

Module 18: Severe Thunderstorms in the United States



Tuscaloosa, Alabama May 18, 2011

Dan Koopman 2011



The
UNIVERSITY
of VERMONT



What is “Severe Weather”?

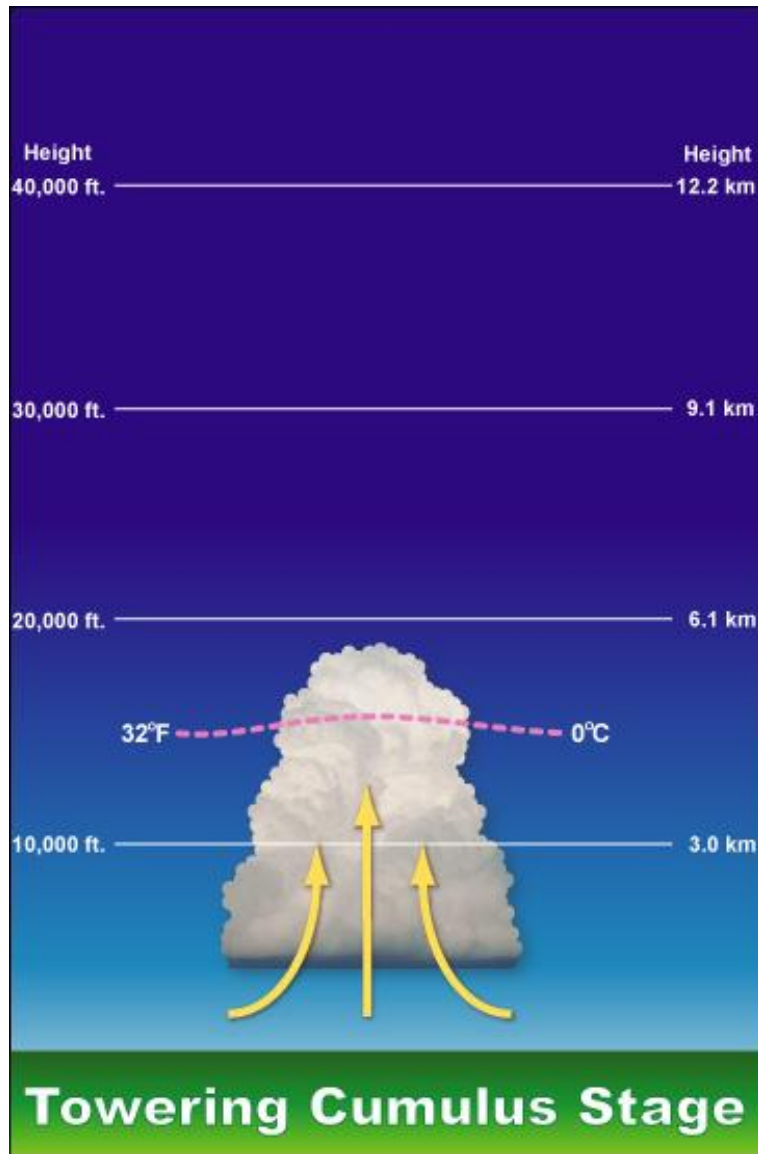
Any meteorological condition that has potential to cause damage, serious social disruption, or loss of human life.

American Meteorological Society: *In general, any destructive storm, but usually applied to severe local storms in particular, that is, intense thunderstorms, hailstorms, and tornadoes.*



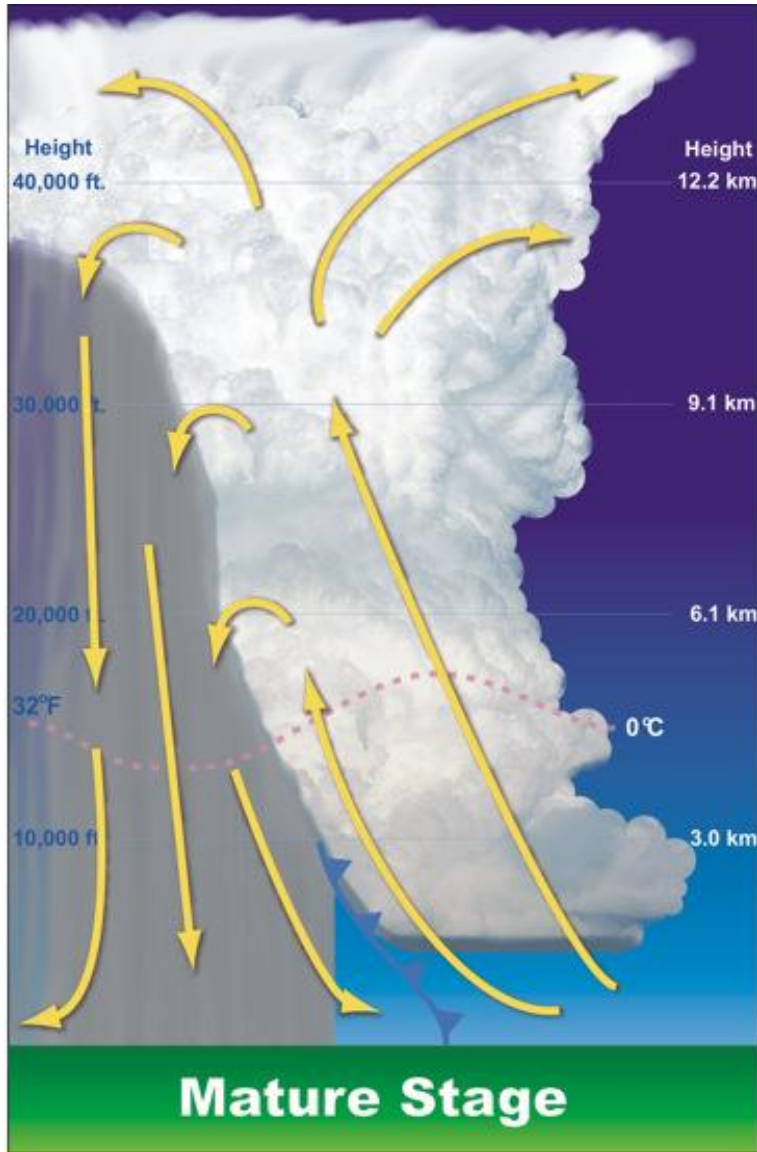
Three Stages of Thunderstorm Development

Stage 1: Cumulus



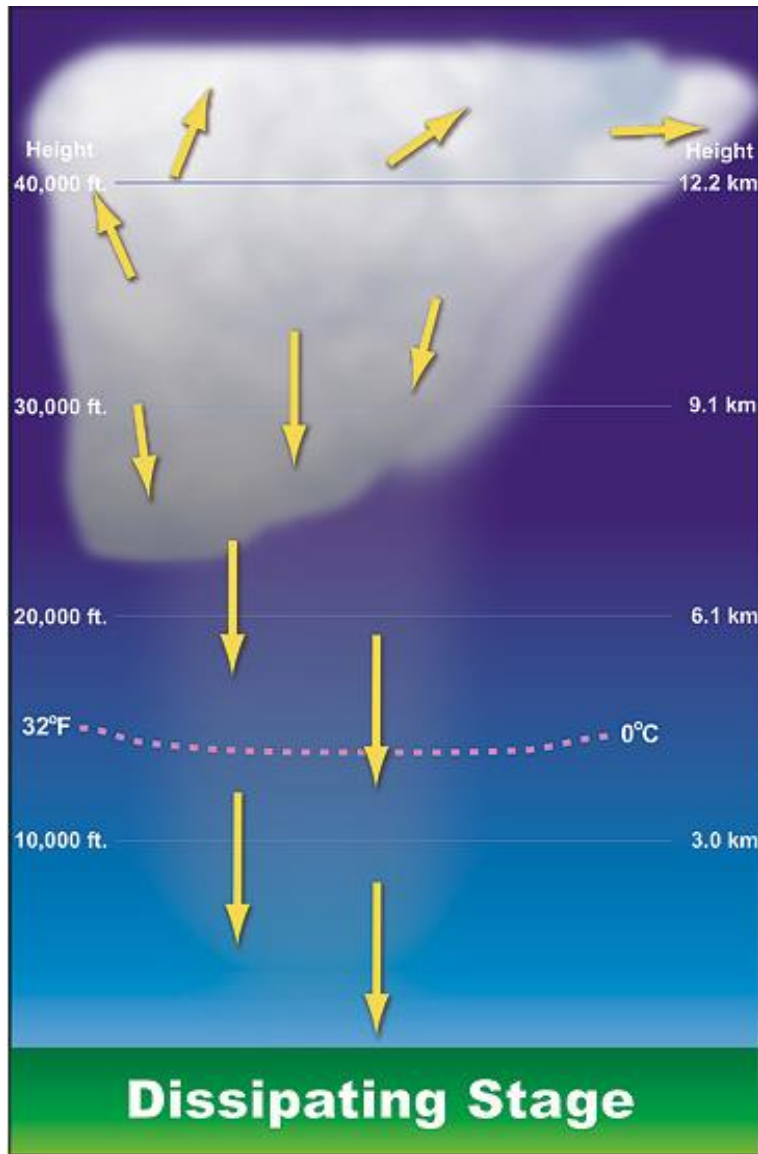
- A warm parcel of air begins ascending vertically into the atmosphere.
- In an unstable environment, the parcel will continue to rise as long as it is warmer than the air around it.
- Billowing, puffy Cumulus Congestus Clouds continue to build in towers.

Stage 2: Mature



- At a certain altitude, the parcel is no longer warmer than its environment. It is unable to rise any further and develops the distinctive “Anvil” shape as seen in this figure.
- In cases of particularly strong updrafts, the vertical velocity of the updraft may be sufficient to penetrate this altitude causing an “overshooting top” to develop above the flat top of the anvil.

Stage 3: Dissipating

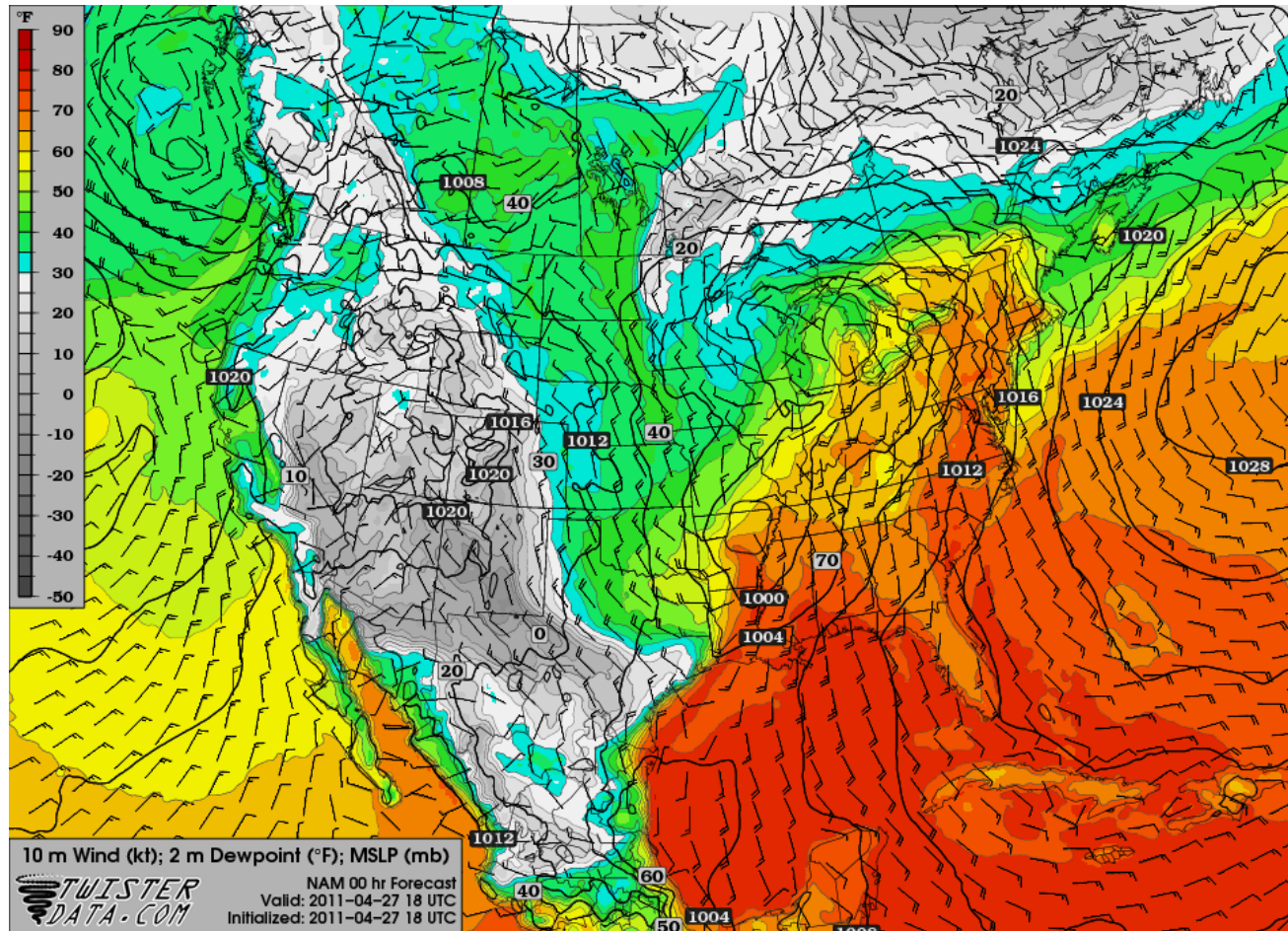


- Convective inflow shut off by strong downdrafts, no more cloud droplet formation, downdrafts continue and gradually weaken until light precipitation rains out
- Water droplets aloft begin to coalesce until they are too heavy to support and begin to fall to the surface, strengthening the downdraft.

Basic Ingredients for Thunderstorms

- Moisture
- Unstable Air
- Forcing Mechanism

Moisture



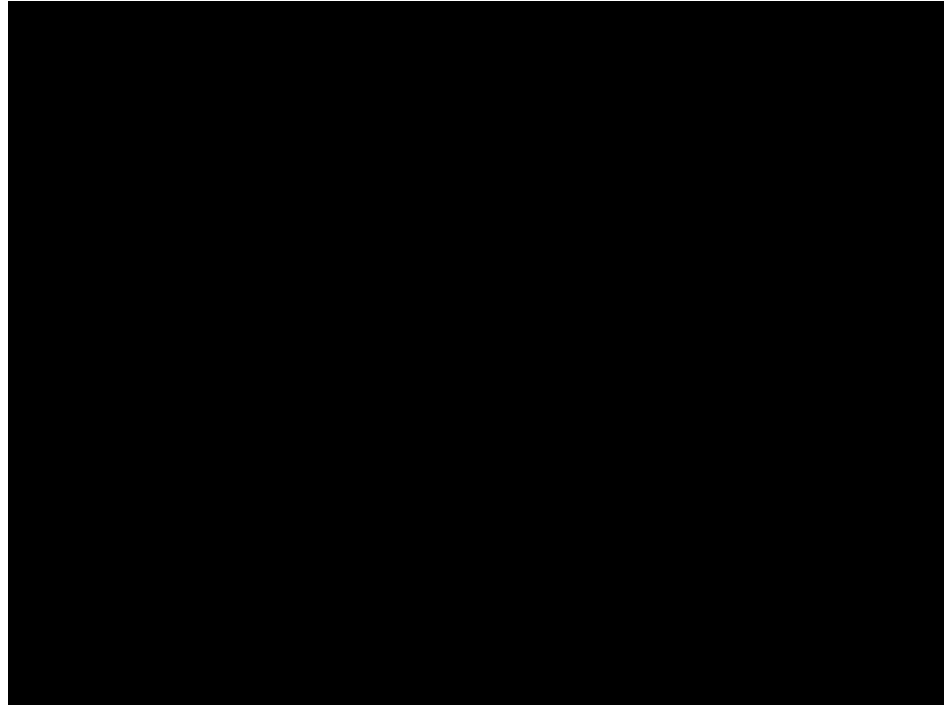
Thunderstorms development generally requires dewpoints $> 50^{\circ} \text{ F}$

Unstable Air

Stable is resistant to change.

When the air is stable, even if a parcel of air is lifted above its original position (say by a mountain for example), its temperature will always remain cooler than its environment, meaning that it will resist upwards movement.

Unstable air occurs when a parcel's temperature is higher than the environment surrounding it. The parcel will rise vertically until it reaches the same temperature as the air around it.



Forcing Mechanisms

1. Unequal Heating at surface (Differential Heating)
2. Topographic Features
3. Lifting along shallow boundaries of converging surface winds

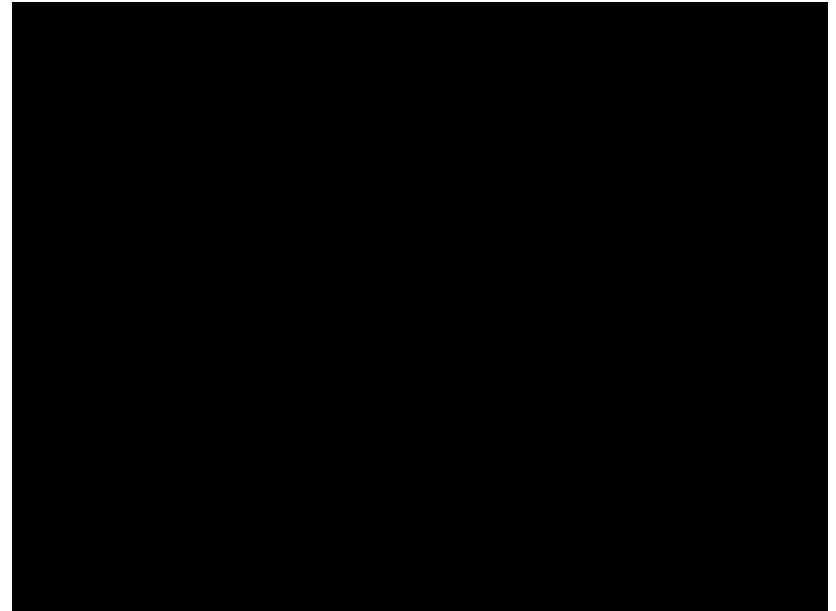
1. Unequal (Differential) Heating at Surface

- Differential Heating occurs because of differences in thermal properties of Earth materials and the lower atmosphere.
- Differential Surface Heating can cause convective uplift when a air parcel warmer than the surrounding ambient air is able to rise high into the atmosphere.
- This upward force generated by convective uplift is called Buoyancy



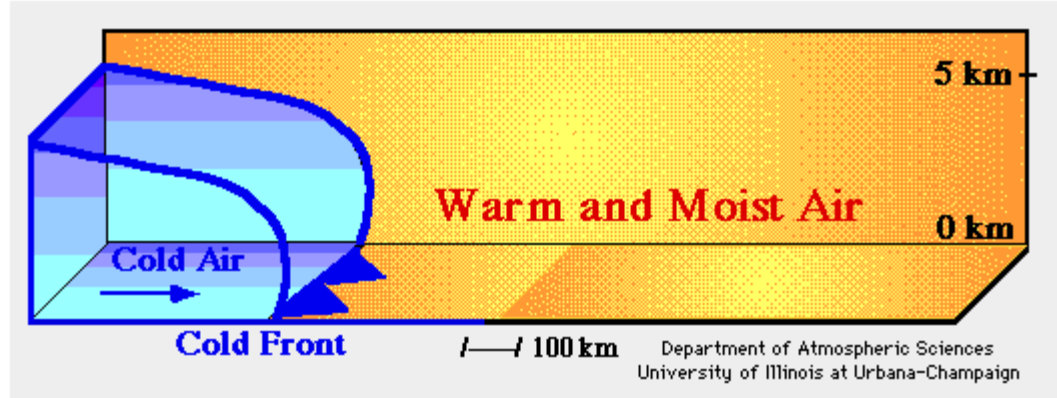
2. Topographic Features

Air bodies that encounter topographic features such as mountains are forced to rise to higher altitudes, causing conditions favorable to thunderstorm development. These are often called “upslope” thunderstorms.

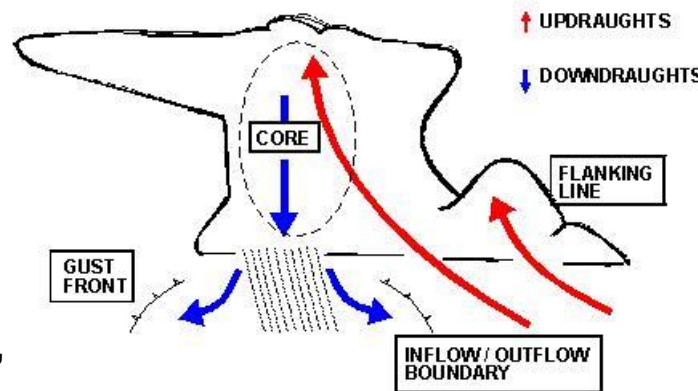


3. Boundary Lifting

- Cold front lifting:
 - Cold, dense air acts as a “wedge” and causes warm air to rise, creating a lifting mechanism.



- Outflow Boundary lifting
 - The downdraft exiting the system in the form of a “Gust Front” or “Outflow Boundary” is sometimes sufficient to act as a lifting mechanism for new storms



A black and white satellite image of South Florida, showing the coastline and surrounding waters. The image is used as a background for the text.

GOES-9

**GOES Project
NASA-GSFC**

**Rapid-scan test
8 am - 8 pm EDT
July 2, 1995**

South Florida

July 13th edition

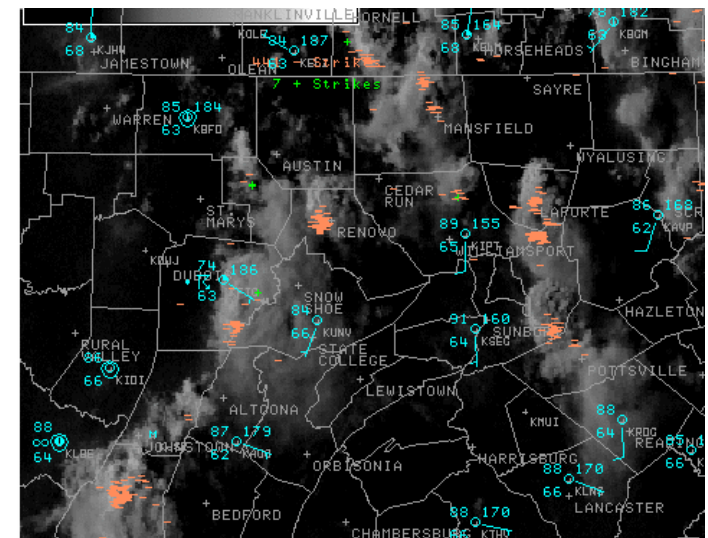
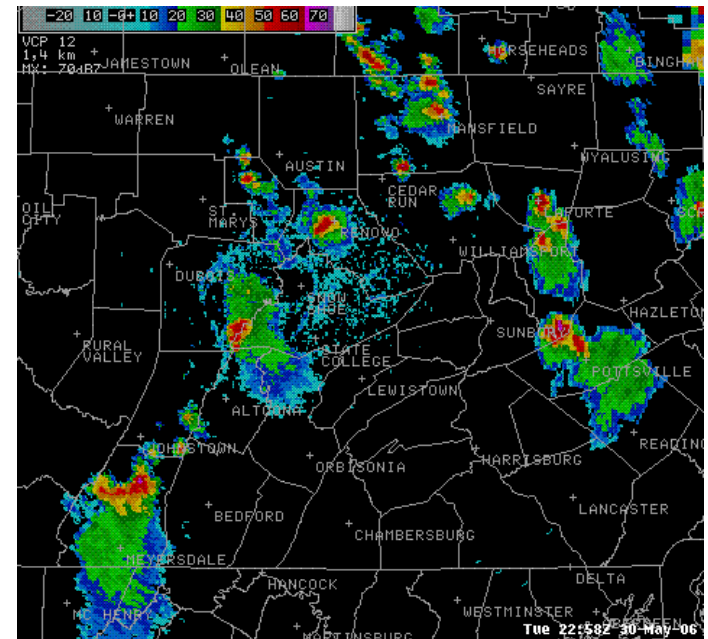
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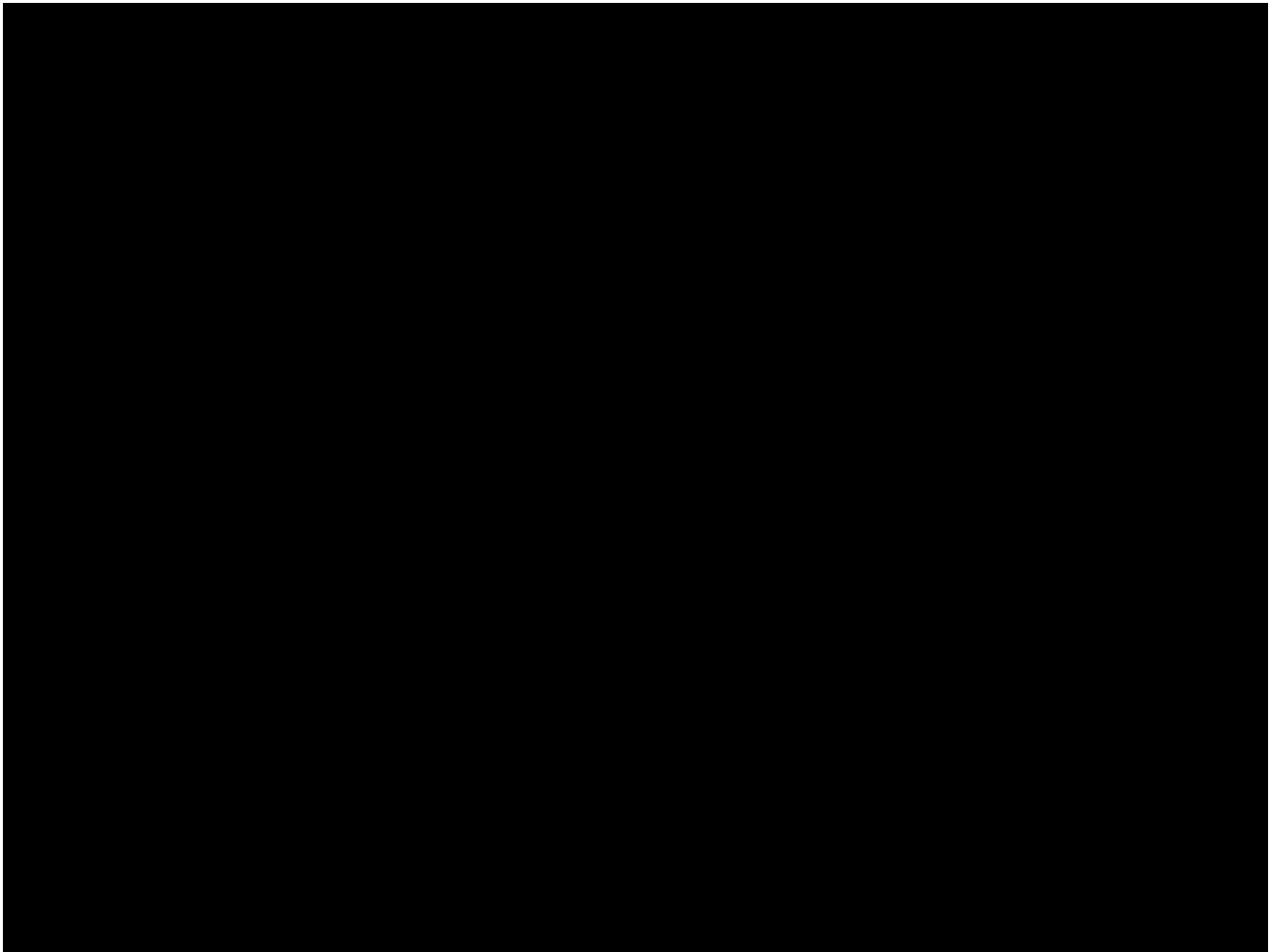
Types of Thunderstorms

- Single Cell Storms (Air mass Thunderstorm)
- Multicell Cluster Storm
- Multicell Line Storm (Squall Line)
- Supercell (SEVERE)

Single Cell Storms (Air Mass Thunderstorm)

- Lifting mechanism is rising air from surface heating. This generally limits the geography of these storms to warm and tropical areas.
- Usually last around minutes - generally there is no wind shear, causing the downdrafts to dampen out the updrafts.
- Oftentimes the Gust Front of one cell triggers the growth of another, changing from a Single Cell Storm to a Multicell System.
- Most single cell storms are usually not severe. However, it is possible for a single cell storm to produce a brief severe weather event. When this happens, it is called a **pulse severe storm**. Their updrafts and downdrafts are slightly stronger, and typically produce hail that barely reaches severe limits and/or brief microbursts. Brief heavy rainfall and occasionally a weak tornado are possible. Though pulse severe storms tend to form in more unstable environments than a non-severe single cell storm, they are usually poorly organized and seem to occur at random times and locations, making them difficult to forecast.

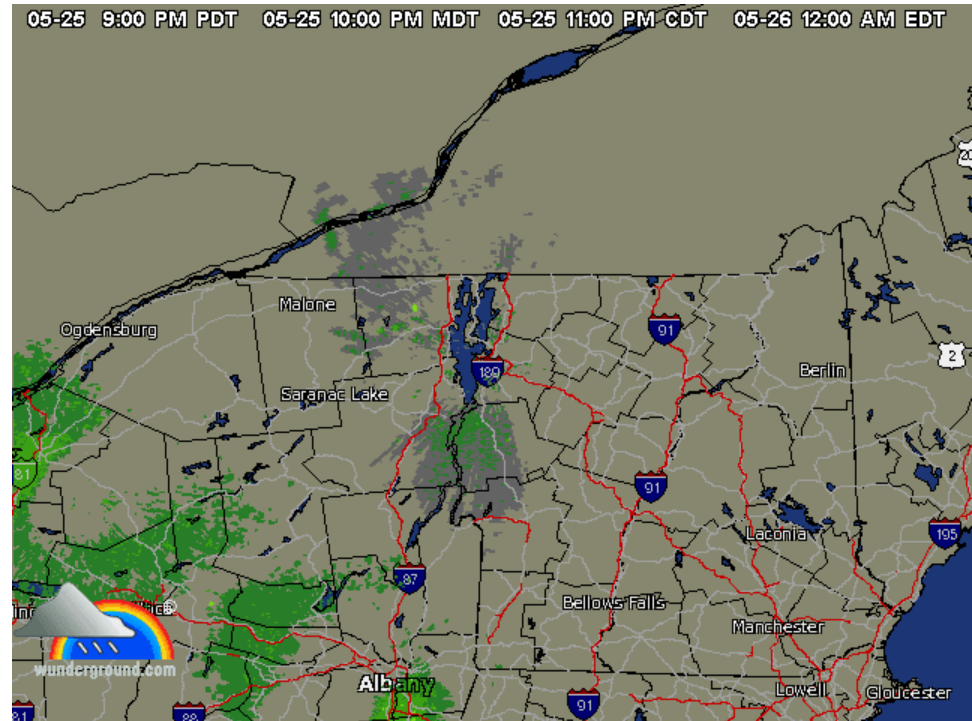




[Redacted text]

Multicell Cluster Storm

- Most common type of thunderstorm.
- Consists of a group of cells, moving along as one unit, with each cell in a different phase of the thunderstorm life cycle.
- Cluster forms in an unstable environment, where the outflows of several initial storms serve as the lifting mechanism for others to form.
- Mature cells are usually found at the center of the cluster with dissipating cells at the downwind edge of the cluster.
- Can produce moderate size hail, flash floods and weak tornadoes.
- Multicell Clusters can also produce damaging straight line winds, which are born from Micro- and Macro- bursts (associated with Severe Thunderstorms.)



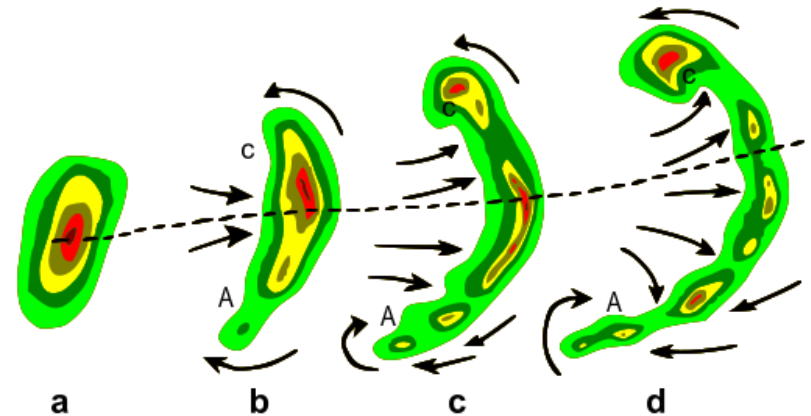
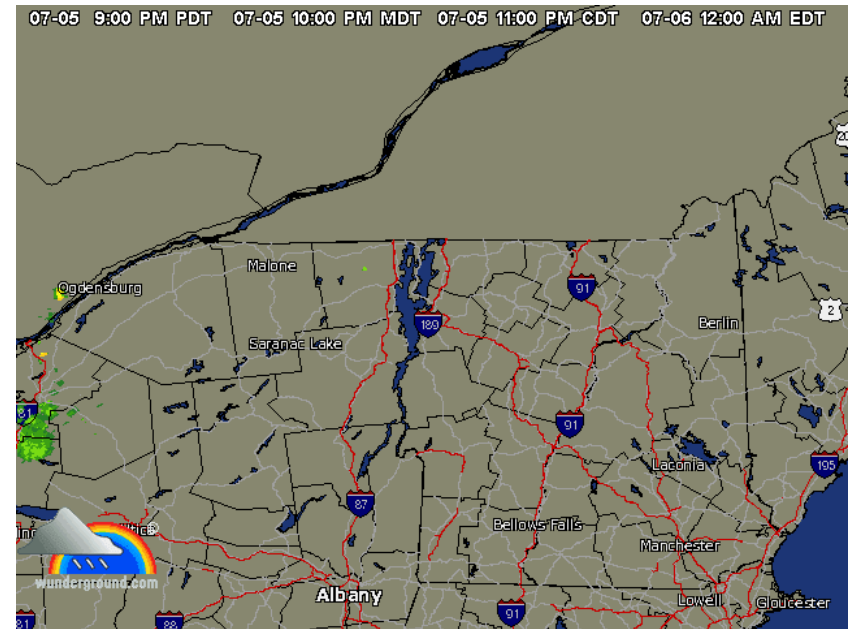
Composite RADAR Loop for May 28, 2011 - Multicell Cluster storm developing in the afternoon over the Champlain Valley

Multicell Line Storm (Squall Line)

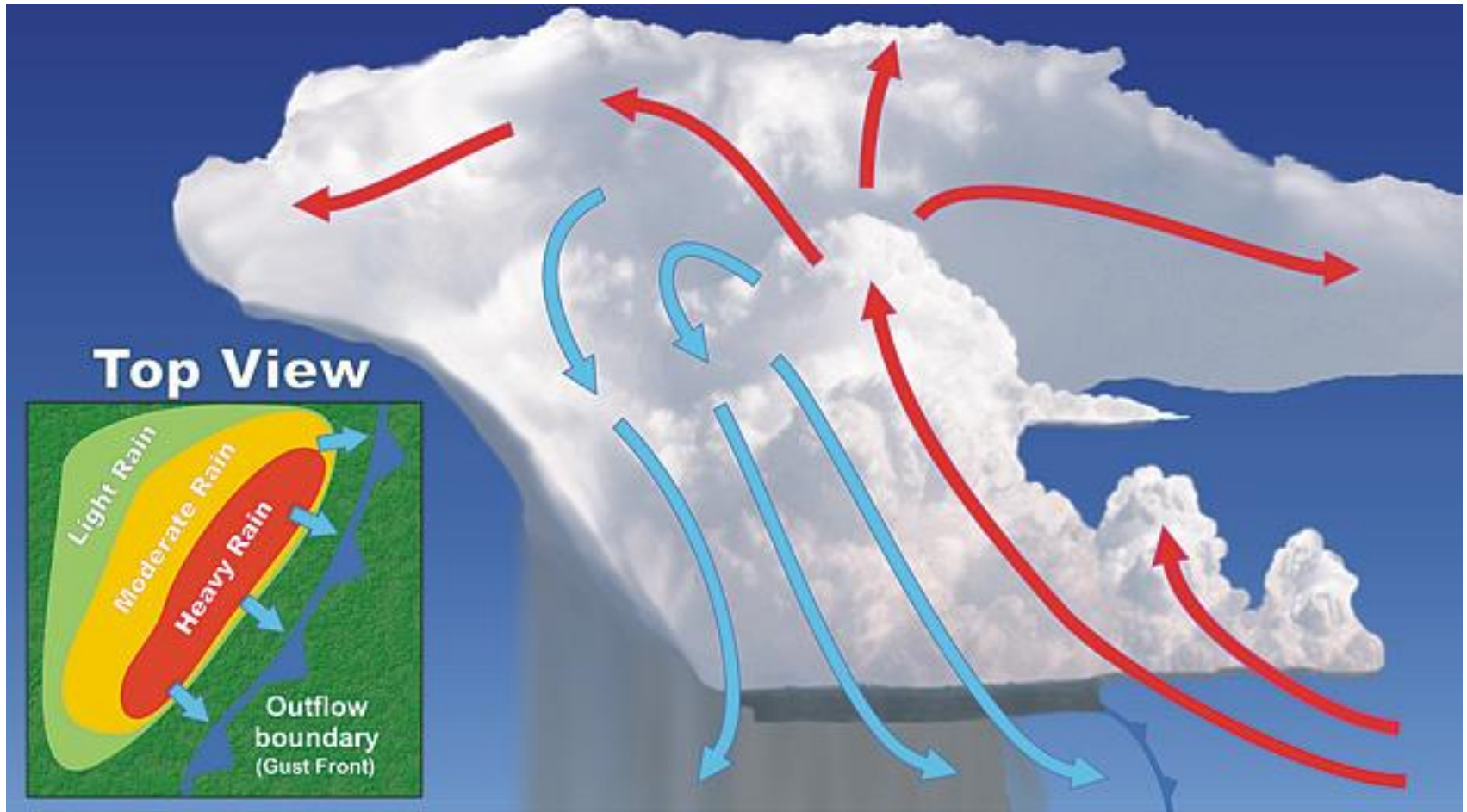
The multicell line storm, or squall line, consists of a long line of storms with a continuous well-developed gust front at the leading edge of the line. The line of storms can be solid, or there can be gaps and breaks in the line.

Squall lines can produce hail up to golf-ball size, heavy rainfall, and weak tornadoes, but they are best known as the producers of strong downdrafts. Occasionally, a strong downburst will accelerate a portion of the squall line ahead of the rest of the line. This produces what is called a bow echo. Bow echoes can develop with isolated cells as well as squall lines. Bow echoes are easily detected on radar but are difficult to observe visually.

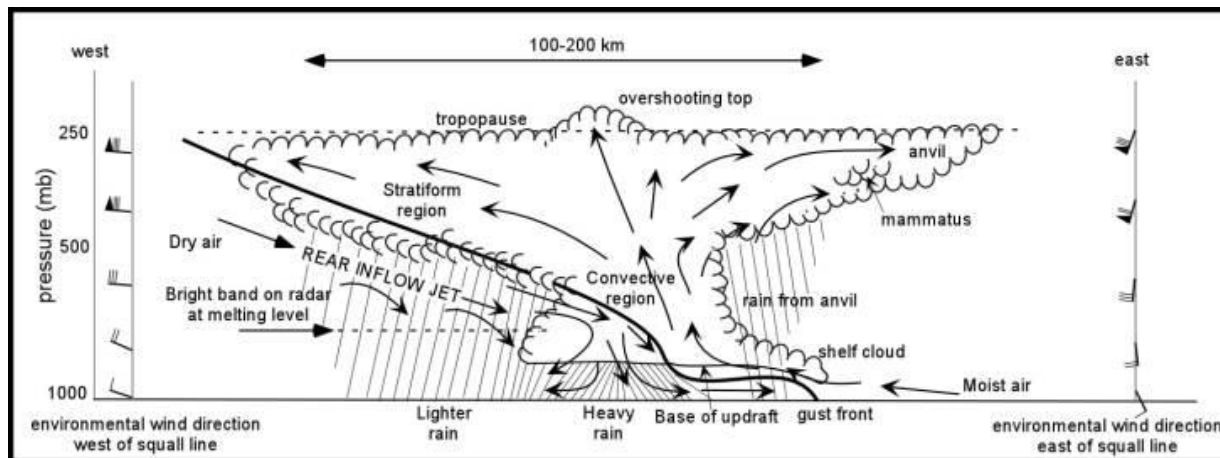
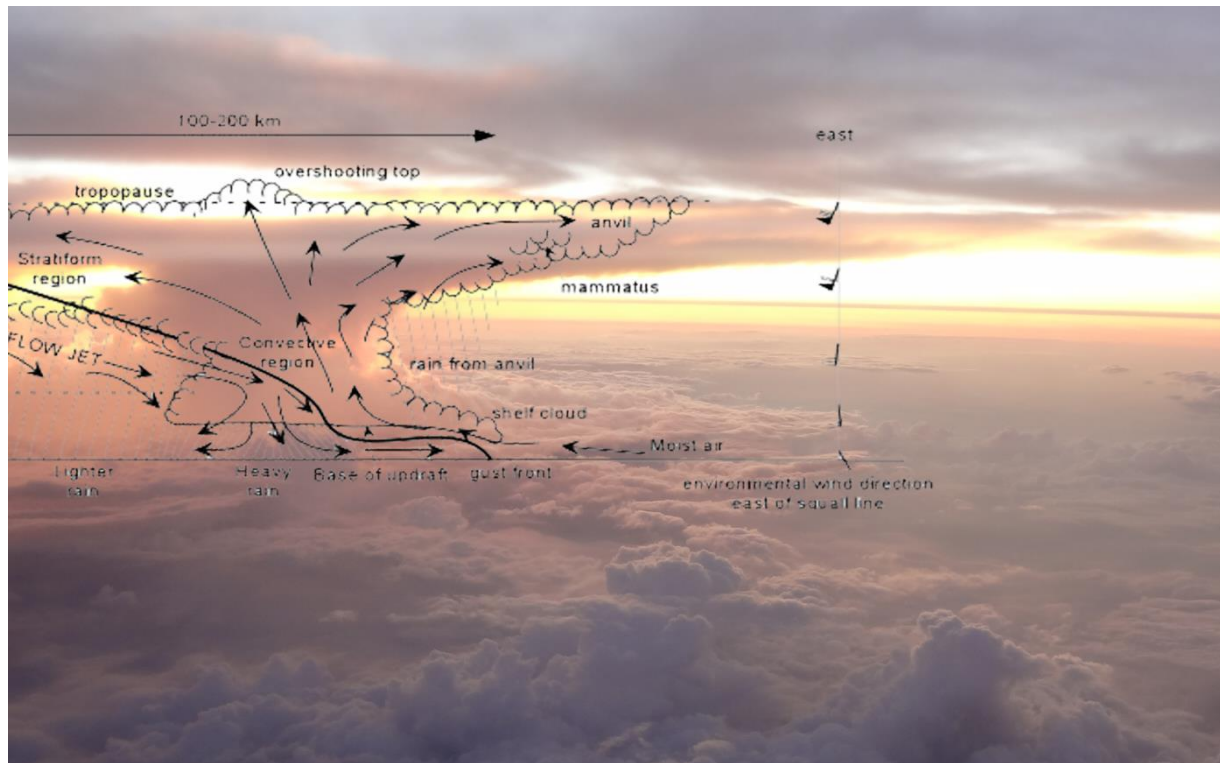
Courtesy of the NOAA National Severe Storms Laboratory (NSSL)



Multicell Line Schematic



Mechanics of a Storm Cell



Severe Thunderstorms

Produce 1" hail

OR

Surface Wind Gusts \geq 50 knots (58 mph)

OR

Produce a Tornado

Supercell Storm

- highly organized thunderstorm.
- similar to the single-cell storm as they both have one main updraft: the difference in the updraft of a supercell is that the updraft is extremely strong (150-175 mph)
- Supercells also differ in that they have persistent rotation of the updraft.
- The rotating updraft of a supercell (called a mesocyclone when visible on radar) helps the supercell to produce extreme severe weather events, such as large hail (more than 2 inches in diameter), strong downbursts of 80 miles an hour or more, and strong to violent tornadoes.

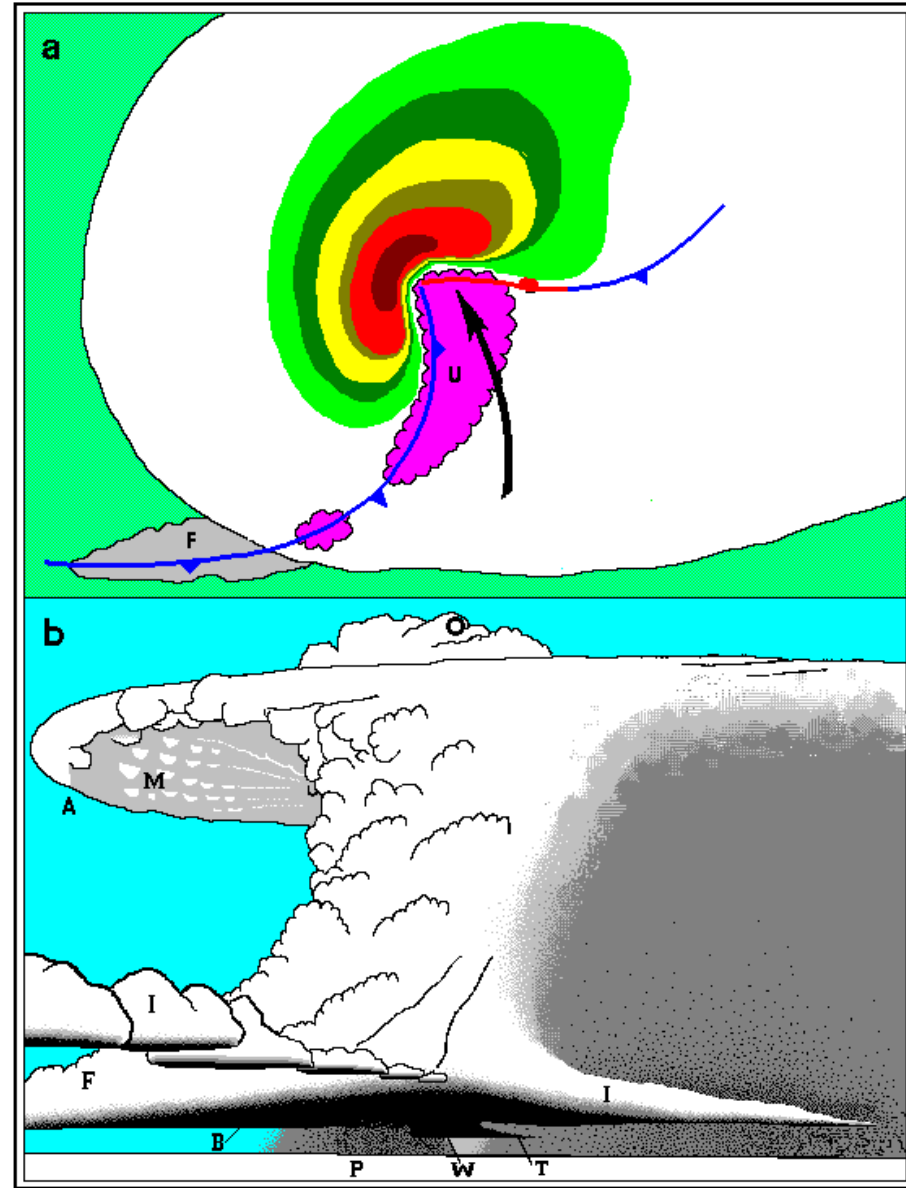
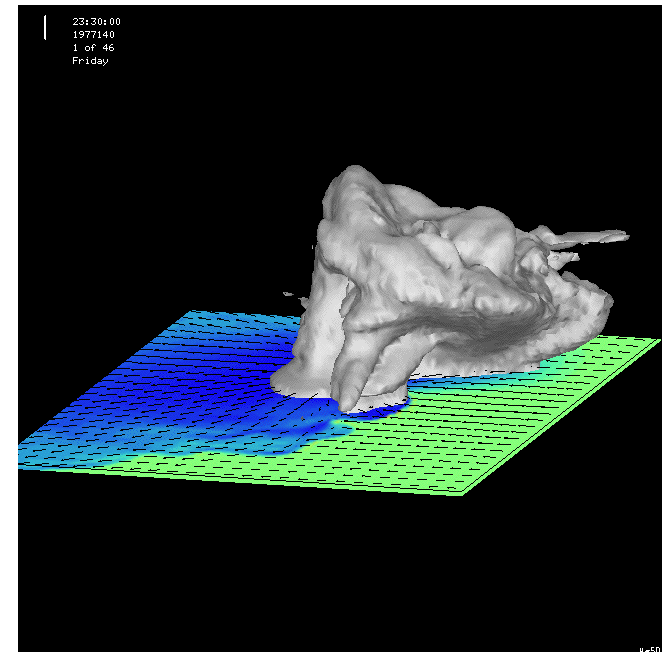
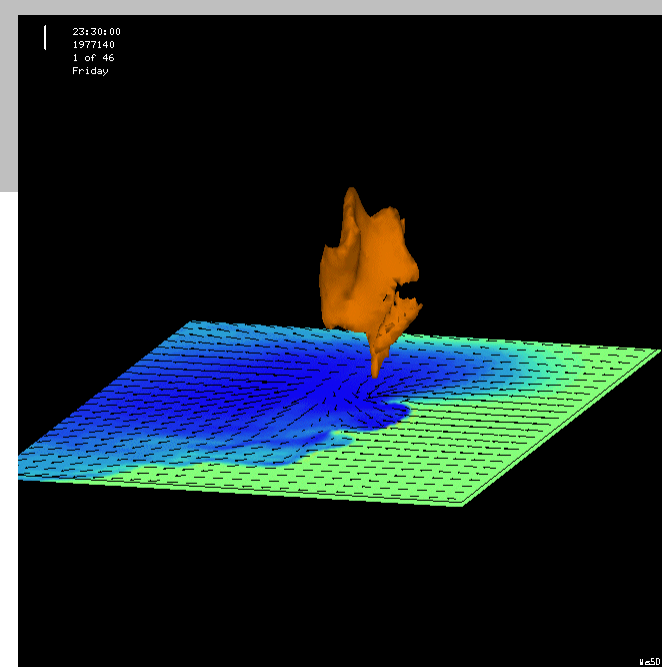


Fig. 3. HP storm (HP supercell). Schematic view from above of an HP storm (a), and visual features of the same storm as might be seen from the east or southeast (b). In (a), regions of radar reflectivity are colored according to intensity. Scalloped lines and violet shading indicate the region of main updraft (U). Surface inflow is indicated by arrow. Frontal symbols indicate location of gust front. Features in (b) include overshooting top (O), back-sheared anvil (A), wall cloud (W; often obscured by precipitation), tail cloud (T), inflow band (I), rain-free base (B), and regions of heavy precipitation (P). Compare with figures 5 and 7.

Supercell Continued

- Wind shear at different levels causes rotation of the strong updraft.
- As precipitation is produced in the updraft, the strong upper-level winds blow the precipitation downwind.
- Hardly any precipitation falls back down through the updraft, so the storm can survive for long periods of time.

The leading edge of the precipitation from a supercell is usually light rain. Heavier rain falls closer to the updraft with torrential rain and/or large hail immediately north and east of the main updraft. The area near the main updraft (typically towards the rear of the storm) is the preferred area for severe weather formation.

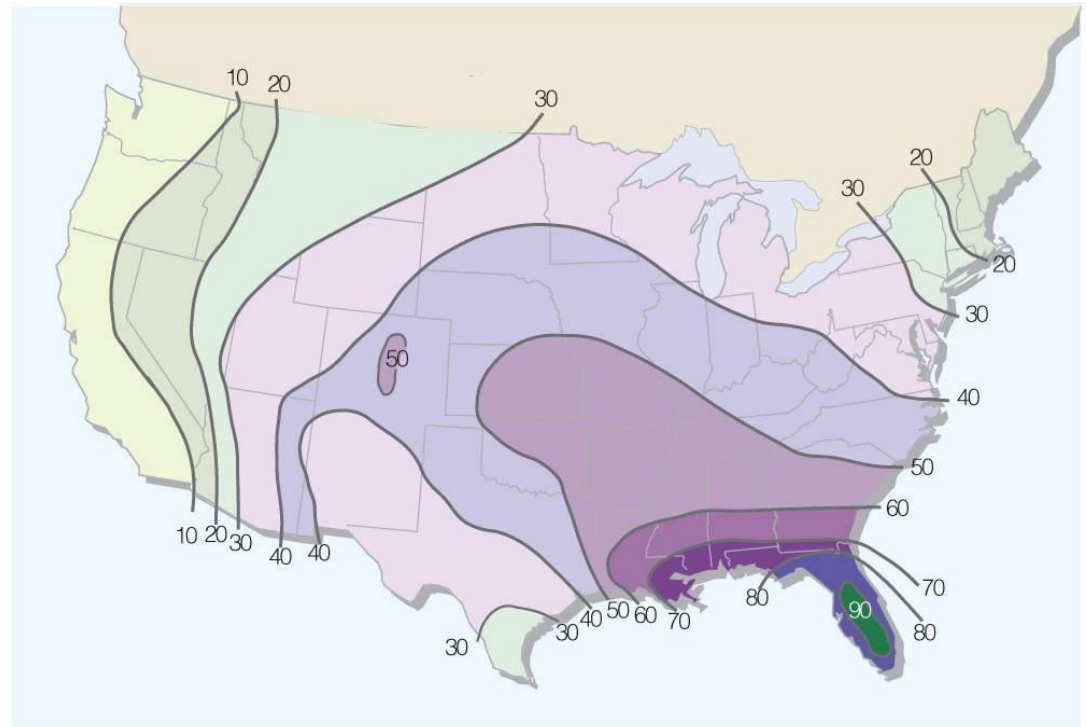


*Animations courtesy of UCLA
atmospheric sciences*

The Geography of Thunderstorms

This graphic shows the average number of days with Thunderstorms per year.

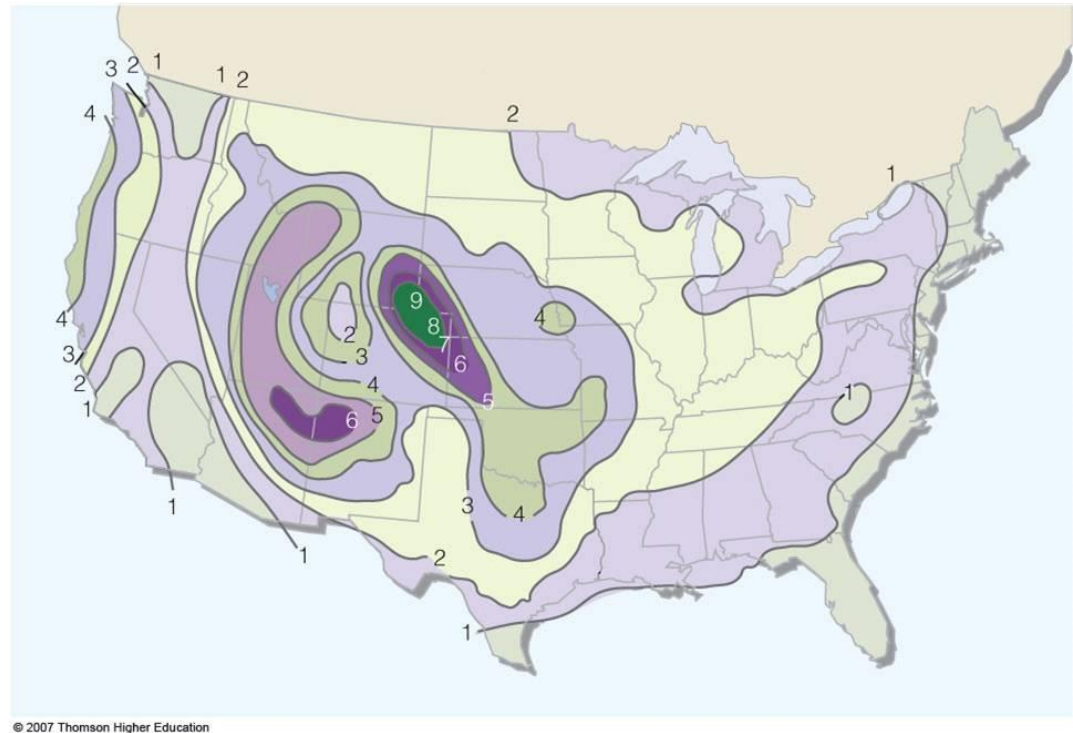
Notice that Florida and the Southeastern United States have the highest frequency of Thunderstorms – this is due to the intense moisture and heating that the region provides throughout the summer.



© 2007 Thomson Higher Education

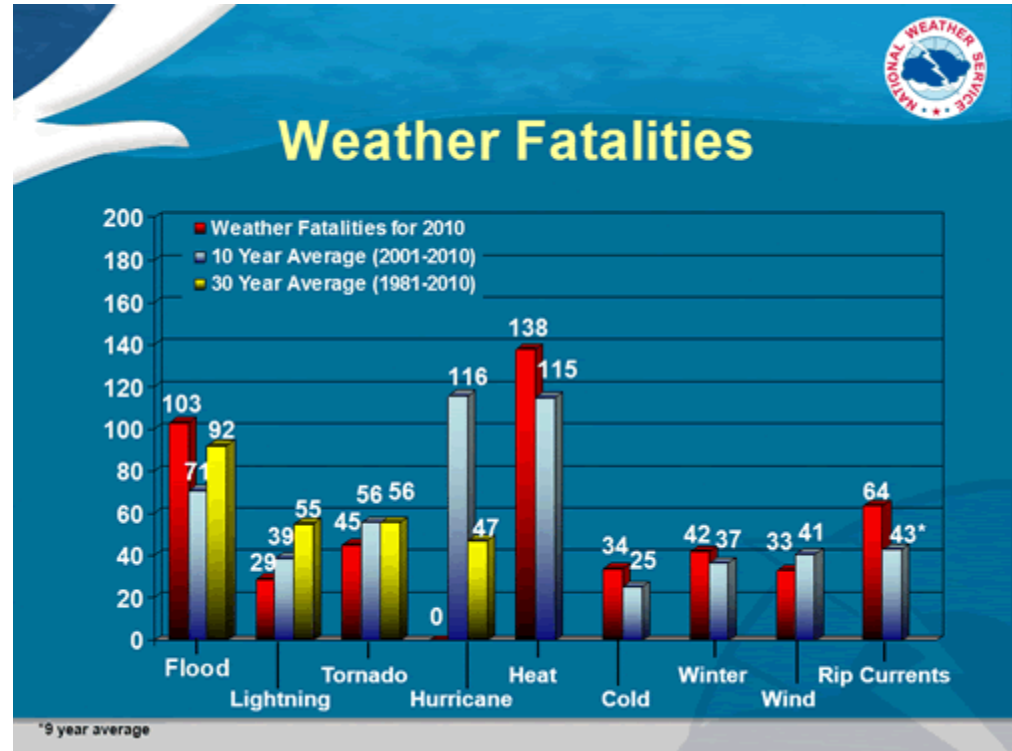
Geography of Severe Thunderstorms

- Although the frequency of Thunderstorms in the Southeast (especially in Florida) is higher, the frequency of *SEVERE* Thunderstorms is much higher over the Plains States.
- In warmer places like Florida, there is a much deeper layer of warm air, which melts any hail falling down from high altitudes. This lack of hail keeps the storm from being classified as Severe.



Severe Thunderstorm Hazards

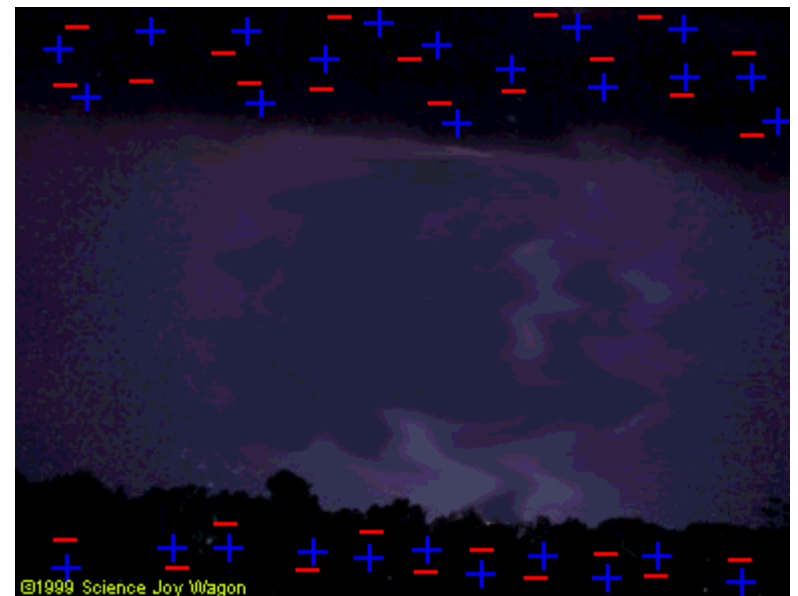
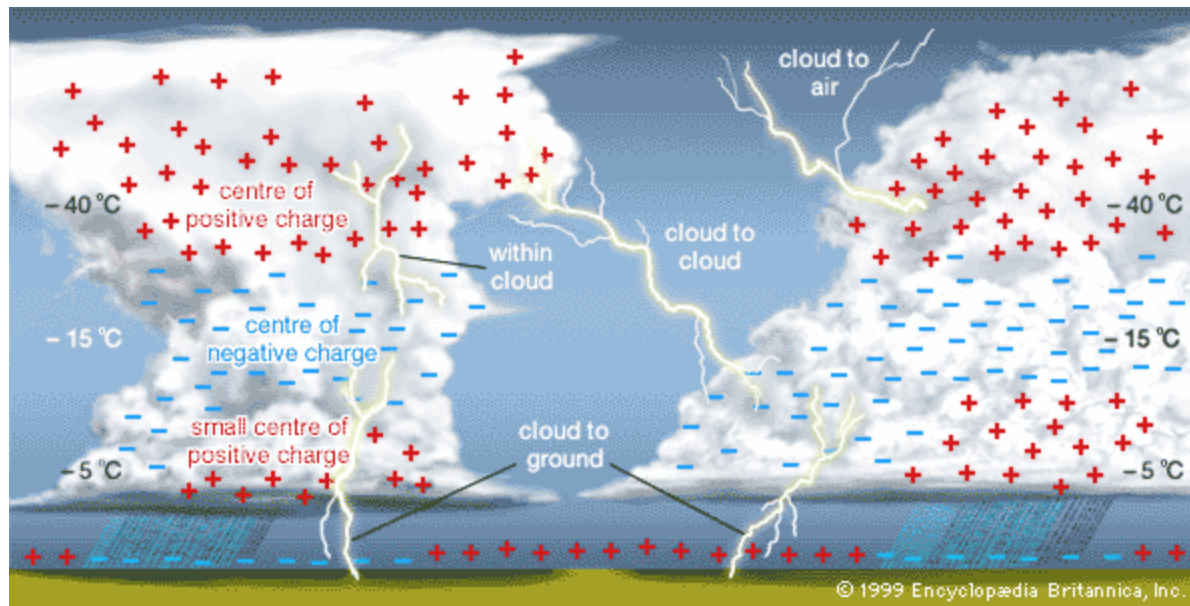
- Lightning
- Hail
- Flash Flooding
- Wind Damage
- Tornadoes



Lightning

Lightning

- Discharge of electricity that occurs in mature thunderstorms
- In a normal “fair weather” situation, the surface is generally negatively charged and the upper atmosphere is generally positively charged.
- Lightning occurs when separate regions containing opposite electrical charges exist within a cumulonimbus cloud.



Hail

Hail

Hailstones grow by collision with supercooled water drops. (Supercooled drops are liquid water drops surrounded by air that is below freezing - a common occurrence in thunderstorms.) There are two methods by which the hailstone grows: *wet growth* and *dry growth*.

Wet Growth

- In wet growth, the hailstone nucleus (a tiny piece of ice) is in a region where the air temperature is below freezing, but not super cooled. Upon colliding with a supercooled drop the water does not immediately freeze around the nucleus.
- Instead liquid water spreads across the tumbling hailstones and slowly freezes. Since the process is slow, air bubbles can escape resulting in a layer of clear ice.

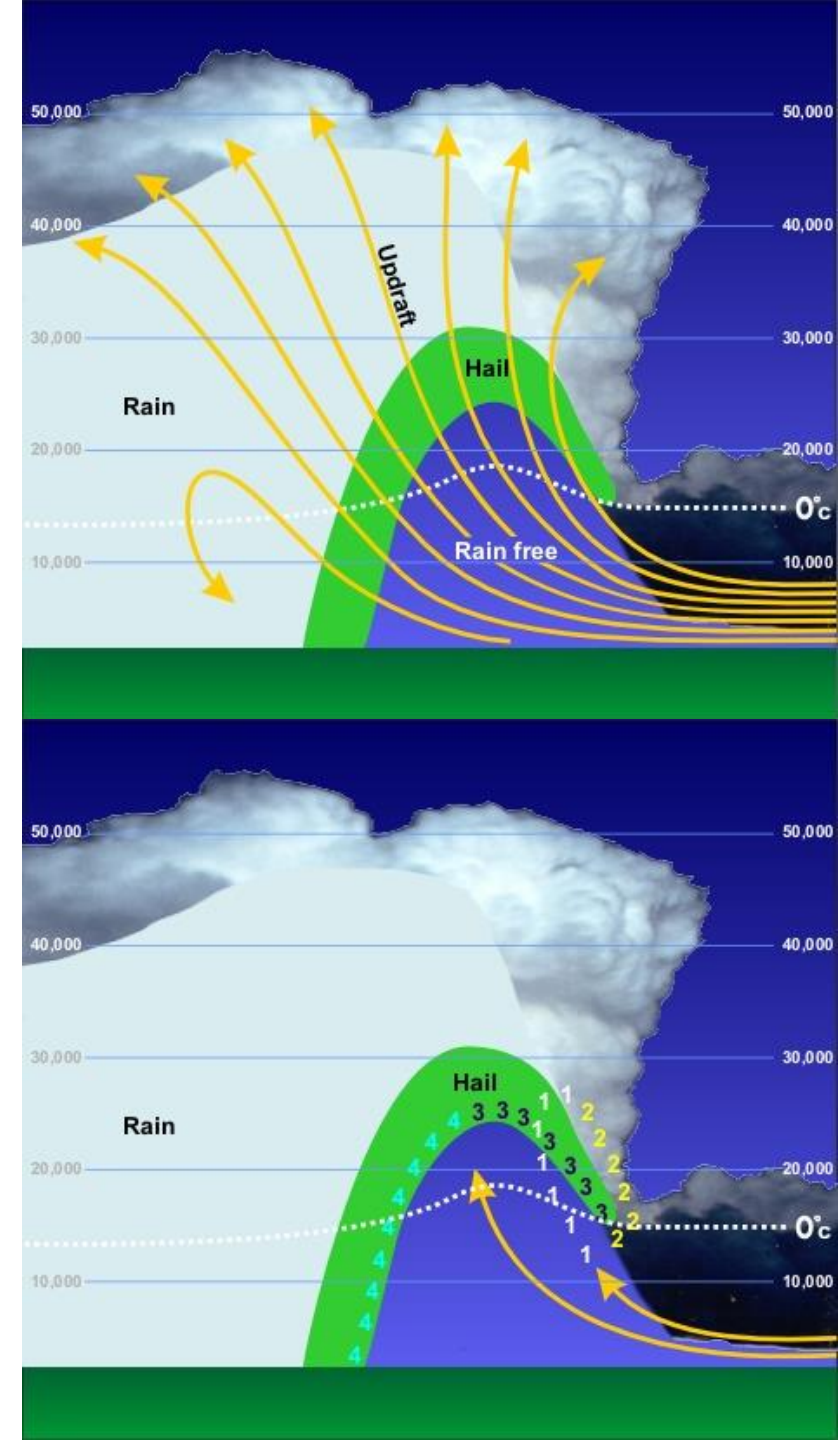
Dry Growth

- With dry growth, the air temperature is well below freezing and the water droplet immediately freezes as it collides with the nucleus. The air bubbles are "frozen" in place, leaving cloudy ice (Rime Ice)

Strong updrafts create a rain-free area in supercell thunderstorms (above right). This area is known as the **WER**, which stands for "weak echo region". This term, WER, comes from an apparently rain free region of a thunderstorm which is bounded on one side AND above by very intense precipitation indicated by a strong echo on radar.

This rain-free region is produced by the updraft and is what suspends rain and hail aloft producing the strong radar echo.

1. The hail nucleus, buoyed by the updraft is carried aloft by the updraft and begins to grow in size as it collides with supercooled raindrops and other small pieces of hail.
2. Sometimes the hailstone is blown out of the main updraft and begins to fall to the earth.
3. If the updraft is strong enough it will move the hailstone back into the cloud where it once again collides with water and hail and grows. This process may be repeated several times.
4. In all cases, when the hailstone can no longer be supported by the updraft it falls to the earth. The stronger the updraft, the larger the hailstones that can be produced by the thunderstorm.



Wind

Wind

Downbursts: strong winds produced by a downdraft over a horizontal area up to 6 miles (10 kilometers)

- Air rises, cools to point of condensation forming water droplets.
- Clouds grow vertically
- Near center of updraft, particles start to collide and coalesce, forming larger drops
- This continues until the drops can no longer be supported by the rising air
- Droplet begins to fall, friction causes rising air to start falling back towards surface. Some of this falling rain evaporates.
- This evaporation causes heat energy to be removed from the sinking air, cooling it further (Evaporational Cooling)
- This process causes increasingly faster falling of air, creating a downdraft that spreads out over the surface in the form of a gust front

Downbursts are broken down into two categories: Microbursts and Macrobusts

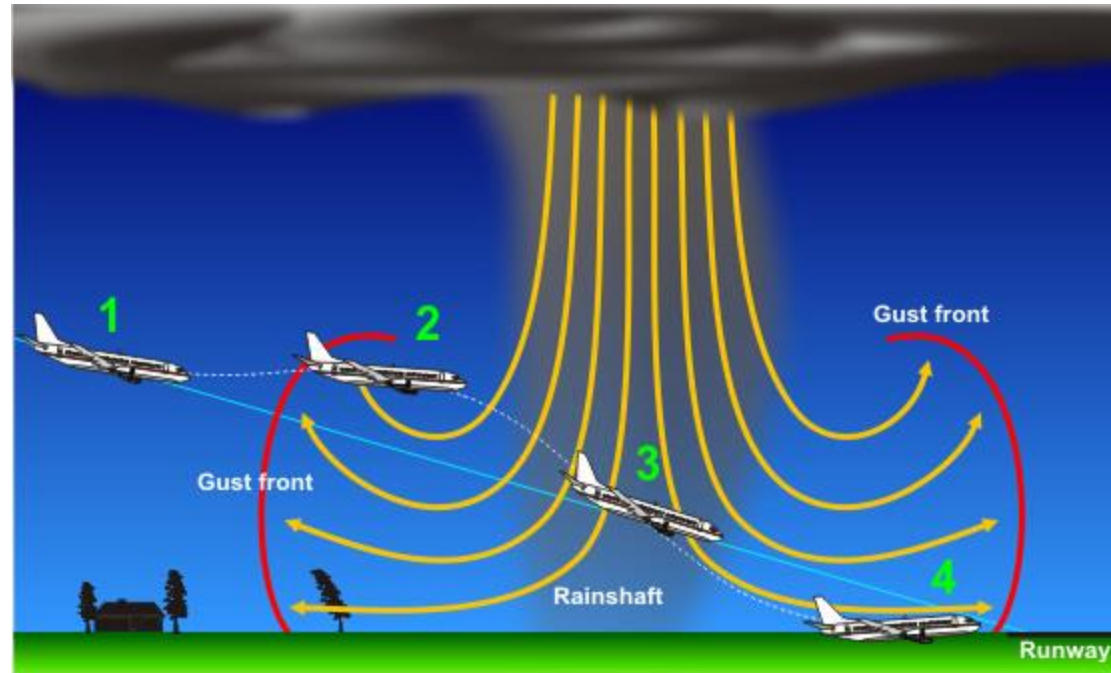
Microburst

A microburst is a small downburst with an outflow less than 2½ miles (4 kilometers) in horizontal diameter and last for only 2-5 minutes. Despite their small size, microbursts can produce destructive winds in excess of 160 mph. They can also create hazardous conditions for pilots and have been responsible for several disasters



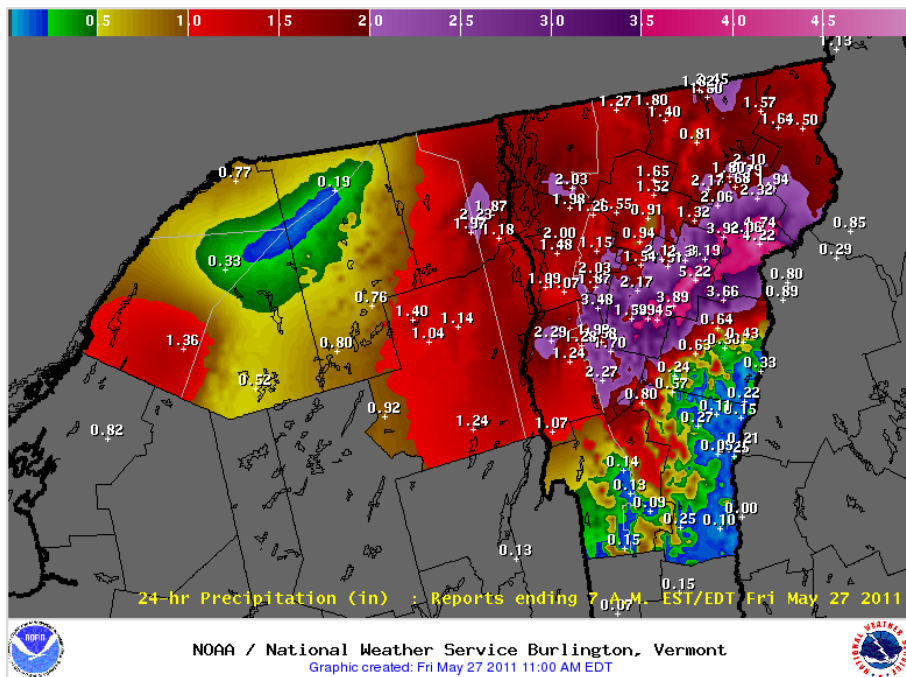
Macrobursts

A macroburst has a horizontal extent more than 2½ miles (4 km) in diameter. While not quite as strong as a microburst, they can produce winds as high as 130 mph (210 km/h). Damaging winds generally last longer, from 5 to 20 minutes, and produce tornado-like damage up to an EF-3 scale.



Flash Flooding

- Slow-moving thunderstorms have the potential to discharge large amounts of water over small areas.
- Multicell Systems can also produce a series of storms that hit the same area one after the other, commonly known as the “Train Effect.”

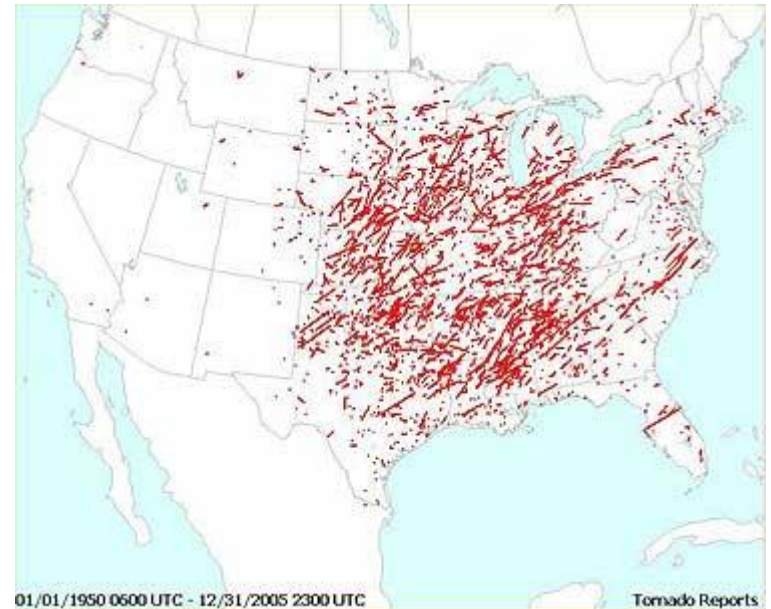


Tornado

Geography of Tornadoes

As with the Geography of Severe Thunderstorms, the conditions necessary to spawn Tornadoes are regionally dependent.

This map shows F3 tornado tracks between 1950 and 2005. Although there are some isolated tornadoes East of the Appalachian Mountains or West of the Great Plains, they are quite infrequent when compared to the statistics for the Mississippi River Valley.



*F3 Tornadoes between 1950 and 2005
University of Nebraska-Lincoln High Plains
Regional Climate Center*

Supercell Tornadogenesis

Tornadoes generally form from Supercell Thunderstorms, although there are some that don't. Those that do are said to form by Supercell Tornadogenesis:

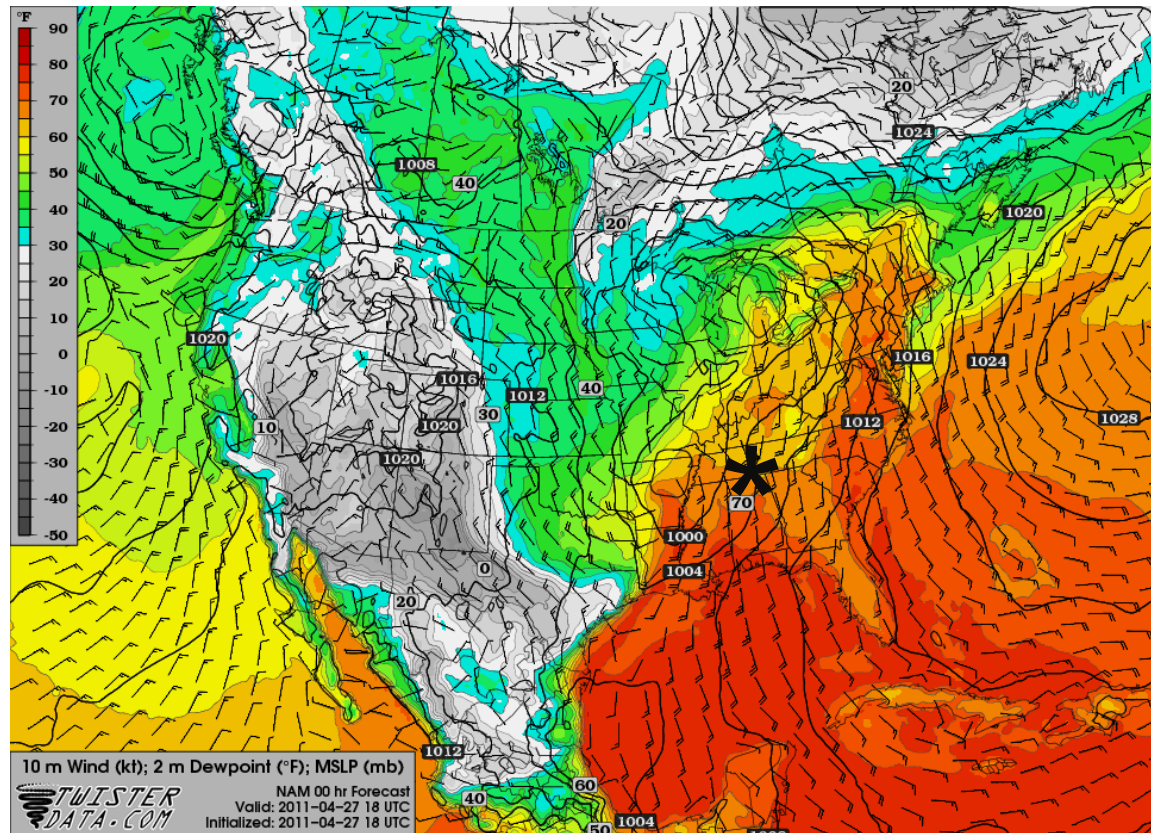
- Wind shear causes different directions and wind speeds at different altitudes
- The updraft lifts the rotating column of air creating both cyclonic and anti-cyclonic rotation
- Direction shear amplifies the cyclonic rotation and diminishes the anti-cyclonic rotation, leaving just the cyclonic rotation
- This cyclonic rotation becomes known as the mesocyclone

Damage f scale		Little Damage	Minor Damage	Roof Gone	Walls Collapse	Blown Down	Blown Away	
		f0	f1	f2	f3	f4	f5	
Windspeed F scale		17 m/s	32	50	70	92	116	142
		F0	F1	F2	F3	F4	F5	
		40 mph	73	113	158	207	261	319
<div> <div></div> <div>To convert f scale into F scale, add the appropriate number</div> </div>								
Weak Outbuilding	-3	f3	f4	f5	f5	f5	f5	
Strong Outbuilding	-2	f2	f3	f4	f5	f5	f5	
Weak Framehouse	-1	f1	f2	f3	f4	f5	f5	
Strong Framehouse	0	F0	F1	F2	F3	F4	F5	
Brick Structure	+1	-	f0	f1	f2	f3	f4	
Concrete Building	+2	-	-	f0	f1	f2	f3	

Fig. 2.4-1 The Fujita tornado scale (F scale) pegged to damage-causing windspeeds. The extent of damage expressed by the damage scale (f scale) varies with both windspeed and the strength of structures.

Advanced Background on Severe Storms

Back to Moisture



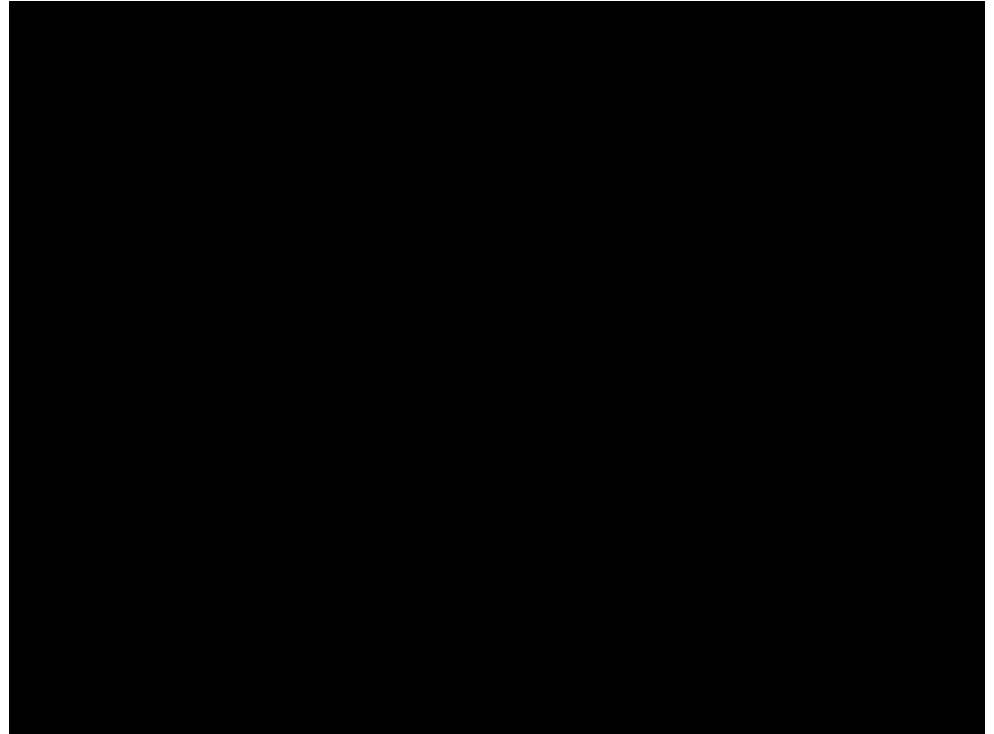
Generally speaking, surface moisture with dew points $> 55^{\circ}$ F are required to fuel dangerous Severe Thunderstorms. At 7:00 a.m. on April 27, 2011, the dew point in Tuscaloosa, Al was already over 70° F

Why? Moist Adiabatic Lapse Rate has a more stable parcel lapse rate with lower Dewpoints.

Understanding Vertical Development and Severe Potential

Level of Free Convection (LFC)

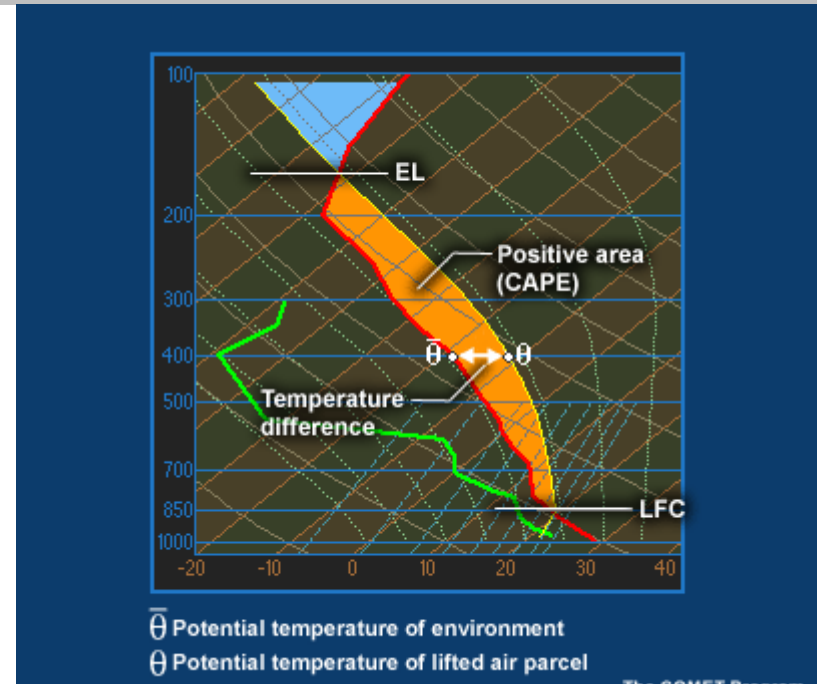
- Once the air parcel crosses over from the Dry Adabat to the Moist Adabat, the Lifting Condensateion Level (LCL) is reached.
- As the parcel continues to rise, it becomes warmer and less dense than the surrounding air. This is the definition of instability.
- If there is no convective inhibition acting on the parcel, the LCL becomes known as the Level of Free Convection (LFC)



Equilibrium Line

When the temperature of the rising air parcel finally intersects the environmental temperature at altitude, the Equilibrium Line (EL) is met.

At this point, the parcel is no longer warmer than its surroundings and thus flattens out and begins to sink. It is at this point that the classic flat-topped anvil cloud begins to form.



However, in strong convective updrafts, the velocity of air ascending towards the EL can be so high that it is able to “pierce” the boundary and shoot up beyond the flat top. This is easily seen in satellite imagery and is indicative of a Severe Thunderstorm.



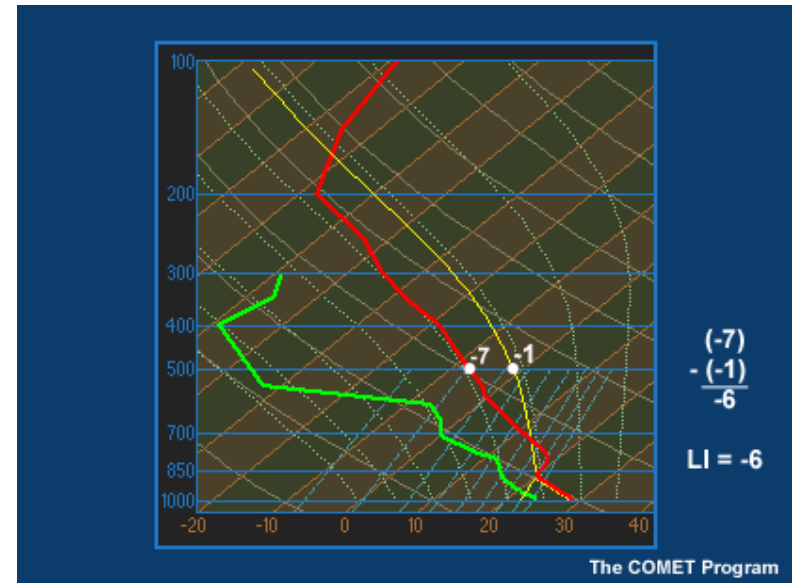
Lifted Index

The Lifted Index (LI) refers to the difference in temperature between an air parcel lifted adiabatically and the temperature of the environment at a given pressure height, usually after the LCF is reached.

- If the value is *positive*, the atmosphere is *stable*, the buoyancy is *negative*, and the parcel will *sink*.
- If the value is *negative*, the atmosphere is *unstable*, the buoyancy is *positive*, and the parcel will *rise*.

LI values less than -6 are generally favorable for Severe Weather, and LI values of -10 to -12 are not uncommon over the Plains States

Although LI is easy to calculate, it only gives information about *one level* of the troposphere and thus does not always portray an accurate representation of the convective power of a given place and time.



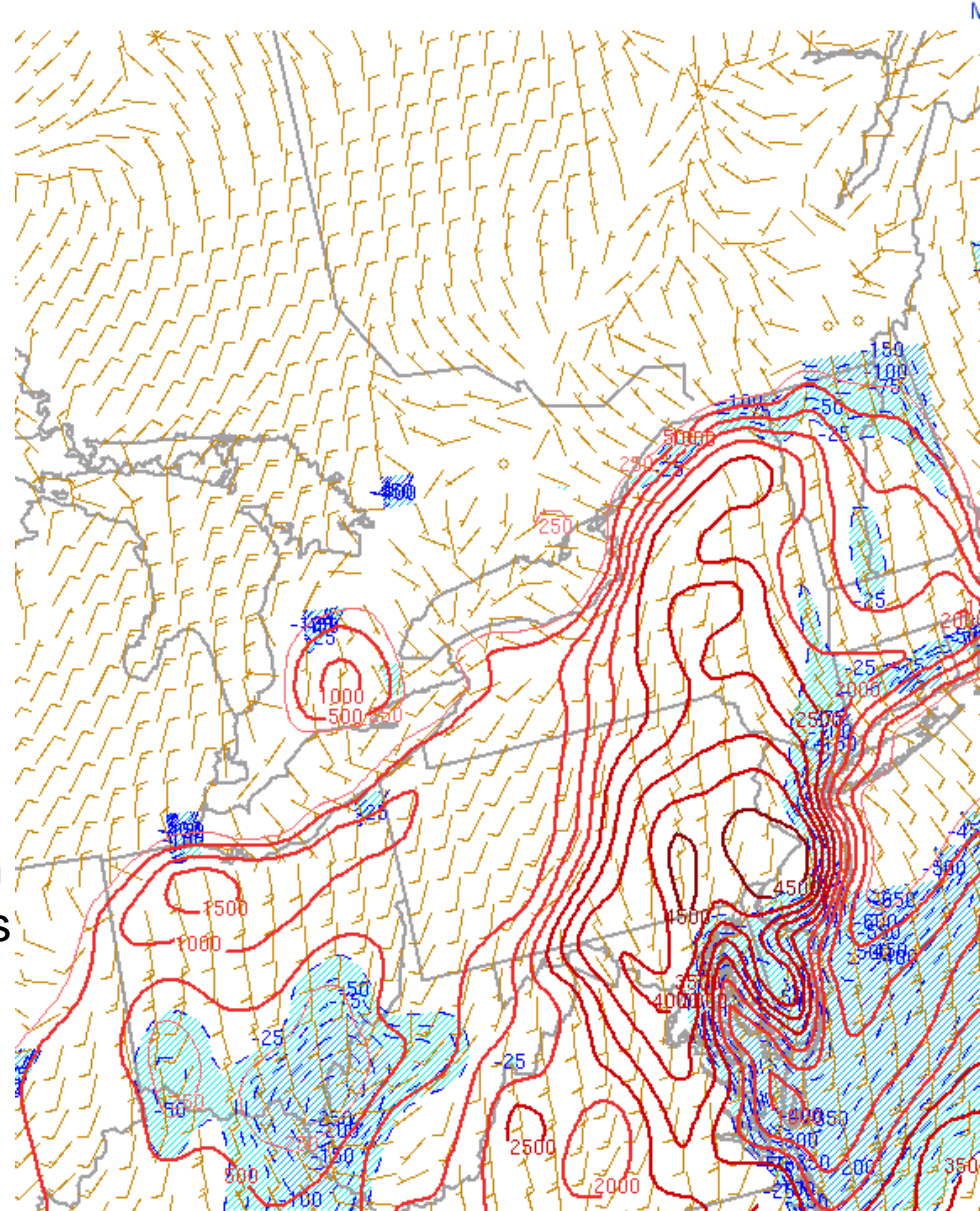
CAPE

Convective Available Potential Energy

This is a measurement of the total difference in temperature between the air parcel and the environmental temperature for the *entire distance* from the LFC to the EL.

CAPE is measured in units of Joules/Kg, and is often in the range of 1000-2000 Joules/Kg. CAPE values higher than 5000 Joules/Kg are possible however.

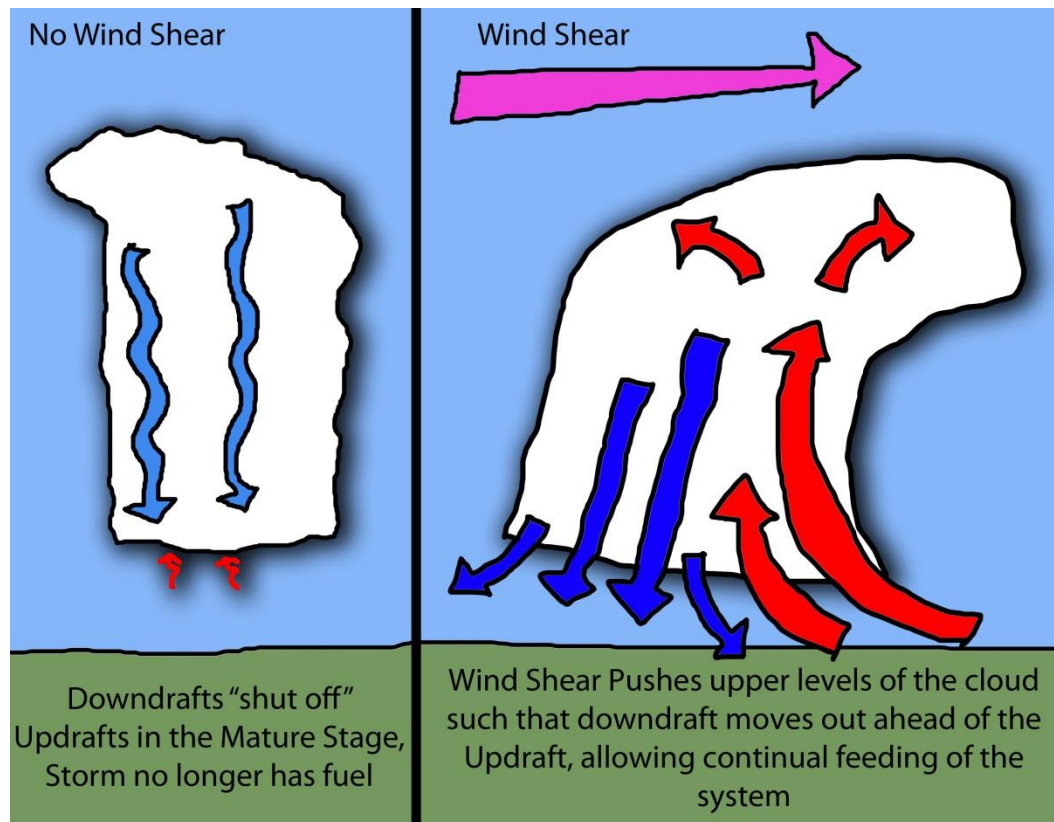
Understanding about how much Energy a convective system has in combination with other observations can give meteorologists an important understanding of what the system may develop as time goes on.



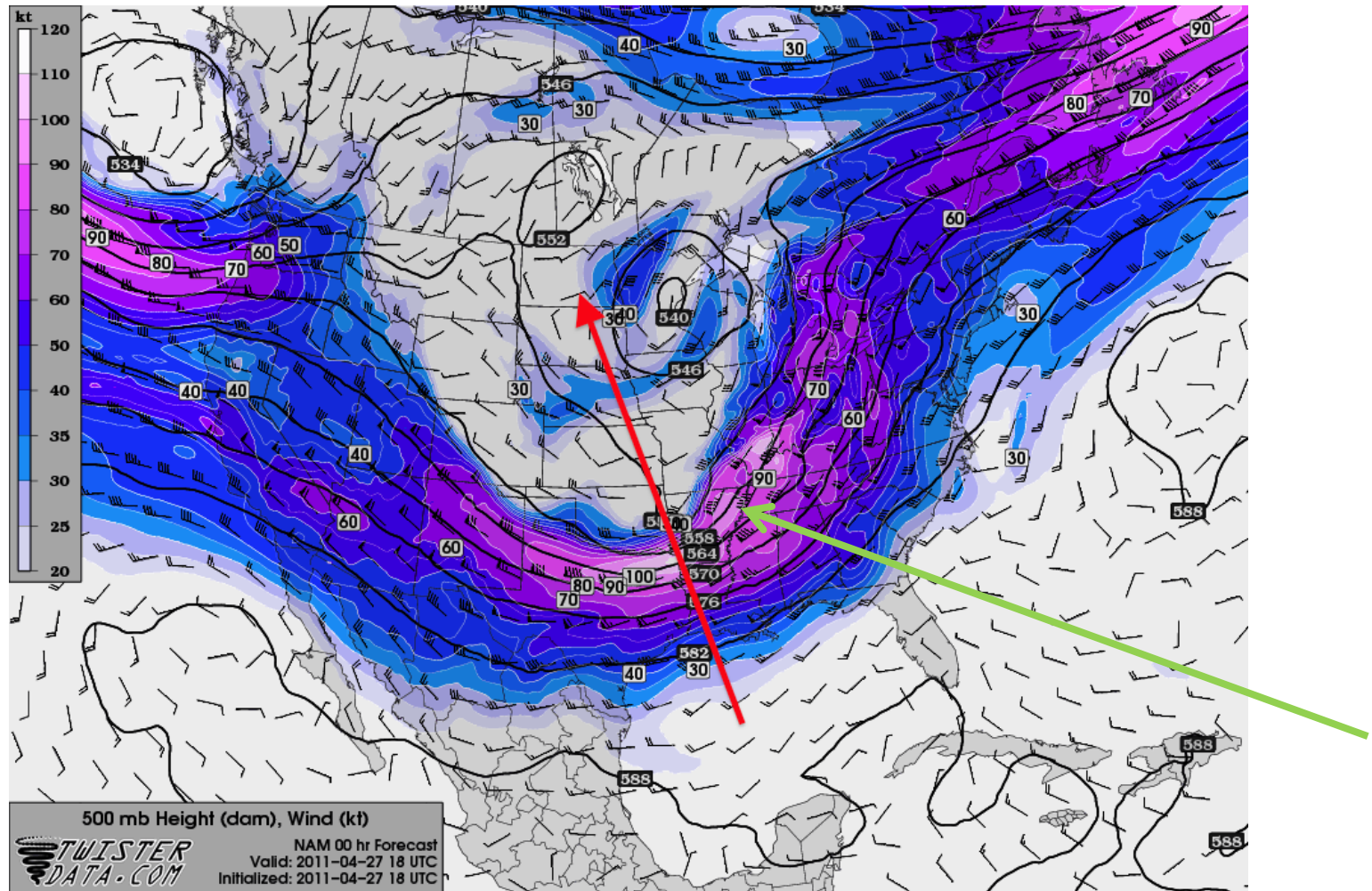
110526/2000 SBCAPE (contour) and SBCIN (J/kg, shaded)

Wind Shear

- Change in either Speed or Direction of wind with increasing height
- It is calculated by determining the change in wind speed and direction from the surface to 6km (slightly above the standard height of 500mb)
- Values above 35 knots are generally seen in long-lasting supercells.



Jet Stream



This map shows the 500mb Jet Stream on April 27, 2011 – Notice the Concentration of Strong Winds (60 – 80 knots) over Tuscaloosa, Alabama... The Red Arrows shows center of Trough, Green Arrow shows High Upper Level winds over Tuscaloosa.

Advanced Background on Tornadoes

Tornadic Formation

Dynamic Pipe Effect

- Development begins when horizontal winds coming together from different directions are strong at 3-4 km above the ground, but weak or absent at the ground.
- This causes rotation aloft
- Young tornado builds downward via the Dynamic Pipe Effect (DPE):
 - Air is *unable* to pass through the sides of the rotating walls of the belt, but can pass through the ends like a pipe.
 - The vacuum created within the pipe draws weakly rotating air up into the pipe's lower end. This causes the air to spin faster and integrate into the pipe.
 - This process of air being sucked up continues until the pipe contacts the ground.

Bottom Up Formation

- This process is believed to occur as a result of tilting of the horizontal circulation along the forward flank gust front as it moves under the ascending updraft.
- Air behind the gust front is cool, negatively buoyant, and descending. In the updraft air adjacent to the gust front, air is warm, positively buoyant, and ascending.
- This leads to a sense of rotation along the interface between the gust front and warm air.
- If this region advances under the strong updraft of the mid-level mesocyclone, it can be tilted to the vertical, leading to rapid rotation very close to earth's surface.
- With further vortex stretching, the rotation can spin up to become a 'bottom up' tornado.

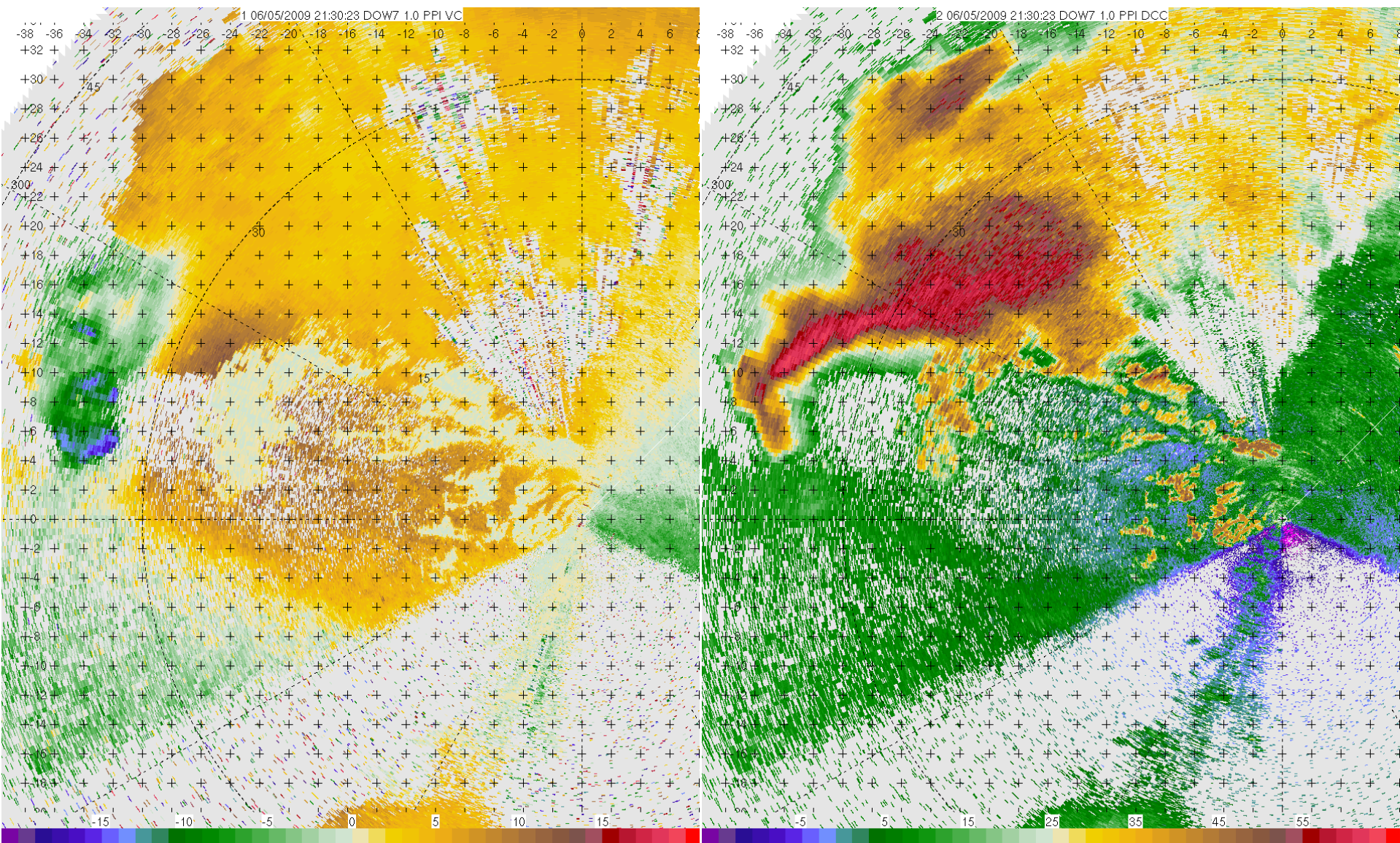
Vortex Breakdown

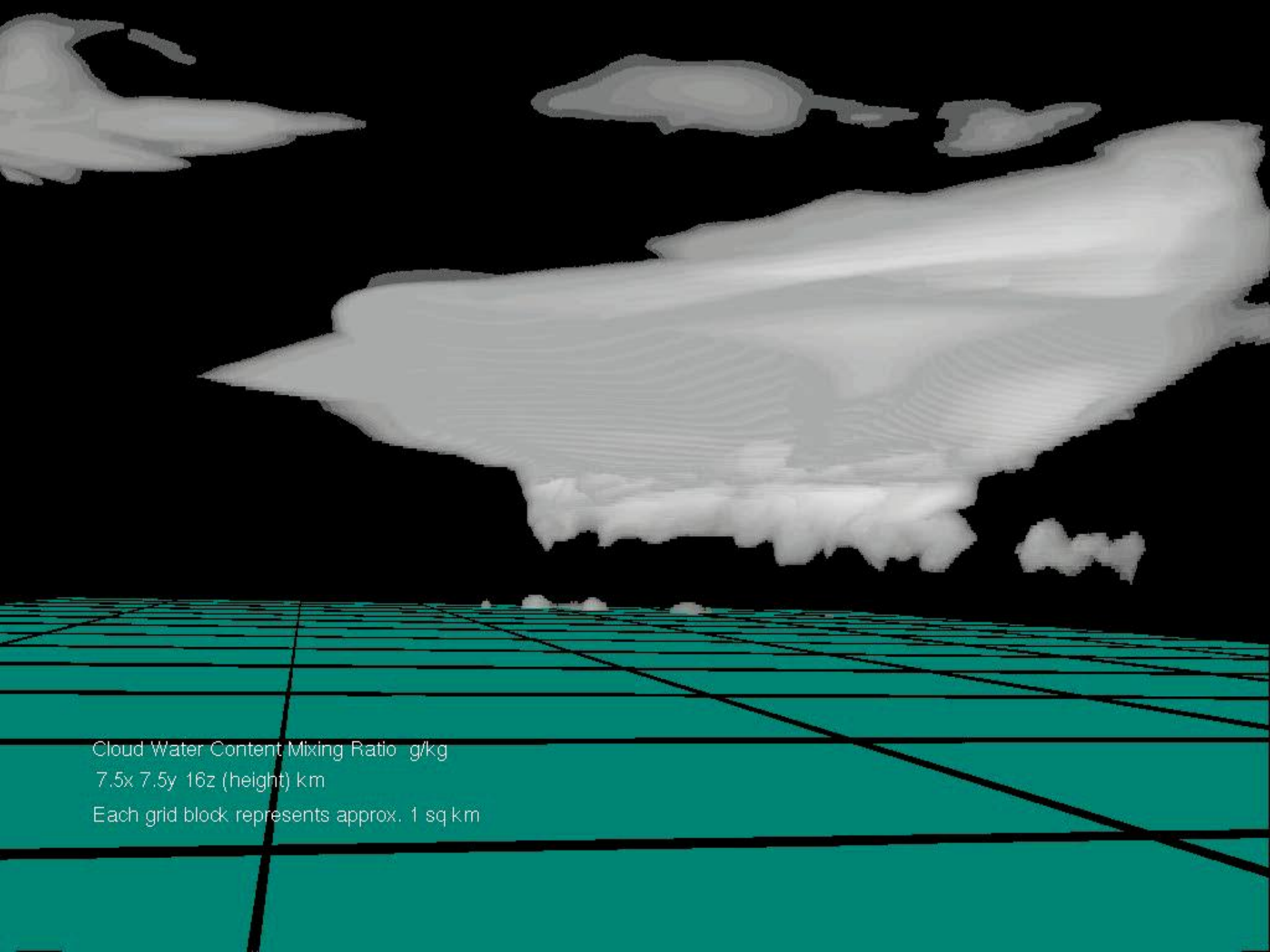
- Most tornadoes remain as a narrow column of rising rotation air, but vortex breakdown can occur in some tornadoes, which can cause the tornado to expand to a very large size.
- The tornado vortex transforms from a rotating updraft to a structure with a downdraft at its core.
- Updraft displaced to the outside of the central downdraft.
- When the central downdraft reaches the ground, strong wind shear between the downdraft and updraft areas lead to the formation of smaller vortices, called suction vortices.
- The strongest winds in tornadoes occur in suction vortices (can be 290mph).

Hook Echo

The “Hook Echo” is a region of a tornadic supercell that generally appears as a “hook-like” curl along the southwestern edge of the system when viewed in a RADAR image. It almost always signals an impending Tornado.

When Hook Echos are observed in a system, the NWS will issue a Tornado Warning for that area.





Cloud Water Content Mixing Ratio g/kg
7.5x 7.5y 16z (height) km
Each grid block represents approx. 1 sq km