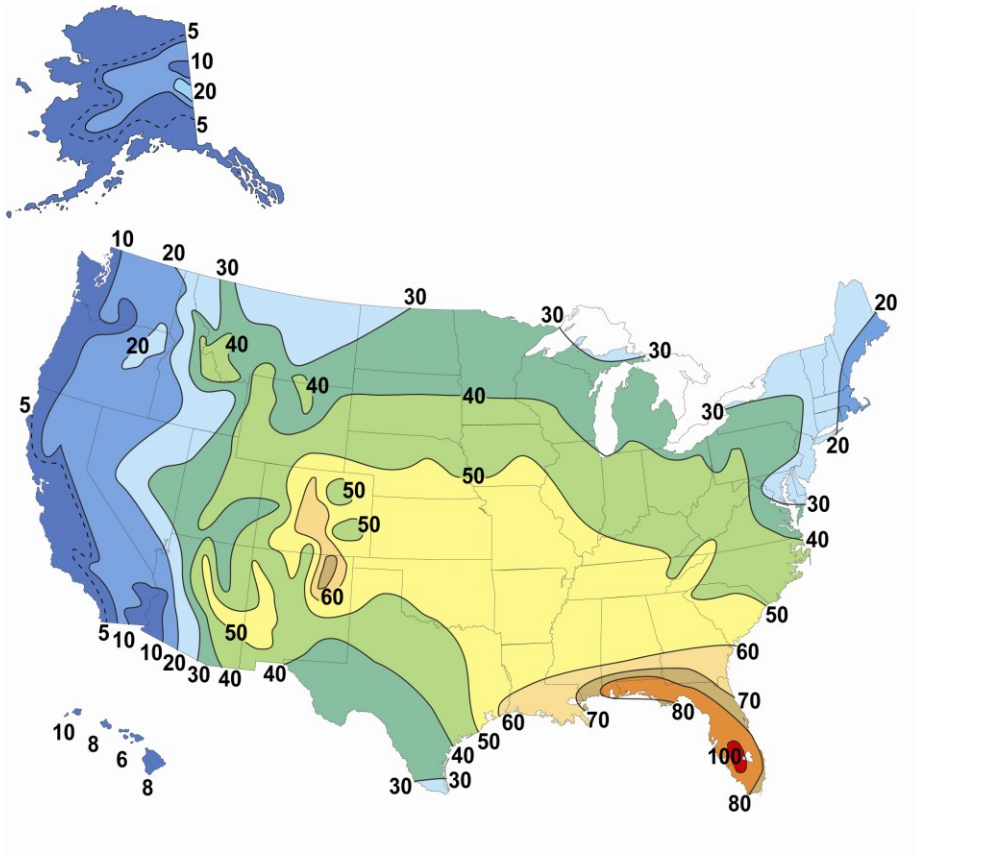
Thunderstorm Basics

Part of the fascination many people have with thunderstorms is the mystery that surrounds them. Leading researchers are still learning about many of the phenomena associated with thunderstorms. But, in order to understand thunderstorm related spectacles like tornadoes, lightning, and hail you must have a basic knowledge of fundamental thunderstorm characteristics.

Thunderstorm Climatology

At any given moment, there are thousands of thunderstorms in progress worldwide. Most of these storms are beneficial, bringing needed rainfall. A small percentage of the storms that are able to be monitored are classified as severe, producing large hail (one inch in diameter or larger), strong wind gusts of 58 mph or greater, or tornadoes.

Although the greatest known occurrences of severe thunderstorms in the United States stretch from Texas to Minnesota, it is important to note that no place in the United States is immune to the threat of severe weather.



Average Annual Thunderstorm Days

Thunderstorm Ingredients

All thunderstorms require the following three ingredients: moisture, instability, and lift.

Moisture forms the clouds and precipitation associated with thunderstorms. Primary moisture sources include the Atlantic and Pacific Oceans, and the Gulf of Mexico. The Great Lakes can also provide moisture for thunderstorms, and in the Midwest, evapo-transpiration from farmlands can enhance the low-level moisture

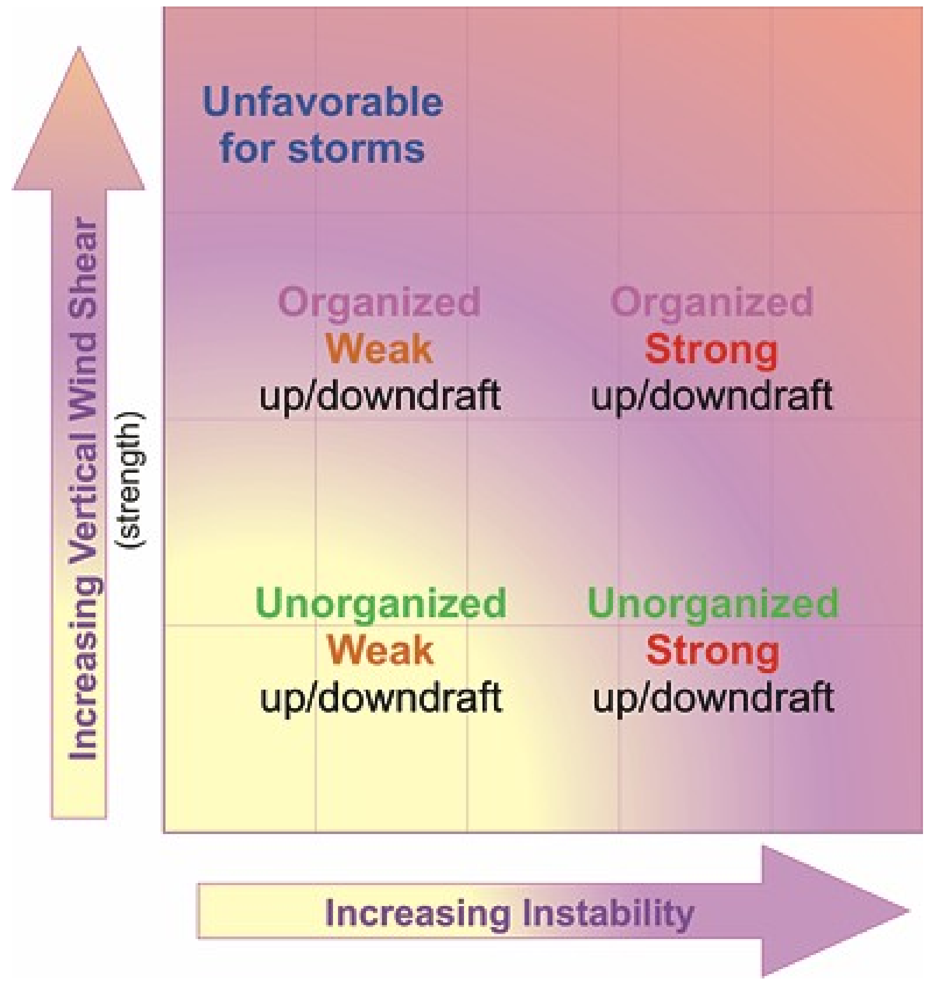
Instability is typically marked by relatively warm and moist air close to the ground, with relatively cold air a few miles above the ground. Instability provides an environment favorable for a storm's updrafts and downdrafts.

Lift provides the mechanism for the air to begin rising, and to set the thunderstorm process in motion. Sources of lift can include differential solar heating, fronts, drylines, outflow boundaries, and flow up the sides of mountains.

Adding to the Mix – Vertical Wind Shear

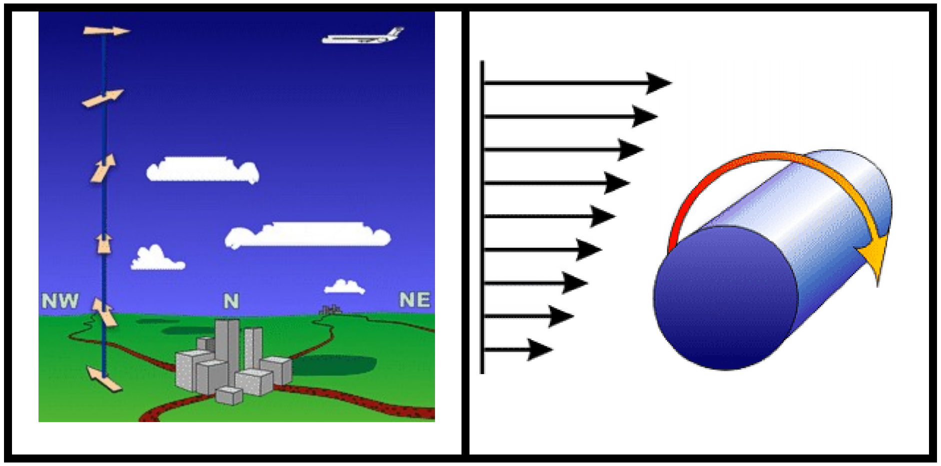
Vertical wind shear helps storms become well-organized and long-lived; characteristics associated with severe thunderstorms. Vertical wind shear through a deep layer (3-5 miles) separates the updraft and downdraft areas in the storm, and can induce rotation, at times intense, in the storm's mid levels. Storms that develop in weak-shear environments can still produce brief hail and microbursts, and even weak tornadoes.

Generally, the greater the instability, the stronger the updrafts and downdrafts may become. The greater the vertical wind shear, the higher the chance of storms becoming organized and long-lived. Increasing vertical wind shear will also generally increase the potential of rotation within the storm.



In a similar fashion, low-level vertical wind shear (in the lowest 1 mile or less of the atmosphere) can help generate low-level rotation in a storm. This can increase the storm's tornado potential, and increase the likelihood of significant severe weather from the storm.

Storms which track along stationary surface boundaries may find an environment favorable for enhanced low-level shear. This in turn could increase low-level mesocyclone intensity in the storm.



Examples of directional shear (left) and speed shear (right)

Thunderstorm Life Cycle

Thunderstorms generally last from 30 to 60 minutes, but because they continue to form new updrafts, the overall storm system can last for over 8 hours. Thunderstorms have three distinct stages shown in the next few pages.

1. **Developing Stage** (Cumulus or Towering Cumulus) [Figure 1]
   - Updraft (upward moving column of air) develops
   - Storm begins to produce precipitation within the upper portion of the cloud
   - Downdraft (downward moving column of air) initiates as precipitation begins to fall

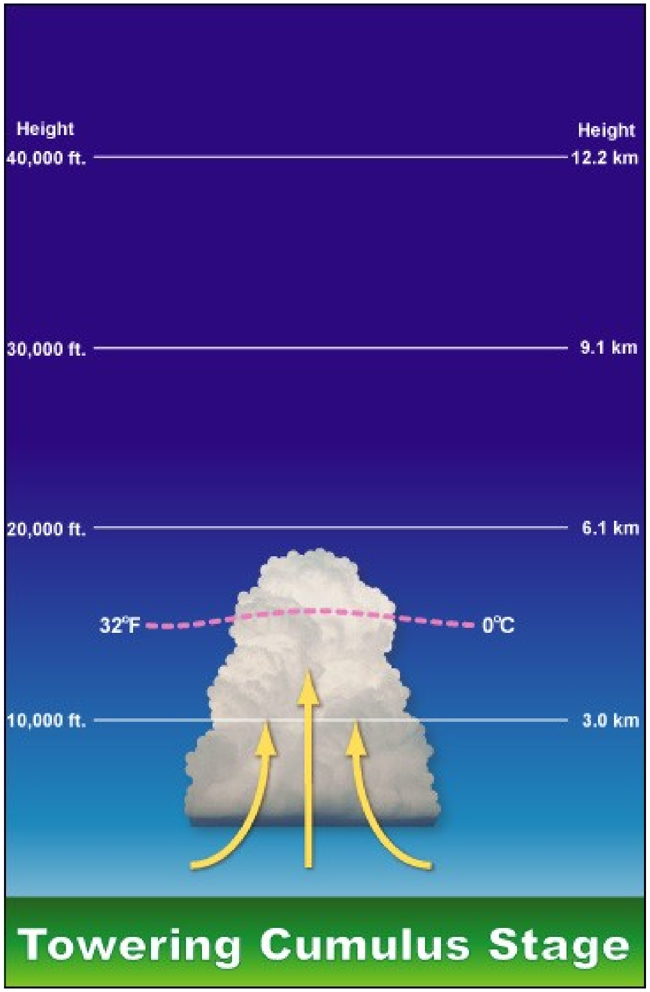


Figure 1

2. **Mature Stage** [Figure 2]
    - Coexistence of updraft and downdraft
    - Formation of gust front (rain-cooled air spreading out along the ground)
        - Usually the winds associated with a gust front are not severe, but in extreme cases wind gusts in excess of 58 mph can develop

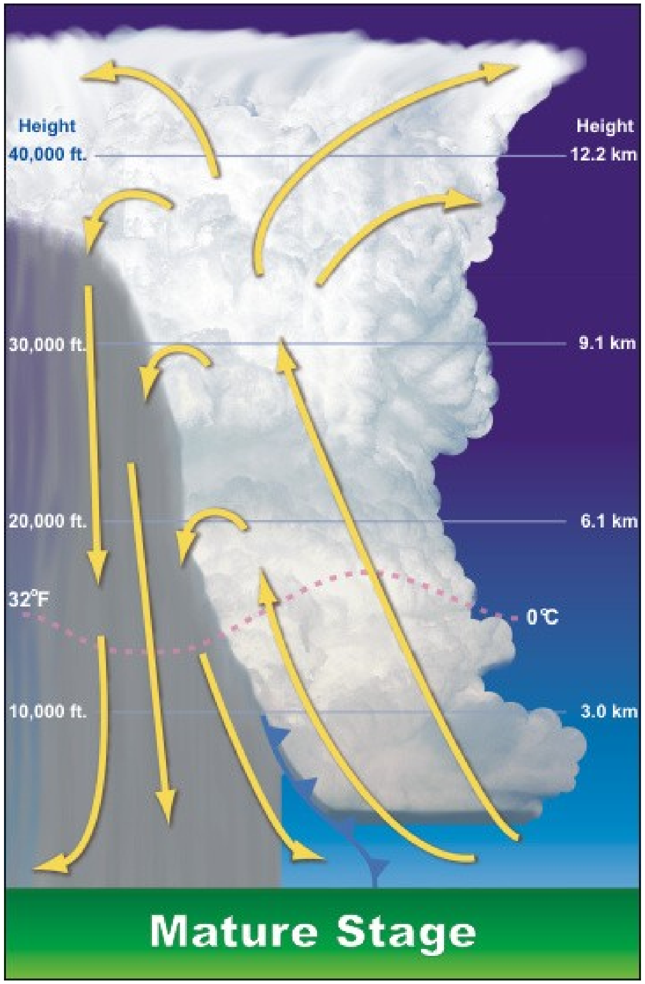


Figure 2

3. **Dissipation Stage** [Figure 3]
    - Dominated by downdraft
    - Gust front cuts off the storm's inflow by moving out a long distance from the storm
    - Sometimes you can see an "Orphan Anvil" which is the remnants of an anvil with the storm dissipated below.

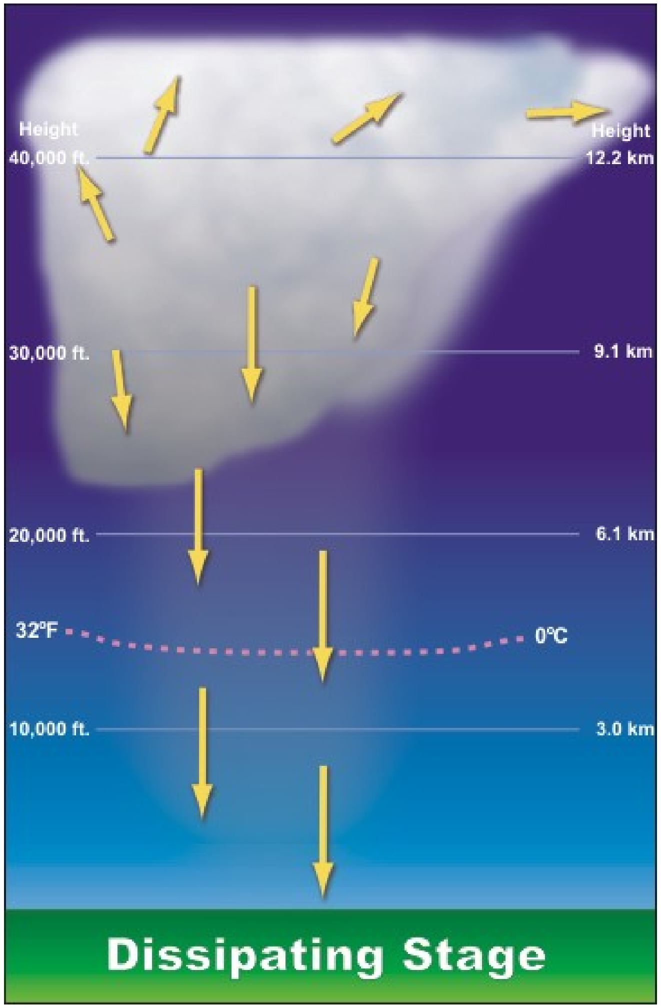


Figure 3

Severe Thunderstorms

A severe storm has either one of or a combination of the following types of weather:

- Hail that is one inch or larger, the size of a quarter
- Wind gusts of 58 mph or higher (50 knots)
- Tornado

The Storm Prediction Center issues tornado and severe thunderstorm watches, while the local weather forecast office issues the tornado or severe thunderstorm warnings.

Watch: Conditions are favorable in a region for severe thunderstorms and/or tornados to develop. They are generally issued for a 6 hour time period, but can be shorter or longer than that. Actions should be taken to be ready for storms in the near future, and to protect property before the storms may arrive in your area.

Warning: There is either an imminent threat or an actual occurrence of large hail, damaging winds or a tornado. When a warning is issued, action should be taken immediately to protect life. Warnings are generally issued for 30 to 60 minutes.

Features Indicating Strong/Severe Storms:

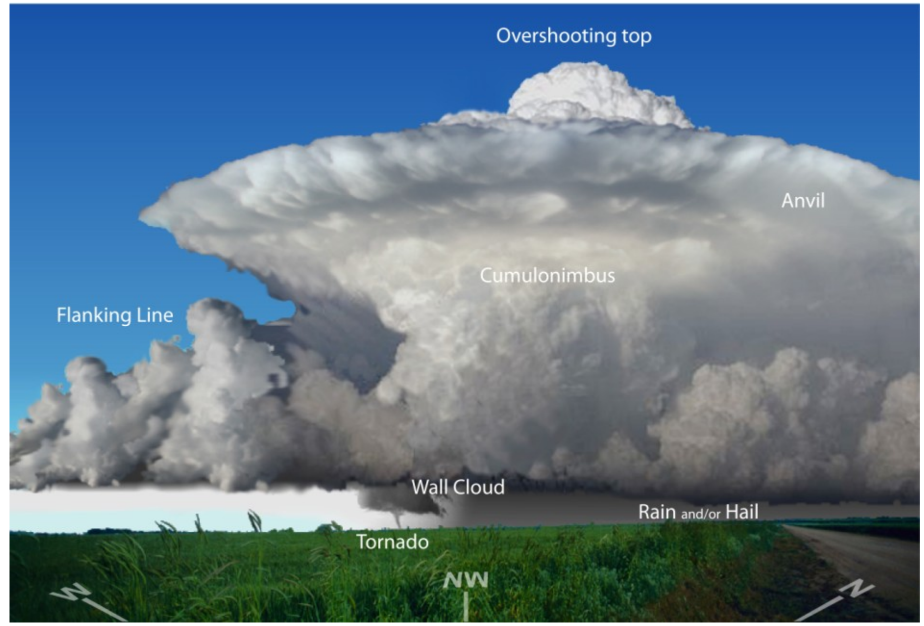


Figure 4 Thunderstorm Schematic

Anvil: The elongated cloud at the top of the storm that spreads down-wind with the upper level steering winds.

- The anvil will be solid, not wispy, and will have sharp, well defined edges

Overshooting Top: A dome of cloud, located directly above the main storm updraft tower and above the anvil. If the overshooting top is persistent and lasts for 10 minutes or longer, it is generally a sign of a very strong thunderstorm updraft.

Supercell in the distance. Notice the thick anvil and the large overshooting top. Photo by Gene Rhoden.

Main Storm Tower: The "trunk" of the storm, or visible updraft of the storm from its base near the ground to just below the anvil.

- A vertically oriented tower, with sharp, well defined edges
- A solid, cauliflower appearance
- Visible rotation, and possibly striations evident in the clouds

Rain-free Base: The area of a storm that is below the updraft tower of the storm. It is generally on the south or southwestern flank of a storm.

Wall Cloud: An isolated lower cloud below the rain-free base and below the main storm tower. Wall clouds are often located on the trailing (typically south or southwest) flank of a storm. With some storms, such as high precipitation supercells, the wall cloud area may be obscured by precipitation or located on the leading flank of the storm. Wall clouds associated with potentially severe storms can have the following characteristics:

- A persistent feature that lasts for 10 minutes or more
- Visible rotation occurs in some wall clouds
- Lots of rising or sinking motion within and around the wall cloud

Wall Cloud and Rain Free Base. Photo by Brian Morganti

Wall cloud with the rain free base above the photographer and the precipitation core behind the wall cloud. Photo by Roger Hill

Flanking Line: A row of cumulus clouds stair-stepping up to the main storm tower.   New storm cells develop from the flanking line which extends from the south to southwest side of a thunderstorm.

The flanking line of a thunderstorm. Photo by Matt Ziebell

Upper level storm features that are viewable when you are at long distances from the storm:

- A solid overshooting top that persists for 10 minutes or more
- Overshooting tops that may dissipate, followed by new ones
- A solid anvil with sharply defined edges

Why? An overshooting top is a signal of a strong updraft, and if more persistent, is a sign that the storm of interest is becoming organized and has found additional sources of energy to continue to strengthen. If the overshooting top suddenly collapses, a burst of precipitation, hail, or damaging wind may be imminent. As the storm weakens it will take on a more wispy, fuzzy appearance.

Supercell in the distance. Photo by Brian Morganti

Mid-level storm features that may be easy to see:

- A solid, vertically oriented storm tower with a cauliflower appearance
- A flanking line, with clouds building toward the main storm tower

Looking northeast into a thunderstorm with the flanking line pointing to the south-southwest. Photo by Tom Warner

Why? A solid looking and vertically oriented storm tower indicates a strong updraft exists within the storm, along with a favorable shear environment. If the storm tower tilts noticeably downwind with height, strong wind shear may limit the storms ability to sustain an updraft and thus produce severe weather. A flanking line indicates the storm is drawing air from many miles away and likely will sustain itself or intensify for some time.

What to look for when you're close to a storm:

-A rain-free cloud base with a large and intense storm tower above

-A wall cloud that persists for 10 minutes or longer, especially if it is violently rotating

-Rapid vertical motion (up or down) within the wall cloud or other areas of the rain-free cloud base

Why? A rain-free cloud base indicates a strong updraft, where precipitation (including hail) is not heavy enough to fall to the ground. When a rotating wall cloud is present there is a much higher potential for tornado development. Wall clouds begin to rotate as the mesocyclone associated with the storm begins to develop toward the surface, and when combined with the proper atmospheric conditions, will support tornadoes.

Lower level storm features including the updraft and downdraft area. Photo by Jim LaDue

Thunderstorm Types

Thunderstorms can be categorized by their physical characteristics. These characteristics include the presence or absence of storm-scale rotation, the number of updrafts and downdrafts present at any given time, and the orientation of updrafts and downdrafts with respect to one another.

Important environmental parameters determining longevity and organization of storms include:

- Wind shear (higher values: greater organization)
- Buoyancy (higher values: greater updraft intensity)
- Type and orientation of forcing mechanism

There is a continuous spectrum of storms in nature, but four broad categories can be discussed with the understanding that at times it may be difficult to place a storm into any one specific category:

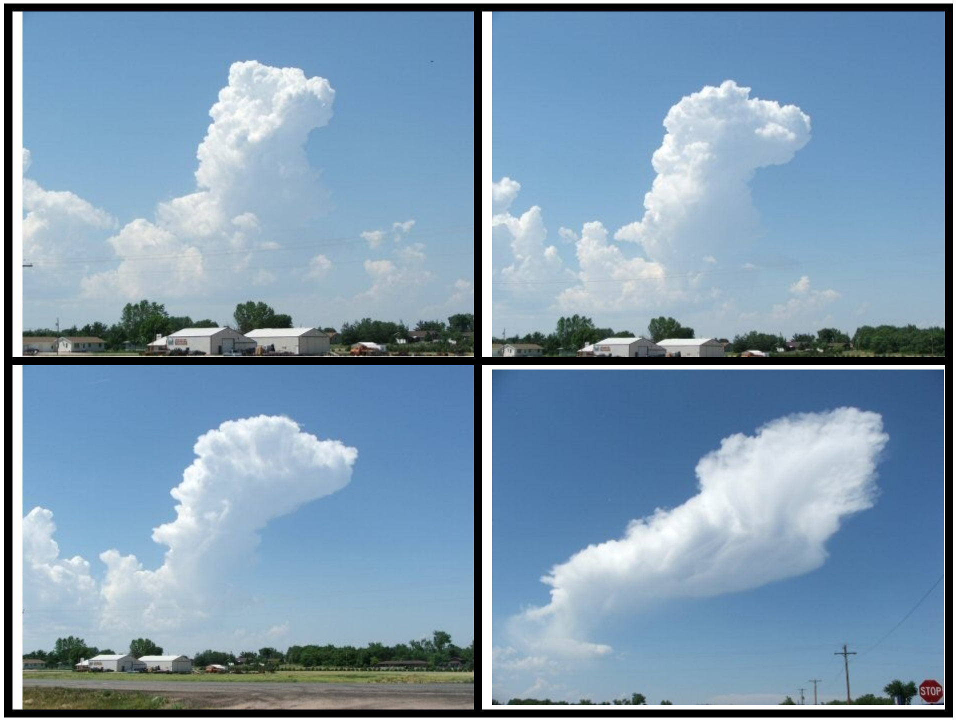
- **Ordinary cell:** Short lived, may produce brief severe weather events
- **Pulse:** A convective bubble producing brief severe weather that can occur in an ordinary or multicellular cluster storm
- **Multicellular Cluster:** Most common type of storm consisting of a group of ordinary cells at various stages of the thunderstorm life cycle
- **Multicellular Line:** A long line of storms with a continuous, well developed gust front along the leading edge
- **Supercell:** A highly organized thunderstorm with an extremely strong updraft, supercells exhibit persistent storm-scale rotation of the updraft-downdraft couplet, which is called a mesocyclone

At times, a thunderstorm will transition from one type to another over its lifetime.

Ordinary Cell:

This single storm forms when there is weak shear in the atmosphere.

- Short lived
- Downdraft forms within 15-20 minutes after cell initiation
- Within 25 to 30 minutes, the updraft weakens and the outflow stabilizes
- Small hail, usually not severe
- Gusty winds, usually not severe



A series showing an ordinary storm cell's life cycle. These photos were taken in a span of 21 minutes. Photos by Phil Kurimski

The Pulse Storm

- Usually not severe
- Short life, generally 30-45 minutes
- Form in weak vertical wind shear

Given the right environmental conditions, these storms can create:

- Brief, small to moderate size hail
- Microburst winds, usually less than 70 mph
- Weak tornado
- Damage isolated in nature

The Multicell Cluster Storm

- Most common type of thunderstorm
- Consists of a group of cells moving as a single unit
- Each cell is in different stage of thunderstorm life cycle
- Storm may last for several hours
- Occasionally supercells may make up a multicell cluster
- Grow as the vertical wind shear increases

The new updrafts in the cluster form within a persistent lifting zone where low level convergence is present, such as:

- Cold or warm front
- Pressure trough
- Dry line
- Outflow boundary from nearby storms
- Terrain features

Multicellular thunderstorm. Photo by Gary Woodall.

Each cell which develops in the lifting zone will move downwind as it matures and dissipates. In a typical scenario during the spring and summer months:

- New cells initiate on W-SW edge of cluster
- Dissipating cells weaken on E-NE edge of cluster
- Each cell may last 20-30 minutes
- Clusters as a whole often last an hour or more

Given the right environmental conditions, the cells can become severe cell within the multicellular cluster producing:

- Brief small to moderate size hail
- Microburst winds
- Weak tornadoes
- Heavy rainfall in a short time period

The Multicell Line Storm

- Frequently called “squall line”
- A long line of storms with individual storm outflows merging to produce a continuous, well developed gust front which marks leading edge of rain-cooled air
- Spotters often observe a shelf or roll cloud along gust front
- Line of storms is often oriented north-south, or northeast-southwest
- Some supercells may be embedded along the line
- Updrafts continually re-form at leading edge of system with rain and hail following behind

Individual thunderstorm updrafts and downdrafts along the line can become quite strong, resulting in episodes of large hail and strong outflow winds which move rapidly ahead of system.

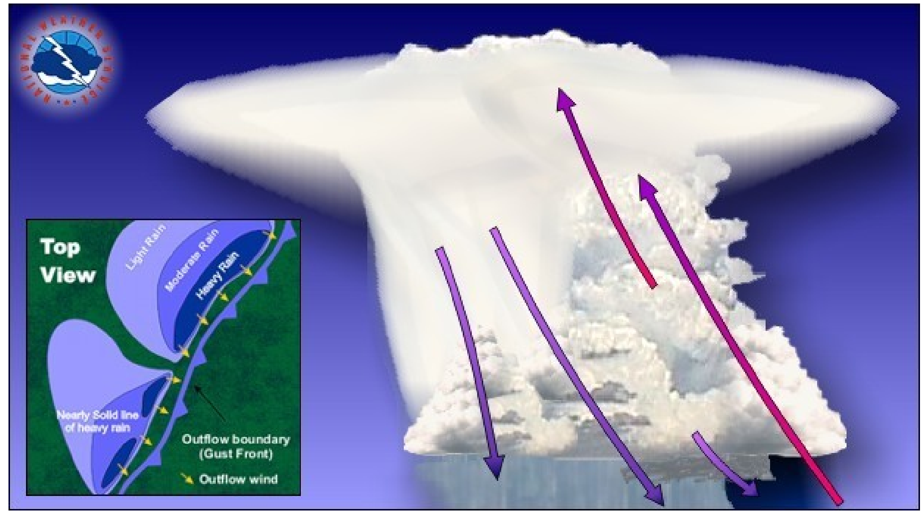


Figure 5 Multicellular line

Storms located on the end of a squall line, or along a break in the line tend to be stronger and may behave more like supercells, with a corresponding higher potential to produce a tornado. However, tornadoes have also been observed elsewhere along a multicell line of storms.

Given the right environmental conditions, multicell line storms can produce:

- Strong downburst winds
- Heavy rainfall
- Moderate-sized hail
- Occasional tornadoes

Shelf Cloud in Illinois. Photo by Walker Ashley

The Supercell

Classification of supercellular storms is highly subjective and there is a lot of research that is being done in this area. We do know the following about supercells though:

- Highly organized storm
- Updrafts can attain speeds over 100 miles per hour
- Can produce extremely large hail and strong-violent tornadoes
- Rear-flank downdraft can produce damaging outflow winds in excess of 100 mph
- Pose a high threat to life and property

It is very important that spotters become familiar with the visual aspects of these intense thunderstorms. Two important characteristics distinguish supercells from ordinary thunderstorms:

- The presence of a persistent rotating updraft-downdraft couplet known as a mesocyclone
- The rear-flank downdraft (RFD) is the downdraft portion of the updraft-downdraft couplet of a mesocyclone

The presence of a strong mesocyclone greatly enhances updraft intensity, persistence and overall storm organization. The thermodynamic characteristics of the RFD and its evolution during a storm's lifetime have been shown to play a crucial role in tornado formation.

Supercells can produce the following elements:

- Large hail and potentially torrential rainfall immediately adjacent to the storm updraft
- Smaller hail and lighter rainfall at greater distances from the updraft
- RFDs producing strong, sometimes damaging outflow
- Tornadoes

Supercell Variations

All supercells share the common characteristic of storm-scale rotation, which may gives a striated or corkscrew appearance to the storm's updraft. Dynamically, all supercells are fundamentally similar. However, supercells often appear quite different visually from one storm to another depending on:

- The amount of precipitation accompanying the storm
- Whether precipitation falls adjacent to, or is removed from, the storm's updraft

Storm-relative wind fields play an important role in precipitation distribution in and around the storm's updraft.

Based on their visual appearance, supercells are often qualitatively labeled as:

- Rear Flank Supercell - Low precipitation
- Classic
- Front Flank Supercell - High precipitation

Supercell Thunderstorm. Photo by Roger Hill

Rear Flank Supercell - Low Precipitation (LP)

- Updraft is on the rear flank of the storm
- Barber pole or corkscrew appearance of updraft is possible
- Precipitation sparse or well removed from the updraft, often is transparent and you can't see it
- Large hail is often difficult to discern visually
- No hook echo evident

Rear Flank(LP) Supercell. Photo by Roger Edwards

Figure 6. Rear Flank (LP) Supercell Schematic

Classic (CL) Supercell

- The majority of supercells fall in this category
- Large, flat updraft base
- Generally has a wall cloud with it
- Striations or banding around the periphery of the updraft
- Heavy precipitation falling adjacent to the updraft
- Large hail likely
- Potential for strong, long-track tornadoes
- Translucent hook, most of it ahead of the updraft

Classic Supercell photo by Bill Martin

Figure 7. Classic Supercell Schematic

Front Flank Supercell – High Precipitation (HP)

- Updraft is on the front flank of the storm
- Precipitation almost surrounds updraft at times
- Generally has a wall cloud with it, but it may be obscured by the heavy precipitation
- RFD filled with precipitation
- May have an associated shelf cloud with it
- Tornadoes potentially rain-wrapped
- Extremely heavy precipitation with flash flooding
- Opaque hook, most of it behind the updraft

HP Supercell photo by Al Moller.

Figure 8. Front Flank (HP) Supercell Schematic ***(need updated graphic)***

Visual Clues of Supercells

Several clues may be visually evident that suggest a storm is a supercell.

- **A rotating wall cloud** suggests the presence of a **mesocyclone**, or rotating updraft
- **Striations** on the sides of the storm, streaks of cloud or bands of cloud that give the storm a “corkscrew” or “barber pole” appearance, indicate that the storm’s updraft is rotating, generally seen with the Rear-Flank Supercell (LP). These striations appear as **bands of cloud** on the sides of the storm, and give the storm’s updraft a **barrel shaped** look
- Often times the updraft area will have a **rounded base**, again indicating that a mesocyclone is present
- Finally, **inflow cloud bands**, such as the **beaver’s tail**, feed into the storm from the forward flank core. The beaver’s tail is a smooth flat cloud band that extends out from the eastern edge of the **rain-free base** toward the east.

Inflow band. Photo by Roger Edwards

Non-Tornadic Severe Weather

Hail: The National Weather Service issues a severe thunderstorm warning for hail when the hail size is one inch or larger. When reporting hail to the National Weather Service, it is best to relate the hail size to coins or athletic balls. The following sizes are generally used when reporting hail:

BB	<1/4"
Pea	¼"
Dime	7/10"
Penny	¾"
Nickel	7/8"
Quarter	1"
Half Dollar	1 ¼"
Walnut or large marble	1 ½"
Golf Ball	1 ¾"
Hen Egg	2"
Tennis Ball	2 ½"
Baseball	2 ¾"
Tea Cup	3"
Grapefruit	4"
Softball	4 ½"

Large Hailstones. Photo by Mark Schmidt

Damaging Winds: The National Weather Service issues warnings when the winds from a thunderstorm are 58 mph (50 knots) or higher.

Downbursts are an area of strong, often damaging winds produced by air rapidly descending in a thunderstorm. They cover an area that can be less than 1 mile to greater than 20 miles. Downbursts have various terminologies depending on what is occurring, including:

- **Wet:** Rainfall accompanies the damaging winds
- **Dry:** Very little rainfall accompanies the damaging winds, and a lot of dust is kicked up off of the ground
- **Microburst:** A downburst that covers an area less than 2.5 miles with peak winds that last 3-7 minutes, and can have wind speeds in excess of 150 mph. Due to the small areal extent of a microburst, they are sometimes very difficult to detect with weather radar
- **Macroburst:** A downburst that covers an area greater than 2.5 miles, and can last for well over 10 minutes

Large convective windstorms: These types of wind events are formed by large scale synoptic forcing that creates long-lived and widespread damage. They include:

- **Bow Echo:** A bow-shaped line of convective cells, best seen on radar, which is often associated with swaths of damaging straight line winds and small tornadoes

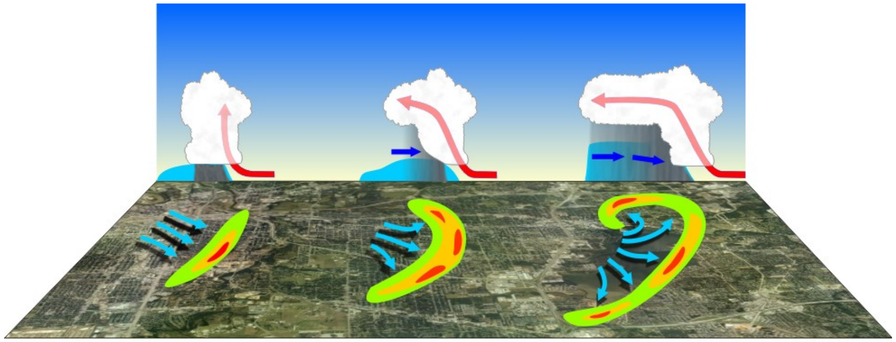


Figure 9. Schematic showing the development and progression of a bow echo

- **Derecho:** A long-lived, widespread, convectively induced straight line thunderstorm with damaging winds that is best seen on radar

Estimating Wind Speed: It's often difficult to estimate wind speed, especially in the plains where there are few physical indicators to observe damage. Below is a guide to estimating wind speeds.

Speed (mph)	Effects
25-31	Large branches in motion
32-38	Whole trees in motion
39-54	Twigs break off trees, wind impedes walking
55-72	Damage to TV antennas, large branches break off trees
73-112	Peels surfaces off roofs, windows broken, trailer homes overturned
113+	Roofs blown from houses, weak buildings and trailer homes destroyed, large trees uprooted, train cars blown off tracks

Spotting downbursts: There are several visual signs that a downburst is either occurring or about to occur. These include:

- **Virga:** Precipitation that is streaking from the cloud that isn't reaching all the way to the ground. The atmosphere below the clouds tends to be very dry and the rainfall evaporates before it touches the ground. There tends to be gusty winds in the area when virga is noted

Virga with a dry microburst. Photo by Brian Morganti

- **Rain foot:** The rain foot is a pronounced outward deflection of the precipitation area near the ground, marking an area of strong outflow winds

Wet downburst that has a rain foot on the left of the rain shaft area. Photo by Brian Morganti

A wet microburst. Photo by Jim LaDue.

- **Dust foot**: A plume of dust/dirt that is raised as the downburst reaches the ground and moves away from the impact point

Dust Foot/Microburst Photo by Brian Morganti

Flash Floods

- Flooding that rises and falls quite rapidly with little or no advance warning is considered to be a flash flood
- Occur in mountainous terrain, but can also occur in urban areas as the sewer systems do not allow for quick drainage of the water, and where large areas of pavement do not allow the water to soak into the ground
- Flash flooding is usually due to heavy rainfall, storm surge, ice jams or dam breaks

1997 Fort Collins Flash Flood. Photo by John Weaver

Lightning

- Electrical discharge within thunderstorms, heavy snowstorms, hurricanes, volcanic eruptions, and large wildfires
- At any given moment, there are about 40 lightning flashes per second occurring globally

Photo by Tom Warner, Devils Tower, Wyoming

- **Cloud to Ground:** This is a lightning strike that has contact from within the cloud to the ground, or even one that looks to connect from the ground up to the cloud. This is the type of lightning that causes from 50 to 100 deaths to several hundred injuries every year
- **Cloud to Cloud/Intracloud:** This lightning helps illuminate the cloud features, but it is not hazardous to spotters on the ground. It occurs within the cloud, or jumps from one cloud to another, never reaching the ground
- **Positive Charged Lightning:** This type of lightning makes up less than 5% of all lightning strikes, but it is the most dangerous. The majority of positive lightning originates in the upper levels of the storm, and has a much stronger charge to it than a negative lightning strike. These strikes are very bright, and appear to last for a longer duration than the negative strikes. They are also known for being good fire starters when they strike the ground, or trees. They can cause a strike that is more than 10 miles away from the parent thunderstorm.

Positive Lightning Strike Photo by Tom Warner

- **Negative Charged Lightning:** Negative lightning makes up over 95% of all lightning strikes. While the electrical charge isn't nearly as strong as a positive strike, because it is more frequent, it is still a significant threat to those who are outdoors without proper shelter