching the evolution of cloud types provides insights into the past and future weather.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Radiation Fog

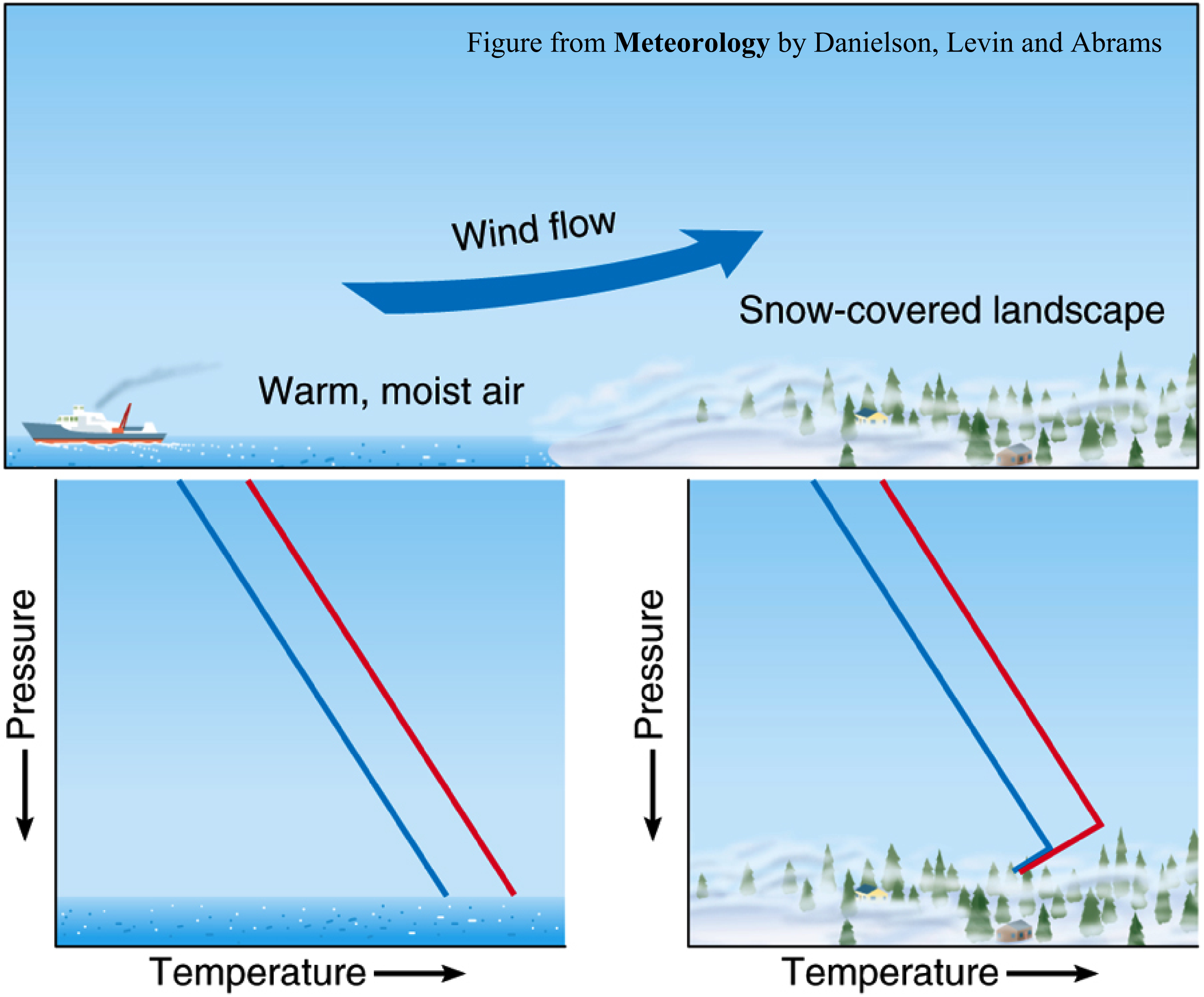



- Example of how night-time cooling can cause radiation fog, and later cause a stratus layer.
- Why is it called radiation fog?

Figure from **Meteorology** by Danielson, Levin and Abrams

# Advection Fog




- Advection fog is caused when relatively warm moist air is blown (advected) over a cooler surface.

# Precipitation

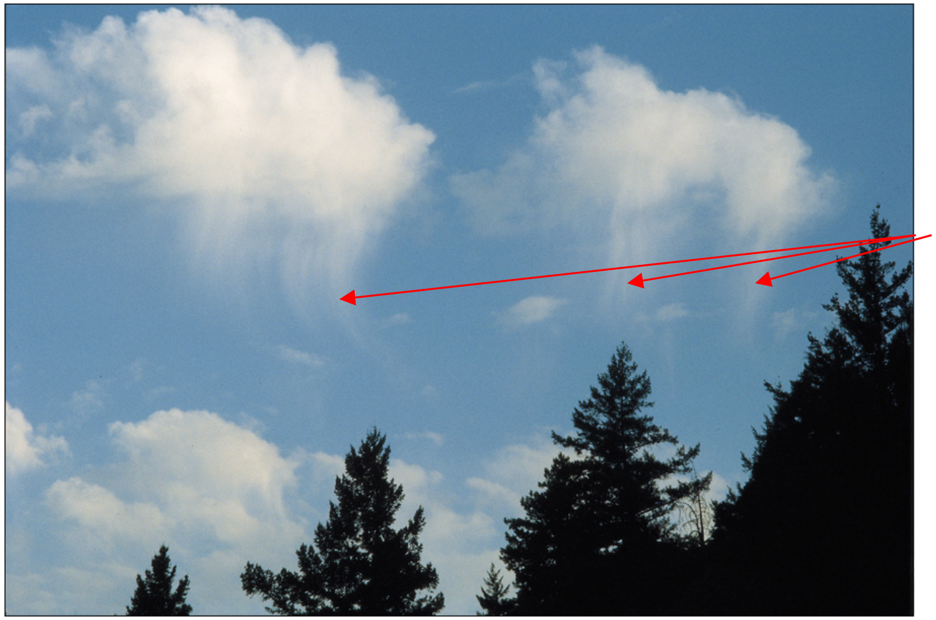
## Chapter 6 of Meteorology

## Chapter 7 of UWC
## Chapter 8 in MSE

Topics:
Two processes of precipitation formation
Why don't most clouds generate precipitation
How the different types of precipitation form
Cloud Seeding and precipitation modification

# Precipitation (Strict Definition)

- Definition: Liquid and solid $H_20$ that falls and reaches the ground.
- Dew and frost do not fall → not considered to be precipitation.
- Cloud droplets fall too slowly to be considered (and they usually don't reach the ground)
- Virga is not considered precipitation.



Rain does not reach the surface.

Why doesn't it reach the surface?

# Droplet Growth Through Condensation

- The mass of a droplet is proportional to its volume, which is proportional to the radius cubed.
- The mass of a cloud droplet is very small compared to a raindrop.
- Typical droplet growth curve is shown in the in the bottom figure.
- The rate of growth due to condensation slows as the droplet grows.

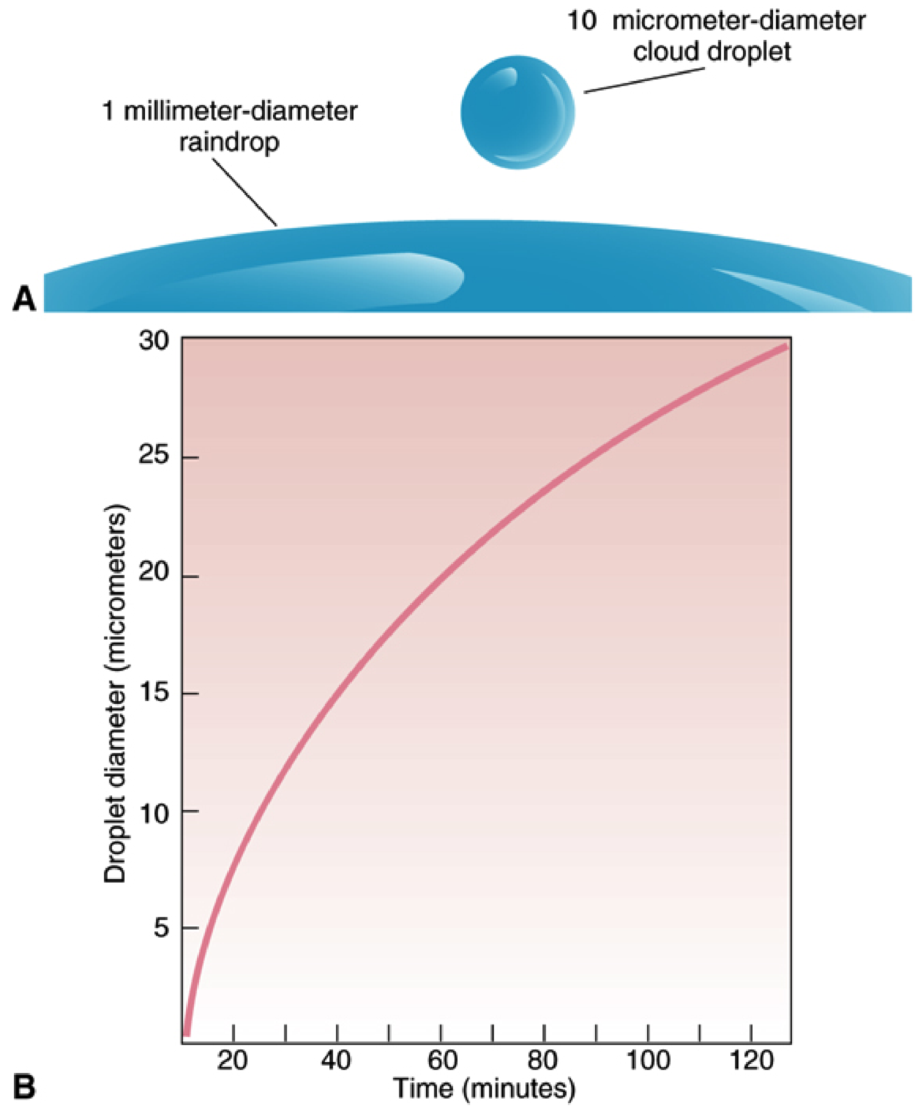



Figure from **Meteorology** by Danielson, Levin and Abrams

# Growth Through Collision and Coalescence

- Collision refers to droplets hitting (colliding) with each other.
- Coalescence refers to droplets that have collided sticking together.
- Example: if droplets on two fingers are brought close enough together, the two droplets will merge into one droplet.

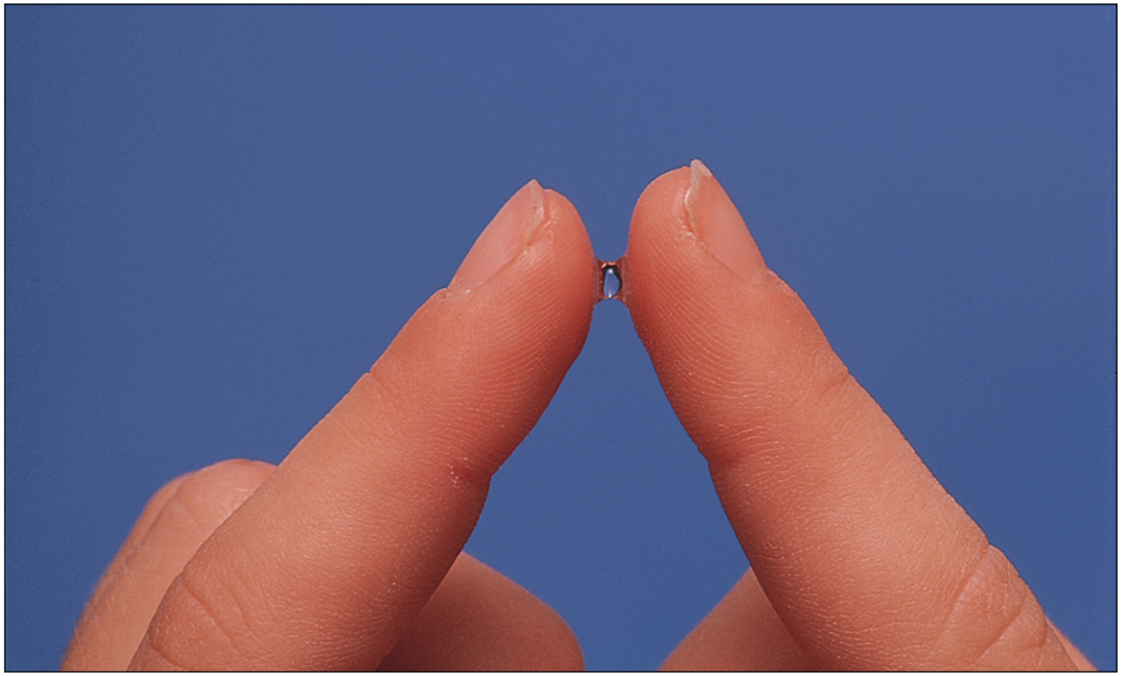
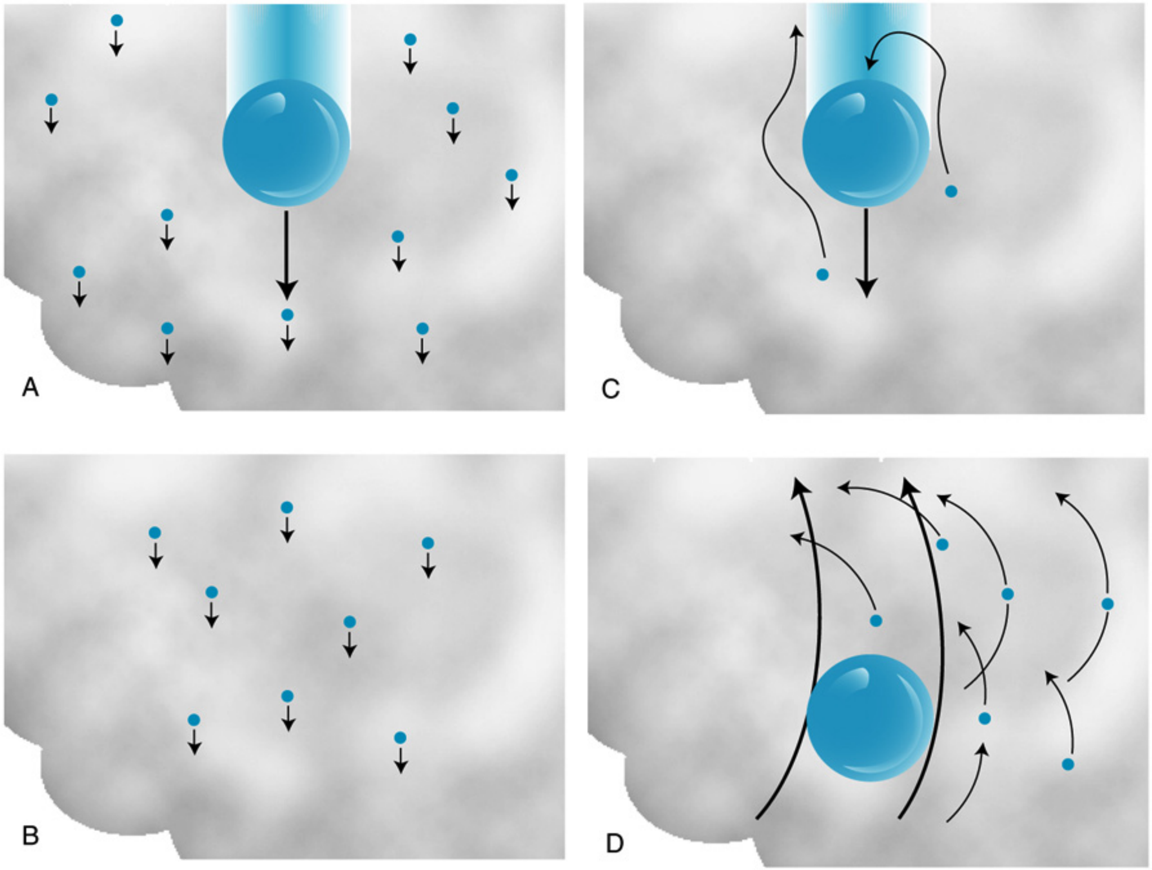


Figure from **Meteorology** by Danielson, Levin and Abrams

# Droplet Collisions Within a Cloud

- Water droplets collide with each other.
- A) The terminal velocity of large drops is greater than small drops.
- B) droplets of similar size rarely collide.
- C) Large droplets sweep through and collide with smaller droplets.
- D) Turbulence can cause additional collisions.




- The collision and coalescence processes are the key growth mechanisms for large droplets.

Figure from **Meteorology** by Danielson, Levin and Abrams

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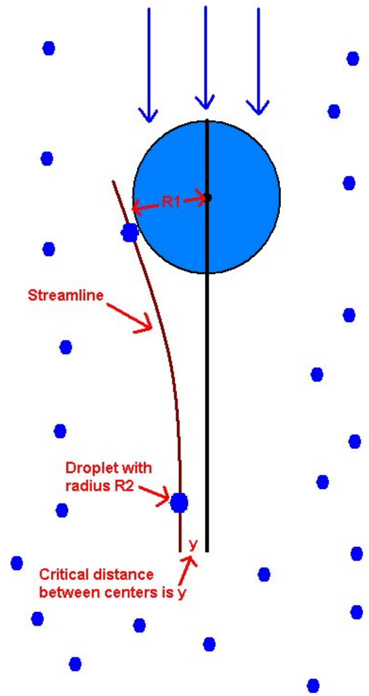
# Coalescence




- Collision efficiency ($E$) = # drops collide / # of droplets in path

$$E = \frac{y^2}{(R1 + R2)^2}$$

- Some droplets that collide do not stick.
- Coalescence efficiency = # of droplets coalesced / # of drops that collided
- Ochs et al. (1986) measured laboratory coalescence efficiencies for collector drops with radii between 128 and 300 microns and found that the coalescence efficiency decreased from 1.0 to 0.39 as the ratio of the collected to collector drop radii decreased.

- Collection efficiency = Coalescence efficiency * Collision efficiency

# Raindrop Breakup

- Small Raindrops and droplets are approximately round.
  - These are quite stable.
- Relatively large rain drops tend to distort (when falling) more than small drops.
  - In extreme cases, they can become almost doughnut shaped
- Raindrops that are greater than 5mm will break up as they fall.

# How Important is Collision and Coalescence?

- Collision & Coalescence is the dominant process in warm clouds.
  - Warm clouds have cloud temperatures greater than freezing.
- However, warm cloud precipitation is rare – particularly in mid and high latitudes.
- Most precipitating clouds have a portion of their volume with temperatures below freezing.

# Equilibrium Vapor Pressure: Ice vs. Water

- The saturation vapor pressure over ice is smaller than other water.
- Consider a parcel of air that is saturated over ice, and another parcel that is saturated over water.
- If these parcels mix, then the supercooled water will begin to evaporate, and deposition will occur on the ice.

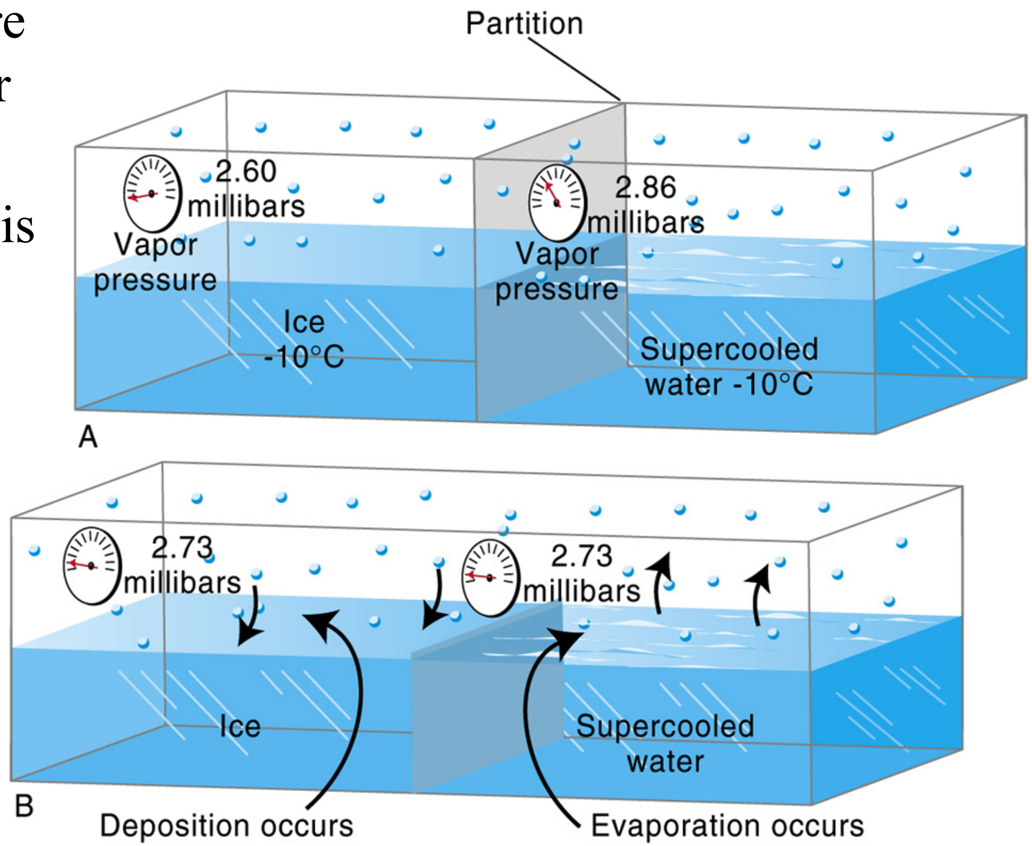



Figure from **Meteorology** by Danielson, Levin and Abrams

# Saturation Mixing Ratio Curves

- The saturation mixing ratio for water is greater than the value for ice.
- A parcel over ice may be saturated over ice, but not over water.

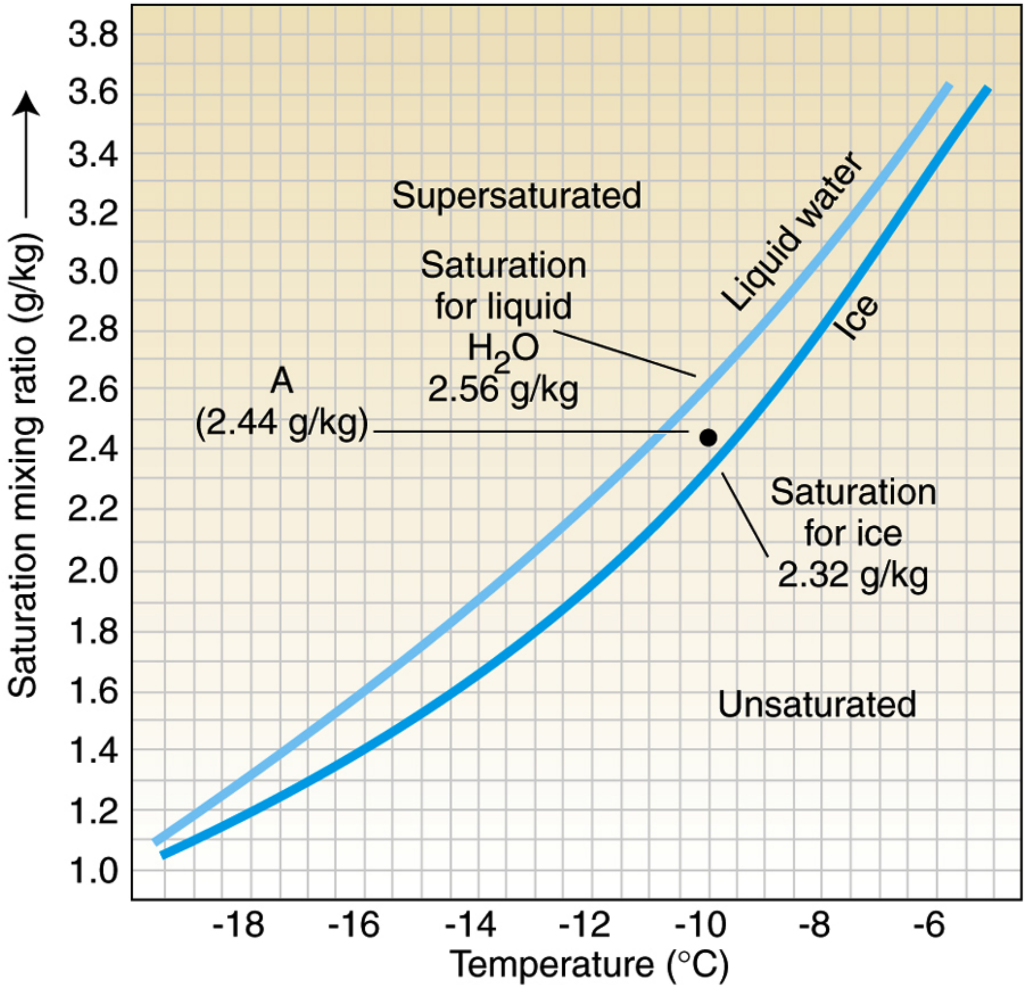



Figure from **Meteorology** by Danielson, Levin and Abrams

# Precipitation Formation: Bergeron-Findeisen Process

- The Bergeron Process is the in-cloud formation of ice particles from supercooled water droplets.
- Supercooled water evaporates, and is then deposited on the ice crystals.

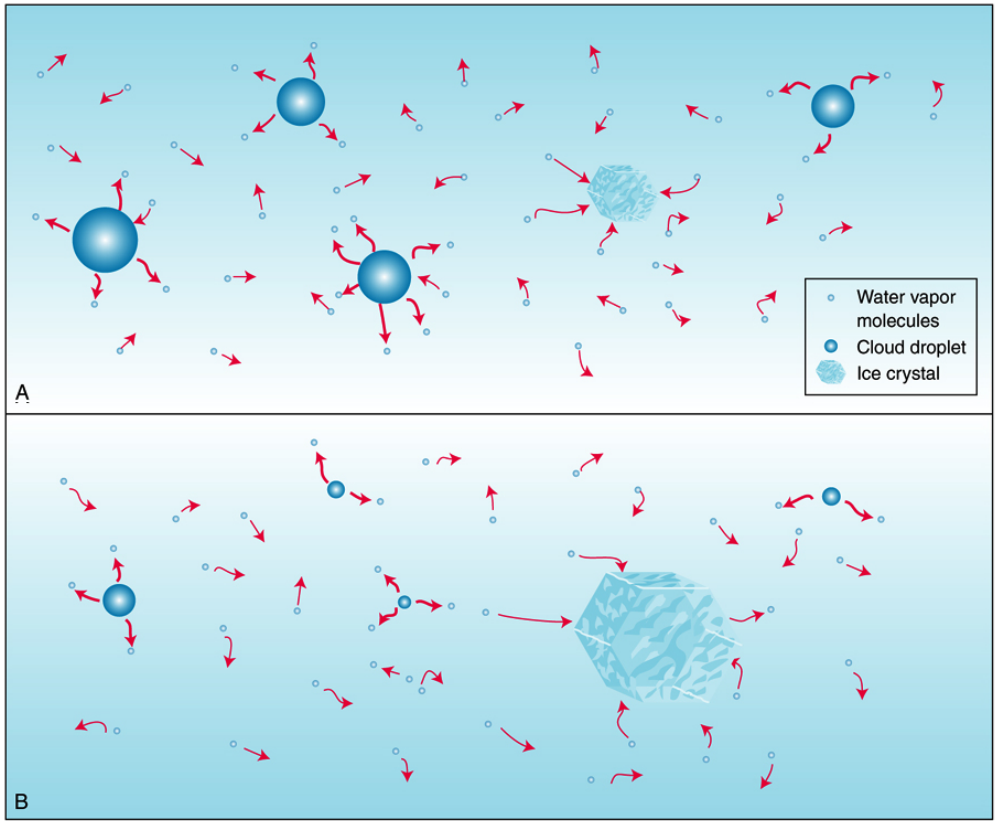


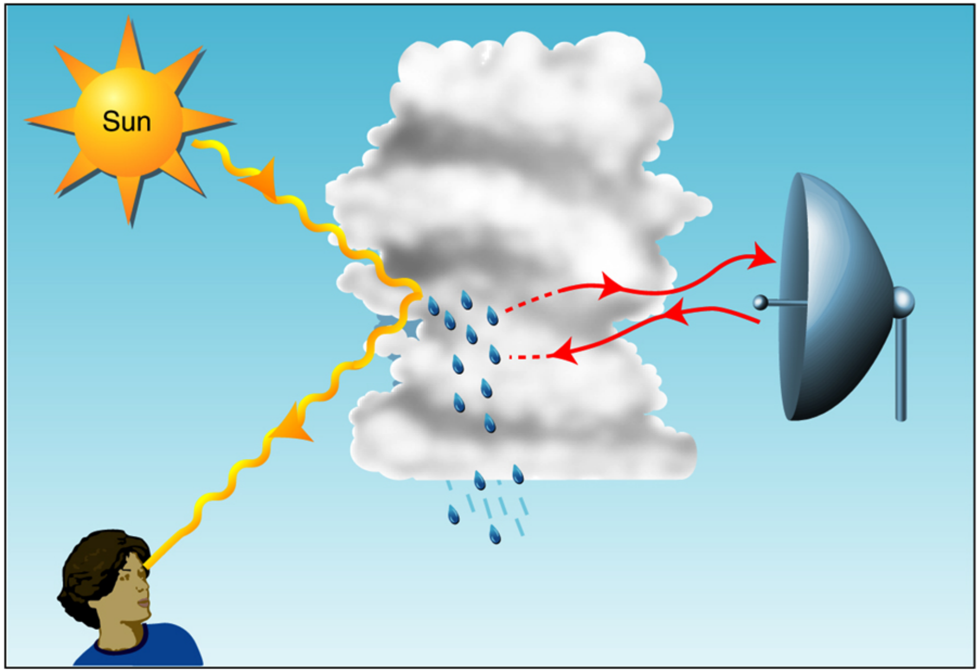

Figure from **Meteorology** by Danielson, Levin and Abrams

# Virga

- Virga is seen as wispy streaks hanging from clouds.
- Droplets evaporate before hitting the ground.
- Virga is more likely to occur when the drops are small.

Figure from **Meteorology** by Danielson, Levin and Abrams

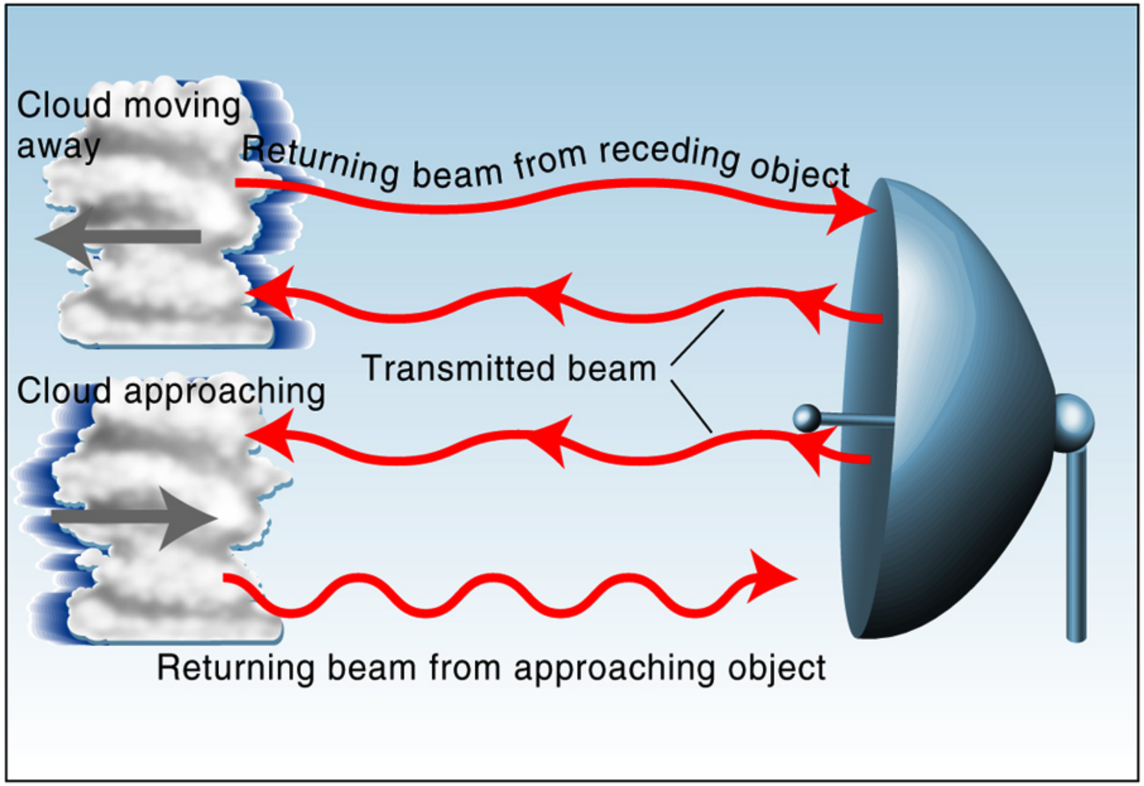
# Doppler Radar Schematic




- Short wave lengths (e.g. visible) light are reflected from clouds.
- Longer wavelengths interact with drops.
- Other key concepts:
  - Radar emits the signal and receives the fraction that is scattered back (an active system).
  - The eye only receives (a passive system).

Figure from **Meteorology** by Danielson, Levin and Abrams

# Doppler Radar




Doppler Effect: $\Delta \nu = 2\, V_{Tr} / \lambda$

Where $\nu$ is the frequency, $V_{Tr}$ is the radial velocity of the target, and $\lambda$ is the wavelength of the transmitted signal.

Figure from **Meteorology** by Danielson, Levin and Abrams

- Older radars gave information on the distance of the objects.
  - As measured by the return time.
  - Range = $\Delta time * c / 2$
- Doppler radars also measure the frequency of the returned signal.
  - Motion of the target, towards or away from the radar, modifies the frequency.
  - Higher frequency if the target is moving closer.
  - Lower frequency if moving away.

# ELEVEATION RANGE OF COVERAGE OF HORIZONATAL NEXRAD SCANS

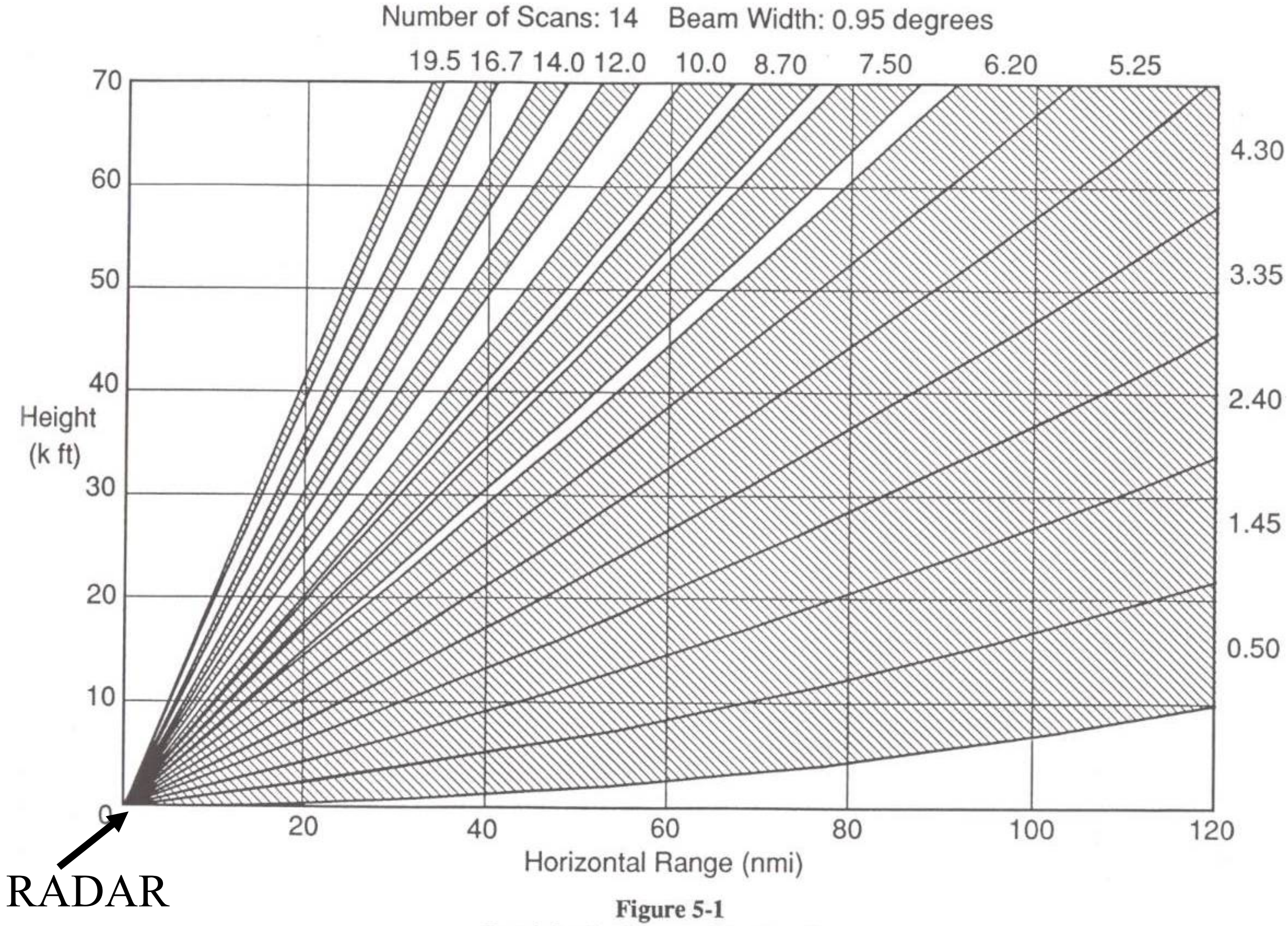
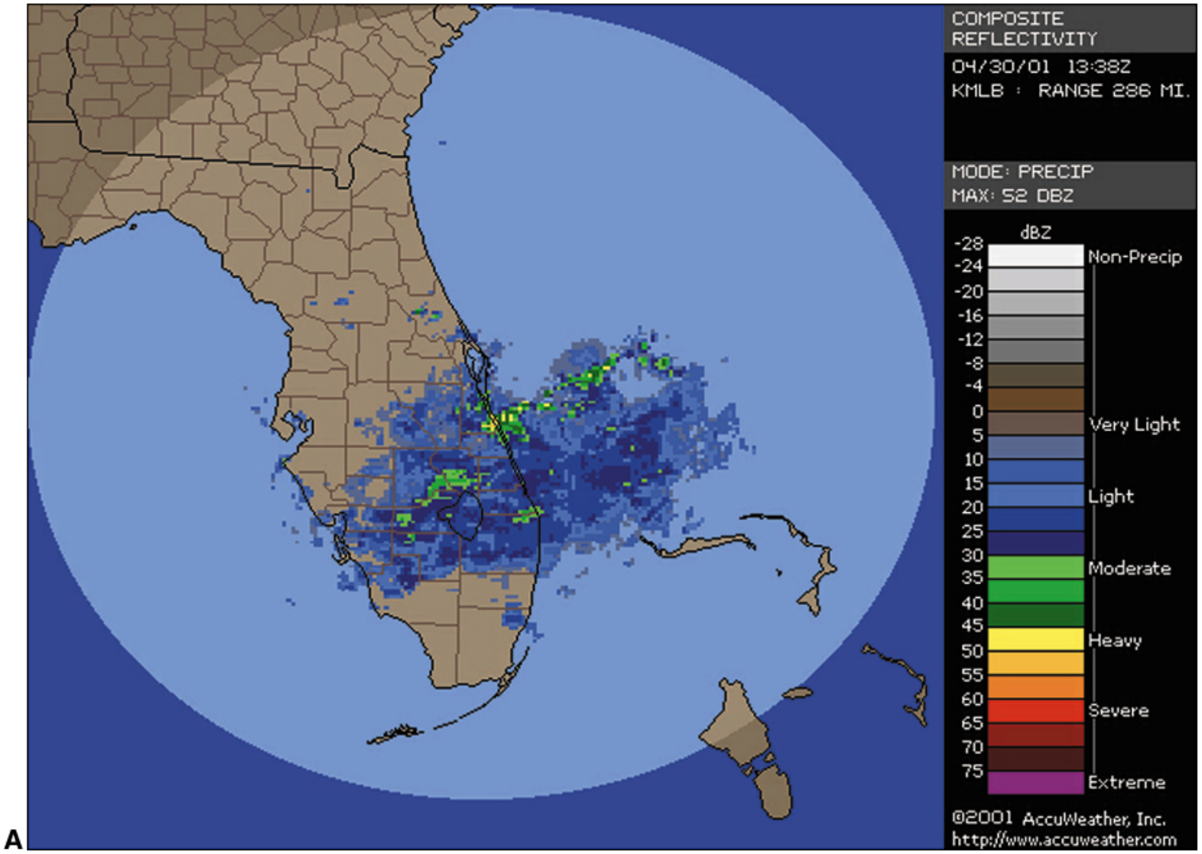



**Figure 5-1**
**Precipitation/Severe Weather Scan**
**Volume Coverage Pattern 11**

# Radar Example: Composite Reflectivity




- NEXRAD radars scan at a set of fixed elevation angles.
- For any of these angles, the height of the target increases with distance.
- Composite reflectivity is the greatest signal returned from any height within the column.

Figure from **Meteorology** by Danielson, Levin and Abrams

# What kind of units are decibels (dB)?

- Decibels are the units commonly seen for the strength of radar signal ($Z$) returned by a target.

  $\log(Z) = \log(\textit{received power}) + 2 \log(\textit{range}) + \textit{constant}$.

- The range term compensates for the loss of signal with distance.
  - How does the power fall off with range?
  - $range^x$, what is $x$?
- The range of values for $Z$ is very large, so the log of the values (*dBZ*) is commonly used.

  $dBZ = 10 \log(Z)$

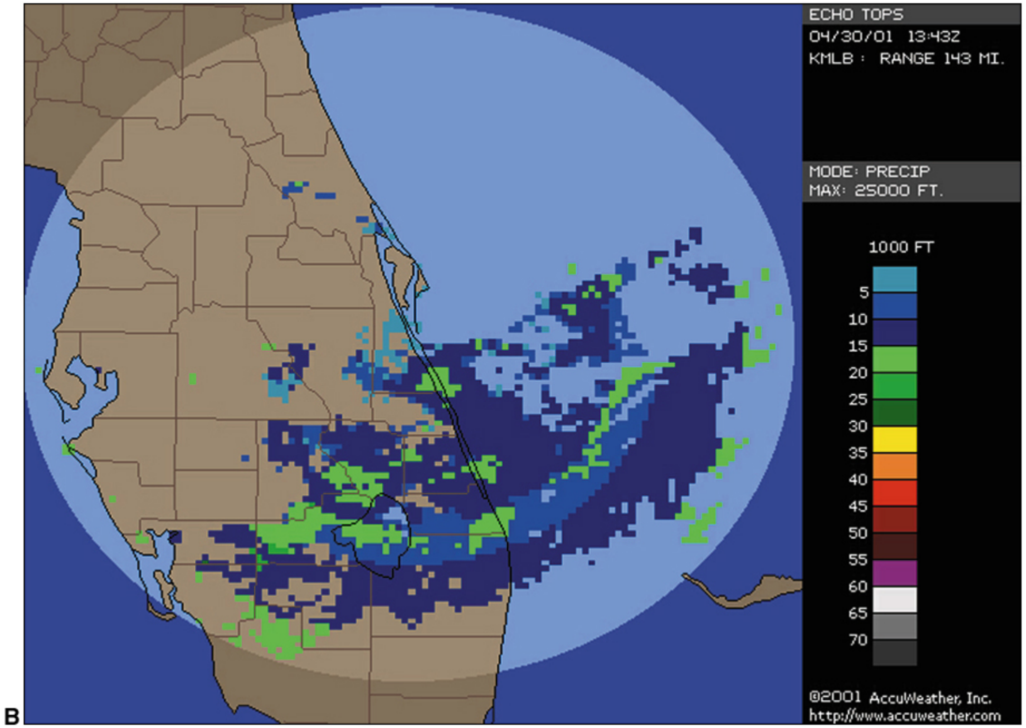
- Larger and more numerous drops return more received energy:

  $\textit{Received power} = \mathrm{sum}(D^6) / V$

  Where $D$ is the droplet diameter, and $V$ is the volume of the air holding the drops.

  - Is the volume ($V$) constant? What about droplets per unit volume?

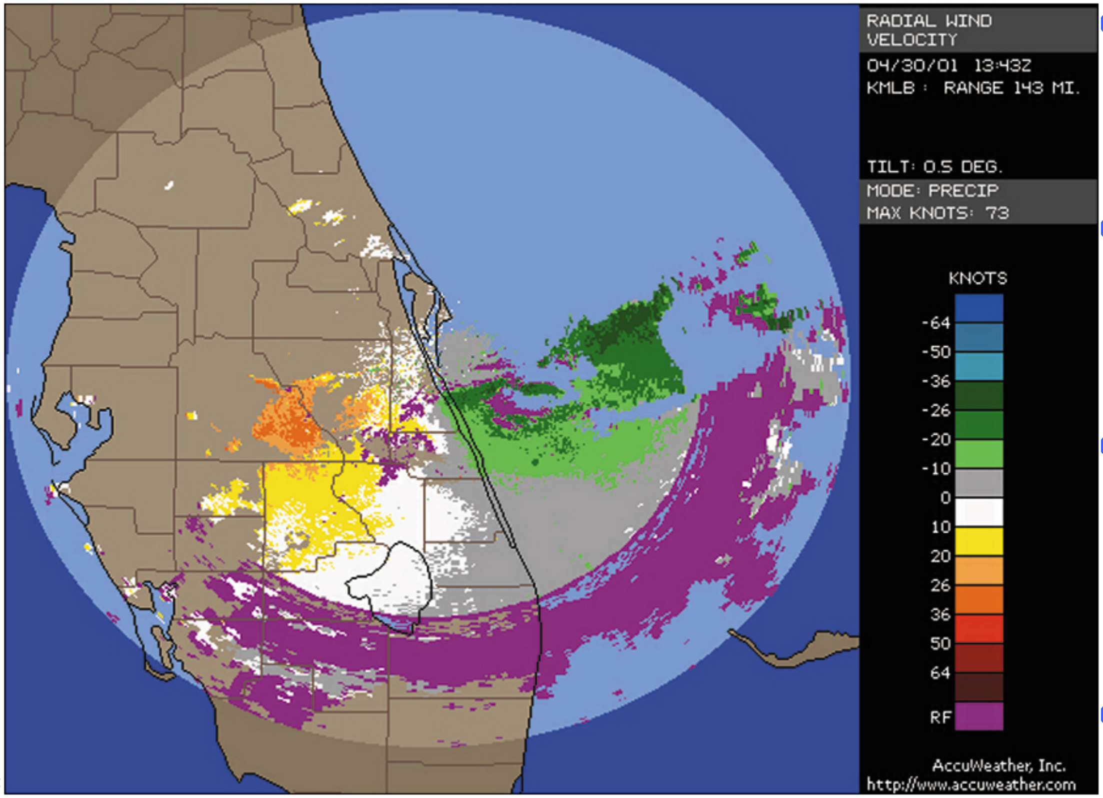
# Echo Tops




- Echo tops indicate the altitude of the highest objects for which the returned signal is greater than a threshold.
- This is an estimate of the height of cloud tops.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Radar example: Radial Wind Velocity

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- The Doppler effect is used to determined radial velocity.
- Radial means towards or away from the radar.
  - Away is positive.
- A large shift in speed indicates great shear (change in velocity with distance).
- High wind speeds, with a shift in sign, indicates a tornado.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Mystery Radial Velocity Example: What are we seeing?

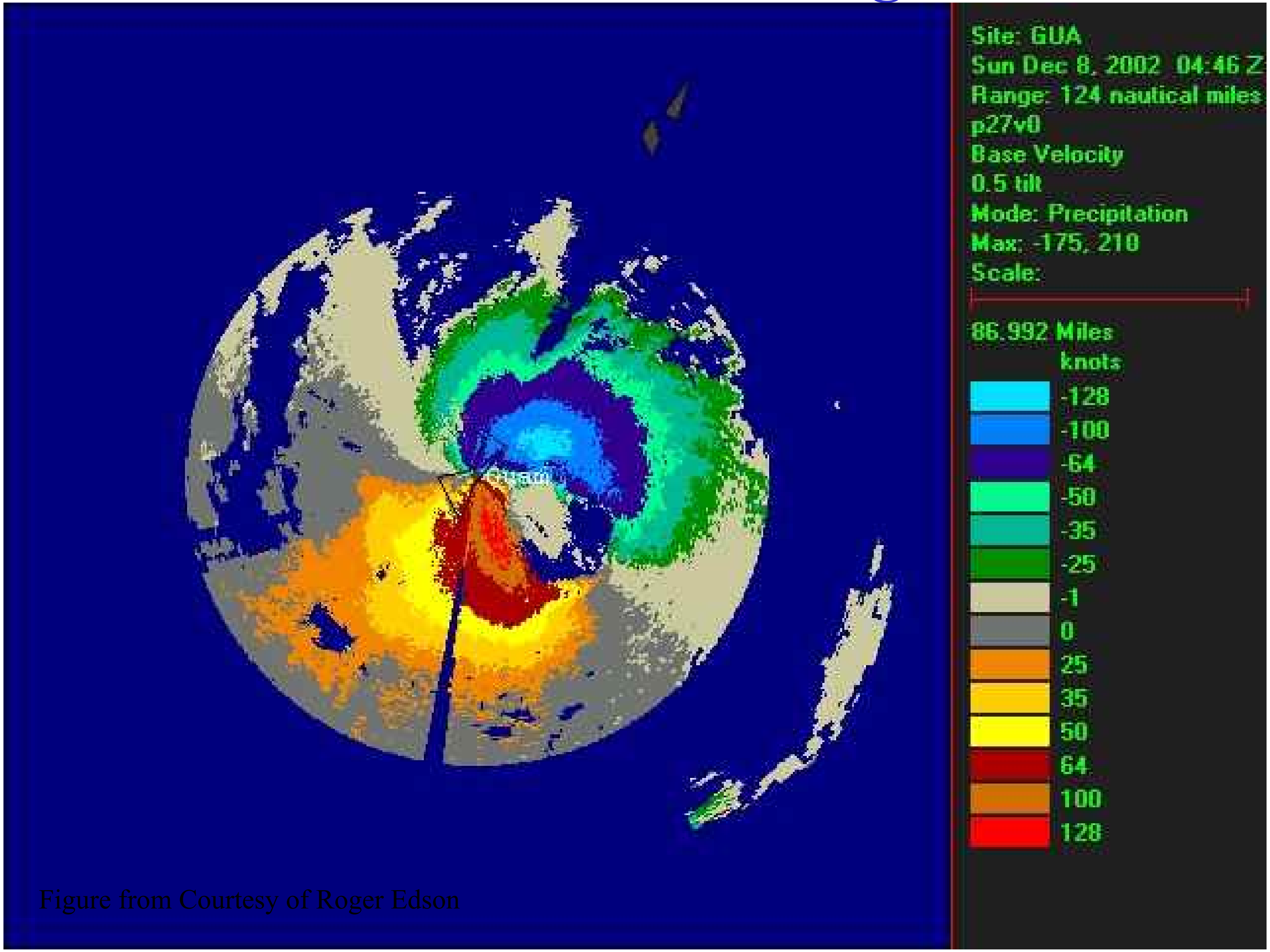



Figure from Courtesy of Roger Edson

# Precipitation Associated with Super Typhoon in Previous Example

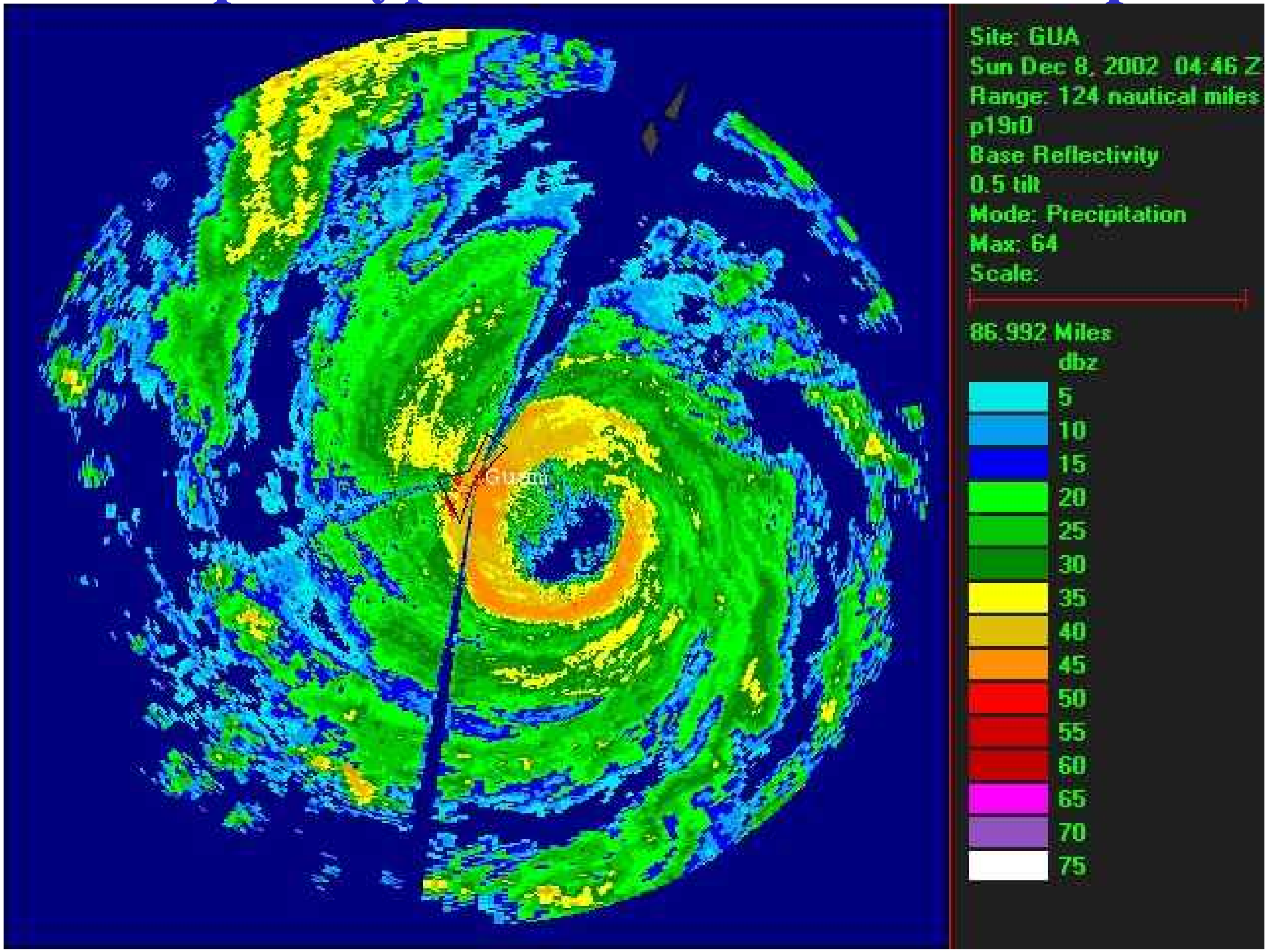
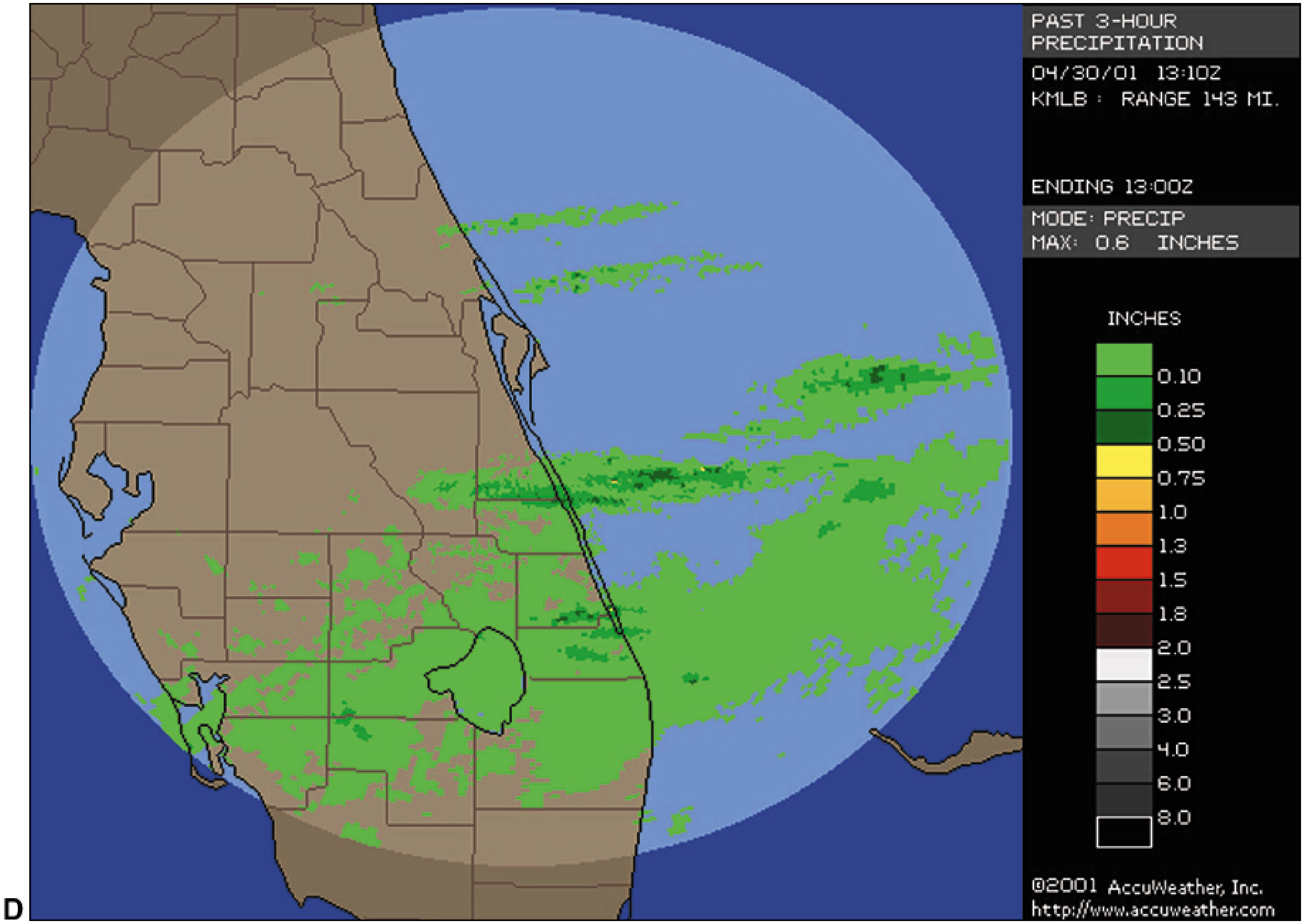



Figure courtesy of Roger Edson

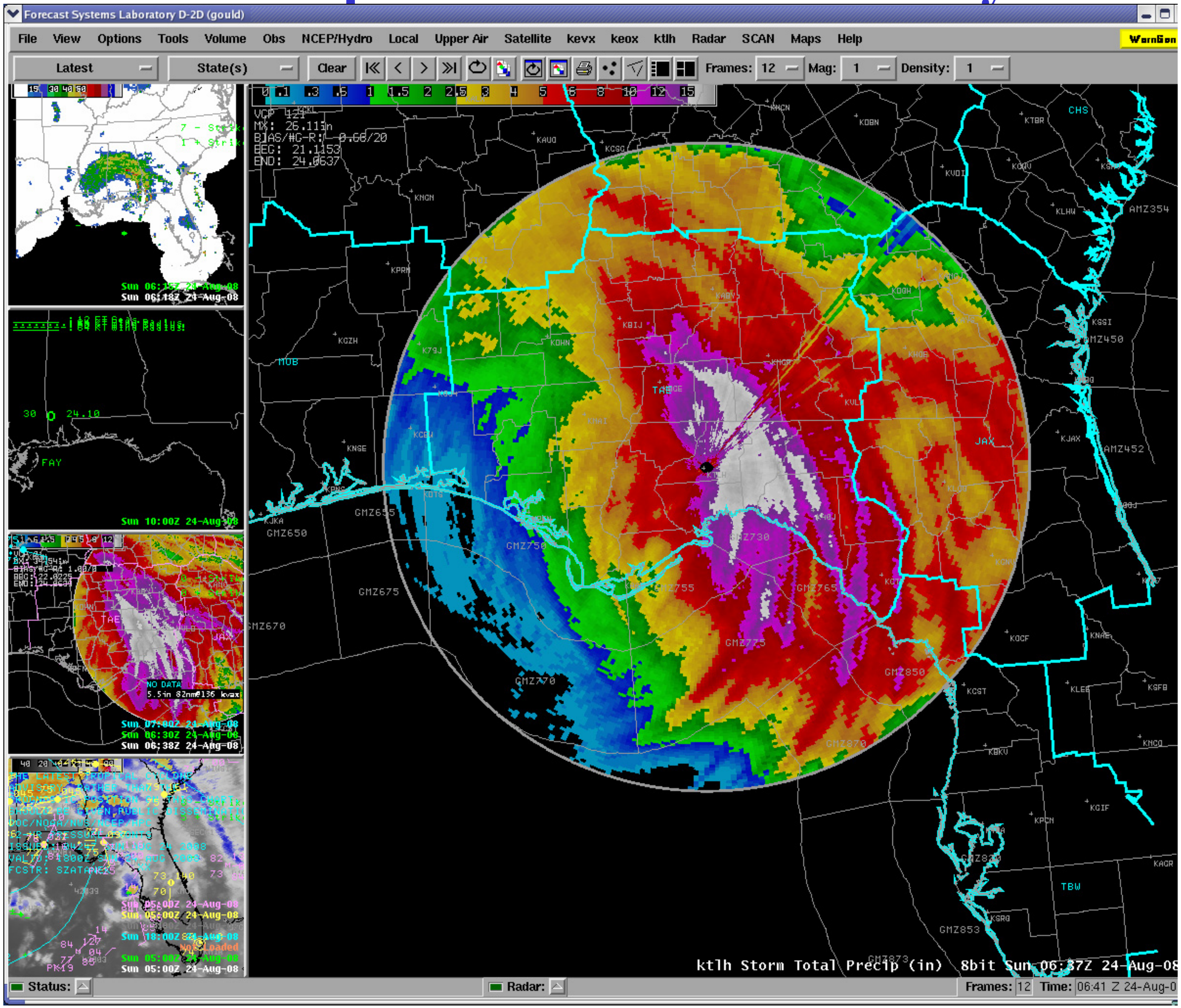
# Past 3-hour Precipitation




- Sum of precipitation over the prior three hours.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Precipitation Totals From Fay 2008

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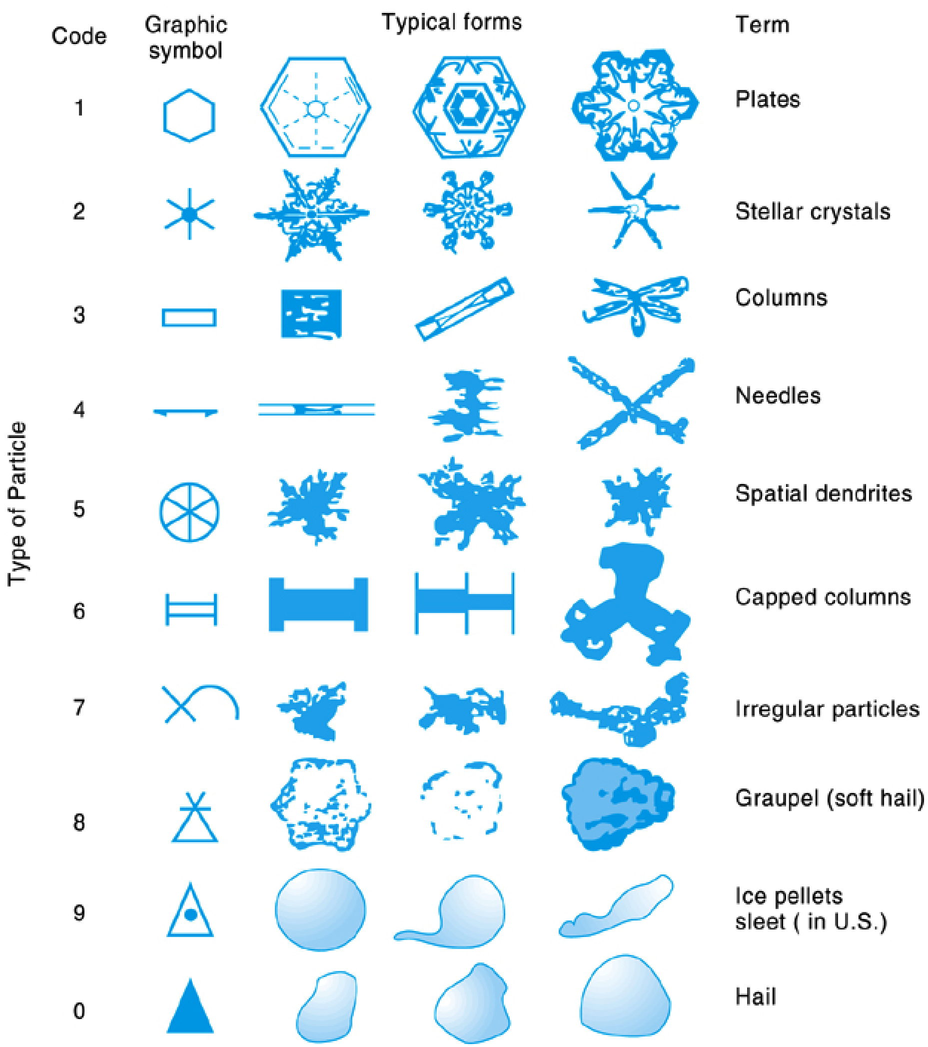
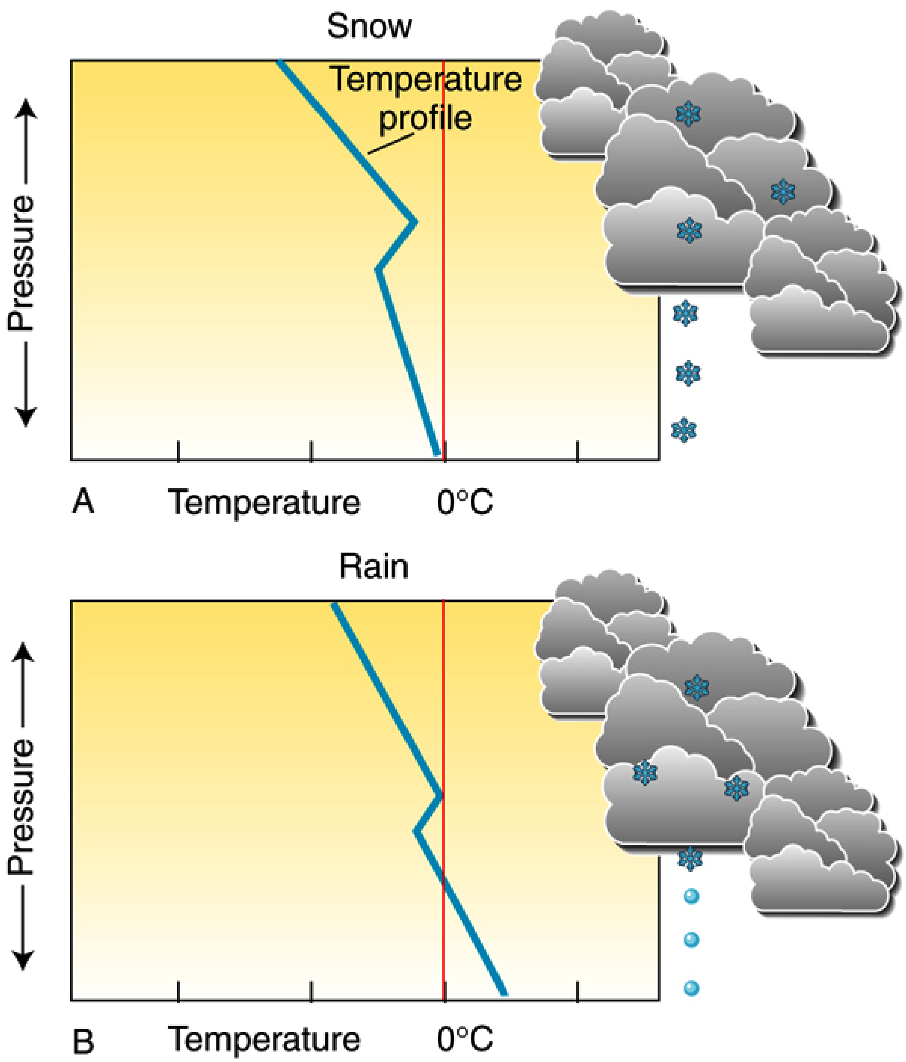
# Classification of Snow and Ice Forms




- There are many different shapes (structures) of ice crystals.
- The shape that forms as water condenses onto the crystal is a function of temperature and relative humidity.
- Flakes can collide and stick together, forming larger flakes called dendrites.
- Melting and refreezing can change the shape
  - Related to sleet and hail formation.

Figure from **Meteorology** by Danielson, Levin and Abrams

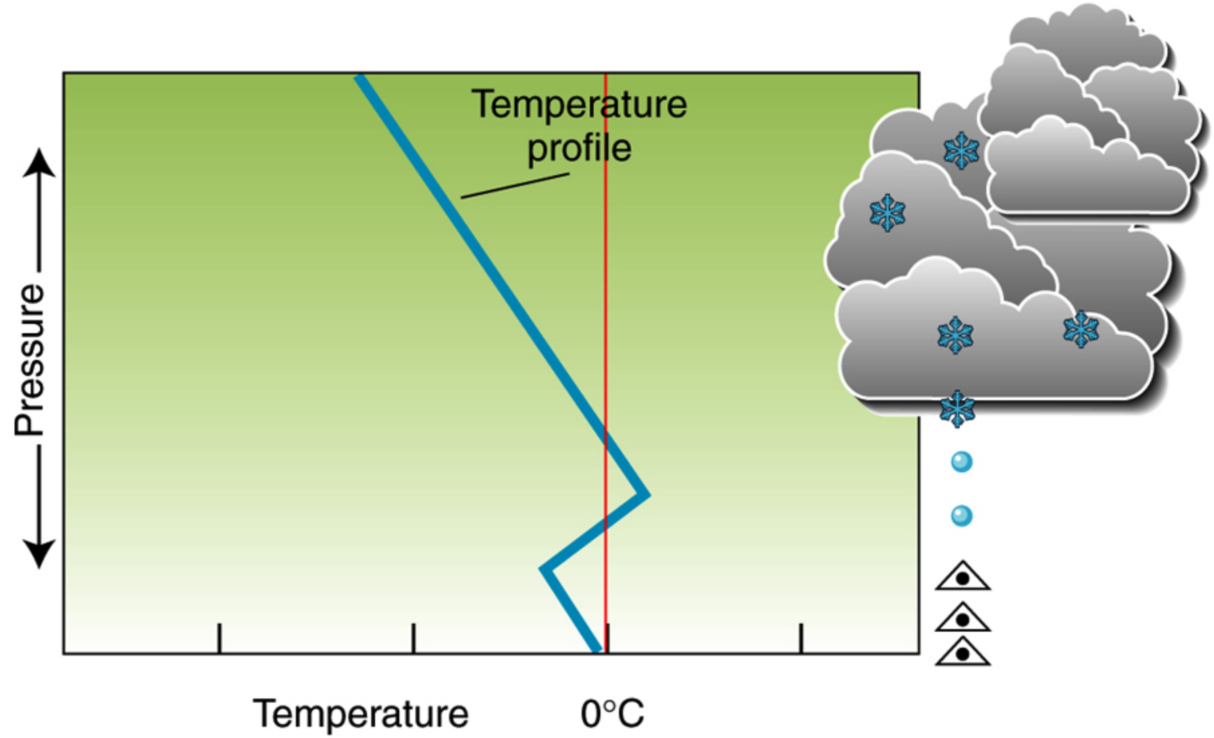
# Precipitation Types: Rain or Snow




- If the temperature profile is always <0°C, the precipitation will be snow.
- If parts of the profile are warmer than freezing, the snow will start to melt as it enters the warmer air.
- Partial melting → wet snow
- Near fully melted → rain.

Figure from **Meteorology** by Danielson, Levin and Abrams

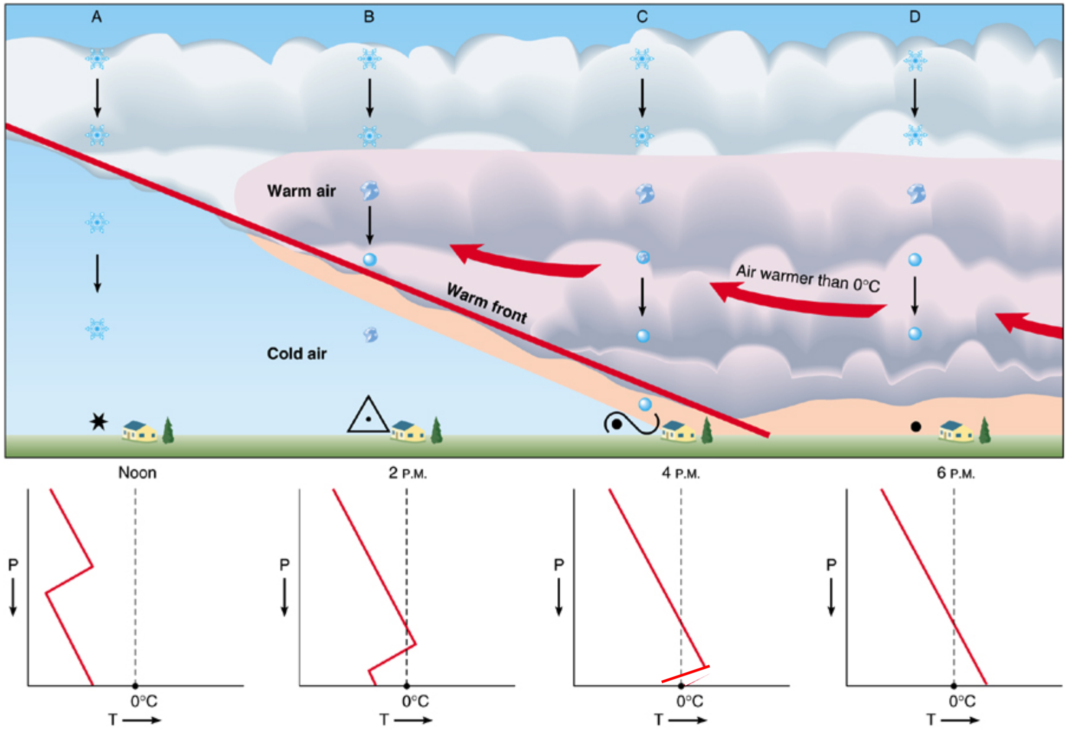
# Profile That Accompanies Sleet




- In the U.S., ‘sleet’ is defined as ice pellets.
- Definitions vary from country to country (hence great confusion in meaning).
- Ice pellets are usually formed when falling snow flakes (or ice pellets) move through regions rich in supercooled droplets.
- Alternatively, falling snow can melt and subsequently freeze while falling.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Warm Front Precipitation Types




- Warm fronts usually cause light to moderate rain, freezing rain, or sleet.
- Freezing rain causes a create deal of structural damage.
  - Also a great danger to transportation.
  - Severe problem in NE U.S. and Eastern Canada.

Figure from **Meteorology** by Danielson, Levin and Abrams

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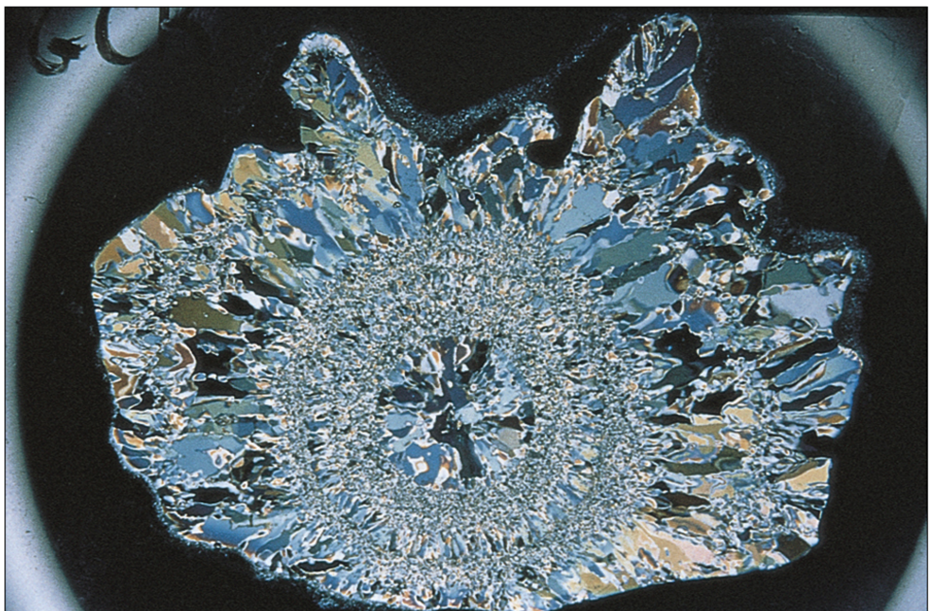
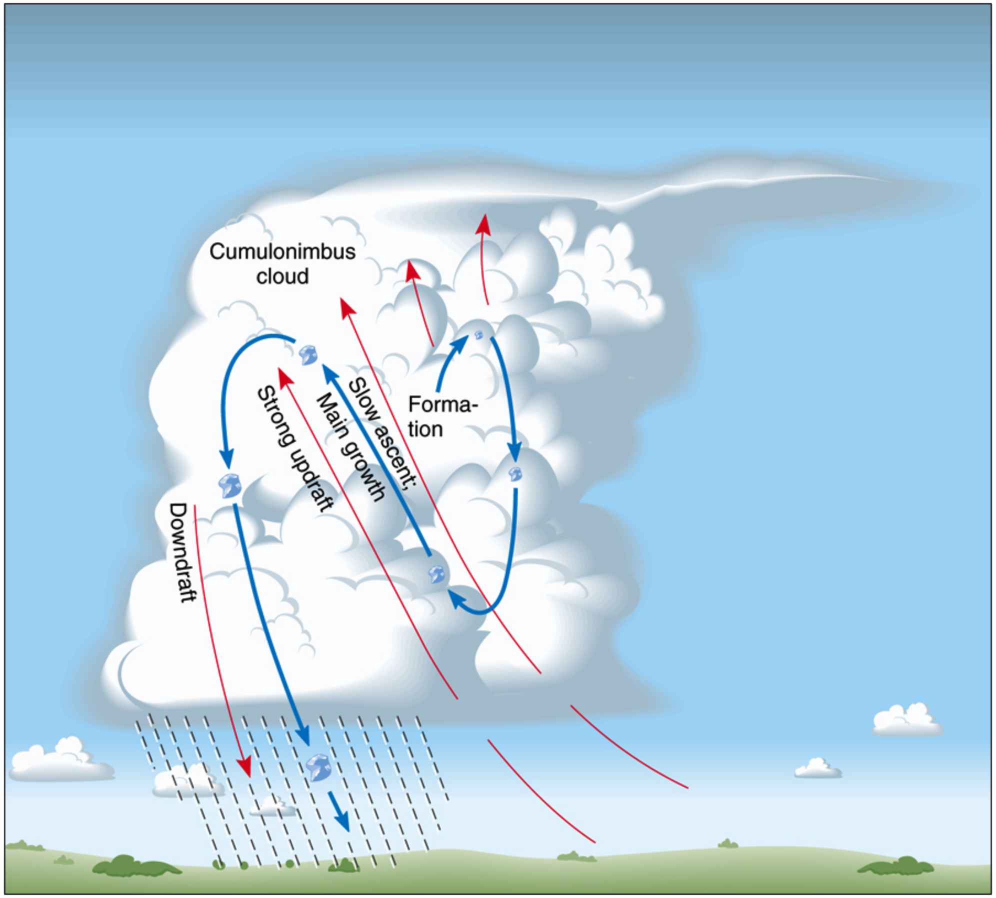
# Hail



- Hail is a lump of ice with >5mm diameter.
  - Hail can be a danger to life and property.
  - One hail storm in the former Soviet Union is said to have killed 200 cattle.
- The largest hail stone recovered weighed 0.75 kg (1.67 lbs).
  - After loss due to melting.

Figure from **Meteorology** by Danielson, Levin and Abrams

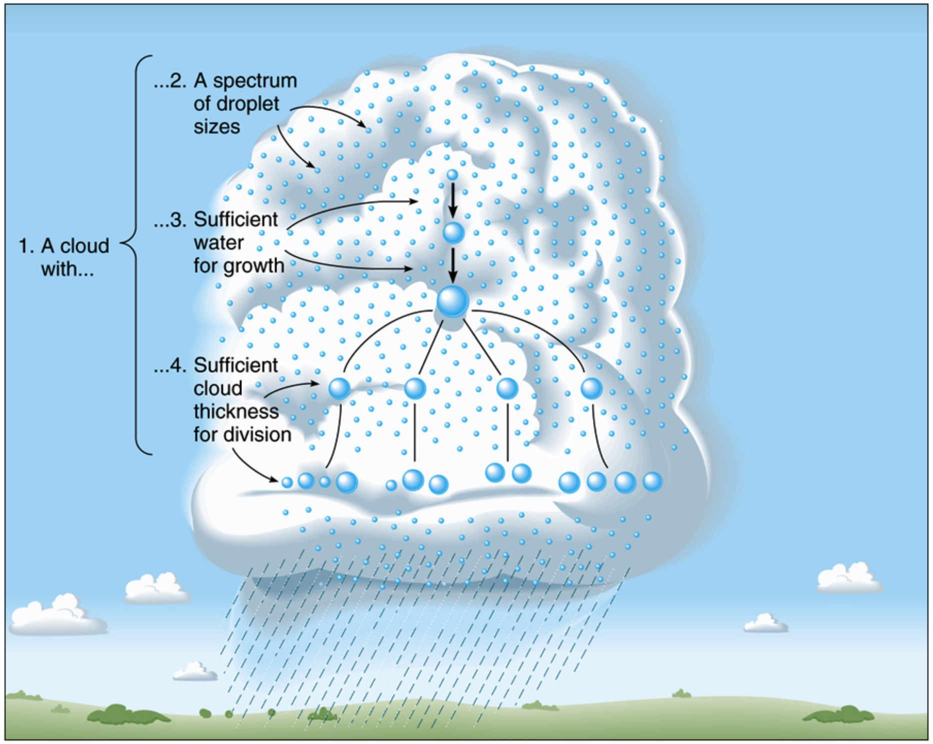
# Hail Formation and Growth




- Hail grows by collision & sticking.
- Grows very large if carried up by updrafts.
  - Possibly multiple times (1-4?)
- Cumulonimbus clouds have very strong updraft and downdraft regions.
- Terminal velocity for a large hailstone is very fast! An updraft must be extremely strong to carry them up.
  - Can exceed 40 $ms^{-1}$ in mid-latitude storms

Figure from **Meteorology** by Danielson, Levin and Abrams

# Precipitation Modification: Warm Rain




Model of Precipitation via Collision & Coalescence

- How could warm rainfall be stimulated?
  - That is, how do we get more out of the bottom of the cloud?
- Enhancing droplet growth at any level above the cloud bottom should be useful.
- The greatest advantage comes from increasing either the growth rate at the top, or the number of large droplets.

Figure from **Meteorology** by Danielson, Levin and Abrams

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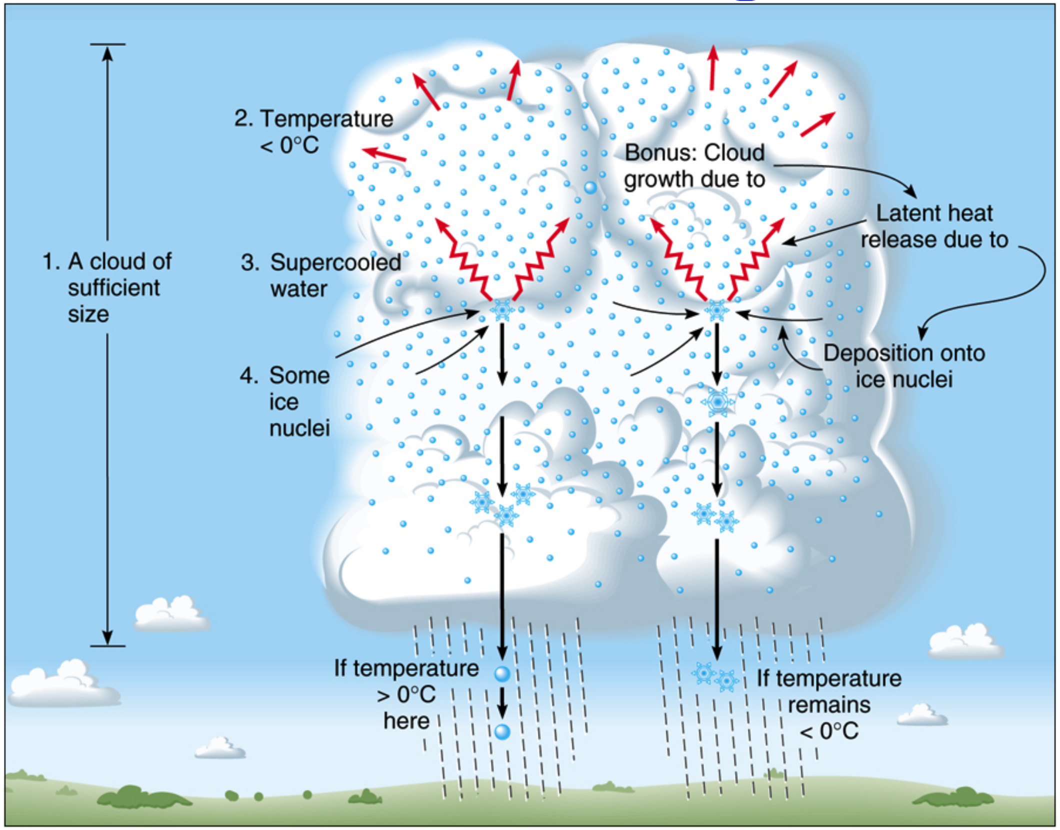
# Precipitation Modification: Bergeron Process




- Again seeding the cloud top is the most effective approach.
- Seeding with dry ice (frozen $CO_2$) was developed by Vincent Schaefer (1946).
- Dry ice has a temperature of –78.5°C (-109°F) which is far colder than the –39°C needed for spontaneous (homogeneous) nucleation.

Model of Precipitation via Three-phase Process

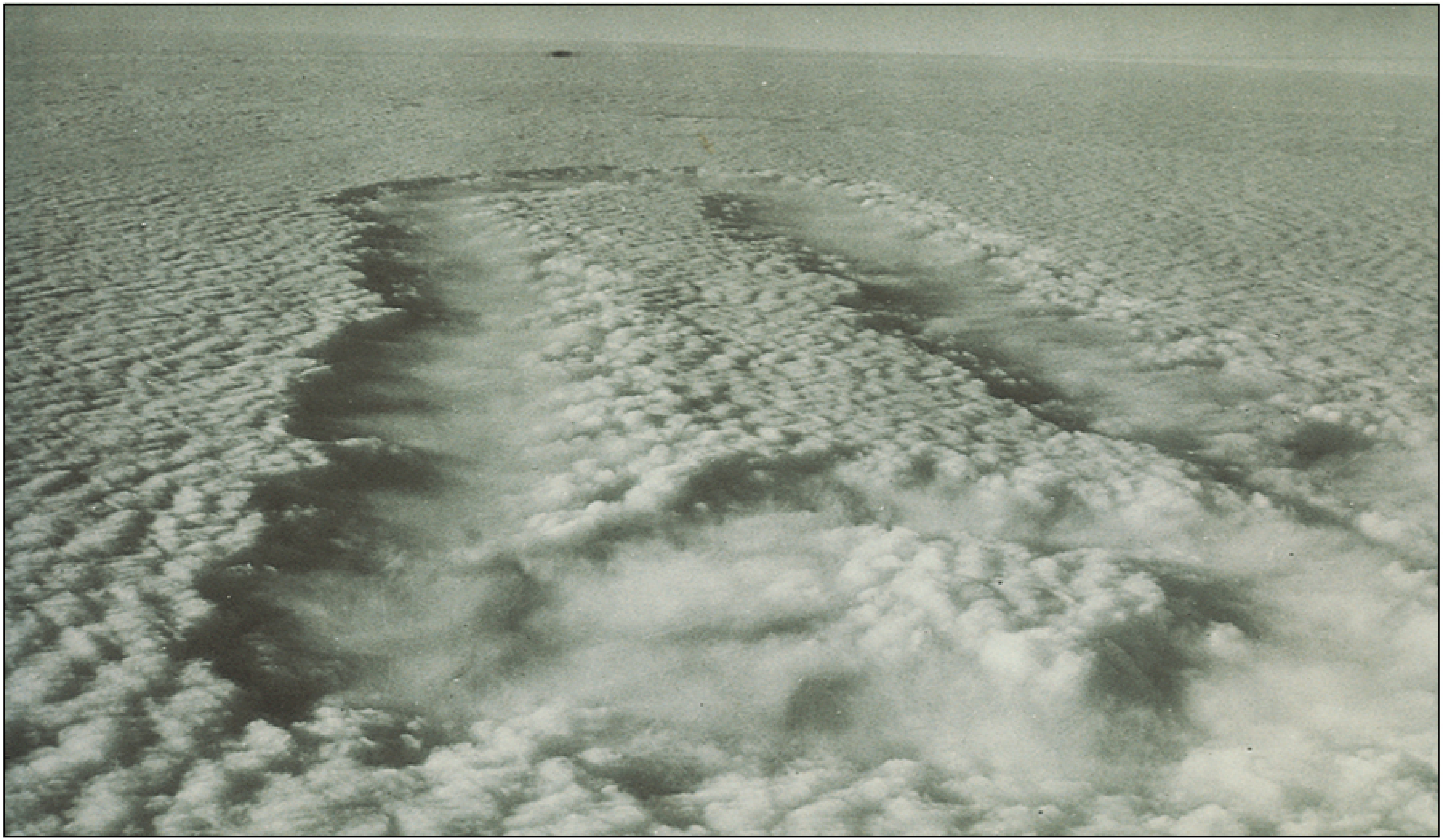
Figure from **Meteorology** by Danielson, Levin and Abrams

# Trails of Tiny Ice Crystals

- Homogeneous nucleation occurs in the track of the falling dry ice particles.
- Presumably the air in the track is cold enough for homogeneous nucleation.

Figure from **Meteorology** by Danielson, Levin and Abrams

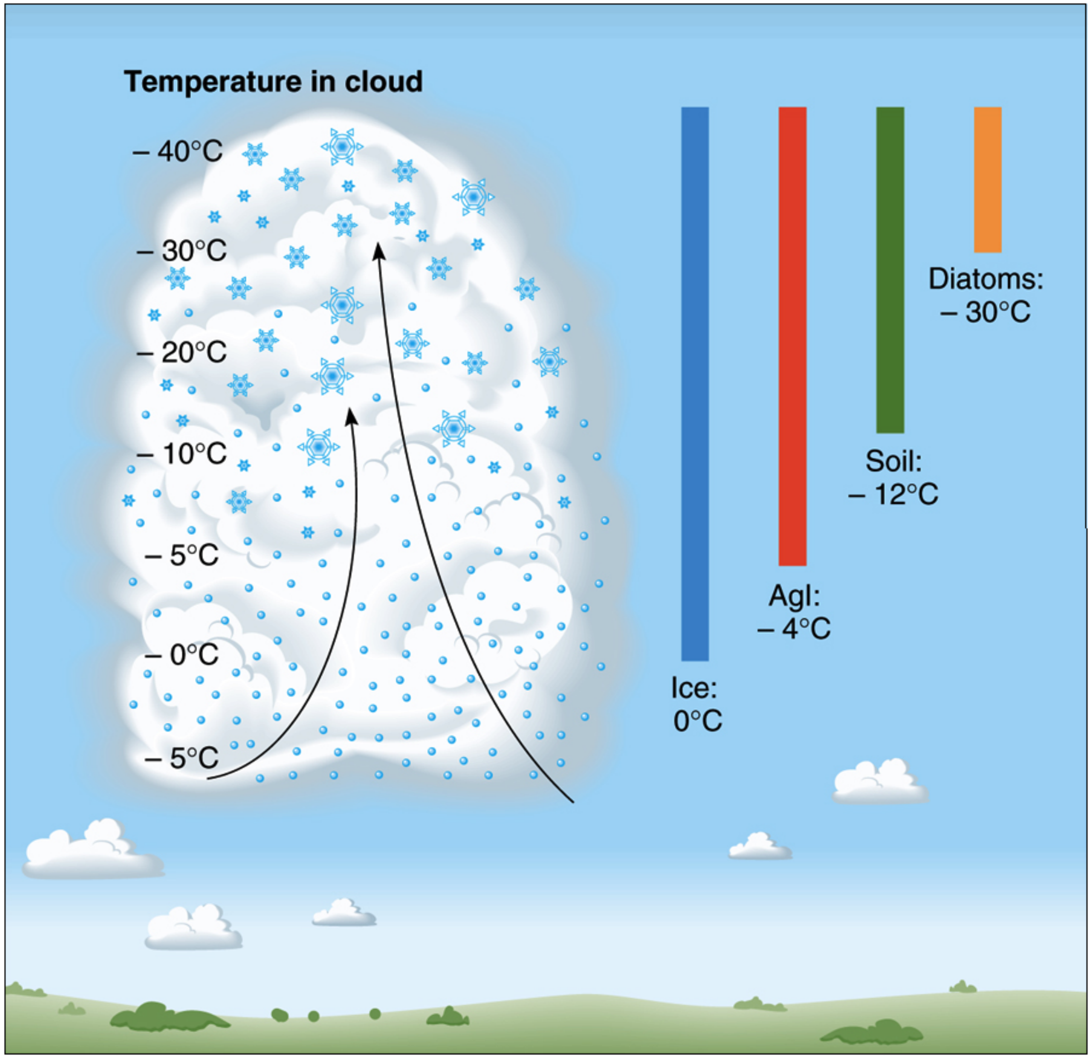
# Dry Ice Seeding



- The U-shaped path was made by dry ice seeding from an airplane.

Figure from **Meteorology** by Danielson, Levin and Abrams

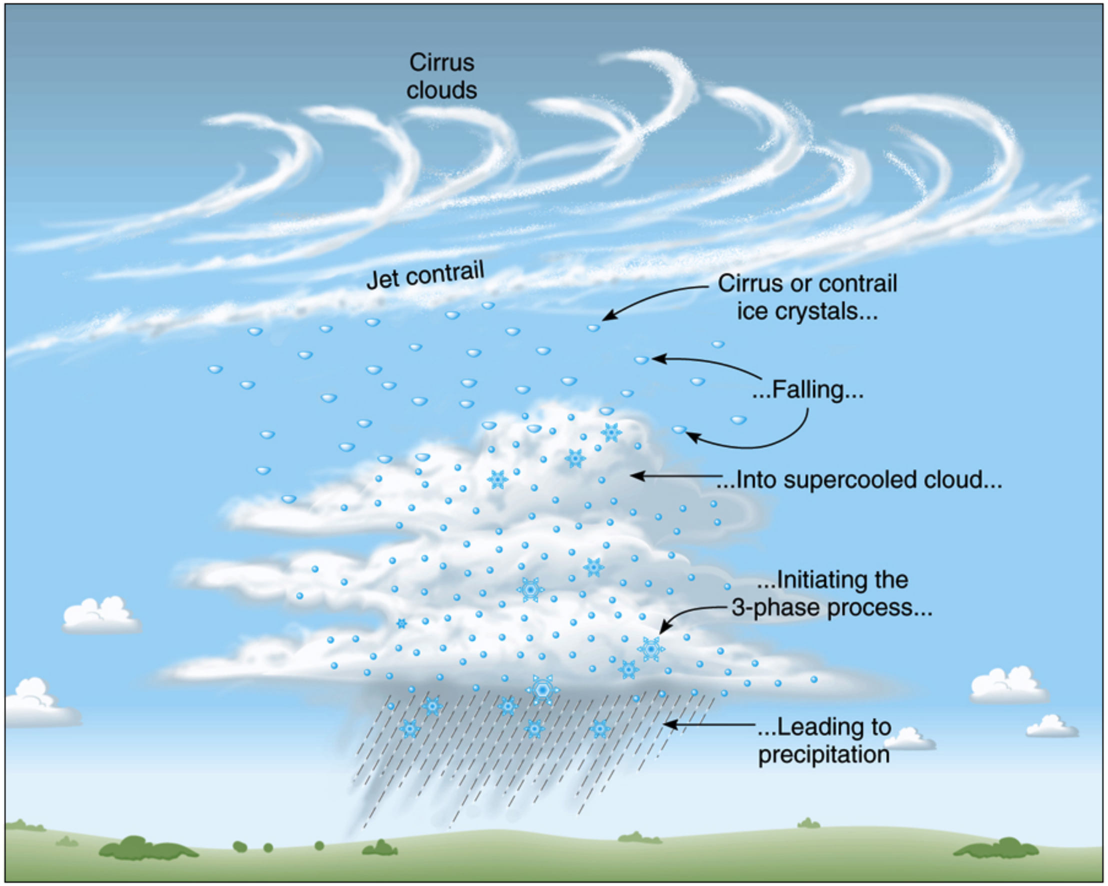
# Silver Iodide Seeding




- Silver Iodide (AgI) seeding was developed by Bernard Vonnegut (1946).
- AgI has a molecule structure similar to $H_2O$.
- AgI becomes new condensation nuclei.
- It is slightly less effective than ice.
- It becomes effective only for air temperatures < -4°C, which is much better than other particles (e.g., soil is effective for air temperatures < -12°C).

Figure from **Meteorology** by Danielson, Levin and Abrams

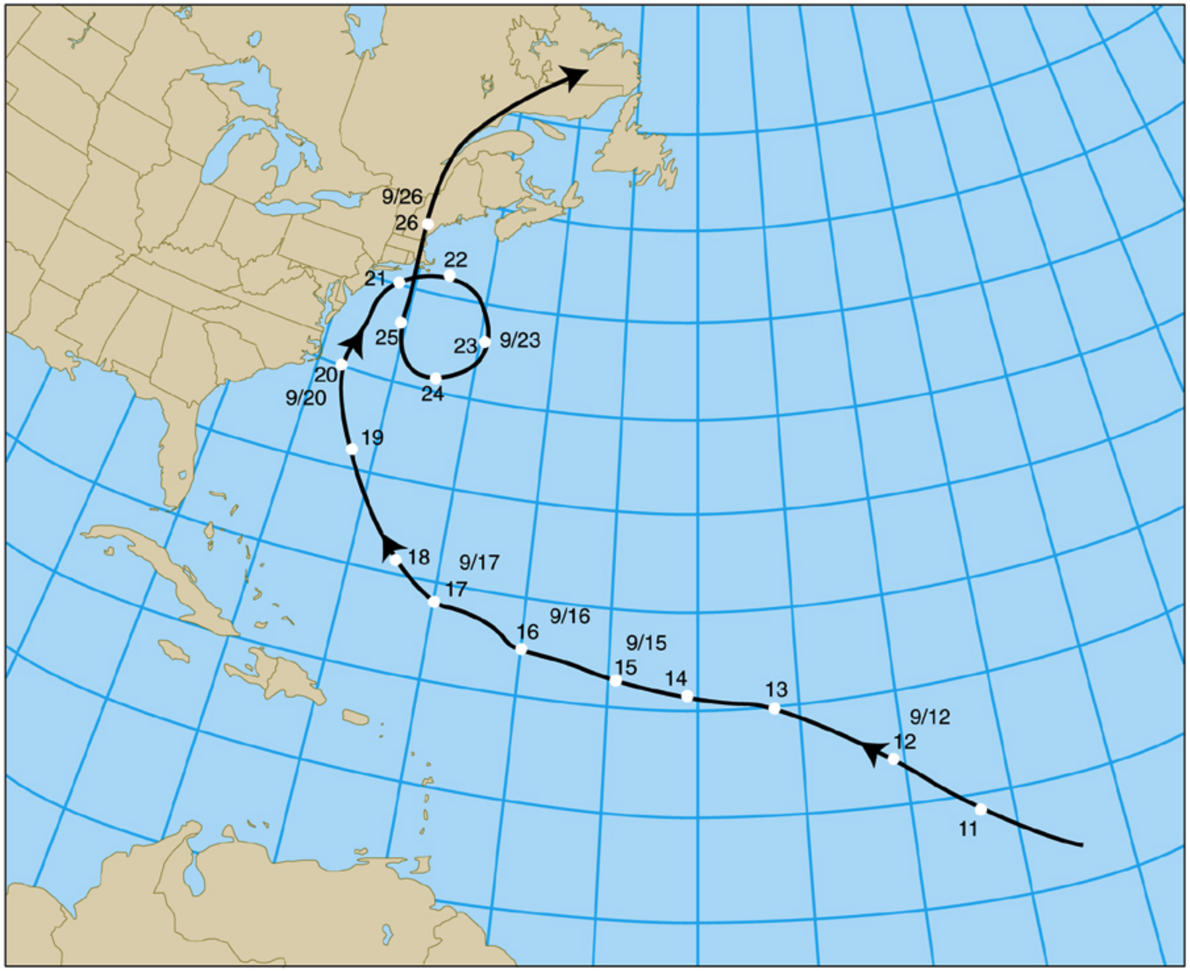
# Jet Contrail Seeding




- Jet contrails are made of ice crystals.
- These crystals fall.
- Some reach clouds prior to loosing all their $H_2O$ to water vapor.
- Those reaching clouds act as condensation nuclei.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Example: Path of Hurricane Esther, 1961




- There was an attempt to disrupt the growth cycle of hurricane Esther early in its existence.
- It subsequently made landfall, forcing the scientists to show that their experiment did not alter the path or increase the intensity.

Figure from **Meteorology** by Danielson, Levin and Abrams

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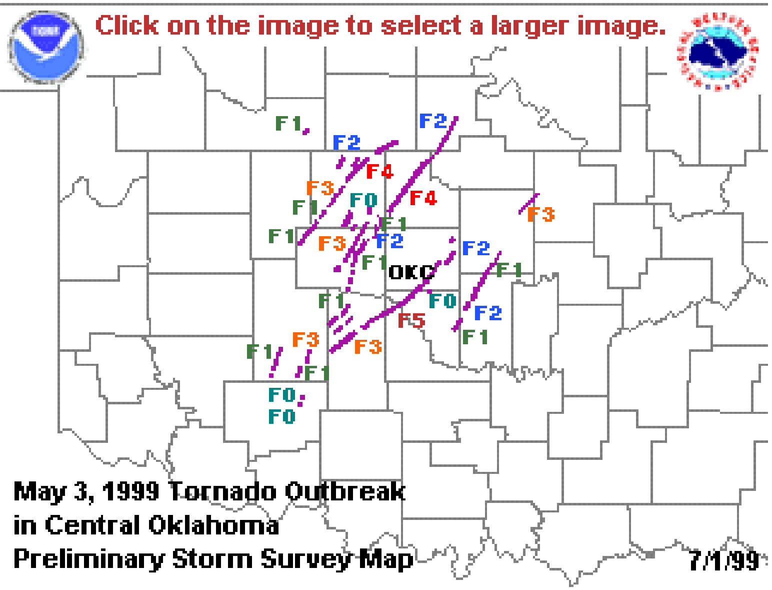
# Example: Cloud Seeding and Flood

- In 1972, a could seeding experiment took place near Rapid City, SD.
- Torrential rains occurred.
- A devastating flash flood occurred, which killed over 200 people!

- Even if such occurrences are unrelated to the cloud seeding, the public perception will greatly reduce the likelihood of future experiments.

# Thunderstorms and Tornadoes




Chapter 9.2 of Atmos. Sci.

Chapter 11 of UWC

Chapter 15 of MSE

Goals

Basic Concepts for Lightning

Identify stages of thunderstorm development

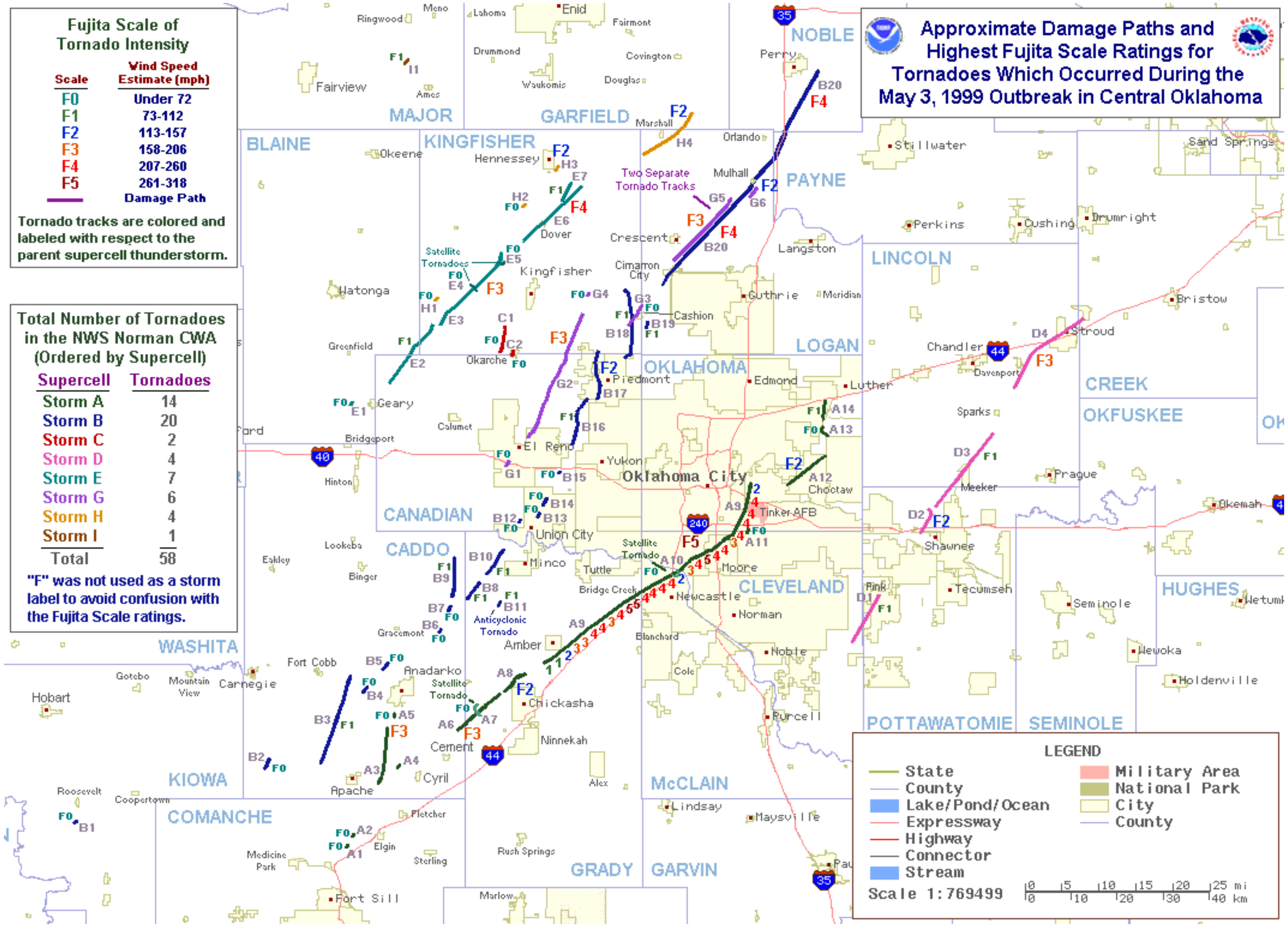
Familiar with conditions for tornado formation

# Example of Destruction

- Pekin Tornado
- 5/12/03
- Picture courtesy of Pilot: Greg Neaveill Co-Pilot & Photographer: Brian Goudie of Deverman Advertising

# Oklahoma Outbreak (May 3rd, 1999)

# Oklahoma Outbreak (May 3rd, 1999)




- 58 Tornadoes from 8 supercells.
- Including F4 and F5 events.

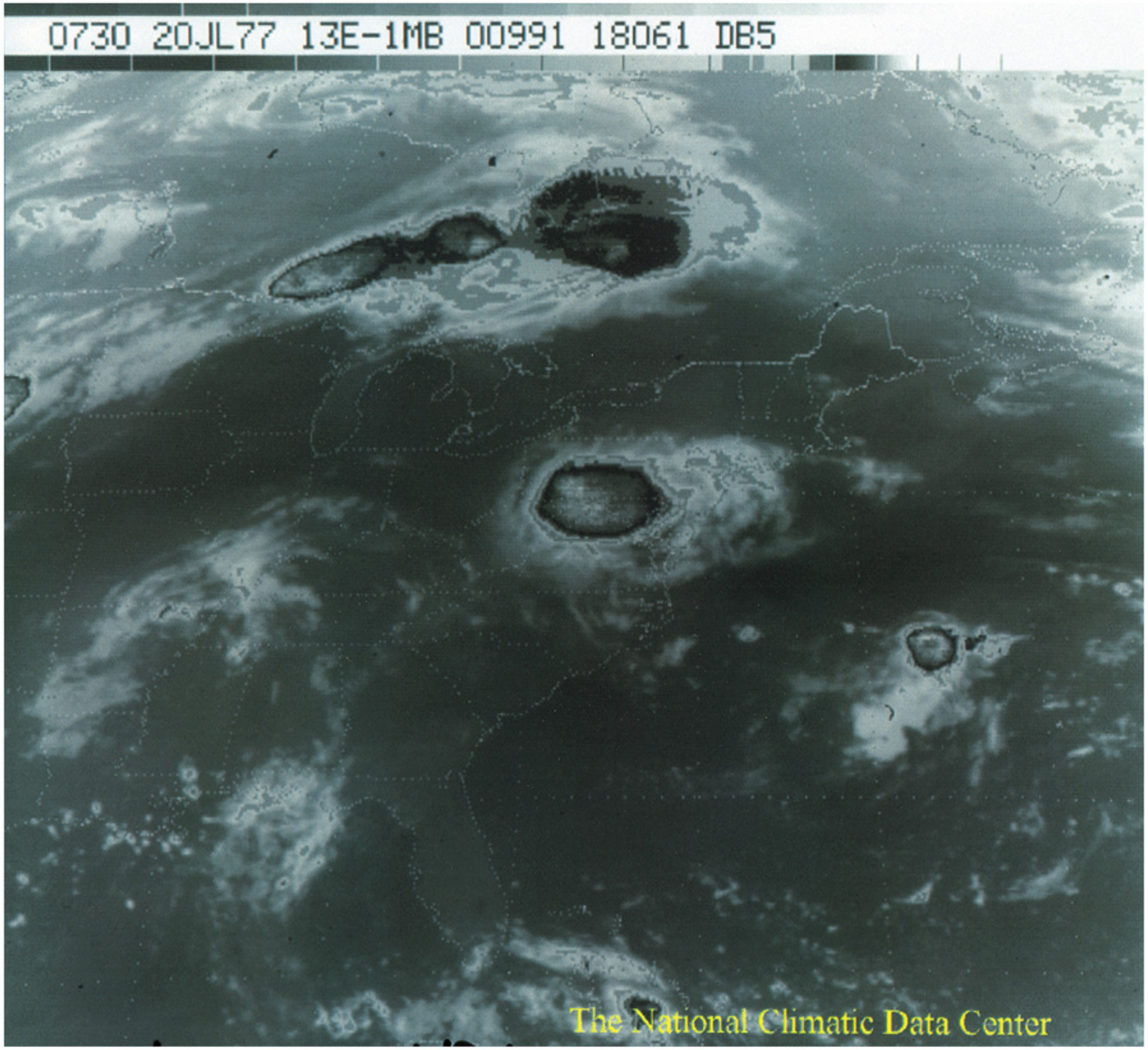
Graphics and information from http://www.srh.noaa.gov/oun/storms/19990503/

bourassa@met.fsu.edu

# Lightning

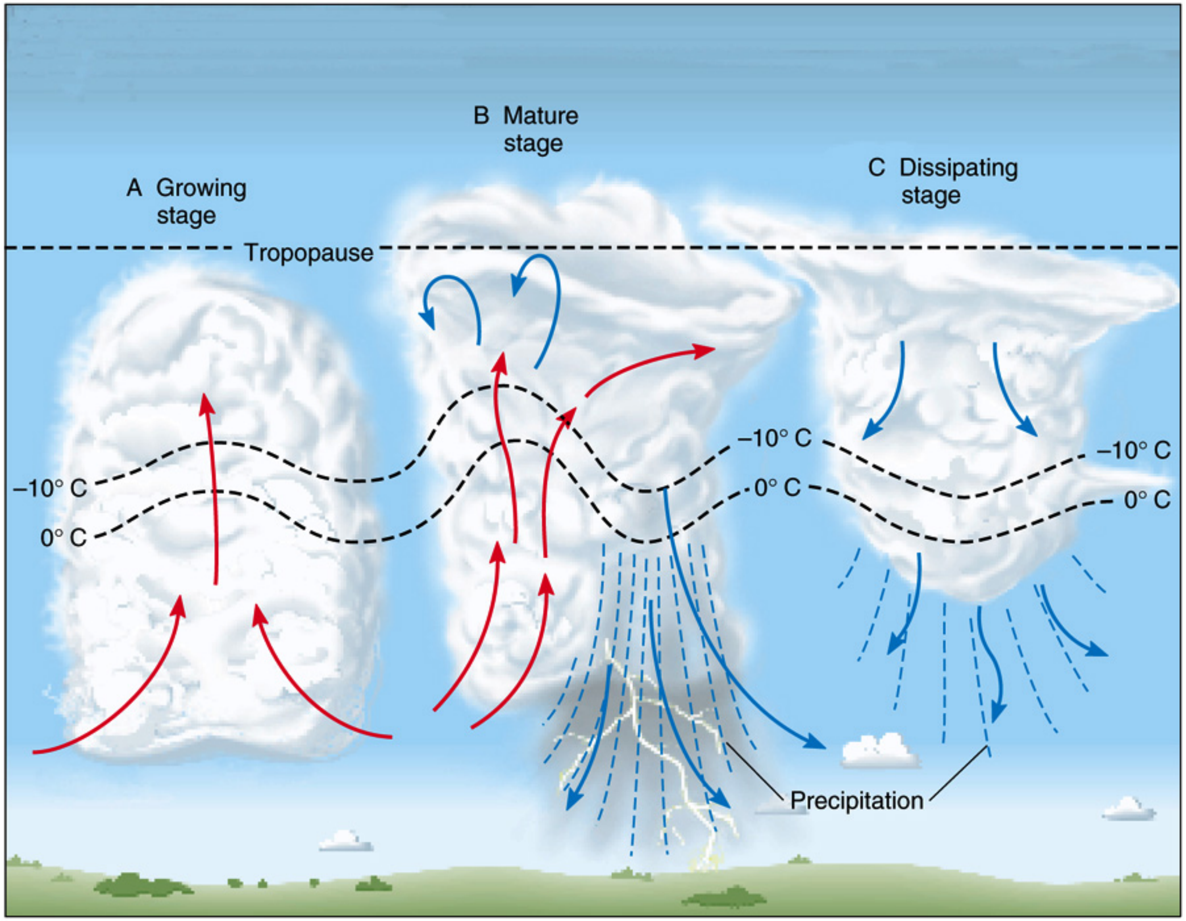
- Despite the lack of media coverage, lightning is the one of the most lethal meteorological phenomena (particularly on golf courses).

# Thunderstorms




- Extreme thunderstorms can cover an area greater than most states.

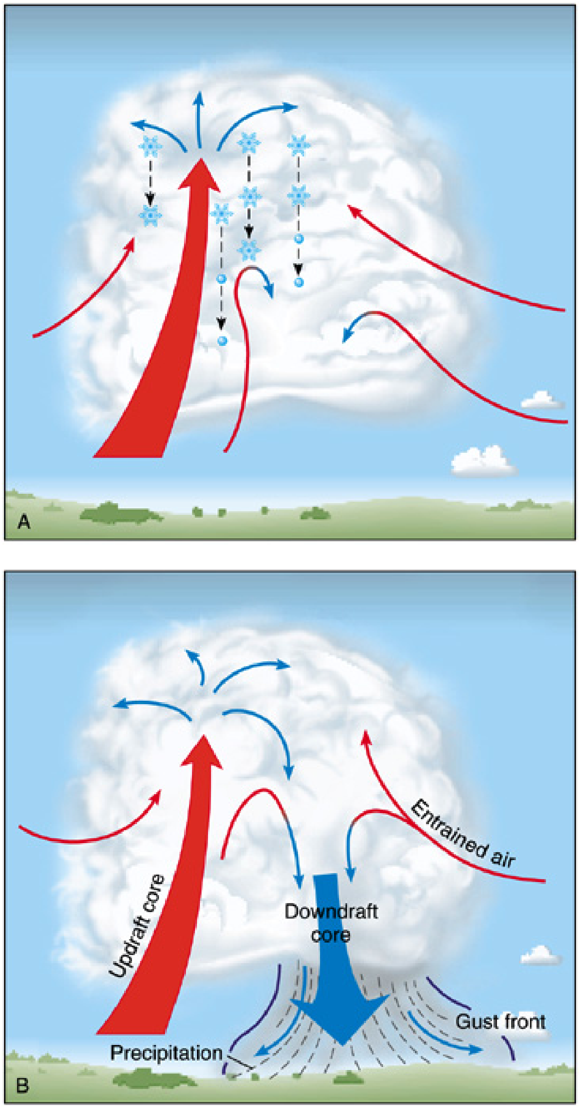
# Thunderstorm Growth Stages




- A) Growing stage. Development as per usual cumulus development, but larger and more buoyant.
- B) Mature stage.
  - Stronger updraft (typically 10 to 20 ms$^{-1}$) and downdraft.
  - Precipitating.
  - Can overshoot tropopause
- C) Dissipating stage.
  - Cold downdraft cuts off inflow

Figure from **Meteorology** by Danielson, Levin and Abrams

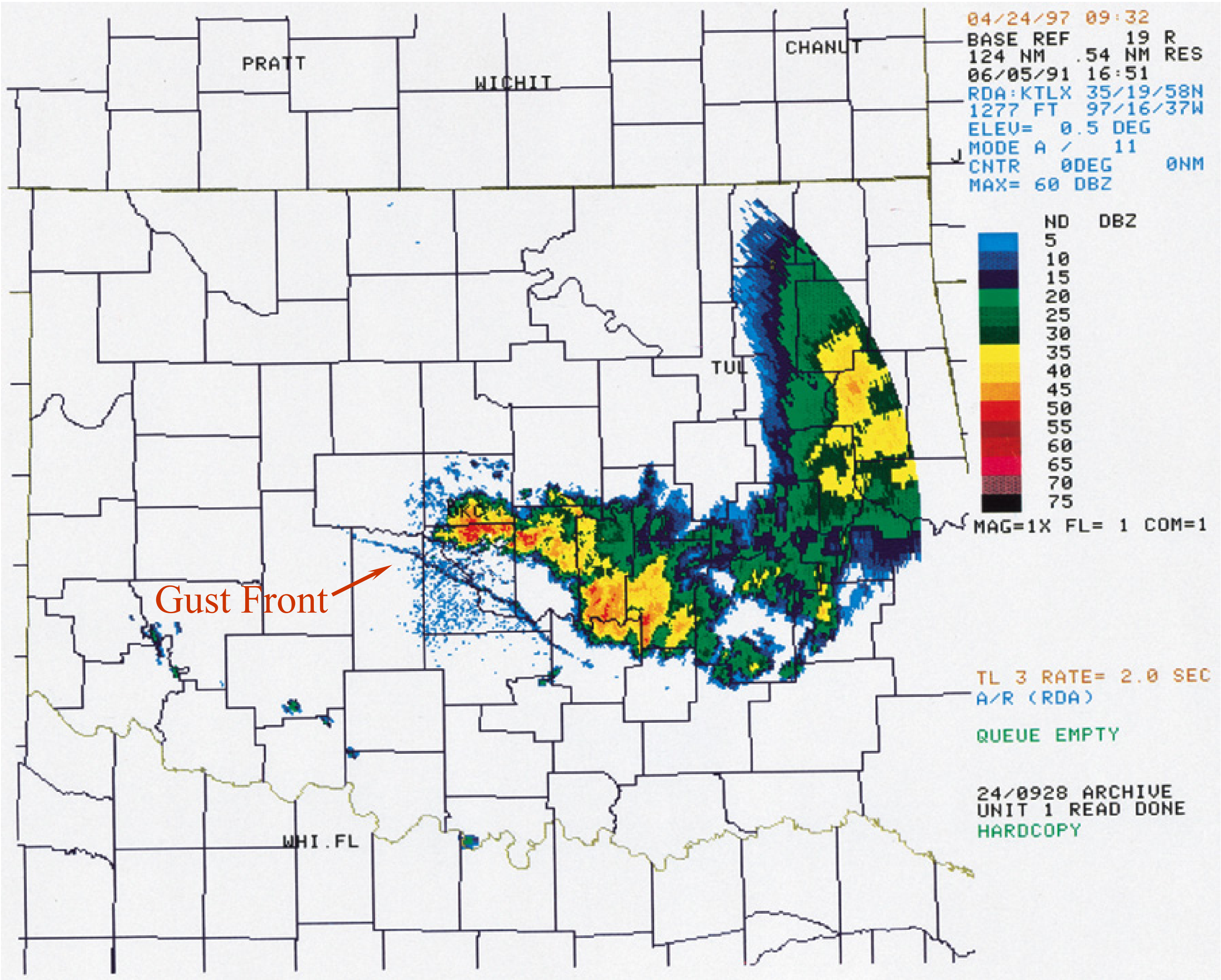
# Development of Downdraft and Gust Front




- Typically the transition from cumulus to mature stage takes 15 to 30 minutes.
- Downdrafts are enhanced by evaporative cooling, which causes an increase in the local density.
- Precipitation drag, air dragged by falling particles, could also contribute.
- Upon reaching the ground, the downdraft spreads in the horizontal, becoming a gust front.
- In extreme cases, such as downbursts or microbursts, the winds generated by downdrafts can be as fast and devastating as a tornado.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Radar Image/Oklahoma Thunderstorm




- NEXRAD image of an Oklahoma thunderstorm.
- The strong storm is seen in the brighter colors.
- A gust front can easily be seen to the Southwest of the storm.

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# A Dry Microburst

- Downbursts are exceptionally strong localized downdrafts, that result in a violent flow along the ground.
- Microbursts are smaller, shorter-lived downbursts, that are usually accompanied by precipitation.
  - The figure shows dust blown by a microburst.
  - Note the roll structure – this is not just straight-line flow.

# Physics of Downbursts

- Three factors contribute to downdrafts
  - Vertical pressure gradients that act to decrease the (upward) pressure gradient force.
    - Clearly a non-hydrostatic situation!
  - Precipitation drag
    - As rain falls the air exerts a frictional drag, slowing the relative motion of the droplets, and limiting the relative motion to the terminal velocity.
    - The droplets exert an equal and opposite drag on the air, causing it to accelerate in the relative direction that the droplets are moving.
  - Evaporative cooling
    - Increases the density of the air.
    - Decreases the buoyancy.

# Example of Atmospheric Sounding Typical of Storm Environment

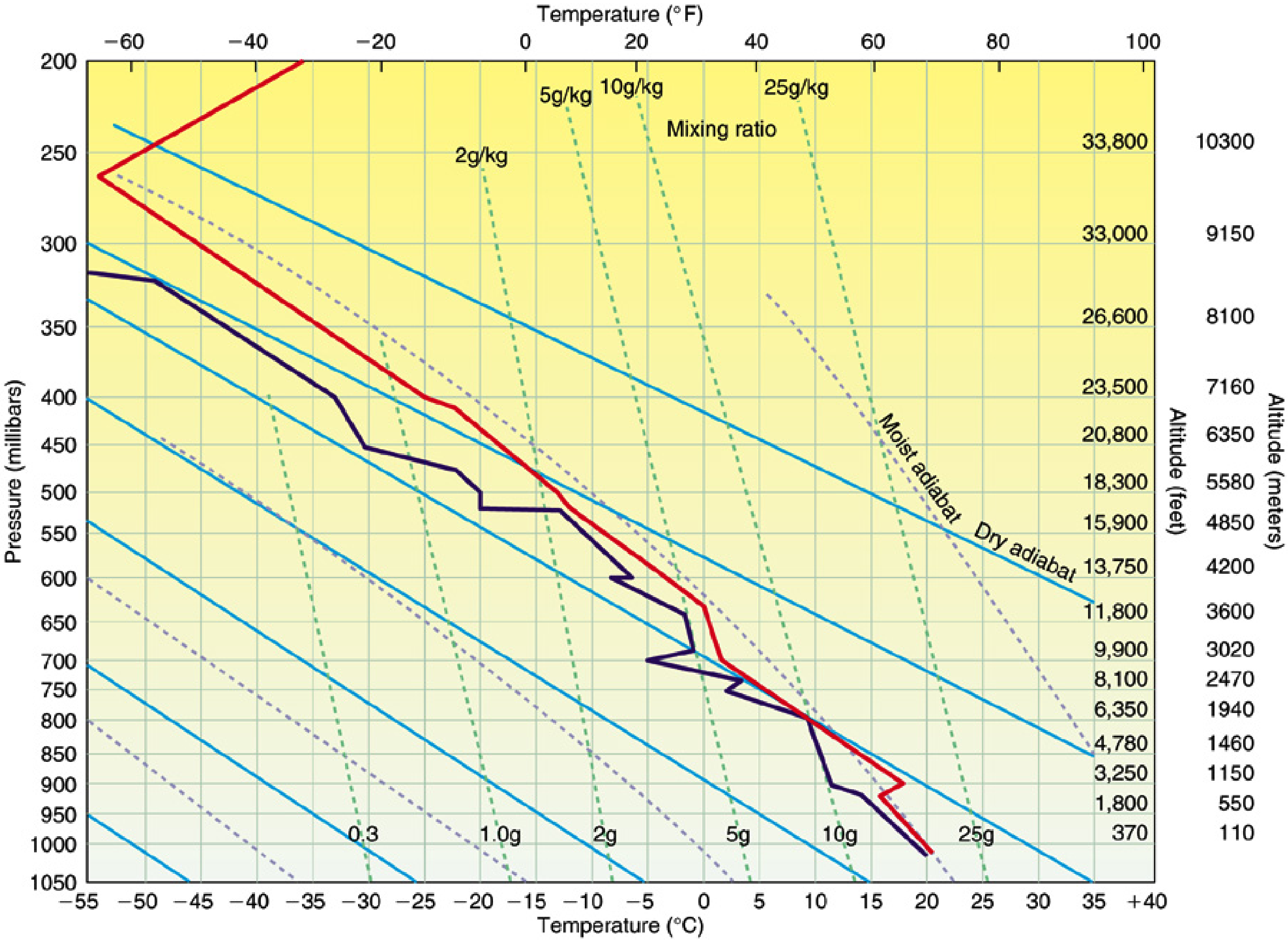



Figure from **Meteorology** by Danielson, Levin and Abrams

- Sounding from Tallahassee, FL
- Early morning.
- Air temperature profile in red, and dew point in blue.
- The airmass is conditionally unstable.
- The airmass is nearly saturated.
- If air parcels begin rising, they will continue to rise to quite a large height.
- How high?

# Level of Free Convection (LFC) & Limit of Convection (LOC)

- If the heat near the surface is not trapped by a somewhat stable layer, then the heated air will be slowly released, at about the same rate that it is produced, resulting in only small clouds.
- The development of large cumulus clouds requires the stable capping layer, and a triggering event to lift the surface air through that layer.
- If the triggering event can lift the air to the lifting condensation level (LCL), then clouds will form. However, reaching the LCL might not heat the air sufficiently for it to continue rising.
- If the air reaches the Level of Free Convection (LFC), it will be warmer than its environment, and continue to rise.
- The rising air will eventually reach a height where it is not warmer than its environment. If momentum and the upward push of air below were not factors, the air would not rise above this level.
  - This height is the Limit of Convection (LOC).
  - In many cases it is near the tropopause.

# Convectively Available Potential Energy (CAPE)

- Violent thunderstorms and powerful updrafts require a tremendous release of energy from the environment.
- One measure of this energy is Convectively Available Potential Energy (CAPE).
- Recall that energy (work) is equal to force times distance.
- In this case, the relevant force is buoyancy. The acceleration (force/mass) due to buoyancy is

$$a = \frac{F_{bouyancy}}{m} = \left(T_{v,p} - T_{v,e}\right)|g| / T_{v,e}$$

  - Where $T_v$ is the virtual temperature, and the subscript $p$ indicates the rising parcel, and the subscript $e$ indicates the environment.
  - Note that buoyancy is based on a ratio of densities, but the ideal gas law can be used to convert density to virtual temperatures.
- To determine work, we then multiply by the distance over which this acceleration is applicable, and add (integrate) each region between the LFC and the LOC.

# CAPE Continued

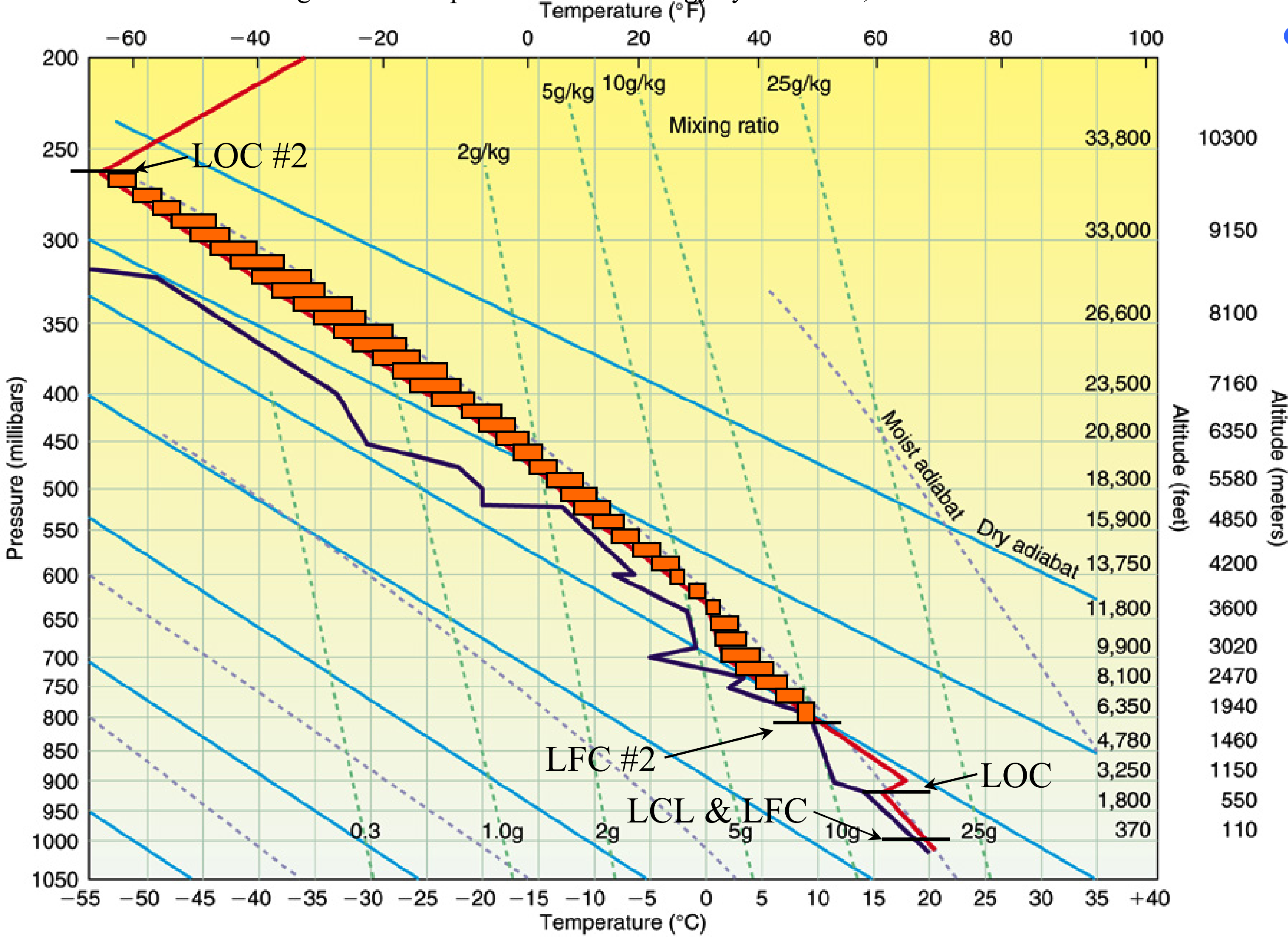
- Multiplying force per unit mass by distance ($\Delta z$) we obtain the energy produced ($W$) per unit mass of rising air.

$$\frac{W_{bouyancy}}{m} = \left[ \left( T_{v,p} - T_{v,e} \right) \left| g \right| / T_{v,e} \right] \Delta z$$

- The work is determined for each layer where the acceleration due to buoyancy is constant. Different layers can contribute different amounts of energy.
- An example is given on the next slide.

# Example of CAPE

Figure from adapted from **Meteorology** by Danielson, Levin and Abrams

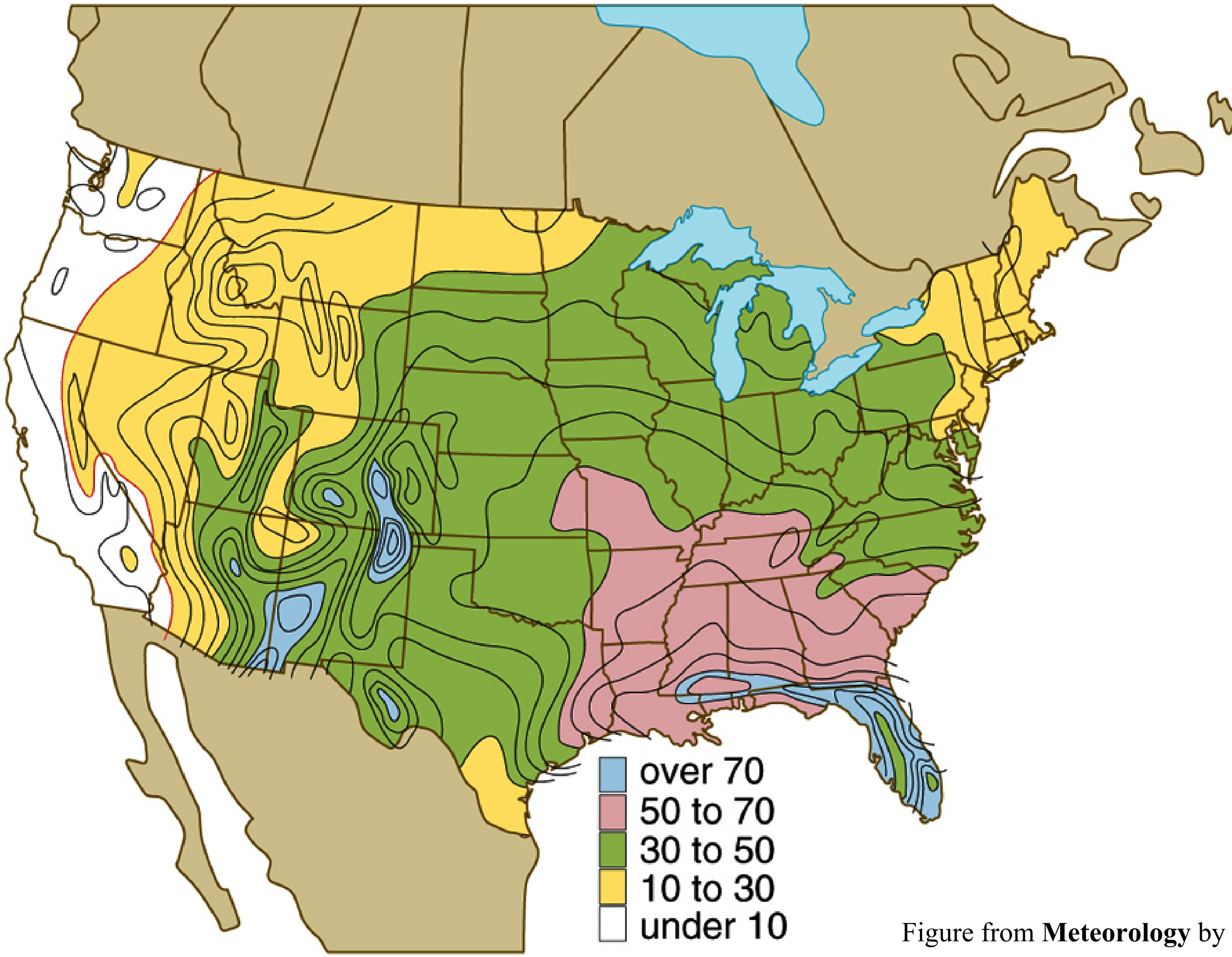



- CAPE is proportional to $T_v - T_v$.
- CAPE is proportional to the total orange area.
- The estimate becomes better as the change in height ($\Delta z$) becomes smaller.

# Triggering Mechanisms

- Conditionally unstable air is a prerequisite of thunderstorm formation; however, it is not a necessary condition. A triggering mechanism is required to provide the sufficient initial upward motion.
  - The air must be raised to the LCL
- Examples of triggering events:
  - Boundaries between air masses:
    - Fronts,
      - Dry lines,
      - Sea breeze fronts,
    - Gust fronts from storms or large cumulus clouds.
  - Other triggers:
    - Atmospheric waves related to buoyancy,
    - Mountains (orographic lifting and buoyancy waves),
    - Localized areas of sufficient surface heating.

# Average Thunderstorm Days




- The average number of days with thunderstorms.
- Contour interval is five per day.
- The blue regions in the west appear to be errors, as do greens in central Florida.
- Why is Florida so active?

Figure from **Meteorology** by Danielson, Levin and Abrams

bourassa@met.fsu.edu

# Severe Thunderstorm Environment

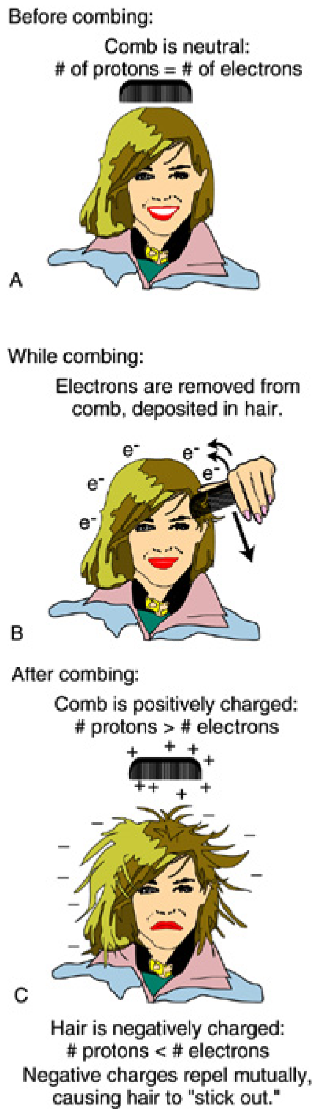
- The most intense thunderstorms have environmental profiles similar to that on the previous slide, with perhaps more CAPE.
- The dew point temperature in the boundary layer is a fairly good indicator of the energy that can be supplied to the storm.
  - Recall that large dew point temperature require large temperatures.
  - Consequently they are associated with strong energy transfer from the surface.
- Cold air aloft increases the (conditional) instability.
  - The environmental sounding remains far to the left of the conditions of the rising parcel.
- Dry air at mid levels contributes to downburst intensity.
- Low level statically stable cap on the boundary layer allows the build up of low level energy.
- Strong winds aloft increase the odds of tornadic thunderstorms.
- Boundary layer wind shear allows more energy to be fed into a storm, consequently prolonging it's existence.

# Thunder and Lightning

- Lightning is a huge discharge of static electricity.
- Thunder is produced by the motion of the air induced by the tremendous heating caused by the release of a small fraction of the lightning's energy into the air.
- Our understanding of the physics of lightning is remarkably limited.
  - In Nov. 2003, a paper was published demonstrating that previous concepts were insufficient, and could not offer an explanation.

- Electrical charge is a basic property of matter.
- Quite often it is neutral (a balance of positive and negative charges).
- For static electricity, there is an imbalance of charges.
- Electrons (negatively change particles) can move from one object to another.

# A Common Example of Ionization




- The comb and hair each begin with a neutral charge.
- The hair can attract electrons from the comb.
  - The comb becomes positively charged, and
  - The hair becomes negatively charged
- Note that like charges repel each other, while unlike charges attract.
- The electrons distribute themselves throughout the hair, trying to achieve maximum separation.
- This goal is best achieved when the hair occupies a greater volume.
- The electrical repulsion will work against gravity and hair spray to move the hair.

When this effect is achieved outdoors without mechanical aids, what does this suggest?

Figure from **Meteorology** by Danielson, Levin and Abrams

# Charge Buildup and Discharge

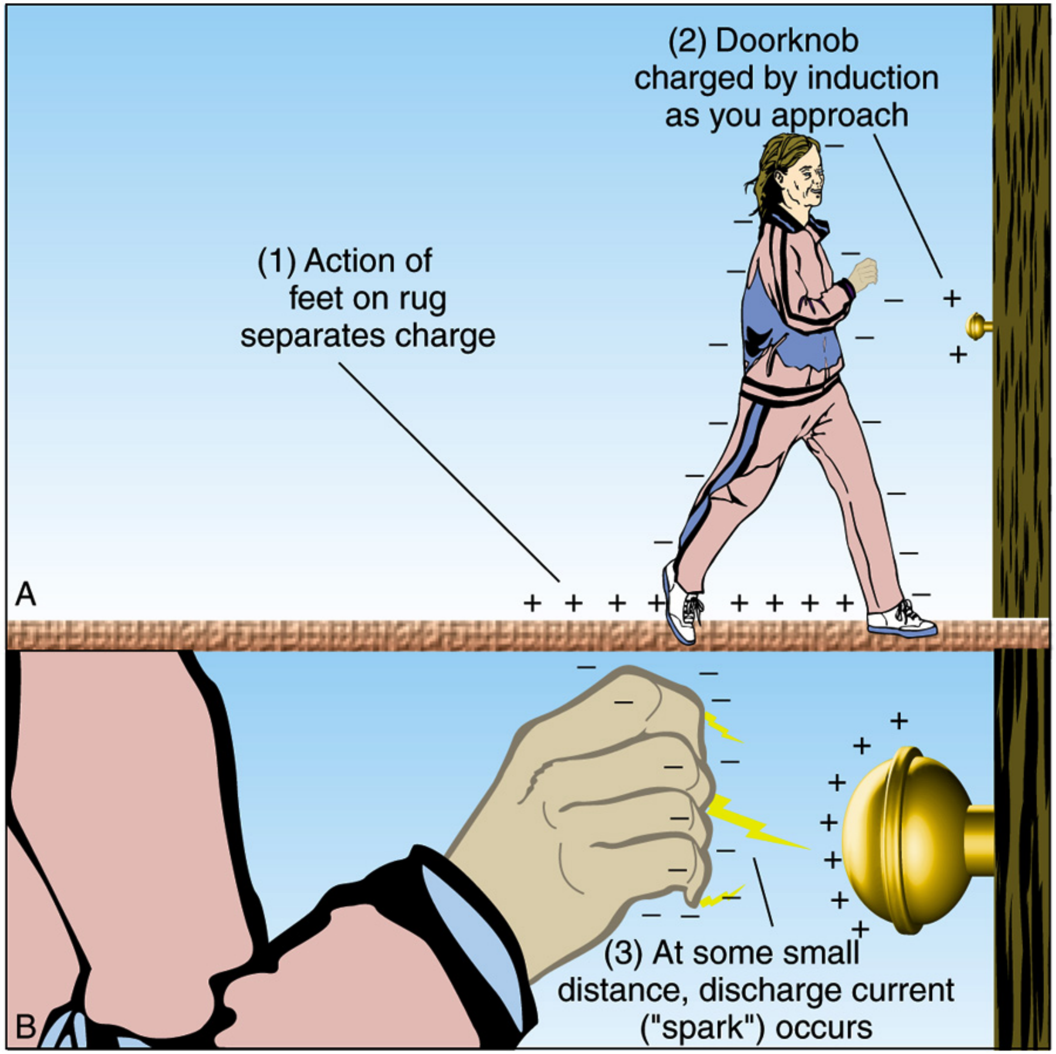



Figure from **Meteorology** by Danielson, Levin and Abrams

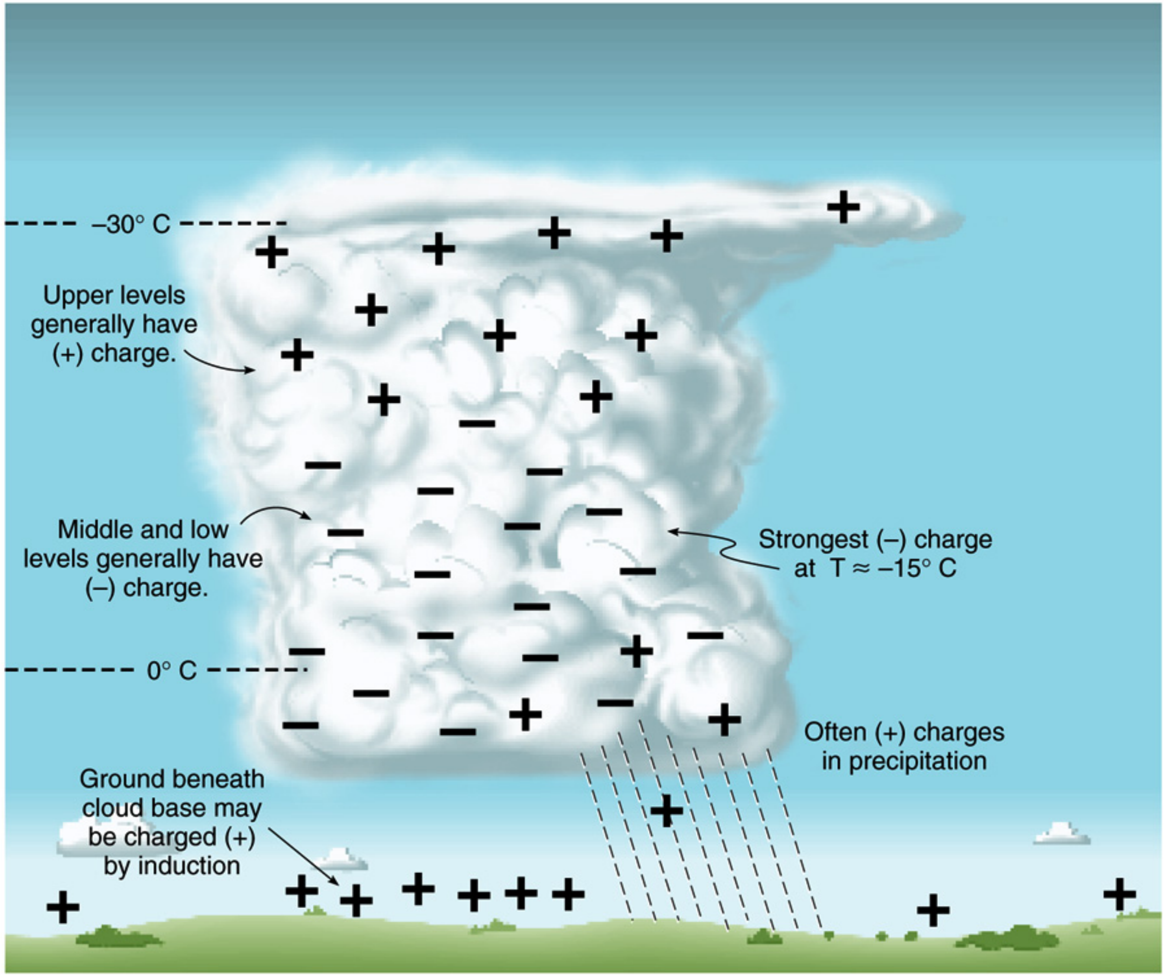
- There are many activities that cause the buildup of static electricity.
  - E.g., walking with slippers on a carpet, or rubbing a cat's fur.
- The voltage difference must be enough to ionize the air through which it would travel.
  - $\Delta V \geq B\, d$, where $\Delta V$ is the voltage difference, $B$ ($3*10^9$ V$km^{-1}$ for dry air) is the breakdown potential, and $d$ is the distance.
- If the voltage difference or distance is small enough, a spark will occur.

# Lightning

- Why is it safe in a car (other than the sound and the flash)?
- Why should you not seek shelter under a tree?

- For those of you with surge protectors, read page 343 of MSE, to see the likely current that a direct hit will cause. You can assess the quality of your surge protector.

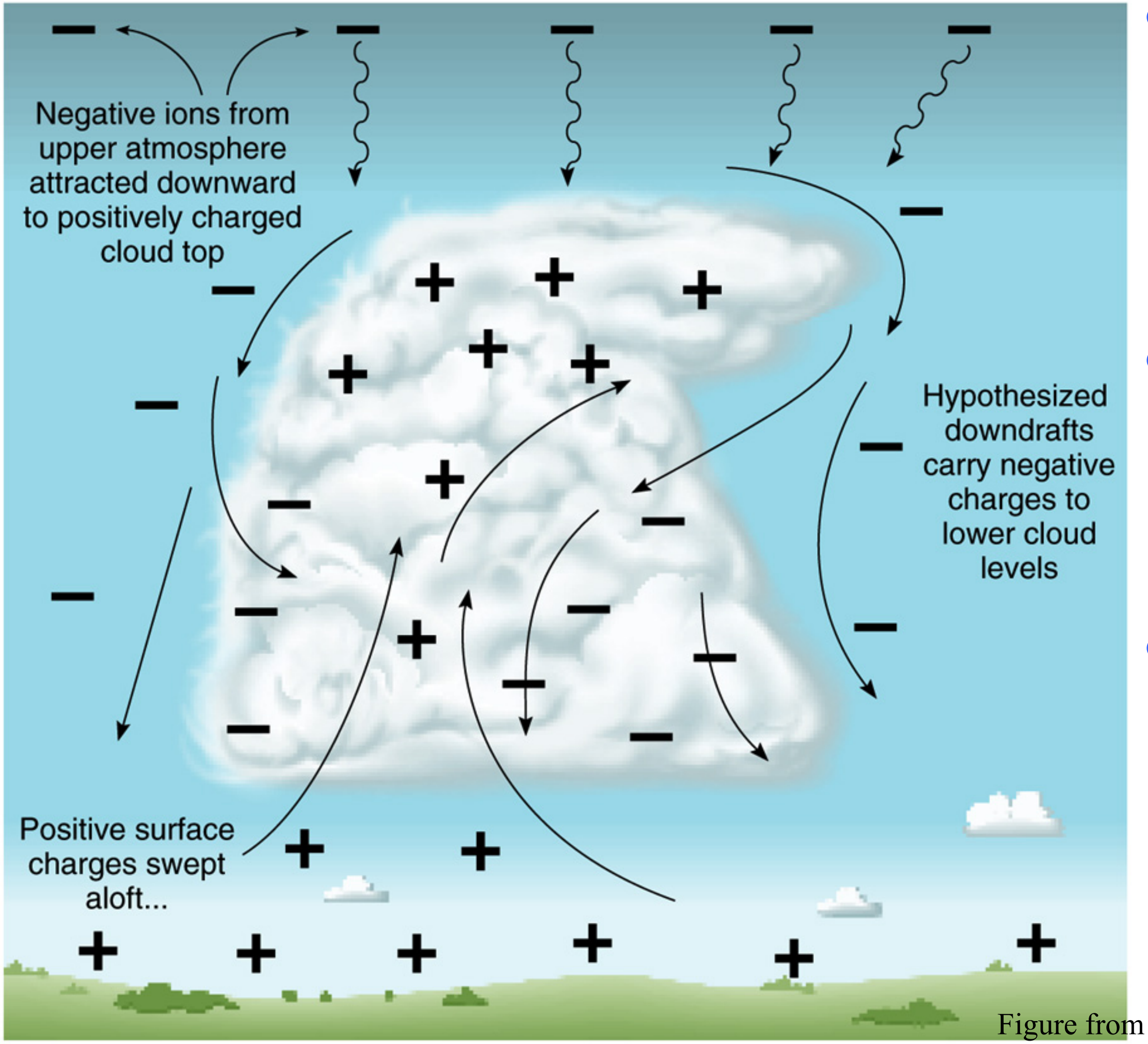
# Electric Charge in Thunderstorms




- In situ observations indicate that the greatest negative charge typically occur in thunderstorms at the height where the temperature is –15°C.
  - A region of active precipitation formation.
- The mechanism for causing the change imbalance needed for lightning is not known.

Figure from **Meteorology** by Danielson, Levin and Abrams

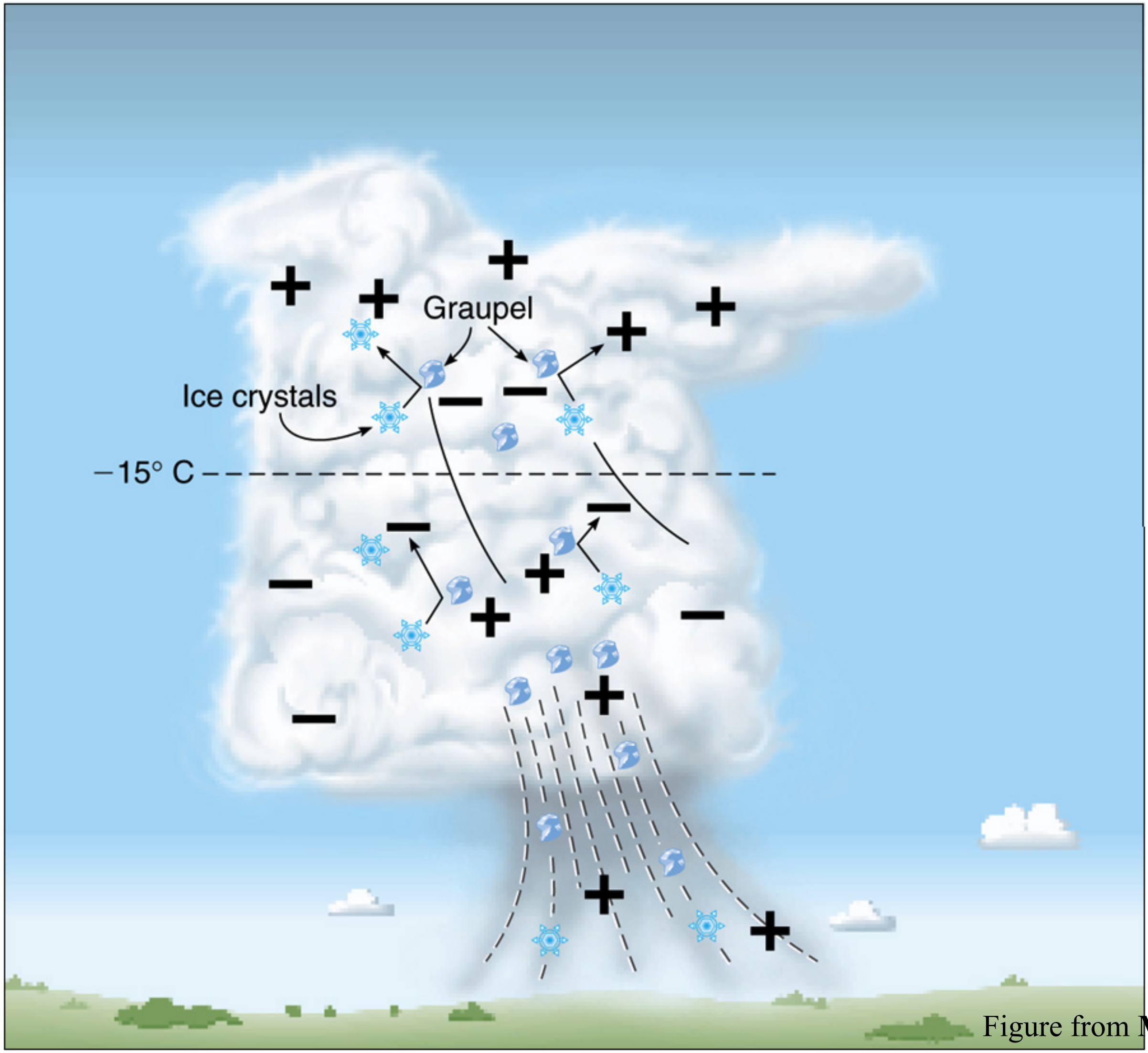
# Convection Hypothesis




- One hypothesis is that convection moves positively charged air from near the surface to the upper regions of the cloud.
- Negatively charged particles above the cloud are then drawn towards the top of the cloud.
- Negatively charged particles at the outer edge of the downdraft region encounter the positive charged particles in the updraft.

Figure from **Meteorology** by Danielson, Levin and Abrams

# A Precipitation Hypothesis

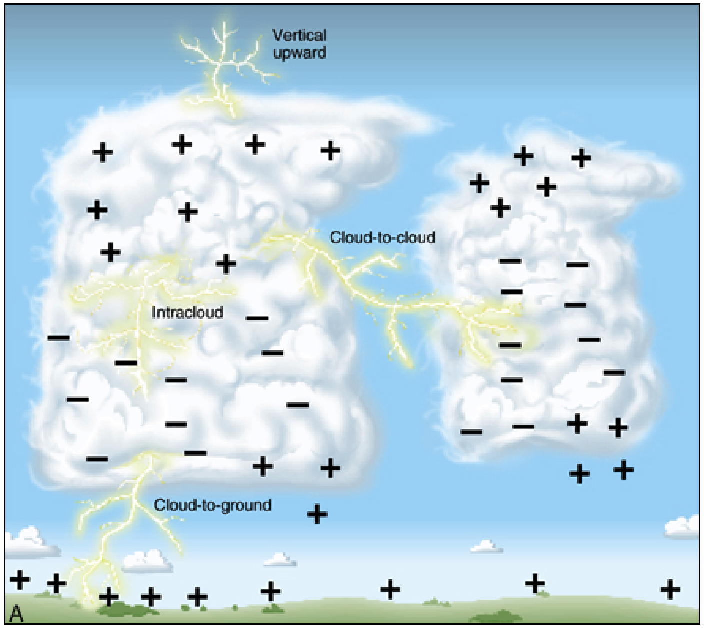



- Graupel particles and ice crystals collide in the cloud.
- Negative charge moves from the ice to the graupel.
- Updrafts carry the lighter particles higher, causing the top of the cloud to have a positive charge.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Lightning

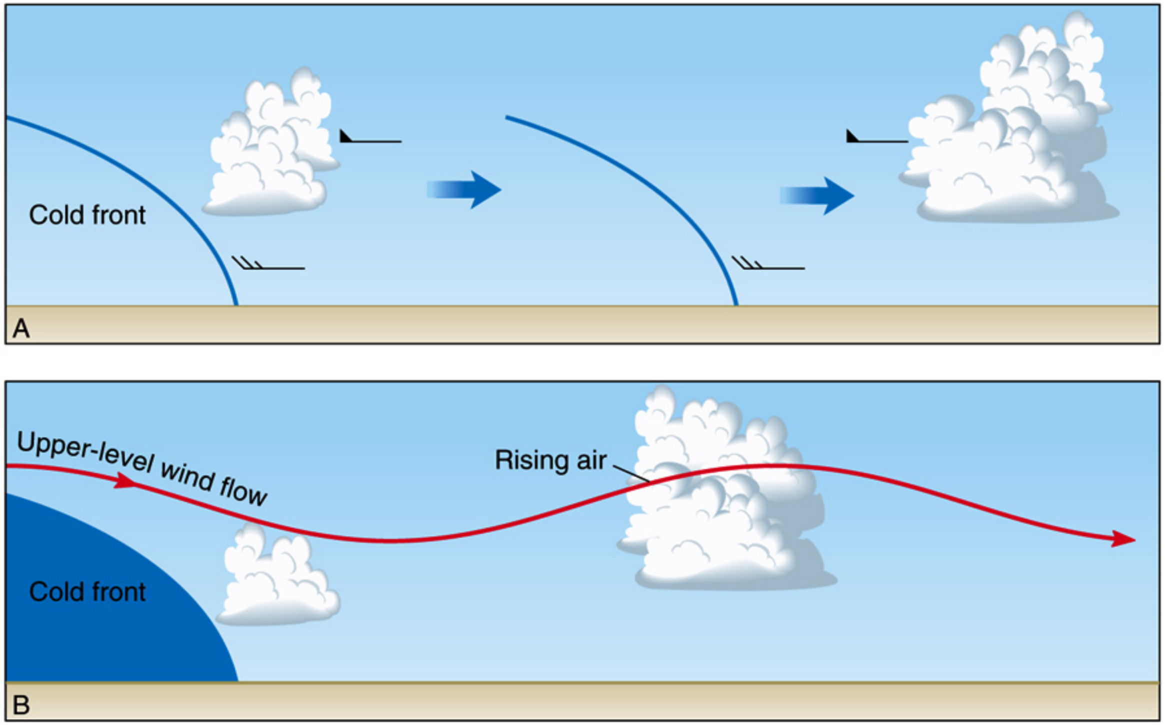
Figure from **Meteorology** by Danielson, Levin and Abrams





- There are several types of lightning:
  - Cloud to ground,
  - Cloud to cloud,
  - Intracloud, and
  - Vertical upward lightning.
- The cloud to ground lightning ionizes a trail through the air, followed thousandths of a second later by an upward strike from the surface to the cloud.
- The entire sequence is called a lightning flash.
- What causes thunder?

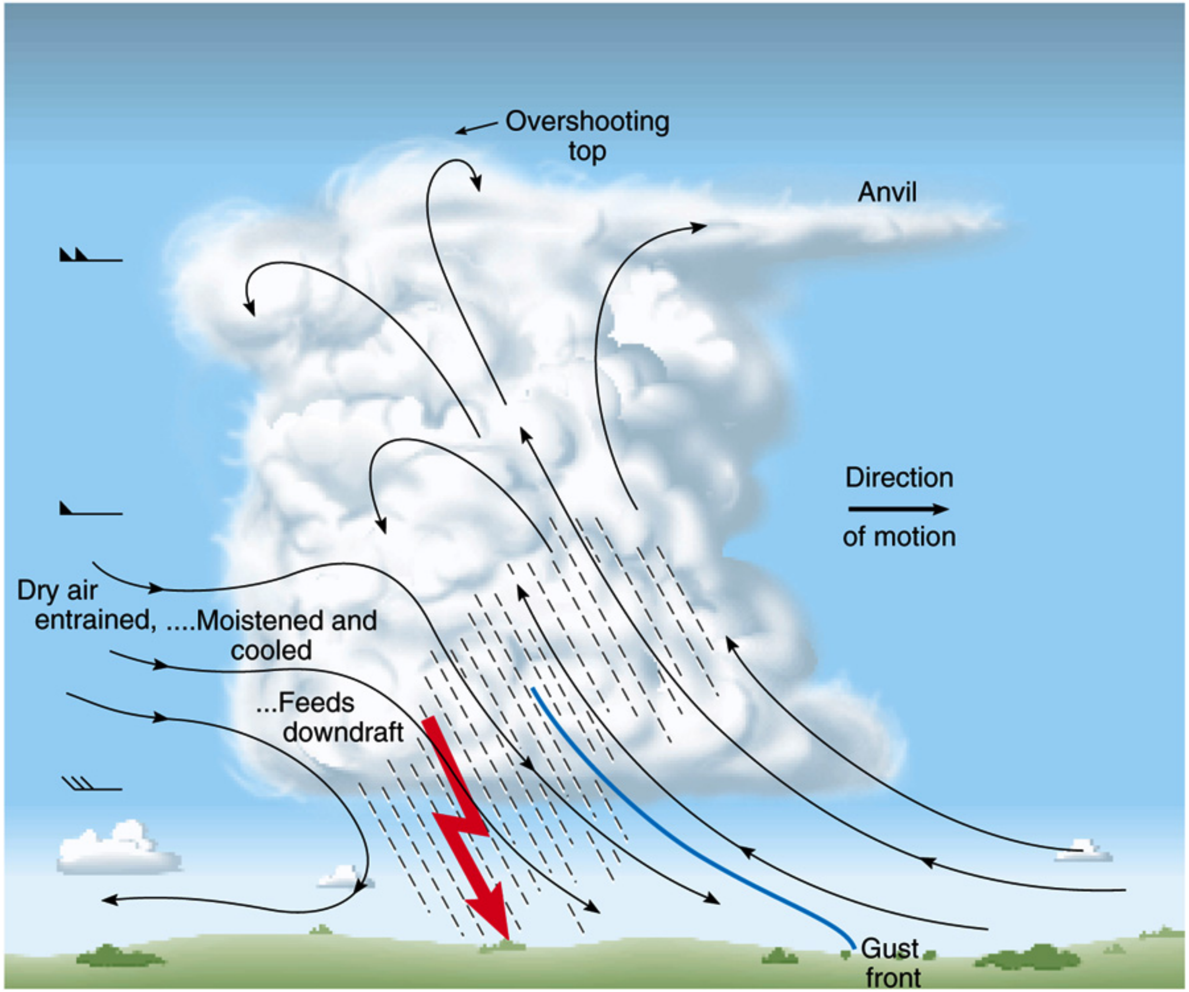
# Squall Line Formation




- Above are two examples of mechanisms that form lines of thunderstorms (squall lines) ahead of a front, making them prefrontal squall lines.
- In the top image, the thunderstorms are generated at the front, then advected ahead of the front.
- In the bottom case, vertical wave motion induced by the front causes lifting ahead of the front.

Figure from **Meteorology** by Danielson, Levin and Abrams

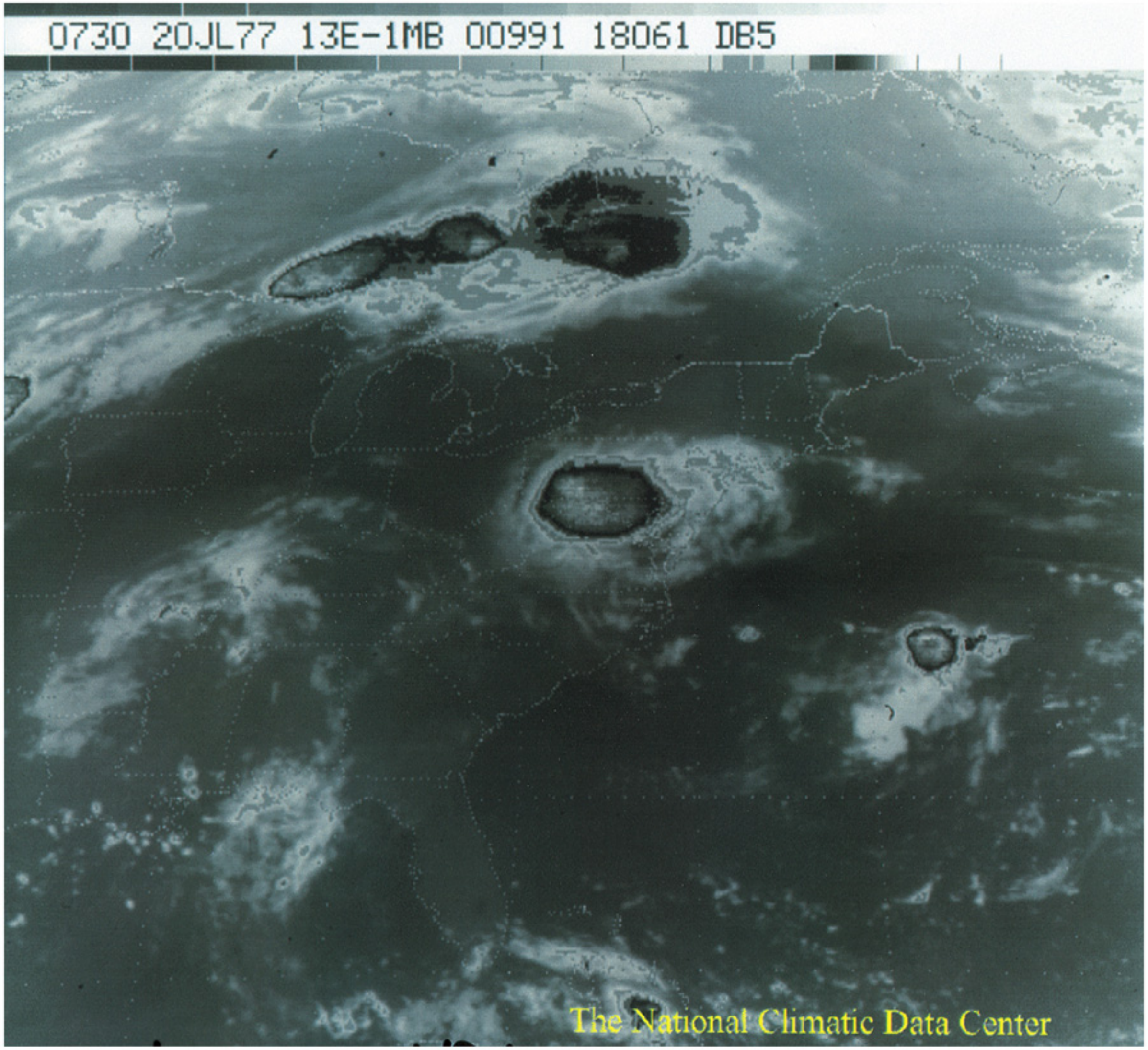
# Frontal Thunderstorm Structure




- The structure of the frontal thunderstorm is slightly different from that of an airmass thunderstorm.
- The frontal thunderstorm is pushed forward with the advancing gust front.
- It is not cut off from its supply of warm moist air.
- Tilting backwards also allows precipitation formed in the updraft region to fall in the downdraft region.

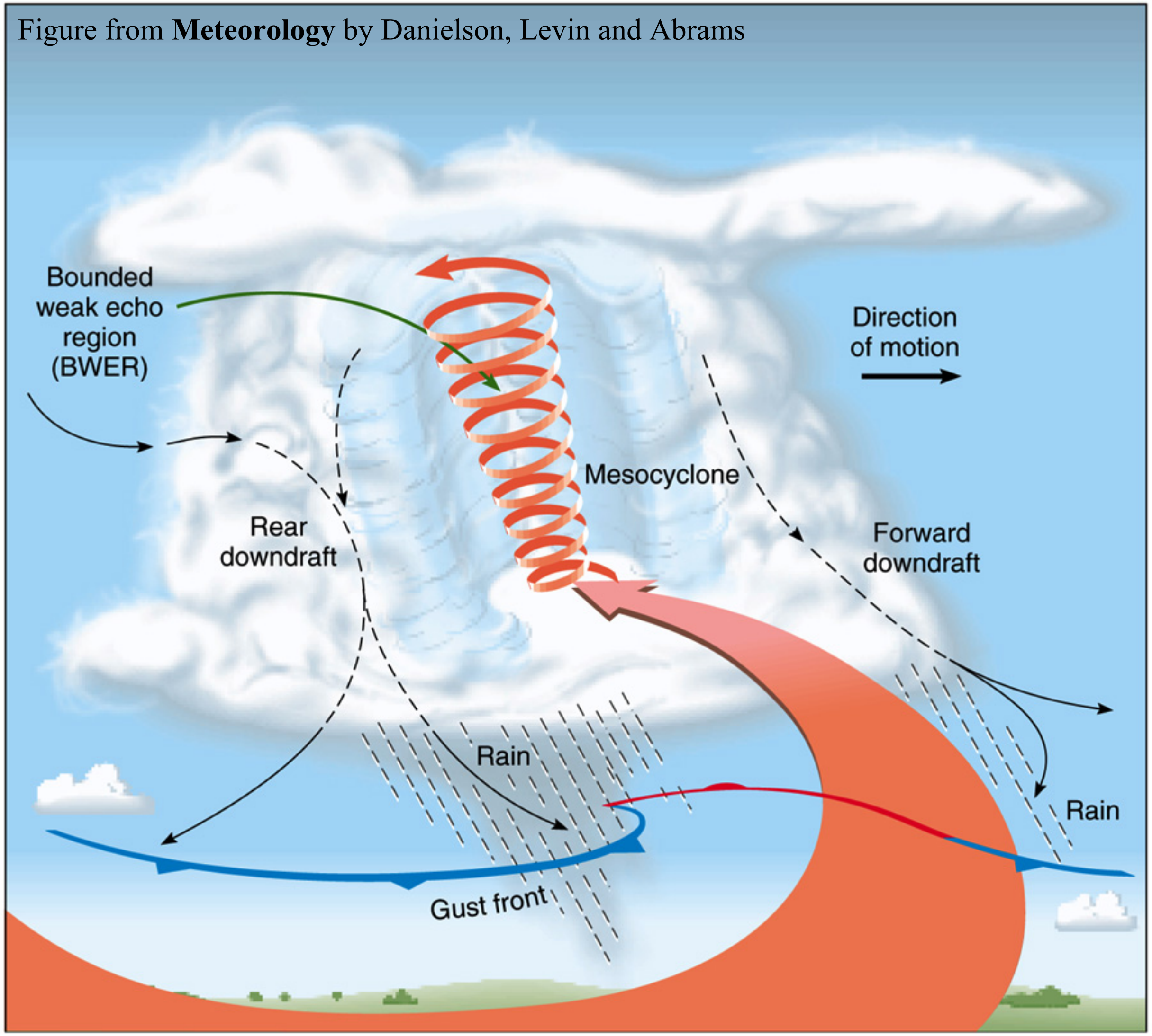
Figure from **Meteorology** by Danielson, Levin and Abrams

# Mesoscale Convective Complexes (MCCs)




- MCCs are large collections of of thunderstorm cells.
- Many MCCs contain squall lines and multicell thunderstorms.
- Typical MCC diameter is 400km.
- The MCC over Pennsylvania brought hours of heavy rain, leading to massive floods in Johnstown, \$100M in damages, and the loss of 76 lives.

# Supercell Circulation




- Supercells are exceedingly large and long lived thunderstorms.
- These storms are highly destructive!
- The gust front and updraft region resemble frontal lows.
- There are often two or three downdraft regions.
- Mesocyclones can form within the supercell, resulting in a bounded region of little precipitation.

# Bounded Weak Echo Region Image

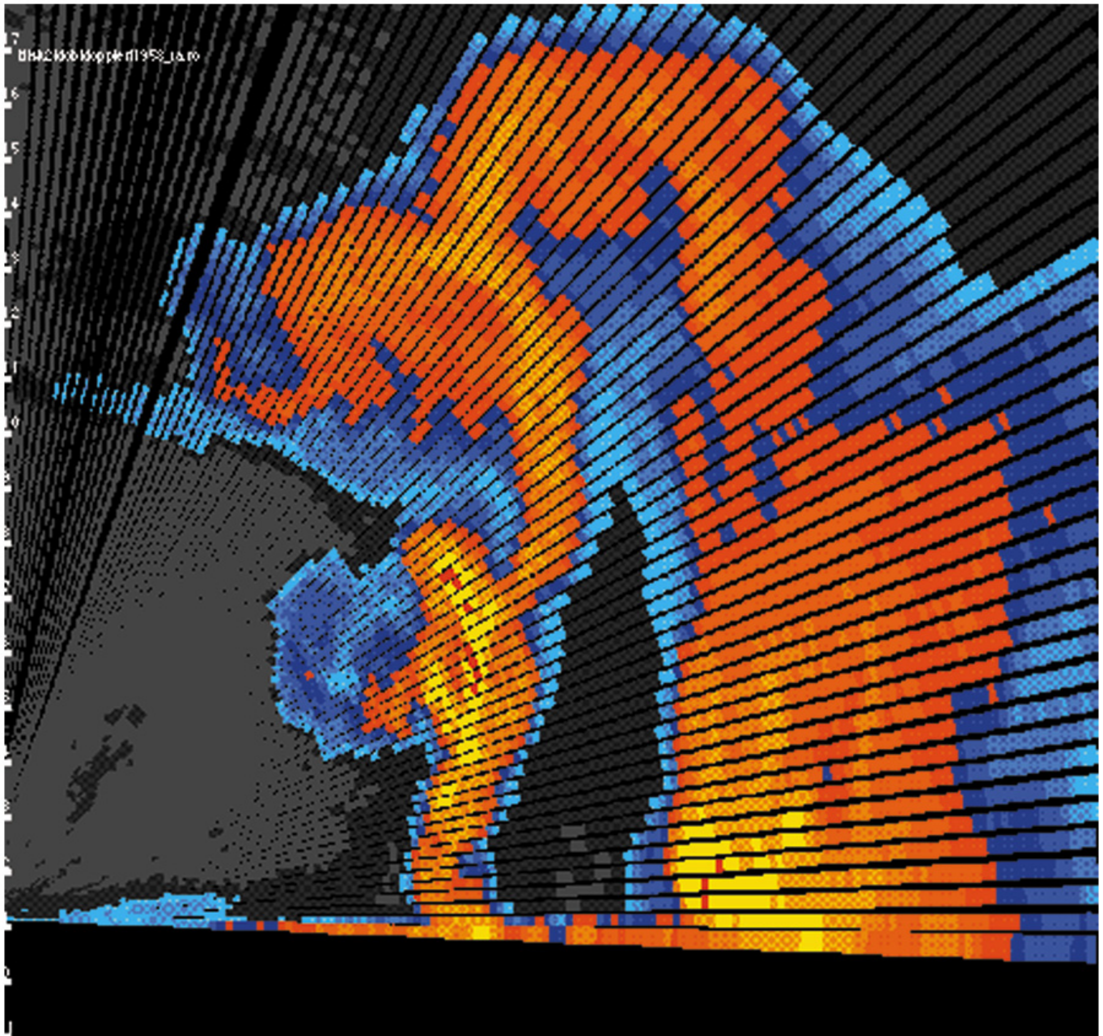
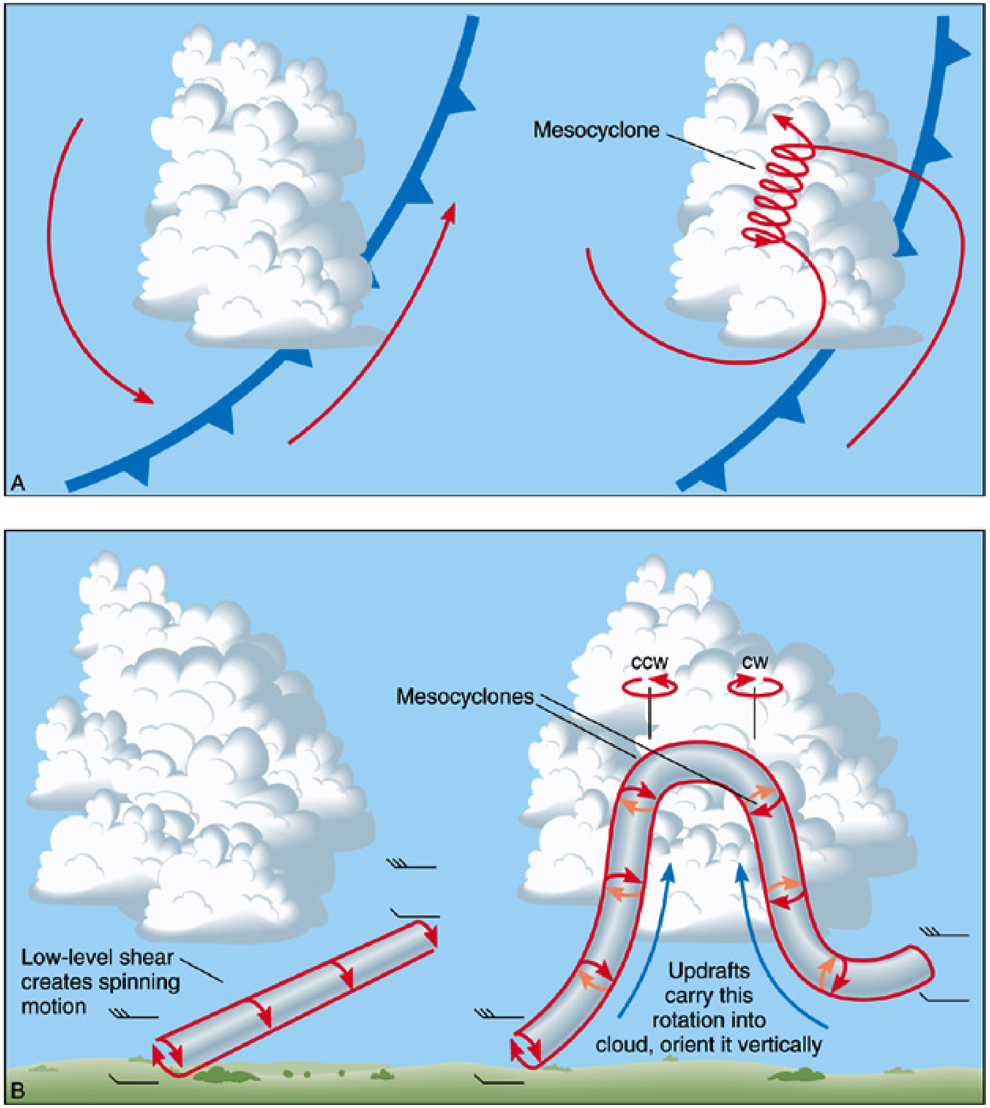


Figure from **Meteorology** by Danielson, Levin and Abrams

- The bounded region in a supercell with little precipitation is called the bounded weak echo region (BWER).
- Radars record weak signals in this region.
- Updrafts in this region can reach 50 $ms^{-1}$.
- The weak radar signal indicates that there is little precipitation.
- Perhaps because there is too little time for it to form.
- A BWER is a good indication of a very powerful storm!

# Supercell Rotation Sources




- Small mesocyclones (rotating systems) are found in some thunderstorms, particularly frontal thunderstorms and supercells.
- This rotating motion might contribute to the long life of these storms.
- In the top example, the thunderstorm is formed in an area of preexisting rotation, which is presumably accelerated by convergence.
- In the second case, a surface roll is sucked up the updraft.
  - Stretching the roll presumably tightens and accelerates.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Fujita Scale

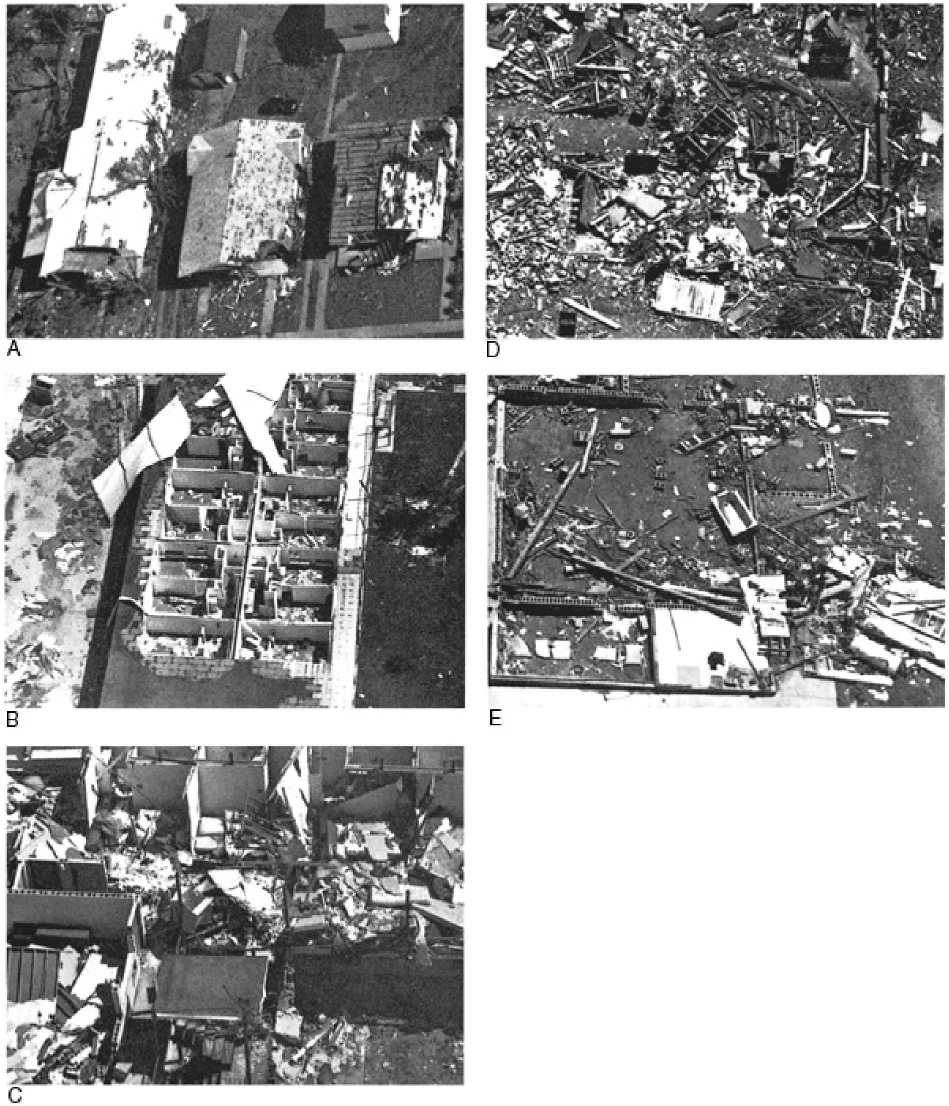
| Class | % of all Tornadoes | Fujita Category | Wind Speed ($ms^{-1}$) | Damage |
|---|---|---|---|---|
| Weak | 29% | F0 | 17.5 – 31 | Small trees uprooted |
| | 40% | F1 | 31.5 – 48.5 | Trailer homes damaged |
| Strong | 24% | F2 | 49 – 68 | Roofs torn off houses |
| | 6% | F3 | 68.5 – 89.5 | Cars lifted off the ground |
| Violent | 4% | F4 | 90 – 113 | Houses destroyed |
| | <1% | F5 | 113.5 – 138 | Steel structures destroyed |
| | Never verified | F6 | 138.5 – 165 | Inconceivable |

- The Fujita scale ranges from F0 to F12, but ratings above F5 are rarely mentioned because they cannot be confirmed from damage surveys.
- Created by Theodore Fujita, based primarily on wind speed.

# Enhanced Fujita Scale

| Scale | Wind speed | | Relative frequency | Potential damage | |
|---|---|---|---|---|---|
| | mph | km/h | | | |
| **EF0** | 65–85 | 105–137 | 53.5% | Light damage.<br>Peels surface off some roofs; some damage to gutters or siding; branches broken off trees; shallow-rooted trees pushed over.<br>Confirmed tornadoes with no reported damage (i.e. those that remain in open fields) are always rated EF0. |  |
| **EF1** | 86–110 | 138–178 | 31.6% | Moderate damage.<br>Roofs severely stripped; mobile homes overturned or badly damaged; loss of exterior doors; windows and other glass broken. |  |
| **EF2** | 111–135 | 179–218 | 10.7% | Considerable damage.<br>Roofs torn off well-constructed houses; foundations of frame homes shifted; mobile homes completely destroyed; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground. |  |
| **EF3** | 136–165 | 219–266 | 3.4% | Severe damage.<br>Entire stories of well-constructed houses destroyed; severe damage to large buildings such as shopping malls; trains overturned; trees debarked; heavy cars lifted off the ground and thrown; structures with weak foundations blown away some distance. |  |
| **EF4** | 166–200 | 267–322 | 0.7% | Devastating damage.<br>Well-constructed houses and whole frame houses completely leveled; cars thrown and small missiles generated. |  |
| **EF5** | >200 | >322 | <0.1% | Total destruction.<br>Strong frame houses leveled off foundations and swept away; automobile-sized missiles fly through the air in excess of 100 m (300 ft); steel reinforced concrete structure badly damaged; high-rise buildings have significant structural deformation; incredible phenomena will occur.<br>So far there have been two EF5 tornadoes recorded since the Enhanced Fujita Scale was introduced on February 1, 2007. The most recent one occurred in Parkersburg, Iowa on May 25, 2008 and leveled half the city. *See Greensburg, Kansas tornado, Northeast Iowa supercell* |  |

# Tornado Damage Analyses




- Examples of damage caused by different classes of tornadoes.
- Based on the descriptions from the previous page, can you estimate the Fujita category from the storm damage in these images?

Figure from **Meteorology** by Danielson, Levin and Abrams

# Suction Vortices Within a Tornado

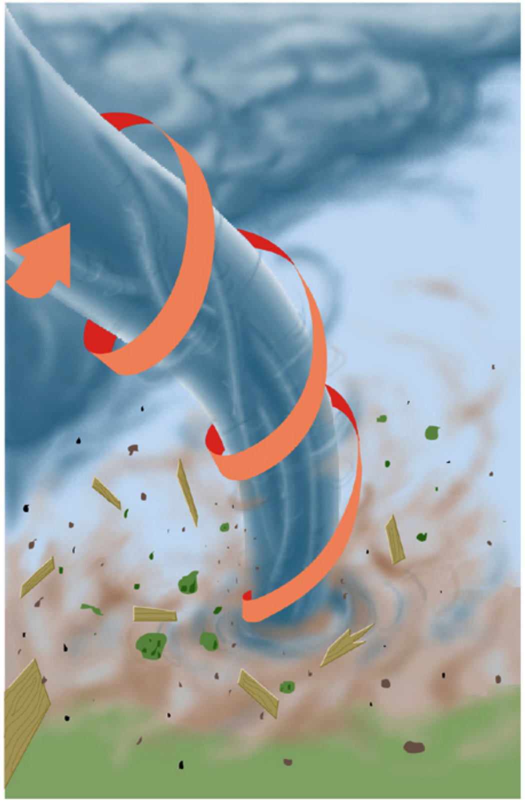


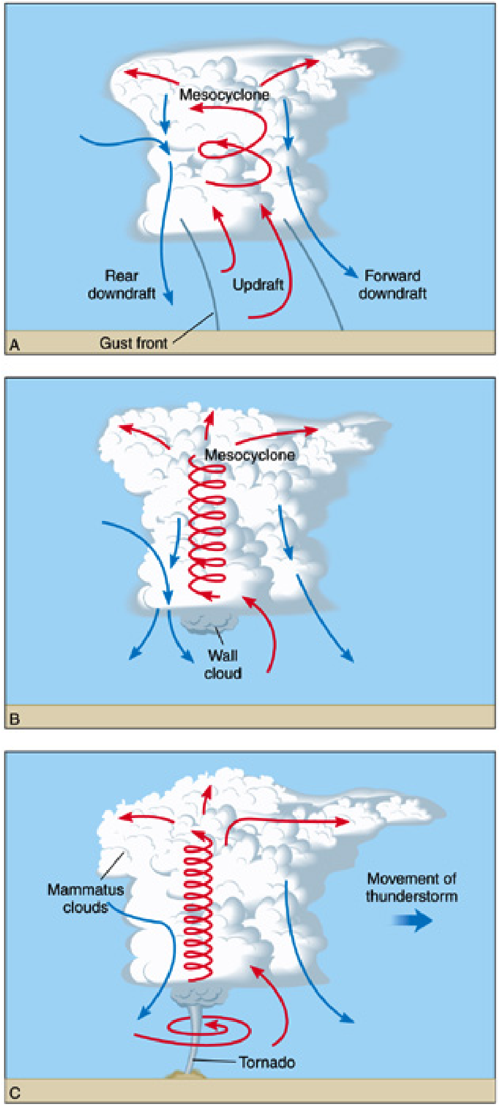
Figure above from **Meteorology** by Danielson, Levin and Abrams

- Major tornadoes have smaller vortices within the larger outer vortex.
- Page 343 of Meteorology quotes an eye witness report from the center of a major tornado.
- Smaller suction vortices were shed from the inner wall of the outer vortex.
- Indirect evidence of such vortices can be found in the damage patterns of major tornadoes.
- It is believed that these smaller vortices are responsible for the more extreme tornado damage.

http://www.nhn.ou.edu/~feldt/images/vortexloops.jpg

**Rather interesting aerial view of looping vortex suction marks near Cashion, OK from the May 3rd, 1999 tornado. This photo was taken by John Jarboe of the NWS.**

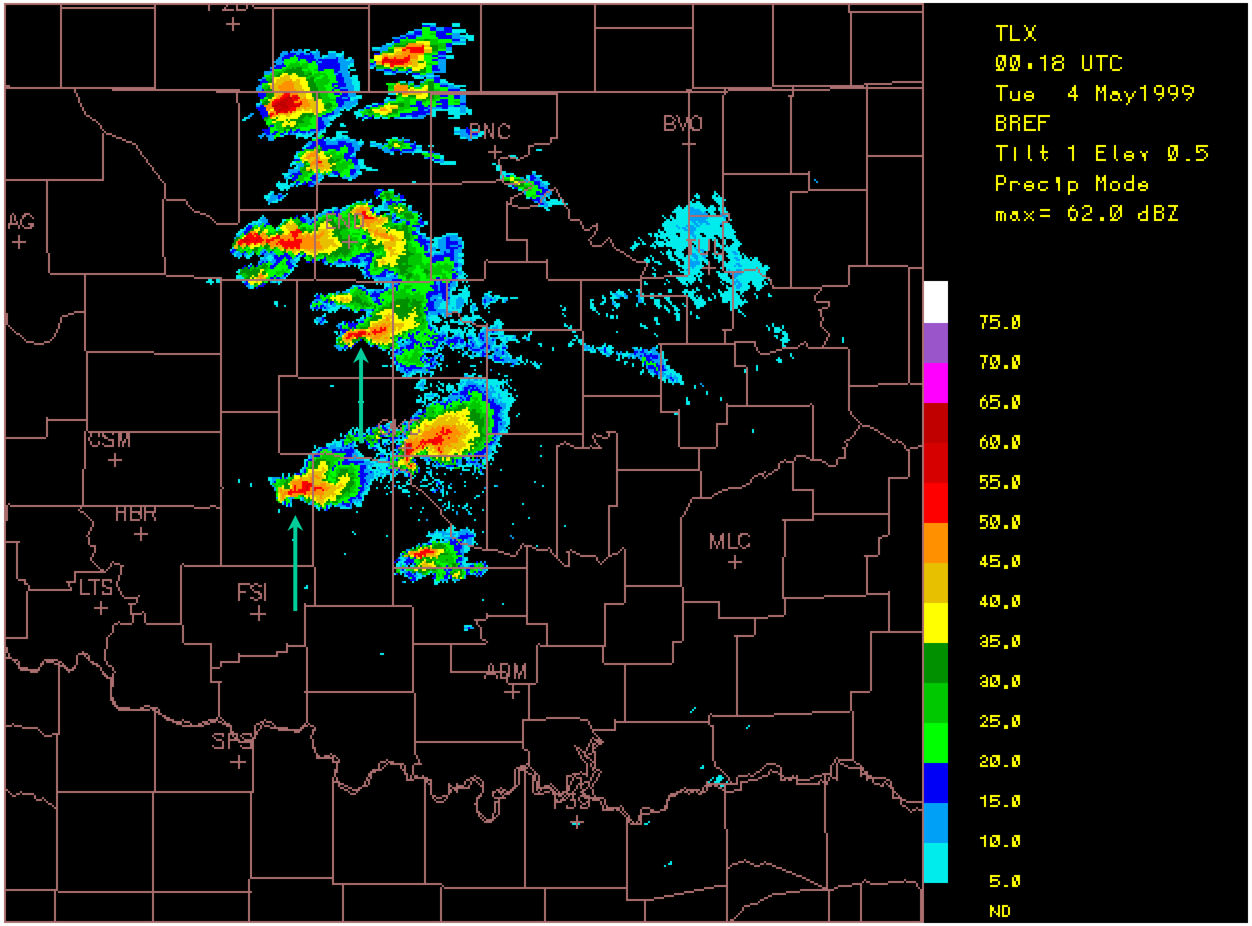
# Tornado Formation Stages




- Tornadoes are spawned by thunderstorms, and in most cases from intense thunderstorms such as supercells.
- There is no single (unified) theory of tornado formation.
- The figures indicate the tornado formation process within supercells.
- Processes we have already discussed form a mesocyclone within the supercell (Fig. A).
- In the transition stage (Fig. B), the mesocyclone is stretched, resulting in a more narrow and faster rotating vortex. A wall cloud forms, and extends below the cloud base. The wall cloud usually forms to the rear of the thunderstorm.
- In the last stage (Fig. C), a funnel cloud or tornado (a funnel cloud that reaches the ground) forms.

Figure from **Meteorology** by Danielson, Levin and Abrams

# The Hook Echo Signature

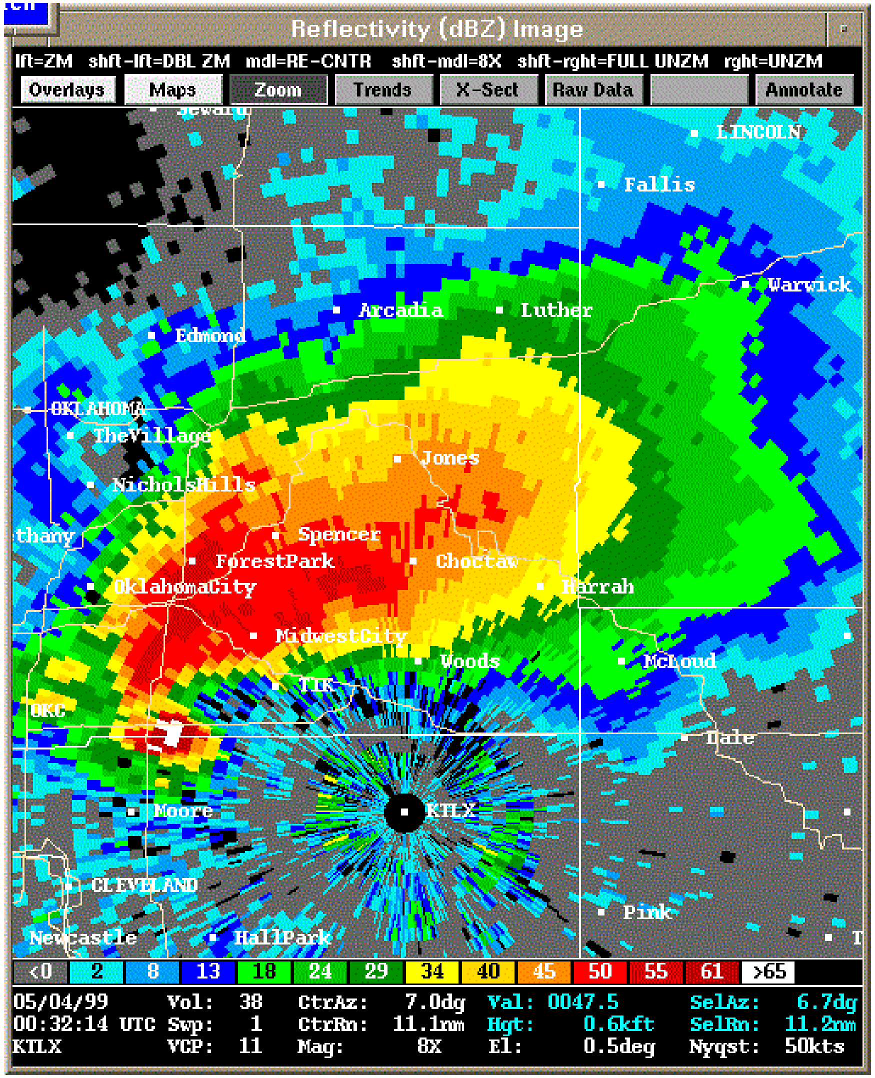



- A hook shaped echo from the weather radar indicates a thunderstorm with the characteristics needed to produce tornadoes.
- This example is from the Oklahoma outbreak.

Graphics and information from http://www.srh.noaa.gov/oun/storms/19990503/

# Hook Echo From Moore, OK

- http://www.mindspring.com/~jbeven/ar040032z.gif
- Classic hook echo and tornado vortex signature from the May 3rd, 1999, Moore, OK tornado.




Graphics and information from
http://www.srh.noaa.gov/oun/storms/19990503/

# Example Wall Clouds & Funnel Clouds, and Tornadoes

A

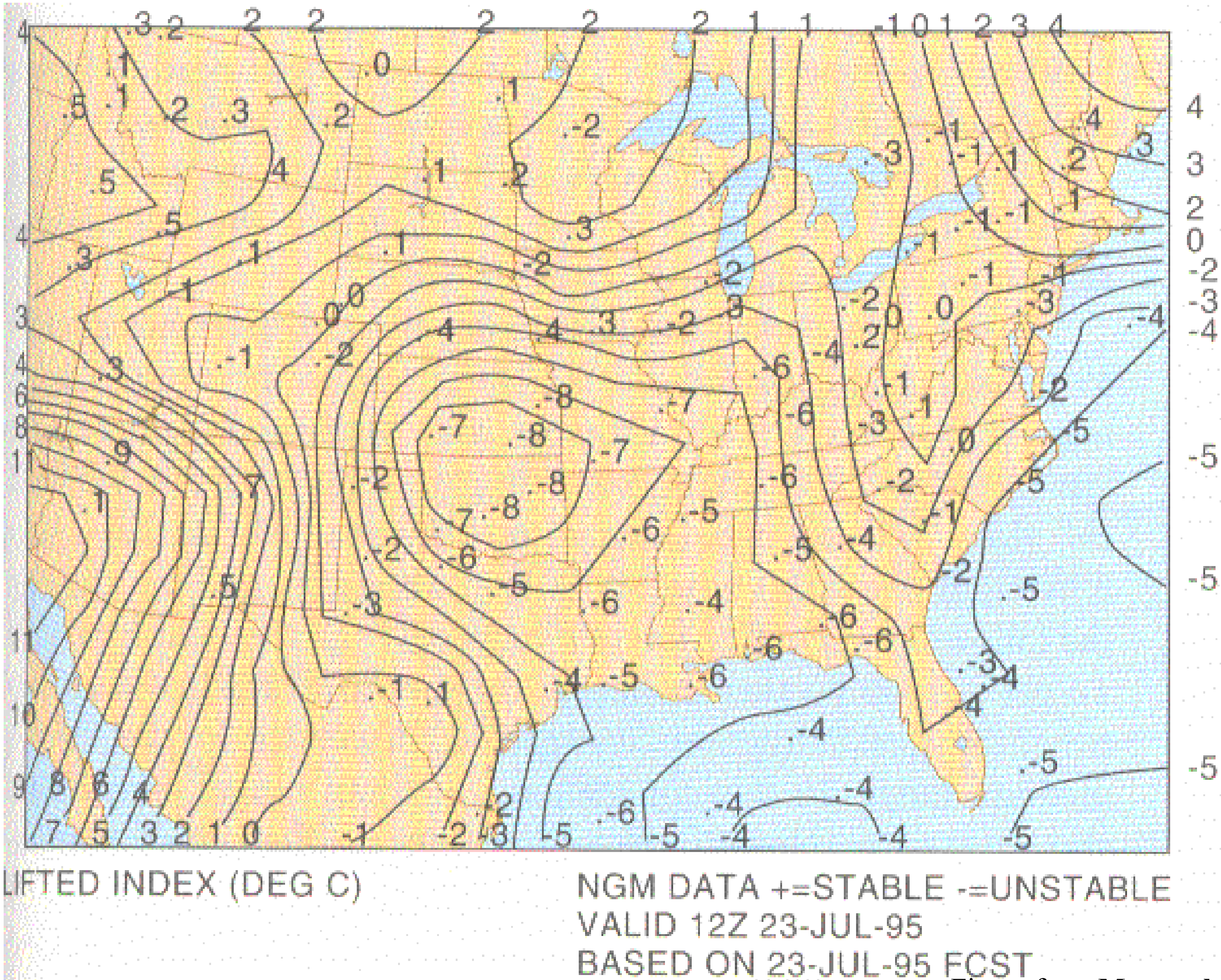
B

Above: Video snapshot of the Moore/Oklahoma City tornado just southeast of Amber, Oklahoma at about 6:30 PM CDT on May 3, 1999. The tornado was captured on video by Oklahoma Climatological Survey employees Renee McPherson, Michael Wolfinbarger, Andrew Reader and Christopher Duvall.

# Moisture and Stability

- The stability of the air, and the associated moisture content are important considerations in summer forecasts.
  - Why in summer and not winter? What are we assuming?
- Moisture aloft:
  - Typically moisture in the 850 to 700mb fields is examined.
  - If there is a layer of moist air, topped by a layer of dry air, it is more likely that the air will become unstable. Why?
- If the upper part of the layer cools at the dry adiabatic lapse rate, and the lower part cools at the moist adiabatic lapse rate, what happens to the densities at these heights?
- There is an index (the lifted index) for stability that can easily be computed.

# The Lifted Index




- The Lifted Index (LI) considers the atmospheric stability (stratification) of the air mass
- The LI is equal to the environmental temperature air 500 mb MINUS the temperature of a surface parcel lifted to 500 mb

Figure from **Meteorology** by Danielson, Levin and Abrams

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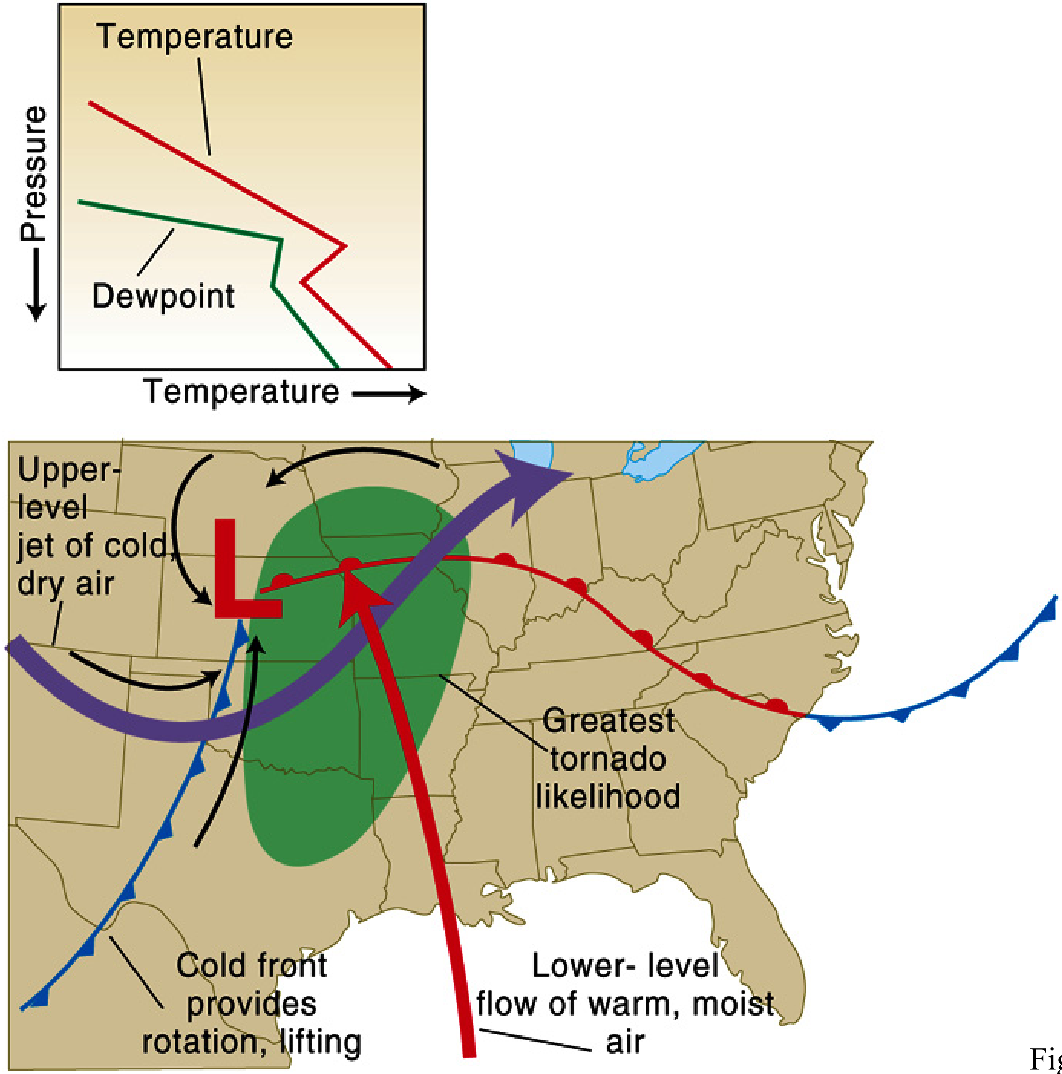
# Interpreting the Lifted Index

**The Lifted Index (LI)**

| RANGE IN K | COLOR | AMOUNT OF INSTABILITY | THUNDERSTORM PROBABILITY |
|---|---|---|---|
| more than 11 | BLUE | Extremely stable conditions | Thunderstorms unlikely |
| 8 to 11 | LIGHT BLUE | Very stable conditions | Thunderstorms unlikely |
| 4 to 7 | GREEN | Stable conditions | Thunderstorms unlikely |
| 0 to 3 | LIGHT GREEN | Mostly stable conditions | Thunderstorm unlikely |
| -3 to -1 | YELLOW | Slightly unstable | Thunderstorms possible |
| -5 to -4 | ORANGE | Unstable | Thunderstorms probable |
| -7 to -6 | RED | Highly unstable | Severe thunderstorms possible |
| less than -7 | VIOLET | Extremely unstable | Violent thunderstorms, tornadoes possible |

- Taken from http://expert.weatheronline.co.uk/lftx_frame.htm

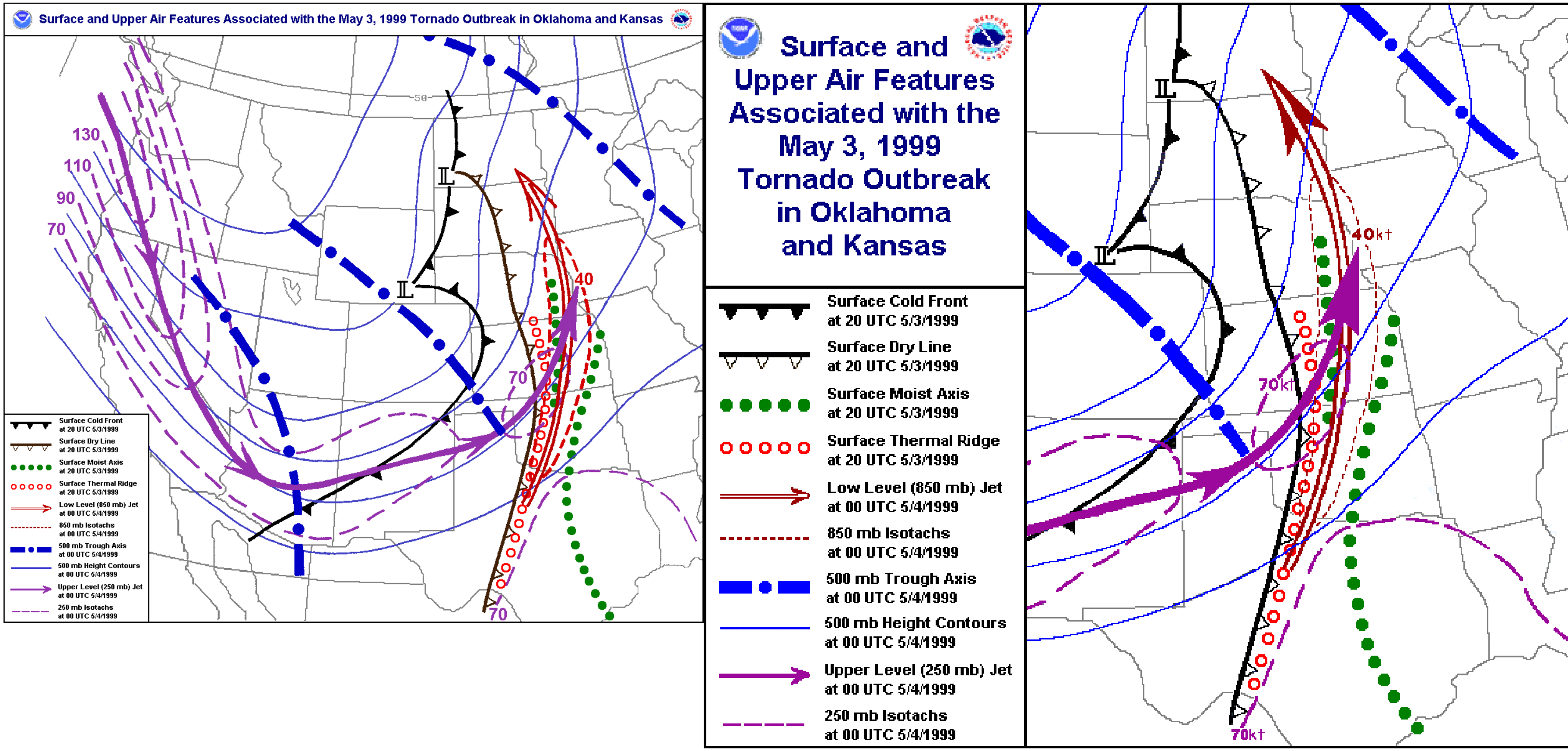
# ‘Ideal’ Conditions for Tornado Formation




- These figures indicate the most likely conditions for tornado formation.
- It is also the most common set of conditions for tornadoes.
- The frontal cyclone provides surface convergence cyclonic flow, and is likely to create surface roll vortices.
- Warm moist air provides the necessary energy input.
- At higher levels, wind from the west advects in a dry cool environment.
- Lifted index is in the range of –6 or less.
- An inversion allows surface energy to buildup.
- Cold front is the trigger.

Figure from **Meteorology** by Danielson, Levin and Abrams

# Conditions For the Oklahoma Outbreak

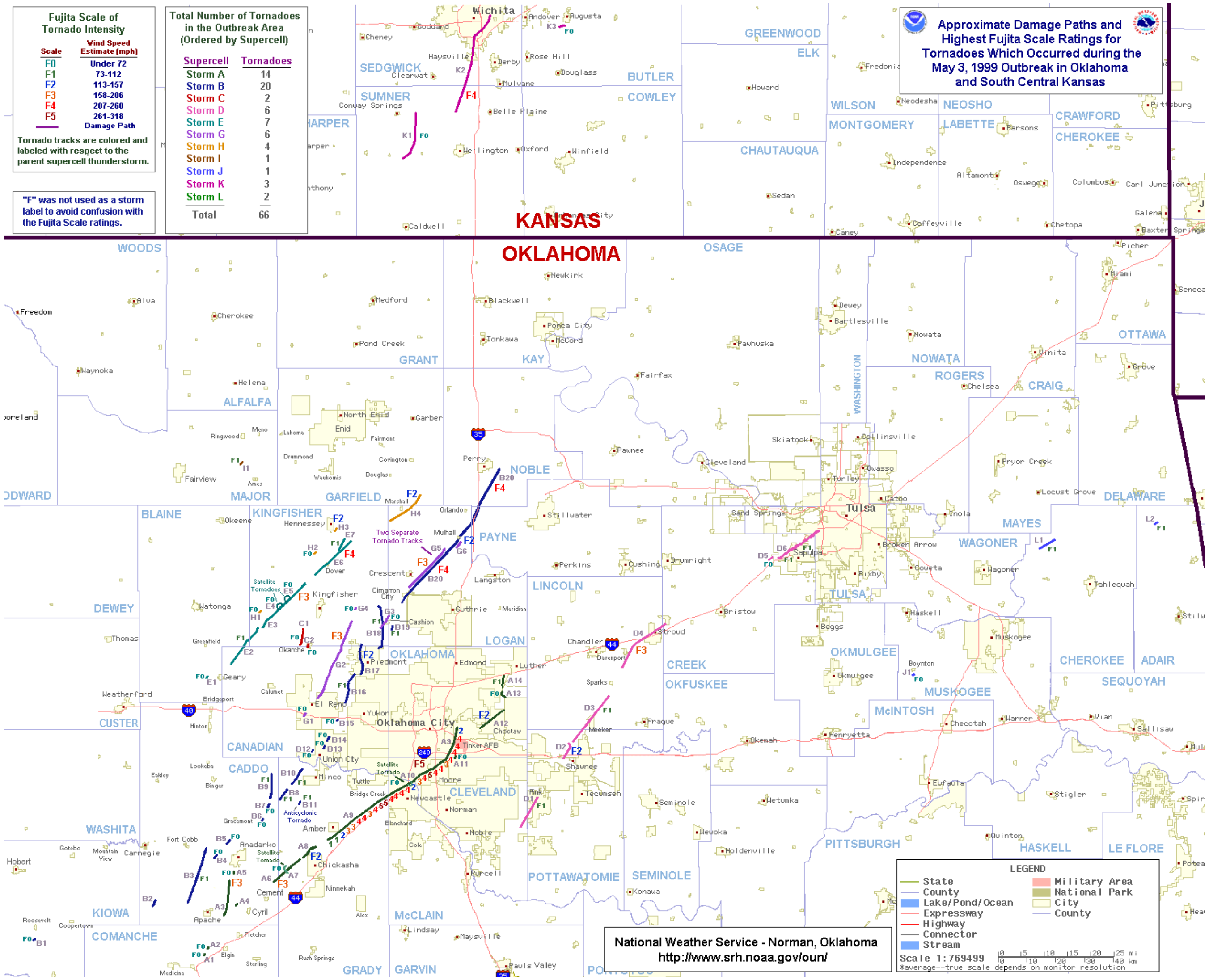



- The situation is more complex and more volatile than the preceding idealized case.

Graphics and information from http://www.srh.noaa.gov/oun/storms/19990503/

# Big Picture for Oklahoma Outbreak

Graphics and information from http://www.srh.noaa.gov/oun/storms/19990503/

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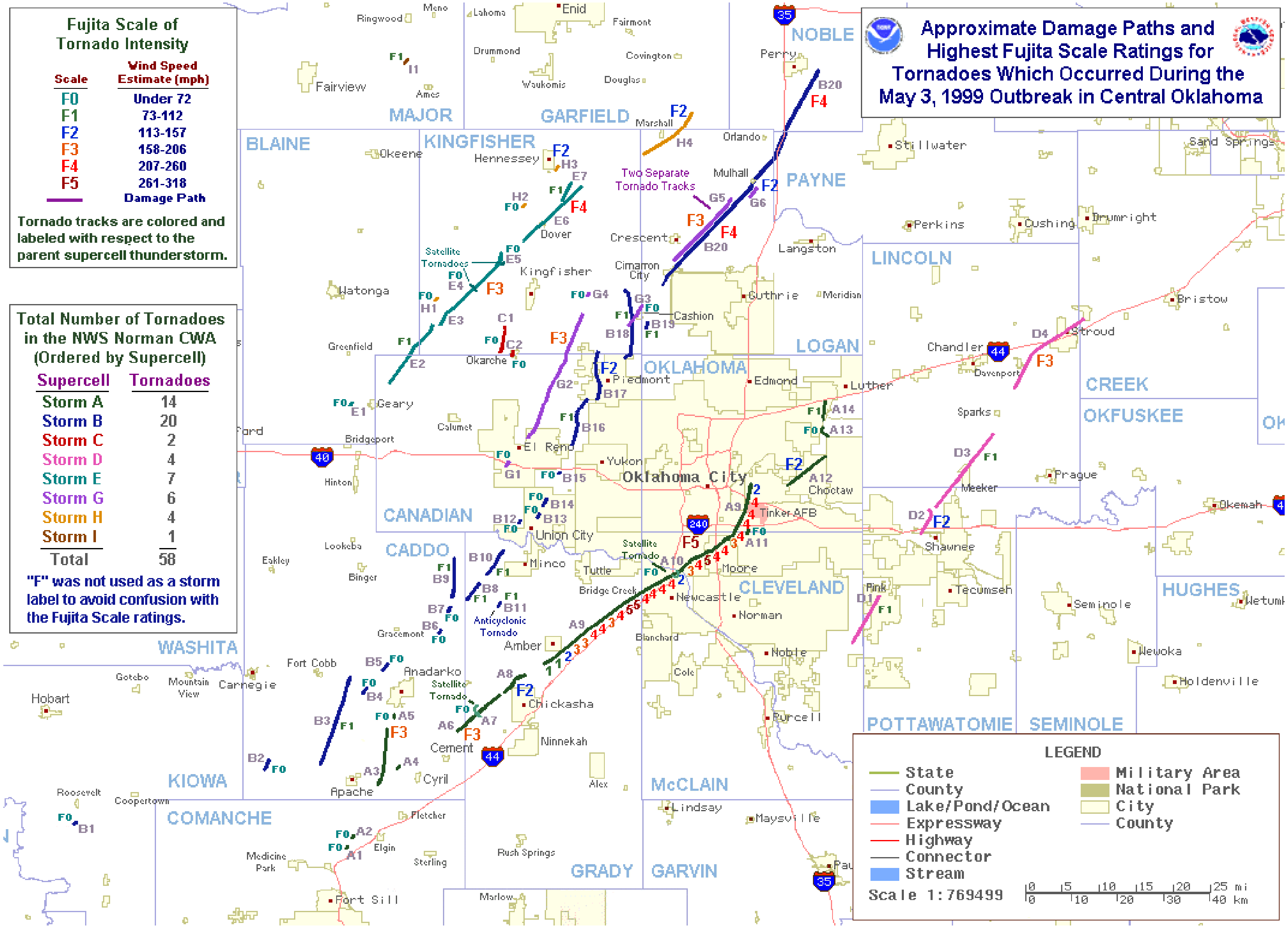
# Oklahoma Outbreak (May 3rd, 1999)

Graphics and information from http://www.srh.noaa.gov/oun/storms/19990503/

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# Aerial Photos of the May 3rd, 1999 Tornado Outbreak

- http://www.srh.noaa.gov/oun/storms/19990503/damage/filmroll2.html

# Aerial Photos of the May 3rd, 1999 Tornado Outbreak


- http://www.srh.noaa.gov/oun/storms/19990503/damage/filmroll2.html

# Aerial Photos of the May 3rd, 1999 Tornado

# Ground Photos of the May 3rd, 1999 Tornado Outbreak

- http://www.cimms.ou.edu/~cimms/damage.htm

# Ground Photos of the May 3rd, 1999 Tornado Outbreak

- http://www.cimms.ou.edu/~cimms/damage.htm

# Ground Photos of the May 3rd, 1999 Tornado Outbreak

- http://www.cimms.ou.edu/~schultz/images/F5/

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# F5 tornado damage pics from Oak Grove, Alabama (April 8, 1998)



- http://lindleyonline.com/tornado.htm
- 32 people killed.

# F5 tornado damage pics from Oak Grove, Alabama (April 8, 1998)



- The aerial photo is of Edgewater, AL and is a short section of the 32 mile path of devastation made the the tornado. Everything is blown away in a storm like this including street signs.
- http://lindleyonline.com/tornado.htm

# NASA photo showing the path of the Moore, OK, tornado from May 3rd, 1999.

http://www.directionsmag.com/images/articles/OKTornado_05_2003/MooreOKtornado.jpg

# Waterspout off Coast of Florida