Chapter 18
Thunderstorms

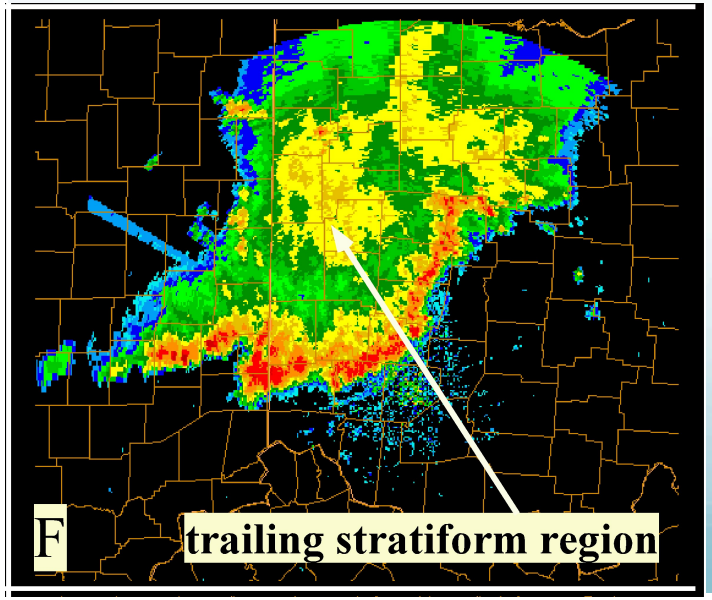
Courtesy of Bruce Lee

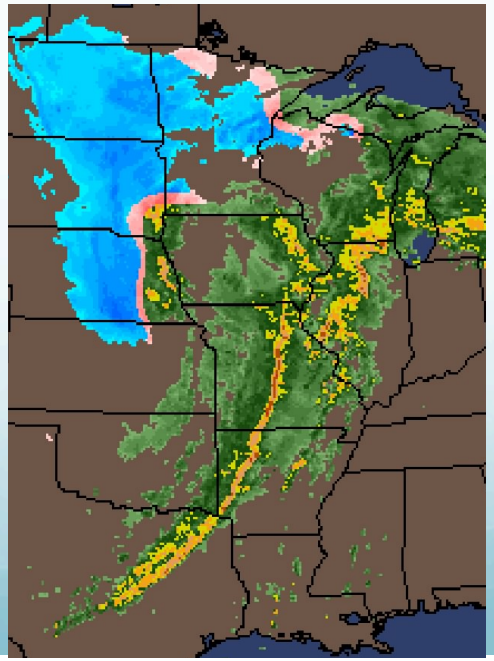
Thunderstorms

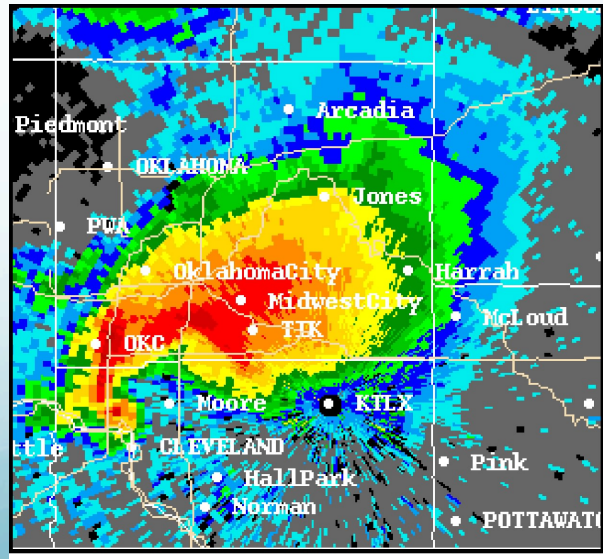
- A thunderstorm is a vertically-developing cloud that produces lightning and thunder.
- What kind of clouds are thunderstorms?
  - Cumulonimbus
- Why do we care about them?
  - They redistribute heat and moisture in our atmosphere
  - The rains from thunderstorms are vital water resources
  - Most are not severe, but occasionally they can produce severe weather (hail, winds, tornadoes)

Types of thunderstorms

- Airmass (ordinary) thunderstorm
- Mesoscale Convective System (MCS)
- Frontal squall line
- Supercell thunderstorm







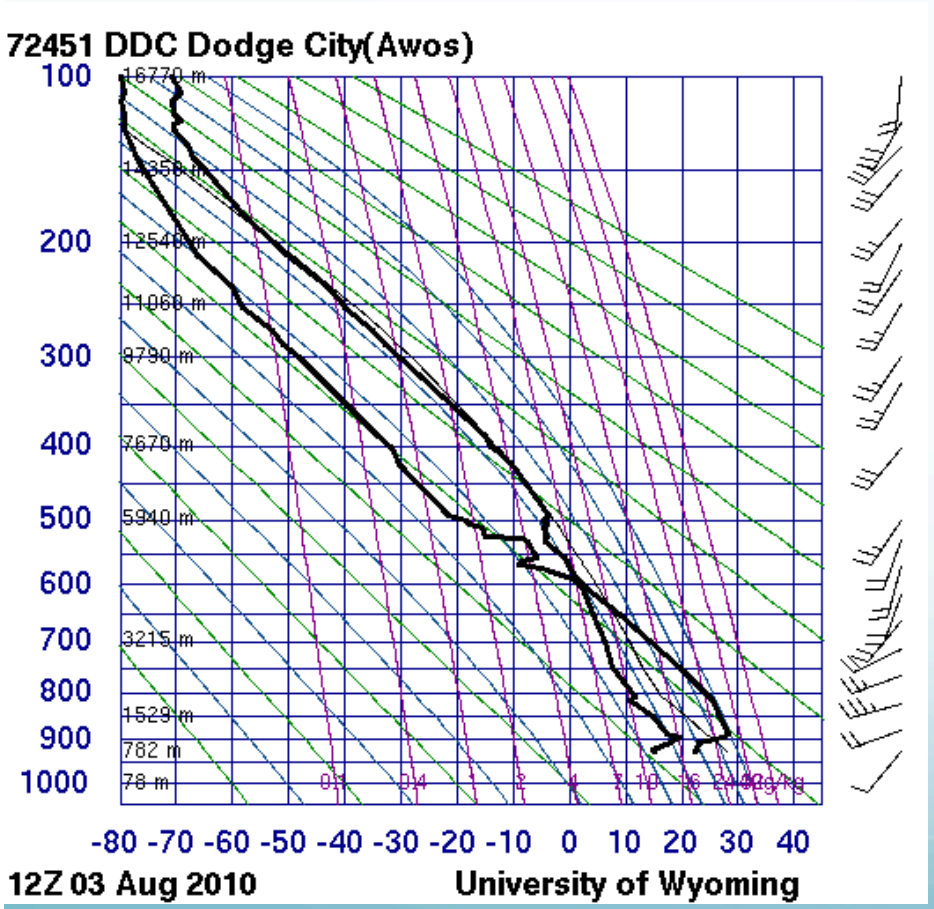
What makes a thunderstorm severe?

- If it has the potential to threaten lives and property
- Considered severe if contains one or more of the following three things is likely or occurs:
  - Hail with diameter >3/4 inch
  - Wind damage or gusts >50 kts
  - A tornado
- What elements required for thunderstorm to form?
  - A source of moisture
  - A conditionally unstable atmosphere
  - A mechanism to trigger the thunderstorm updraft
- What about for a severe thunderstorm?
  - Same three elements as for an ordinary thunderstorm, except also need vertical wind shear
- **Vertical wind shear** – a rapid change in wind speed and/or wind direction with altitude

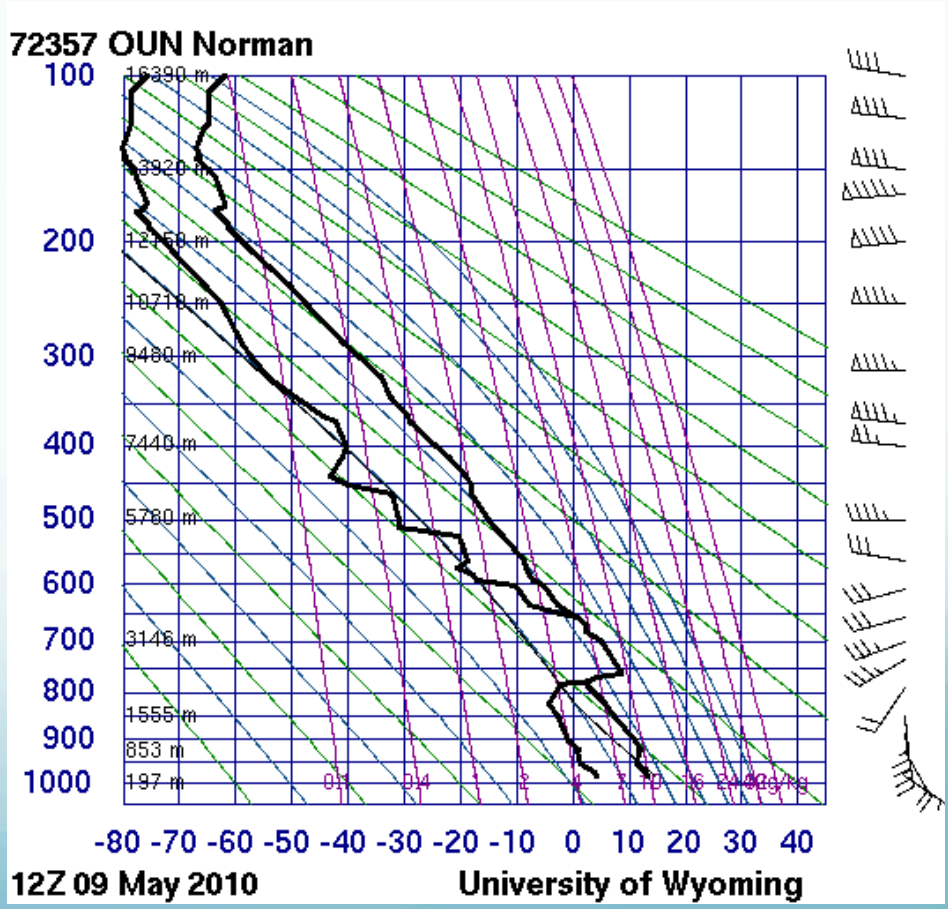
What is vertical wind shear?

What does it look like?

Little to no wind shear



Both speed and directional shear



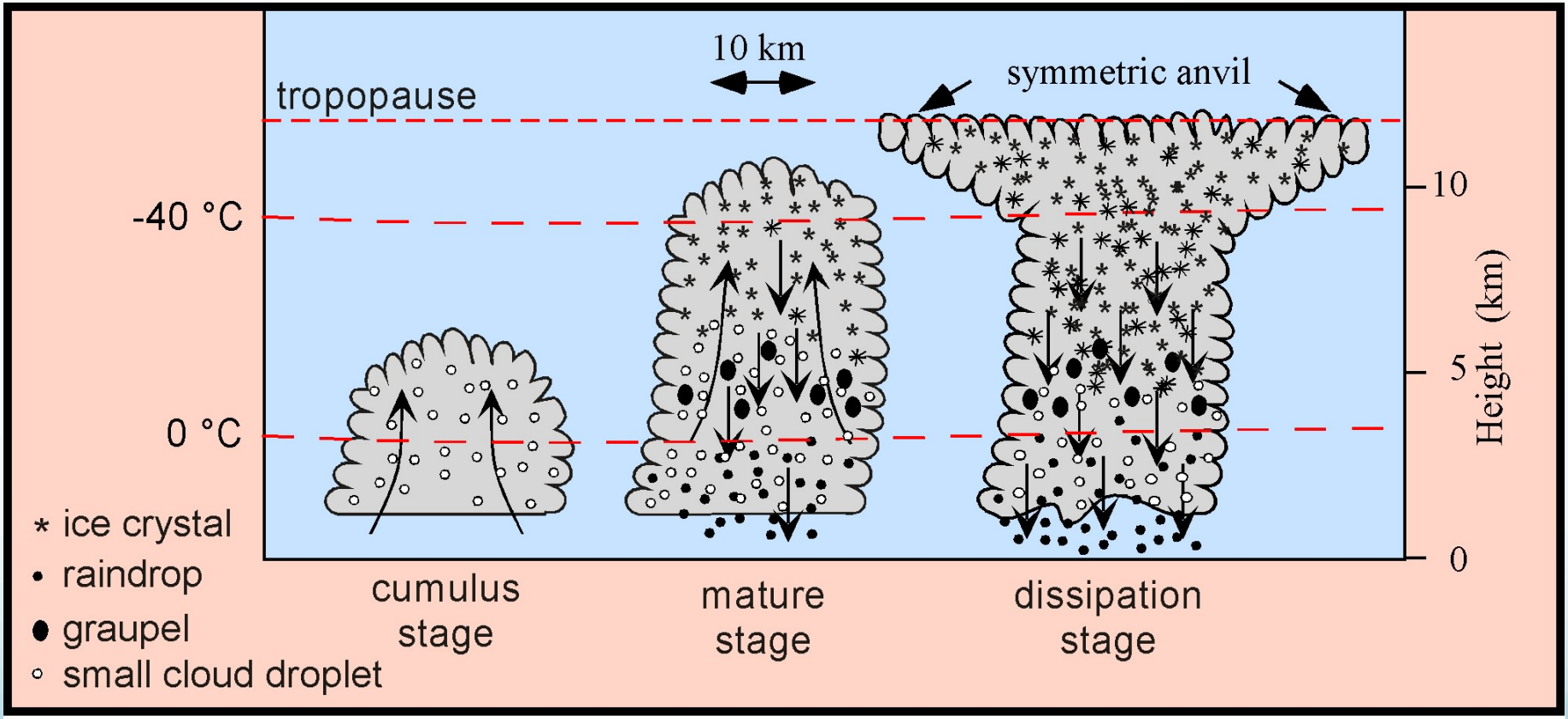
Effect of vertical wind shear on thunderstorms

- No shear:
  - http://severewx.atmos.uiuc.edu/17/online.17.2.noshear.html
- With vertical wind shear:
  - http://severewx.atmos.uiuc.edu/17/online.17.2.shear.html

Airmass Thunderstorms

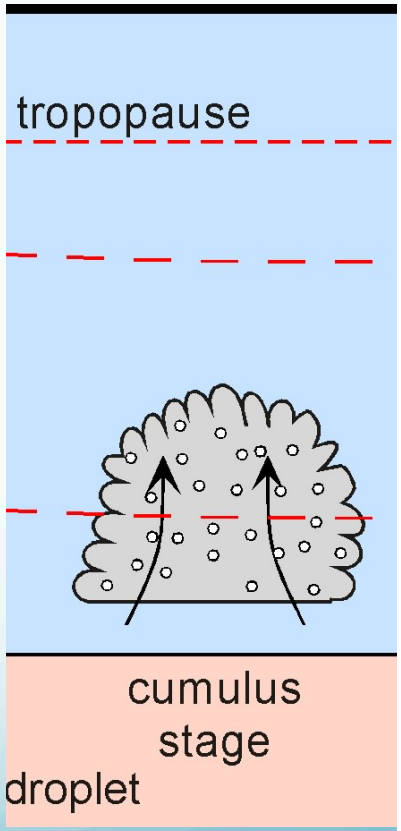
- Isolated thunderstorms that form in the absence of vertical wind shear
- Named as such because they often occur well within an airmass (as opposed to along a front)
  - Also called ordinary thunderstorms
- Triggered by surface heating, lifting along mountain slopes, and along weak boundaries (cool air outflows from other thunderstorms)
  - Often during hot afternoons in the summer
- Typical lifetime of about one hour
  - Short lifetime due to lack of vertical wind shear, and winds aloft are typically weak

3 stages of an airmass storm



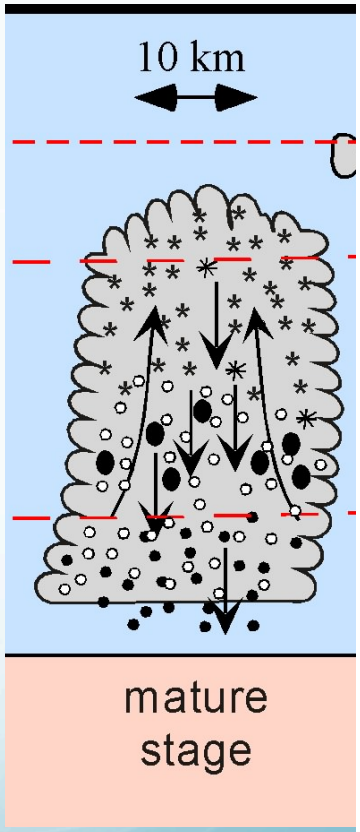
Cumulus stage

- Described by a warm, buoyant plume of rising air
  - **Updraft dominated!**
- What type of particles makeup the cloud in the cumulus stage of a thunderstorm?
  - Liquid cloud droplets
  - Little or no rain drops or ice crystals
- When do ice crystals begin to form in a thunderstorm?
  - When the cloud passes the melting level and reaches cold temperatures of −10 to −20 °C

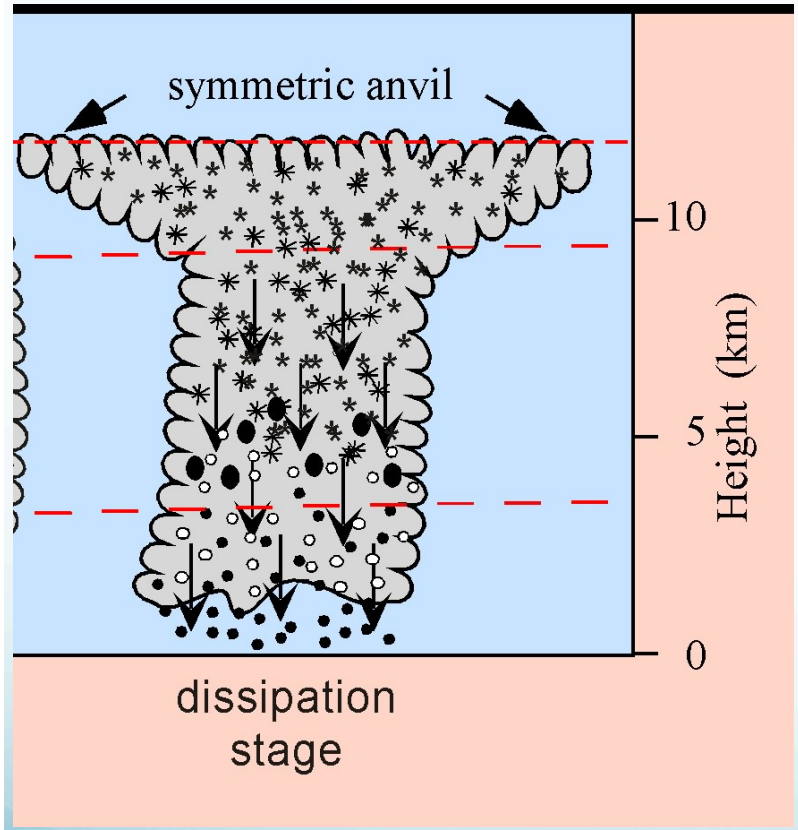


Mature stage

- Described by precipitation beginning to fall from the thunderstorm
  - **Updraft and downdraft coexist!**
- What two factors cause a downdraft to form in an airmass thunderstorm?
  - Precipitation particles falling drag air downward
  - Evaporation as precipitation encounters dry air mixing in from sides and top of cloud causes cooling (dense, colder air sinks)
    - A **cold pool** is created near the surface from the rain-cooled air in the downdraft
    - The dry air mixed in is called **entrainment**
- Where does the downdraft form in relation to the original updraft?
  - Above it, so it falls through the updraft
  - No tilt to the storm due to lack of vertical wind shear



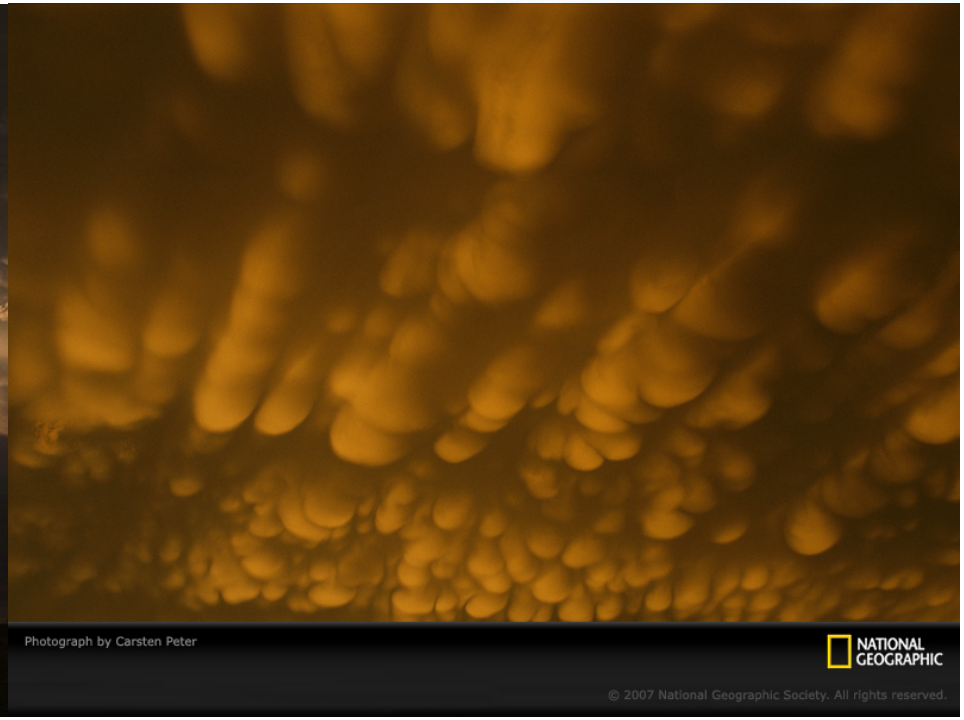
Dissipation stage



Cold pool rushes away from cloud, creating a **gust front**

- Described by the **downdraft dominating the storm**
  - Downdraft suppresses the updraft cutting off the source of moisture to the storm
- **Anvil** – the flat top of a thunderstorm that forms as the thunderstorm updraft hits the tropopause and spreads out horizontally
- What are the characteristics of the anvil of an airmass thunderstorm?
  - Symmetrical with flat top (since no preferential strong wind direction aloft)
  - **Mammatus clouds** – form when particles evaporate in the anvil, creating pockets of cooled air that descend

Courtesy of Alan Moller



Clicker Question

- True or false: A thunderstorm that is producing hail with diameters of ½ inch and winds of 60 kts is a severe thunderstorm.

  A. True

  B. False

Clicker Question

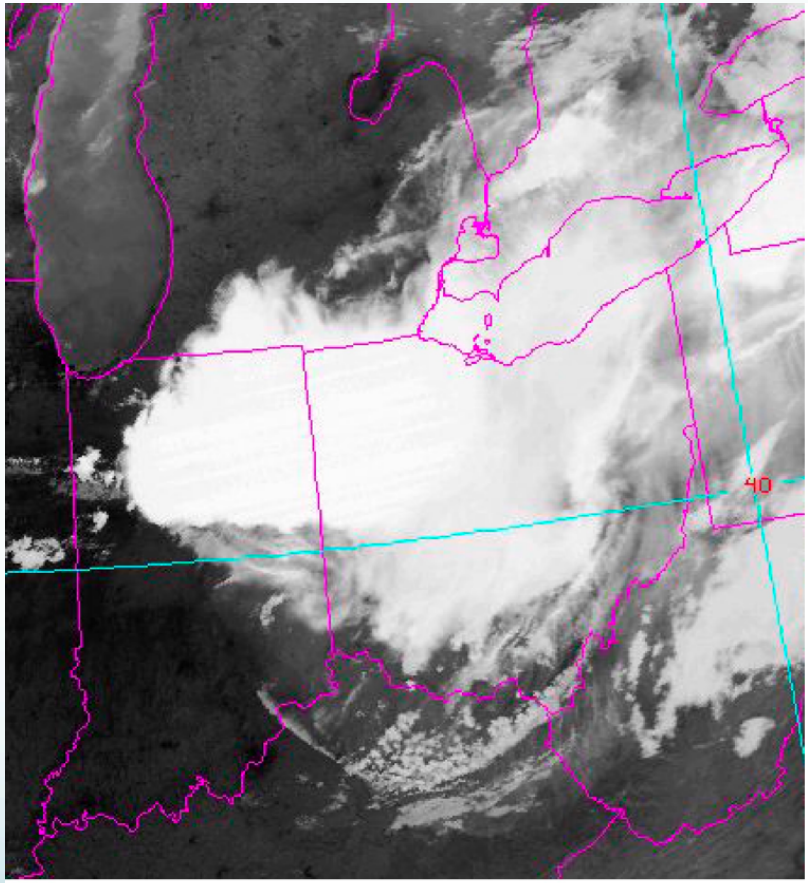
- At which stage of development is an airmass thunderstorm if it has both an updraft and downdraft that coexist?
  A. Growth
  B. Cumulus
  C. Mature
  D. Dissipation

Clicker Question

- What thunderstorm feature is found near the surface and created by rain-cooled air in the downdraft?
  A. Anvil
  B. Mammatus clouds
  C. Cold pool
  D. Updraft

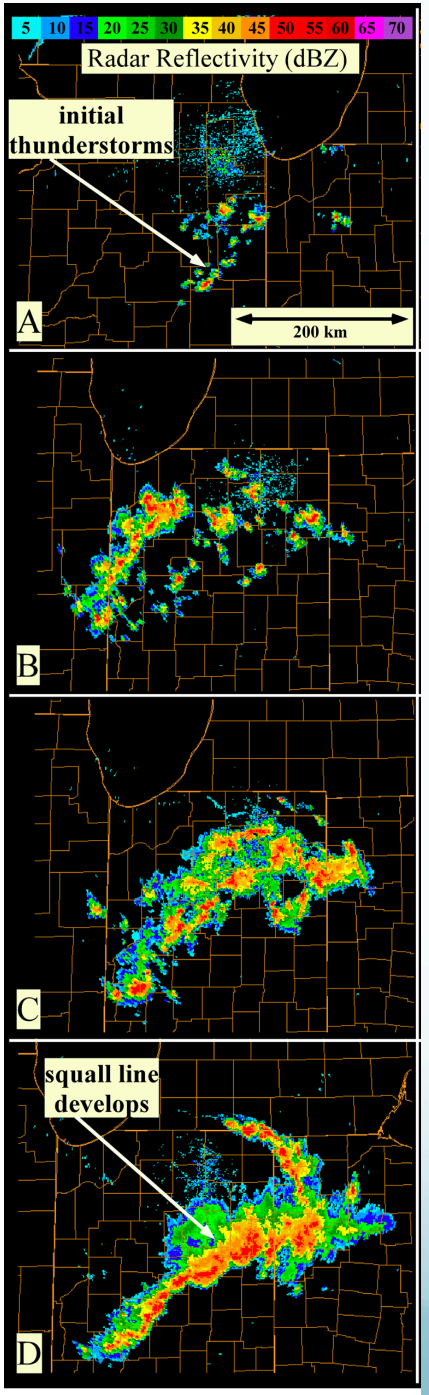
Mesoscale Convective Systems (MCS)

- Why do we care about MCSs?
  - They produce much of the summer rainfall on the Central Plains of North America
- How much area do they cover?
  - Greater than a large U.S. state!
- Typical lifecycle lasts many hours (~8 hrs)
- Can produce strong straight-line winds at the surface and occasionally (weak) tornadoes



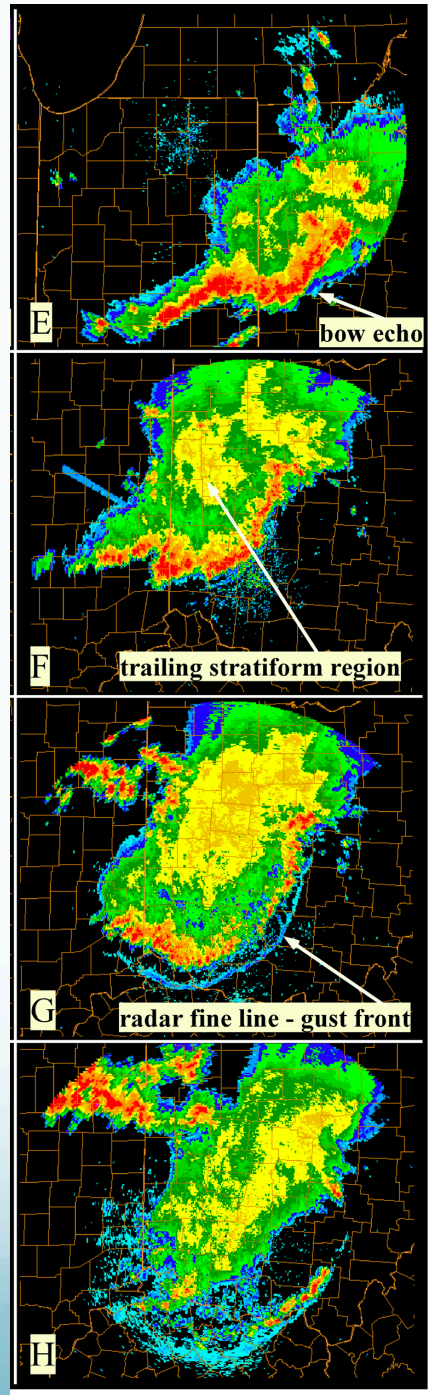
Features/terms defined

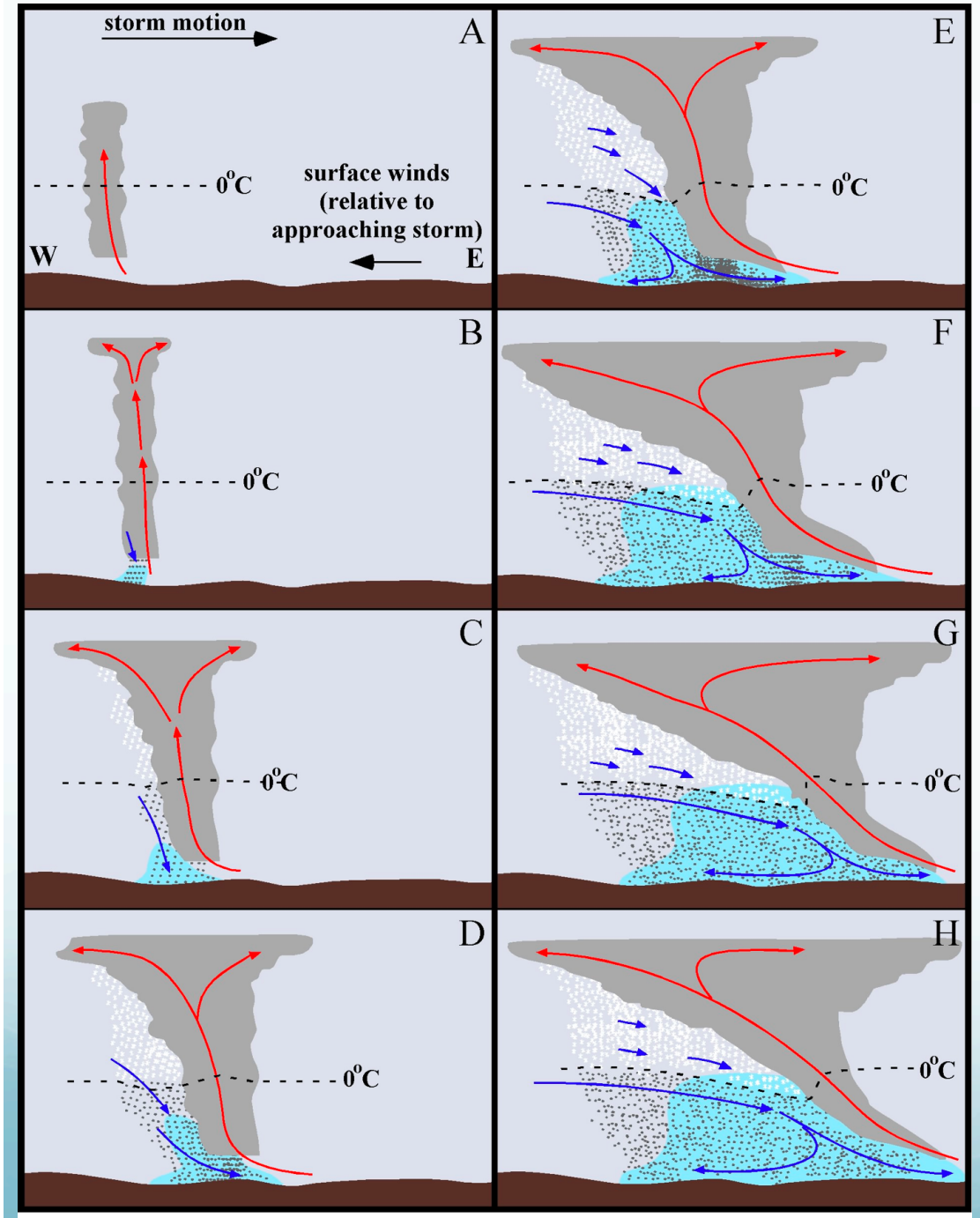
- **Squall line** – a long line of thunderstorms in which adjacent thunderstorm cells are so close together that the heavy precipitation falls in a long continuous line
- **Bow echo** – portion of a squall line that bows outward from MCS
  - Strongest winds along a squall line are often found here
- **Trailing stratiform region** – area of less intense precipitation on rear side of a squall line
- **Gust front** – leading edge of evaporatively cooled air
- **Derecho** – a widespread thunderstorm generated severe windstorm



MCS evolution

- Initial isolated thunderstorms
- Squall line forms as the individual storms organize
  - A bow echo may occur within squall line
- Widespread trailing stratiform region develops
- Gust front forms and propagates ahead of MCS
  - Seen by a **radar fine line**





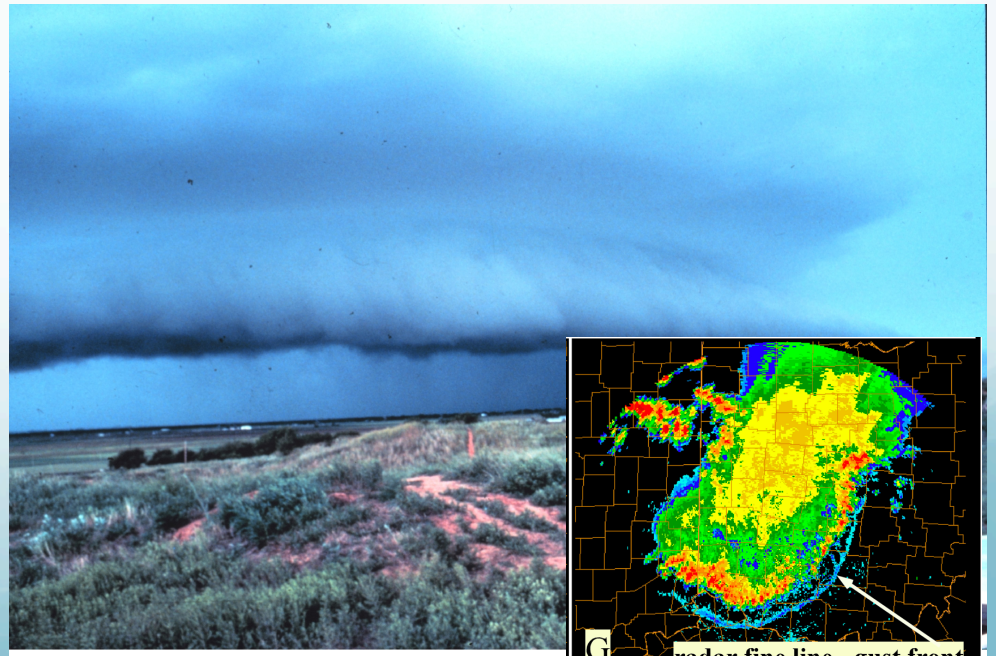
- What is the cold pool? How does it form? **Evaporation of rain**
- What role does the cold pool play in the formation of a squall line? **Provides lifting**
- How does the cold pool alter the updrafts in an MCS? **Tilts them**
- What impact does this have on where precipitation falls? **Falls behind thru more dry air**
  - How does this alter the cold pool? **Enhances**

The gust front

- The gust front is created by the cold pool advancing out ahead of the thunderstorm
  - Strong winds may accompany it
- Since it acts like a mini-cold front, what will happen if the gust front encounters warm, moist air ahead of the storm?
  - Lifting!
  - Cloud formation

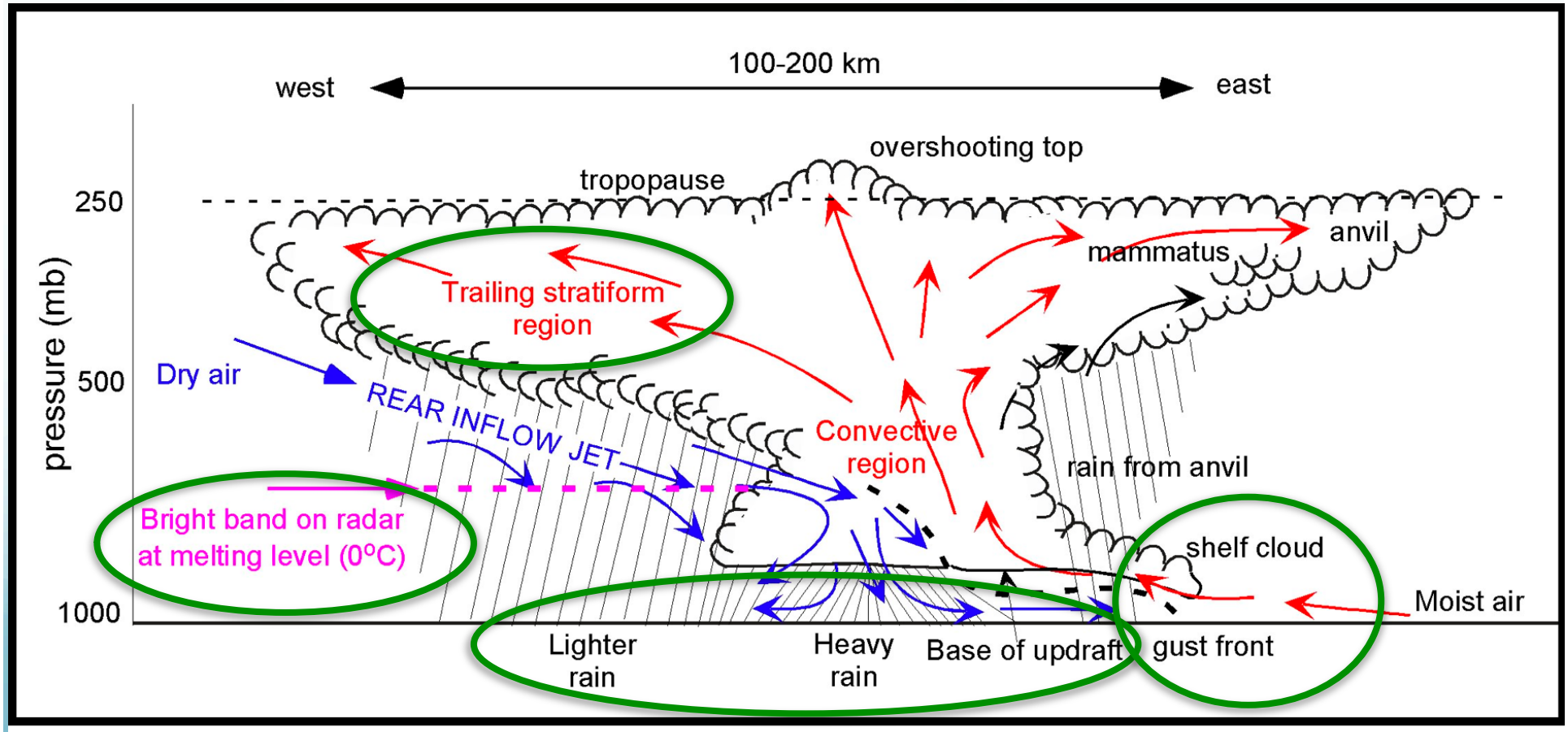
A **shelf cloud** is a type of cloud that forms along a gust front (also called a **roll cloud** if it is more tube-like in appearance)

This cloud may form **a fine line** of weak radar reflectivity

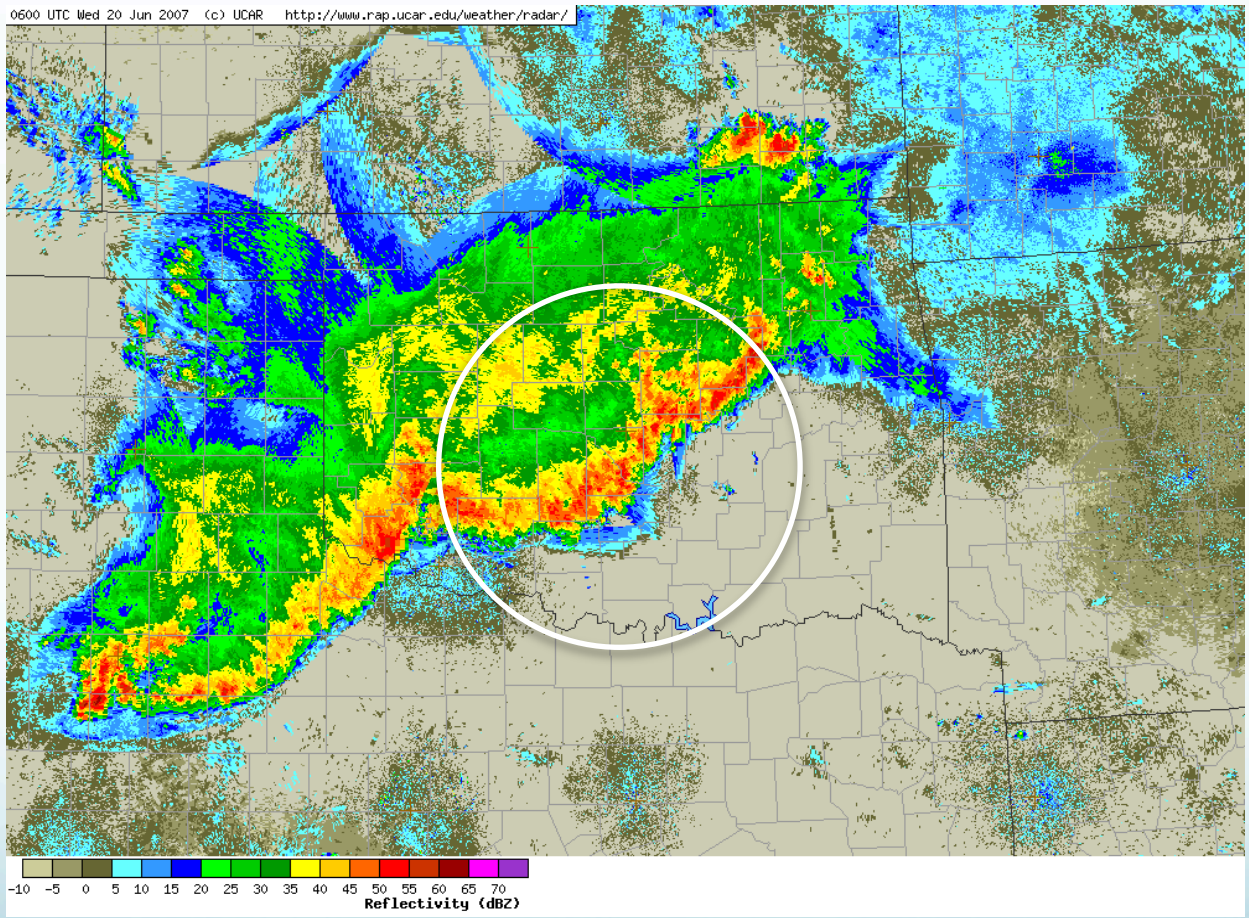


Courtesy of NOAA/NSSL Photo Library

Summary of MCS features



My research with MCS squall lines

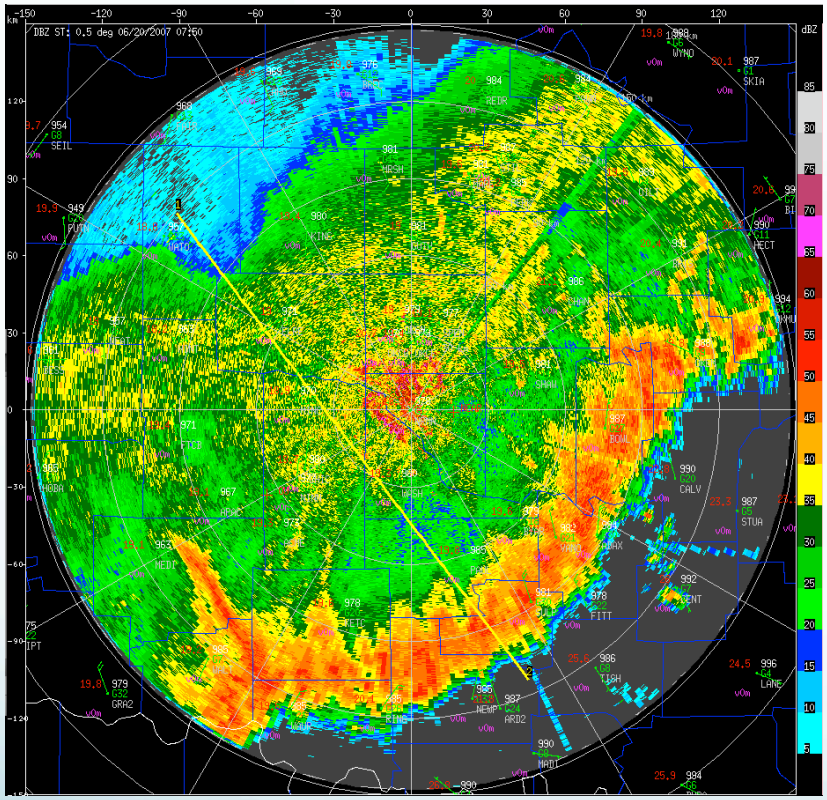


Radar mosaic at 0600 UTC

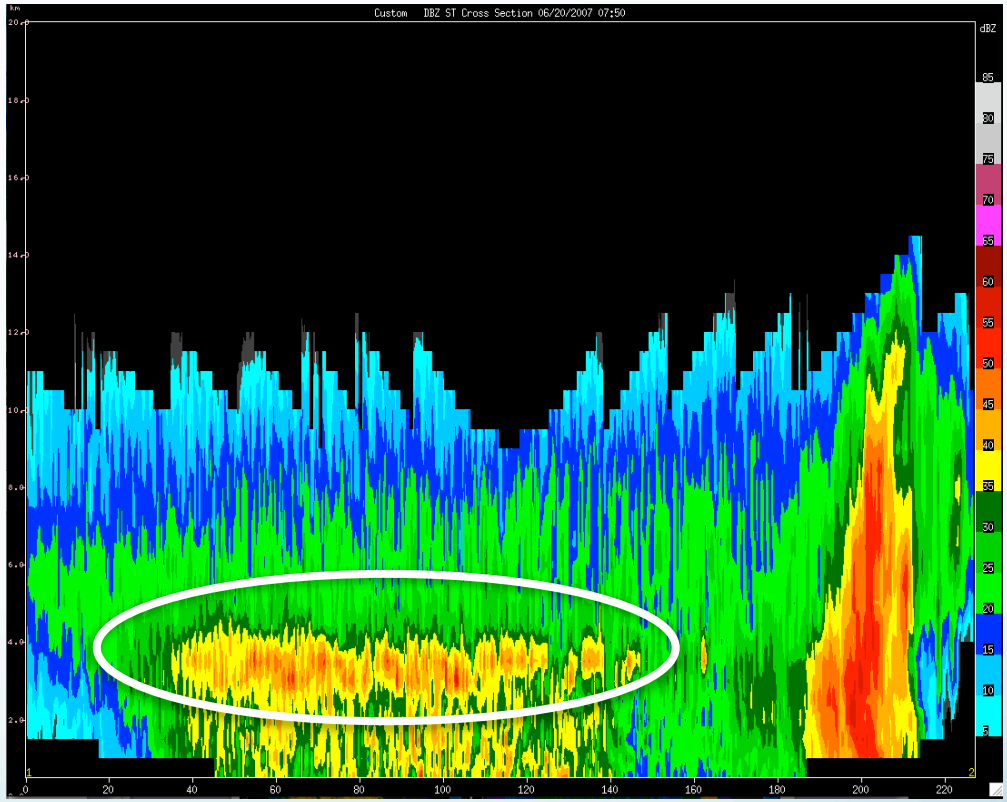
20 June 2007 Squall line over Oklahoma, many squall lines joined together

Bright band in radar data

KOUN Radar reflectivity at 0750 UTC



0.5 deg PPI scan



Interpolated vertical cross section

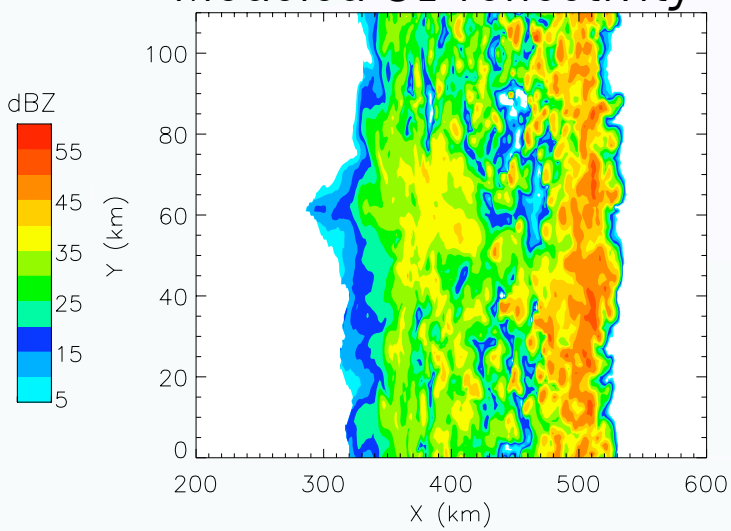
Bright band – A horizontal layer of enhanced radar reflectivity due to the melting of ice/snow. Thus this band is situated near the melting level, and often in stratiform precipitation which is more horizontally stratified.

Why am I studying this squall line?

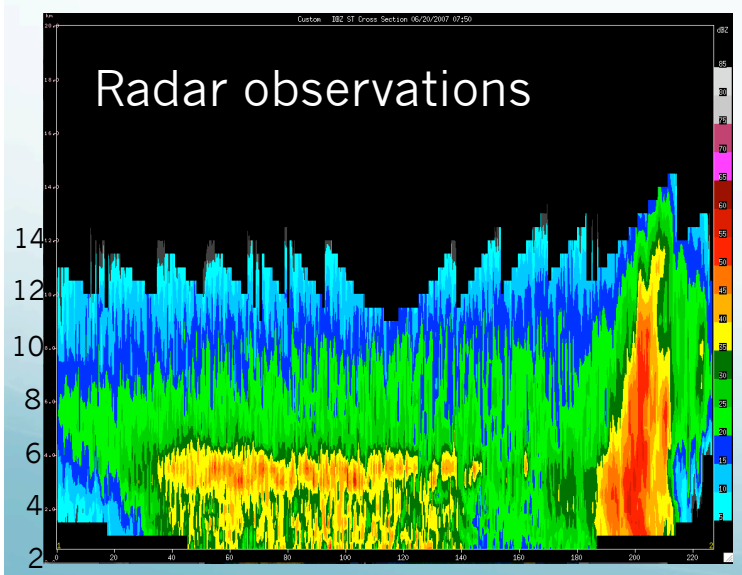
- Recall that MCSs are driven by the cold pool
  - The cold pool creates the gust front and the tilting of the updraft which also then creates the trailing stratiform region.
- What determines the strength of the cold pool?
  - Evaporation of rain!
- What controls evaporation of rain?
  - Dryness of the subcloud layer, as well as the size and concentration of the raindrops
- In cloud models, equations are used to parameterize and solve how much raindrop breakup is occurring.
  - Some breakup schemes create many, small drops
  - Some schemes don't do much breakup at all, leaving some really large raindrops
    - Small raindrops evaporate much more easily than large ones!
- This can effect how the cold pool forms and thus how storms like MCSs evolve in a cloud model, so we compare different drop breakup schemes with the observations to see which is working best and try to fix those that aren't working

Results of different schemes

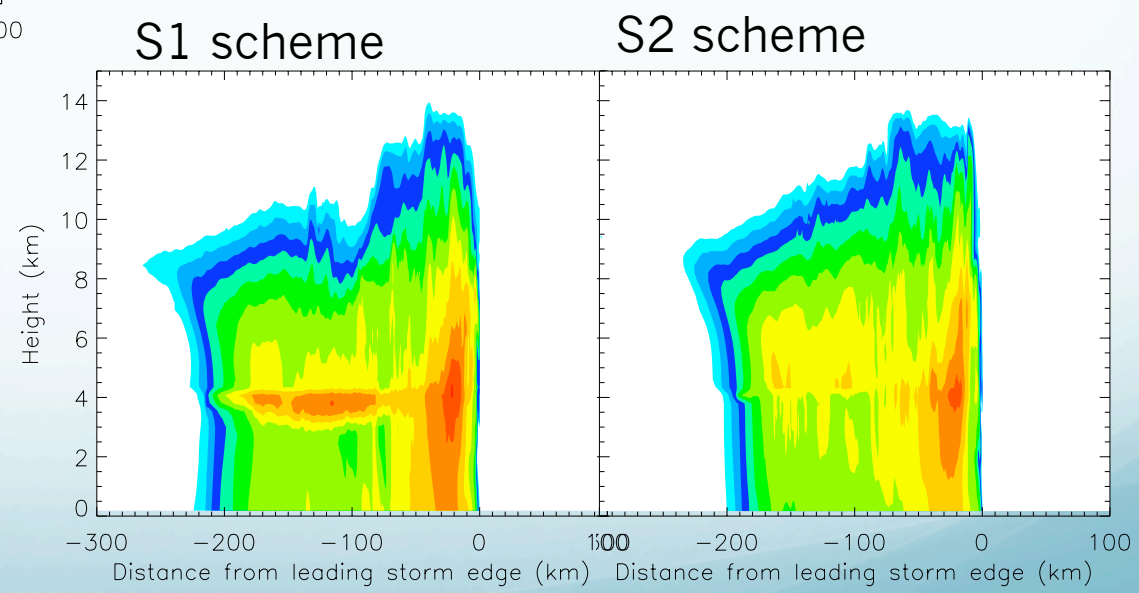
Modeled S1 reflectivity



Comparing 3 raindrop breakup schemes



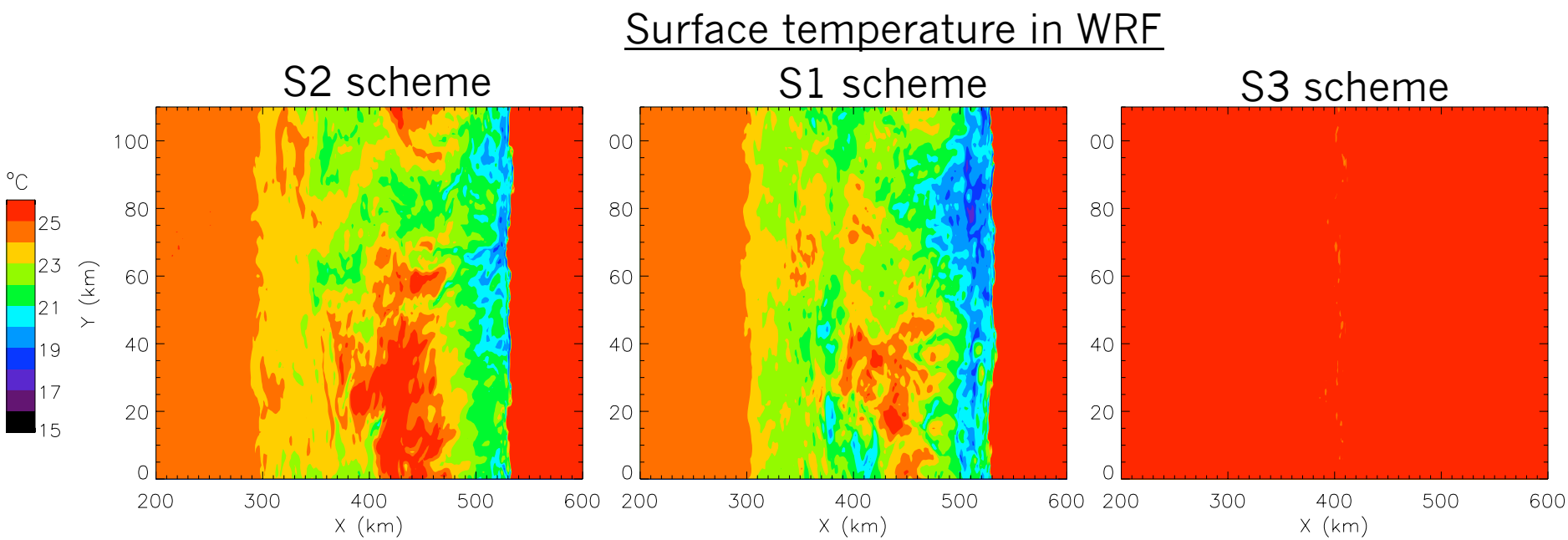
Vertical cross sections of reflectivity



S3 scheme did not even produce a squall line!

Cold pool comparison

- Cold pool formation varies by breakup scheme!
  - No cold pool (or squall line) in S3
  - Realistic spatial distribution of cold pool?
    - We are planning to compare squall line propagation speeds to see which best compares with observations



Clicker Question

- True or false: An MCS can form from an initially disorganized cluster of thunderstorms.
  A. True
  B. False

Clicker Question

- In what order would you expect the following features to develop in a mesoscale convective system?
  A. squall line, disorganized cluster of thunderstorms, trailing stratiform region, bow echo
  B. bow echo, trailing stratiform region, squall line, disorganized cluster of thunderstorms
  C. trailing stratiform region, bow echo, disorganized cluser of thunderstorms, squall line
  D. disorganized cluster of thunderstorms, squall line, bow echo, trailing stratiform region

Clicker Question

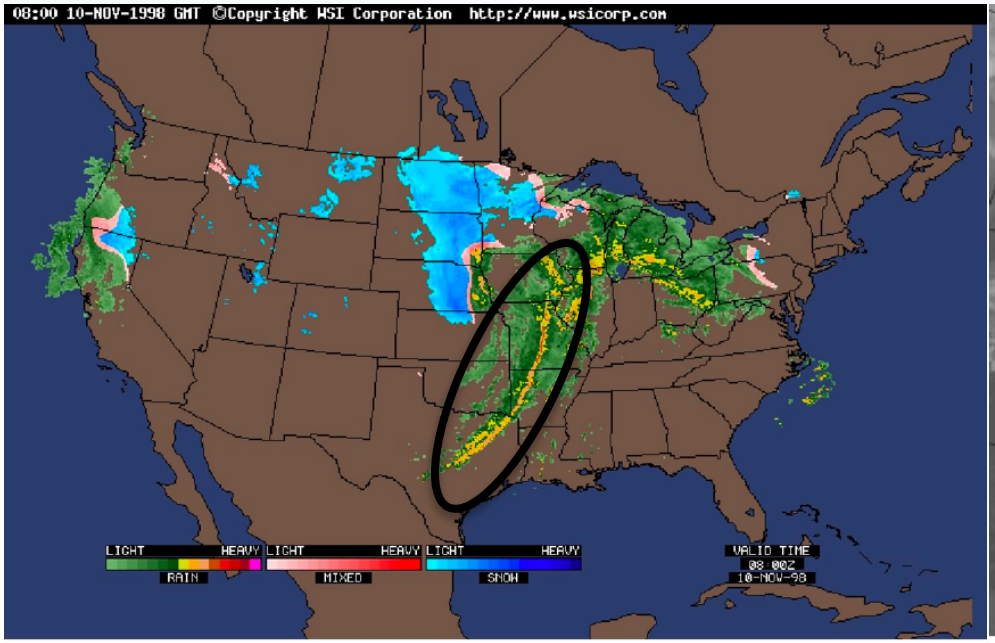
- The leading edge of evaporatively cooled air in a thunderstorm is known as _____.
  A. A derecho
  B. A gust front
  C. A bow echo
  D. A trailing stratiform region

Clicker Question

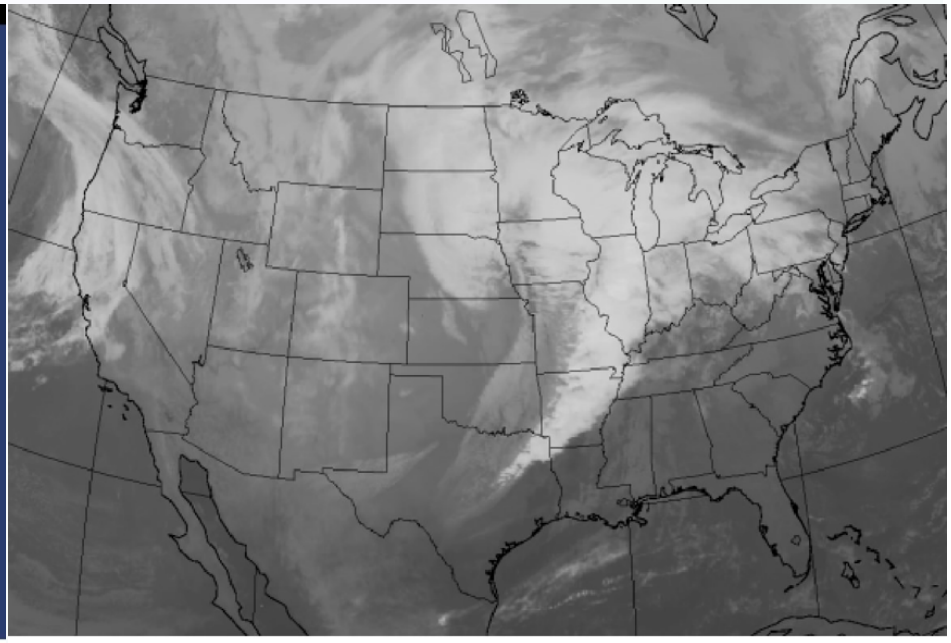
- A radar fine line indicates the position of _____ that forms along a thunderstorm _____.

  A. a shelf cloud, gust front
  B. mammatus clouds, updraft
  C. a shelf cloud, updraft
  D. mammatus clouds, gust front

Frontal squall lines



Courtesy of Weather Services International Corporation



Courtesy of the Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign

- What is the appearance of a frontal squall line on a radar reflectivity image?
- From a satellite perspective, what part of a mid-latitude cyclone comma cloud does a frontal squall line form?

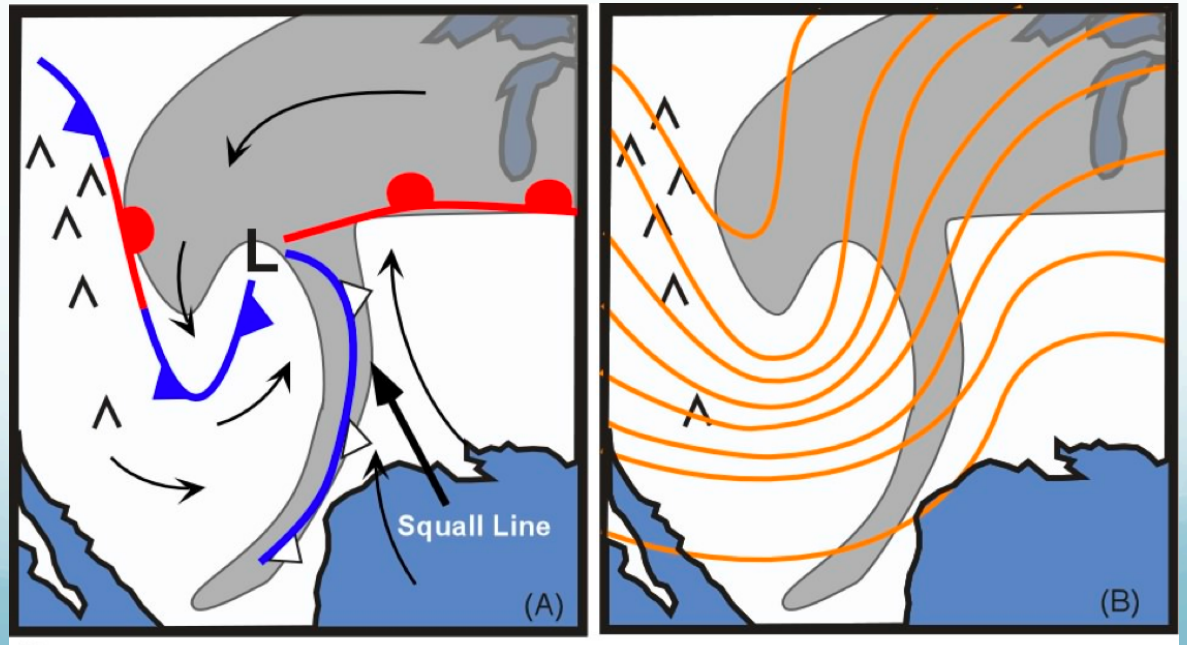
Tail

Characteristics

- What is the lifetime of a frontal squall line?
  - Long: many hours to days
- Where do frontal squall lines typically form?
  - In warm, moist air ahead of cold fronts and dry lines or ahead of upper level fronts
- How do the winds change from the surface to aloft ahead of a frontal squall line?

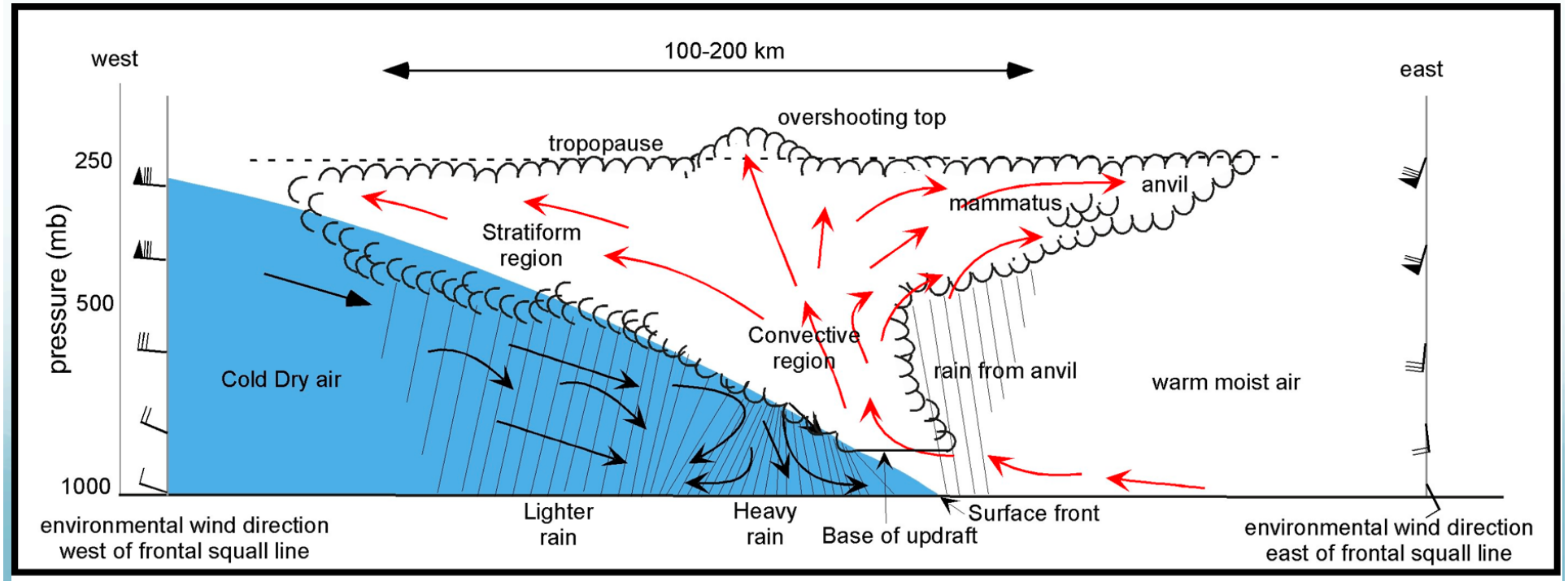
<u>Surface winds:</u>
Southeasterly or southerly

<u>Mid/upper winds:</u>
Southerly to southwesterly, much stronger



Key features of a frontal squall line

- What mechanism is responsible for lifting the conditionally unstable air to its level of free convection (LFC) in a frontal squall line?
- What causes the anvil of a squall line to form?
- Why do mammatus clouds form?



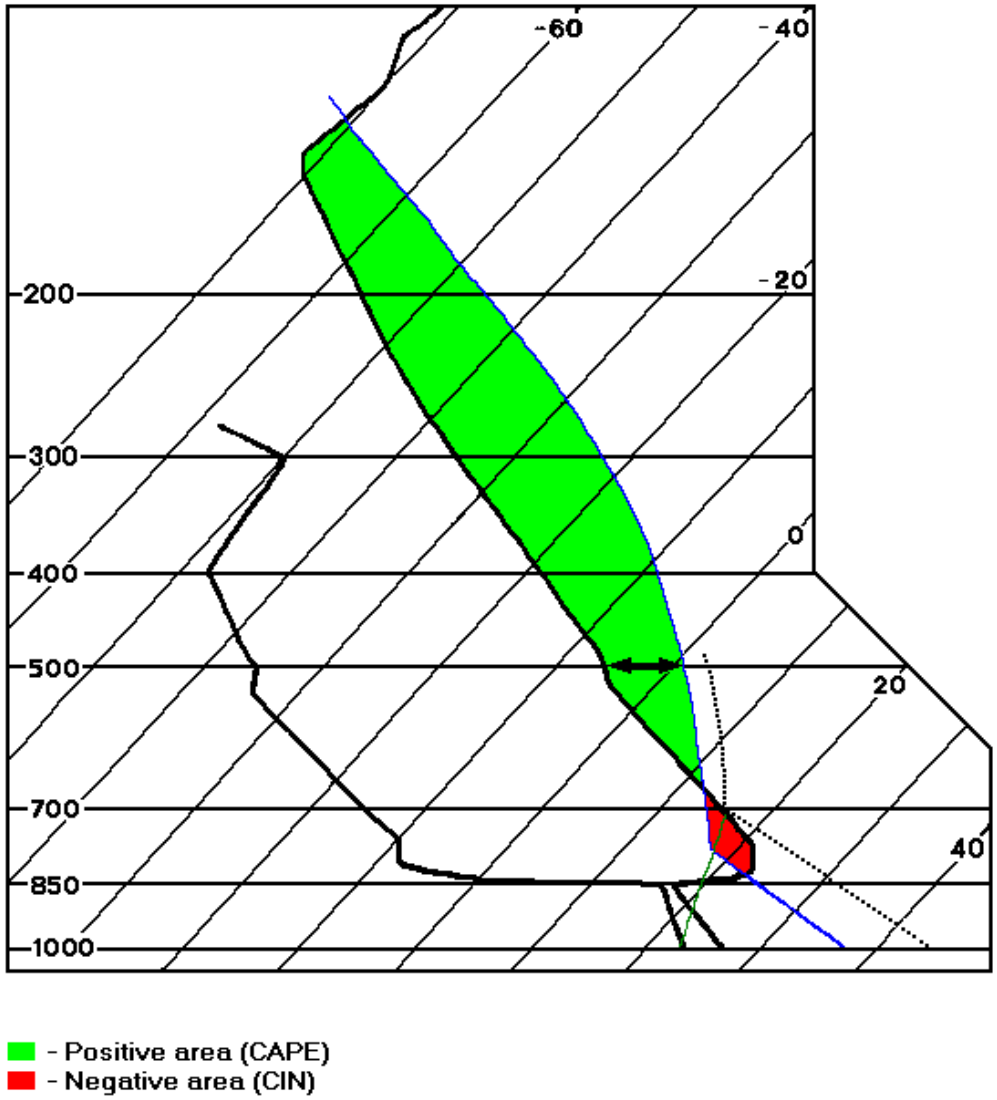
Overshooting top – the portion of the updraft that penetrates the tropopause

Supercell thunderstorms

- **Supercell thunderstorm** – a rotating thunderstorm
- Supercell thunderstorms are responsible for creating the majority of the most dangerous severe thunderstorm weather and strongest tornadoes that form in the United States.
- How strong is the updraft in a supercell thunderstorm?
  - 20-40 m/s (45-90 mph!!!), up to 50 m/s (or 100 mph!)
- What conditions are required for a supercell thunderstorm to form?
  - Moisture source, conditionally unstable environment, and trigger mechanism, along with vertical wind shear
- How can conditional instability develop in the atmosphere?
  - When air is heated near the surface while colder air aloft moves over the heated region

CAPE

- **CAPE** – convective available potential energy
  - A measure of the instability
- What does CAPE tell us about the strength of an updraft in a thunderstorm?
  - It's a measure of the maximum upward speed that a rising parcel will attain
- Higher CAPE = stronger, more severe storm

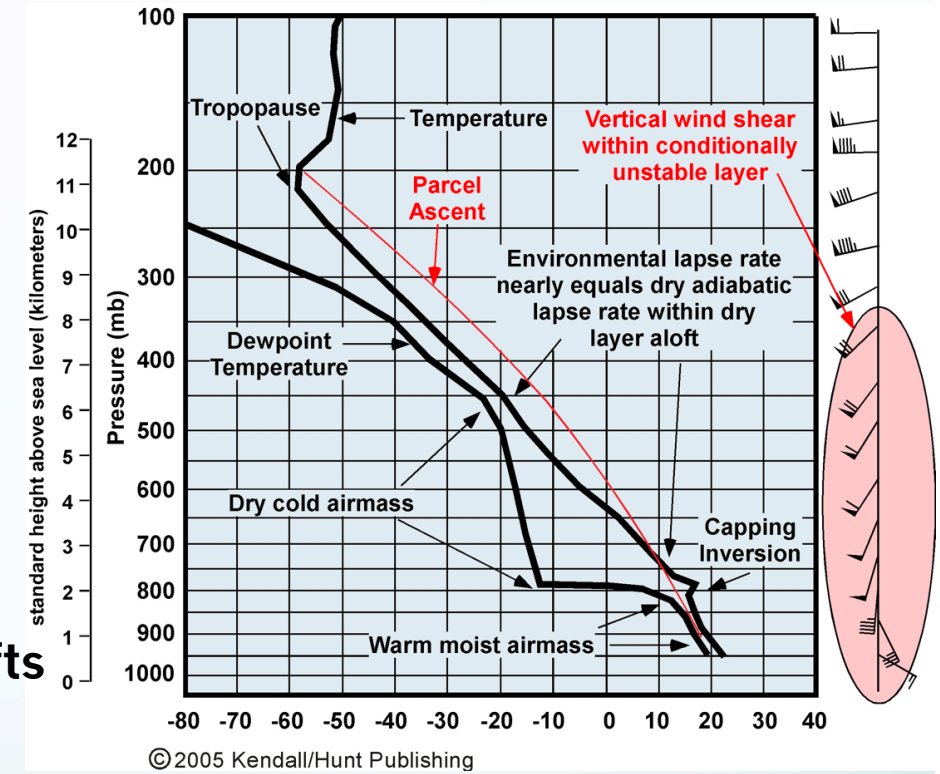


Supercell environment

Moisture, instability, and wind shear

- What is the source of warm, moist air at low levels in this sounding? **Gulf of Mexico**
- What is the source of cold, dry air at upper levels in this sounding? **Mountains in west**
- What is the role of the capping inversion in supercell formation? **Acts as a lid on updrafts**
- How do the winds change with height in an environment that will support supercell development?

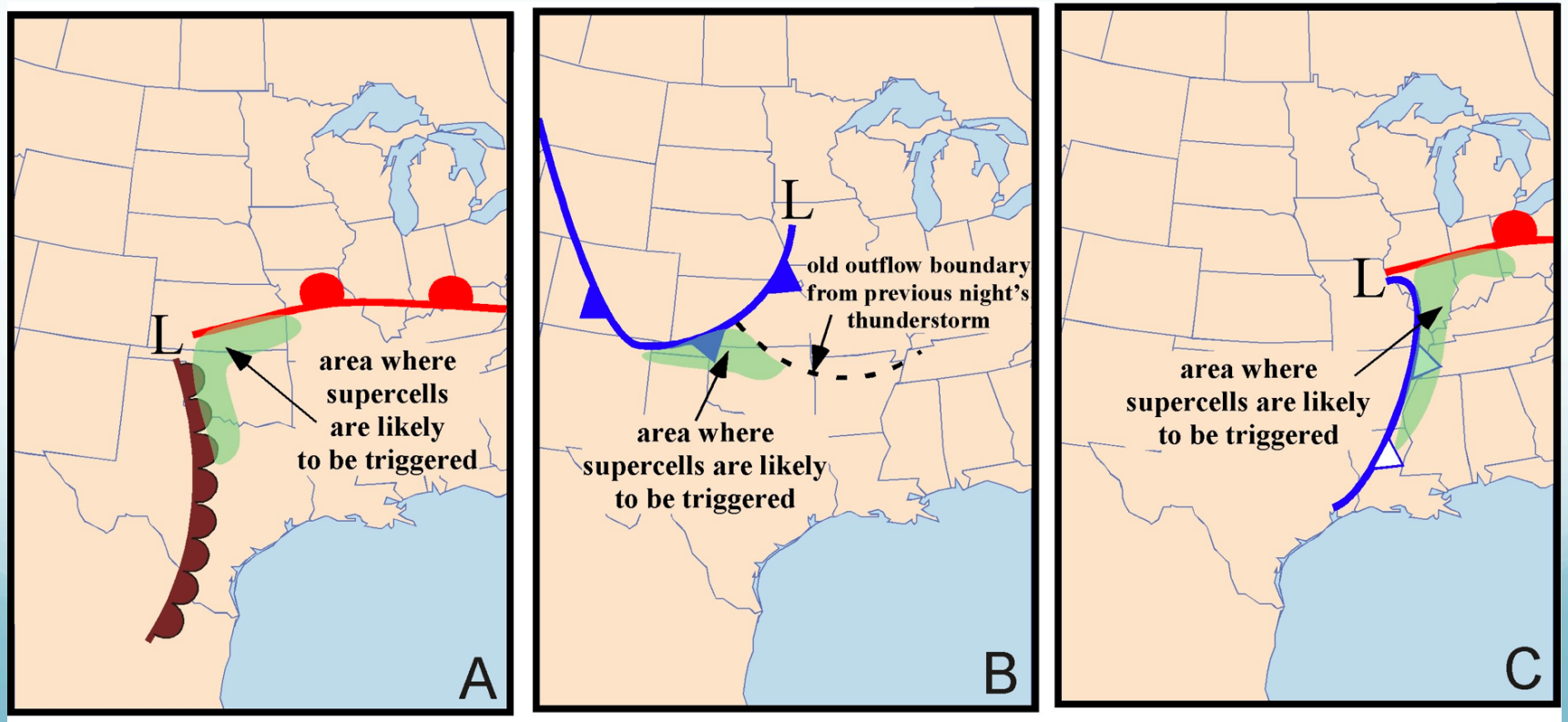
Get stronger with height and turn clockwise!

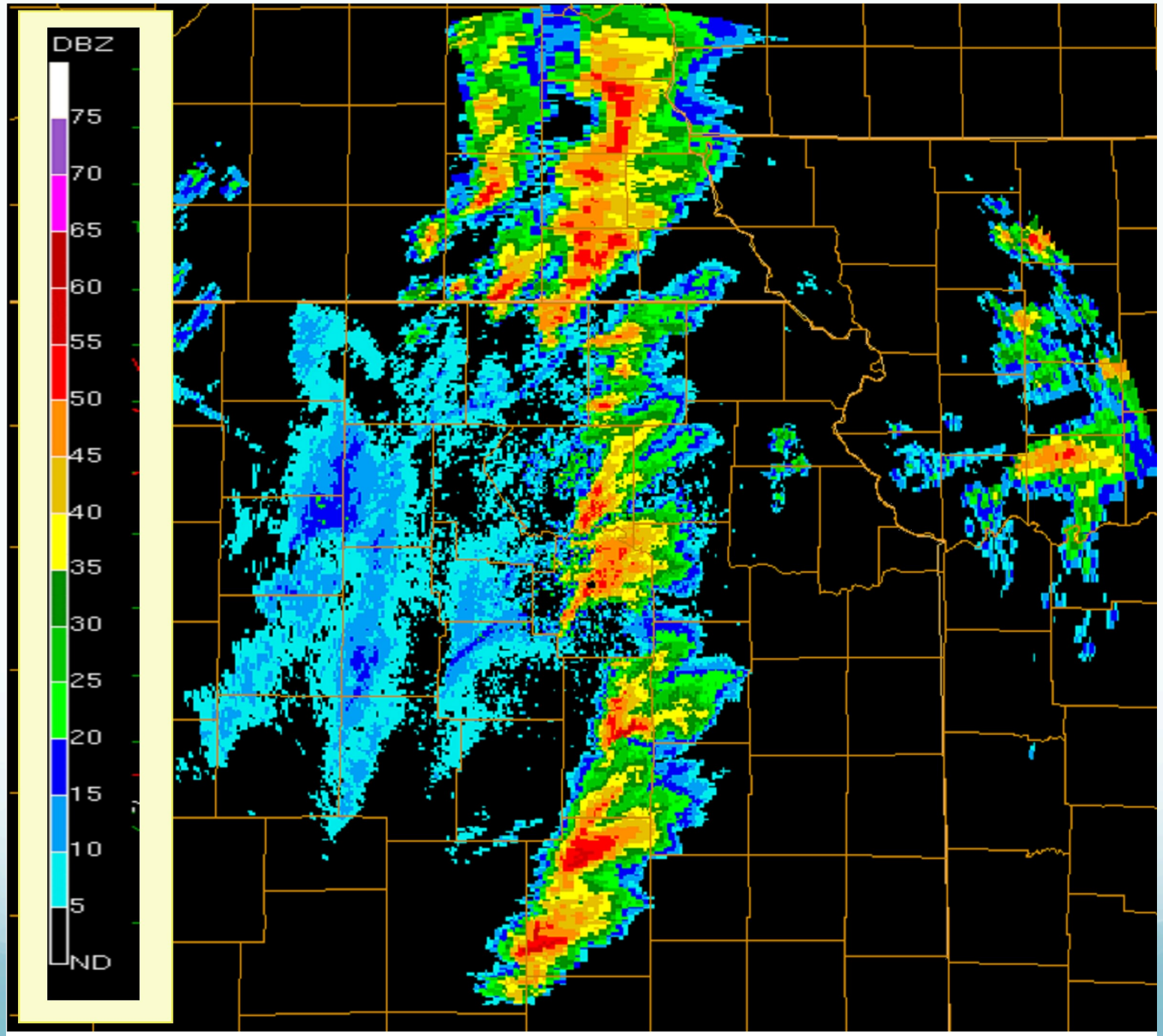


Low level jet – strong southerly low level winds that extend from the surface to a maximum altitude of 3 km

Triggering mechanisms

- How is air near the surface initially lifted to form a supercell thunderstorm?
  - Supercells typically first form where airmass boundaries intersect.





Clicker Question

- A squall line is _____.
  A. an individual thunderstorm cell
  B. a long line of thunderstorms in which heavy precipitation falls in a long continuous line
  C. a rotating thunderstorm
  D. all of the above

Clicker Question

- A frontal squall line is most likely to form _____.
  A. in the interior of an airmass away from fronts
  B. along a cold front
  C. along a dry line
  D. along an upper level front
  E. b), c), and d) are all likely places for a squall line to form

Clicker Question

- What environmental condition does a supercell require that distinguishes it from an air mass thunderstorm?
  A. Moisture source
  B. Conditional instability
  C. Vertical wind shear
  D. Triggering mechanism for the updraft

Clicker Question

- If a sounding in Norman, Oklahoma shows 2500 J/kg of CAPE in the atmosphere, while at Dodge City, Kansas the CAPE is 1000 J/kg. Which location, if any, is likely to get the strongest, most severe thunderstorms?

  A. Norman would have the strongest storms
  B. Dodge City would have the strongest storms
  C. Both would get thunderstorms of equal intensity
  D. Neither would get thunderstorms

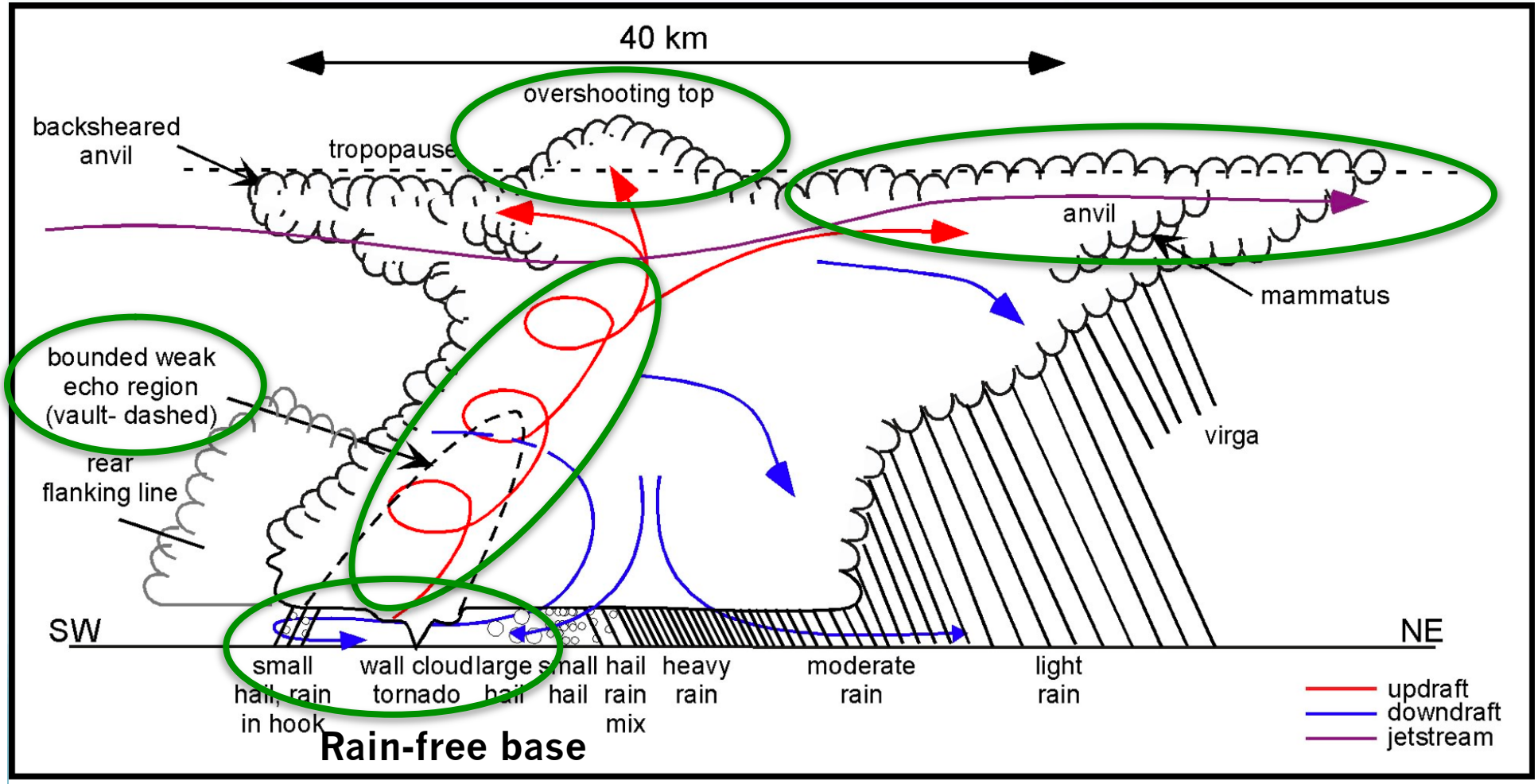
Clicker Question

- A strong updraft in a supercell thunderstorm can be as strong as _____.

  A. 1 mph
  B. 10 mph
  C. 100 mph
  D. 1000 mph

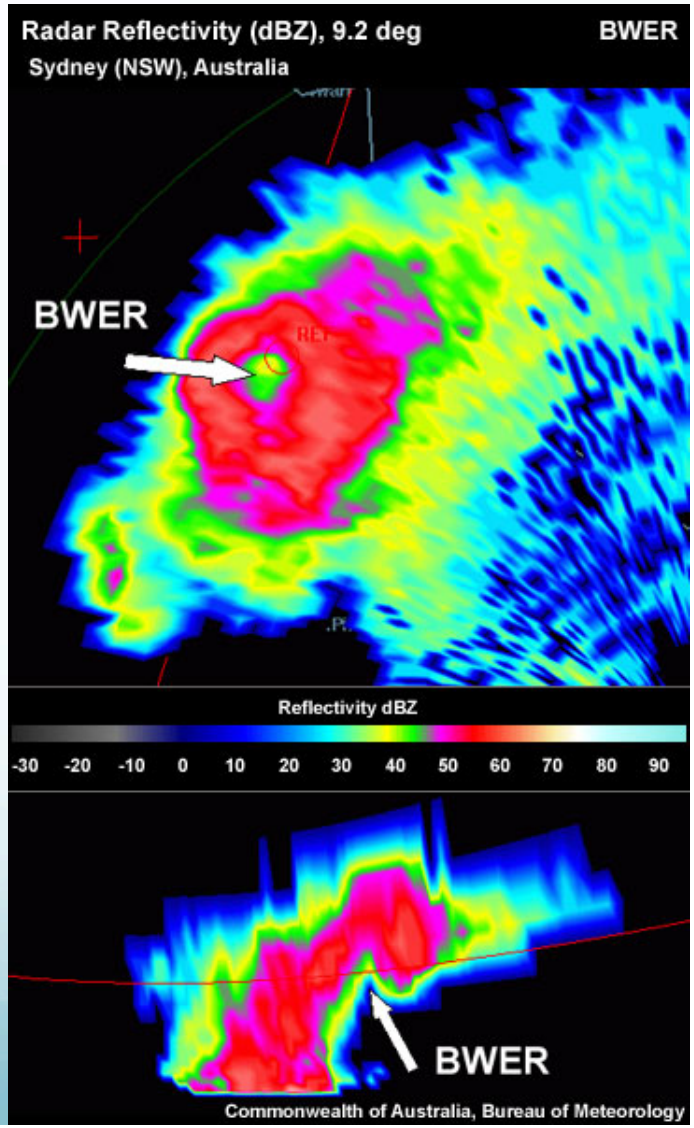
Key features of a supercell

- **Mesocyclone** – rotating updraft



What is a BWER?

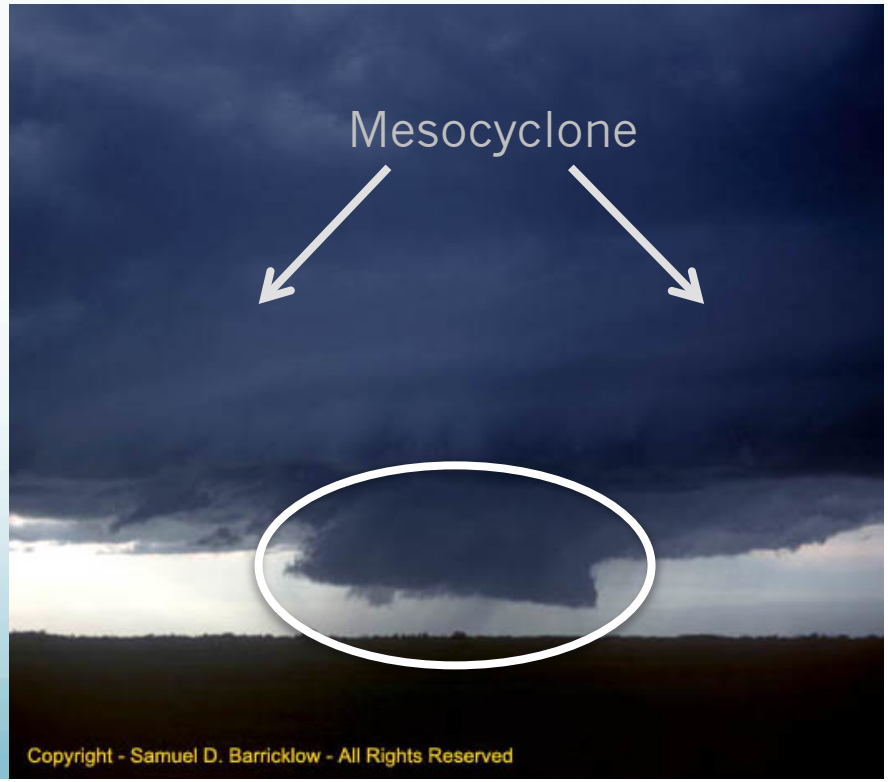
- **Bounded Weak Echo Region (BWER)** – an area of low reflectivity on a radar image of a supercell thunderstorm
  - Also called a echo-free vault
- When there is a strong updraft, the air is carried upward so fast that there isn't time for precipitation-sized drops to form, so the radar doesn't see any precipitation in the updraft core
  - Thus, the BWER is a way to identify where the updraft is



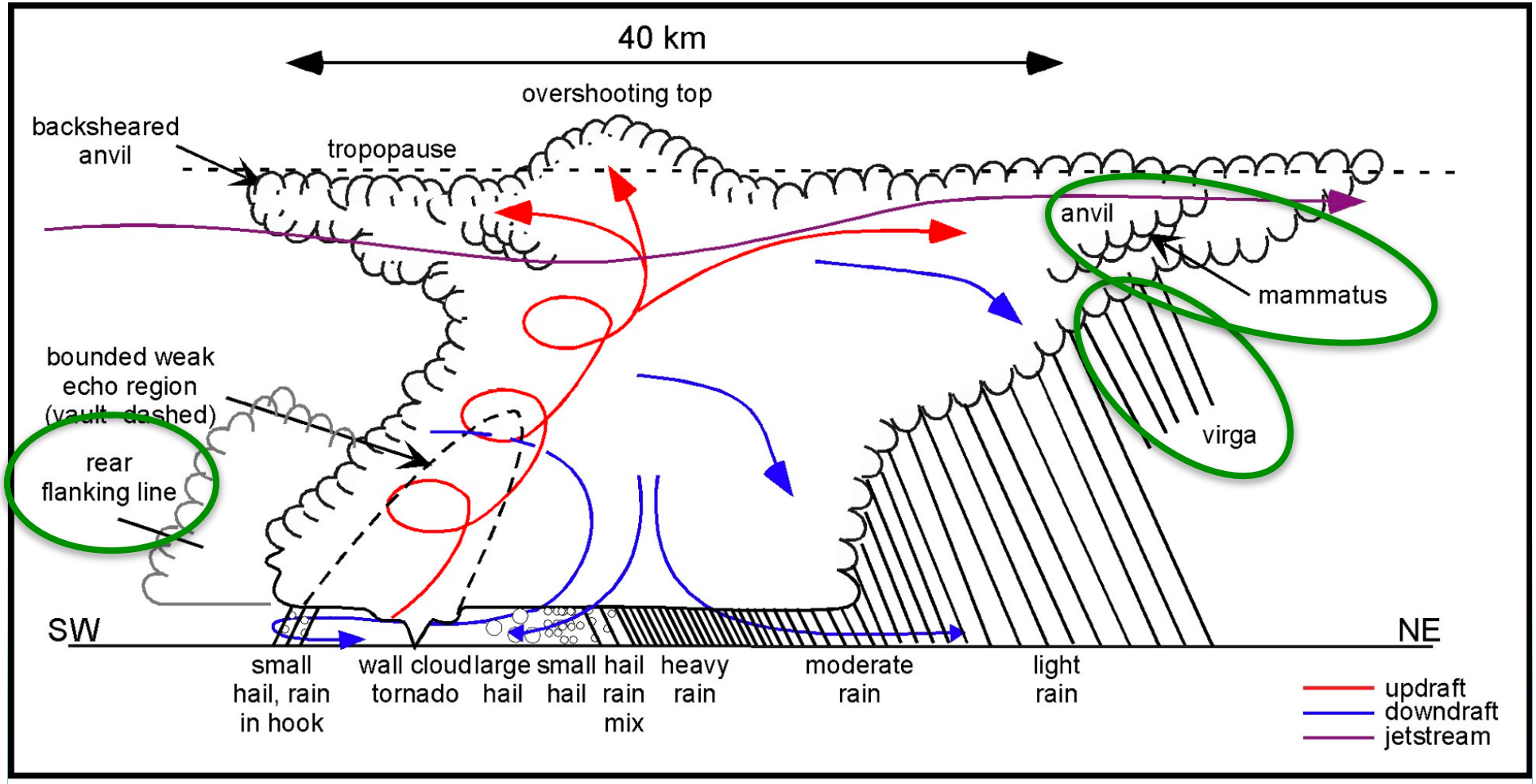
Rain-free base and wall cloud

- **Wall cloud** – a lowered cloud base in the vicinity of the updraft that is often observed to be rotating
- Why is there a rain free base near the updraft?

Because the updraft carries the cloud particles upward and the middle and upper level winds are strong and carry those drops away from the updraft (base) to fall out as precipitation downwind in the supercell

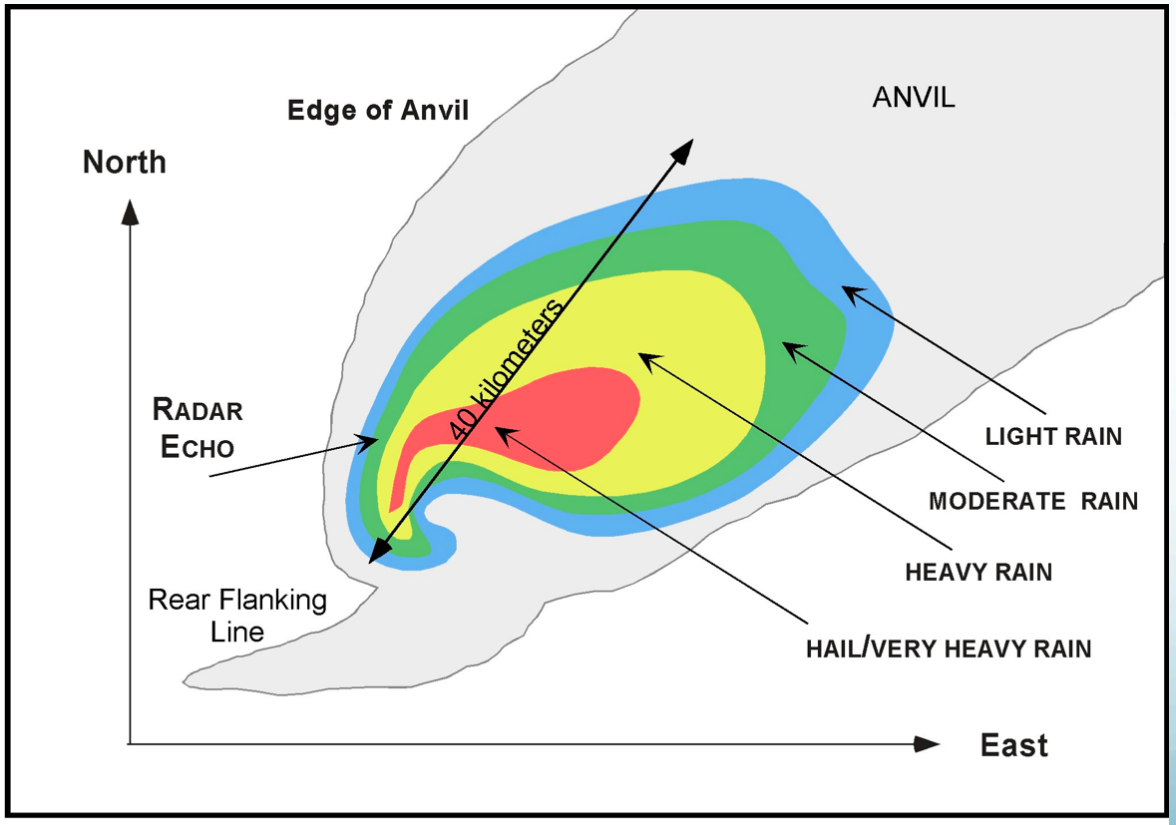


A few more features



Where does precipitation fall?

- NOT below the updraft (in the rain-free base), rather downwind of the updraft, in the **forward flank**
- What types of precipitation fall in the forward flank?



Close to updraft:
Heaviest precipitation, hail

Farther from updraft:
Lighter precipitation

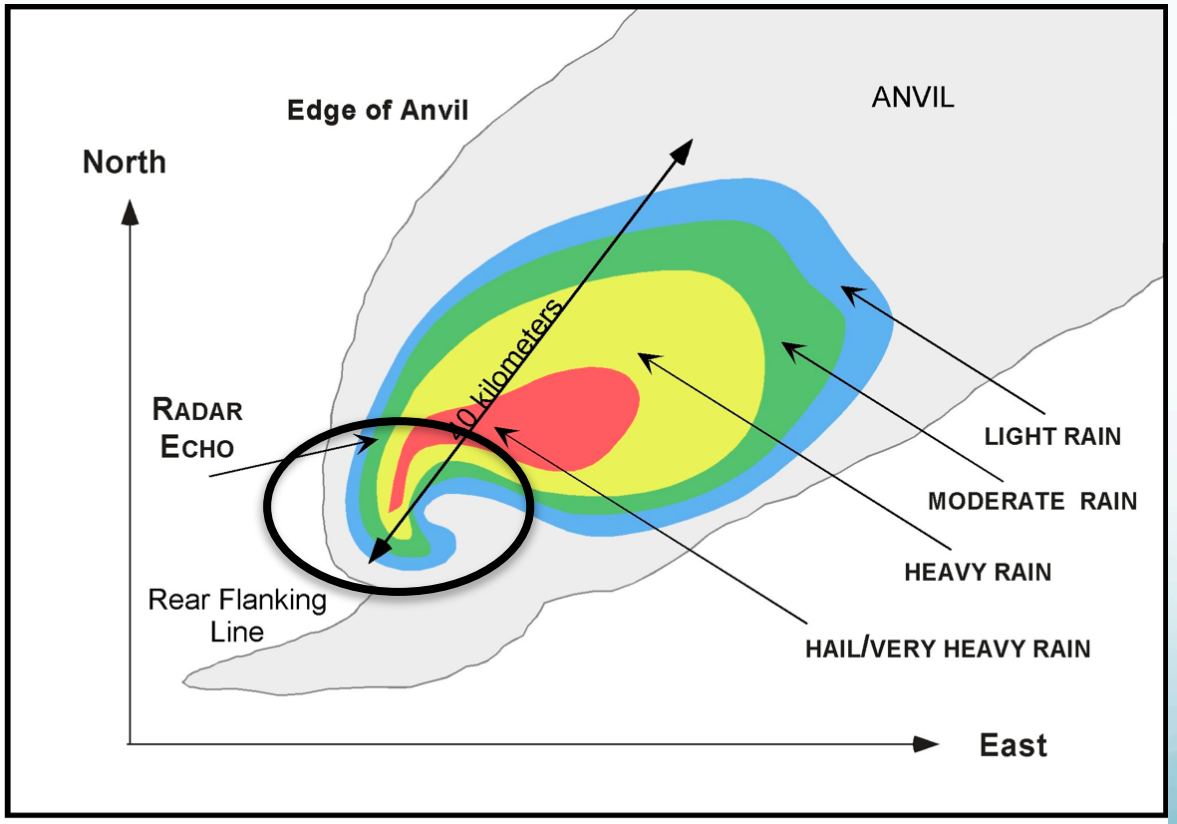
What causes this distribution of precipitation in a supercell?

Distance from the updraft

Stronger updrafts can support larger precipitation particles

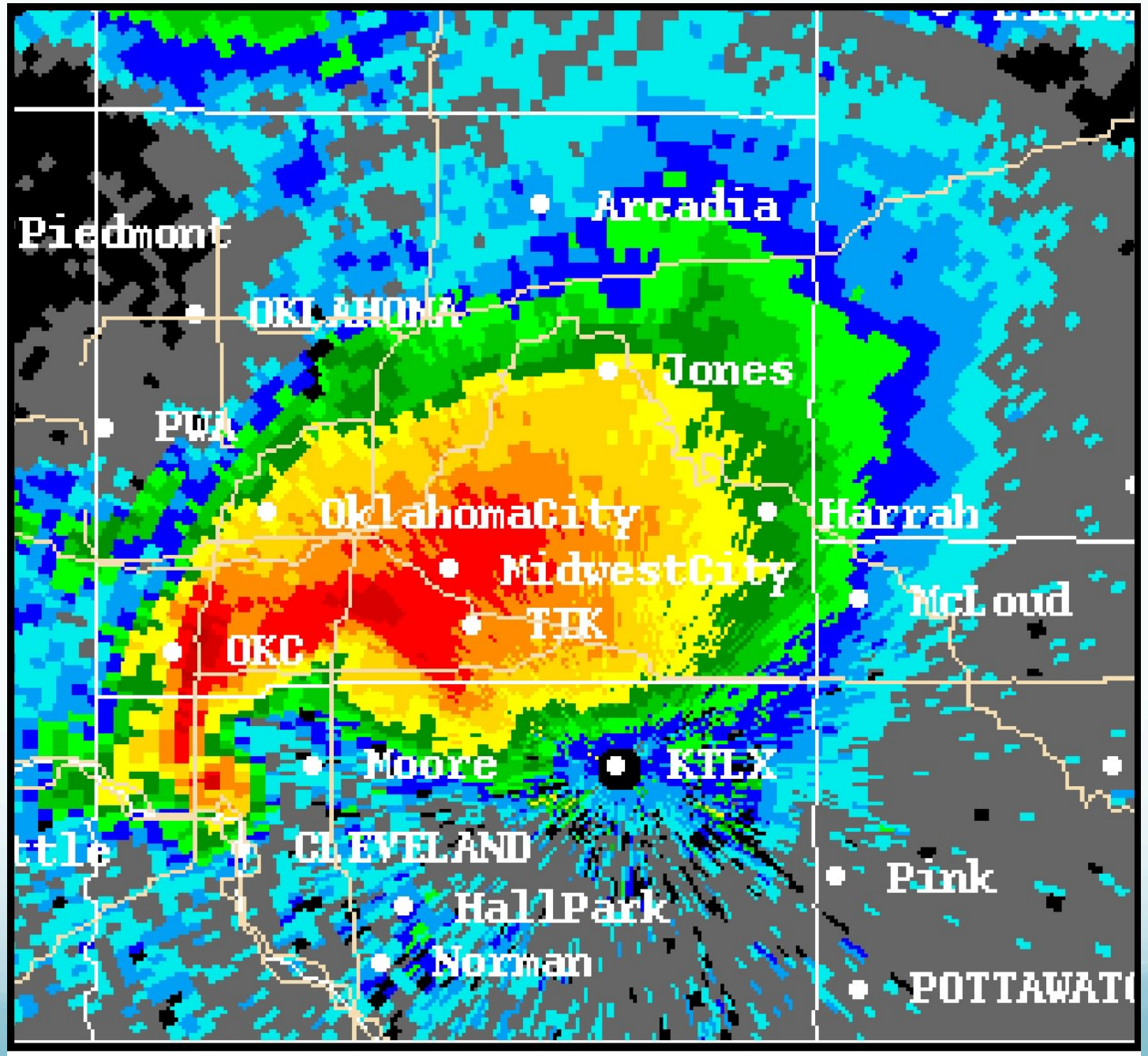
What else is going on?

- Where else is there precipitation falling in a supercell and why would it fall there?



The hook echo – Where the rear flank downdraft wraps around the echo-free base of the rotating updraft

Rear flank downdraft – The downdraft created by precipitation falling along the rear flank of the supercell

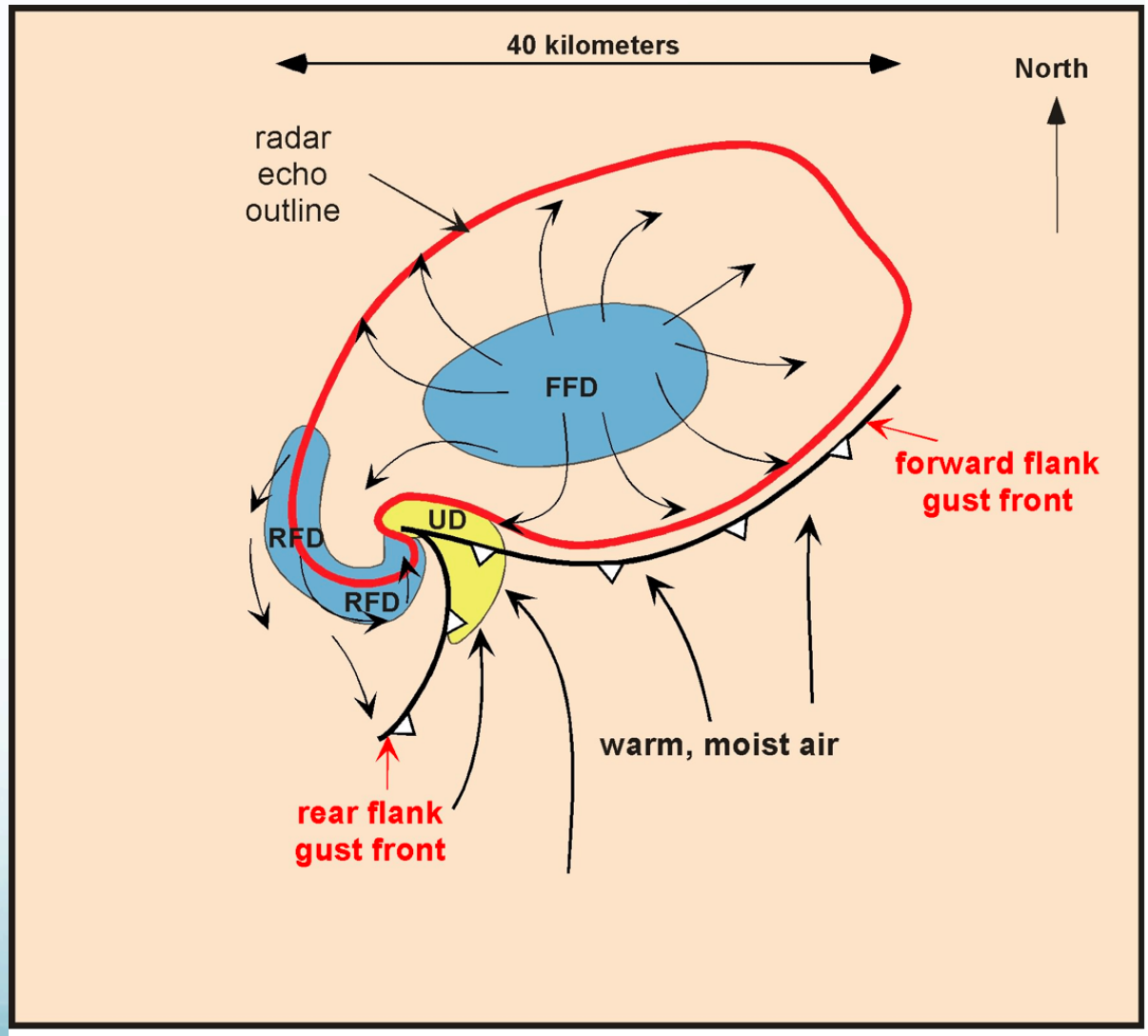


Updrafts and downdrafts

- UD – updraft
- FFD – forward flank downdraft
- RFD – rear flank downdraft
- Gust fronts mark the leading edge of FFD and RFD air at the surface.
- What causes the FFD and RFD to form?

Evaporation/drag of precip

- New thunderstorm cells form along the RFD gust front.



Clicker Question

- The rain free base in a supercell occurs _____.

A. below the forward flank downdraft
B. below the updraft
C. below the rear flank downdraft
D. both a) and c)

Clicker Question

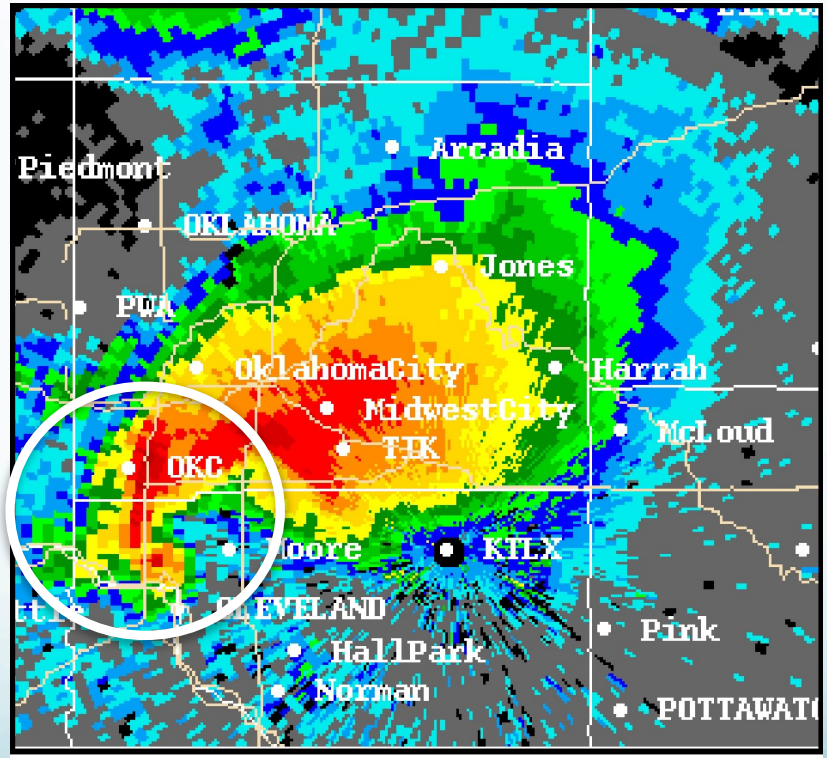
- The bounded weak echo region of a supercell is an area of _____ reflectivity on a radar image.
  A. No
  B. Low
  C. High

Clicker Question

- The most likely place for a supercell to initially form is _____.
  A. along a cold front
  B. along a dryline
  C. along an upper level front
  D. where airmass boundaries intersect

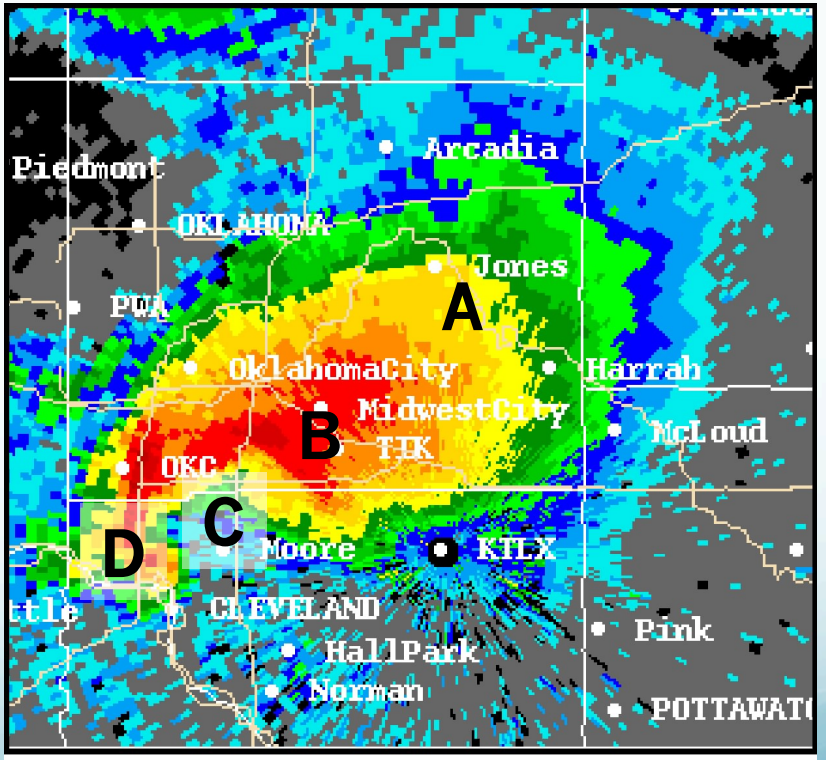
Clicker Question

- What feature of a supercell is contained in the highlighted area?
  A. BWER
  B. Anvil
  C. Forward flank
  D. Hook echo



Clicker Question

- You would infer the updraft is located at which point in this radar image of a supercell?
  A. A
  B. B
  C. C
  D. D



Supercells and tornadoes

- Supercells are the most common storm type that produce tornadoes, especially the strongest tornadoes
- They often form below the mesocyclone, and emerge from the wall cloud
- A key supercell feature that indicates a very well formed mesocyclone is the hook echo
  - This is also often used to identify supercells that may be producing, or have the potential to produce, tornadoes

Supercell tornado outbreak

- http://severewx.atmos.uiuc.edu/18/050399.reflectivity.html
- May 3, 1999 in Oklahoma, passing through Oklahoma City