Chapter 18: Thunderstorm

Courtesy of Bruce Lee

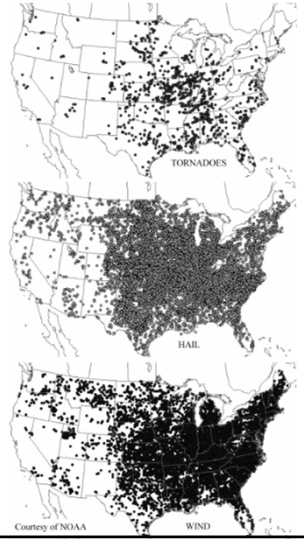
- Airmass Thunderstorm
- Mesoscale Convective Systems
- Frontal Squall Lines
- Supercell Thunderstorm

Thunderstorm

- Thunderstorms, also called cumulonimbus clouds, are tall, vertically developed clouds that produce lightning and thunder.
- The majority of thunderstorms are not severe.
- The National Weather Service reserves the word "severe" for thunderstorms that have potential to threaten live and property from wind or hail.
- A thunderstorm is considered severe if:

(1) Hail with diameter of three-quarter inch or larger, or
(2) Wind damage or gusts of 50 knots (58mph) or greater, or
(3) A tornado.

Locations of Severe Weather Events (in 2006)



Courtesy of NOAA

Four Elements for Severe Thunderstorms

(1) A source of moisture

(2) A conditionally unstable atmosphere

(3) A mechanism to tiger the thunderstorm updraft either through lifting or heating of the surface

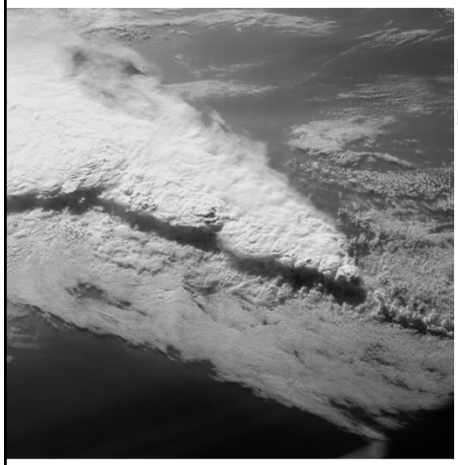
(4) Vertical wind shear: a rapid change in wind speed and/or wind direction with altitude

(2), (3), (4) most important for developing destructive thunderstorms

Lifting

- ***In cool season*** (late fall, winter, and early spring), lifting occurs along boundaries between air masses ➔ fronts
- When fronts are more distinct, very long lines of thunderstorms can develop along frontal boundaries ➔ **frontal squall lines**.
- ***In warm season*** (late spring, summer, early fall), lifting can be provide by less distinct boundaries, such as the leading edge of a cool air outflow coming from a dying thunderstorm.
- Thunderstorms developed along these subtle boundaries in the warm season often undergo a self-organized process and lead to the a kind of severe storm called "**mesoscale convective system**" (MCS).
- "***Meso-scale***" refers to atmospheric processes that occurs on a scale of a few hundreds hundreds kilometers.

Squall Line



(download from Mark R. Petersen of LANL)

- ❑ Squall: "a violent burst of wind"
- ❑Squall Line: a long line of thunderstorms in which adjacent thunderstorm cells are so close together that the heavy precipitation from the cell falls in a continuous line.

Wind Shear

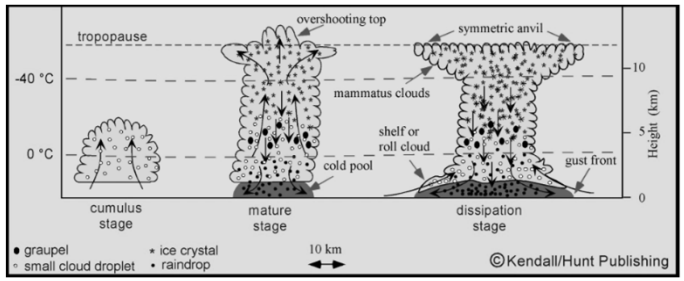
- If winds increase rapidly with height ahead of a strong front or a less distinct boundary, thunderstorms triggered along that boundary may organize into violent storms call "**supercell thunderstorms**".
- Supercells can occur along a line or individually, but always have their own circulations that are related to the storm's rotation and the vertical shear in the atmosphere.
- Supercells develop most often when strong winds are present in the upper troposphere and winds in the lowest kilometers or two of the atmosphere increase rapidly and change direction with altitude.
- Supercells can occur in both cool and warm seasons

Airmass Thunderstorm (non severe)

Courtesy of Alan Moller

- Isolated thunderstorms that form in the absence of vertical wind shear.
- They are called airmass thunderstorms because they often form within an airmass.
- They can be triggered by surface heating, lifting along mountain slope, or cool air outflow from other thunderstorm.
- Typical lifetime of about an hour.

Lifecycle of a Non-Severe Airmass Thunderstorm



- Airmass thunderstorms tend to form far from frontal boundaries.
- They go through three stages: cumulus, mature, and dissipation.
- Cumulus stage: updraft; clouds compose of small liquid cloud droplets.
- Mature stage: reach tropopause; form anvil; produce downdraft and cold pool (due to evaporation of precipitation)
- Dissipation stage: downdraft dominates updraft; produce a cool air outflow.
- The outflow produces a gust front, which lift warm air ahead and form shell or roll clouds.

Mammatus Clouds

- Mammatus clouds are often form at the base of thunderstorm anvils.
- These clouds are composed of pockets of evaporationally-cooled air that descend, transporting cloud particles downward within them.

Shell or Roll Cloud

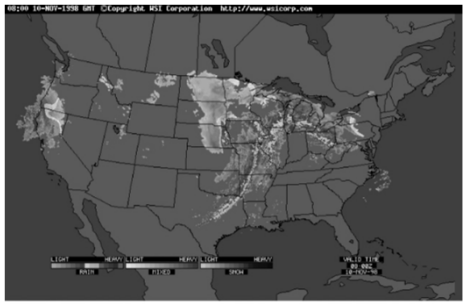
- During the dissipation stage, an airmass thunderstorm will typically produce an outflow of cool air.
- The cool air, generated by evaporation of rain within downdrafts, spreads outward away from the thunderstorm after reaching the surface, producing a gust front.
- Clouds will typically form over the gust front as warm air is lifted over the spreading cool pool.
- These cloud features are called shelf clouds or roll clouds, depending on their shape.

Shell or Roll Cloud

Three Types of Severe Thunderstorms

- Frontal Squall Lines
- Mesoscale Convective Systems
- Supercell Thunderstorm

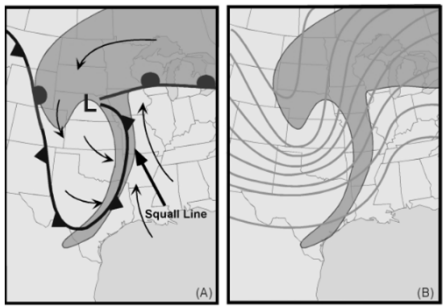
Frontal Squall Lines



Courtesy of Weather Services International Corporation

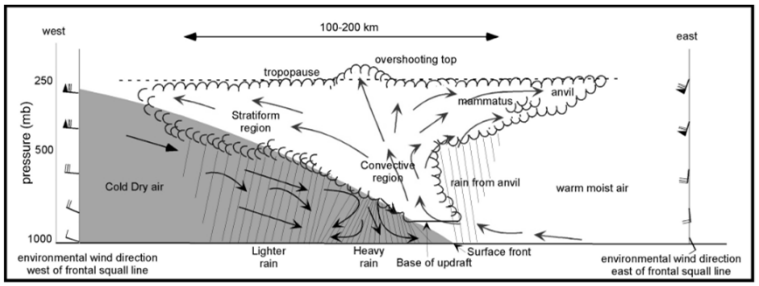
- Frontal squall lines form in the warm, moist air ahead of surface cold fronts, drylines, or upper-level fronts.
- Squall lines are typically hundreds of kilometers long.
- Frontal squall lines commonly form the "tail" of the common cloud pattern in extratropical cyclones.

Typical Environment for Frontal Squall Line



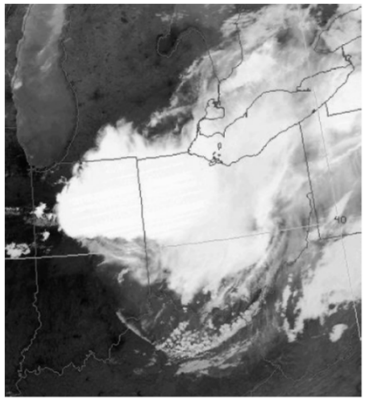
- At the surface, ahead of the front, winds from the south-southeast transport warm, moist air into the line of thunderstorms. The front provides the lift to trigger the squall line.
- In the upper troposphere, a trough is located west of the squall line. Winds east of the squall line aloft are typically southwesterly or southerly. West of the squall line the winds are more westerly.

Key Features of a Frontal Squall Line



- As the cold air mass advances, warm moist air ahead of it is forced to rise.
- Once the moist air is lifted to its level of free convection, the air rises creating deep thunderstorms.
- The stratosphere acts as a lid on the storms.
- Cold, dry air typically approaches the line of thunderstorms from the west behind the front.

Mesoscale Convective Systems

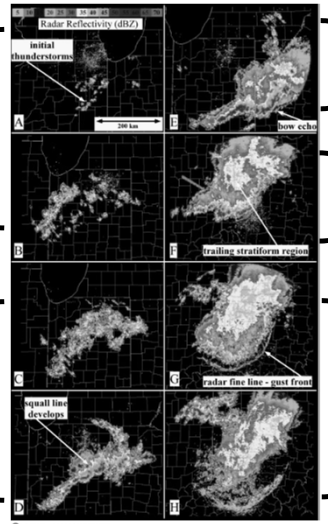


- MCSs produce much of the summer rainfall on the Central Plains of North America.
- They can progress over a large geographic area during their lifetime.
- Their cloud shield can often cover an area larger than a large state.

Development of Mesoscale Convective System

Storms appear as a disorganized cluster

More intense storms organized into an arc-shaped squall line



One or more segments of the squall line bow out producing a bow echo

Trailing stratiform regions is formed, which is a widespread region of less intense precipitation

The stratiform regions become larger and more widespread. Eventually thunderstorms decay, leaving the stratiform regions continue to produce precipitation

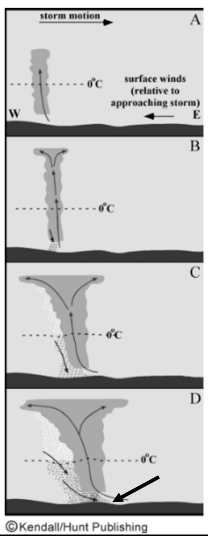
Another View of the Development of MCS

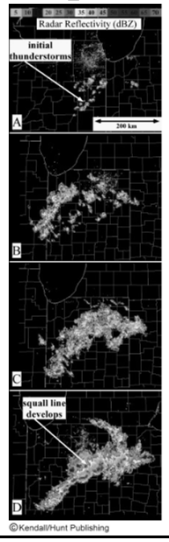
initial thunderstorm with upright updrafts

evaporation of the falling precipitation Produces a cold pool (blue)

Cold pool spreads cool air outward and begins to form a line of thunderstorm

new updrafts develop along the advancing cold pool air and begins to form a line of thunderstorm



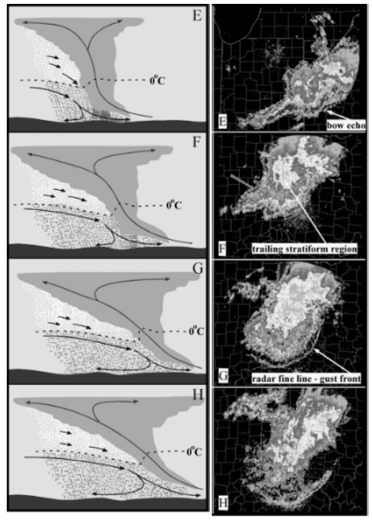


Another View of the Development of MCS

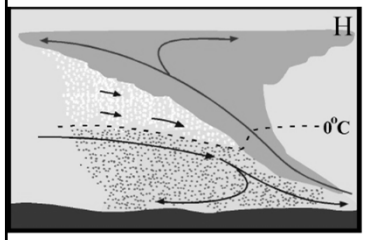
cold pool advances forward into the warmer air; the updrafts forming along and over it and tilt rearward

As the updrafts tilt, rains falling from the storms fall further to the rear of the updrafts

At some point, the cold pool becomes deep and cold enough to rush outward toward the warm air feeding into the thunderstorm; the leading edge of the rushing air is the gust front; a ***rear inflow jet*** (long blue) forms and flows toward the gust front.

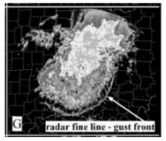


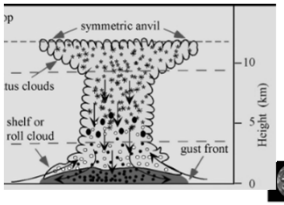
Gust Front



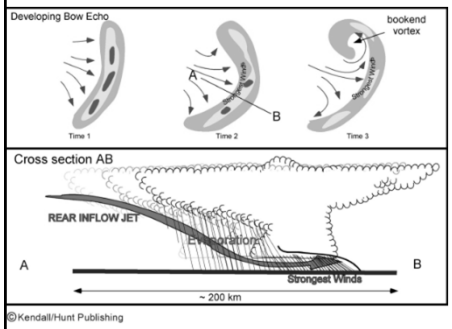

Courtesy of NOAA/NSSL Photo Library

- The surface wind behind the gust front can be severe (80-100 knots; 92-115 mph).
- A shelf/roll (a tube-like) cloud often forms over the gust front.
- On radar, the shelf cloud appears as a fine line.



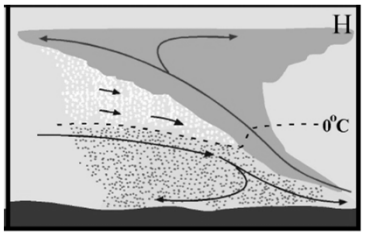


A Bow Echo shown in Radar Reflectivity



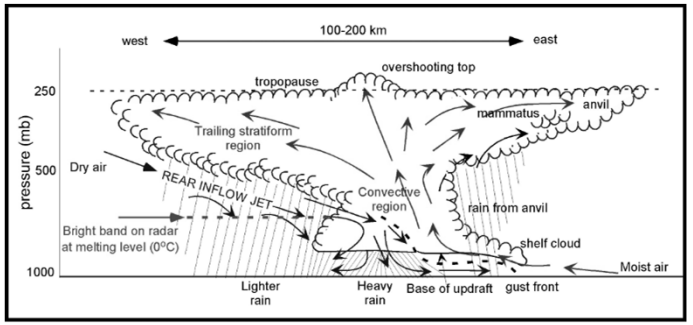
- The character of the outward rush of air depends on the low-level wind shear in the environment ahead of the squall line.
- In some situations, the outrush will occur along a large segment of the line creating a large bow echo 150-200 km long.
- The bow often develops rotating eddies on either end, which is called "bookend vortices".
- Small tornadoes sometime observed within the northern booked vortex.

Front-to-Rear Flow



- Aloft above the rear inflow jet, air flows upward and rearward over the cold pool.
- This flow is called "front-to-rear flow" (the long red arrows).
- As the cold pool deepens and the outrush proceeds, the updrafts within the front-to-rear flow attain a greater tilt.
- The clouds extend further to the rear of the original line of thunderstorms.
- These clouds become the trailing stratiform region and can lead to significant rainfall.

Key Features of a Thunderstorm in a Mature MCS



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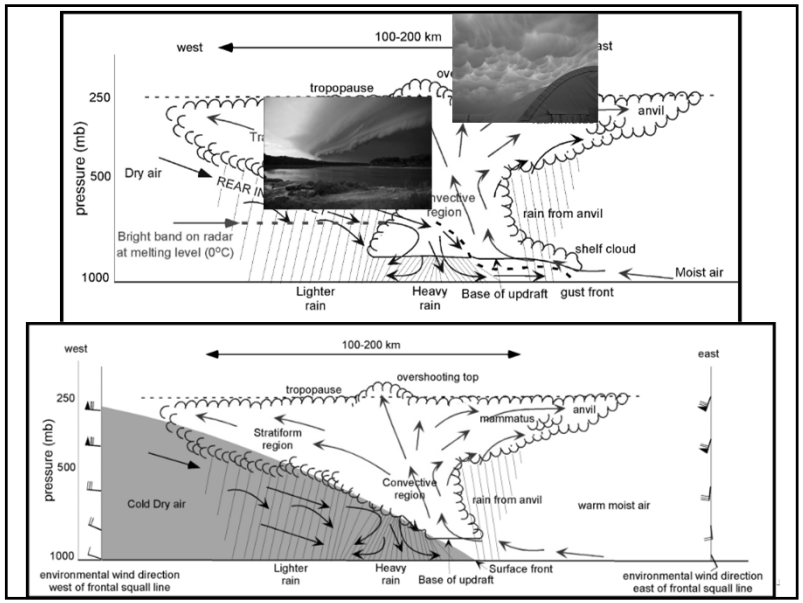
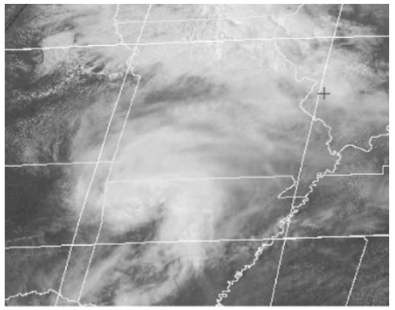
- ***Heavy Rain***: from the convective region; just rear (west) of the updraft region
- ***Lighter Rain***: fall further to the west from the trailing stratiform region (where air rises slowly). Light rains also fall to the east of the convective region from anvil.



Mesoscale Convective Vortex (MCV)



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- Near the end of the MCS lifecycle, the trailing stratiform region decays, leaving a large area of clouds.
- During the formation of the stratiform region, latent heat was released and leads to the formation of a weak low-pressure region at middle levels within the stratiform region, causing the clouds to slowly rotate.
- These rotating clouds are called "mesoscale convective vortex" (M

Supercell Thunderstorms

Courtesy of Bruce Lee

- Supercell thunderstorms are the most intense thunderstorms in Earth's atmosphere.
- Supercell thunderstorms always rotate.
- They account for most severe tornadoes, damaging winds, and most large hails.

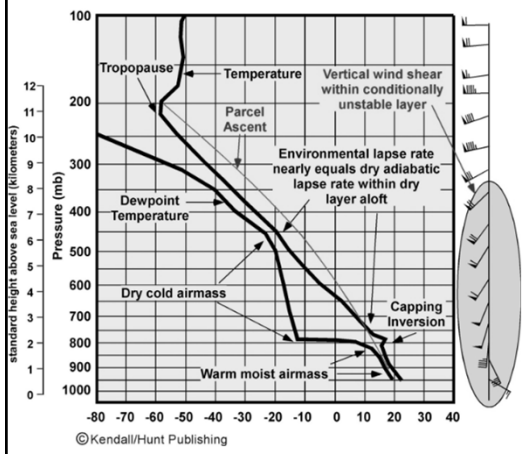
Four Key Ingredients for Supercell

- An environment that is conditionally unstable – humid and warm at the surface and dry and very cold aloft.
- Very moist air in the lower troposphere.
- Moderate to strong vertical wind shear through the depth of the unstable layer.
- A triggering mechanism.

Convective Available Potential Energy (CAPE)

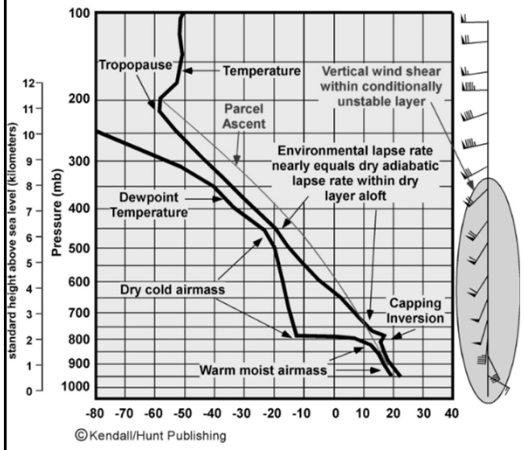
- CAPE is a direct measurement of the instability of the atmsophere.
- CAPE tells us how much positive bounancy is accumulated over an air parcel's trajectory above its level of free convection.
- CAPE is a measure of the maximum upward speed of a rising air parcel will attain along its trajectory.
- CAPE values range from 0 to over 3000 joules/kilogram.
- Supercell thunderstorms form when CAPE>1500 joules/kg.

A Typical Sounding in the Supercell Environment



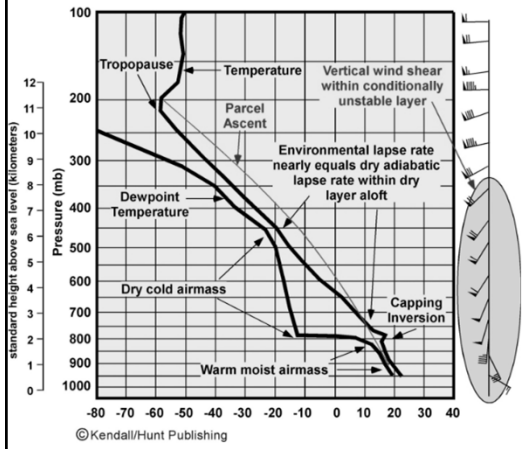
- A conditionally unstable atmosphere (high CAPE).
- Warm moist air in the lower troposphere.
- Dry cold air in the middle troposphere.
- Over the Great Plains, where supercells are most common, the moist airmass typically originates over the Gulf of Mexico, while the dry airmass originated over the mountain to the west.
- These two airmasses are separated by a capping inversion.

Supercell Environment: CAPE and Energy



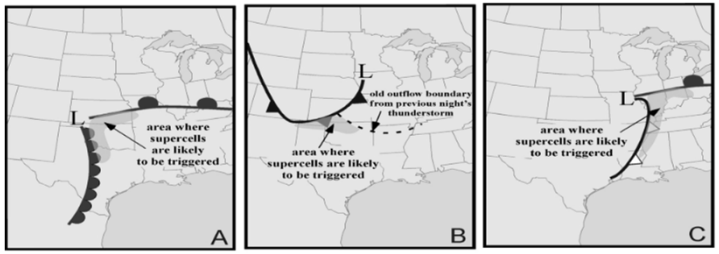
- Once a air parcel breaks through the capping inversion, it will rush upward as a violent updraft toward the tropopause.
- The rising air derives its energy from the release of latent heat from the condensation of water vapor
- The moist air at the surface feeds this updraft, providing the fuel necessary to drive the rapidly growing supercell.

Supercell Environment: Wind Shear



- For supercells, it is critical that the environmental winds increase rapidly with height within the layer of maximum instability.
- A narrow band of very strong winds often develops just above the surface in the warm moist air on the Great Plains, which is called the ***low-level jet***.
- The jet extends from just above the ground to just above the capping inversion with a core speed of 50 knots.
- The low-level jet transports warm, moist air northward in the lower atmosphere and provides low-level wind shear that supports storm rotation

Triggering Mechanisms for Supercell Thunderstorm



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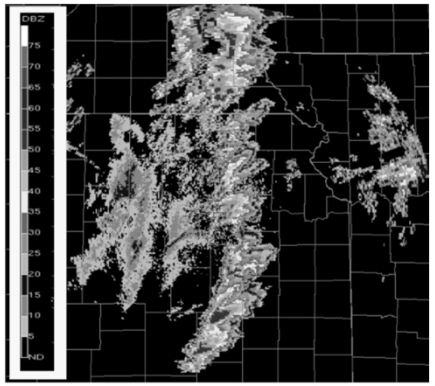
- Provided the instability, moisture, and shear are in place, supercells can form in a number of weather patterns where a triggering mechanism exists to list the warm moist air to the level of free convection.

(A) Warm moist airs located ahead of a dry line and south of a warm front. Lifting can occur on either or both boundaries.

(B) A cold front advances toward an old outflow boundary from thunderstorm that occurred the previous day. Cold front produces lifting along the front and the boundary.

(C) Lifting can also be produced along the intersection between an upper-level front and a warm front.

A Line of Supercell in eastern Kansas and Nebraska



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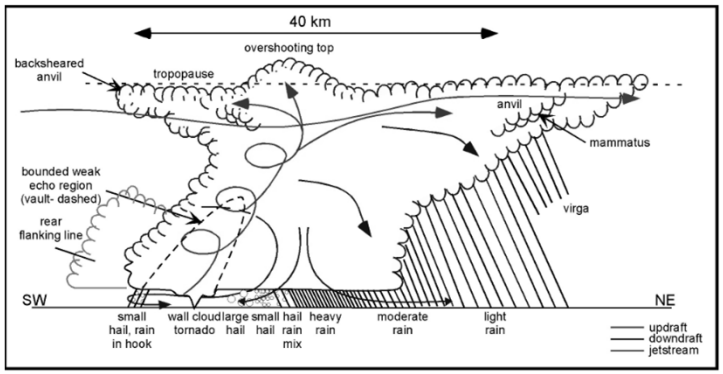
- Once a single supercell develops, gust front outflows from the first storm will often trigger new supercells.
- The new cells often triger in rapid succession along the boundaries, creating a line of supercells.

Cross Section of a Classic Supercell Thunderstorm



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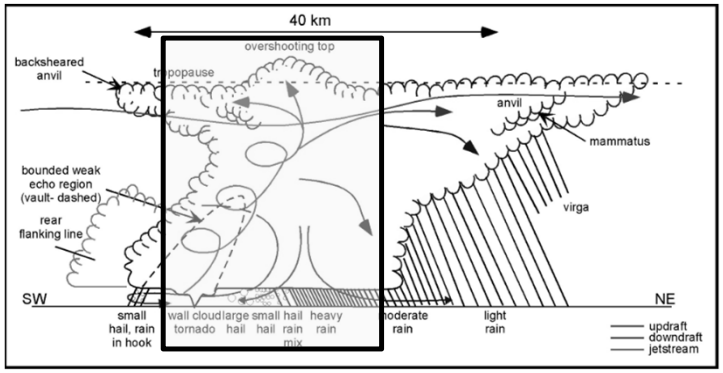
- A typical Supercell that occurs on the Central Plains of the United States.

Virga

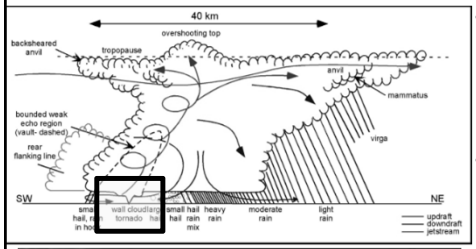
(from https://pilotworkshop.com/tips/clouds_to_avoid/)

Mesocyclone



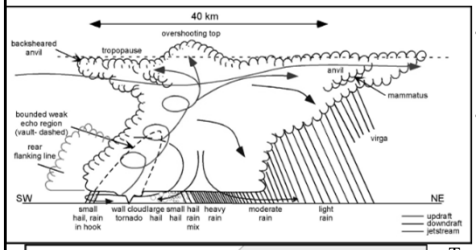
- The rotating updraft, also called the mesocyclone, is located on the southwest side of the storm and typically ranges from about 5 to 10 km in diameter, and tilts northeastward with altitude.
- The top of the mesocyclone is called the overshooting top.
- The base of the mesocyclone is rain free, because precipitation is carried away by the strong updraft.

Wall Cloud and Tornado

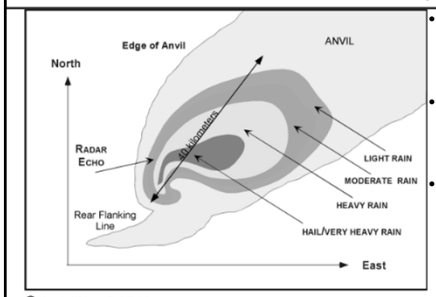


- A region of lower cloud, called the wall cloud, will often appear hanging from the rain-free cloud base, and often will be visibly rotating.
- If a tornado develops, it will most ofetn emerge from the wall cloud.

Precipitation



- Strong upper-level winds blow the ice particles downstream (northeastward) into the storm's anvil.
- Often precipitation falling out of the leading edge of the anvil evaporates into drier air aloft, creating visible streaks called ***virga.***



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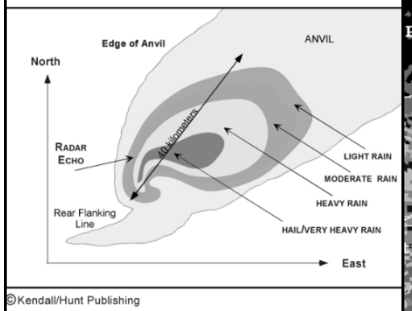
- To the southwest of the supercell, a line of convection cells, called the rear flanking line, will often form.
- Heavy precipitation, including large hail, will fall on the perimeter of the updraft, right next to the rain free base.
- Moving northeast through the thunderstorm, away from the rain free base one would encounter smaller hail, heavy rain, moderate rain, and then light rain.

Precipitation in radar Image



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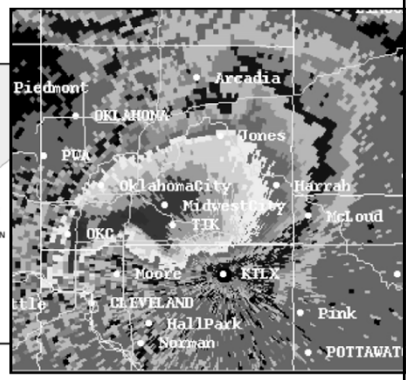

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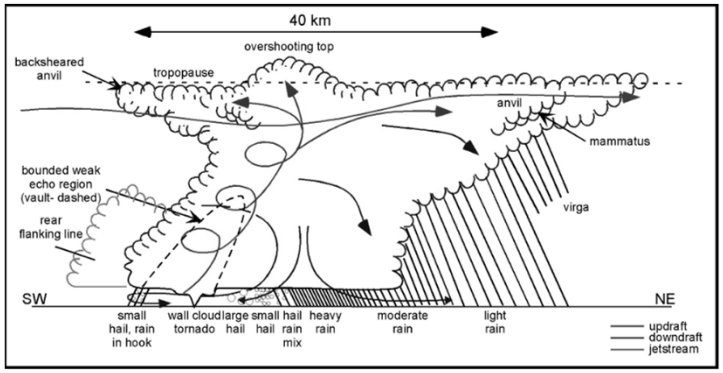
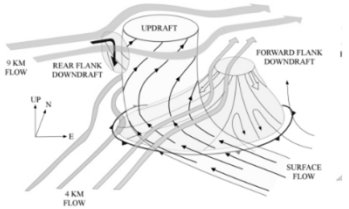
Movement of Supercell



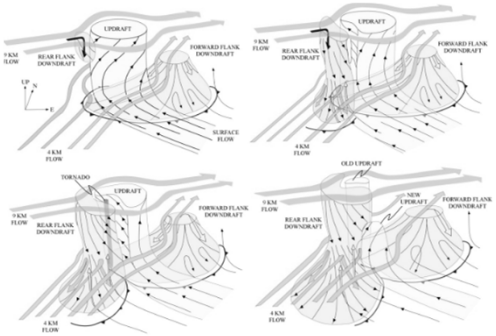
- Supercells move in the direction of the mid-tropospheric winds, which are generally southwesterly.
- Meteorologists call the northeast side of the supercell the forward flank of the storm and the southwest side the rear flank because of the movement of the supercell.

3D View of Supercell – Initial Development



- The inflow to the updraft initially approaches the core of the updraft from all direction.
- Precipitation quickly begins to fall to the north, northeast, and east, as precipitation particles within the storm are carried downwind of the updraft core by the middle- and upper-level winds.
- When precipitation falls, evaporation cooling and drag lead to the formation of downdrafts.
- The first downdraft to form is the ***forward flank downdraft (FFD).***
- The downdraft air reaches the surface and spreads rapidly outward in all directions, creating at its leading edge the forward flank gust front (the cold front symbols).
- As the mid-level air approaching the storm from the southwest encounters the updraft, cloud and precipitation particles on the rear flank of the storm mix with dry air and evaporate.
- This air cools and descends to the surface and forms the ***rear flank downdraft (RFD)***
- New cells often triggered along the rear flank gust front.

3D View of Supercell

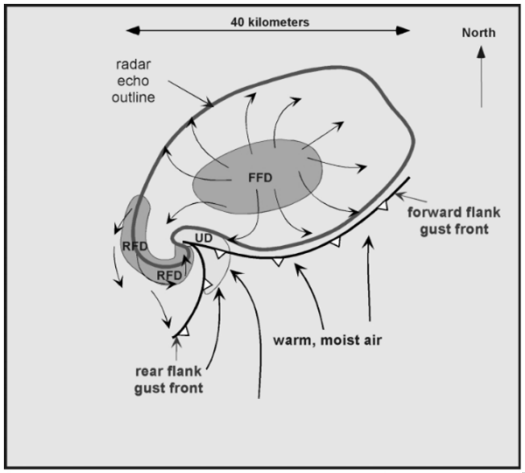


(B) Full formation of both forward and rear downdrafts.

(C) The mature supercll with a strong rotating updraft and tornado (red) located at the coupling of the updraft and rear flank downdraft.

(D) The decaying supercell storm – the rear flank downdraft wrapping around the updraft and cutting off the supply of warm, moist air. A new updraft is forming to the **southeast** of the previous updraft.

Horizontal View of the Supercell



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