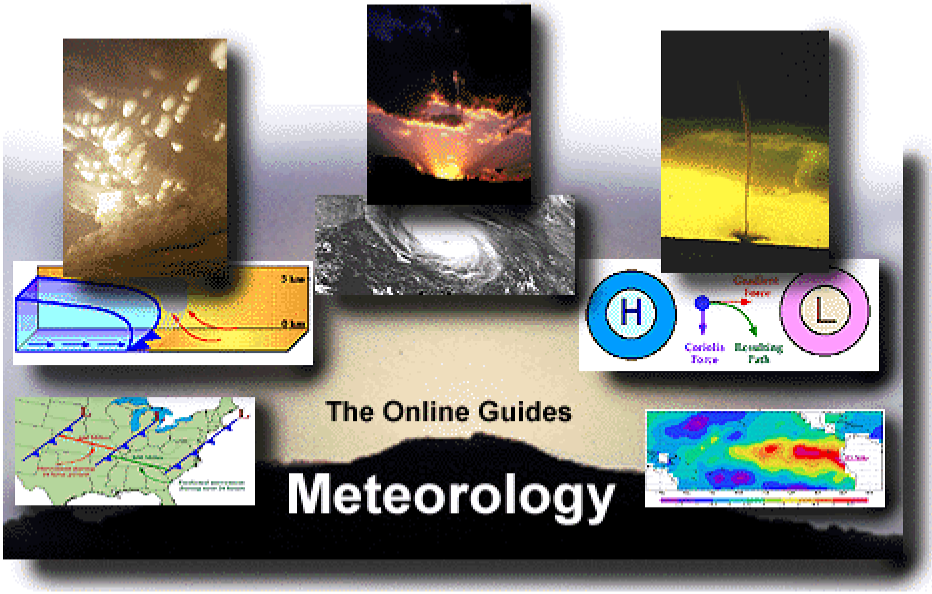


Graphic by: Steven E. Hall

The Online Meteorology Guide is a collection of web-based instructional modules that use multimedia technology and the dynamic capabilities of the web. These resources incorporate text, colorful diagrams, animations, computer simulations, audio and video to introduce fundamental concepts in the atmospheric sciences. Selected pages link to (or will soon link to) relevant classroom activities and current weather products to reinforce topics discussed in the modules and allow the user to apply what has been learned to real-time weather data. Available modules include:

Modules
Last Update:
09/02/99

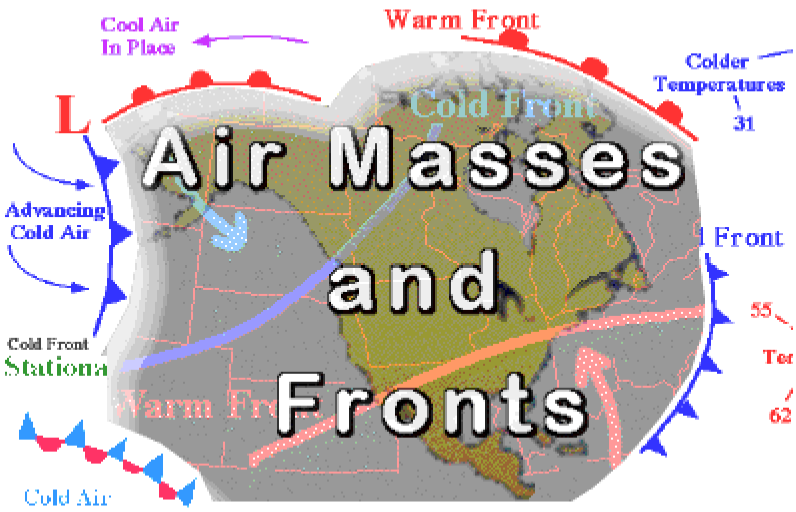
The anatomy of hurricanes, how they develop and why they are so dangerous.

El Niño
Why El Niño develops and the global impact it has on weather patterns and economics.

Hydrologic Cycle
The circulation and conservation of the earth's water.

The target audience for the Online Meteorology Guide is high school and undergraduate level students. However, these resources have been used by instructors throughout K-12, undergraduate and graduate level education. Contents of the Online Meteorology Guide were developed by graduate students and faculty through our efforts in the Collaborative Visualization Project (CoVis), which was funded by the National Science Foundation. These resources have been reviewed by faculty and scientists at the University of Illinois and the Illinois State Water Survey. Many of these resources were tested in a classroom environment and have been modified based upon teacher and student feedback.

The navigation menu (left) for this module is called "Meteorology" and the available modules are listed as menu items, beginning with this introduction. Click on the menu item of interest to go to that particular module. In addition, this entire web server is accessible in both "graphics" and "text"-based modes, a feature controlled from the blue "User Interface" menu (located beneath the black navigation menus). More information about the user interface options, the navigation system, or WW2010 in general is accessible from About This Server.



Graphic by: Yiqi Shao

The purpose of this module is to introduce air masses, where they originate from and how they are modified. Clashing air masses in the middle latitudes spark interesting weather events and the boundaries separating these air masses are known as fronts. This module examines fronts, with detailed explanations about cold fronts and warm fronts. Finally, different types of advection are introduced; temperature, moisture and voriticity advection. The Air Masses and Fronts module has been organized into the following sections:

Sections
Last Update:
07/27/97

Air Masses
Air masses that commonly influence weather in the United States.

Fronts
Boundaries separating air masses. Includes warm fronts, cold fronts, occluded and stationary fronts and dry lines.

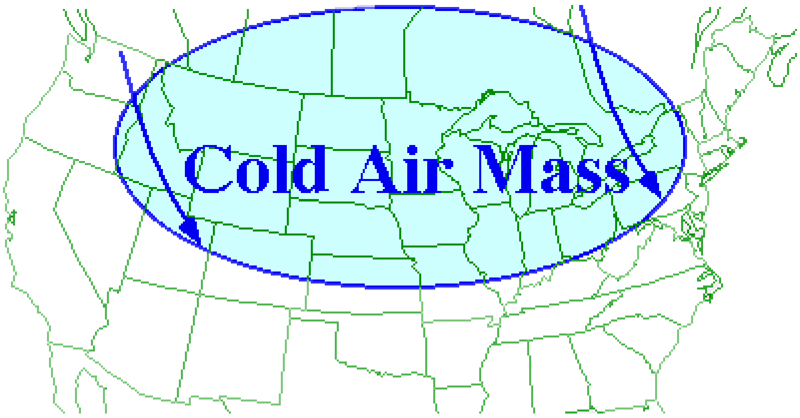
Advection
Introduces advection and describes the differences between warm and cold advection.

Acknowledgments
Those who contributed to the development of this module.

The navigation menu (left) for this module is called "Air Masses, Fronts" and the menu items are arranged in a recommended sequence, beginning with this introduction. In addition, this entire web server is accessible in both "graphics" and "text"-based modes, a feature controlled from the blue "User Interface" menu (located beneath the black navigation menus). More information about the user interface options, the navigation system, or WW2010 in general is accessible from About This Server.

Air Masses
uniform bodies of air

An air mass is a large body of air that has similar temperature and moisture properties throughout. The best source regions for air masses are large flat areas where air can be stagnant long enough to take on the characteristics of the surface below. Maritime tropical air masses (mT), for example, develop over the subtropical oceans and transport heat and moisture northward into the U.S.. In contrast, continental polar air masses (cP), which originate over the northern plains of Canada, transport colder and drier air southward.

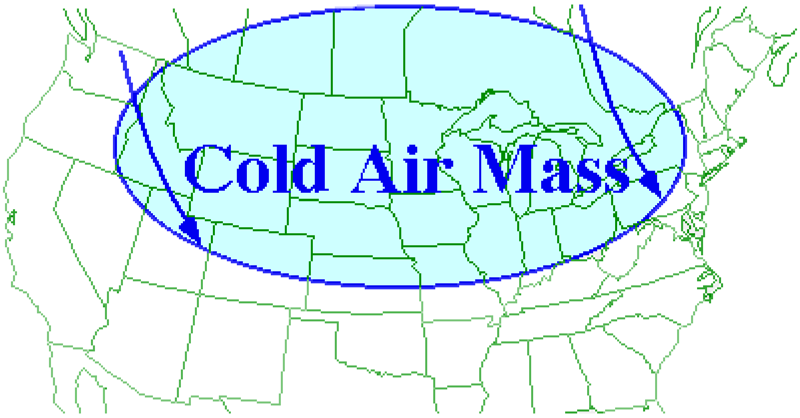


Once an air mass moves out of its source region, it is modified as it encounters surface conditions different than those found in the source region. For example, as a polar air mass moves southward, it encounters warmer land masses and consequently, is heated by the ground below. Air masses typically clash in the middle latitudes, producing some very interesting weather.

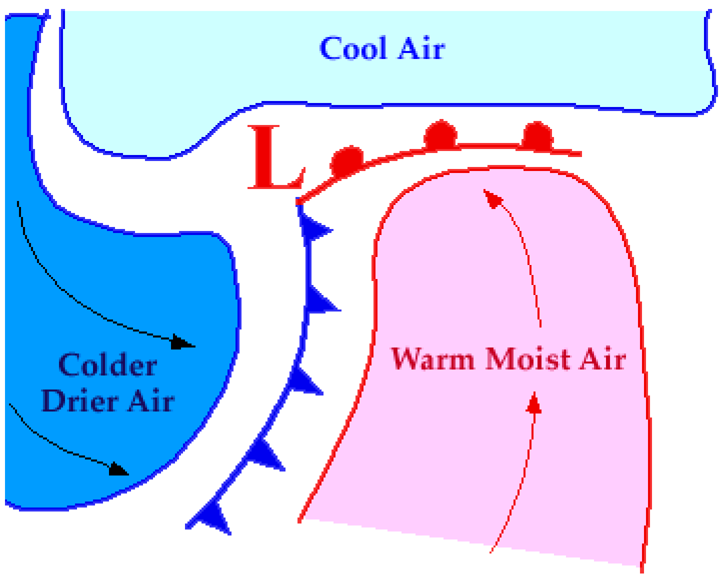
Continental Polar Air Masses

cold temperatures and little moisture

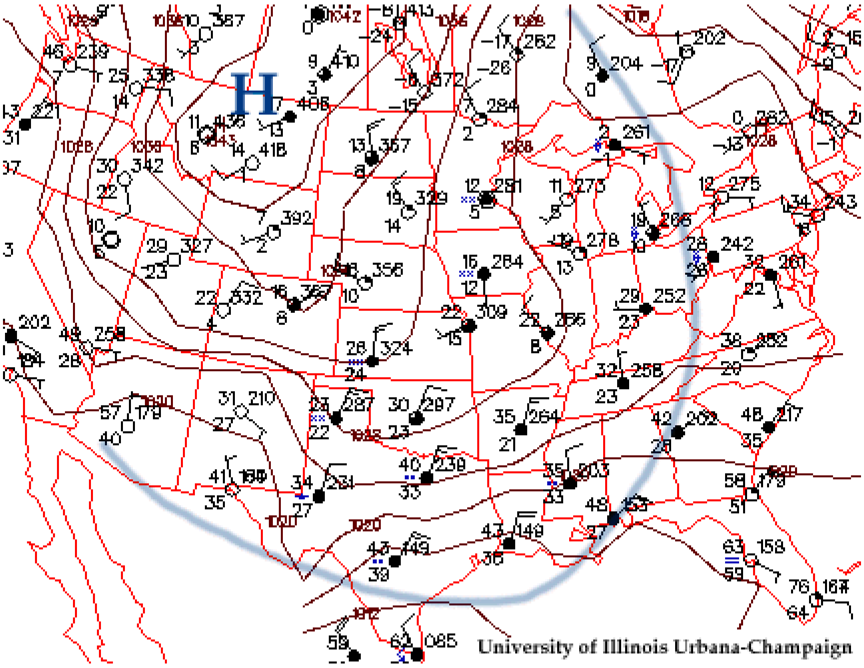
Those who live in northern portions of the United States expect cold weather during the winter months. These conditions usually result from the invasion of cold arctic air masses that originate from the snow covered regions of northern Canada. Because of the long winter nights and strong radiational cooling found in these regions, the overlying air becomes very cold and very stable. The longer this process continues, the colder the developing air mass becomes, until changing weather patterns transport the arctic air mass southward.



Arctic air masses move about as a shallow area of high pressure, commonly known as an "Arctic High". Northerly winds associated with a cyclone and trailing anticyclone, (the center of the arctic air mass), transport the colder air southward. Since the terrain is generally flat and free of any significant topographical features, arctic air masses entering the United States and can easily slide all the way to Texas and Florida.



Below is a map of surface observations and the leading edge of a large arctic air mass blanketing much of the United States has been highlighted by the blue line. The center of this air mass is a high pressure center located in northern Montana (indicated by the blue "H").

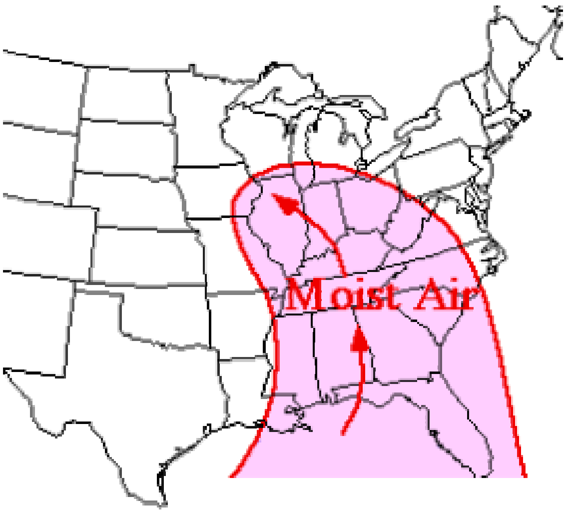


From these reports, we see that most stations in the arctic air mass generally exhibit relatively colder temperatures, with lower dew point temperatures, and winds generally out of the north. Notice that on the other side of the blue boundary, outside of this air mass, surface conditions are much different, which indicates the presence of an entirely different air mass.

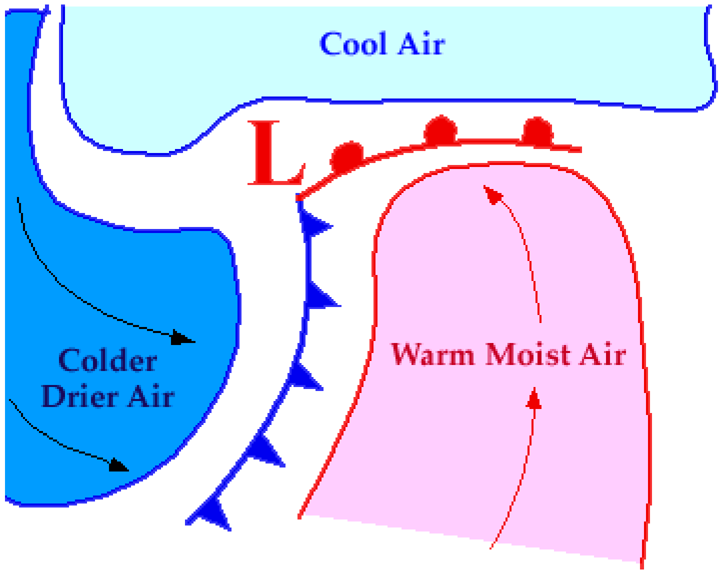
Maritime Tropical Air Masses

warm temperatures and rich in moisture

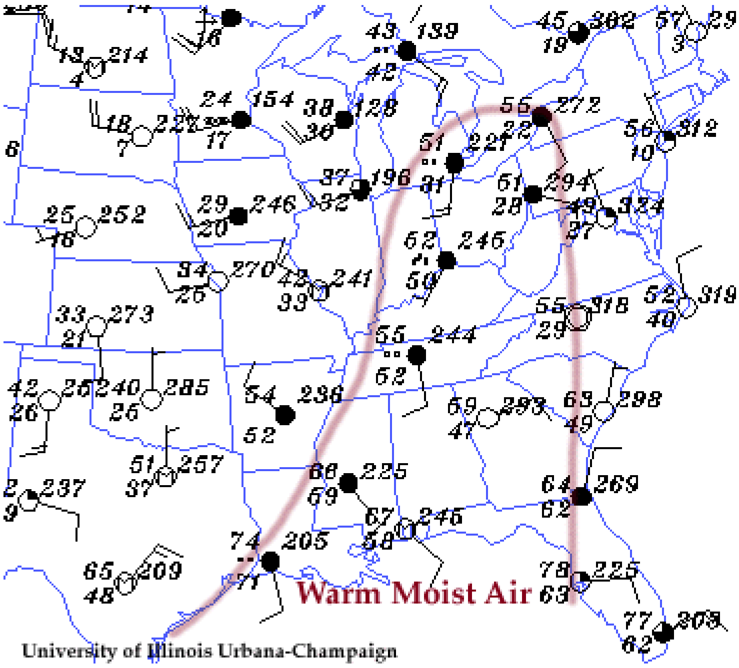
Maritime tropical air masses originate over the warm waters of the tropics and Gulf of Mexico, where heat and moisture are transferred to the overlying air from the waters below. The northward movement of tropical air masses transports warm moist air into the United States, increasing the potential for precipitation.



Tropical air masses are generally restricted to the southern states during much of the winter. However, southerly winds ahead of migrating cyclones occasionally transport a tropical air mass northward during the winter season.



Below is a map of surface observations and the leading edge of a tropical air mass surging northward into the Ohio Valley has been highlighted in red. Southerly winds behind the boundary signify the continued northward transport of warm moist air.

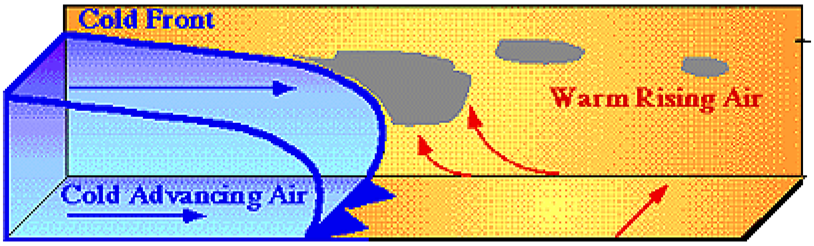


From these reports, we see that most stations in the tropical air mass generally exhibit relatively warmer temperatures, with higher dew point temperatures, and winds generally out of the south. Notice that on the other side of the red boundary, outside of this air mass, surface conditions are much different, which indicates the presence of an entirely different air mass.

Fronts

the boundaries between air masses

A front is defined as the transition zone between two air masses of different density. Fronts extend not only in the horizontal direction, but in the vertical as well. Therefore, when referring to the frontal surface (or frontal zone), we referring to both the horizontal and vertical components of the front (see figure below; red lines show horizontal and vertical motion, blu line show horizontal motion).



The types of fronts discussed in this module include:

Fronts
Last Update:
07/25/97

Stationary Front
A front that is not moving.

Cold Front
Leading edge of colder air that is replacing warmer air.

Warm Front
Leading edge of warmer air that is replacing cooler air.

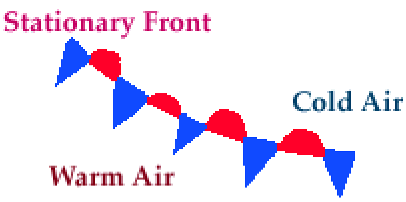
Occluded Front
When a cold front catches up to a warm front.

Dry Line
Separates a moist air mass from a dry air mass.

Stationary Front

a front that is not moving

When a warm or cold front stops moving, it becomes a stationary front. Once this boundary resumes its forward motion, it once again becomes a warm front or cold front. A stationary front is represented by alternating blue and red lines with blue triangles pointing towards the warmer air and red semicircles pointing towards the colder air.



A noticeable temperature change and/or shift in wind direction is commonly observed when crossing from one side of a stationary front to the other.

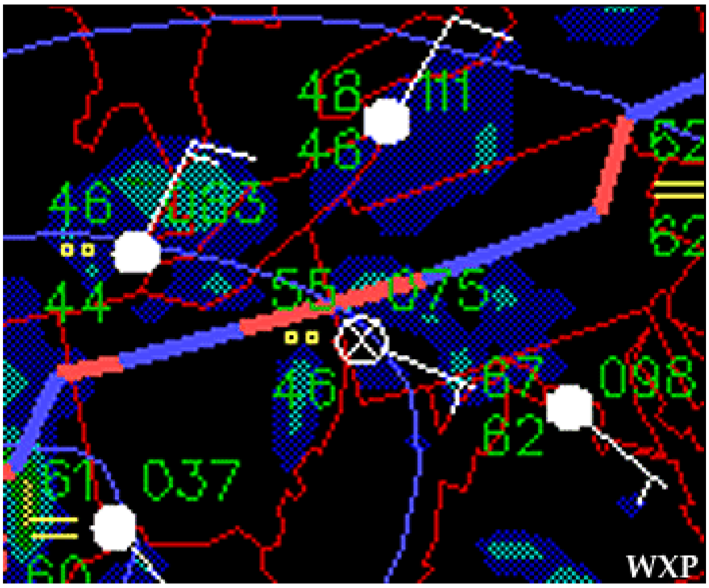


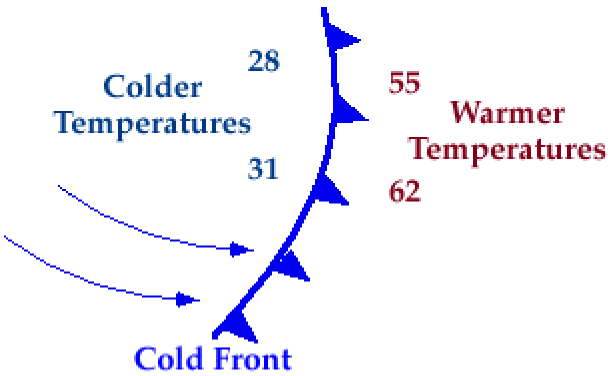
Image by: [WXP Purdue]

In the map above, temperatures south of the stationary front were in the 50's and 60's with winds generally from the southeast. However, north of the stationary front, temperatures were in the 40's while the winds had shifted around to the northeast. Cyclones migrating along a stationary front can dump heavy amounts of precipitation, resulting in significant flooding along the front.

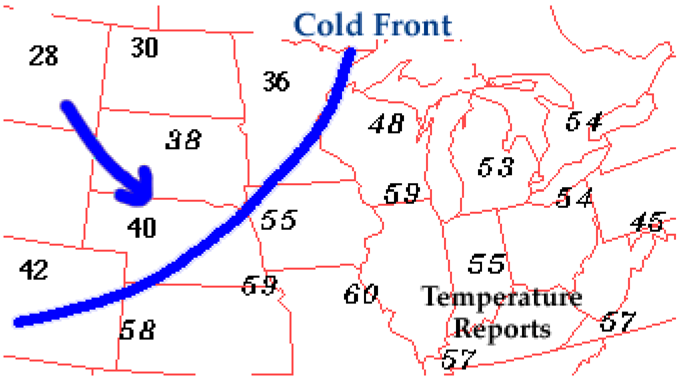
Cold Front

transition zone from warm air to cold air

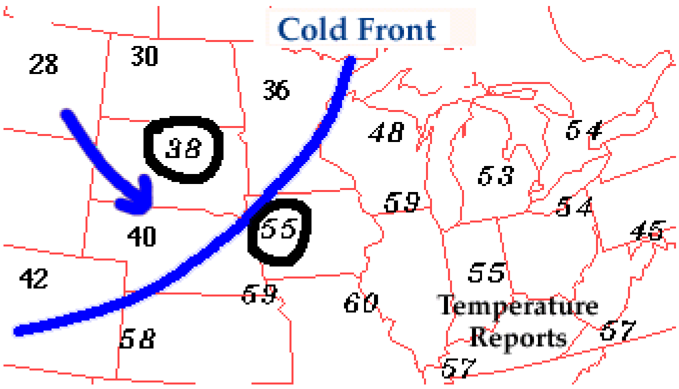
A cold front is defined as the transition zone where a cold air mass is replacing a warmer air mass. Cold fronts generally move from northwest to southeast. The air behind a cold front is noticeably colder and drier than the air ahead of it. When a cold front passes through, temperatures can drop more than 15 degrees within the first hour.



Symbolically, a cold front is represented by a solid line with triangles along the front pointing towards the warmer air and in the direction of movement. On colored weather maps, a cold front is drawn with a solid blue line.



There is typically a noticeable temperature change from one side of a cold front to the other. In the map of surface temperatures below, the station east of the front reported a temperature of 55 degrees Fahrenheit while a short distance behind the front, the temperature decreased to 38 degrees. An abrupt temperature change over a short distance is a good indicator that a front is located somewhere in between.



If colder air is replacing warmer air, then the front should be analyzed as a cold front. On the other hand, if warmer air is replacing cold air, then the front should be analyzed as a warm front. Common characteristics associated with cold fronts have been listed in the table below.

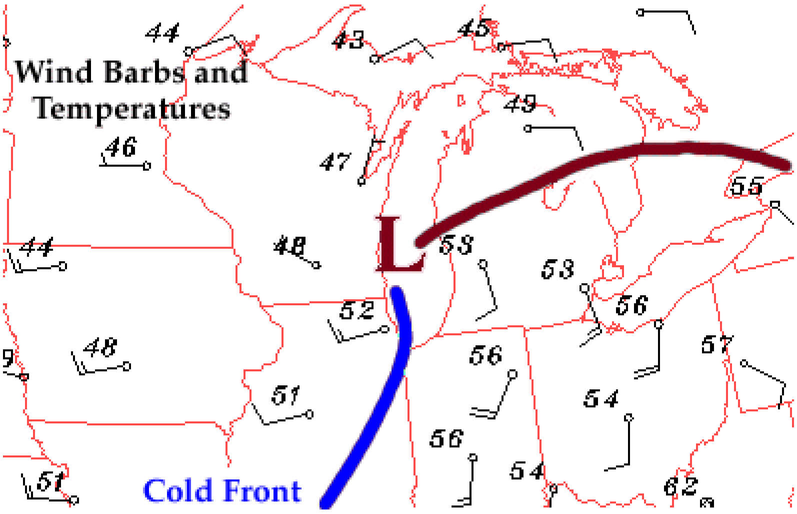
	Before Passing	While Passing	After Passing
Winds	south-southwest	gusty; shifting	west-northwest
Temperature	warm	sudden drop	steadily dropping
Pressure	falling steadily	minimum, then sharp rise	rising steadily
Clouds	increasing: Ci, Cs and Cb	Cb	Cu
Precipitation	short period of showers	heavy rains, sometimes with hail, thunder and lightning	showers then clearing
Visibility	fair to poor in haze	poor, followed by improving	good, except in showers
Dew Point	high; remains steady	sharp drop	lowering

Table adapted from: Ahrens, (1994)

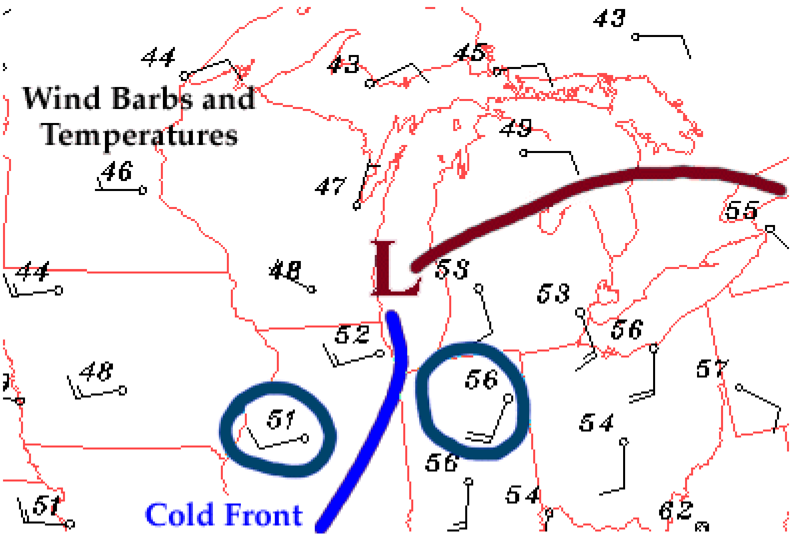
Finding Cold Fronts Using Wind Direction

shift from south-southwest to west-northwest

Cold fronts are not always identifiable by simply examining the temperature field alone. Other fields must also be taken into consideration. For example, below is a surface weather map with an analyzed low pressure center (red "L") and associated cold front (blue line) and warm front (red line). The numbers are surface temperature reports and the symbols are wind barbs, indicating wind direction and wind speed.



At the time this map was generated, temperatures ahead of the cold front were in the 50's, while behind the front, temperatures were only slightly colder (in the 40's and 50's). However, notice the change in wind direction (as indicated by the wind barbs) from one side of the cold front to the other. Winds ahead of the cold front were generally from south-southwest, while behind the front, winds had shifted around and were blowing out of the west. This sudden shift in wind direction was the key indicator that a cold front was present.

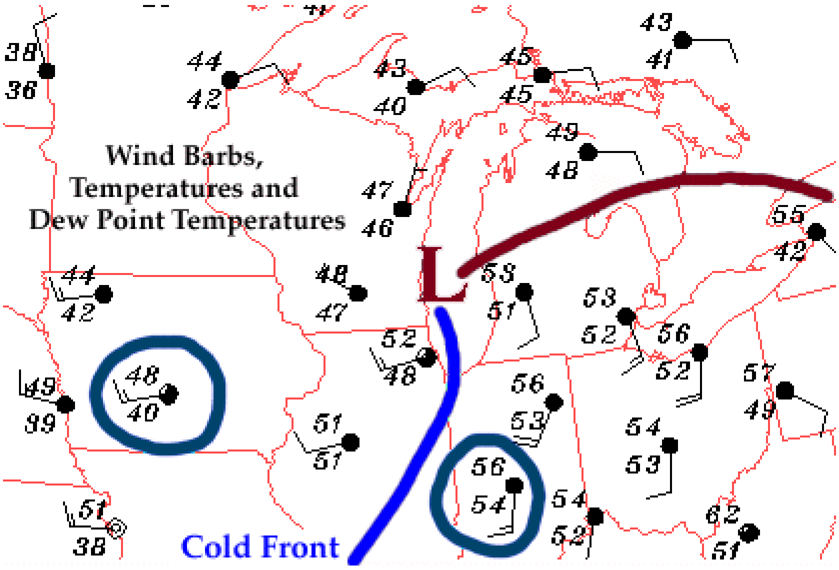


A sudden change in wind direction is commonly observed with the passage of a cold front. Before the front arrives, winds ahead of the front (in the warmer air mass) are typically out of the south-southwest, but once the front passes through, winds usually shift around to the west-northwest (in the colder air mass).

Finding Cold Fronts Using Dew Points

lower dew point temperatures behind the cold front

Another indication of a possible frontal passage is a change in the air's relative humidity. The air mass ahead of a cold front is typically more moist than the air mass behind it. The surface map below contains reports of temperature, dew point temperature, and wind barbs. Higher dew points indicate a higher moisture content of the air. Ahead of the cold front analyzed below, dew point temperatures were generally in the 50's, while behind the front, dew point values dropped off into the 30's and 40's.

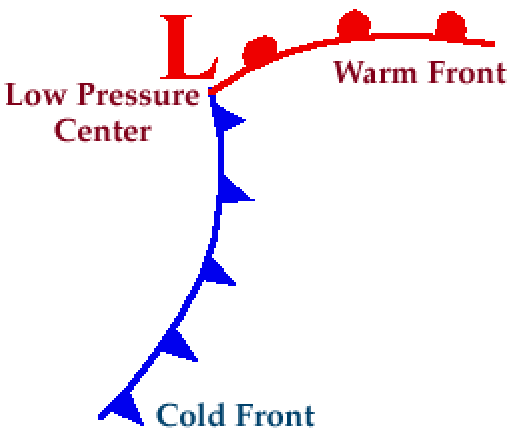


This decrease in dew point temperature indicated the presence of drier air behind the cold front. A noticeable change in the air's relative humidity is commonly observed with the passage of a cold front. Before the front arrives, the air typically feels more humid (in the warmer air mass), but once the front passes through, the humidity decreases and the air feels drier.

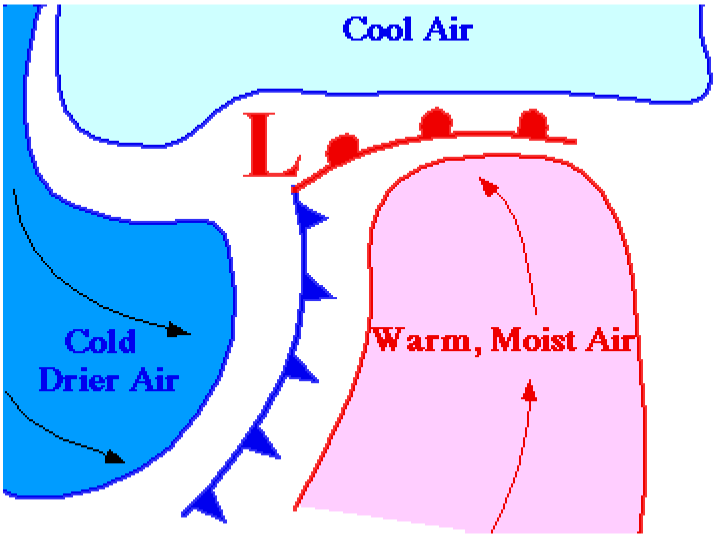
Cyclones and Associated Cold Front

leading edge of colder air mass

Below is a simple model of a cyclone with a cold front extending to the south from the center of low pressure and a warm front extending to the east ahead of the storm.



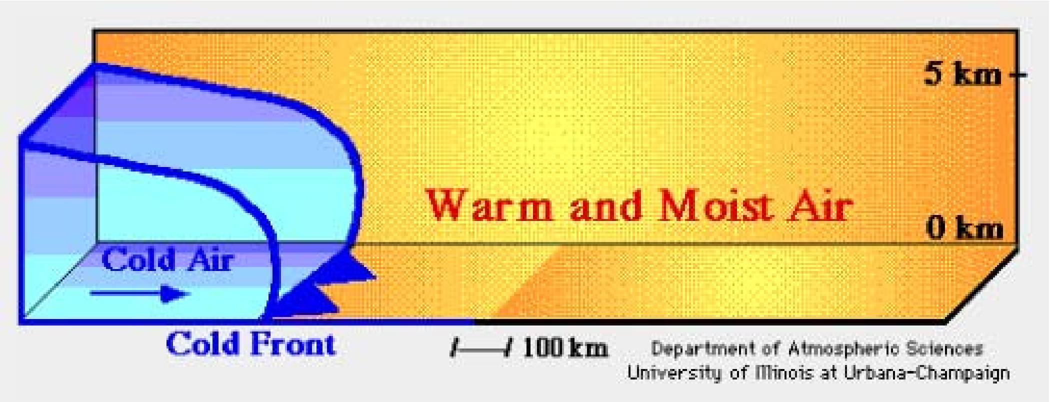
At low levels, several air masses of distinctly different origin may be found in varying parts of the cyclone. The cold front marks the leading edge of a colder and drier air mass being wrapped southeastward by north-northwesterly winds behind the low.



Clouds and precipitation usually develop along and ahead of the cold front as the colder air mass lifts the warm moist air ahead of it.

Precipitation Along a Cold Front
lifting the warm moist air ahead of it

The animation below is a sequence of vertical cross sections that depict the development of precipitation ahead of and along a cold front. The surging blue mass represents colder air behind the cold front (solid blue line) while the yellow shading indicates the warm moist air mass ahead of the front.

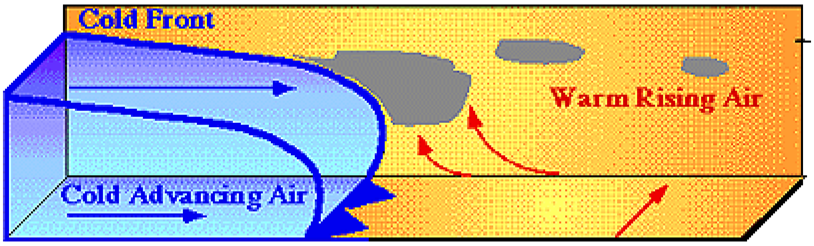


Animation by: Hall http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/af/frnts/cfrnt/prcp.rxml

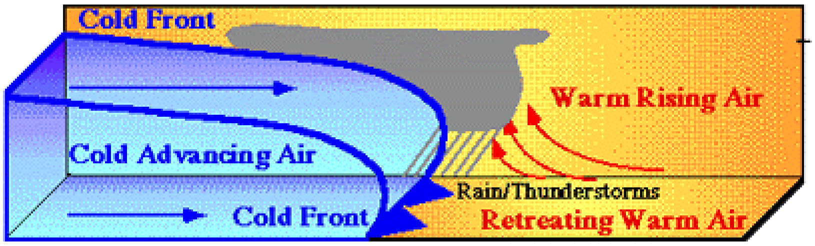
As the front advances, the colder air lifts the warmer air ahead of it (red arrows). The air cools as it rises and the moisture condenses to produce clouds and precipitation ahead of and along the cold front. In contrast to lifting along a warm front, upward motions along a cold front are typically more vigorous, producing deeper clouds and more intense bands of showers and thunderstorms. However, these bands are typically quite narrow and move rapidly just ahead of the cold front.

A Closer Examination of the Animation:
Initially, the cold air mass wedges into the warmer air mass ahead of it, (separated from each other

by the cold front). The lighter warm air is lifted upwards by the denser cold air and if enough water vapor condenses, clouds develop.



If condensation of water vapor persists, precipitation may develop, typically in a narrow band just ahead of the cold front.

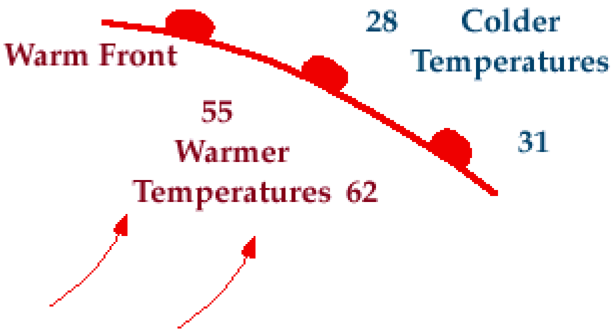


Due to the steep slope of a cold front, vigorous rising motion is often produced, leading to the development of showers and occasionally severe thunderstorms.

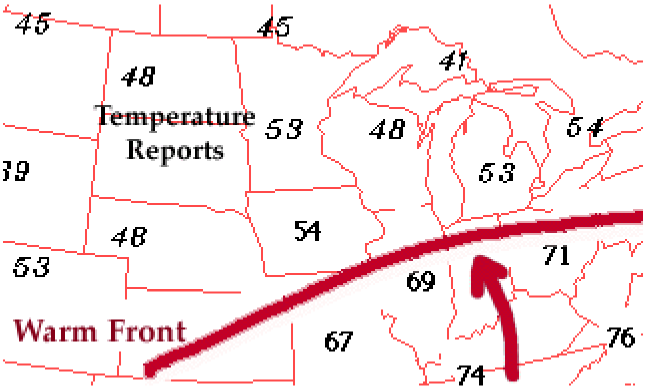
Warm Front

transition zone from cold air to warm air

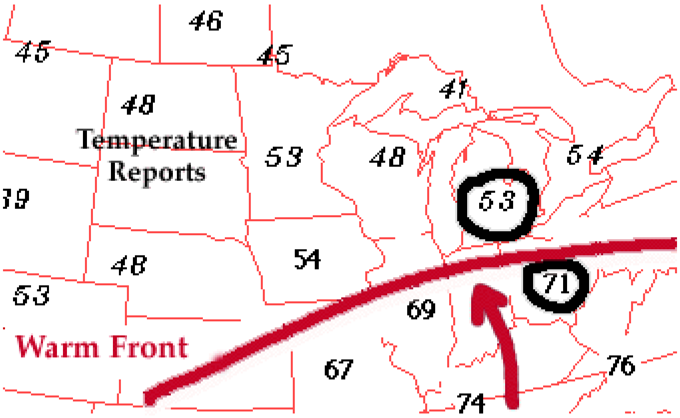
A warm front is defined as the transition zone where a warm air mass is replacing a cold air mass. Warm fronts generally move from southwest to northeast and the air behind a warm front is warmer and more moist than the air ahead of it. When a warm front passes through, the air becomes noticeably warmer and more humid than it was before.



Symbolically, a warm front is represented by a solid line with semicircles pointing towards the colder air and in the direction of movement. On colored weather maps, a warm front is drawn with a solid red line.



There is typically a noticeable temperature change from one side of the warm front to the other. In the map of surface temperatures below, the station north of the front reported a temperature of 53 degrees Fahrenheit while a short distance behind the front, the temperature increased to 71 degrees. An abrupt temperature change over a short distance is a good indication that a front is located somewhere in between.



If warmer air is replacing colder air, then the front should be analyzed as a warm front. If colder air is replacing warmer air, then the front should be analyzed as a cold front. Common characteristics associated with warm fronts have been listed in the table below.

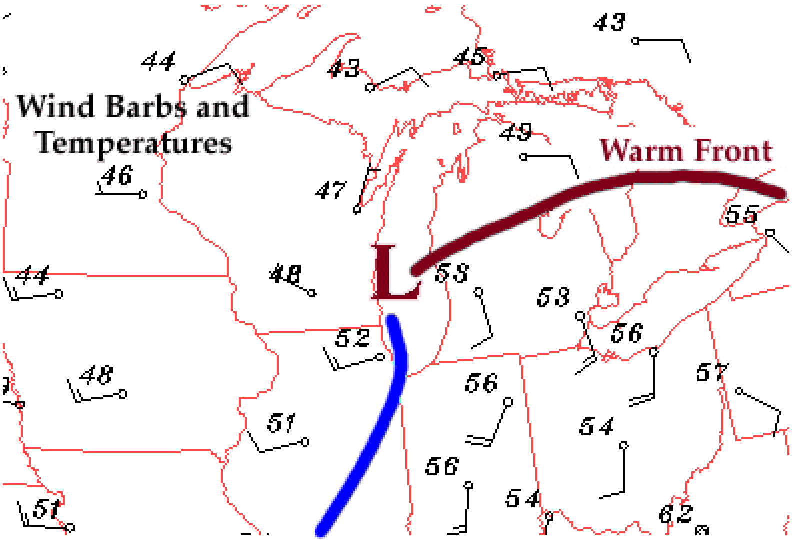
	Before Passing	While Passing	After Passing
Winds	south-southeast	variable	south-southwest
Temperature	cool-cold, slow warming	steady rise	warmer, then steady
Pressure	usually falling	leveling off	slight rise, followed by fall
Clouds	in this order: Ci, Cs, As, Ns, St, and fog; occasionally Cb in summer	stratus-type	clearing with scattered Sc; occasionally Cb in summer
Precipitation	light-to-moderate rain, snow, sleet, or drizzle	drizzle or none	usually none, sometimes light rain or showers
Visibility	poor	poor, but improving	fair in haze
Dew Point	steady rise	steady	rise, then steady

Table adapted from: Ahrens, (1994)

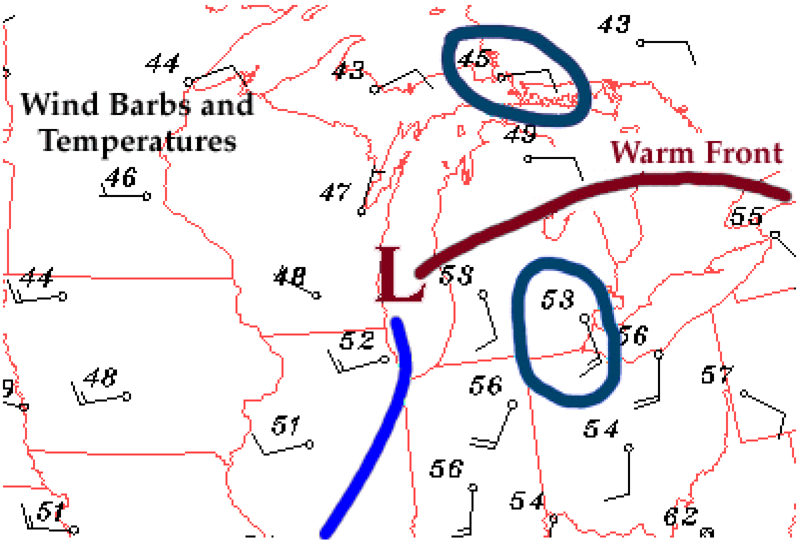
Finding Warm Fronts Using Wind Direction

shift from east-southeast to south-southwest

Warm fronts are not always identifiable by simply examining the temperature field alone. Other fields must also be taken into consideration. For example, below is a surface weather map with an analyzed low pressure center (red "L") and associated cold front (blue line) and warm front (red line). The numbers are surface temperature reports and the symbols are wind barbs, indicating wind direction and wind speed.



At the time this map was generated, temperatures ahead of the warm front were in the 40's, while behind the front, temperatures were only slightly warmer (in the 50's). However, notice the change in wind direction (as indicated by the wind barbs) from one side of the warm front to the other. Winds ahead of the warm front were generally from the east, while behind the front, winds had shifted around and were blowing out of the south. This sudden shift in wind direction was the key indicator that a warm front was present.

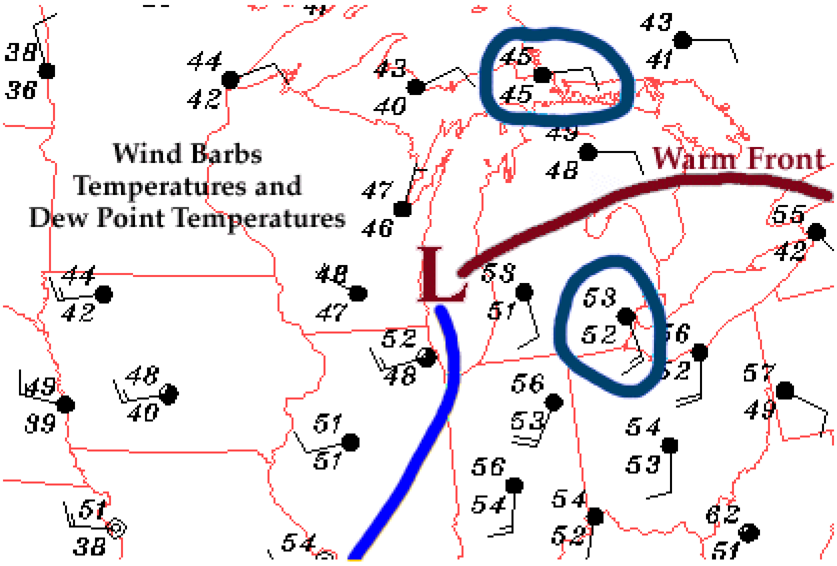


A sudden change in wind direction is commonly observed with the passage of a warm front. Before the front arrives, winds ahead of the front (in the cooler air mass) are typically from the east, but once the front passes through, winds usually shift around to the south-southwest (in the warmer air mass).

Finding Warm Fronts Using Dew Points

higher dew point temperatures behind the warm front

Another indication of a possible frontal passage is a change in the air's relative humidity. The air mass behind a warm front is typically more moist than the air mass ahead of the front. The surface map below contains reports of temperature, dew point temperature, and wind barbs. Higher dew points indicate a higher moisture content of the air. Ahead of the warm front analyzed below, dew point temperatures were generally in the 40's, while behind the front, dew point values climbed into the 50's.

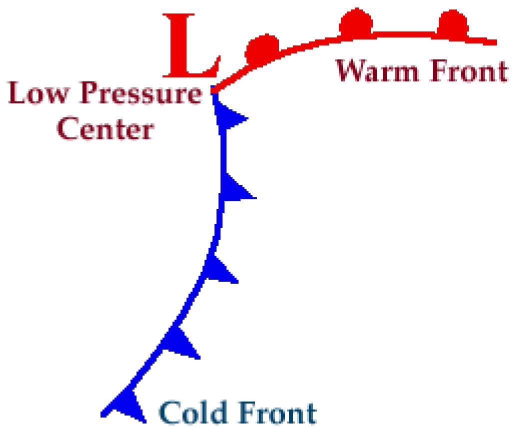


This increase in dew point temperature indicated that the air behind the warm front contained more moisture. A noticeable change in the air's relative humidity is commonly observed with the passage of a warm front. Before the front arrives, the air typically feels less humid than after the warm front passes through.

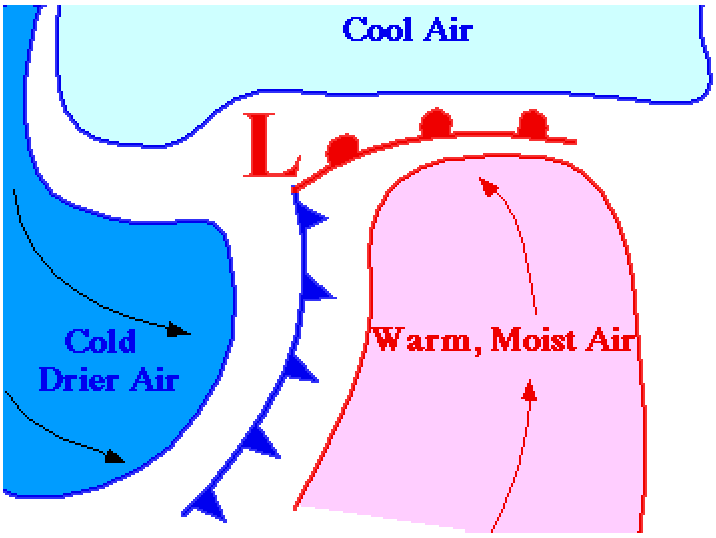
Cyclones and Associated Warm Front

leading edge of warmer air mass

Below is a simple model of a cyclone with a cold front extending to the south from the center of low pressure and a warm front extending to the east ahead of the storm.



At low levels, several air masses of distinctly different origin may be found in varying parts of the cyclone. The warm front marks the leading edge of warm moist air being pulled northward by southerly winds ahead (east) of the low.

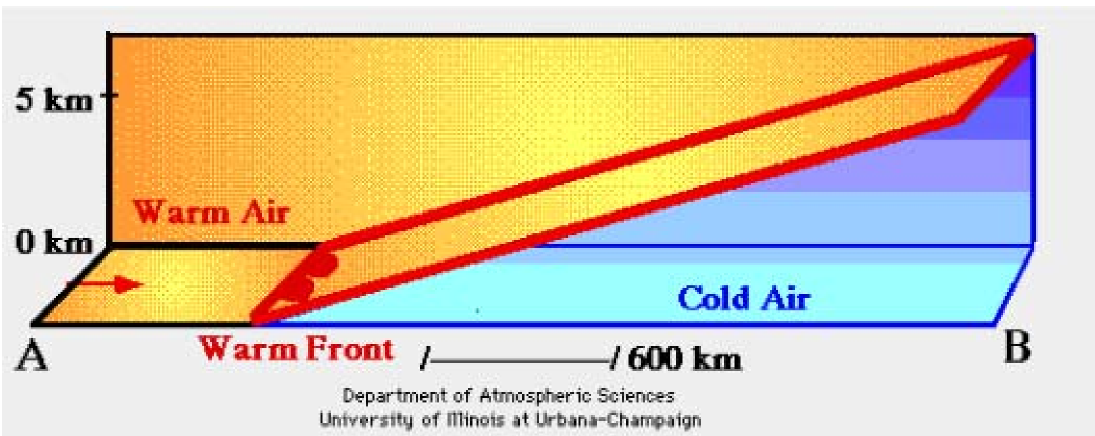


Clouds and precipitation usually develop along and ahead of the warm front as warm moist air rides up and over the colder air ahead of it.

Precipitation Along a Warm Front

warm moist air overriding colder air

The animation below is a sequence of vertical cross sections depicting the development of precipitation ahead of and along a warm front. The region shaded in blue represents a colder air mass while the yellow shading indicates the warm moist air behind the warm front (solid red line).



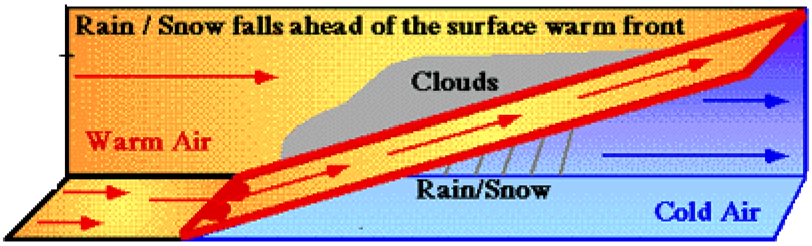
Animation by: Hall http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/af/frnts/wfrnt/prcp.rxml

The frontal zone slopes up and over the colder air mass ahead of it. Warm air rides along the front (up and over the cold air mass), cooling as it rises, producing clouds and precipitation in advance of the surface warm front. Because the lifting is very gradual and steady, generally wide spread and light intensity precipitation develops ahead of a warm front.

A Closer Examination of the Animation:
Initially, a warm air mass (in yellow) nudges against a colder air mass (in blue) ahead of it,

(separated from each other by the warm front). The lighter warm moist air behind the front is lifted upward and "overrides" the colder air.

As the [air rises, it cools], and if enough water vapor [condenses], widespread clouds and precipitation develop.

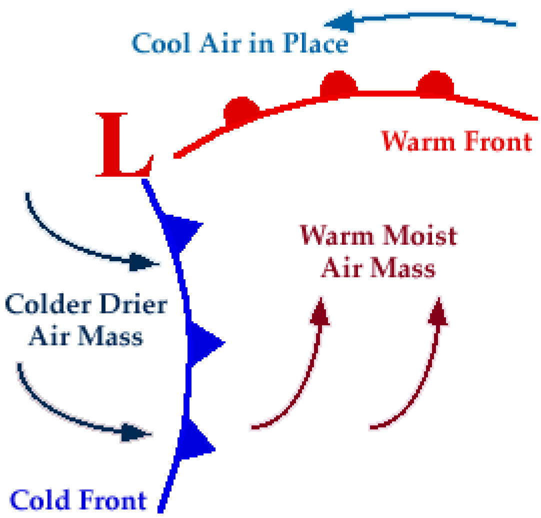


A layer of thin clouds is occasionally observed more than a thousand kilometers in advance of a surface warm front. As the front gets closer, the clouds thicken and eventually light precipitation begins to fall. Because the frontal surface gently slopes up and over the cold air mass ahead of it, the upward motions associated with warm fronts are typically not as strong as the vigorous upward motions that occur ahead of a cold front.

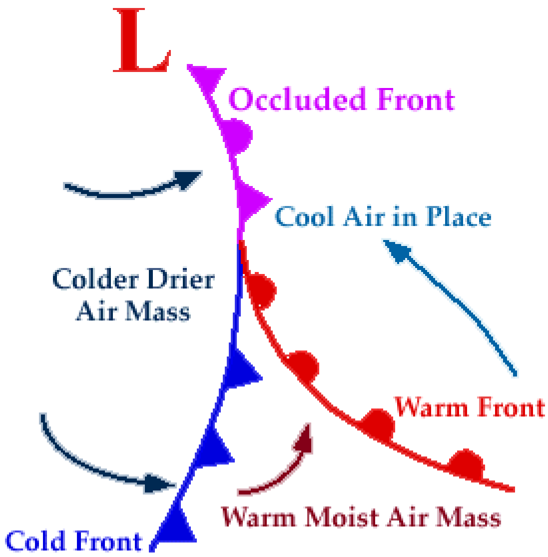
Occluded Front

when a cold front overtakes a warm front

A developing cyclone typically has a preceding warm front (the leading edge of a warm moist air mass) and a faster moving cold front (the leading edge of a colder drier air mass wrapping around the storm). North of the warm front is a mass of cooler air that was in place before the storm even entered the region.



As the storm intensifies, the cold front rotates around the storm and catches the warm front. This forms an occluded front, which is the boundary that separates the new cold air mass (to the west) from the older cool air mass already in place north of the warm front. Symbolically, an occluded front is represented by a solid line with alternating triangles and circles pointing the direction the front is moving. On colored weather maps, an occluded front is drawn with a solid purple line.



Changes in temperature, dew point temperature, and wind direction can occur with the passage of an occluded front. In the map below, temperatures ahead (east of) the front were reported in the low 40's while temperatures behind (west of) the front were in the 20's and 30's. The lower dew point temperatures behind the front indicate the presence of drier air.

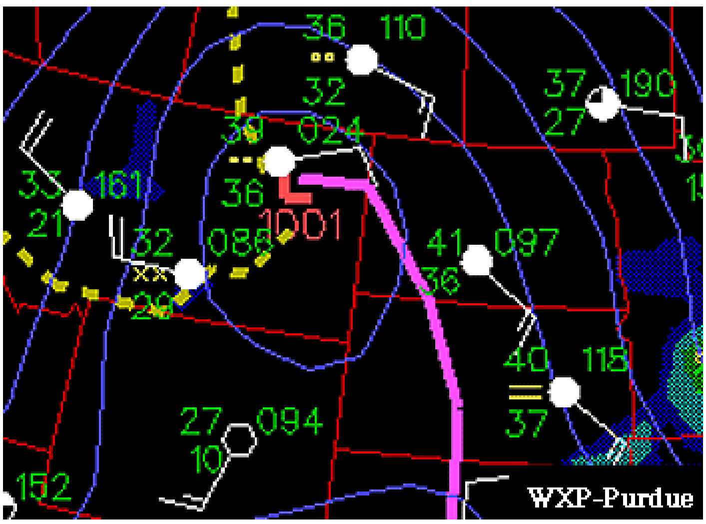


Image by: WXP Purdue

A noticeable wind shift also occurred across the occluded front. East of the front, winds were reported from the east-southeast while behind the front, winds were from the west-southwest. Common characteristics associated with occluded fronts have been listed in the table below.

		Before Passing		While Passing		After Passing
Winds		southeast-south		variable		west to northwest
Temperature						

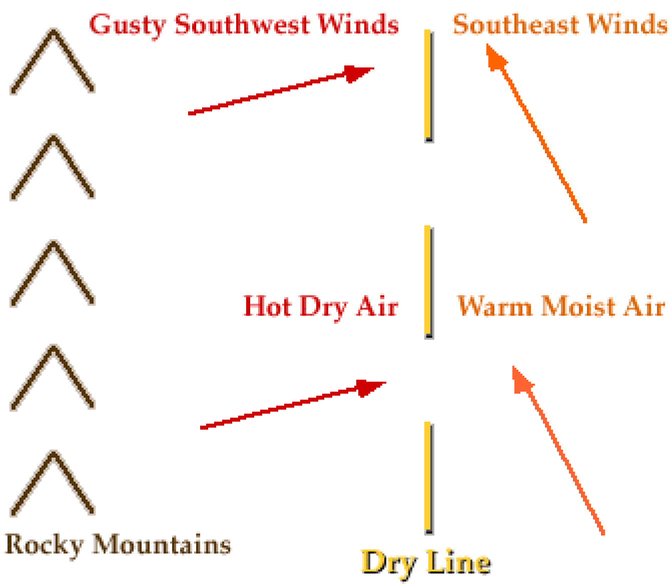
Cold Type Warm Type	cold-cool cold	dropping rising	colder milder
Pressure	usually falling	low point	usually rising
Clouds	in order: Ci, Cs, As, Ns	Ns, sometimes Tcu and Cb	Ns, As or scattered Cu
Precipitation	light, moderate or heavy precipitation	light, moderate or heavy continuous precipitation or showers	light-to-moderate precipitation followed by general clearing
Visibility	poor in precipitation	poor in precipitation	improving
Dew Point	steady	usually slight drop, especially if cold-occluded	slight drop, although may rise a bit if warm-occluded

Table adapted from: Ahrens, (1994)

Dry Line

a moisture boundary

A dry line is a boundary that separates a moist air mass from a dry air mass. Also called a "Dew Point Front", sharp changes in dew point temperature can be observed across a dry line. Dry lines are most commonly found just east of the Rocky Mountains, separating a warm moist air mass to the east from a hot dry air mass to the west.



States like Texas, New Mexico, Oklahoma, Kansas, and Nebraska frequently experience dry lines in the spring and summer. Dry lines are extremely rare east of the Mississippi River.

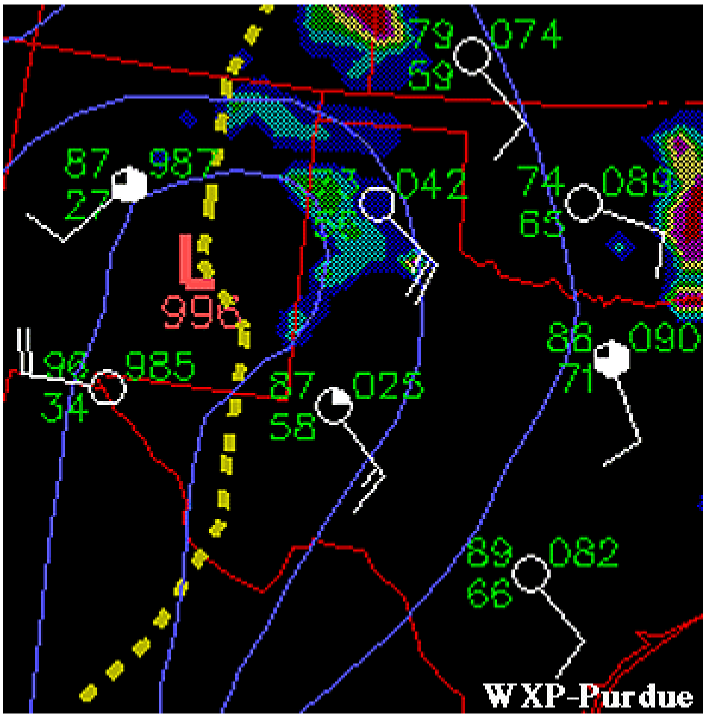


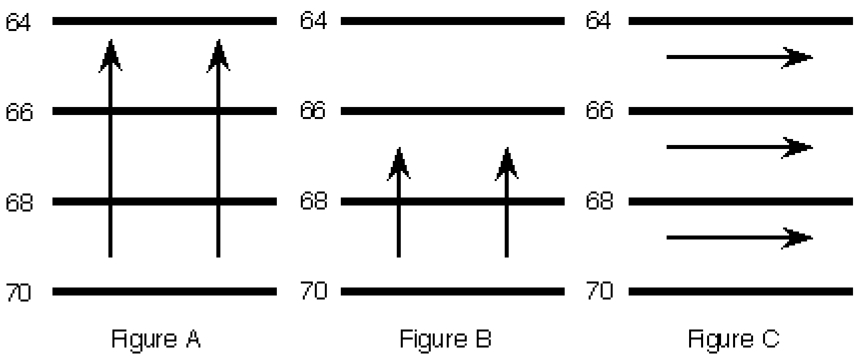
Image by: WXP Purdue

Dew points east (ahead) of the dry line shown above range from the upper 50's to low 70's with winds from the southeast. West of the dry line, dew points were in the 20's and 30's, a decrease of nearly 50 degrees. Air temperatures ahead of the dry line were generally in the 70's and 80's while behind the dry line, temperatures ranged from the mid 80's to mid 90's. Drier air behind dry lines lifts the moist air ahead of it, triggering the development of thunderstorms along and ahead of the dry line (similar to cold fronts). It is not uncommon for tornadic supercells to develop along a dry line.

Advection

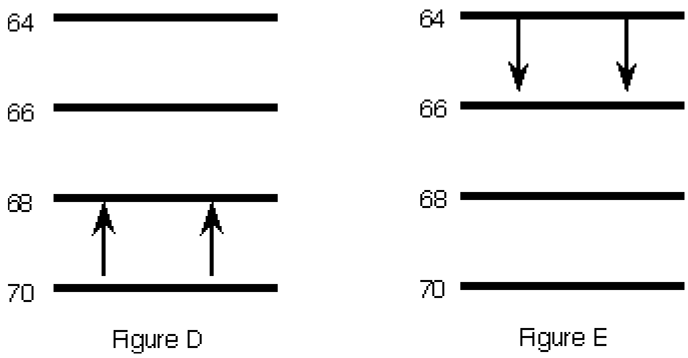
transport of something from one region to another

The term advection refers to the transport of something from one region to another. Meteorologists are most interested in the advection of variables like temperature, moisture and vorticity. Assessing advection on weather maps is dependent upon two factors; 1) the strength of the wind and 2) the angle of the wind relative to the lines of equal value (isolines) of the variable being advected. The strongest advection occurs when the winds are oriented perpendicular (at 90 degrees) relative to the isolines. No advection occurs if the winds are parallel to the isolines. The figures below depict three different examples of temperature advection. The arrows are wind vectors and the horizontal lines are isotherms (lines of constant temperature) in degrees Fahrenheit.



The wind vectors are longer in Figure A than they are in Figure B, which implies that the winds are stronger in Figure A. Since in both cases the winds are aligned perpendicular to the isotherms, stronger advection is occurring in Figure A than Figure B, because of the stronger winds in A. In Figure C, no advection is occurring because the wind vectors are parallel to the isotherms, indicating no horizontal transport of temperature.

Positive and Negative Advection:
There are essentially two types of advection: positive and negative. Figure D below shows positive advection with higher values of a variable (in this case temperature) being advected towards lower values. The end result of positive advection is to increase the variable values in the direction the wind is blowing.



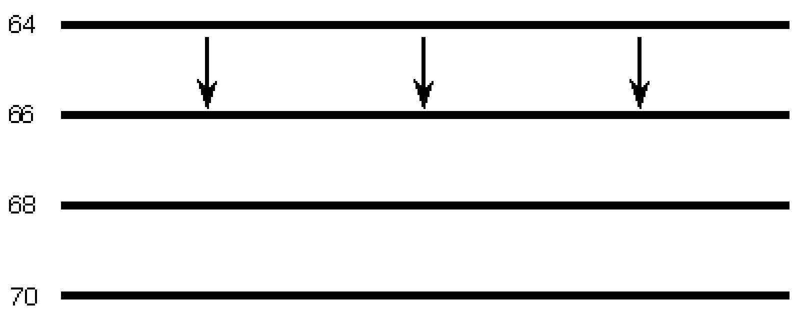
Animation by: Van Dorn

On the other hand, Figure E shows negative advection, since lower values of a variable (in this case temperature) are being advected towards higher values of the same variable. The end result of negative advection is to decrease the variable values in the direction the wind is blowing

Cold Advection

cold air moves into a warmer region

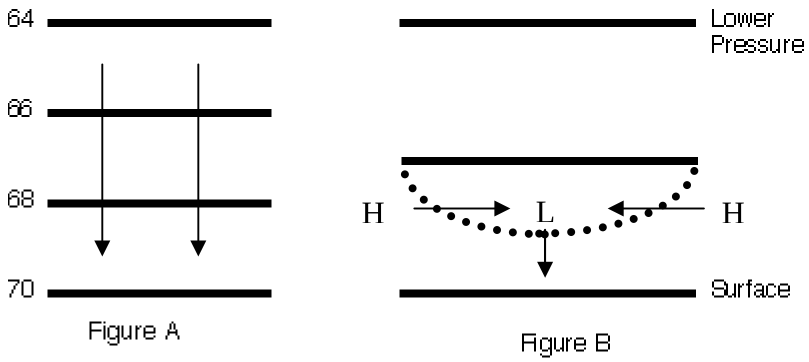
Cold advection is the process in which the wind blows from a region of cold air to a region of warmer air. The following animation depicts a very simple example of cold advection. The horizontal lines are isotherms in degrees Fahrenheit and the arrows represent wind vectors. Winds are blowing from a region of cold air to a region of warmer air, which results in cooling of the warmer region. As the cold advection persists, temperatures in the warmer region will begin to decrease as the colder air moves into the region of warmer air.



Animation by: Van Dorn

The net result of cold advection is to make a region cooler. The animation below shows (in a very general sense) how cold advection can lead to sinking motion. Cold advection is occurring in Figure A while Figure B shows a vertical cross section through the region of cold advection. In Figure B, the horizontal lines are isobars and the arrows represent wind vectors. It is important to note that

Figure A is along the ground and that Figure B is from the ground up to a higher level in the atmosphere, directly above the region of cold advection.



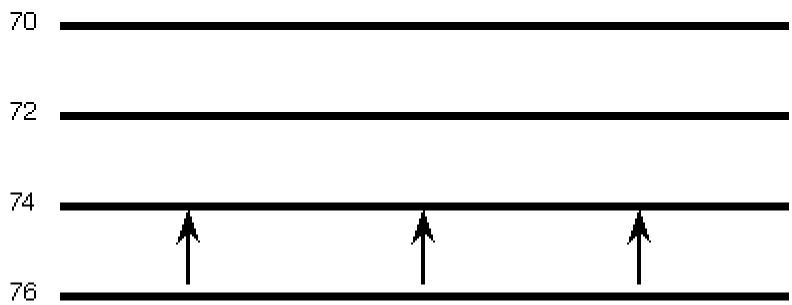
Animation by: Van Dorn http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/af/adv/cadv.rxml

With the onset of cold advection (Figure A), the isobar in Figure B starts to bend downward since colder air is more dense and occupies less room than warmer air. The bending of the isobar due to cold advection creates a localized area of low pressure ("L" in Figure B"), thus altering the pressure gradient force. As air moves from the regions of high pressure ("H" in Figure B) to the local region of lower pressure, air is pushed downward from above, which is the sinking motion that is caused by cold advection.

Warm Advection

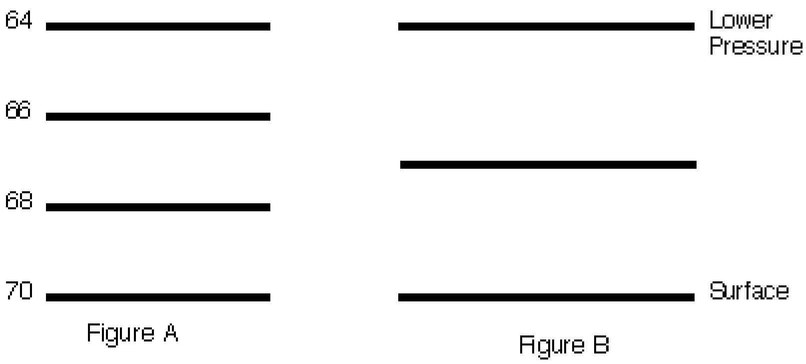
warm air moves into a cooler region

Warm advection is the process in which the wind blows from a region of warm air to a region of cooler air. The following animation depicts a very simple example of warm advection. The horizontal lines are isotherms in degrees Fahrenheit and the arrows represent wind vectors. Winds are blowing from a region of warm air to a region of colder air, which results in a warming of the colder region. As the warm advection persists, temperatures in the colder region will begin to increase as the warmer air moves into the region of colder air.



Animation by: Van Dorn

The net result of warm advection is to make a region warmer. The animation below shows (in a very general sense) how warm advection can produce upward motion. Warm advection is occurring in Figure A while Figure B shows a vertical cross section through the region of warm advection. It is important to realize that Figure A is along the ground and that Figure B is from the ground up to a higher level in the atmosphere, directly over the region of warm advection.



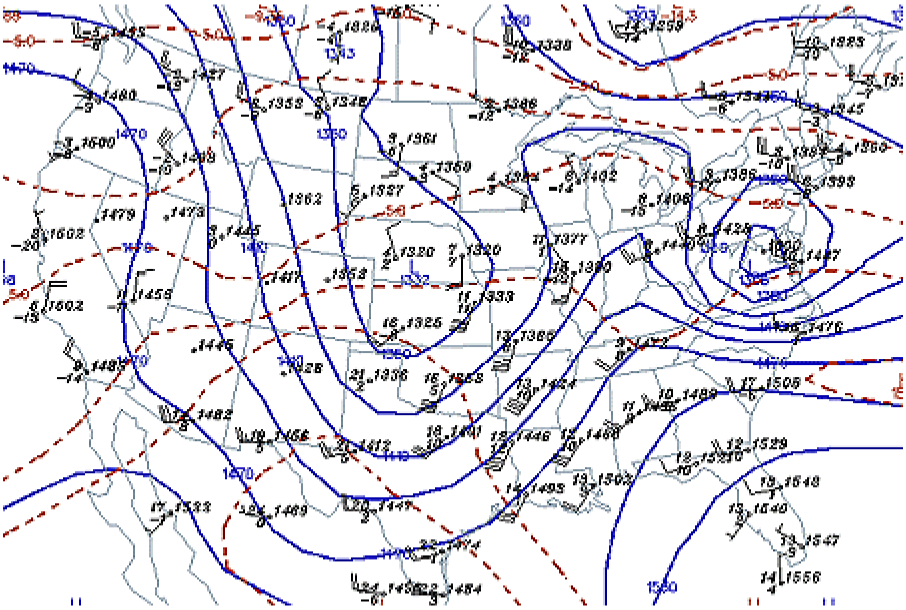
Animation by: Van Dorn

With the onset of warm advection (Figure A), the isobar in Figure B starts to bend upward since warmer air is less dense and occupies more space than colder air. The bending of the isobar due to warm advection creates a localized area of high pressure ("H" in Figure B), thus altering the pressure gradient force. As air moves from the local region of high pressure to the regions of lower pressure ("L" in Figure B), air is drawn upward from below, which is the rising motion produced by warm advection.

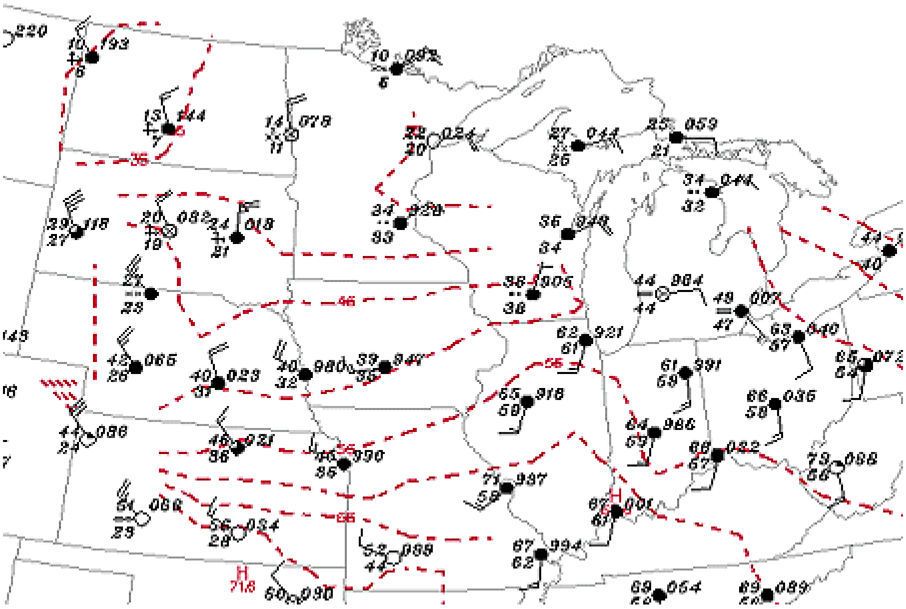
850 mb Temperature Advection

an indicator of surface changes to come

Warm advection at 850 mb is often indicative of rising temperatures at the surface, while cold advection at this level often precedes falling temperatures. Regions of strongest temperature advection are found where geopotential height contours (blue) and isotherms (red) are nearly perpendicular to each other. For example, on the following 850 mb surface, the strongest cold advection is occurring from Montana to New Mexico, while the strongest warm advection is occurring from eastern Texas into Illinois.



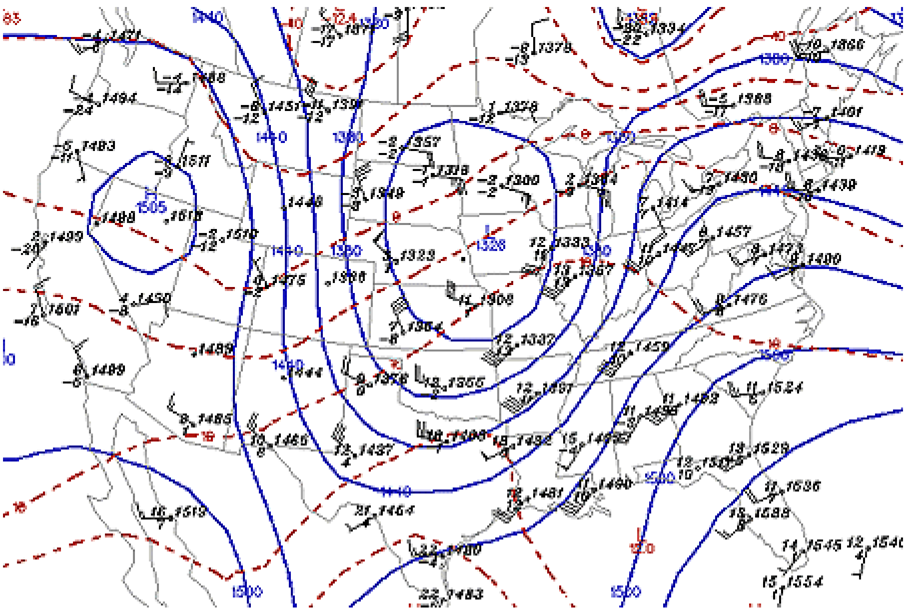
The influence of thermal advection at 850mb is typically felt at the surface about a day later (map below). In the area under cold advection, temperatures ranged from the 20's to 40's, with winds generally out of the northwest bringing colder air southward from Canada.



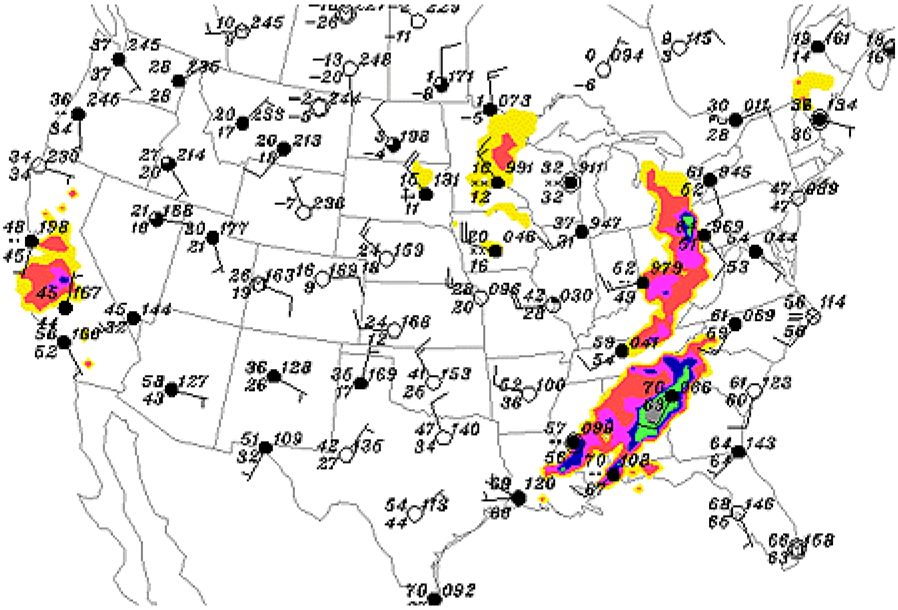
Regions in the area of warm advection, however, were experiencing temperatures in the 60's, providing these areas with a Spring day in early January.

Moisture Advection
along the 850 mb surface

Moisture advection is horizontal transport of moisture, which plays a very important role in the development of precipitation. If little moisture is available, it is unlikely that precipitation will form. However, if a cyclone is supplied with an abundance of moisture, there is an increased likelihood that heavy precipitation will develop. Regions of moisture advection are often co-located with regions of warm advection. For the regions of greatest moisture advection, look for areas where the geopotential height contours (blue) and isodrosotherms (dashed red) are nearly perpendicular (map below).



The greatest moisture advection was occurring from Texas into Illinois, as moist air from the Gulf of Mexico was being advected northward by southerly winds ahead of an intensifying low pressure system. This rich moisture supply was enough for showers and thunderstorms to develop as indicated by the radar echoes stretching from Ohio southward to Louisiana (below).

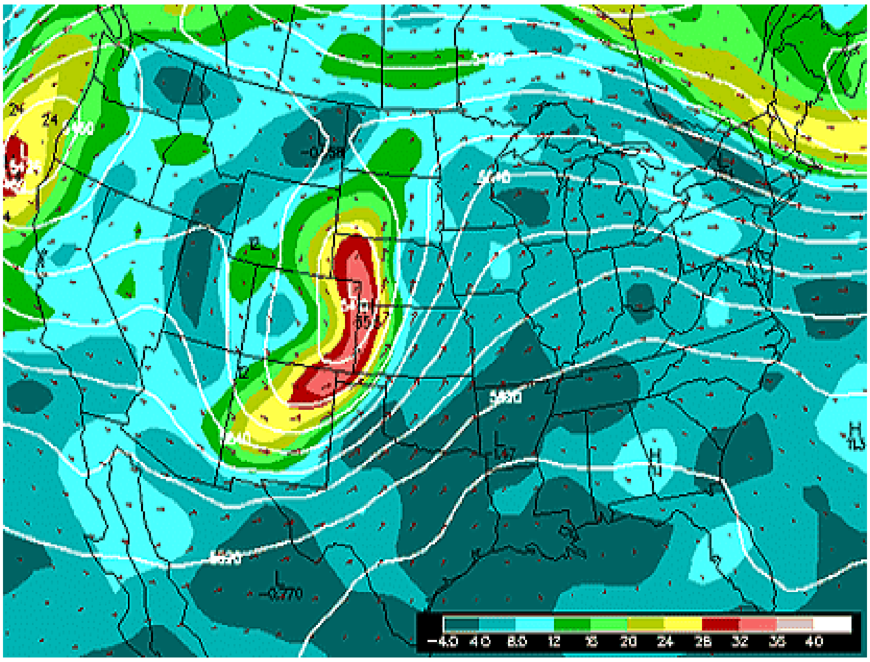


Notice how the precipitation was located in the region where the strongest moisture advection was occurring. Also note that the areas experiencing dry advection (the western states, which were under advection of drier air from the north) had no rainfall.

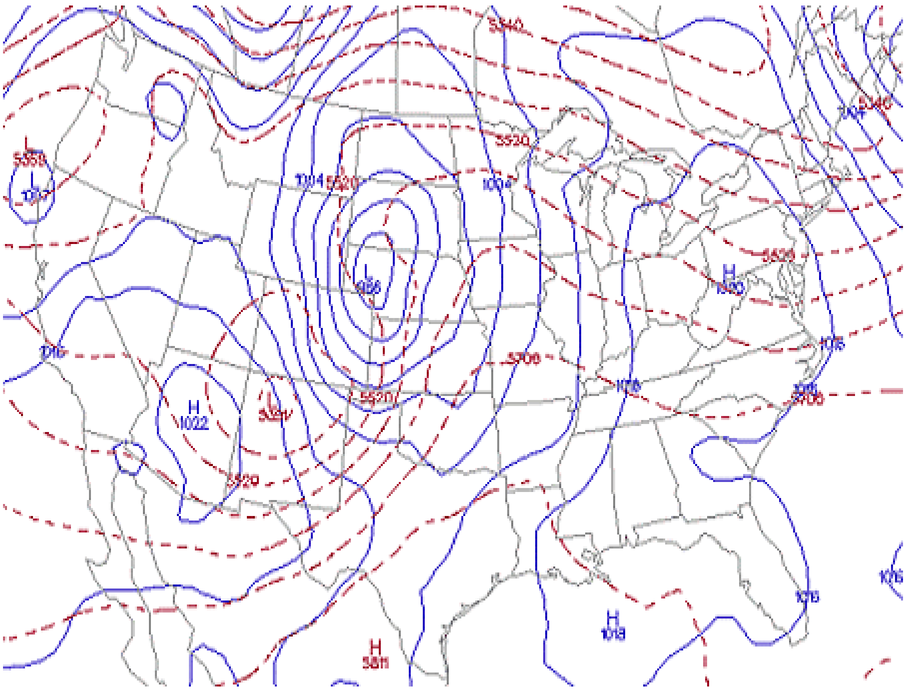
Vorticity Advection

leads to rising/falling pressures at the surface

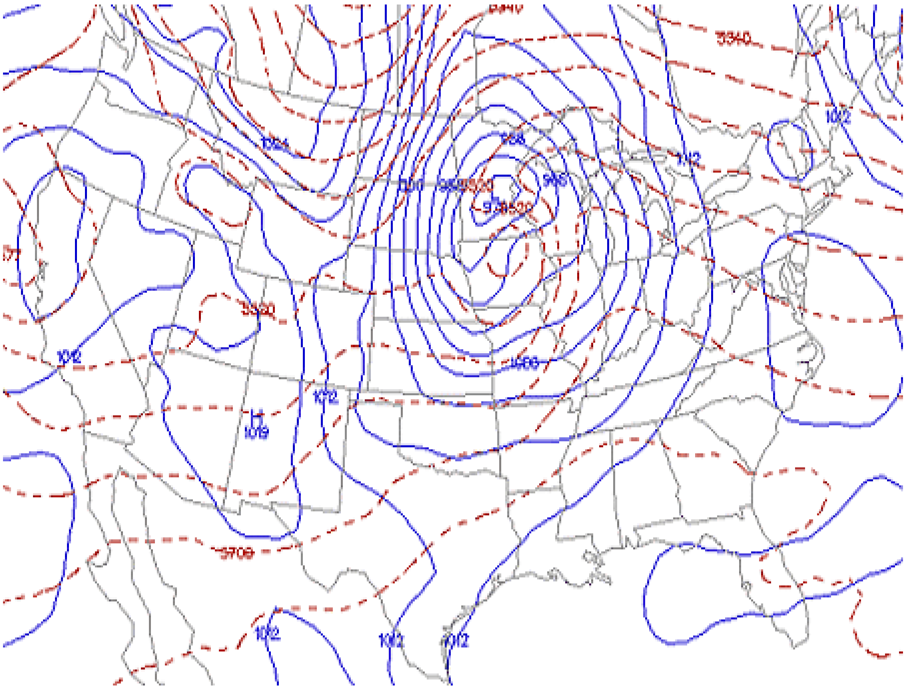
Vorticity is the localized rotation of the air. Air that rotates counterclockwise, such as in cyclones and troughs, is said to have positive vorticity. Clockwise rotating air, such as in high pressure systems and ridges, has negative vorticity. The advection of vorticity at high levels will result in a response at the surface which will attempt to offset the effects of the advection. More specifically, vorticity advection is indicative of rising motion/falling pressures at the surface. For example, look at this 500 mb map for 12Z, October 29, 1995.

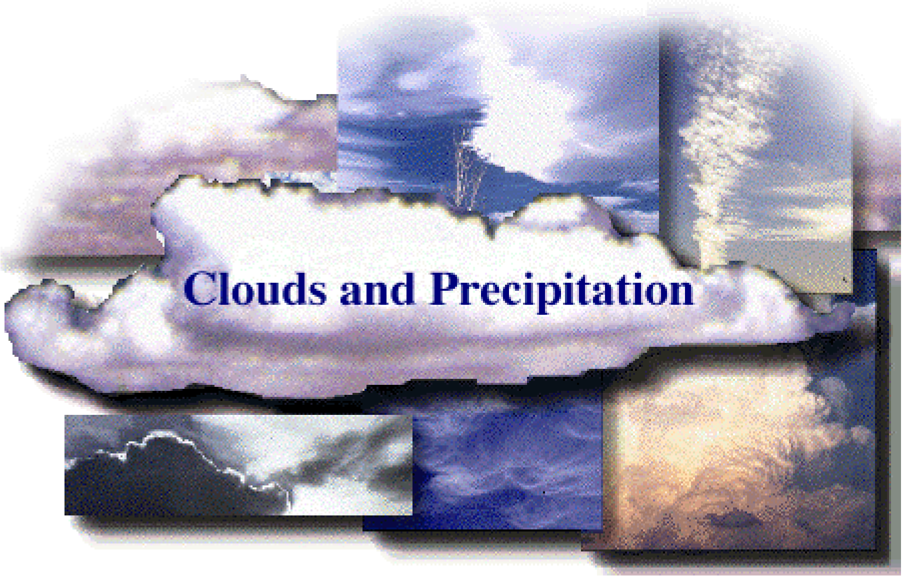


Now look at these two maps of surface pressure (solid lines) from 12Z October 29,1995 and 0Z October 30,1995.



Notice how the surface low has deepened in the area of strong vorticity advection.





Graphic by: Yiqi Shao

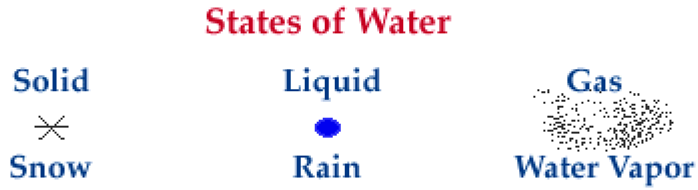
A cloud is a visible aggregate of tiny water droplets and/or ice crystals suspended in the atmosphere and can exist in a variety of shapes and sizes. Some clouds are accompanied by precipitation; rain, snow, hail, sleet, even freezing rain. The purpose of this module is to introduce a number of cloud classifications, different types of precipitation, and the mechanisms responsible for producing them. The Clouds and Precipitation module has been organized into the following sections:

Sections
Last Update:
07/21/97

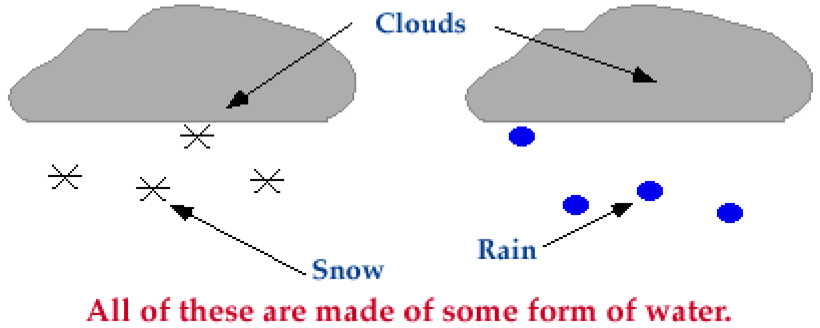
The States of Water

solid, liquid, gas

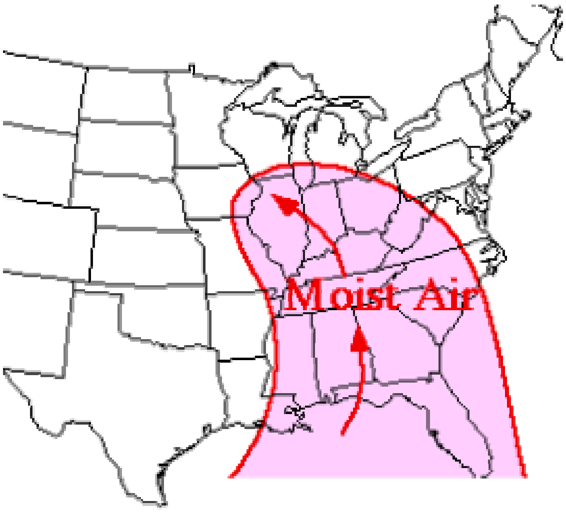
Water is known to exist in three different states; as a solid, liquid or gas.



Clouds, snow, and rain are all made of up of some form of water. A cloud is comprised of tiny water droplets and/or ice crystals, a snowflake is an aggregate of many ice crystals, and rain is just liquid water.



Water existing as a gas is called water vapor. When referring to the amount of moisture in the air, we are actually referring to the amount of water vapor. If the air is described as "moist", that means the air contains large amounts of water vapor. Common sources of moisture for the United States are the warm moist air masses that flow northward from the Gulf of Mexico and western Atlantic Ocean as well as the moist Pacific air masses brought onshore by the westerlies.



As cyclones move eastward from the Rocky Mountains, southerly winds ahead of these storm systems transport the warm moist air northward. Moisture is a necessary ingredient for the production of clouds and precipitation.

Relative Humidity

indicates how moist the air is

What's relative umidity?

Air, in our normal environment, always holds humidity. The number of water molecules in the air can vary substantially, e.g. it can be as dry as in a desert or as humid as in the tropics. There is an upper limit for the amount of humidity which air can hold at a given temperature. Beyond this limit saturation occurs. If for some reason the humidity level is pushed up to this limit, condensation occurs and fog or water droplets form. Relative humidity tells you what percentage of this maximum amount of humidity is present in the air. In contrast to relative humidity, absolute humidity denotes the absolute amount of humidity in the air regardless of the saturation level expressed as the total mass of water molecules per air volume. The maximum possible amount of humidity as well as the actual present amount of humidity in the air are defined by so called water vapor pressures. According to Dalton's law, total air pressure is the sum of the partial vapour pressures of its components and water vapor pressure is one of them:

$P_{total} = P_{water\ vapour} + P_{oxygen} + P_{nitrogen} + P_{others}$

P_{total} = Total air pressure

$P_{water\ vapour}$ = Partial water vapour pressure

The maximum amount of humidity, which air can hold, is defined by the so-called saturation water vapor pressure. This is a function of temperature. See: Figure 1 Saturation water vapor pressure. If the partial water vapor pressure is equal to the saturation water vapor pressure, condensation occurs. Mathematically, relative humidity is expressed as the ratio of the partial water vapour pressure divided by the saturation water vapour pressure as a percentage (RH).

$$RH(\%) = \frac{P_{water\ vapour}}{P_{saturation}} \bullet 100$$

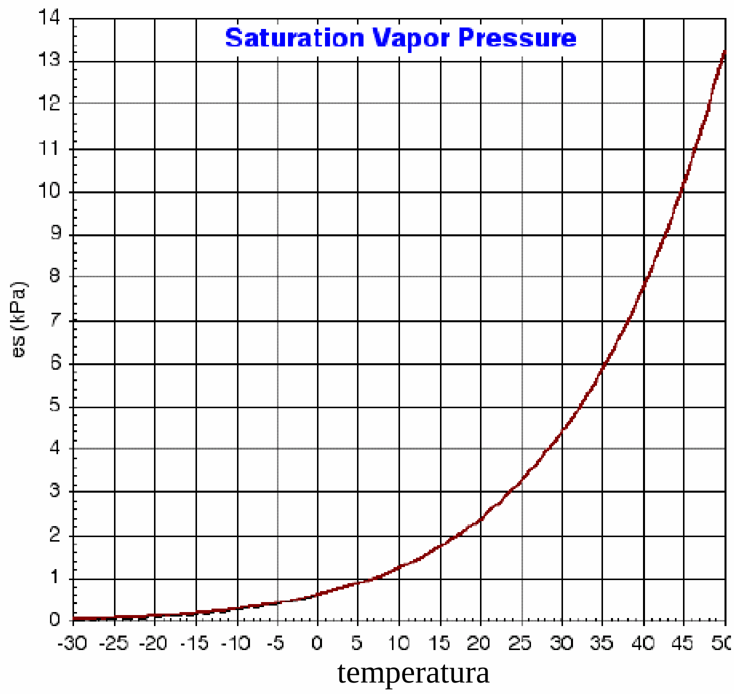


Figure 1 Saturation water vapor pressure

If temperature rises or falls in a closed system, the saturation vapor pressure will increase or decrease. As a consequence, the relative humidity will drop or rise.

Saturation water vapor pressure is not a function of total air pressure, but partial water vapor pressure is. If for example the total air pressure in a closed system is increased, relative humidity will increase as well, because the partial water vapor pressure increases proportionally to the overall pressure increase according to Dalton's law and saturation vapor pressure stays the same

What's dew point?

Another very important figure in conjunction with relative humidity is the dew point. The dew point is defined as the temperature at which the present amount of humidity in the air starts to condensate. E.g. if air has a temperature of 40°C (104°F) and a relative humidity of 50%, condensation will occur when the air is cooled down to 27.6°C (81.7°F). At the dew point, RH is 100%. The dew point can be taken from the graph in Figure 1: the partial water vapor pressure at 50% and 40°C is half the saturation water vapor pressure at 40°C. Now, the dew point is where the 50% at 40°C (104°F) blue line crosses the saturation water vapor pressure curve, i.e. at 27.6°C, see Figure 2 . There are sensors that directly measure dew point. However it can also be calculated by using relative humidity and temperature as inputs The dew point is a measure for absolute humidity. Consequently, the dew point of air will remain constant in a closed system (unventilated room) even if the air is heated or cooled locally.

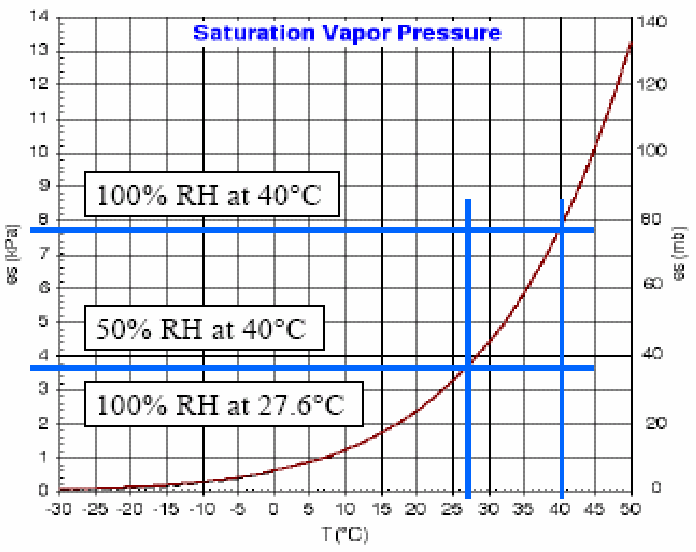


Figure 2 Graphical determination of dew point

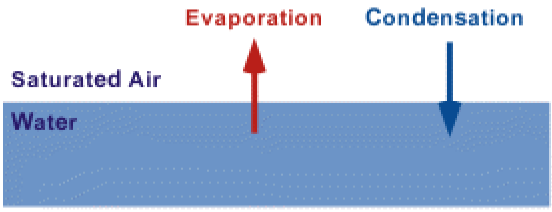
However relative humidity may be defined as the ratio of the water vapor density (mass per unit volume) to the saturation water vapor density, usually expressed in percent:

$$\textbf{Relative Humidity (RH)} = \frac{\text{(Actual Vapor Density)}}{\text{(Saturation Vapor Density)}} \times 100\%$$

Relative humidity is also approximately the ratio of the actual to the saturation vapor pressure.

$$\textbf{RH} = \frac{\text{(Actual Vapor Pressure)}}{\text{(Saturation Vapor Pressure)}} \times 100\%$$

Actual vapor pressure is a measurement of the amount of water vapor in a volume of air and increases as the amount of water vapor increases. Air that attains its saturation vapor pressure has established an equilibrium with a flat surface of water. That means, an equal number of water molecules are evaporating from the surface of the water into the air as are condensing from the air back into the water.



Saturation vapor pressure is a unique function of temperature as given in the table below (and in figure 1 above). Each temperature in the table may be interpreted as a dew point temperature, because as the ground cools, dew will begin to form at the temperature corresponding to the vapor pressure in this table.

(C) Temp	(F)	Sat Vapor Prs (mb)	(C) Temp	(F)	Sat Vapor Prs (mb)
-18	00	1.5	18	65	21.0
-15	05	1.9	21	70	25.0
-12	10	2.4	24	75	29.6
-09	15	3.0	27	80	35.0
-07	20	3.7	29	85	41.0
-04	25	4.6	32	90	48.1
-01	30	5.6	35	95	56.2
02	35	6.9	38	100	65.6
04	40	8.4	41	105	76.2
07	45	10.2	43	110	87.8
10	50	12.3	46	115	101.4
13	55	14.8	49	120	116.8
16	60	17.7	52	125	134.2

Chart adapted from: Ahrens

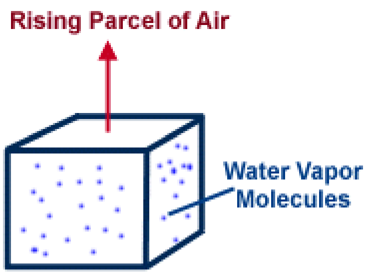
For example, if the water vapor pressure in the air is 10.2 millibars (mb), dew will form when the ground reaches 45 degrees Fahrenheit (F). The relative humidity for air containing 10.2 mb of water vapor is simply 100% times 10.2 mb divided by the saturation vapor pressure at the actual temperature. For example, at 70 F the saturation vapor pressure is 25 mb, so the relative humidity would be

RH = 100% X (10.21 / 25.0) = 41%

Rising Air

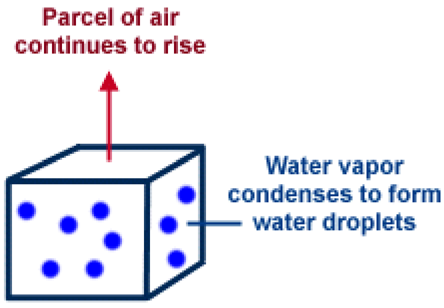
a key process in the production of clouds and precipitation

Imagine a block of air, or air parcel, rising upward through the atmosphere. The air parcel expands as it rises and this expansion, or work, causes the temperature of the air parcel to decrease.



As the parcel rises, its humidity increases until it reaches 100%. When this occurs, cloud droplets begin forming as the excess water vapor condenses on the largest aerosol particles. Above this point the cloud droplets grow by condensation in the rising air.

If the cloud is sufficiently deep or long lived, precipitation will develop.

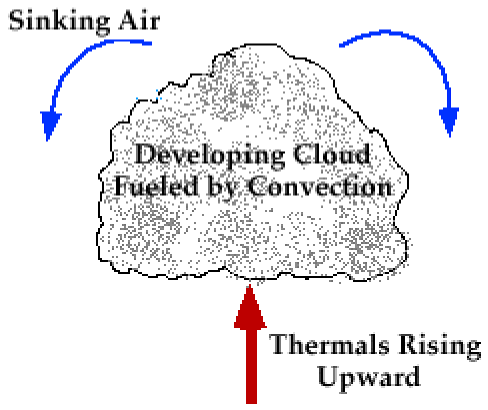


The upward motions that generate clouds and lead to precipitation can be produced by convection in unstable air, convergence of air near cloud base, lifting of air by fronts and lifting over elevated topography such as mountains.

Lifting by Convection

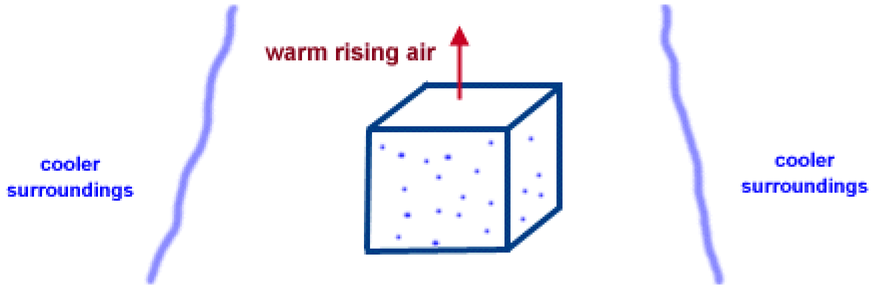
upward moving thermals

In meteorology, convection refers primarily to atmospheric motions in the vertical direction.



As the earth is heated by the sun, bubbles of hot air (called thermals) rise upward from the warm surface. A thermal cools as it rises and becomes diluted as it mixes with the surrounding air, losing some of its buoyancy (its ability to rise).

An air parcel will rise naturally if the air within the parcel is warmer than the surrounding air (like a hot air balloon). Therefore, if cool air is present aloft with warm air at lower levels, thermals can rise to great heights before losing their buoyancy.



Successive thermals following the same path usually rise higher than previous ones, and if a thermal is able to rise high enough to cool to its saturation point, the moisture within condenses and becomes visible as a cloud.

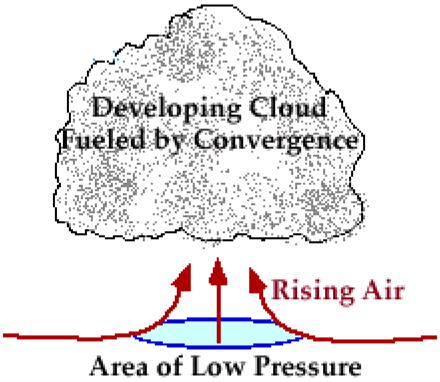
Photograph by: Holle

When a deep stable layer exists just above the cloud base, continued vertical growth is restricted and only fair weather cumulus are able to form. However, if a deep unstable layer (cold air aloft) is present, continued vertical growth is likely, leading to the development of a cumulonimbus cloud, which contains raindrops. Once the supply of thermals is cut off, the cloud begins to dissipate and eventually disappears. Convective clouds are typically much more vertically developed than those clouds generated by convergence lifting.

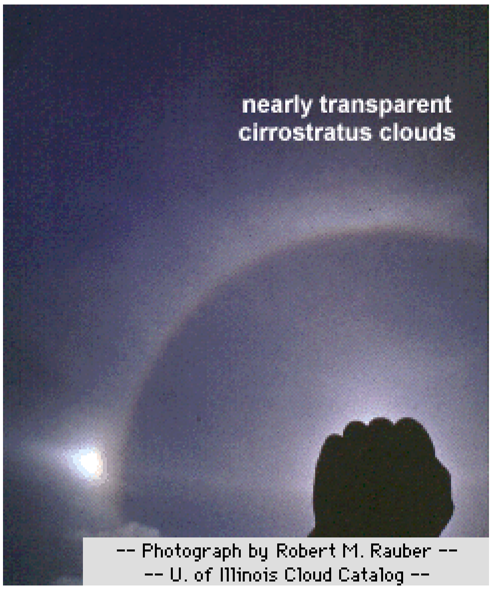
Lifting by Convergence

broad lifting of an entire layer of air

Convergence is an atmospheric condition that exists when there is a horizontal net inflow of air into a region. When air converges along the earth's surface, it is forced to rise since it cannot go downward.



Large scale convergence can lift a layer of air hundreds of kilometers across.



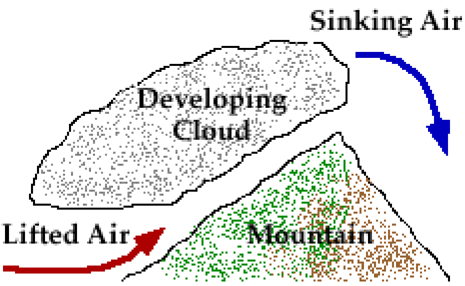
Photograph by: Rauber

Vertical motions associated with convergence are typically much weaker than the small-scale vertical motions associated with convective processes. As a result, clouds generated through convergence, for example cirrostratus clouds, are typically less vertically developed than convective clouds.

Lifting Due To Topography

produces orographic clouds

When air is confronted by a mountain, it is lifted up and over the mountain, cooling as it rises. If the air cools to its saturation point, the water vapor condenses and a cloud forms.



These types of clouds are called "orographic clouds", which develop in response to lifting forced by the topography the earth.

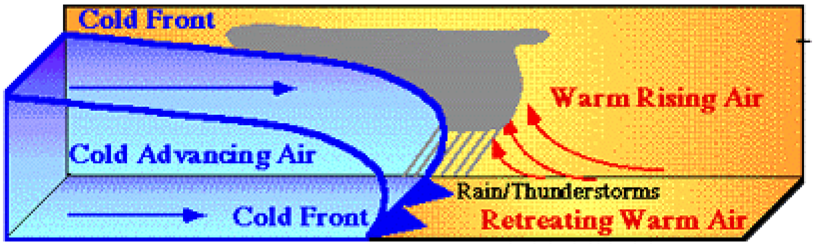
Photograph by: Holle

The exact type of cloud that develops depends upon the moisture content and stability of the air.

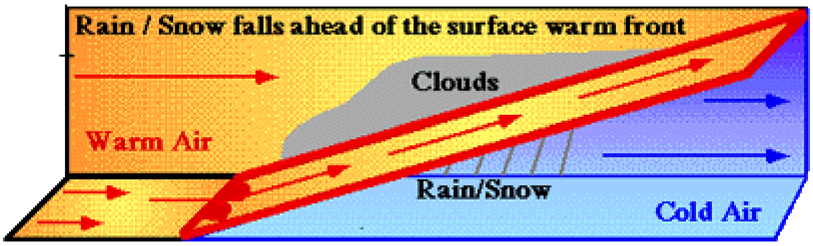
Lifting Along Frontal Boundaries

when air masses interact

Lifting also occurs along frontal boundaries, which separate air masses of different density.



In the case of a cold front, a colder, denser air mass lifts the warm, moist air ahead of it. As the air rises, it cools and its moisture condenses to produce clouds and precipitation. Due to the steep slope of a cold front, vigorous rising motion is often produced, leading to the development of showers and occasionally severe thunderstorms.

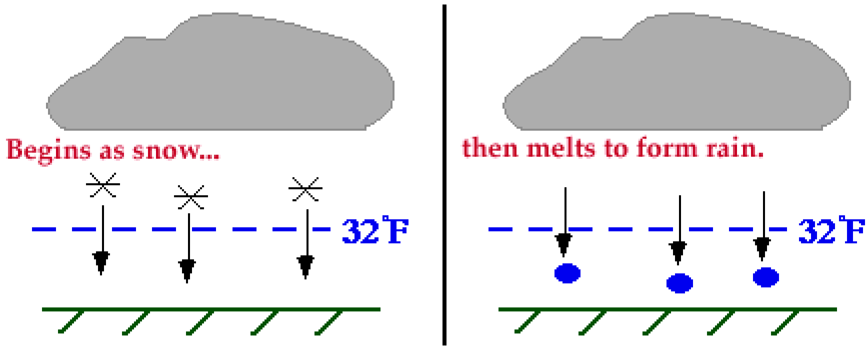


In the case of a warm front, the warm, less dense air rises up and over the colder air ahead of the front. Again, the air cools as it rises and its moisture condenses to produce clouds and precipitation. Warm fronts have a gentler slope and generally move more slowly than cold fronts, so the rising motion along warm fronts is much more gradual. Precipitation that develops in advance of a surface warm front is typically steady and more widespread than precipitation associated with a cold front

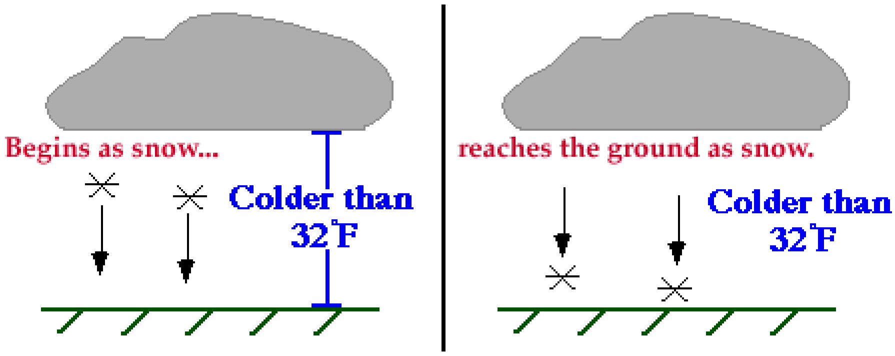
Rain or Snow?

dependent upon temperature

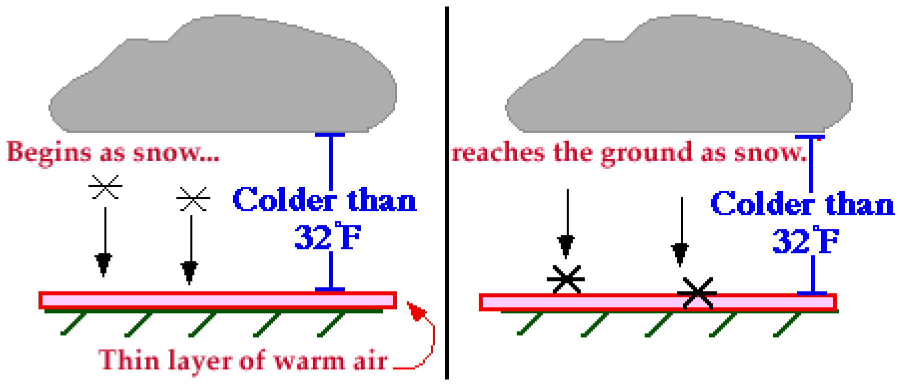
Precipitation typically forms high in the atmosphere where the temperature is below freezing. As ice crystals form aloft and fall toward the surface, they collect each other to form large snowflakes. If ground temperature is above 32 F, the freezing level must be located somewhere above the ground. As the falling snow passes through the freezing level into the warmer air, the flakes melt and collapse into raindrops. During the summer months, it is not uncommon for the freezing level to be found at a level above cloud base.



When the air temperature at the ground is less than 32 F, the snowflakes do not melt on the way down and therefore reach the ground as snow.



Occasionally, we observe snow reaching the ground even though the outside temperature is above freezing. This occurs when a very thin layer of warm air is found near the surface.



Since the layer of warm air is so shallow, the precipitation reaches the ground as snow before it has a chance to melt and become rain. For more about precipitation, visit the precipitation section of this module.

Cloud Types

common cloud classifications

Clouds are classified into a system that uses Latin words to describe the appearance of clouds as seen by an observer on the ground. The table below summarizes the four principal components of this classification system (Ahrens, 1994).

Latin Root	Translation	Example
cumulus	heap	fair weather cumulus
stratus	layer	altostratus
cirrus	curl of hair	cirrus
nimbus	rain	cumulonimbus

Further classification identifies clouds by height of cloud base. For example, cloud names containing the prefix "cirr-", as in cirrus clouds, are located at high levels while cloud names with the prefix "alto-", as in altostratus, are found at middle levels. This module introduces several cloud groups. The first three groups are identified based upon their height above the ground. The fourth group consists of vertically developed clouds, while the final group consists of a collection of miscellaneous cloud types.

Photograph by: Knupp

High-Level Clouds

High-level clouds form above 20,000 feet (6,000 meters) and since the temperatures are so cold at such high elevations, these clouds are primarily composed of ice crystals. High-level clouds are typically thin and white in appearance, but can appear in a magnificent array of colors when the sun is low on the horizon.

Photograph by: Holle

Mid-Level Clouds

The bases of mid-level clouds typically appear between 6,500 to 20,000 feet (2,000 to 6,000 meters). Because of their lower altitudes, they are composed primarily of water droplets, however, they can also be composed of ice crystals when temperatures are cold enough.

Low-level Clouds

Low clouds are of mostly composed of water droplets since their bases generally lie below 6,500 feet (2,000 meters). However, when temperatures are cold enough, these clouds may also contain ice particles and snow.

Photograph by: Holle

Vertically Developed Clouds

Probably the most familiar of the classified clouds is the cumulus cloud. Generated most commonly through either thermal convection or frontal lifting, these clouds can grow to heights in excess of 39,000 feet (12,000 meters), releasing incredible amounts of energy through the condensation of water vapor within the cloud itself.

Photograph by: Holle

Other Cloud Types

Finally, we will introduce a collection of miscellaneous cloud types which do not fit into the previous four groups.

Classifications

Last Update: 07/09/97

High-Level Clouds
Cloud types include: cirrus and cirrostratus.

Mid-Level Clouds
Cloud types include: altocumulus, altostratus.

Low-Level Clouds
Cloud types include: nimbostratus and stratocumulus.

Clouds with Vertical Development
Cloud types include: fair weather cumulus and cumulonimbus.

Other Cloud Types
Cloud types include: contrails, billow clouds, mammatus, orographic and pileus clouds.

Cirrus Clouds

thin and wispy

The most common form of high-level clouds are thin and often wispy cirrus clouds. Typically found at heights greater than 20,000 feet (6,000 meters), cirrus clouds are composed of ice crystals that originate from the freezing of supercooled water droplets. Cirrus generally occur in fair weather and point in the direction of air movement at their elevation.

Cirrus can form from almost any cloud that has undergone glaciation and can be observed in a variety of shapes and sizes. Possibilities range from the "finger-like" appearance of cirrus fall streaks to the uniform texture of more extensive cirrus clouds associated with an approaching warm front.

Photograph by: Holle

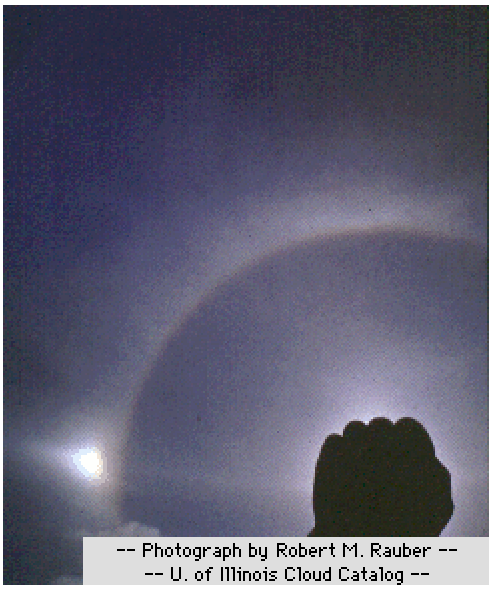
Fall streaks form when snowflakes and ice crystals fall from cirrus clouds. The change in wind with height and how quickly these ice crystals fall determine the shapes and sizes the fall streaks attain. Since ice crystals fall much more slowly than raindrops, fall streaks tend to be stretched out horizontally as well as vertically. Cirrus streaks may be nearly straight, shaped like a comma, or seemingly all tangled together.

Similar to fall streaks is virga, which appears as streamers suspended in the air beneath the base of precipitating clouds. Virga develops when precipitation falls through a layer of dry air and evaporates before reaching the ground.

Cirrostratus Clouds

sheet-like and nearly transparent

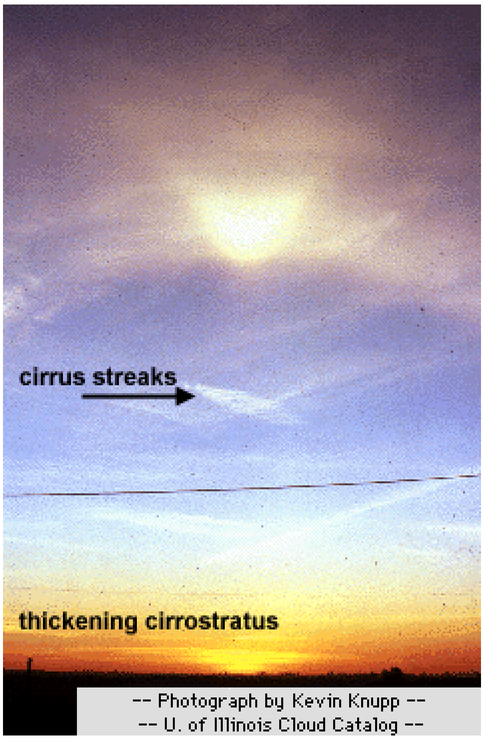
Cirrostratus are sheet-like, high-level clouds composed of ice crystals. Though cirrostratus can cover the entire sky and be up to several thousand feet thick, they are relatively transparent, as the sun or the moon can easily be seen through them. These high-level clouds typically form when a broad layer of air is lifted by large-scale convergence.



Photograph by: Rauber

Sometimes the only indication of their presence is given by an observed halo around the sun or moon. Halos result from the refraction of light by the cloud's ice crystals. Cirrostratus clouds, however, tend to thicken as a warm front approaches, signifying an increased production of ice crystals. As a result, the halo gradually disappears and the sun (or moon) becomes less visible.

When the sun is low on the horizon, cirrostratus clouds can appear in a magnificent array of colors as longer wavelengths of sunlight (red, yellow, and orange) are reflected off of the clouds.



Photograph by: Knupp

The cirrus streaks in this photograph are aligned in a southwest to northeast direction, indicative of warmer air advancing at higher levels. Lower on the horizon, thickening cirrostratus clouds effectively hide the sun, signifying changing weather ahead. As the warm front approaches, these clouds will thicken and be replaced lower and more dense

Altocumulus Clouds

parallel bands or rounded masses

Photograph by: Holle

Altocumulus clouds are composed primarily of water droplets and are located between 6,500 and 20,000 feet (2,000 to 6,000 meters) above the ground.

Photograph by: Holle

Altocumulus may appear as parallel bands (top photograph) or rounded masses (bottom photograph). Typically a portion of an altocumulus cloud is shaded, a characteristic which makes them distinguishable from the high-level cirrocumulus. Altocumulus clouds usually form by convection in an unstable layer aloft, which may result from the gradual lifting of air in advance of a cold front. The presence of altocumulus clouds on a warm and humid summer morning is commonly followed by thunderstorms later in the day.

Also found at mid-levels are altostratus clouds, which are often confused with high-level cirrostratus. One distinguishing feature is that a halo is not observed around the sun (or moon) when viewed through altostratus, but is a common feature associated with cirrostratus clouds. In fact, the sun (or moon) is only vaguely visible through altostratus clouds and appears as if it were shining through frosted glass.

Nimbostratus Clouds
dark, low-level clouds with precipitation

Nimbostratus are dark, low-level clouds accompanied by light to moderately falling precipitation. Low clouds are primarily composed of water droplets since their bases generally lie below 6,500 feet (2,000 meters). However, when temperatures are cold enough, these clouds may also contain ice particles and snow.

Photograph by: Holle

The sun (or moon) is not visible through nimbostratus clouds, which distinguishes them from mid-level altostratus clouds. Because of the fog and falling precipitation commonly found beneath and around nimbostratus clouds, the cloud base is typically very diffuse and difficult to accurately determine.

Stratocumulus Clouds
low, lumpy layer of clouds

Stratocumulus clouds generally appear as a low, lumpy layer of clouds that is sometimes accompanied by weak intensity precipitation. Stratocumulus vary in color from dark gray to light gray and may appear as rounded masses, rolls, etc., with breaks of clear sky in between.

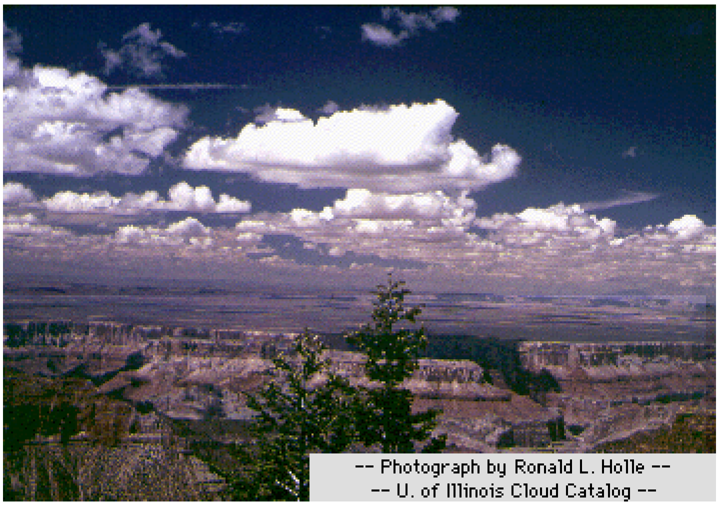
Photograph by: Holle

Since the individual elements of stratocumulus are larger than those of altocumulus, one can easily decipher between the two cloud types by extending your arm toward the sky. Altocumulus elements are about the size of a thumb nail while stratocumulus are about the size of a fist (Ahrens, 1994).

Fair Weather Cumulus Clouds

puffy cotton balls floating in the sky

Fair weather cumulus have the appearance of floating cotton and have a lifetime of 5-40 minutes. Known for their flat bases and distinct outlines, fair weather cumulus exhibit only slight vertical growth, with the cloud tops designating the limit of the rising air. Given suitable conditions, however, harmless fair weather cumulus can later develop into towering cumulonimbus clouds associated with powerful thunderstorms.



Photograph by: Holle

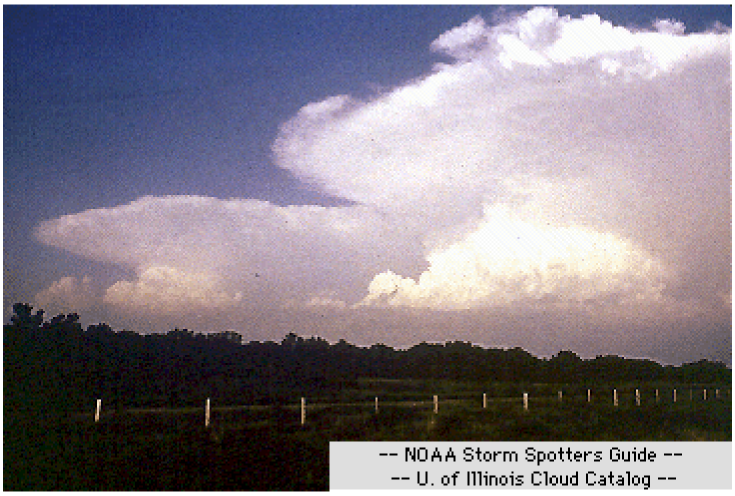
Fair weather cumulus are fueled by buoyant bubbles of air, or thermals, that rise upward from the earth's surface. As they rise, the water vapor within cools and condenses forming cloud droplets. Young fair weather cumulus have sharply defined edges and bases while the edges of older clouds appear more ragged, an artifact of cloud erosion. Evaporation along the cloud edges cools the surrounding air, making it heavier and producing sinking motion (or subsidence) outside the cloud.

Photograph by: Holle

The downward motion inhibits further convection and the growth of additional thermals from below, which is why fair weather cumulus typically have expanses of clear sky between them. Without a continued supply of rising air, the cloud begins to erode and eventually disappears.

Cumulonimbus Clouds
reaching high into the atmosphere

Cumulonimbus clouds (Cb) are much larger and more vertically developed than fair weather cumulus. They can exist as individual towers or form a line of towers called a squall line. Fueled by vigorous convective updrafts (sometimes in excess 50 knots), the tops of cumulonimbus clouds can easily reach 39,000 feet (12,000 meters) or higher.



Photograph by: NOAA

Lower levels of cumulonimbus clouds consist mostly of water droplets while at higher elevations, where temperatures are well below 0 degrees Celsius, ice crystals dominate. Under favorable atmospheric conditions, harmless fair weather cumulus clouds can quickly develop into large cumulonimbus clouds associated with powerful thunderstorms known as supercells.

Photograph by: Knupp

Supercells are large thunderstorms with deep rotating updrafts and can have a lifetime of several hours. Supercells can produce frequent lightning, large hail, damaging winds, and tornadoes.

Photograph by: Holle

These storms tend to develop during the afternoon and early evening when the effects of heating by the sun are strongest. For more information about supercells and other types of severe weather phenomena, visit the Severe Storm Spotters Guide.

Contrails

condensation trails

A contrail, also known as a condensation trail, is a cirrus-like trail of condensed water vapor often resembling the tail of a kite. Contrails are produced at high altitudes where extremely cold temperatures freeze water droplets in a matter of seconds before they can evaporate.

Photograph by: Knupp

Contrails form through the injection of water vapor into the atmosphere by exhaust fumes from a jet engine. If the surrounding air is cold enough, a state of saturation is attained and ice crystals develop, producing a contrail.

Photograph by: Holle

If the air in which the contrail develops has a low relative humidity, the cloud particles will quickly evaporate. Even in the presence of higher relative humidities, upper-level winds can spread a contrail apart to produce a horizontal sheet-like cloud. For a contrail to remain in tact for a long period of time, the air must have a high relative humidity in the presence of relatively light winds.

Billow Clouds

produced by Kelvin-Helmholtz instability

Billow clouds are created from instability associated with air flows having marked vertical shear and weak thermal stratification. The common name for this instability is Kelvin-Helmholtz instability. These instabilities are often visualized as a row of horizontal eddies aligned within this layer of vertical shear.

Photograph by: Rilling

Billow clouds are created in the upward branch of each of the eddies if the air within this branch has a high enough relative humidity that, upon lifting, the air parcel reaches saturation. Individual billow clouds generally have life times of a few minutes. The presence of billow clouds provides a visible signal to aviation interests of potentially dangerous turbulence.

Mammatus Clouds

sagging pouch-like structures

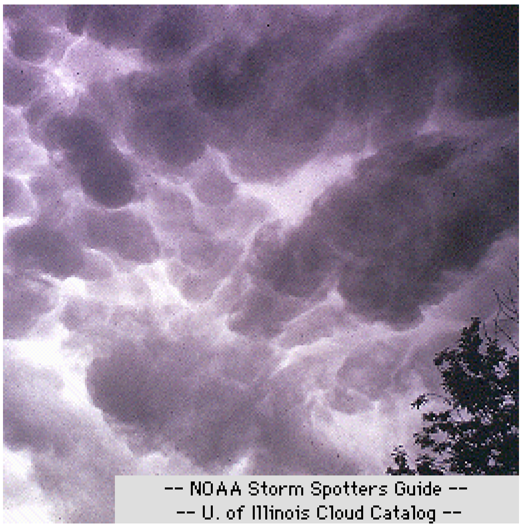
Mammatus are pouch-like cloud structures and a rare example of clouds in sinking air.

Sometimes very ominous in appearance, mammatus clouds are harmless and do not mean that a tornado is about to form; a commonly held misconception. In fact, mammatus are usually seen after the worst of a thunderstorm has passed.

Photograph by: Manikin

As updrafts carry precipitation enriched air to the cloud top, upward momentum is lost and the air begins to spread out horizontally, becoming a part of the anvil cloud. Because of its high concentration of precipitation particles (ice crystals and water droplets), the saturated air is heavier than the surrounding air and sinks back towards the earth.

The temperature of the subsiding air increases as it descends. However, since heat energy is required to melt and evaporate the precipitation particles contained within the sinking air, the warming produced by the sinking motion is quickly used up in the evaporation of precipitation particles. If more energy is required for evaporation than is generated by the subsidence, the sinking air will be cooler than its surroundings and will continue to sink downward.



The subsiding air eventually appears below the cloud base as rounded pouch-like structures called mammatus clouds.

Photograph by: NOAA

Mammatus are long lived if the sinking air contains large drops and snow crystals since larger particles require greater amounts of energy for evaporation to occur. Over time, the cloud droplets do eventually evaporate and the mammatus dissolve.

Mammatus typically develop on the underside of a thunderstorm's anvil and can be a remarkable sight, especially when sunlight is reflected off of them.

Photograph by: NOAA

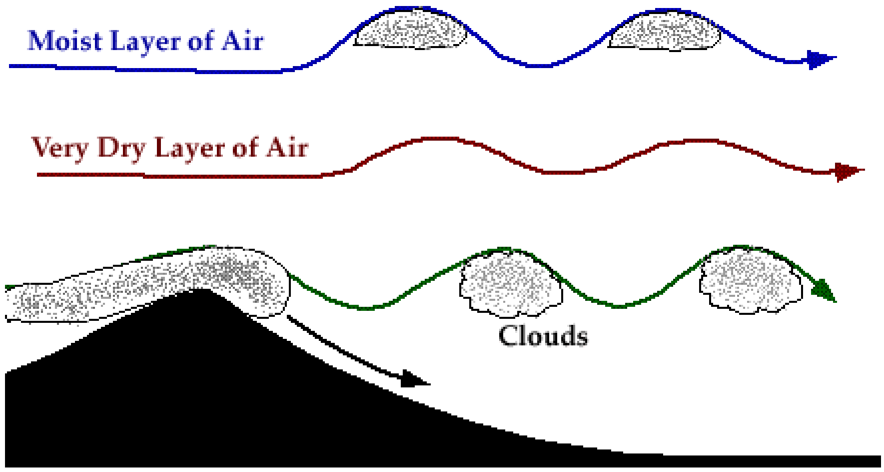
Orographic Clouds

forced by the earth's topography

Orographic clouds are clouds that develop in response to the forced lifting of air by the earth's topography (mountains for example).

Photograph by: Holle

Air passing over a mountain oscillates up and down as it moves downstream (as shown in the diagram below). Initially, stable air encounters a mountain, is lifted upward and cools through expansion as it rises. If the air cools to its saturation temperature during this process, the water vapor within condenses and becomes visible as a cloud.



Upon reaching the mountain top, the air is heavier than the environment and will sink down the other side, warming as it descends. Once the air returns to its original height, it has the same buoyancy as the surrounding air. However, the air does not stop immediately because it still has momentum carrying it downward. With continued descent, the air becomes warmer than the surroundings and begins to accelerate back upward towards its original height (beginning the cycle again). It is during the upper-most ascent phase of this cycle that clouds develop. In regions where air is descending, skies are clear.

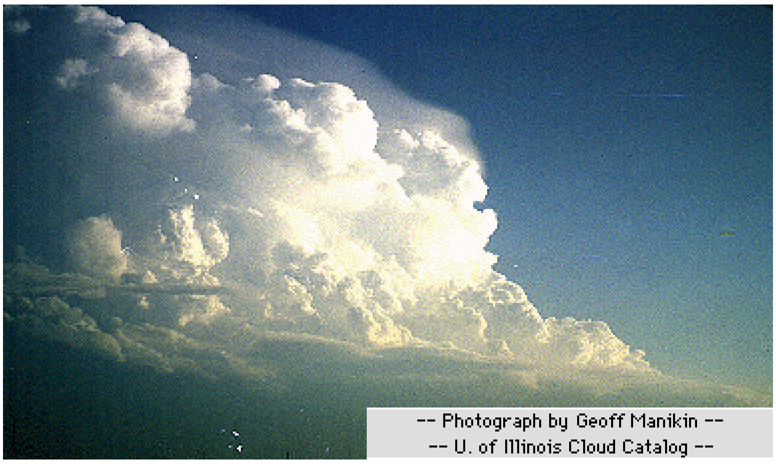
Photograph by: Holle

The lifting of moist air can result in the generation of clouds, while lifting drier air may not produce any clouds at all. The oscillations continue as the air moves further downstream from the mountains but are eventually dampened out by mixing and friction.

Pileus Clouds

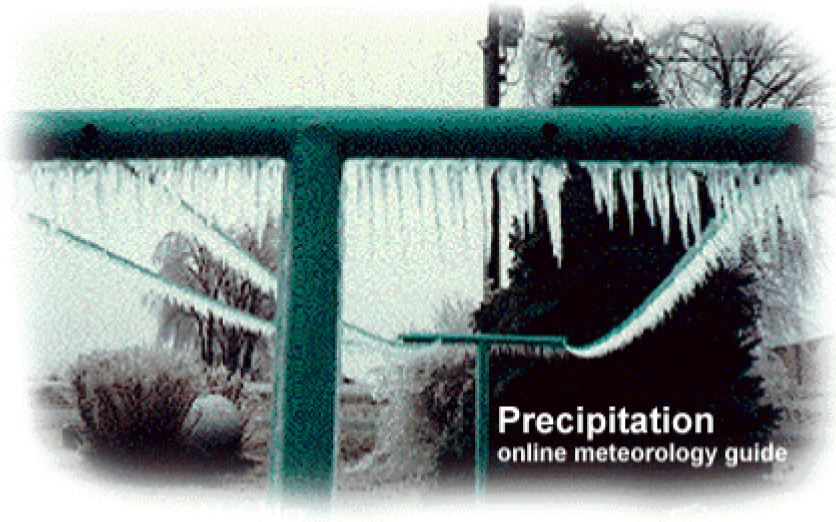
smooth capping clouds

Pileus (Latin for "skullcap") is a smooth cloud found attached to either a mountain top or growing cumulus tower.



Photograph by: Manikin

The lifted air that produces pileus clouds is typically drier than the moist air from lower levels often responsible for cumulus clouds. There is little tendency for any significant vertical growth in pileus clouds, which is why they take on a smoother, horizontal shape.



Photograph by: Norene McGhiey

When cloud particles become too heavy to remain suspended in the air, they fall to the earth as precipitation. Precipitation occurs in a variety of forms; hail, rain, freezing rain, sleet or snow. This portion of the Clouds and Precipitation module focuses on precipitation and has been organized into the following sections.

Sections
Latest Update:
07/21/97

Rain and Hail
Atmospheric conditions that lead to the development of rain and hail.

Freezing Rain
A detailed look at freezing rain, associated dangers and the conditions that lead to its development.

Sleet
Atmospheric conditions that lead to the development of sleet.

Snow
Atmospheric conditions that lead to the development of snow.

Acknowledgments
Those who contributed to the Precipitation sections of the Clouds and Precipitation module.

Rain and Hail

liquid and ice precipitation

Rain develops when growing cloud droplets become too heavy to remain in the cloud and as a result, fall toward the surface as rain. Rain can also begin as ice crystals that collect each other to form large snowflakes. As the falling snow passes through the freezing level into warmer air, the flakes melt and collapse into rain drops. The picture below shows heavy rain falling from a Texas thunderstorm.

Photo by: Olthoff

Hail is a large frozen raindrop produced by intense thunderstorms, where snow and rain can coexist in the central updraft. As the snowflakes fall, liquid water freezes onto them forming ice pellets that will continue to grow as more and more droplets are accumulated. Upon reaching the bottom of the cloud, some of the ice pellets are carried by the updraft back up to the top of the storm.

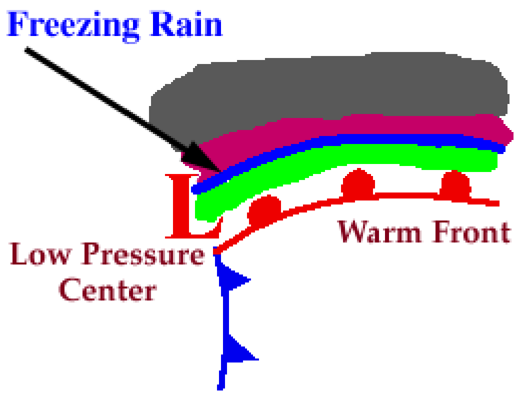
Photo by: NSSL

As the ice pellets once again fall through the cloud, another layer of ice is added and the hail stone grows even larger. Typically the stronger the updraft, the more times a hail stone repeats this cycle and consequently, the larger it grows. Once the hail stone becomes too heavy to be supported by the updraft, it falls out of the cloud toward the surface. The hail stone reaches the ground as ice since it is not in the warm air below the thunderstorm long enough to melt before reaching the ground.

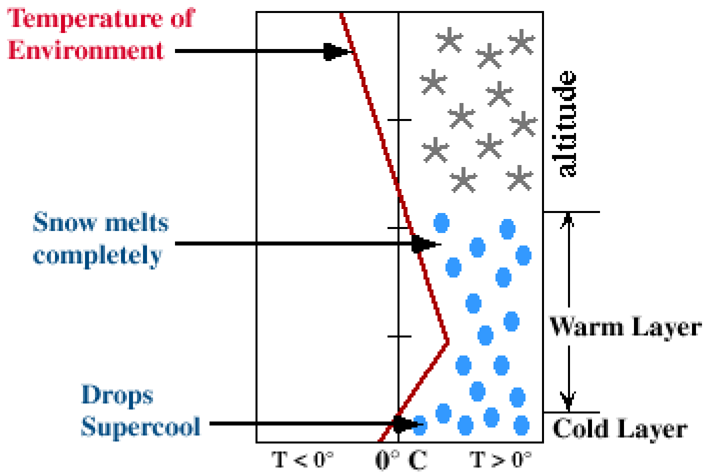
Freezing Rain

supercooled droplets freezing on impact

Ice storms can be the most devastating of winter weather phenomena and are often the cause of automobile accidents, power outages and personal injury. Ice storms result from the accumulation of freezing rain, which is rain that becomes supercooled and freezes upon impact with cold surfaces. Freezing rain is most commonly found in a narrow band on the cold side of a warm front, where surface temperatures are at or just below freezing.



The diagram below shows a typical temperature profile for freezing rain with the red line indicating the atmosphere's temperature at any given altitude. The vertical line in the center of the diagram is the freezing line. Temperatures to the left of this line are below freezing, while temperatures to the right are above freezing.



Freezing rain develops as falling snow encounters a layer of warm air deep enough for the snow to completely melt and become rain. As the rain continues to fall, it passes through a thin layer of cold air just above the surface and cools to a temperature below freezing. However, the drops themselves do not freeze, a phenomena called supercooling (or forming "supercooled drops"). When the supercooled drops strike the frozen ground (power lines, or tree branches), they instantly freeze, forming a thin film of ice, hence freezing rain.

Dangers to People

injuries and automobile accidents

An intense ice storm can paralyze a region in a matter of hours, greatly affecting the people who live there.

Photograph by: McGhiey

Freezing rain is dangerous because it is almost invisible on smooth surfaces and consequently, people are often unaware of its presence. Sidewalks become extremely slick when covered with freezing rain, increasing the likelihood of someone slipping and injuring themselves. Automobile accidents are more likely to occur during an ice storm because of the icy roads.

Photograph by: McGhiey

The weight of ice can damage telephone poles and wires, cutting power and lines of communication to millions of people. During one severe ice storm in New England in 1921, ice that accumulated on the wires between two telephone poles was estimated to weigh over 4 tons. Ice can accumulate up to 4-6 inches deep during the most intense events, forcing businesses to shut down and greatly restricting commuters due to the ice-covered roads.

Dangers to the Environment

damage to trees and threat to animals

The picture below shows a tree nearly bent in half from the weight of the ice on its branches. Entire trees break in half when the weight of the ice becomes too great.

Photograph by: McGhiey

During the 1921 New England ice storm mentioned earlier, Worcester Parks Recreation Department estimated that 7,500 to 8,000 trees were completely destroyed and that an additional 5,000 to 7,000 were going to die from severe damage. Devastation to a forest by an ice storm can be as severe as the damage caused by large tornadoes.

Photograph by: McGhiey

Ice storms also have devastating effects on livestock and birds. Grazing areas covered with ice can cause many livestock to slip and fall, while ice build-up on their nostrils can cause them to suffocate.

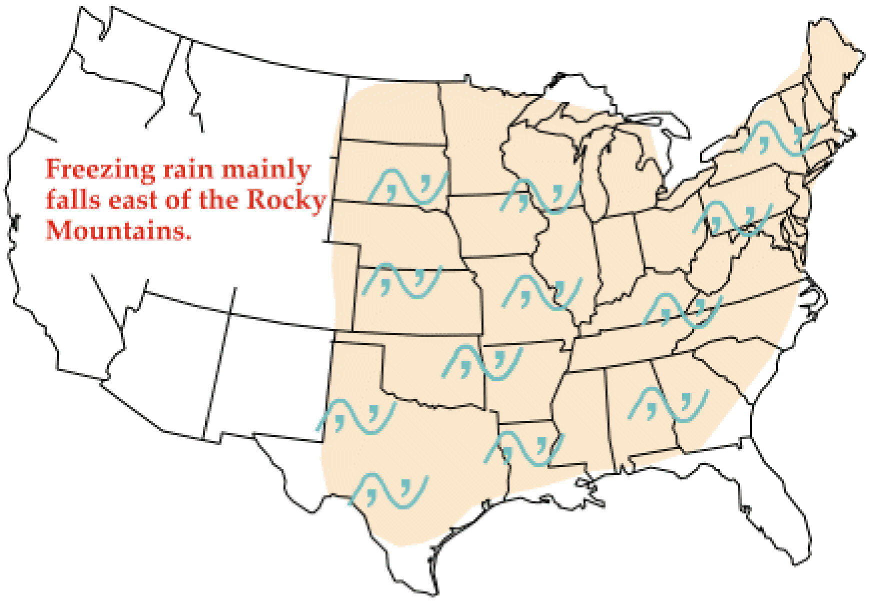
Photograph by: McGhiey

Birds have been found suffocated, their beaks and nostrils having been frozen shut. Birds have also been found frozen to trees or unable to fly due to the weight of the ice on their wings.

Regions of Freezing Rain

generally east of the Rocky Mountains

Except for extreme southern portions of the United States, almost any area east of the Rocky Mountains can experience freezing rain. The area most frequently hit by freezing rain extends over a broad region from Texas northward to Minnesota and then eastward into the Middle Atlantic states and New England.

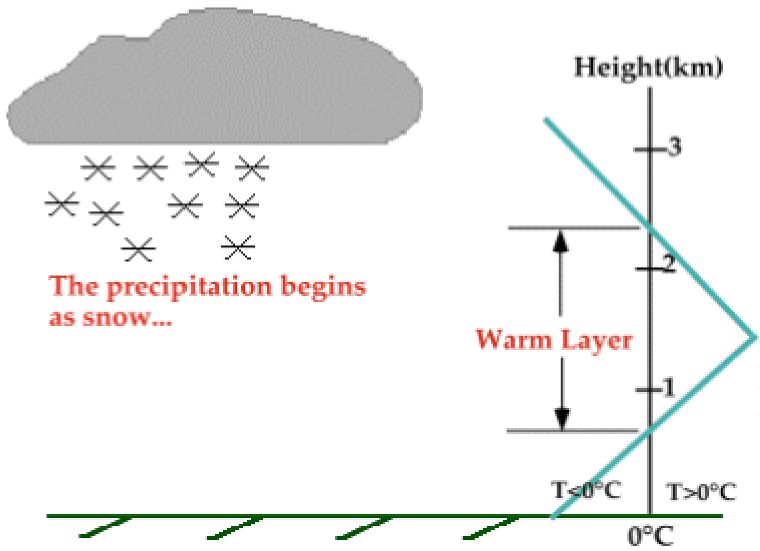


Freezing rain generally does not fall west of the Rockies because one of the key ingredients is missing; shallow arctic air, which is unable to flow over the mountains. The only regions in the West that experience freezing rain are near the Columbia River in southern Washington and northern Oregon. Freezing rain occurs when cold air gets caught in the river valleys and warm moist Pacific air rides over top, creating a favorable set-up for freezing rain.

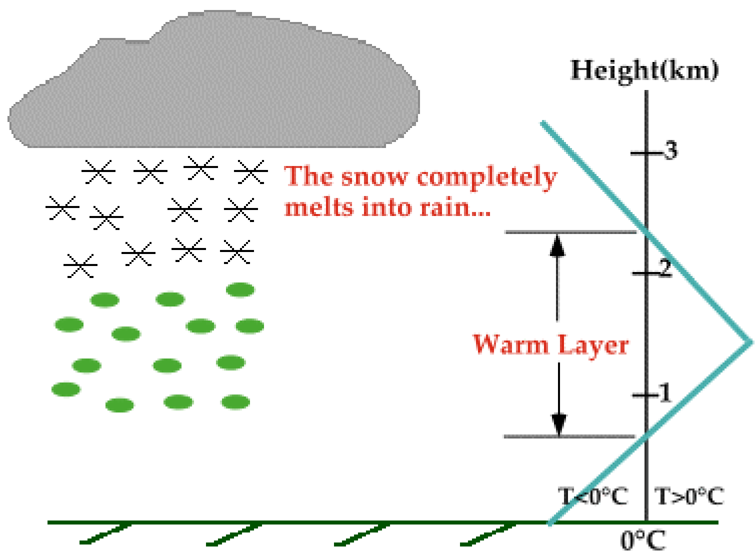
Ice-Crystal Mechanisms

the formation of freezing rain

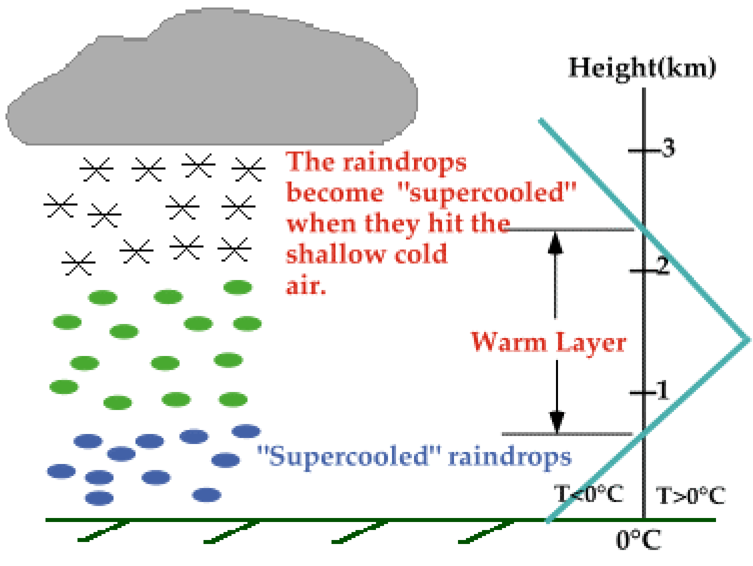
Freezing rain can develop either through ice crystal processes or supercooled warm-rain processes. Ice crystals high in the atmosphere grow by collecting water vapor molecules, which are sometimes supplied by microscopic evaporating cloud droplets. In the figure below, the blue line represents the temperature of the atmosphere and the black line represents the 0C (32F) isotherm (a line of equal temperature). When the blue line is to the right of the black line, the atmosphere is warmer than 0C and when the blue line is to the left, the atmosphere is colder than 0C.



As the snow falls, it encounters a layer of warm air where snow and ice particles completely melt and collapse into raindrops.

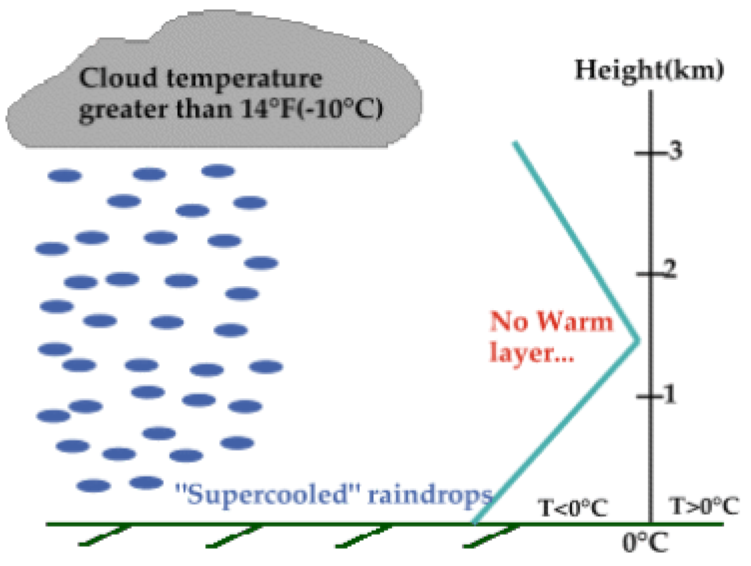


As the raindrops approach the ground, they encounter a layer of cold air and cool to temperatures below 0C. However, since the cold layer is so shallow, the drops themselves do not freeze, a phenomena called supercooling (or forming "supercooled raindrops"). The supercooled raindrops are raindrops that are colder than 0C and freeze on contact when they strike the ground.



Supercooled Warm-Rain Processes
the formation of freezing rain

A less common way that freezing rain forms is through supercooled warm-rain process (SWRP), where cloud top temperatures are warmer than about -10C. Supercooled raindrops develop as microscopic cloud droplets collect one another as they fall. Ice processes are not involved in the formation of these raindrops.



The precipitation falls to the surface as supercooled rain or drizzle and freezes instantly on contact. The raindrops do not freeze within the cold layer because there are very few ice nuclei in the presence of warmer temperatures.

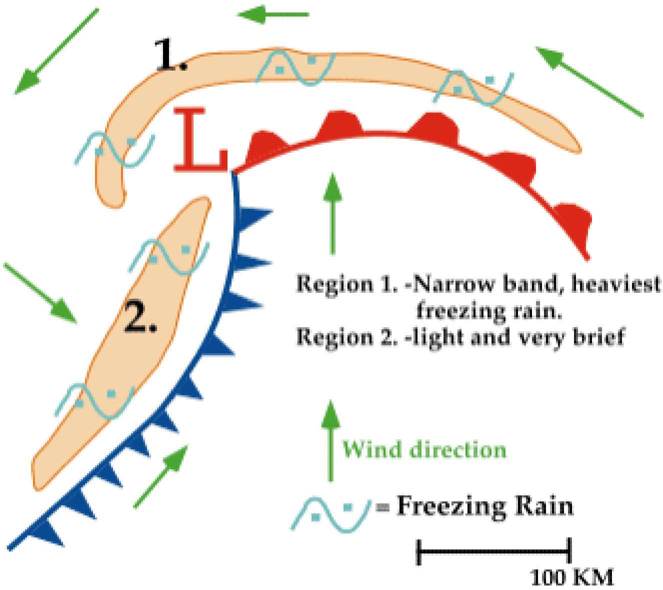
The freezing rain forms a coat of ice on everything. This picture shows several tree branches coated with a thick layer of ice that accumulated during a central Illinois ice storm.

Photograph by: Olthoff

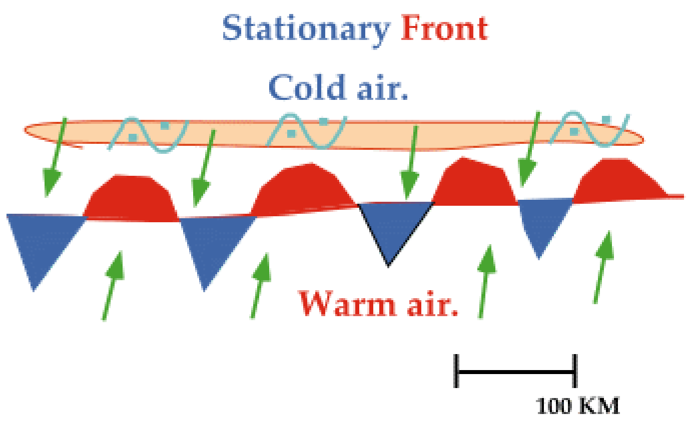
Cyclones and Fronts

the development of freezing rain

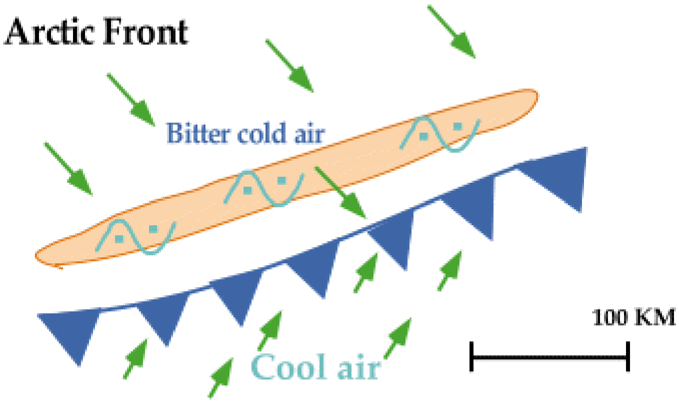
In most cases, freezing rain results from the process of warm moist air "overrunning" colder air. Perhaps the most common overrunning scenario occurs as warm moist air flows up and over a warm front associated with a midlatitude cyclone. The rising air cools, the water vapor condenses, producing a narrow band of freezing rain ahead of the front. This band is typically less than 50 kilometers (30 miles) wide and is represented by region #1 (shaded in orange) in the diagram below. This band is often wrapped around and behind the low pressure center by counterclockwise winds flowing around the cyclone. Some of the most devastating ice storms occur in association with this narrow band of freezing rain.



A second area of freezing rain is typically found behind the cold front, (region #2 shaded in orange in the diagram above). Freezing rain develops as southerly winds at upper levels push warm moist air up and over the cold front, producing precipitation that falls into the colder air. Freezing rain associated with the cold front is usually very light and scattered, and in rare cases, even observed ahead of the front.



Stationary fronts can be associated with the production of freezing rain. A stationary front separates cold air to the north from warm moist air to the south. Freezing rain develops as upper-level winds (typically light and southwesterly) push warm moist air over the colder air north of the stationary front, producing a narrow band of freezing rain on the cold side of the frontal boundary.

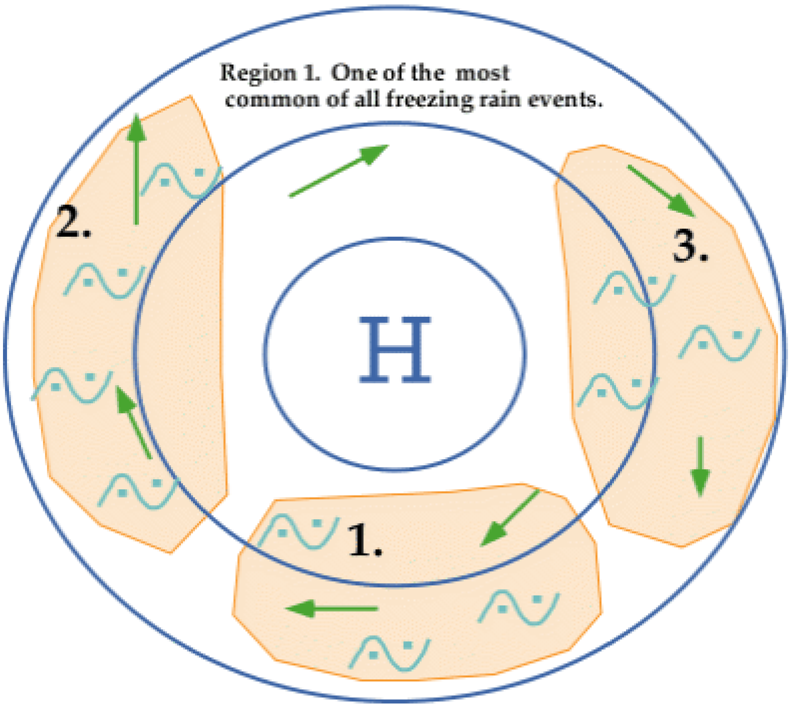


Arctic air masses are typically very shallow and have been known to produce devastating ice storms. Behind a cold front, the air mass is maritime polar (mP), but behind an Arctic front, the air mass is continental polar (cP). As Arctic air advances, it lifts the warm moist air (ahead of the front), producing precipitation that falls into the Arctic air. Sometimes, a band of freezing rain wider than 50 kilometers develops in association with an Arctic front.

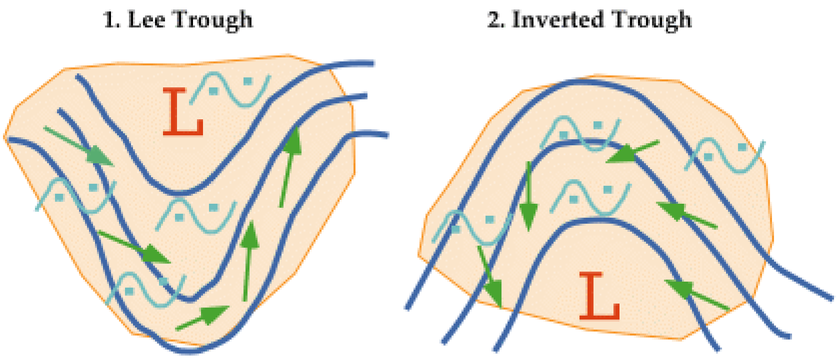
Anticyclones, Lee Troughs and Inverted Troughs

and their roles in the development of freezing rain

In addition to cyclones and frontal boundaries, conditions associated with surface anticyclones can also lead to the development freezing rain. Three areas of freezing rain (shaded in orange below) are commonly observed in the vicinity of an anticyclone and in all three cases, freezing rain typically develops as southwesterly winds at upper levels transport warm moist air up and over the colder air associated with the high.



Pressure troughs, or dips in the pressure field, may also lead to the development of freezing rain. One type of pressure trough, called a "lee trough", is commonly observed in the central United States. West of the trough, surface winds are usually from the northwest while ahead of the trough, winds are southerly. Westerly winds at upper levels typically transport warmer Pacific air that overruns the colder air at the surface, producing freezing rain.

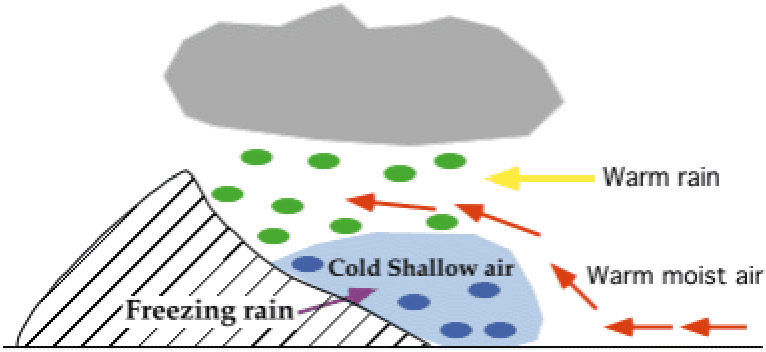


An inverted trough, which is much more common than the lee trough, may also lead to the development of freezing rain. Surface winds west of the inverted trough are north or northwesterly while winds east of the trough are east to northeasterly. The upper-level winds are usually from the southwest to southerly and they overrun the cold air at the surface.

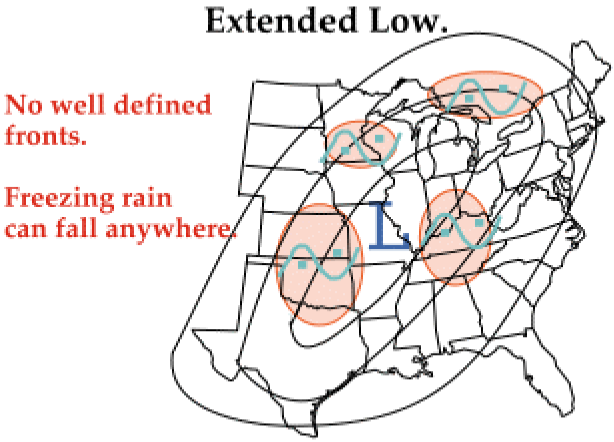
Cold-Air Damming and Extended Lows

their roles in the development of freezing rain

Cold-air damming is common along the East Coast of the United States and occurs when a layer of cold air gets trapped between the coast and inland mountains. Freezing rain develops when warm oceanic air rises up and over the cold air, producing liquid precipitation that falls through the cold layer. The falling droplets become supercooled and freeze on impact with the cold surface.



Another weather pattern that may lead to the development of freezing rain is a broad area of low pressure called an "extended low", which is typically very weak and covers a large area of the country. An extended low has very diffuse frontal boundaries and is often the remnants of a dying cyclone.



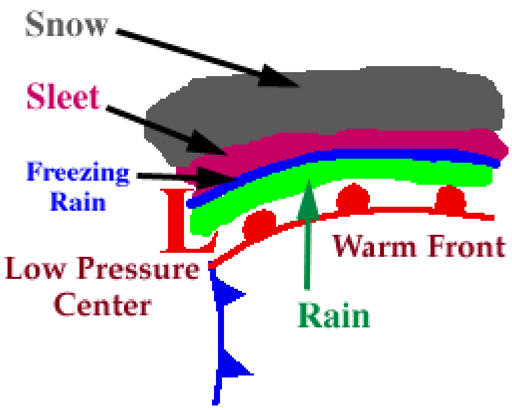
Upper-level winds transport warm moist air up and over the pool of cold air associated with the extended low, and given the right conditions, freezing rain occurs. In addition, convergence associated with the low produces upward motions that may also contribute to the development of freezing rain. Freezing rain can be found anywhere in the vicinity of an extended low since there are typically no preferred regions of development.

Forecasting Freezing Rain

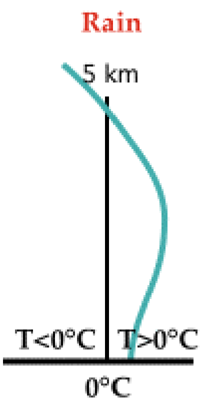
the importance of temperature profiles

Freezing rain is one of the most difficult events to forecast. The smallest variations in temperature (even only tenths of a degree) can mean the difference between rain, freezing rain, sleet or snow. Freezing rain occurs less frequently than other winter weather events and falls in very narrow bands, usually not more than 50 kilometers wide.

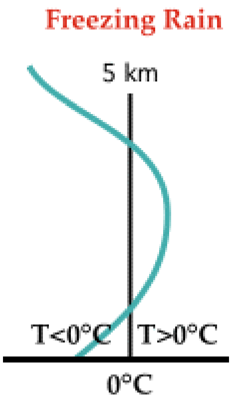
When attempting to forecast a freezing rain event, sounding data is very useful for examining vertical temperature profiles of the atmosphere, which are indicative of what type of precipitation (if any) will likely occur.



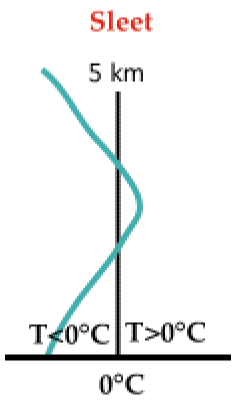
There are four types of soundings associated with the four different types of precipitation (mentioned above). In the following diagrams, the blue line represents the temperature profile of the atmosphere and the black line represents the 0C isotherm (a line of equal temperature). When the blue line is to the right of the black line, it means the atmospheric temperature is warmer than 0C, but when the blue line is to the left of the black line, it means the atmospheric temperature is colder than 0C.



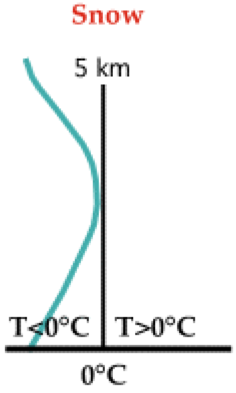
Rain:
The entire temperature profile near the ground is above freezing so all ice particles completely melt and reach the ground as rain.



Freezing Rain:
A shallow layer of cold air lies below a layer of warmer air, which completely melts all ice particles as they pass through. When the raindrops enter the shallow layer of cold air, they supercool and freeze instantly on contact.



Sleet:
The warm layer is very shallow so ice crystals only partially melt as they pass through. Once they enter the cold layer below, they freeze again and strike the ground as ice pellets, or sleet.

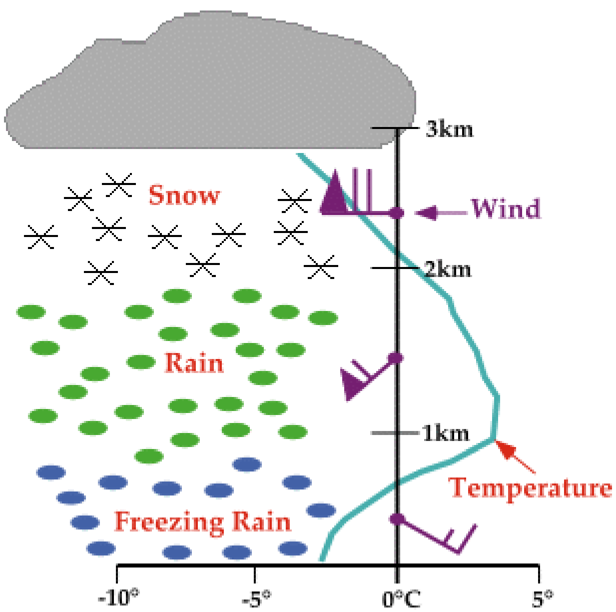


Snow:
The entire sounding is completely below freezing so the precipitation reaches the ground as snow.

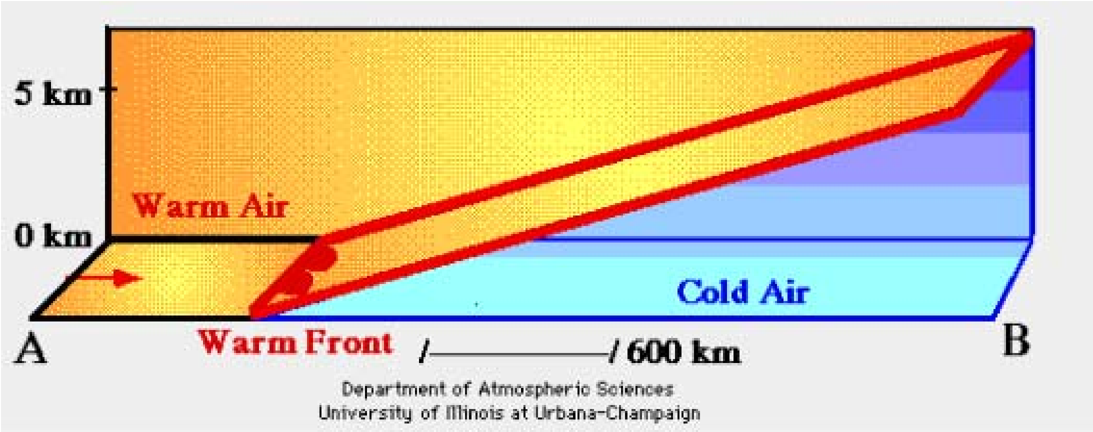
Upper Air Soundings

useful when forecasting for freezing rain

Soundings are the most important tool for identifying potential freezing rain regimes. Three types of soundings can lead to freezing rain and the most common consists of a shallow layer of cold air at the surface with a depth of about 600 meters (1,800 feet).



Above the cold air is a layer of warmer air with a depth of about 1,400 meters (4,200 feet). Winds near the surface are usually east or southeasterly, then veer around to the southwest in the warm air, and finally become westerly in upper levels. The sounding given above represents only an average case.



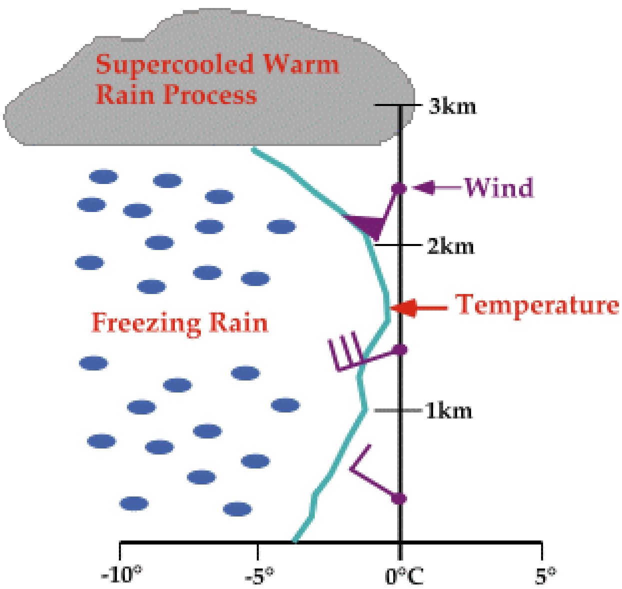
Animation by: Hall

For precipitation to form, something is needed to force the air to rise. Warm air overrunning is the most common process in the production of freezing rain. This occurs as warm air rides up and over colder air, (as in the animation above), the water vapor condenses, producing clouds and precipitation. When the precipitation falls through an atmosphere with a temperature profile similar to the one described above, freezing rain is a likely result.

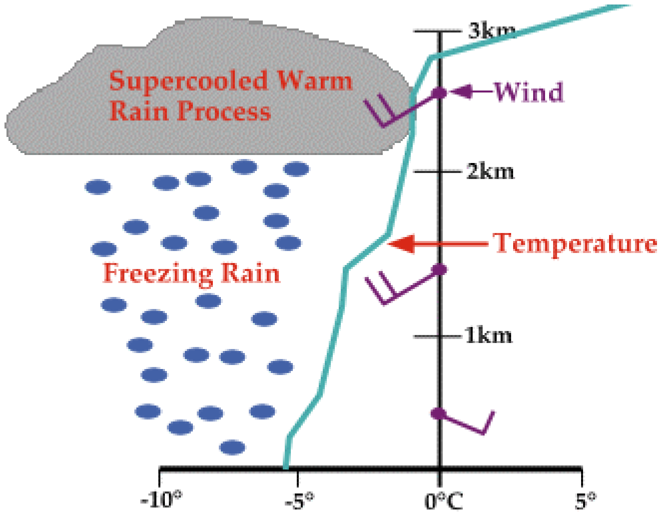
SWRP Sounding

supercooled warm-rain process

Below is a sounding that typically results in freezing rain through Supercooled Warm Rain Processes (SWRP). Throughout the sounding profile, the temperature never exceeds 0C (32F). The process begins as supercooled raindrops grow by collision and coalescence, and since the temperature throughout the cloud is warmer than about -10C, the cloud is generally free of ice crystals. This is important because if ice crystals were present, the cloud drops would instead grow by ice crystal processes, producing snow and not freezing rain. Winds are typically out of the west or northwest at the surface, veering to the southwest in middle and upper levels.



In the second sounding, the temperature exceeds 0C (32F) above the cloud. This type of sounding is commonly observed in the Southern Plains where very warm mid-level air from the Mexican plateau overrides colder air in the surface layers. Winds at the surface are usually from the east or southeast and veer around to the southwest or west in middle and upper levels.

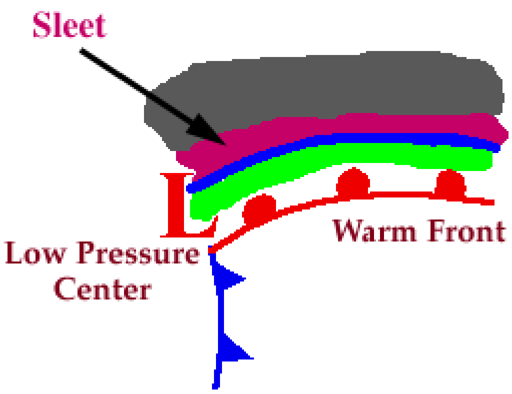


The best way to forecast freezing rain is to examine forecast model soundings for profiles similar to the ones described in this module. One web site providing these products is the Northern Illinois University's Storm Machine. One can choose the city and model and receive the appropriate forecast soundings, from which a forecast can be made about when and where freezing rain will occur.

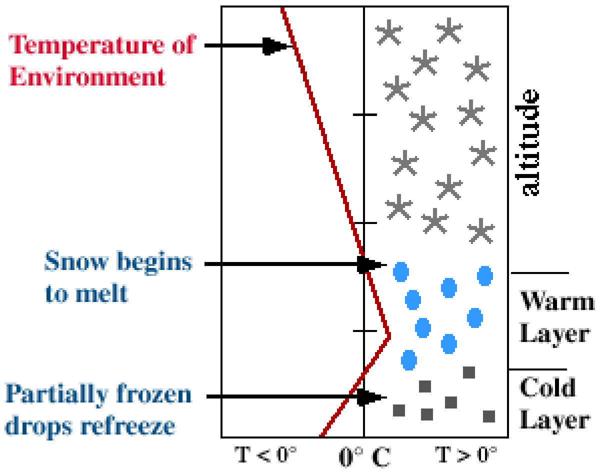
Sleet

frozen raindrops that bounce on impact with the ground

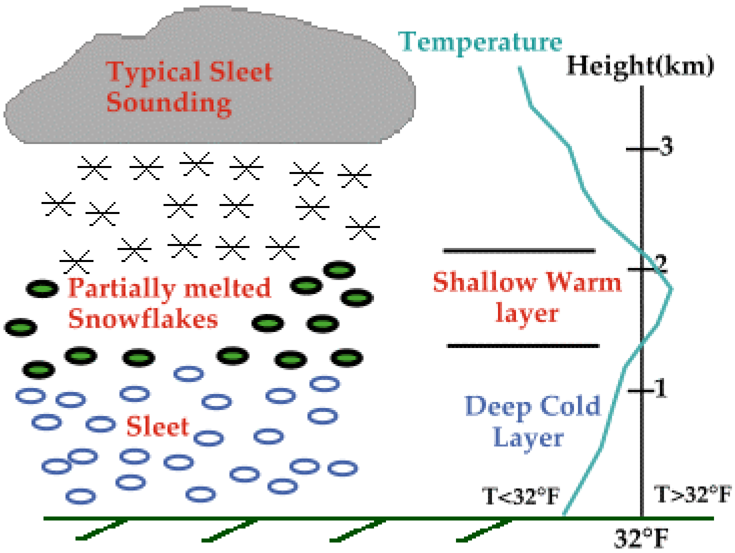
Progressing further ahead of the warm front, surface temperatures continue to decrease and the freezing rain eventually changes over to sleet. Areas of sleet are located on the colder side (typically north) of the freezing rain band.



Sleet is less prevalent than freezing rain and is defined as frozen raindrops that bounce on impact with the ground or other objects. The diagram below shows a typical temperature profile for sleet with the red line indicating the atmosphere's temperature at any given altitude. The vertical line in the center of the diagram is the freezing line. Temperatures to the left of this line are below freezing, while temperatures to the right are above freezing.



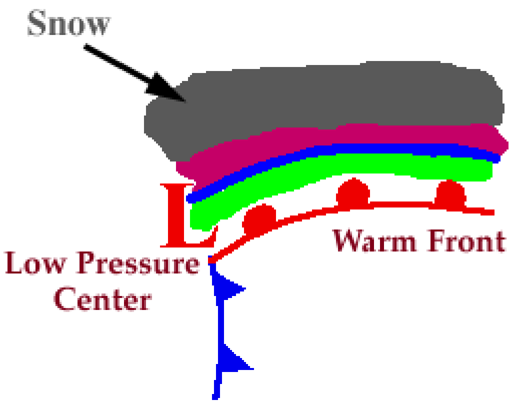
Sleet is more difficult to forecast than freezing rain because it develops under more specialized atmospheric conditions. It is very similar to freezing rain in that it causes surfaces to become very slick, but is different because its easily visible.



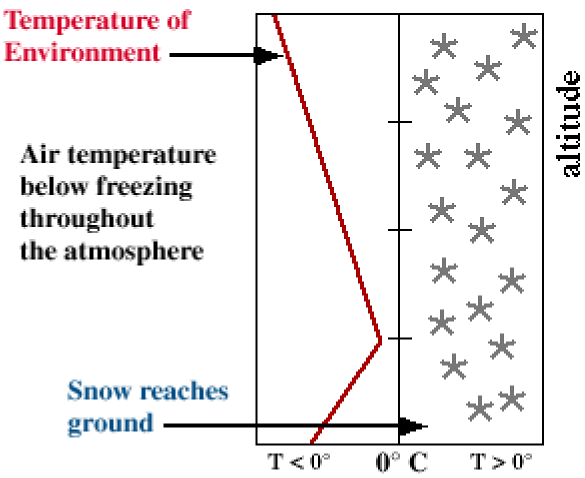
Snow

an aggregate of ice crystals

Progressing even further away from the warm front, surface temperatures continue to decrease and the sleet changes over to snow.



Snowflakes are simply aggregates of ice crystals that collect to each other as they fall toward the surface. The diagram below shows a typical temperature profile for snow with the red line indicating the atmosphere's temperature at any given altitude. The vertical line in the center of the diagram is the freezing line. Temperatures to the left of this line are below freezing, while temperatures to the right are above freezing.



Since the snowflakes do not pass through a layer of air warm enough to cause them to melt, they remain in tact and reach the ground as snow.

Graphic by: Yiqi Shao

Periodically, the flourishing fish populations commonly found off the west coast of Peru South America are replaced by the sight of dead fish littering the water and beaches. Unusual weather conditions occur around the globe as jet streams, storm tracks and monsoons are shifted. Such disarray is caused by a warm current of water that appears every three to seven years in the eastern Pacific Ocean called El Niño. This module introduces El Niño, conditions are responsible for its occurrence, plus the impact it has on the rest of the world. The El Niño instructional module has been organized into the following sections:

Sections
Last Update:
04/28/98

Definition
Introduces El Niño, when El Niño events have been recorded and how it compares to La Niña.

'97-'98 Event
Provides a brief insight into the most recent El Niño event.

Upwelling
Introduces upwelling, the thermocline and how they impact local sea life populations.

Non-El Niño Years
Typical oceanic and atmospheric conditions that exist in the tropical Pacific when no El Niño is present..

El Niño Events
Conditions that lead to an El Niño event and how El Niño influences upwelling processes, tropical rainfall and local fish populations.

Sea Surface Temperatures
El Niño visualized through sea surface temperature anomaly plots.

Impacts on Weather
The influence of El Niño on weather conditions worldwide.

Economic Impacts
Reduction in local fish populations, which in turn affect local industry and market prices worldwide.

Detection and Prediction
Methods and resources used by NOAA for detecting and predicting the presence of El Niño.

Acknowledgments
Those who contributed to the development of this module.

El Niño
a warm current of water

El Niño (Spanish name for the male child), initially referred to a weak, warm current appearing annually around Christmas time along the coast of Ecuador and Peru and lasting only a few weeks to a month or more. Every three to seven years, an El Niño event may last for many months, having significant economic and atmospheric consequences worldwide. During the past forty years, ten of these major El Niño events have been recorded, the worst of which occurred in 1997-1998. Previous to this, the El Niño event in 1982-1983 was the strongest. Some of the El Niño events have persisted more than one year.

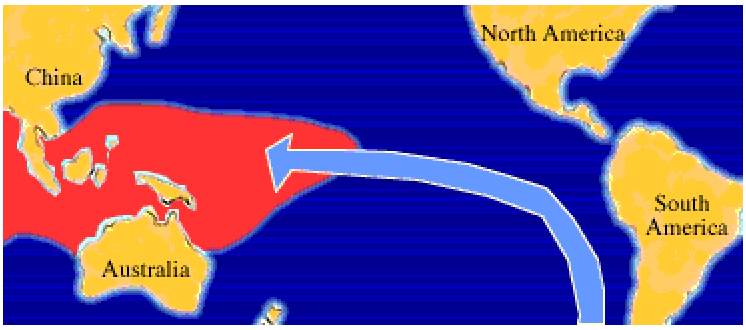
El Niño Years			
1902-1903	1905-1906	1911-1912	1914-1915
1918-1919	1923-1924	1925-1926	1930-1931
1932-1933	1939-1940	1941-1942	1951-1952
1953-1954	1957-1958	1965-1966	1969-1970
1972-1973	1976-1977	1982-1983	1986-1987
1991-1992	1994-1995	1997-1998	

Selected text from: CPC ENSO Main Page

In the tropical Pacific, trade winds generally drive the surface waters westward. The surface water becomes progressively warmer going westward because of its longer exposure to solar heating.

El Niño is observed when the easterly trade winds weaken, allowing warmer waters of the western Pacific to migrate eastward and eventually reach the South American Coast (shown in orange).

The cool nutrient-rich sea water normally found along the coast of Peru is replaced by warmer water depleted of nutrients, resulting in a dramatic reduction in marine fish and plant life.



Animation by: Shao

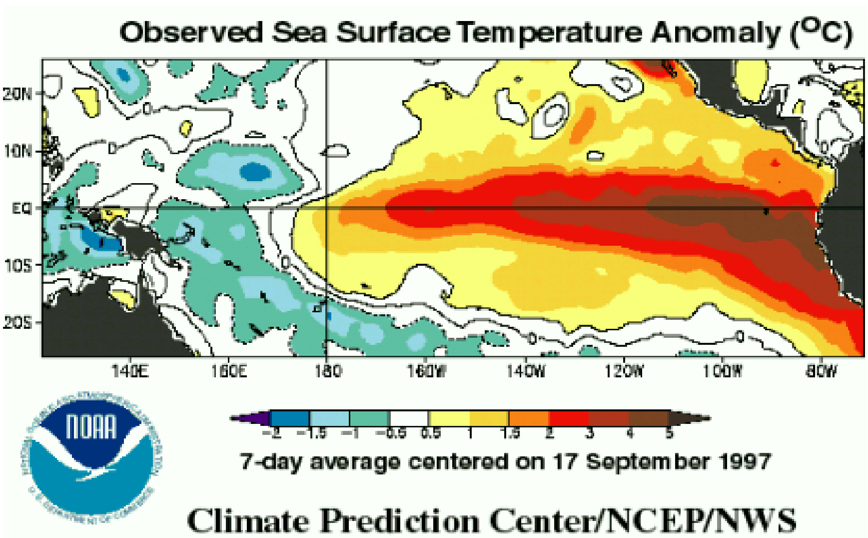
In contrast to El Niño, La Niña (female child) refers to an anomaly of unusually cold sea surface temperatures found in the eastern tropical Pacific. La Niña occurs roughly half as often as El Niño.

La Niña Years			
1904-1905	**1909-1910**	**1910-1911**	**1915-1916**
1917-1918	**1924-1925**	**1928-1929**	**1938-1939**
1950-1951	**1955-1956**	**1956-1957**	**1964-1965**
1970-1971	**1971-1972**	**1973-1974**	**1975-1976**
1988-1989	**1995-1996**		

1997-1998 El Niño

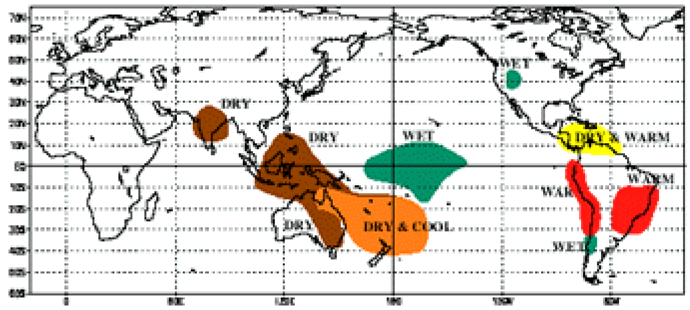
the most recent event

The most recent El Niño event began in the spring months of 1997. Instrumentation placed on Buoys in the Pacific Ocean after the 1982-1983 El Niño began recording abnormally high temperatures off the coast of Peru. Over the next couple of months, these strength of these anomalies grew. The anomalies grew so large by October 1997 that this El Niño had already become the strongest in the 50+ years of accurate data gathering. The image below displays the Sea Surface Temperature (SST) Anomalies in degrees Celsius for the middle of September, 1997. By this time, the classic El Niño pattern has almost fully ripened, with maxima above +4 degrees Celsius.



Droughts in the Western Pacific Islands and Indonesia as well as in Mexico and Central America were the early (and sometimes constant) victims of this El Niño. These locations were consistent with early season El Niños in the past. A global view of the normal climatic effects of El Niño can be seen below.

WARM EPISODE RELATIONSHIPS JUNE - AUGUST



WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY

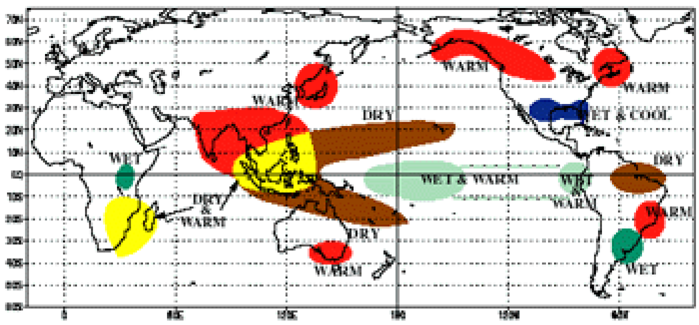


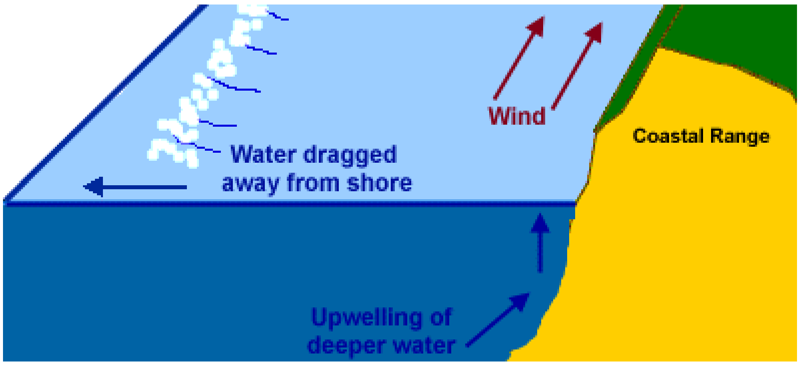
Image by: [CPC ENSO Main Page]

The effects El Niño have on United States' weather is less obvious. Back in 1982-1983, the U.S. Gulf States and California received excessive rainfall. As the winter approached, forecasters expected excessive rainfall to occur again. Indeed, portions of central and southern California suffered record-breaking rainfall amounts. Damage consisted not only of flooding, but mudslides Some mudslides destroyed communities in a flash -- causing many casualties. Other problems could be found in the Gulf states, as severe weather was above average. Even though no one particular storm can be blamed on El Niño, many forecasters do believe the event did increase the chances for such severe weather to occur.

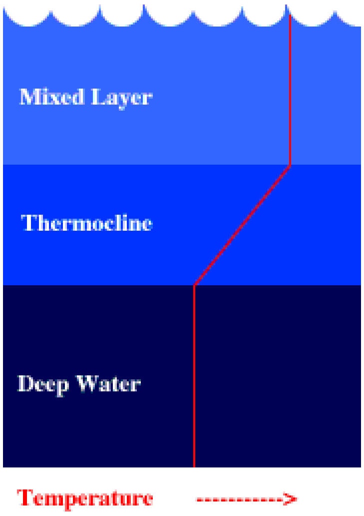
Upwelling

the transport of deeper water to shallow levels

One oceanic process altered during an El Niño year is upwelling, which is the rising of deeper colder water to shallower depths. The diagram below shows how upwelling occurs along the coast of Peru. Because of the frictional stresses that exist between ocean layers, surface water is transported at a 90 degree angle to the left of the winds in the southern hemisphere, 90 degrees to the right of the winds in the northern hemisphere. This is why winds blowing northward parallel to the coastline of Peru "drag" surface water westward away from shore.



Nutrient-rich water rises from deeper levels to replace the surface water that has drifted away and these nutrients are responsible for supporting the large fish population commonly found in these areas. The effectiveness of upwelling and its ability to support abundant sea life is greatly dependent upon the depth of the thermocline.



The thermocline is the transition layer between the mixed layer at the surface and the deep water layer. The definitions of these layers are based on temperature.

The mixed layer is near the surface where the temperature is roughly that of surface water. In the thermocline, the temperature decreases rapidly from the mixed layer temperature to the much colder deep water temperature.

The mixed layer and the deep water layer are relatively uniform in temperature, while the thermocline represents the transition zone between the two.

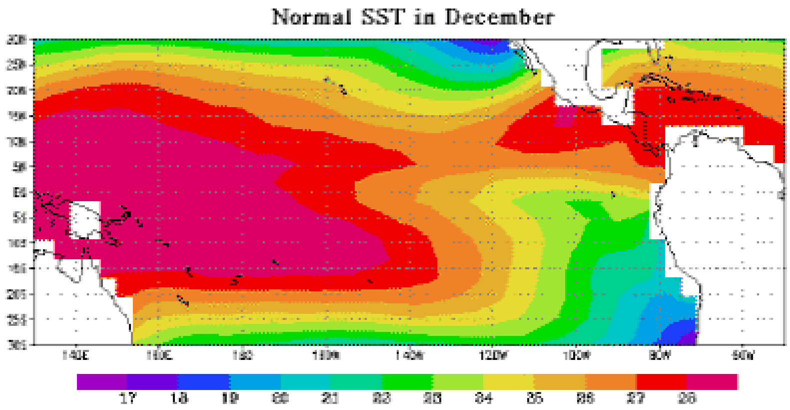
A deeper thermocline (often observed during El Niño years) limits the amount of nutrients brought to shallower depths by upwelling processes, greatly impacting the year's fish crop.

Non El Niño Years

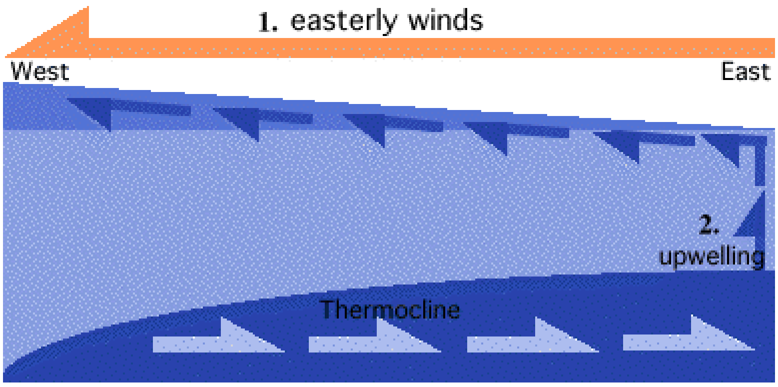
colder water in the eastern tropical Pacific

The easterly trade winds of the tropics drag the surface waters of the eastern Pacific away from the coastlines of the Americas. As it moves away, the water is deflected northward (in the northern hemisphere) by the Coriolis force and southward (in the southern hemisphere), causing water to move away from the equator in both directions. Upwelling in the eastern Pacific brings colder water up from deeper levels to replace the surface water that has been dragged away.

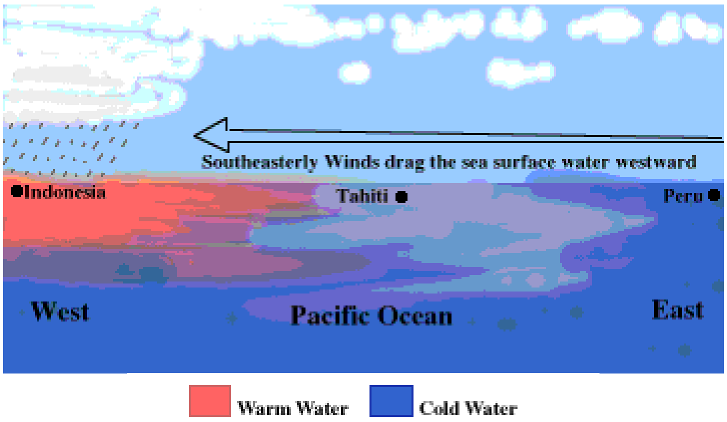
Sea surface temperature (SST) data reveals the presence of colder water in the eastern tropical Pacific. The following plot of average sea surface temperatures from 1949-1993 shows that the average December SSTs were much cooler in the eastern Pacific (less than 22 degrees Celsius) than in the western Pacific (greater than 25 degrees Celsius), gradually decreasing from west to east.



The [trade winds] accumulate warm surface water around Indonesia, raising the sea level roughly half a meter higher in the western Pacific. As [upwelling] persists, the level of the [thermocline] rises to shallower depths off the South American coast and is depressed in the western Pacific. The upwelled water is rich in nutrients and [supports an abundance of fish and marine life].



As surface water propagates westward, it is heated by the atmosphere and the sun, allowing warmer waters to accumulate in the western Pacific. The cooler water in the eastern Pacific cools the air above it, and consequently the air becomes too dense to [rise and produce clouds and rain]. In the western Pacific however, the overlying air is heated by the warmer waters below, destabilizing the lower atmosphere and increasing the likelihood of precipitation.

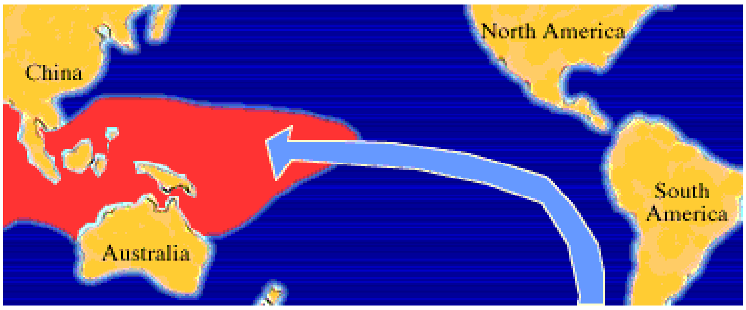


This is why during most non El Niño Years, heavy rainfall is found over the warmer waters of the western Pacific (near Indonesia) while the eastern Pacific is relatively dry.

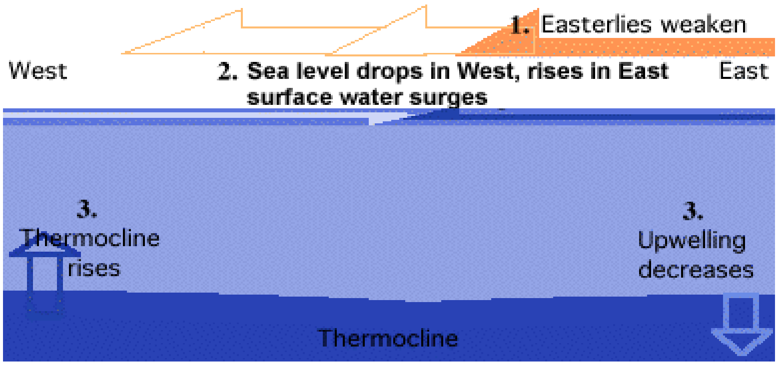
El Niño Events

results from weakening easterly trade winds

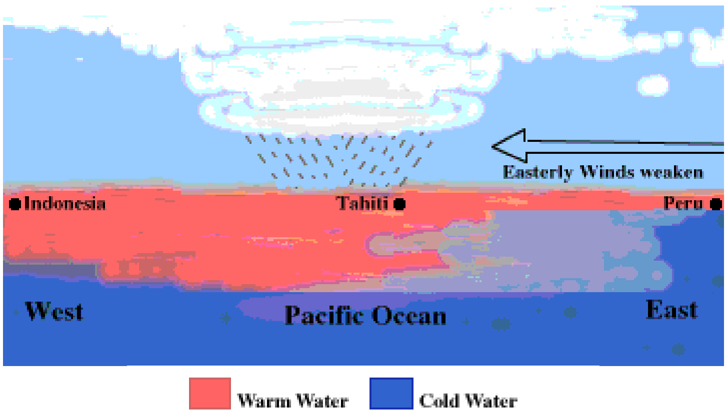
The easterly trade winds are driven by a surface pressure pattern of higher pressure in the eastern Pacific and lower pressure in the west. When this pressure gradient weakens, so do the trade winds. The weakened trade winds allow warmer water from the western Pacific to surge eastward, so the sea level flattens out.



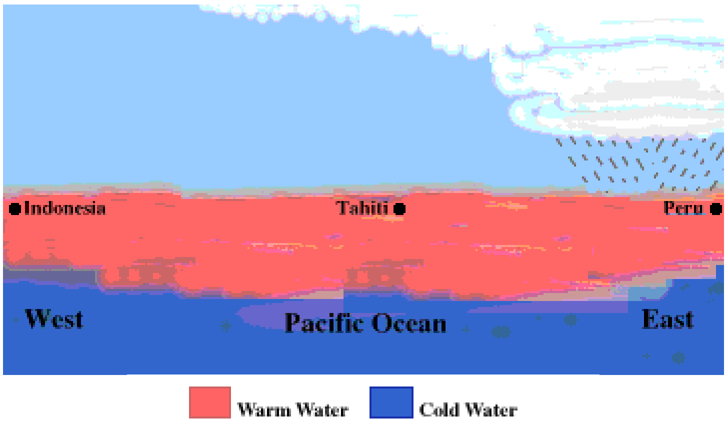
This leads to a build up of warm surface water and a sinking of the thermocline in the eastern Pacific. The deeper thermocline limits the amount of nutrient-rich deep water tapped by upwelling processes. These nutrients are vital for sustaining the large fish populations normally found in the region and any reduction in the supply of nutrients means a reduction in the fish population.



Convective clouds and heavy rains are fueled by increased buoyancy of the lower atmosphere resulting from heating by the warmer waters below. As the warmer water shifts eastward, so do the clouds and thunderstorms associated with it, resulting in dry conditions in Indonesia and Australia while more flood-like conditions exist in Peru and Ecuador.



El Niño causes all sorts of unusual weather, sometimes bringing rain to coastal deserts of South America which never see rain during non-El Niño years. The flooding results in swarming mosquitoes and the spread of disease.



The air-sea interaction that occur during an El Niño event feed off of each other. As the pressure falls in the east and rises in the west, the surface pressure gradient is reduced and the trade winds weaken. This allows more warm surface water to flow eastward, which brings with it more rain, which leads to a further decrease of pressure in the east because the latent heat of condensation warms the air...and the cycle continues.

El Niño Sea Surface Temperatures

a look at the El Niño event from 1982-83

An El Niño event is identified by warmer than normal sea surface temperatures (SSTs). An SST anomaly plot, like the one given below, shows the difference between the observed SSTs and the normal SSTs for a given month. This particular plot depicts the SST anomaly from December of 1982.

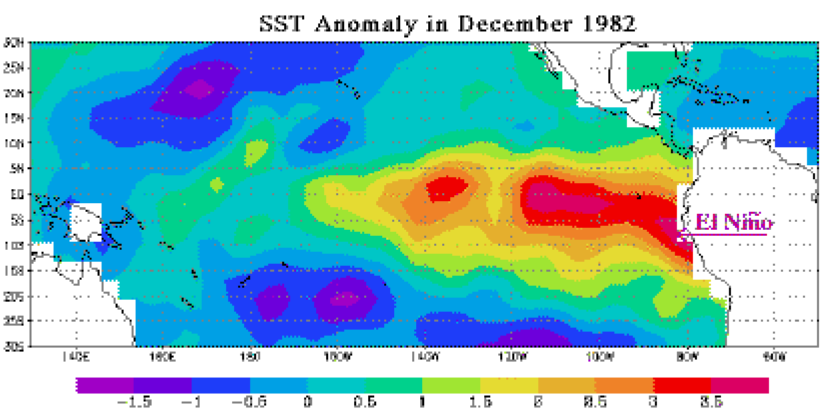
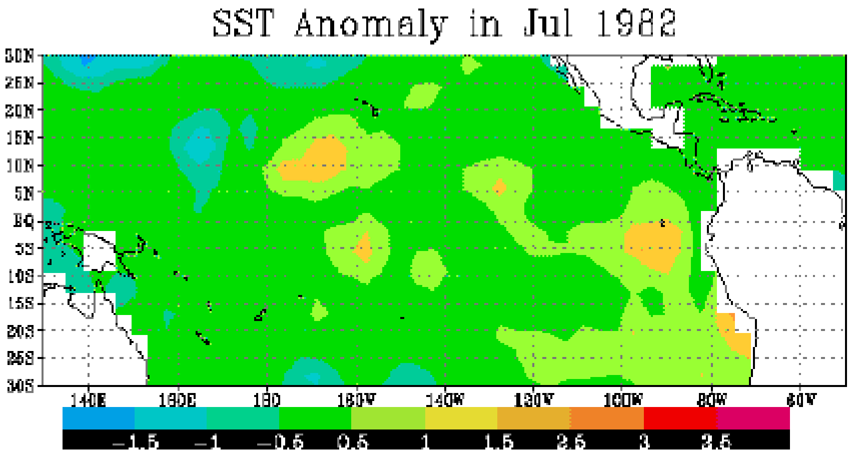


Image by: Liu

The yellow and red shadings of the eastern Pacific indicate that the waters were considerably warmer than normal. In fact, the El Niño event of 1982-83 was the strongest this century, with an SST anomaly exceeding 3.5 degrees Celsius.



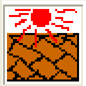
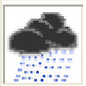
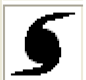
Animation by: Liu

This animation depicts the SST anomaly field from the El Niño event of 1982-83 (August 1982 to June 1983). The yellows and reds in the eastern Pacific indicate the warming associated with the El-Niño event.

Atmospheric Consequences of El Niño

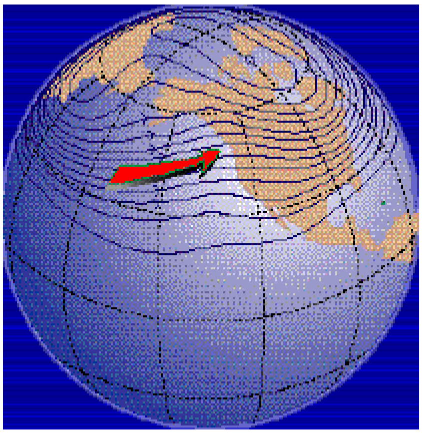
influencing weather patterns worldwide

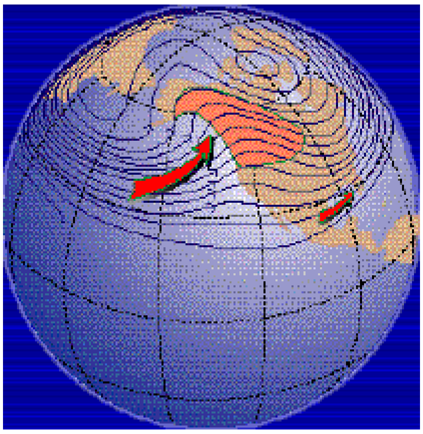
During an El Niño year, tropical rains usually centered over Indonesia shift eastward, influencing atmospheric wind patterns world wide. Possible impacts include: a shifting of the jet stream, storm tracks and monsoons, producing unseasonable weather over many regions of the globe. During the El Niño event of 1982-1983, some of the abnormal weather patterns observed included:.

	Drought in Southern Africa, Southern India, Sri Lanka, Philippines, Indonesia, Australia, Southern Peru, Western Bolivia, Mexico, Central America
	Heavy rain and flooding in Bolivia, Ecuador, Northern Peru, Cuba, U.S. Gulf States
	Hurricanes in Tahiti, Hawaii

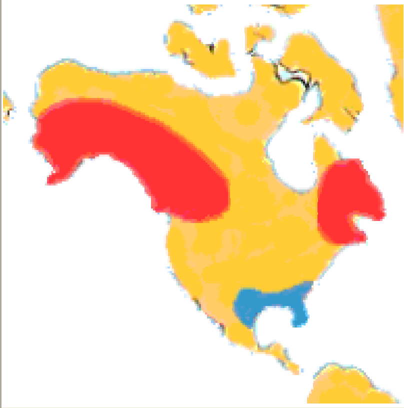
The 1982-83 El Niño strengthened the upper-level ridge that was present off the West coast of the United States. (This intensification is represented by the increased amplitude of the wave in the right panel below : Images by: DAS, University of Washington).

Normal Winter **El Niño Winter**





The amplification led to a warming in the near-Pacific regions of North America, extending from Alaska to the northern Plains of the United States (orange shading).



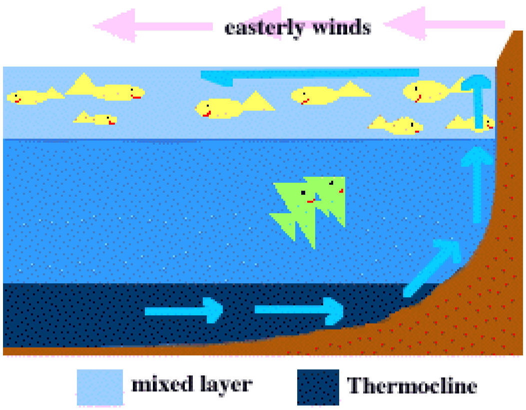
Simultaneously, the deepening of the winter upper-level trough (typically found over the eastern US) produced heavier than normal rains in the southern states (blue shading).

As a result of the 1982-83 El Niño event, wide spread flooding occurred across the southern United States.

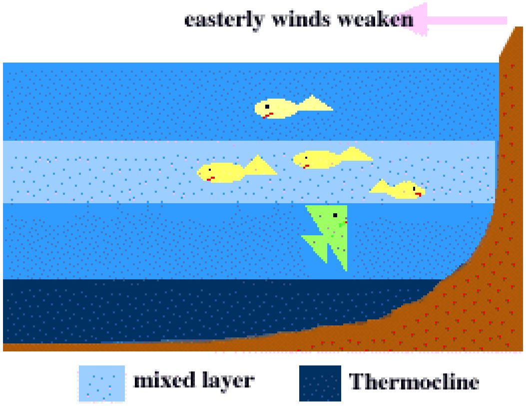
Economic Consequences of El Niño

and the influence on prices worldwide

The coast of Peru is one of five major fishing grounds in the world (along with the coastal waters of California, Namibia, Mauritania, and Somalia). The abundance of fish is supported by the upwelling of nutrient rich waters from deeper levels (below the thermocline).



During non-El Niño years, the southeast trade winds, drag surface water westward away from shore. As surface water moves away, upwelling brings up colder waters from depths of 40-80 meters or more. This deep sea water is rich in nutrients which can sustain large fish populations.



During an El Niño event, the southeast trade winds weaken and so does the amount upwelling in the eastern Pacific.

The deeper thermocline means that any upwelling that does occur is unable to tap into the rich nutrients found in deeper waters. Consequently, warm nutrient-poor water predominates the region and a decrease in the fish population is observed.

A reduction of the fish population reduces the amount of fishmeal produced and exported (by local industry) to other countries for feeding poultry and livestock. If the world's fishmeal supply decreases, more expensive alternative feed sources must be used, resulting in an increase in poultry prices worldwide.

Detection and Prediction of El Niño

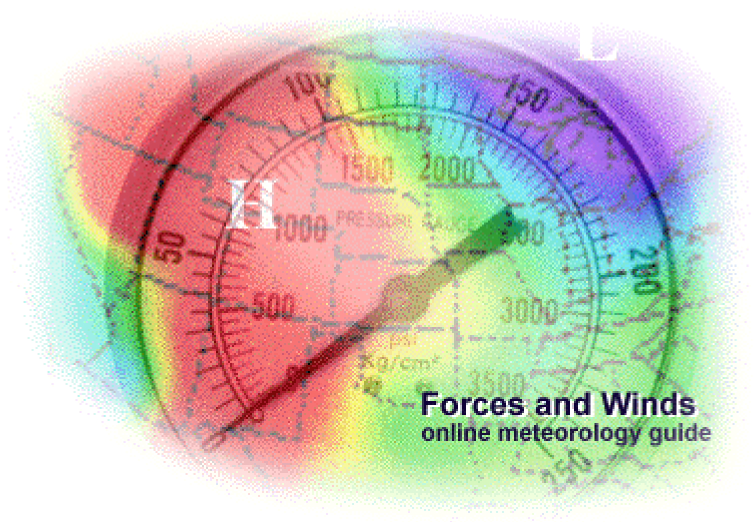
current detection and numerical prediction systems

There are several means used for El Niño detection; satellites, moored ATLAS and PROTEUS buoys, drifting buoys, sea level analysis, and XBT's. Since El Niño influences global weather patterns and affects human lives and ecosystems, prediction of an El Niño event is becoming increasingly important. For short term prediction (up to 1 year) of climate variations, current observations in the Tropical Pacific are vital. Numerical models are used in many places for El Niño prediction and research. Here are some of the latest El Niño forecasts.

Given that numerical models predicting El Niño must do so months in advance, they are not as reliable as those used in predicting the weather, which forecast only days in advance. They have, however, progressed to the point where they can reproduce the characteristics of a typical El Niño event and some industries use these forecasts as an indicator of the coming fish harvest.

Forecasts are presented in terms of possible conditions for South America:
(1) near normal conditions,
(2) a weak El Niño with a slightly wetter than normal growing season,
(3) a full blown El Niño with flooding,
(4) cooler than normal waters offshore, with higher than normal chance of drought in South America.

Once the forecast is issued, management of agriculture, water supplies, fisheries, and other resources can be modified.



Graphic by: Yiqi Shao ;
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/fw/home.rxml

The weight of the air above an object exerts a force per unit area upon that object and this force is called pressure. Variations in pressure lead to the development of winds, which in turn influence our daily weather. The purpose of this module is to introduce pressure, how it changes with height and the importance of high and low pressure systems. In addition, this module introduces the pressure gradient and Coriolis forces and their role in generating wind. Local wind systems such as land breezes and sea breezes will also be introduced. The Forces and Winds module has been organized into the following sections:

Sections
Last Update:
09/02/99

Pressure
Introduces pressure, associated characteristics, and high and low pressure centers.

Pressure Gradient Force
A net force that is directed from high to low pressure.

Coriolis Force
The apparent deflection of objects due to the earth's rotation.

Geostrophic Wind
Winds that result from a balance of Coriolis and pressure gradient forces.

Gradient Wind
Winds that blow parallel to isobars, but are not geostrophic.

Friction
How friction near the surface affects geostrophic and gradient wind.

Boundary Layer Wind
More on how friction affects low level winds.

Sea Breezes
Atmospheric conditions that lead to the development of sea breezes.

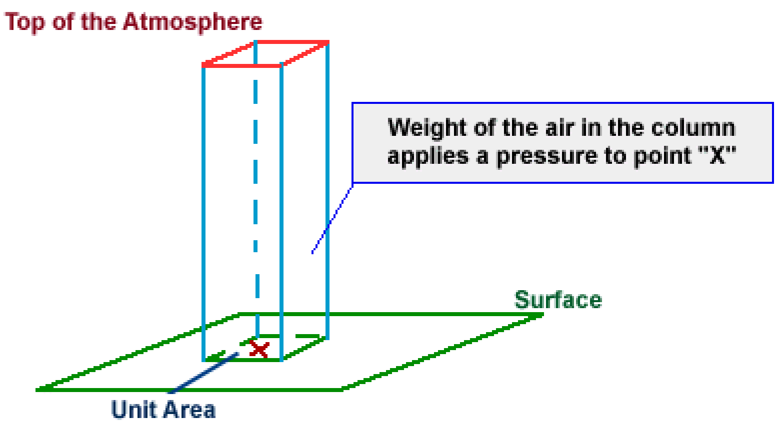
Land Breezes
Atmospheric conditions that lead to the development of land breezes.

Acknowledgments
Those who contributed to the development of this module.

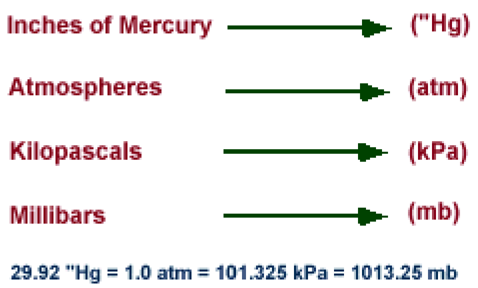
Atmospheric Pressure

force exerted by the weight of the air

Atmospheric pressure is defined as the force per unit area exerted against a surface by the weight of the air above that surface. In the diagram below, the pressure at point "X" increases as the weight of the air above it increases. The same can be said about decreasing pressure, where the pressure at point "X" decreases if the weight of the air above it also decreases.



Thinking in terms of air molecules, if the number of air molecules above a surface increases, there are more molecules to exert a force on that surface and consequently, the pressure increases. The opposite is also true, where a reduction in the number of air molecules above a surface will result in a decrease in pressure. Atmospheric pressure is measured with an instrument called a "barometer", which is why atmospheric pressure is also referred to as barometric pressure.



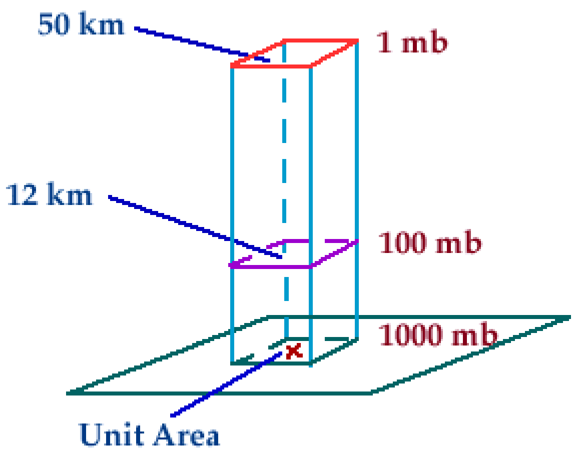
In aviation and television weather reports, pressure is given in inches of mercury ("Hg), while meteorologists use millibars (mb), the unit of pressure found on weather maps.

As an example, consider a "unit area" of 1 square inch. At sea level, the weight of the air above this unit area would (on average) weigh 14.7 pounds! That means pressure applied by this air on the unit area would be 14.7 pounds per square inch. Meteorologists use a metric unit for pressure called a millibar and the average pressure at sea level is 1013.25 millibars.

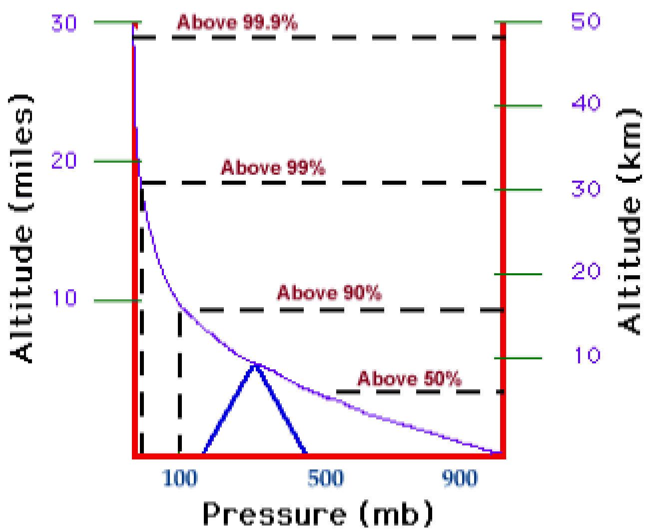
Pressure with Height

pressure decreases with increasing altitude

The number of air molecules above a surface changes as the height of the surface above the ground changes. For example, there are fewer air molecules above the 50 kilometer (km) surface than are found above the 12 km surface. Since the number of air molecules above a surface decreases with height, pressure likewise decreases with height.



Most of the atmosphere's molecules are held close to the earth's surface by gravity. Because of this, air pressure decreases rapidly at first, then more slowly at higher levels.

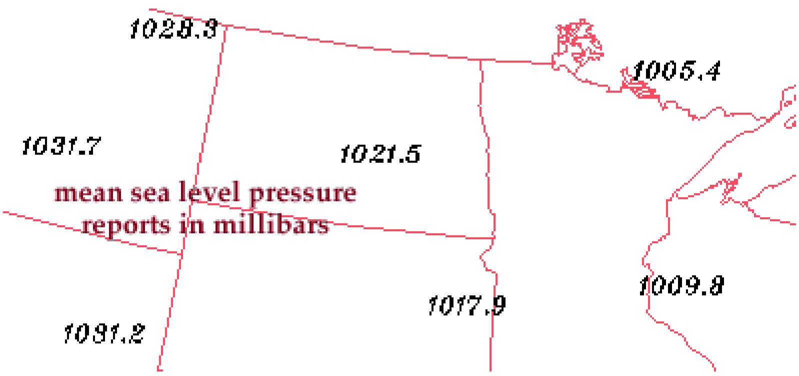


Since more than half of the atmosphere's molecules are located below an altitude of 5.5 km, atmospheric pressure decreases roughly 50% (to around 500 mb) within the lowest 5.5 km. Above 5.5 km, the pressure continues to decrease, but at an increasingly slower rate (to about 1 mb at 50 km).

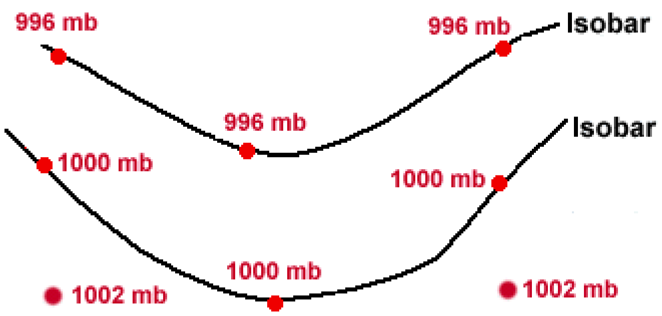
Isobars

lines of constant pressure

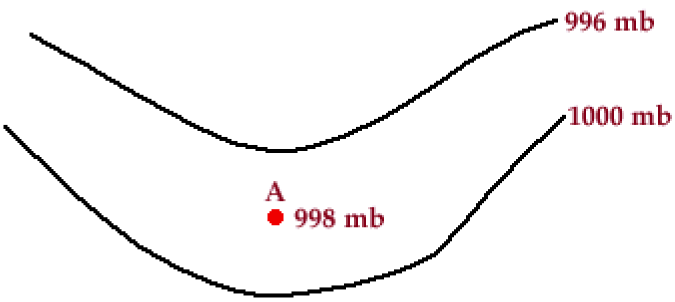
A line drawn on a weather map connecting points of equal pressure is called an "isobar". Isobars are generated from mean sea-level pressure reports and are given in millibars.



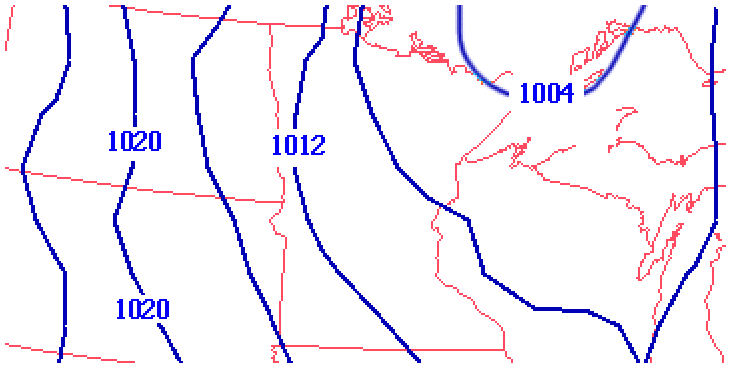
The diagram below depicts a pair of sample isobars. At every point along the top isobar, the pressure is 996 mb while at every point along the bottom isobar, the pressure is 1000 mb. Points above the 1000 mb isobar have a lower pressure and points below that isobar have a higher pressure.



Any point lying in between these two isobars must have a pressure somewhere between 996 mb and 1000 mb. Point A, for example, has a pressure of 998 mb and is therefore located between the 996 mb isobar and the 1000 mb isobar.



Sea-level pressure reports are available every hour, which means that isobar maps are likewise available every hour. The solid blue contours (in the map below) represent isobars and the numbers along selected contours indicate the pressure value of that particular isobar.

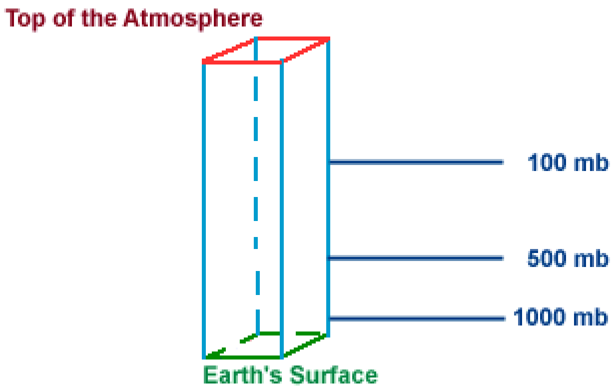


Such maps are useful for locating areas of high and low pressure, which correspond to the positions of surface cyclones and anticyclones. A map of isobars is also useful for locating strong pressure gradients, which are identifiable by a tight packing of the isobars. Stronger winds are associated with stronger pressure gradients.

Constant Pressure Surfaces

a surface of equal pressure, also called an isobaric surface

A constant pressure (or isobaric) surface is a surface in the atmosphere where the pressure is equal everywhere along that surface. For example, the 100 millibar (mb) surface is the surface in the atmosphere where the pressure at every point along that surface is 100 mb. Since pressure decreases with height, the altitude of the 100 mb surface is higher than the 500 mb surface, which is likewise higher than 1000 mb. Meteorologists use pressure as a vertical coordinate to simplify thermodynamic computations which are performed on a routine basis.



Measurements of the upper atmosphere (temperature, pressure, winds, etc.) are taken by instruments on weather balloons as they rise upward from the earth. When referring to the 500 mb surface, we mean a location in the atmosphere where the pressure has been measured to be 500 mb. The approximate heights and temperatures for several constant pressure surfaces have been listed below:

Pressure	Approximate Height	Approximate Temperature
Sea Level	0 m 0 ft	15 C 59 F
1000mb	100 m 300 ft	15 C 59 F
850 mb	1500 m 5000 ft	05 C 41 F
700 mb	3000 m 10000 ft	-05 C 23 F
500 mb	5000 m 18000 ft	-20 C -04 F
300 mb	9000 m 30000 ft	-45 C -49 F

200 mb 100 mb	12000 m 40000 ft 16000 m 53000 ft	-55 C -67 F -56 C -69F

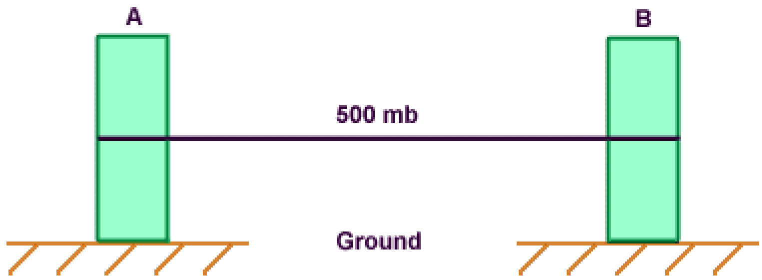
Chart from: WXP Purdue

The atmospheric variables typically plotted on isobaric maps include: height of the pressure surface, temperature, moisture content and wind speed and direction.

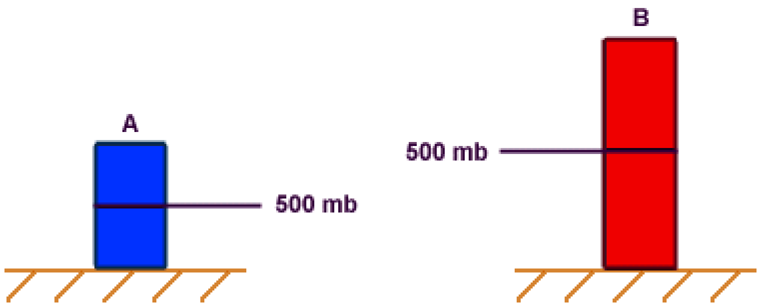
Pressure and Temperature

the relationship between pressure surfaces and temperature

The height of a given pressure surface above the ground varies with temperature. As an example, consider two identical columns of air (A and B). Since they are identical, the 500 mb surface is found at the same height in each column.



Cooling column A and heating column B changes the height of the 500 mb surface in each column. Since colder air contracts, the height of the 500 mb surface in column A decreases, while in column B, the warm air expands, raising the height of the 500 mb surface.

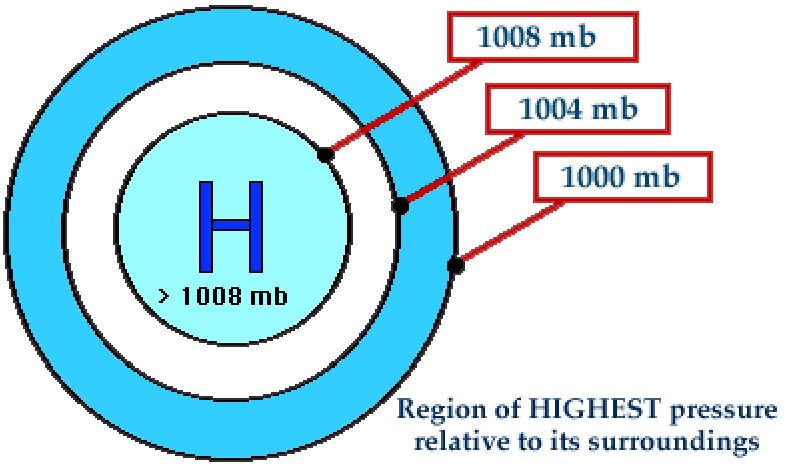


Therefore, where the temperatures are colder, a given pressure surface will have a lower height than if the same pressure surface was located in warmer air.

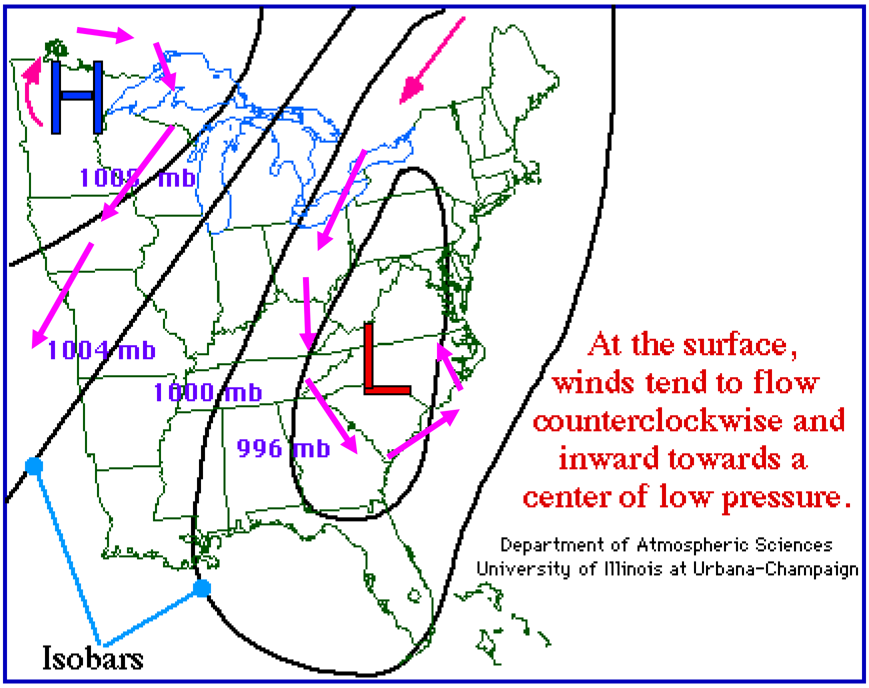
High Pressure Centers

also known as anticyclones

A high pressure center is where the pressure has been measured to be the highest relative to its surroundings. That means, moving in any direction away from the "High" will result in a decrease in pressure. A high pressure center also represents the center of an anticyclone and is indicated on a weather map by a blue "H".



Winds flow clockwise around a high pressure center in the northern hemisphere, while in the southern hemisphere, winds flow counterclockwise around a high.

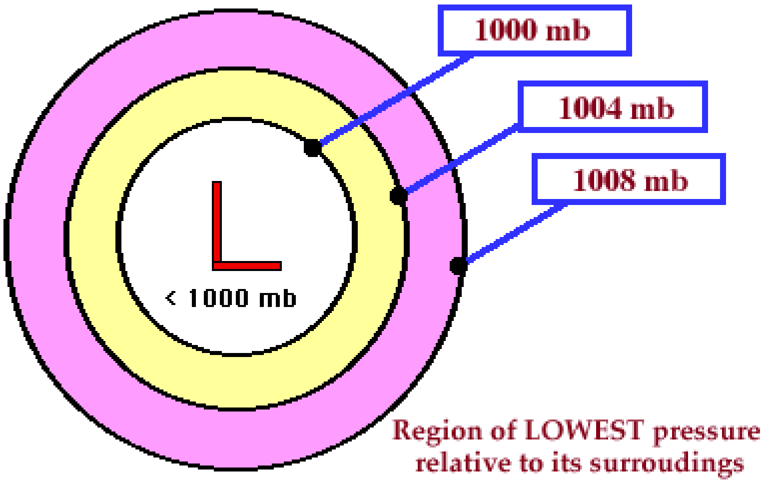


Animation by: Hall

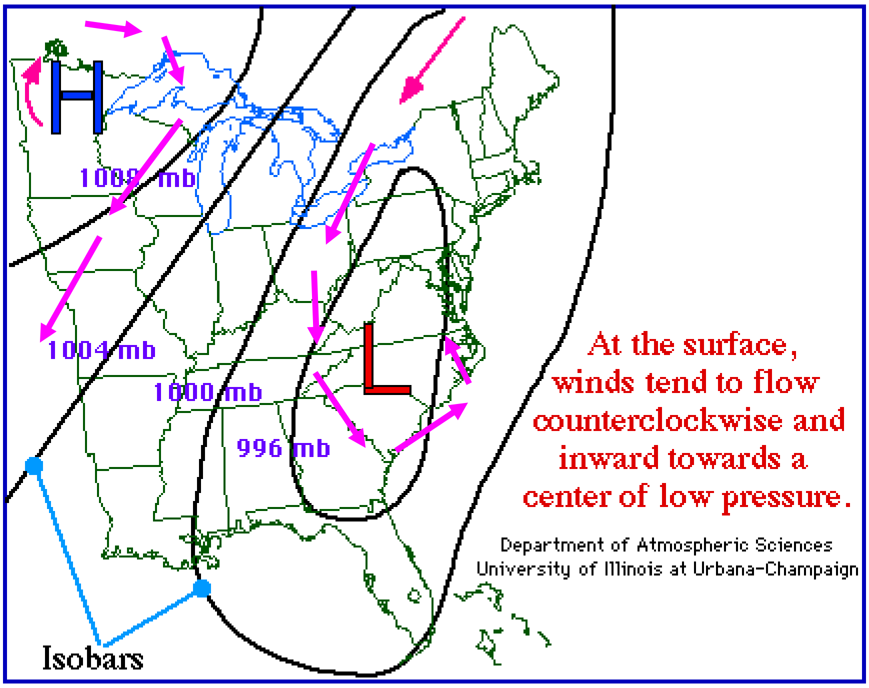
Sinking air in the vicinity of a high pressure center suppresses the upward motions needed to support the development of clouds and precipitation. This is why fair weather is commonly associated with an area of high pressure.

Low Pressure Centers
also known as cyclones

A low pressure center is where the pressure has been measured to be the lowest relative to its surroundings. That means, moving in any horizontal direction away from the "Low" will result in an increase in pressure. Low pressure centers also represent the centers of cyclones.



A low pressure center is indicated on a weather map by a red "L" and winds flow counterclockwise around a low in the northern hemisphere. The opposite is true in the southern hemisphere, where winds flow clockwise around an area of low pressure.



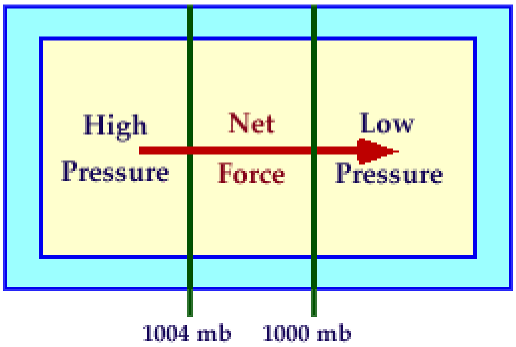
Animation by: Hall

Rising motion in the vicinity of a low pressure center favors the development of clouds and precipitation, which is why cloudy weather (and likely precipitation) are commonly associated with an area of low pressure.

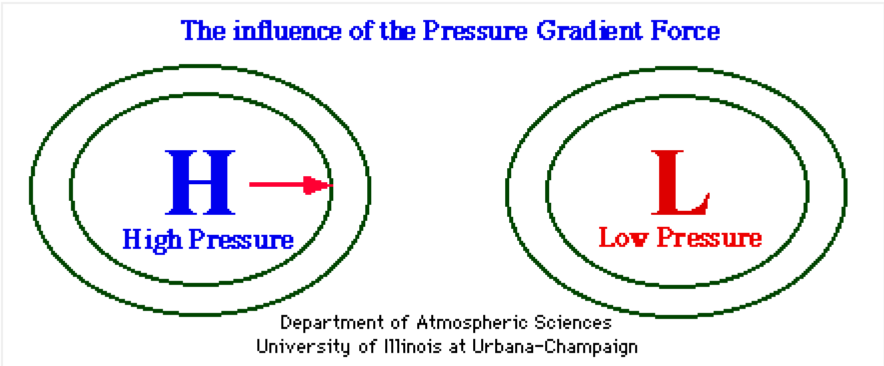
Pressure Gradient Force

directed from high to low pressure

The change in pressure measured across a given distance is called a "pressure gradient".



The pressure gradient results in a net force that is directed from high to low pressure and this force is called the "pressure gradient force".



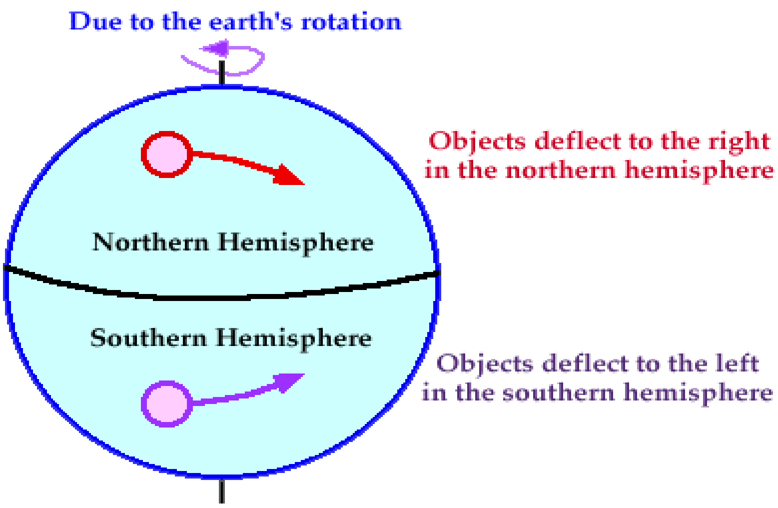
Animation by: Hall

The pressure gradient force is responsible for triggering the initial movement of air.

Coriolis Force

an artifact of the earth's rotation

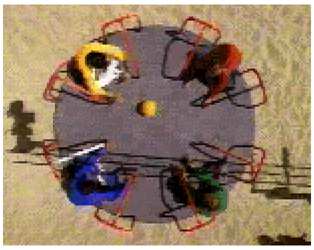
Once air has been set in motion by the pressure gradient force, it undergoes an apparent deflection from its path, as seen by an observer on the earth. This apparent deflection is called the "Coriolis force" and is a result of the earth's rotation.



As air moves from high to low pressure in the northern hemisphere, it is deflected to the right by the Coriolis force. In the southern hemisphere, air moving from high to low pressure is deflected to the left by the Coriolis force.

The amount of deflection the air makes is directly related to both the speed at which the air is moving and its latitude. Therefore, slowly blowing winds will be deflected only a small amount, while stronger winds will be deflected more. Likewise, winds blowing closer to the poles will be deflected more than winds at the same speed closer to the equator. The Coriolis force is zero right at the equator.

This process is further demonstrated by the movie below.



QuickTime (2.0M)
MPEG (0.9M)

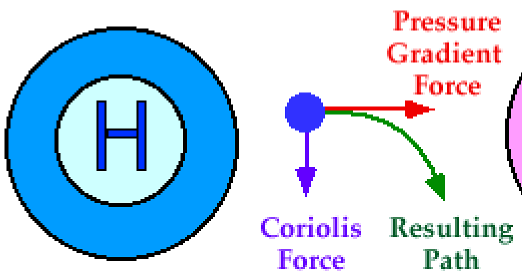
Real Life Example:
This movie of a ball rolling across the surface of a rotating merry-go-round is a helpful demonstration of the Coriolis force.

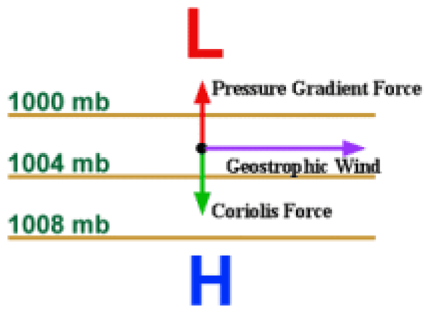
Geostrophic Wind

winds balanced by the Coriolis and Pressure Gradient forces

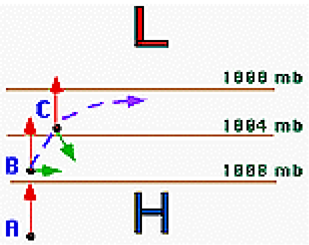
An air parcel initially at rest will move from high pressure to low pressure because of the pressure gradient force (PGF). However, as that air parcel begins to move, it is deflected by the Coriolis force to the right in the northern hemisphere (to the left on the southern hemisphere). As the wind gains speed, the deflection increases until the Coriolis force equals the pressure gradient force.

At this point, the wind will be blowing parallel to the isobars. When this happens, the wind is referred to as **geostrophic**.





The movie below illustrates the process mentioned above, while the diagram at right shows the two forces balancing to produce the geostrophic wind. Winds in nature are rarely exactly geostrophic, but to a good approximation, the winds in the upper troposphere can be close. This is because winds are only considered truly geostrophic when the isobars are straight and there are no other forces acting on it -- and these conditions just aren't found too often in nature.

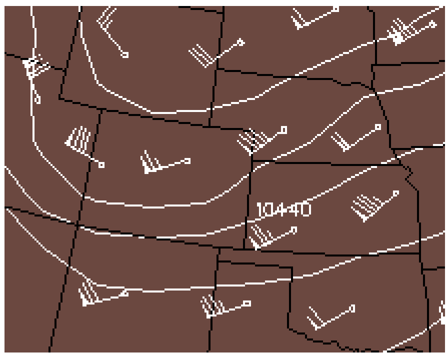


QuickTime (2.0M)
MPEG (0.9M)

Moving Air Parcel:
This animation depicts how the pressure gradient and Coriolis forces influence the movement of air parcels.

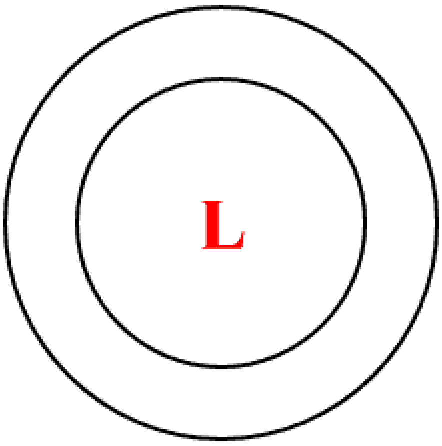
Gradient Wind

non-geostrophic winds which blow parallel to isobars



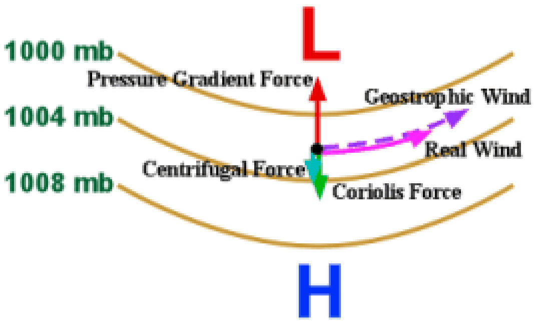
Geostrophic winds exist in locations where there are no frictional forces and the isobars are striaght. However, such locations are quite rare. Isobars are almost always curved and are very rarely evenly spaced. This changes the geostrophic winds so that they are no longer geostrophic but are instead in **gradient wind balance**. They still blow parallel to the isobars, but are no longer balanced by only the pressure gradient and Coriolis forces, and do not have the same velocity as geostrophic winds.

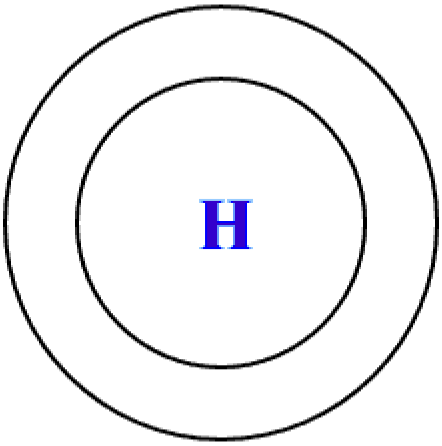
In the diagram below at point A, the parcel of air will move straight north. The pressure gradient and Coriolis forces are present, but when the isobars are curved, there is a third force -- the **centrifugal force**. This apparent force, pushes objects away from the center of a circle. The centrifugal force alters the original two-force balance and creates the non-geostrophic gradient wind.



In this case, the centrifugal force acts in the same direction as the Coriolis force. As the parcel moves north, it moves slightly away from the center -- decreases the centrifugal force. The pressure gradient force becomes slightly more dominant and the parcel moves back to the original radius. This allows the gradient wind to blow parallel to the isobars.

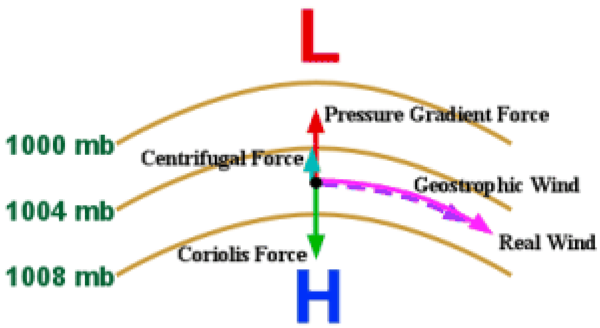
Since the pressure gradient force doesn't change, and all the forces must balance, the Coriolis force becomes weaker. This in turn decreases the overall wind speed. This is where the gradient wind differs from the geostrophic winds. **In this case of a low pressure system or trough, the gradient wind blows parallel to the isobars at a less than geostrophic (subgeostrophic) speed**.





This also applies to high-pressure systems as well. In this case, again starting from point A, the geostrophic wind will blow straight south. This time the centrifugal force is pushing in the same direction as the pressure gradient force, and when it gets slightly further away from the center, the centrifugal force again reduces, but this time that makes the Coriolis Force more dominant and the air parcel will move back to its original radius -- again with the end result being wind blowing parallel to the isobars.

Since the pressure gradient force still doesn't change, the Coriolis force must again adjust to balance the forces. However now it becomes stronger, which in turn increases the overall wind speed. **This means that in a high pressure system or ridge, the gradient wind blows parallel to the isobars faster than geostrophic (supergeostrophic) speed.**

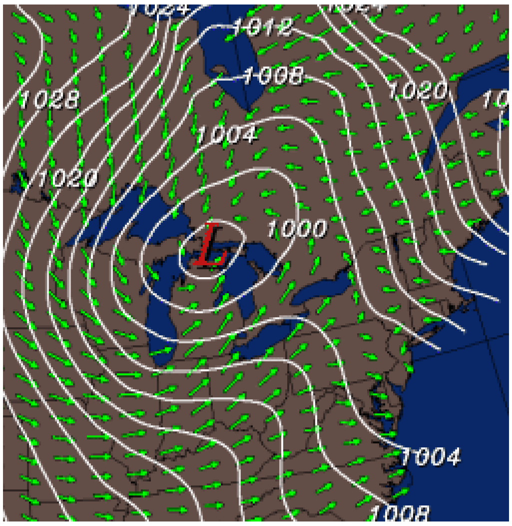


Winds near the surface

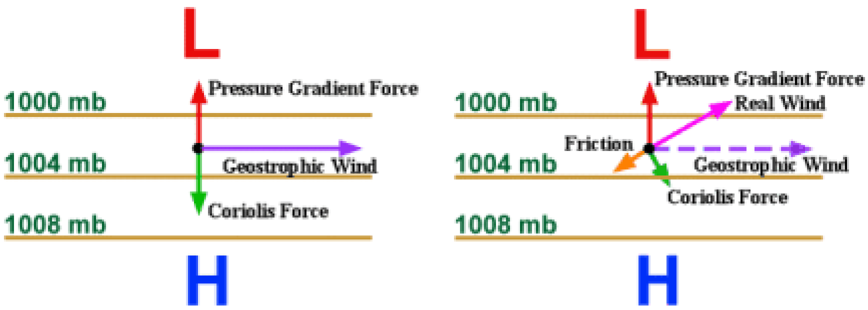
Winds affected by friction

Geostrophic wind blows parallel to the isobars because the Coriolis force and pressure gradient force are in balance. However it should be realized that the actual wind is not always geostrophic -- especially near the surface.

The surface of the Earth exerts a frictional drag on the air blowing just above it. This friction can act to change the wind's direction and slow it down -- keeping it from blowing as fast as the wind aloft. Actually, the difference in terrain conditions directly affects how much friction is exerted. For example, a calm ocean surface is pretty smooth, so the wind blowing over it does not move up, down, and around any features. By contrast, hills and forests force the wind to slow down and/or change direction much more.



As we move higher, surface features affect the wind less until the wind is indeed geostrophic. This level is considered the top of the **boundary (or friction) layer**. The height of the boundary layer can vary depending on the type of terrain, wind, and vertical temperature profile. The time of day and season of the year also affect the height of the boundary layer. However, usually the boundary layer exists from the surface to about 1-2 km above it.



In the friction layer, the turbulent friction that the Earth exerts on the air slows the wind down. This slowing causes the wind to be not geostrophic. As we look at the diagram above, this slowing down reduces the Coriolis force, and the pressure gradient force becomes more dominant. As a result, the total wind deflects slightly towards lower pressure. The amount of deflection the surface wind has with respect to the geostrophic wind above depends on the roughness of the terrain. Meteorologists call the difference between the total and **geostrophic** winds **ageostrophic** winds.

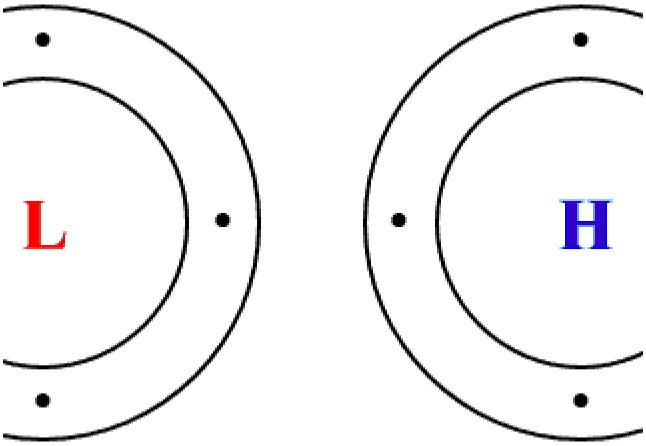
Boundary Layer Winds

more of friction's impact on low level winds

Friction's effects on air motion decrease as the altitude increases -- to a point (usually 1-2 km) where it has no effect at all. The depth of the atmosphere that friction does play a role in atmospheric motion is referred to as the boundary layer. Within the boundary layer, this friction plays a role in keeping the wind from being geostrophic.

If we look at low and high-pressure systems, we can see this mechanism at work. Here in this exmple below, the winds would, without friction effects, be moving counter-clockwise around the center of the low in the northern hemisphere. However, when the surface friction is accounted for, the wind slows down, and therefore the Coriolis force weakens and the pressure gradient force becomes dominant, resulting in the spiraling of air into the center of a low pressure system and away from the center of the high pressure system. This causes convergence in the center of the low pressure system at the surface.

It is this surface convergence which leads to rising air which can create clouds and even cause rain and storms to form.



At the same time, wind flows around a northern hemisphere high-pressure system in a clockwise manner, but when frictional effects are introduced the wind again slows down, and the Coriolis force reduces and the pressure gradient force becomes dominant. In this case, though, the pressure gradient is outward from the center of the high, so the result is that surface wind spirals away from the center. This causes divergence (convergence) in the center of the high (low) pressure system at the surface.

This surface divergence causes sinking motion which supresses cloud development and gives us clear skies.

Below is an interactive tool for you to explore how friction affects the wind as you change the roughness of the terrain and the elevation.

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/fw/bndy.rxml

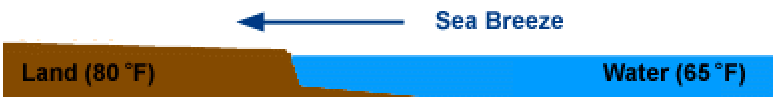
- Does the total wind deflect towards higher or lower pressure in the boundary layer? (isobars in dark gray).

- What happens to the Coriolis force vector as the total wind changes?
- Compare the strength of the pressure gradient force vector and the Coriolis force vector. What happens to them as the altitude changes?
- How does the roughness of the terrain affect the surface wind?
- What are the differences between the northern and southern hemisphere in the example?
- Click the Wind Profile button. A separate window will appear. The red curve shows a trace of the wind vector from the surface to the top of the boundary layer. Its spiral-like appearance was first observed by W. F. Ekman and is called the Ekman spiral. The white line shows the wind vector along that spiral at the current altitude. Meteorologists call these diagrams hodographs and use them as a way to simultaneously observe the wind speed and direction at many altitudes.

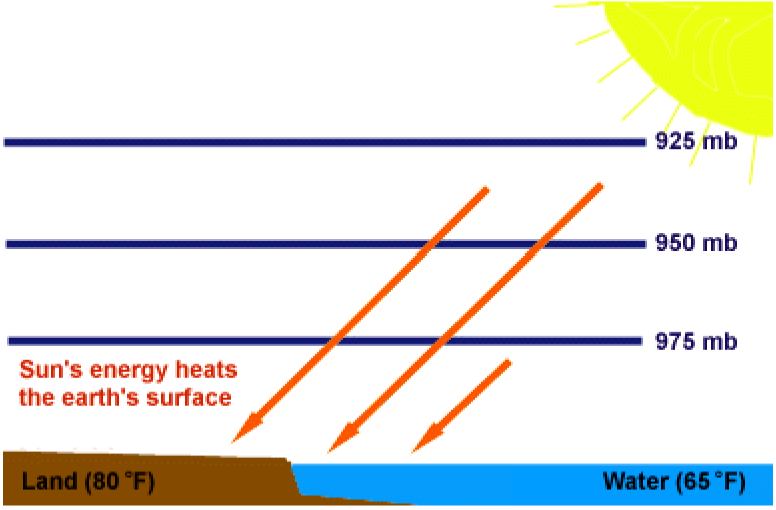
Sea Breezes

a result of uneven surface heating

When spending a day at the beach, a noticeable drop in temperature may occur during the early afternoon as a cool breeze begins to blow off of the water. This wind is known as the "sea breeze", which occurs in response to differences in temperature between a body of water and neighboring land.

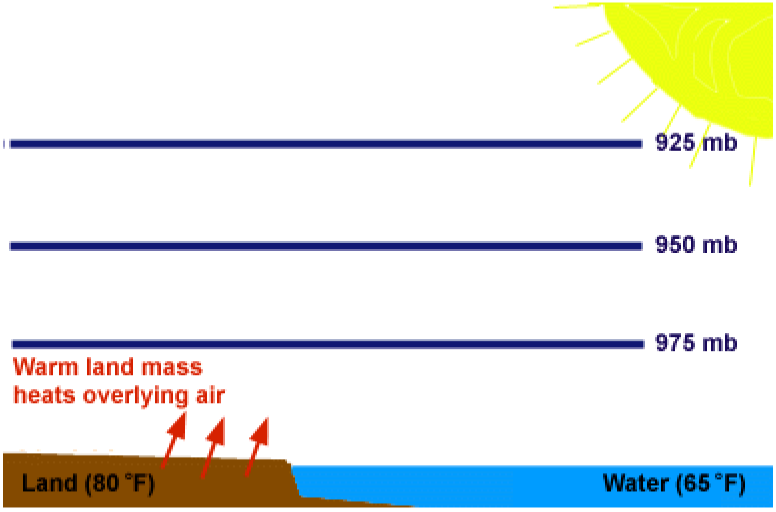


Sea-breeze circulations most often occur on warm sunny days during the spring and summer when the temperature of the land is normally higher than the temperature of the water. During the early morning hours, the land and the water start out at roughly the same temperature. On a calm morning, a given pressure surface will be at the same height above both the land and water.



A few hours later, the sun's energy begins to warm the land more rapidly than the water. By later in the day, the temperature of the land increases while the temperature of the water remains relatively constant. This occurs because water, especially large bodies of water like a lake or ocean, are able to absorb more energy than land without warming.

It is important to remember that the air is not heated directly from above by the sun. In fact, most of the incoming solar energy actually passes right through the atmosphere. However, as the land absorbs this energy, heat is radiated back into the atmosphere (from the earth), warming the overlying air. Some of this heat is transported to higher levels in the atmosphere through convection.

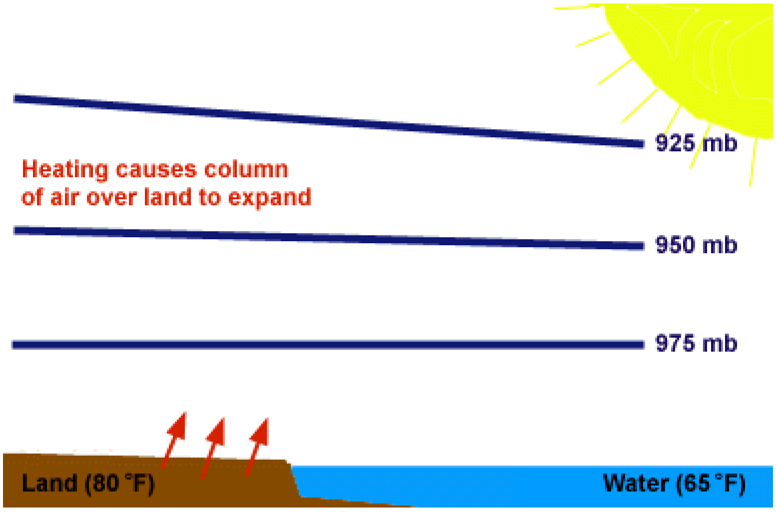


On the other hand, since the temperature of the water remains relatively constant throughout the day, the air over the water is not heated from below (as over land), resulting in lower air temperatures over the water.

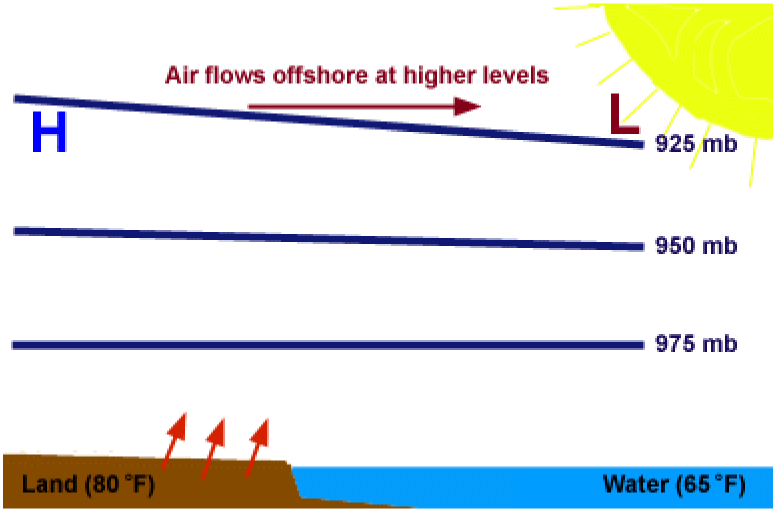
Offshore Flow Aloft

precursor to the sea breeze at the surface

Since warm air is less dense than cool air, the air over land expands in response to heating from the ground below. This expansion leads to an increase in the distance, or "thickness", between constant pressure surfaces within the heated air. Over water, where the air is heated very little, such expansion does not occur and the distance between pressure surfaces remains about the same.



In response to continued heating, an area of high pressure (blue "H") develops at higher levels over land while an area of low pressure (red "L") develops over water.

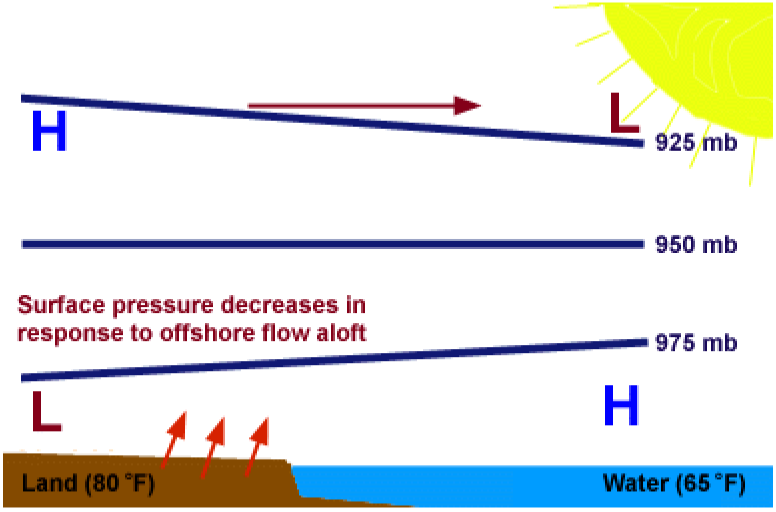


The resulting pressure gradient force causes air at higher levels to flow offshore (from high to low pressure).

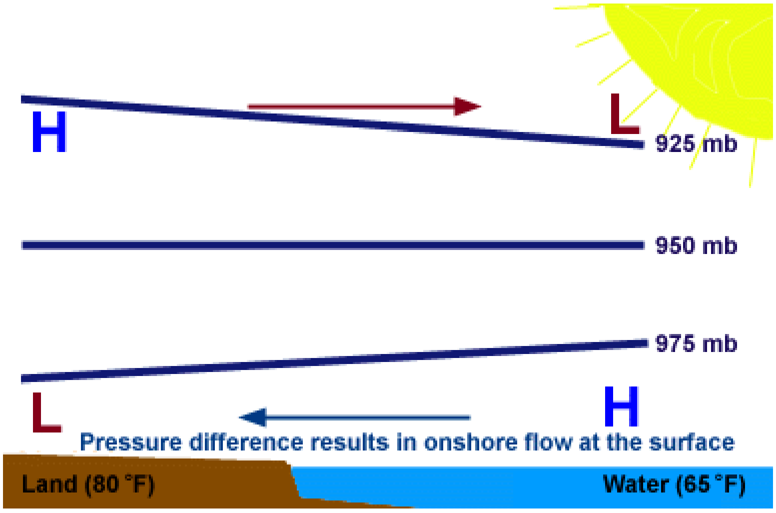
Sea Breeze Develops

cooler air flows onshore

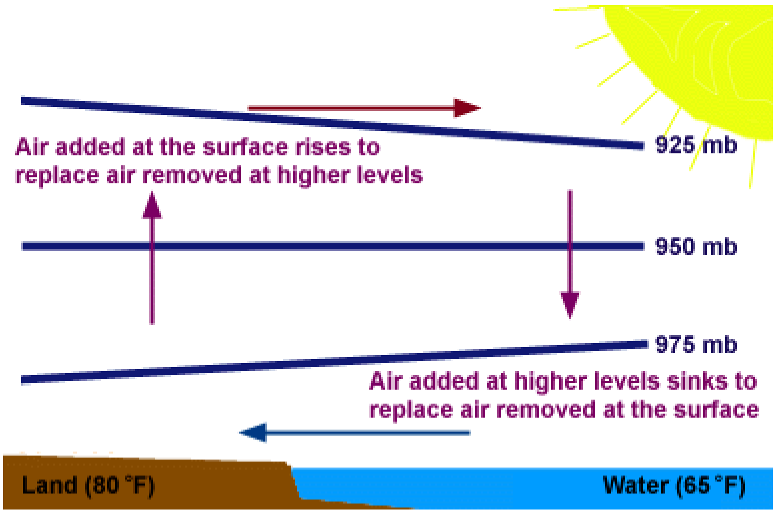
Since the pressure at any location is determined by the weight of the air above it, the removal of air from higher levels causes the pressure at levels below to decrease. In the case of a developing sea-breeze circulation, an area of low pressure develops over land at the surface in response to the removal of air at higher levels by offshore flow. Conversely, an area of surface high pressure develops over water in response to the accumulation of air at higher levels.



These areas of high and low pressure establish a surface pressure gradient which generates an onshore flow of air at the surface, or sea breeze.



Vertical motions are induced in response to the horizontally moving air. Over land, for example, onshore flow causes air to pile up at lower levels while offshore flow removes air from higher levels. As a result, air rises from lower levels to replace the air that is being removed aloft.



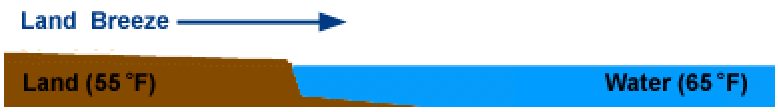
On the other hand, over water, air is accumulating aloft while being removed from lower levels. In response, air descends from higher levels to replace the air that is being removed from lower levels. These rising and sinking motions complete the loop that makes up the **sea-breeze circulation**.

Sea breeze circulations typically penetrate inland a horizontal distance of less than 40 kilometers from shore. This is due to increased surface friction resulting from the topography of the land. As the distance from shore increases, the sea-breeze circulation weakens and is eventually dampened out by friction.

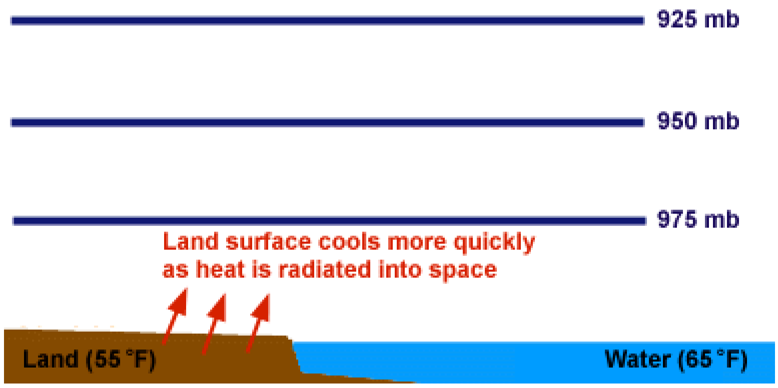
Land Breezes

begin with the cooling of low-level air

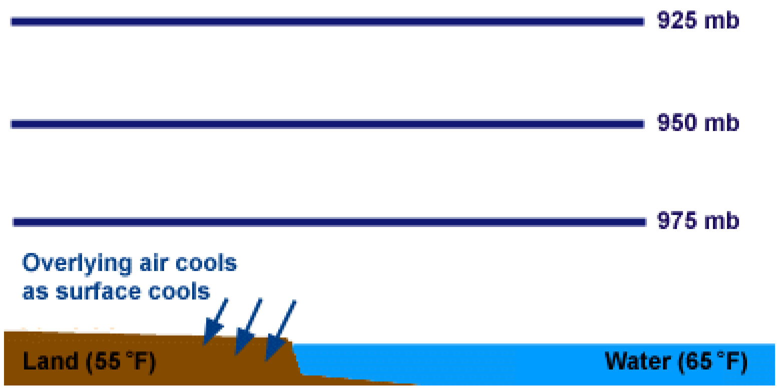
On clear, calm evenings, temperature differences between a body of water and neighboring land produce a cool wind that blows offshore. This wind is called a "land breeze". Land breezes are strongest along the immediate coastline but weaken considerably further inland.



Land-breeze circulations can occur at any time of year, but are most common during the fall and winter seasons when water temperatures are still fairly warm and nights are cool.



On clear and calm evenings, the earth's surface cools by radiating (giving off) heat back into space, and this results in a cooling of the immediately overlying air.

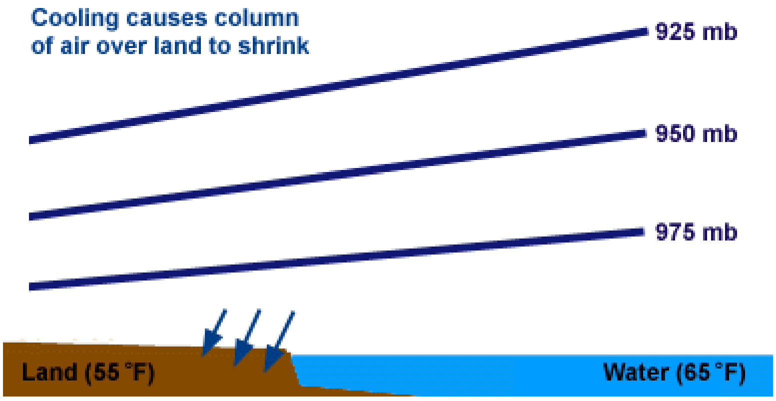


Since the air over land cools more rapidly than the air over water, a temperature difference is established, with cooler air present over land and relatively warmer air located over water.

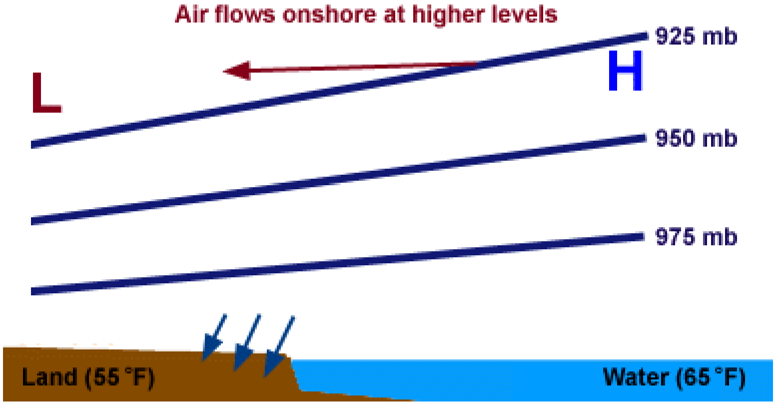
Onshore Flow Aloft

precursor to the land breeze at the surface

Since warm air is less dense than cool air, the air over land contracts in response to radiational cooling from the ground below. This contraction leads to a decrease in the distance, or "thickness", between constant pressure surfaces within the cooled air. Over water, where the air cools much more slowly, such contraction does not occur and the distance between pressure surfaces remains about the same.



In response to additional cooling, an area of low pressure (red "L") develops at higher levels over land while an area of high pressure (blue "H") develops over water.

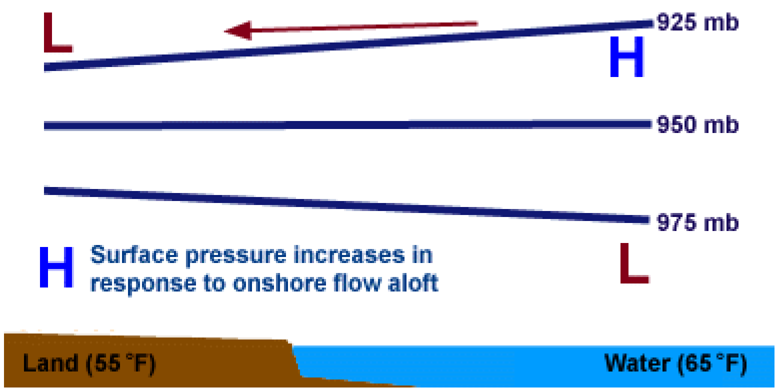


The resulting pressure gradient force causes air at higher levels to flow onshore (from high to low pressure).

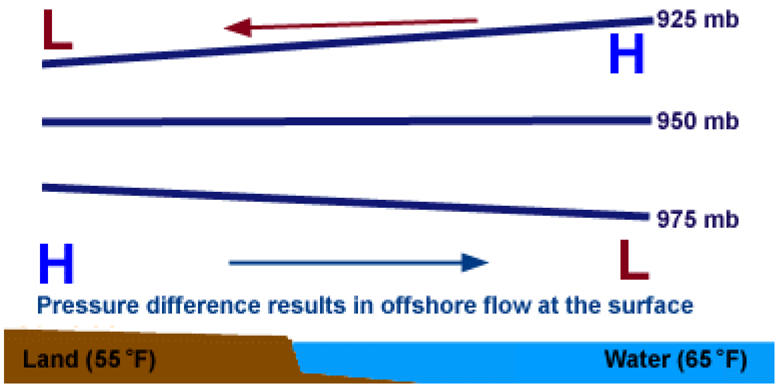
Land Breeze Develops

cooler air flows offshore

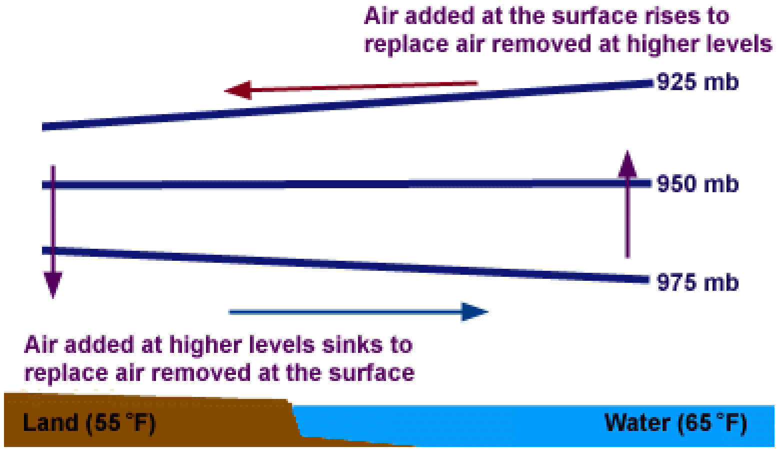
Since the pressure at any location is determined by the weight of the air above it, the accumulation of air at higher levels causes the pressure at levels below to increase. In the case of a developing land-breeze circulation, an area of high pressure develops over land at the surface in response to the accumulation of air at higher levels by onshore flow. Conversely, an area of surface low pressure develops over water in response to the removal of air from higher levels.



These areas of high and low pressure establish a surface pressure gradient which generates an offshore flow of air at the surface, or land breeze.

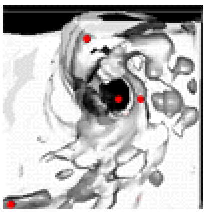


Vertical motions are induced in response to the horizontally moving air. Over water, for example, offshore flow causes air to pile up at lower levels while onshore flow removes air from higher levels. As a result, air rises up from lower levels to replace the air that is being removed aloft.



On the other hand, over land, air is accumulated at higher levels while being removed from lower levels. In response, air descends from higher levels to replace the air that is being removed from lower levels. These rising and sinking motions complete the loop that makes up the land-breeze circulation.

Graphic by: Dan Bramer



Fly through a 3-D Hurricane!
added (1/08/1999)

Requires a VRML player/plugin.
See bottom of page for a recommended one.

Interact with Atlantic hurricanes from 1950-2003!!

Hurricanes are cyclones that develop over the warm tropical oceans and have sustained winds in excess of 64 knots (74 miles/hour). These storms are capable of producing dangerous winds, torrential rains and flooding, all of which may result in tremendous property damage and loss of life in coastal populations. One memorable storm was Hurricane Andrew (pictured above), which was responsible for at least 50 deaths and more than $30 billion in property damage. The purpose of this module is to introduce hurricanes and their associated features, to show where hurricanes develop, and to explain the atmospheric conditions necessary for hurricane development. The Hurricane module has been organized into the following sections:

Sections
Last Update:
09/16/99

model. Requires a VRML player/plugin. See bottom of page for a recommended one.

Movement
The influence of global winds on the movement of hurricanes.

Satellites and Hurricane Hunters
Discusses the tools and means meteorologists use to observe and track hurricanes.

Preparations
Includes a list of matters to consider if you are threatened by a hurricane.

Damage and Destruction
Destructive features associated with hurricanes, plus the Saffir-Simpson Scale for classifying damage potential.

Hurricane Tracks
Track Atlantic Hurricanes interactively from 1950 to 2003.

How They Are Named
The different names given to hurricane-like storms in different parts of the world.

Global Activity
Discusses the regions of the Earth where tropical cyclones can be found.

El Niño
See how El Niño appears to affect hurricane activity.

Acknowledgments
Those who contributed to the development of this module.

Hurricanes

a tropical cyclone with winds > 64 knots

Hurricanes are tropical cyclones with winds that exceed 64 knots (74 mi/hr) and circulate counter-clockwise about their centers in the Northern Hemisphere (clockwise in the Southern Hemisphere).

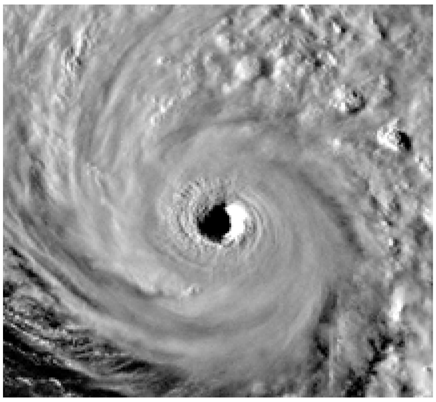
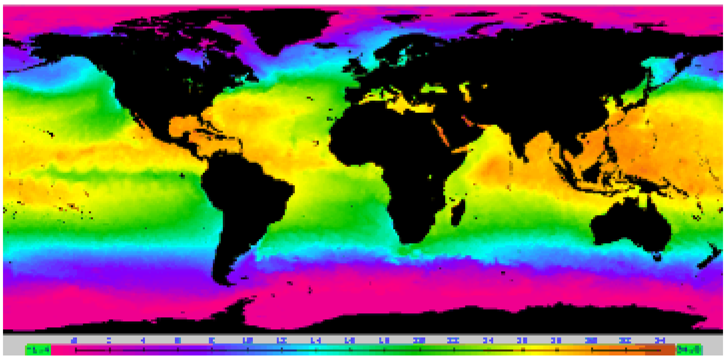


Image by: the GOES Project

Hurricanes are formed from simple complexes of thunderstorms. However, these thunderstorms can only grow to hurricane strength with cooperation from both the ocean and the atmosphere. First of all, the ocean water itself must be warmer than 26.5 degrees Celsius (81°F). The heat and moisture from this warm water is ultimately the source of energy for hurricanes. Hurricanes will weaken rapidly when they travel over land or colder ocean waters -- locations with insufficient heat and/or moisture.



This is a sea surface temperature map for the northern hemisphere summer. The yellow, orange, and red colors show water temperatures warm enough to sustain hurricanes (> 26.5°C).

Image by: OSDPD

Related to having warm ocean water, high relative humidities in the lower and middle troposphere are also required for hurricane development. These high humidities reduce the amount of evaporation in clouds and maximizes the latent heat released because there is more precipitation. The concentration of latent heat is critical to driving the system.

The vertical wind shear in a tropical cyclone's environment is also important. Wind shear is defined as the amount of change in the wind's direction or speed with increasing altitude. The video below shows how wind shear plays a role in hurricane formation.

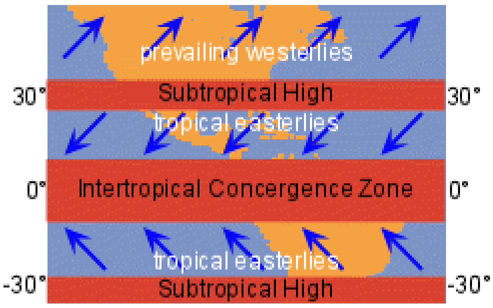
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/grow/home.rxml

When the wind shear is weak, the storms that are part of the cyclone grow vertically, and the latent heat from condensation is released into the air directly above the storm, aiding in development. When there is stronger wind shear, this means that the storms become more slanted and the latent heat release is dispersed over a much larger area.

Initial Development

the storms that become hurricanes

Hurricanes initiate from an area of thunderstorms. These thunderstorms are most commonly formed in one of three different ways. The first is the InterTropical Convergence Zone (ITCZ). The ITCZ is a near-solid ring of thunderstorms surrounding the globe found in the tropics. In the diagram below, the easterly trade winds converge near the equator and create thunderstorms, which can be seen in the satellite image along the equator.



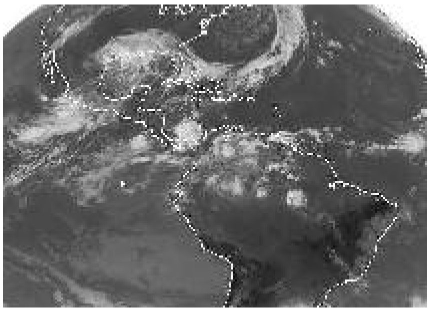
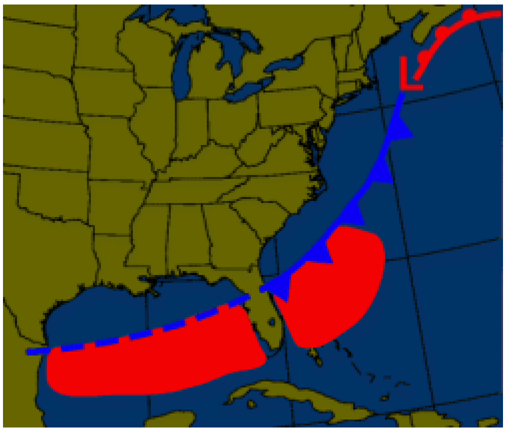


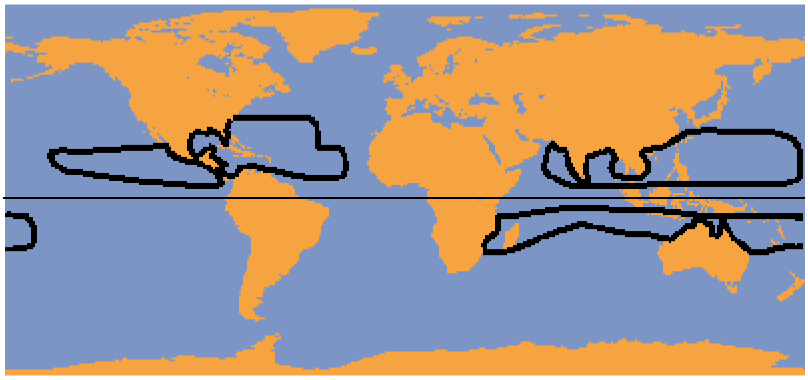
Image by: GOES Server

The second source for thunderstorms that can create hurricanes are from eastward moving atmospheric waves, called easterly waves. Easterly waves are similar to waves in the mid-latitudes, except they are in the easterly trade-flow. Convergence associated with these waves creates thunderstorms that can ultimately reach hurricane strength.



The third mechanism is along old frontal boundaries that drift into the Gulf of Mexico or coastal Florida. The lift associated with these fronts can be enough to initiate storms, and if the atmospheric and oceanic conditions are sufficient, tropical cyclones can develop that way as well.

The map below shows the regions throughout the world where tropical cyclones originate. Tropical cyclones are more commonly found in the northern hemisphere, but the Pacific and Indian Oceans both produce hurricanes in the southern hemisphere. However, in other parts of the world, hurricanes are called by different names.



At the equator, ocean surface temperatures are warm enough to produce hurricanes, but none form. This is because there is not enough coriolis force to create spin and induce a potential hurricane.

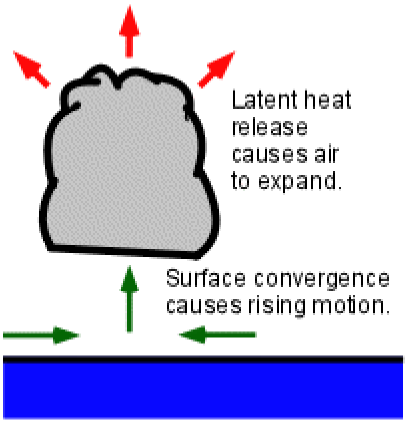
CISK

how thunderstorms become hurricanes

CISK, or "**Convective Instability of the Second Kind**", is a popular theory that explains how thunderstorms can evolve and organize into hurricanes. CISK is a positive feedback mechanism, meaning that once a process starts, it causes events which enhance the original process, and the whole cycle repeats itself over and over. Below is a video explanation of CISK.

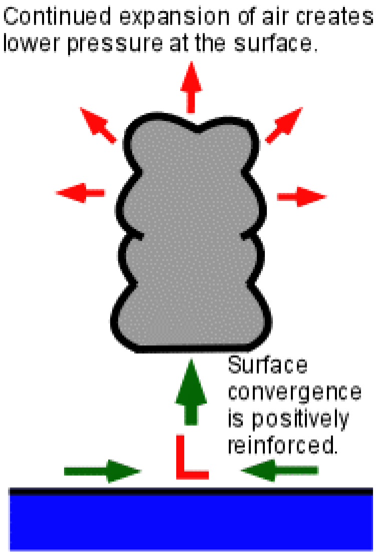
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/grow/cisk.rxml

The surface air that spirals into the center of a low pressure system creates convergence (green horizontal arrows) and forces air to rise in the center (green vertical arrow). This air cools and moisture condenses which releases latent heat into the air. It is this latent heat that provides the energy to fuel these storms.



Latent heat is simply heat released or absorbed by a substance (in this case, water vapor) as it changes its state. When water vapor condenses into liquid, it releases this heat into the surrounding atmosphere. The atmosphere around this condensation then warms.

Since warm air is less dense than cooler air, the warmer air takes up more space. This expansion of this air (red arrows) forces more air outside away from the center of the storm and the surface pressure (which is the weight of the air above the surface) decreases.



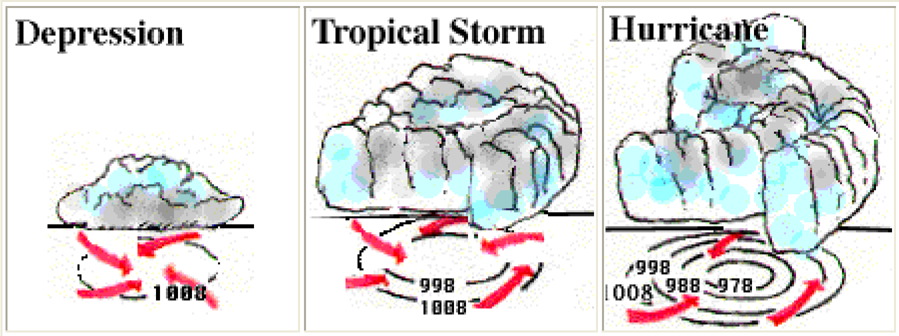
When the surface pressure decreases, a larger pressure gradient is formed, and more air converges towards the center of the storm. This creates more surface convergence and causes more warm moist surface air to rise above the surface. This air, as it cools, condenses into clouds. While it does this, it releases even more latent heat.

This cycle continuously repeats itself each time intensifying the storm until other factors, such as cool water, land, or high wind shear act to weaken it.

Stages of Development

from tropical depression to hurricane

Hurricanes evolve through a life cycle of stages from birth to death. A tropical disturbance in time can grow to a more intense stage by attaining a specified sustained wind speed. The progression of tropical disturbances can be seen in the three images below.



Tropical Depression Tropical Storm Hurricane

Hurricanes can often live for a long period of time -- as much as two to three weeks. They may initiate as a cluster of thunderstorms over the tropical ocean waters. Once a disturbance has become a tropical depression, the amount of time it takes to achieve the next stage, tropical storm, can take as little as half a day to as much as a couple of days. It may not happen at all. The same may occur for the amount of time a tropical storm needs to intensify into a hurricane. Atmospheric and oceanic conditions play major roles in determining these events.

Below, in this satellite image from 1995, we can see different tropical disturbances in each stage are evident. At the far left, Tropical storm Jerry is over Florida, while Hurricanes Iris and Humberto are further east, amongst a couple of tropical depressions.

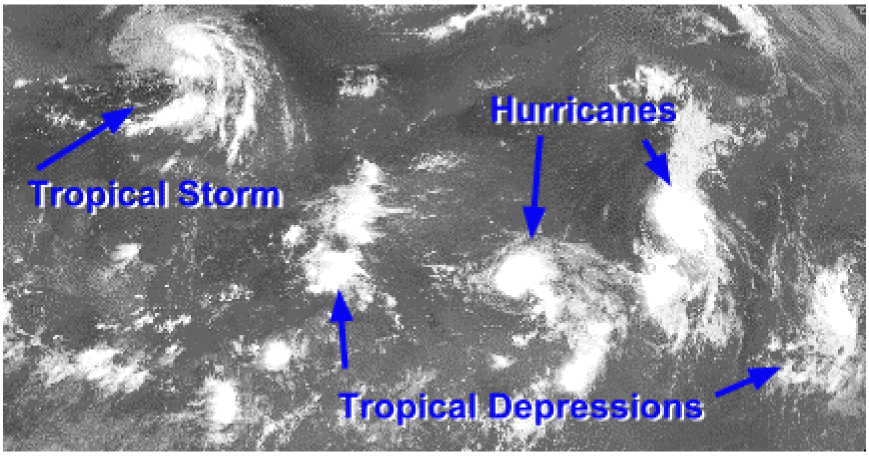
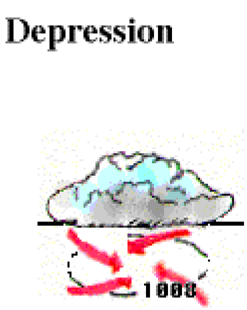


Image by: GOES Project

Tropical Depression



Once a group of thunderstorms has come together under the right atmospheric conditions for a long enough time, they may organize into a tropical depression. Winds near the center are constantly between 20 and 34 knots (23 –39mph).

A tropical depression is designated when the first appearance of a lowered pressure and organized circulation in the center of the thunderstorm complex occurs. A surface pressure chart will reveal at least one closed isobar to reflect this lowering.

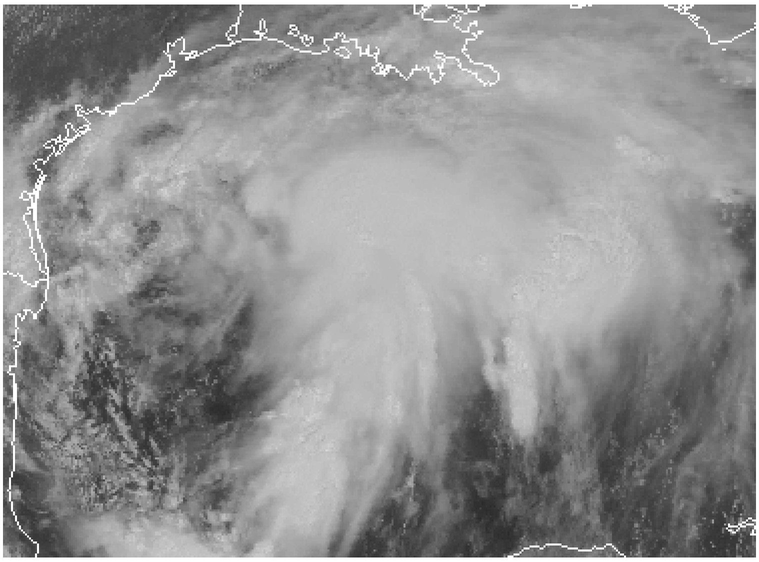
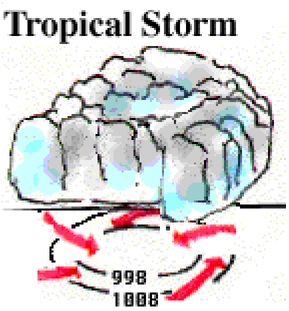


Image provided by TPC : Tropical depression

When viewed from a satellite, tropical depressions appear to have little organization. However, the slightest amount of rotation can usually be perceived when looking at a series of satellite images. Instead of a round appearance similar to hurricanes, tropical depressions look like individual thunderstorms that are grouped together. One such tropical depression is shown here.

Tropical Storms



Once a tropical depression has intensified to the point where its maximum sustained winds are between 35-64 knots (39-73 mph), it becomes a tropical storm. It is at this time that it is assigned a name. During this time, the storm itself becomes more organized and begins to become more circular in shape -- resembling a hurricane.

The rotation of a tropical storm is more recognizable than for a tropical depression. Tropical storms can cause a lot of problems even without becoming a hurricane. However, most of the problems a tropical storm cause stem from heavy rainfall.

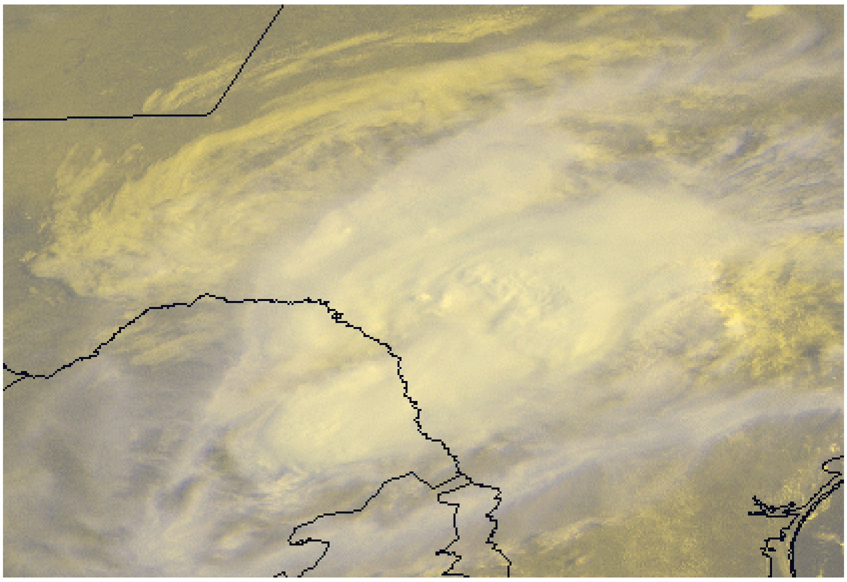


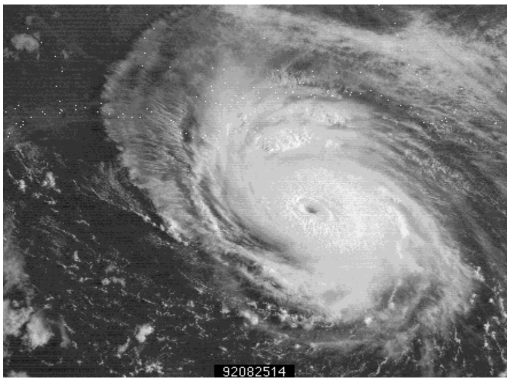
Image by: OSEI : Tropical storm Charlie

The above satellite image is of tropical storm Charlie (1998). Many cities in southern Texas reported heavy rainfall between 5-10 inches. Included in these was Del Rio, where more than 17 inches fell in just one day, forcing people from their homes and killing half a dozen.

Hurricanes

As surface pressures continue to drop, a tropical storm becomes a hurricane when sustained wind speeds reach 64 knots (74 mph). A pronounced rotation develops around the central core.

Hurricanes are Earth's strongest tropical cyclones. A distinctive feature seen on many hurricanes and are unique to them is the dark spot found in the middle of the hurricane. This is called the **eye**. Surrounding the eye is the region of most intense winds and rainfall called the eye wall. Large bands of clouds and precipitation spiral from the eye wall and are thusly called **spiral rain bands**.



http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/stages/cane/home.rxml

Hurricanes are easily spotted from the previous features as well as a pronounced rotation around the eye in satellite or radar animations. Hurricanes are also rated according to their wind speed on the Saffir-Simpson scale. This scale ranges from categories 1 to 5, with 5 being the most devastating. Under the right atmospheric conditions, hurricanes can sustain themselves for as long as a couple of weeks. Upon reaching cooler water or land, hurricanes rapidly lose intensity.

The Eye
the center of the storm

The most recognizable feature found within a hurricane is the eye. They are found at the center and are between 20-50km in diameter. The eye is the focus of the hurricane, the point about which the rest of the storm rotates and where the lowest surface pressures are found in the storm. The image below is of a hurricane (called cyclone in the Southern Hemisphere). Note the eye at the center.

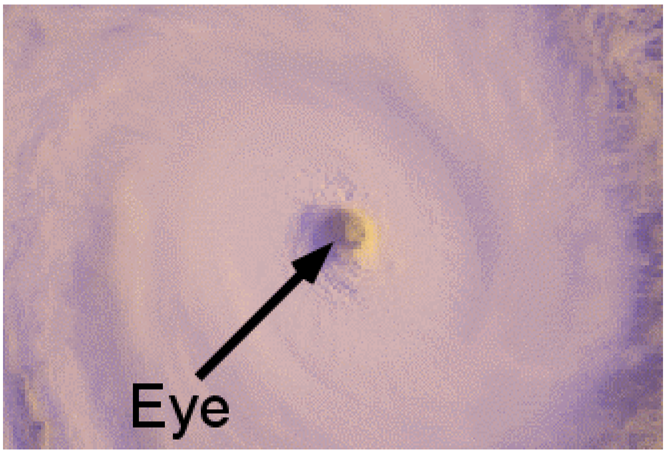


Image by: OSEI

Skies are often clear above the eye and winds are relatively light. It is actually the calmest section of any hurricane.

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/stages/cane/eye.rxml

The eye is so calm because the now strong surface winds that converge towards the center never reach it. The coriolis force deflects the wind slightly away from the center, causing the wind to rotate around the center of the hurricane (the eye wall), leaving the exact center (the eye) calm.

An eye becomes visible when some of the rising air in the eye wall is forced towards the center of the storm instead of outward -- where most of it goes. This air is coming inward towards the center from all directions. This convergence causes the air to actually sink in the eye. This sinking creates a warmer environment and the clouds evaporate leaving a clear area in the center.

The Eye Wall

a hurricane's most devastating region

Located just outside of the eye is the eye wall. This is the location within a hurricane where the most damaging winds and intense rainfall is found. The image below is of a hurricane (called cyclone in the Southern Hemisphere).

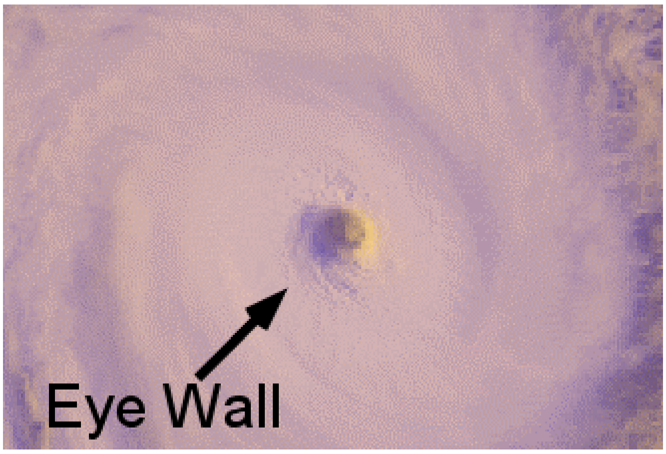


Image by: OSEI

Eye walls are called as such because oftentimes the eye is surrounded by a vertical wall of clouds. The eye wall can be seen in the picture above as the thick ring surrounding the eye.

At the surface, the winds are rushing towards the center of a hurricane -- forcing air upwards at the center. The coriolis force acts on these surface winds, and in the Northern Hemisphere, the deflection is to the right. The convergence at the eye wall is so strong here that the air is being lifted faster and with more force here than any other location of the hurricane. Thus, the moisture transport from the ocean and subsequent latent heat production is maximized.

Spiral Bands

where more rain is found

Radiating outward from the eye wall one can see a banded structure within the clouds. These clouds are called either spiral rain bands (or spiral bands). The image below is of a hurricane (called cyclone in the Southern Hemisphere).

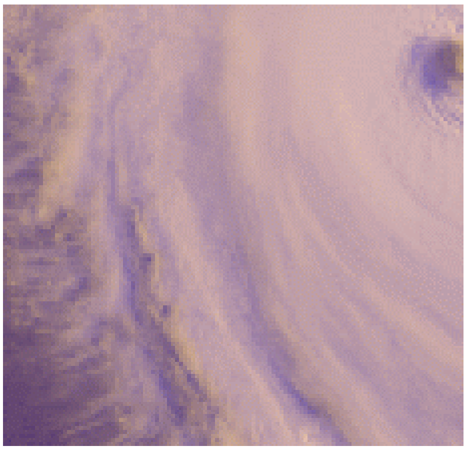
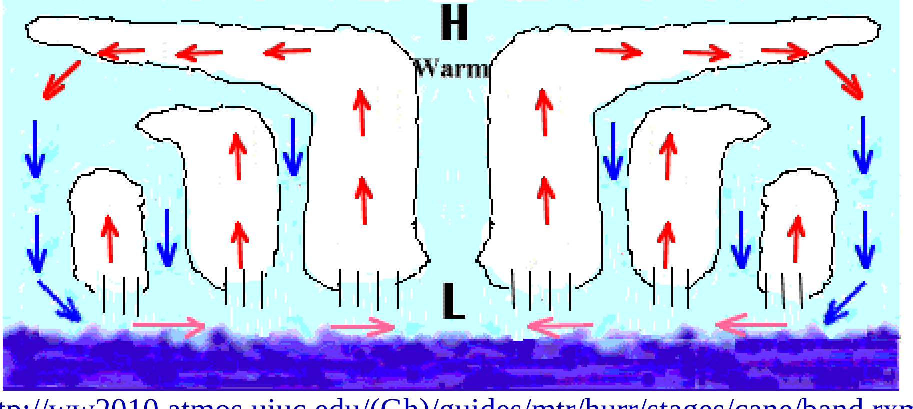


Image by: OSEI

There are sometimes gaps in between these bands where no rain is found. In fact, if one were to travel between the outer edge of the hurricane to its center, one would normally progress from light rain to dry back to slightly more intense rain again over and over with each period of rainfall being more intense and lasting longer until reaching the eye. Upon exiting the eye and moving towards the edge of the hurricane, one would see the same events as they did going in, but in opposite order.



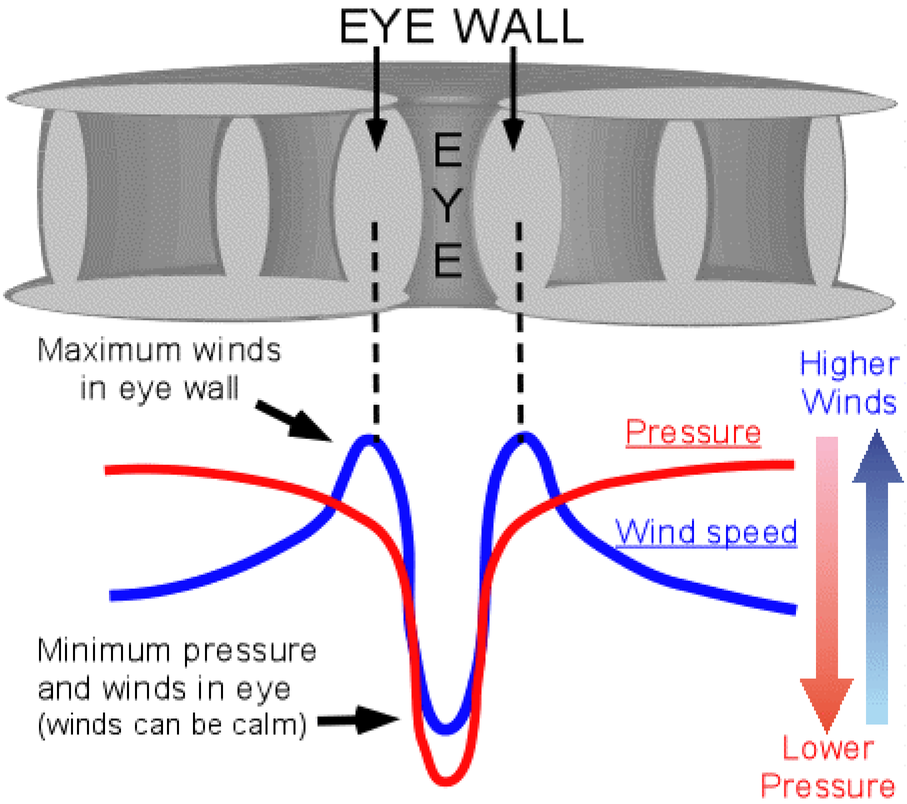
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/stages/cane/band.rxml

A schematic of this banding feature can be seen in the diagram above. The thunderstorms are now organized into regions of rising and sinking air. Most of the air is rising, but there is a small amount found in between the thunderstorms that is sinking.

Pressure and Winds

the distribution across a hurricane

Atmospheric pressure and wind speed change across the diameter of a hurricane. To demonstrate, the diagram below shows a rough profile of wind speed (blue) and surface pressure (red) across a hurricane. Between 100-200 kilometers from the eye, the winds are fast enough to qualify as tropical storm force. The atmospheric pressure here will still be relatively high compared to the storm's center at about 990-1010 millibars. However, the pressure gradually falls and the wind speed rises upon getting closer to the eye wall. It is only over the last 50-100 kilometers that the large changes in pressure and wind speed occur.



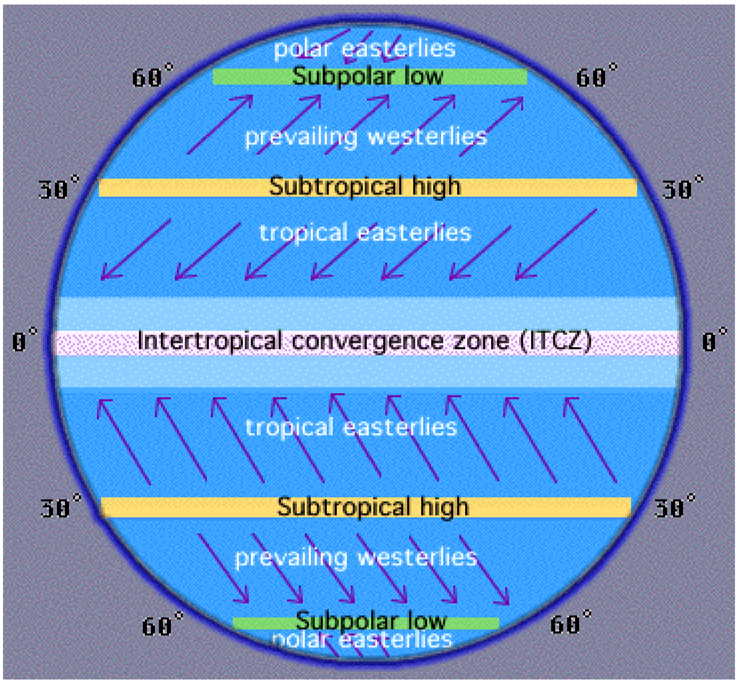
The pressure begins to fall more rapidly while the wind speed simultaneously increases. Within the eye wall, the wind speed reaches its maximum but within the eye, the winds become very light sometimes even calm. The surface pressure continues to drop through the eye wall and into the center of the eye, where the lowest pressure is found. Upon exiting the eye, the wind speed and pressure both increase rapidly. The wind speed again reaches a maximum in the opposite eye wall, and then quickly begins to decrease. The wind and pressure profiles inside a hurricane are roughly symmetrical, so a quick rise in winds and pressure through the eye wall followed by a slower increase in pressure and likewise decrease in wind speed would be expected.

Movement of Hurricanes

steered by the global winds

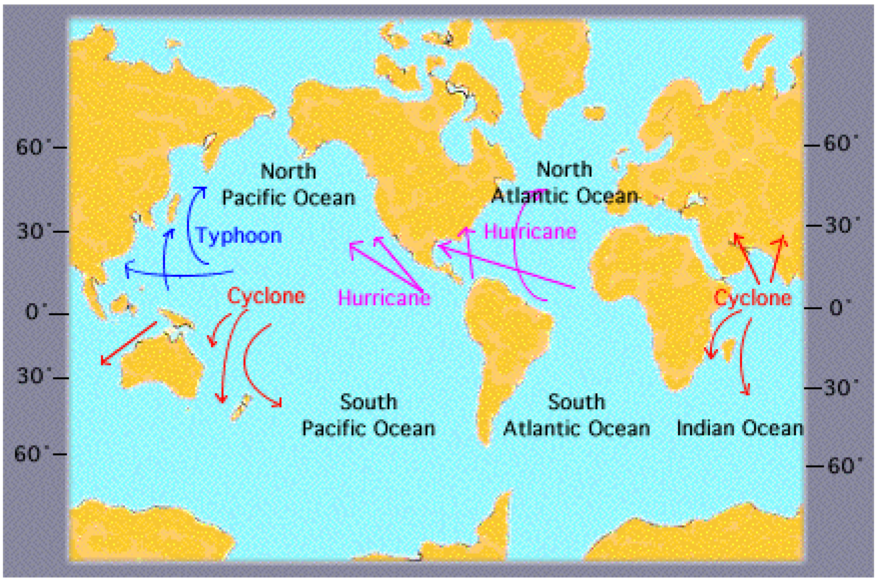
The global wind pattern is also known as the "**general circulation**" and the surface winds of each hemisphere are divided into three wind belts:

- **Polar Easterlies:** From 60-90 degrees latitude.
- **Prevailing Westerlies:** From 30-60 degrees latitude (aka Westerlies).
- **Tropical Easterlies:** From 0-30 degrees latitude (aka Trade Winds).



The easterly trade winds of both hemispheres converge at an area near the equator called the "Intertropical Convergence Zone (ITCZ)", producing a narrow band of clouds and thunderstorms that encircle portions of the globe.

The path of a hurricane greatly depends upon the wind belt in which it is located. A hurricane originating in the eastern tropical Atlantic, for example, is driven westward by easterly trade winds in the tropics. Eventually, these storms turn northwestward around the subtropical high and migrate into higher latitudes. As a result, the Gulf of Mexico and East Coast of the United States are at risk to experience one or more hurricanes each year.



In time, hurricanes move into the middle latitudes and are driven northeastward by the westerlies, occasionally merging with midlatitude frontal systems. Hurricanes draw their energy from the warm surface water of the tropics, which explains why hurricanes dissipate rapidly once they move over cold water or large land masses.

Public Awareness

satellites and hurricane hunters

In the early part of this century, coastal residents may have had less than a day to prepare or evacuate their homes from an oncoming hurricane. Today, these same locations receive warnings to evacuate from one to two days in advance, let alone the extra days they are also aware of its existence. Before satellites and radars, people had very little knowledge of the weather just 100 kilometers offshore.

Obviously it is a vastly different world today. Thanks to satellites, we know about the existence of a tropical cyclone immediately. Meteorologists at the Tropical Prediction Center work to constantly monitor these systems as they move, issuing hurricane watches and warnings (definitions of which are placed below) with adequate time for the public to prepare.

Hurricane Watch:	Hurricane Warning:
A hurricane or an incipient hurricane condition poses a possible threat, generally within36 hours.	*Sustained winds 64 kt (74 mph or 119 kph) or higher associated with a hurricane are expected in a specified coastal area in 24 hours or less.*

**A hurricane warning can remain in effect when dangerously high water or a combination of dangerously high water and exceptionally high waves continue, even though winds may be less than hurricane force.*

Meteorologists and the public also rely on hurricane hunters to learn more about the hurricane. They do this by flying aircraft equipped with weather instruments straight into the middle of these powerful storms. Hurricane hunters are operated by both the Air Force Reserve based at Keesler Air Force Base in Mississippi and the National Oceanic and Atmospheric Administration (NOAA). The two have a long history, making their first flights in 1944. Before satellites were put in space, these planes were the best and sometimes only source of information about a hurricane's position and intensity. When a hurricane hunter airplane is set to fly into a tropical storm or hurricane, it is ready for a long mission. Most commonly, one plane will be in the air for about 11 hours. Scientists on the plane relay the data they collect immediately to the Tropical Prediction Center for analysis.

Image by: U.S. Air Force

Air force reserve hurricane hunters use the WC-130H aircraft seen above to make their flights, while NOAA crews use the WP-3D and GIV-SP. As dangerous as it seems, the hurricane hunters have an extremely clean safety record. A normal crew consists of six: a pilot, co-pilot, navigator, flight engineer, aerial reconnaissance weather officer, and dropsonde system operator.

Public Action

what do you do?

If your home is on or near the coastline where the hurricane's destructive forces will affect it, pay close attention to what the local government and/or police force is recommending. You should also pay attention to radio and TV stations for the latest information.

If evacuating your home is recommended:

- Heed their warning!!
- Plan ahead where you would go -- it may be beneficial to choose a few places like an out of town friend's home or a designated shelter, etc.
- Take the phone numbers of these places with you.
- Take a road map in case the weather forces you onto unfamiliar roads.
- Do not drive over standing water, as floods may have damaged the roads.
  YOU DO NOT KNOW HOW DEEP THE WATER REALLY IS!!!

If you are in the path of a land-falling hurricane, you should prepare a supply kit containing:

- A first aid kit and necessary medications.
- Canned food and an opener, as this food lasts for long periods of time without needing refrigeration.
- Plenty of water. (The Red Cross recommends three gallons of water per person to last three days.)
- Flashlights, a battery powered radio, and extra batteries.
- Raingear, sleeping bags, and protective clothing.

More complete information on this subject as well as how to best prepare your house for a hurricane can be gathered by contacting your local Red Cross chapter.

Damage

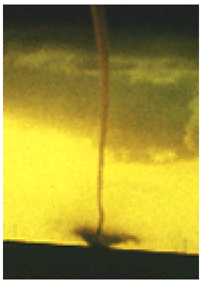
caused by hurricanes

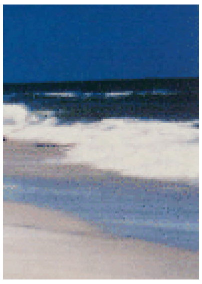
With hurricanes being as powerful as they are, it is not surprising that upon landfall they cause damage and destruction. Even when the hurricane has yet to make landfall, its effects can be dangerous. However, most of the damage caused to man and nature occur as a hurricane makes landfall.


Strong Winds


Storm Surge


Flooding


Tornadoes


Rip Tides

Each of the above phenomena can turn a hurricane into a home-wrecker, a nature-destroyer, and even a killer. Some tropical storms that make landfall cause damage in these ways, but very rarely do they do so in as significant a manner as do hurricanes.

Strong Winds

determines the intensity of a hurricane

Strong winds are the most common means of destruction associated with hurricanes. Their sometimes continuous barrage can uproot trees, knock over buildings and homes, fling potentially deadly debris around, sink or ground boats, and flip cars.

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/damg/wind.rxml

The intensity of a tropical cyclone is measured by the highest sustained wind speed found within it. Once it becomes a hurricane, the relative strength of that hurricane is also measured on a scale based on its greatest wind speed. This scale is named the **Saffir-Simpson scale** for the men who invented it. The scale is listed below.

Saffir-Simpson Hurricane Damage-Potential Scale

Scale Number Category	**Central Pressure** mb inches	**Wind Speeds** mi/hr knots	**Storm Surge** feet meters	**Observed Damage**
1	>=980 >=28.94	74-95 64-82	4-5 ~1.5	some damage to trees, shrubbery, and unanchored mobile homes
2	965-979 28.50-28.91	96-110 83-95	6-8 ~2.0-2.5	major damage to mobile homes; damage buildings' roofs, and blow trees down
3	945-964 27.91-28.47	111-130 96-113	9-12 ~2.5-4.0	destroy mobile homes; blow down large trees; damage small buildings
4	920-944 27.17-27.88	131-155 114-135	13-18 ~4.0-5.5	completely destroy mobile homes; lower floors of structures near shore are susceptible to flooding
5	<"920" <"27.17"	>"155" >"135"	>"18" >"5.5"	extensive damage to homes and industrial buildings; blow away small buildings; lower floors of structures within 500 meters of shore and less than 4.5 m (15 ft) above sea level are damaged

The Saffir-Simpson scale categorizes hurricanes on a scale from 1 to 5. Category 1 hurricanes are the weakest, and 5's the most intense. Hurricanes strong enough to be considered intense start at category 3 or with sustained winds exceeding 96 knots (111 mph). For reference, there have only been three category 5 hurricanes that made landfall on the mainland U.S. (Florida Keys 1935, Camille 1969, and Andrew 1992).

Not only can the winds be dangerous, but the fact that they continually blow upon the water creates another problem - storm surge and high waves. Storm surge and high waves can contribute to water rising as high as 30 feet -- easily enough to devastate homes and businesses along the shore as well as kill those within them. Coastal towns adjacent to large bays or areas with shallow water are especially susceptible to damage by the storm surge.

Storm Surge

a concern to coastal residents

One major cause of hurricane damage is storm surge. Storm surge is the rising of the sea level due to the low pressure, high winds, and high waves associated with a hurricane as it makes landfall. The storm surge can cause significant flooding and cost people their lives if they're caught unexpected.

Storm surge can be understood by looking at the video below. The strong winds blowing towards the shore help push water towards shore on the right side of the hurricane's direction of motion. This piling up contributes to most of the coastal flooding.

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/damg/surg.rxml

Also, the central pressure of a hurricane is so low that the relative lack of atmospheric weight above the eye and eye wall causes a bulge in the ocean surface level. This effect is similar to using a straw. When you use a straw, you decrease the air pressure in the straw, and the high pressure pushing down on the rest of the drink pushes the drink up the straw. Here it is the relative higher pressure on the ocean around the outside the hurricane that lifts the ocean surface in the center.

Photo courtesy of NOAA

Ocean waves also contribute to the overall storm surge as the waves which may only be a couple of meters out at sea grow as the ocean depth decreases to several meters at the shore. The photograph below is of the exact same area as the photograph above, but after the storm surge has caused extensive damage.

Photo courtesy of NOAA

Typical storm surge heights vary with the hurricane's intensity, but they can range from only 1 to more than 5 meters (3 to 25+ feet). The inland penetration of the storm surge's damage can vary depending on the topography. In some locations, like Florida, the landscape is quite flat and if the ocean is raised a couple of meters, the intrusion of the storm surge can be as far as a mile or two. Storm surge creates steady flooding, and can wreck homes and pull boats and cars inland or out to sea. Waters that flow into low-lying areas can remain for weeks.

Heavy rain and Flooding

a problem of any tropical disturbance

Apart from the storm surge, heavy rainfall causes both flash and long term flooding. Tropical storms and hurricanes are known to dump as much as a meter (about 3 feet) of rain in just a couple of days, creating big problems for residents who believe they are safe just because they do not live on or near the coast. In fact flooding kills more people than the strong winds do. Here are some of the rainfall totals which occurred in October of 1995 from the landfall of Hurricane Opal.

Rainfall from Hurricane Opal (1995)	
Ellyson, FL	15.45"
Evergreen, AL	8.10"
Peach Tree City, GA	7.66"
Mobile, AL	7.48"
Pensacola, FL	7.27"
Hurlburt Field, FL	6.64"
Atlanta, GA	6.59"
Fulton Co., GA	6.22"
Anniston, AL	6.09"
Ft Benning, GA	5.25"
Dobbins AFB, GA	5.14"

Data provided by TPC

After a hurricane has come inland, it does begin to deteriorate. However, it still produces a lot of rainfall. Even when a tropical system is as weak as a depression, it is still a very strong storm when compared to average thunderstorms.

Tornadoes
even in hurricanes

With technology in its current state, forecasters can give residents in the path of hurricanes advanced warnings to help prevent casualties due to storm surge, strong winds, and heavy rain, -- each of which claimed many lives during the first half of the century. Now, more people are caught off guard by the tornadoes found in the spiral bands, causing damage similar to that seen in the Midwest.

Photo by: McGhiey

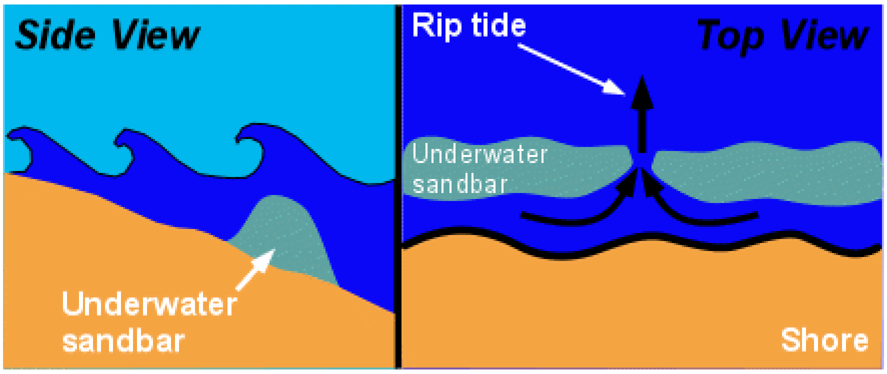
These tornadoes are also found close to or within the eye wall. Often these tornadoes occur in heavy rain storms, making them difficult, if not impossible, to see. Advances in radar technology have given the public more lead time than before, but these twisters are still very dangerous and can cause quite a bit of damage.

Rip Tides
a danger to swimmers

Another almost overlooked aspect of hurricanes and tropical storms are rip tides (or rip currents). Rip tides are strong sea currents which push away from the shore as a strong storm is near. They are formed by the strong winds pushing water towards the shore. Tropical cyclones' winds push waves up against the shoreline even if they are hundreds of miles away, so rip tide warnings are often the first indication of a nearby hurricane.

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/damg/rip.rxml

As seen in the side view diagram below, the incoming waves create an underwater sandbar close to shore, and the waves push more and more water in between the sandbar and the shore until a section of this sandbar collapses.

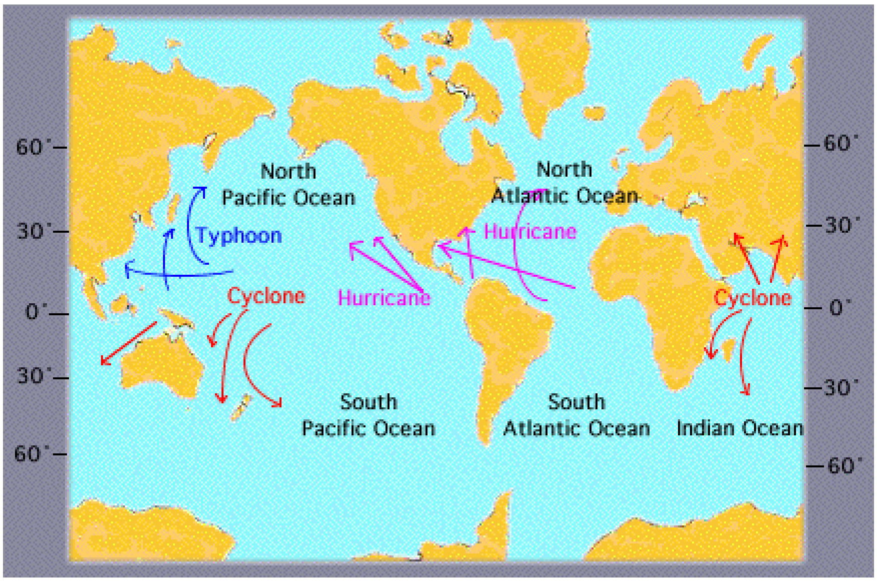


All the excess water is forced through this gap, creating an extremely strong but narrow current away from the shore (seen in top view diagram above). In fact, rip tides are so strong that trying to swim back to shore against the rip tide current will only tire you out and make it that much more difficult for you to survive. Rip tides are narrow enough that if you swim parallel to shore, you can easily escape the current and then swim back to shore.

How They Are Named

differently in different parts of the world

Hurricane-like storms are called by different names in the different regions of the world. For example, the name "hurricane" is given to systems that develop over the Atlantic or the eastern Pacific Oceans. In the western North Pacific and Philippines, these systems are called "typhoons" while in the Indian and South Pacific Ocean, they are called "cyclones".



Since 1953, the Tropical Prediction Center has produced lists of names for hurricanes. As a tropical depression develops into a tropical storm, it is given the next available name on the list, which is prepared in alphabetical order and alternates from between male and female names. The list of storm names for 1999-2004 is given below.

Atlantic Storm Names for 1999-2004

1999	2000	2001	2002	2003	2004
Arlene	Alberto	Allison	Arthur	Ana	Alex
Bret	Beryl	Barry	Bertha	Bill	Bonnie
Cindy	Chris	Chantal	Cristobal	Claudette	Charley
Dennis	Debby	Dean	Dolly	Danny	Danielle
Emily	Ernesto	Erin	Edouard	Erika	Earl
Floyd	Florence	Felix	Fay	Fabian	Frances
Gert	Gordon	Gabrielle	Gustav	Grace	Gaston
Harvey	Helene	Humberto	Hanna	Henri	Hermine
Irene	Isaac	Iris	Isidore	Isabel	Ivan
Jose	Joyce	Jerry	Josephine	Juan	Jeanne
Katrina	Keith	Karen	Kyle	Kate	Karl
Lenny	Leslie	Lorenzo	Lili	Larry	Lisa
Maria	Michael	Michelle	Marco	Mindy	Matthew
Nate	Nadine	Noel	Nana	Nicholas	Nicole
Ophelia	Oscar	Olga	Omar	Odette	Otto
Philippe	Patty	Pablo	Paloma	Peter	Paula
Rita	Rafael	Rebekah	Rene	Rose	Richard
Stan	Sandy	Sebastien	Sally	Sam	Shary
Tammy	Tony	Tanya	Teddy	Teresa	Tomas
Vince	Valerie	Van	Vicky	Victor	Virginie
Wilma	William	Wendy	Wilfred	Wanda	Walter

Eastern Pacific Storm Names for 1999-2004

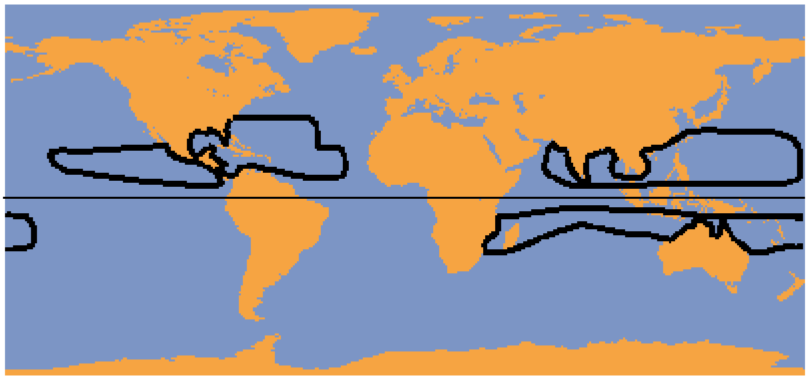
1999	2000	2001	2002	2003	2004
Adrian	Aletta	Adolph	Alma	Andres	Agatha
Beatriz	Bud	Barbara	Boris	Blanca	Blas
Calvin	Carlotta	Cosme	Cristina	Carlos	Celia
Dora	Daniel	Dalilia	Douglas	Dolores	Darby
Eugene	Emilia	Erick	Elids	Enrique	Estelle
Fernanda	Fabio	Flossie	Fausto	Felicia	Frank
Greg	Gilma	Gil	Genevieve	Guillermo	Georgette
Hilary	Hector	Henriette	Hernan	Hilda	Howard
Irwin	Ilerna	Israel	Iselle	Ignacio	Isis
Jova	John	Juliette	Julio	Jimena	Javier
Kenneth	Kristy	Kiko	Kenna	Kevin	Kay

Lidia	Lane	Lorena	Lowell	Linda	Lester
Max	Miriam	Manuel	Marie	Marty	Madeline
Norma	Norman	Narda	Norbert	Nora	Newton
Otis	Olivia	Octave	Odile	Olaf	Orlene
Pilar	Paul	Priscilla	Polo	Patricia	Paine
Ramon	Rosa	Raymond	Rachel	Rick	Roslyn
Selma	Sergio	Sonia	Simon	Sandra	Seymour
Todd	Tara	Tico	Trudy	Terry	Tina
Veronica	Vicente	Velma	Vance	Vivian	Virgil
Wiley	Willa	Wallis	Winnie	Waldo	Winifred
Xina	Xavier	Xina	Xavier	Xina	Xavier
York	Yolanda	York	Yolanda	York	Yolanda
Zelda	Zeke	Zelda	Zeke	Zelda	Zeke

Global Activity

tropical cyclones around the world

Even though Atlantic Ocean hurricanes receive a lot of attention, only 12% of tropical cyclones seen world-wide are located here. These dangerous storms can be found in three of our four oceans, and in both hemispheres. The diagram below shows the regions of the Earth where tropical storms originate.



Approximately 96 tropical cyclones are reported annually. The Western North Pacific Ocean averages more than 25 hurricanes (called typhoons) each year. Another location with great activity is the Indian Ocean. No other part of the world has so much activity in such a small area. This is because of the thunderstorms that develop in association with the nearby ITCZ and the very warm Indian ocean.

The Southern Hemisphere also experiences tropical cyclones. However, they are confined to the Western Pacific and Indian Oceans. Even though ocean temperatures are warm enough, a small region without tropical cyclones exists near the equator. This is because for all the thunderstorm activity that may exist, the coriolis force here is not sufficiently large enough.

Interaction with El Niño

how hurricane frequency may be affected

Researchers continue to investigate possible interactions between hurricane frequency and El Niño. El Niño is a phenomenon where ocean surface temperatures become warmer than normal in the equatorial Pacific. (The chart below shows the anomaly associated with the most recent El Niño in 1997-1998.) In general, warm El Niño events are characterized by more tropical storms and hurricanes in the eastern Pacific and a decrease in the Atlantic, Gulf of Mexico and the Caribbean Sea.

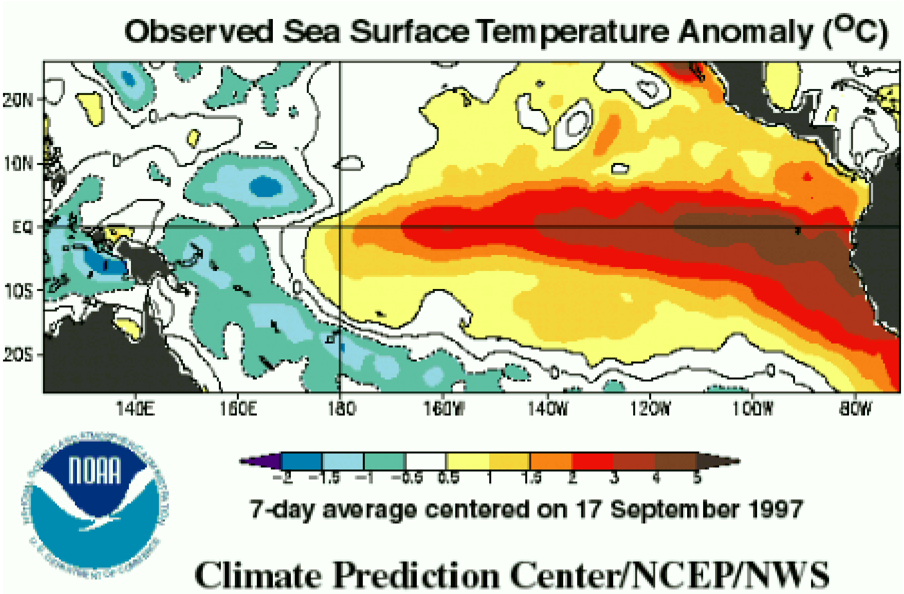
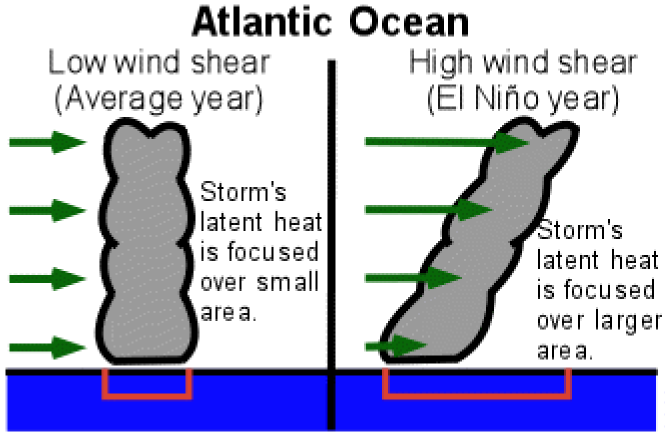


Image courtesy of CPC ENSO Main Page

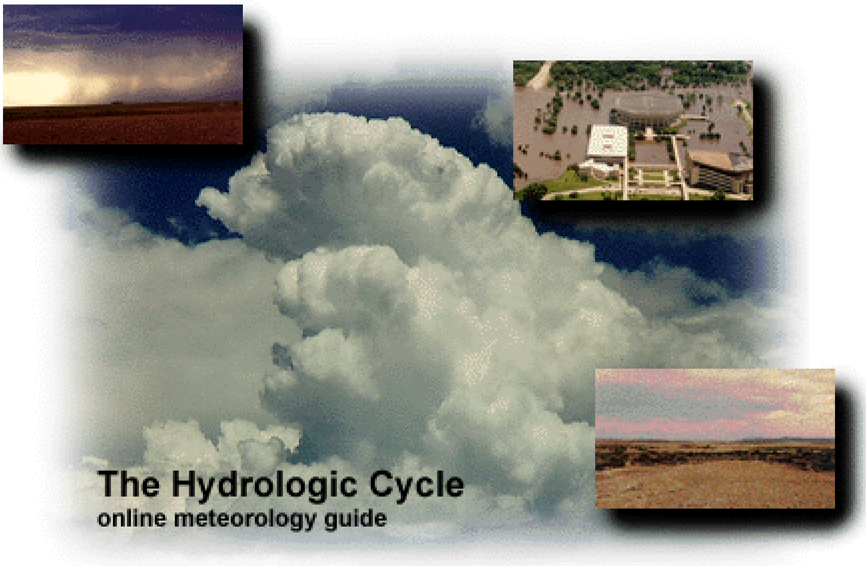
The 1997-98 El Niño event agreed with this theory. In 1997, the Atlantic Ocean had 7 named storms, of which 3 became hurricanes and only one of them intense. Each of these figures were below average yearly values. The average hurricane season is compared against the average El Niño season below.

	Atlantic		**Eastern Pacific**	
	Average	El Niño Avg.	Average	El Niño Avg.
Named storms	9.4	7.1	16,7	17.6
Hurricanes	5.8	4.0	9.8	10.0
Intense Hurricanes	2.5	1.5	4.8	5.5

The primary explanation for the decline in hurricane frequency during El Niño years is due to the increased wind shear in the environment.



In El Niño years, the wind patterns are aligned in such a way that the vertical wind shear is increased over the Caribbean and Atlantic. The increased wind shear helps to prevent tropical disturbances from developing into hurricanes. In the eastern Pacific, the wind patterns are altered in such a way to reduce the wind shear in the atmosphere, contributing to more storms.



Graphic by: Dan Bramer

Water is the source of all life on earth. The distribution of water, however, is quite varied; many locations have plenty of it while others have very little. Water exists on earth as a solid (ice), liquid or gas (water vapor). Oceans, rivers, clouds, and rain, all of which contain water, are in a frequent state of change (surface water evaporates, cloud water precipitates, rainfall infiltrates the ground, etc.). However, the total amount of the earth's water does not change. The circulation and conservation of earth's water is called the "**hydrologic cycle**". The Hydrologic Cycle module has been organized into the following sections:

Sections
Last Update: 07/21/97

The Earth's Water Budget
The distribution of water among the oceans, land and atmosphere.

Evaporation
The transformation of water from a liquid into a gas, a process which humidifies the atmosphere.

Condensation
The transformation of water from a gas into a liquid, and the processes that lead to condensation.

Transport
The movement of water through the atmosphere.

Precipitation
The transfer of water from the atmosphere to land. Rain, snow, hail, sleet, and freezing rain are discussed.

Groundwater
Water located below ground and how it returns to the surface.

Transpiration
Transfer of water to the atmosphere by plants and vegetation.

Runoff
Rivers, lakes, and streams transport water from land to the oceans. Too much rainfall can cause excess runoff, or flooding.

Summary and Example
A brief encapsulation of the hydrologic cycle, plus an example of the hydrologic cycle at work.

Acknowledgments
Those who contributed to the development of this module.

The Earth's Water Budget

storage and fluxes

Water covers 70% of the earth's surface, but it is difficult to comprehend the total amount of water when we only see a small portion of it. The following diagram displays the volumes of water contained on land, in oceans, and in the atmosphere. Arrows indicate the annual exchange of water between these storages.

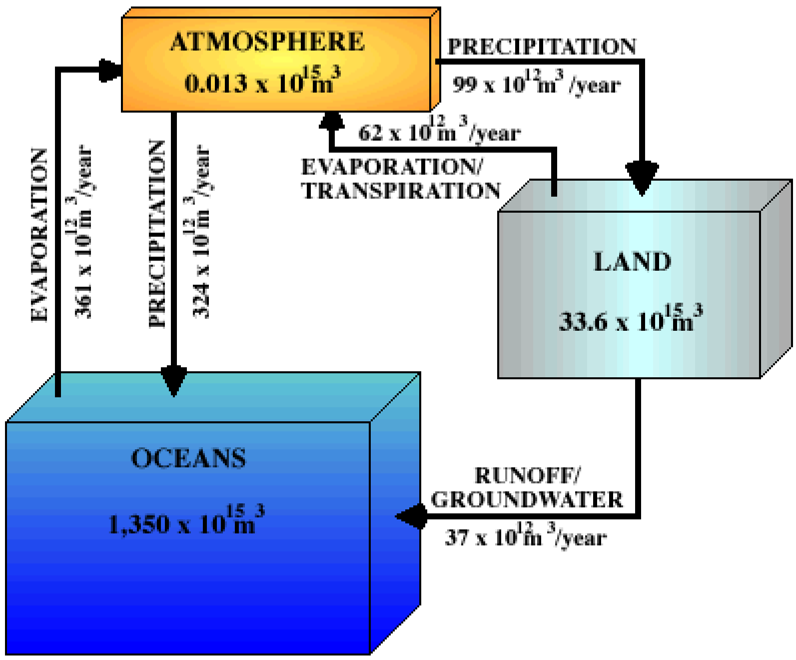


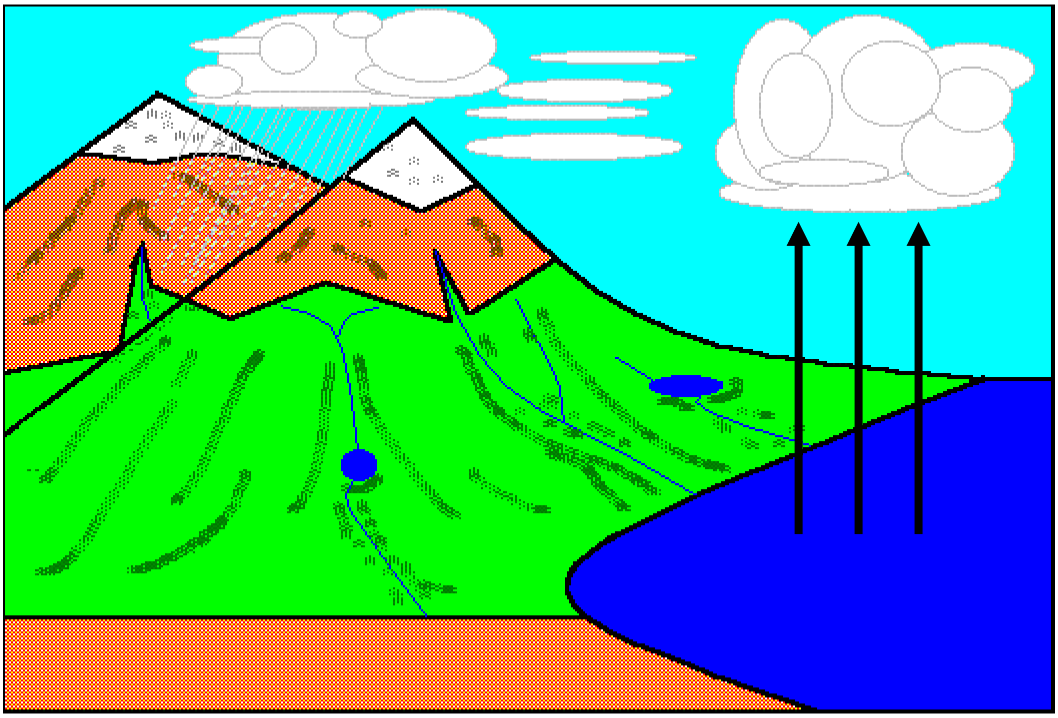
Diagram adapted from: Peixoto and Kettani (1973)

The oceans contain 97.5% of the earth's water, land 2.4%, and the atmosphere holds less than .001%, which may seem surprising because water plays such an important role in weather. The annual precipitation for the earth is more than 30 times the atmosphere's total capacity to hold water. This fact indicates the rapid recycling of water that must occur between the earth's surface and the atmosphere.

To visualize the amount of water contained in these storages, imagine that the entire amount of the earth's annual precipitation fell upon the state Texas. If this was to occur, every square inch of that state would be under 1,841 feet, or 0.3 miles of water! Also, there is enough water in the oceans to fill a five-mile deep container having a base of 7,600 miles on each side.

Evaluation

the conversion of water from a liquid into a gas



Animation by: Bramer

Water is transferred from the surface to the atmosphere through **evaporation**, the process by which water changes from a liquid to a gas.

Approximately 80% of all evaporation is from the oceans, with the remaining 20% coming from inland water and vegetation. Winds transport the evaporated water around the globe, influencing the humidity of the air throughout the world. For example, a typical hot and humid summer day in the Midwestern United States is caused by winds blowing tropical oceanic air northward from the Gulf of Mexico.

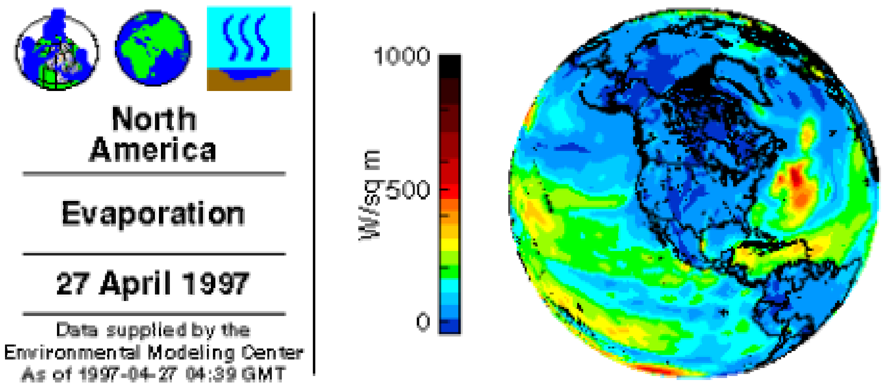
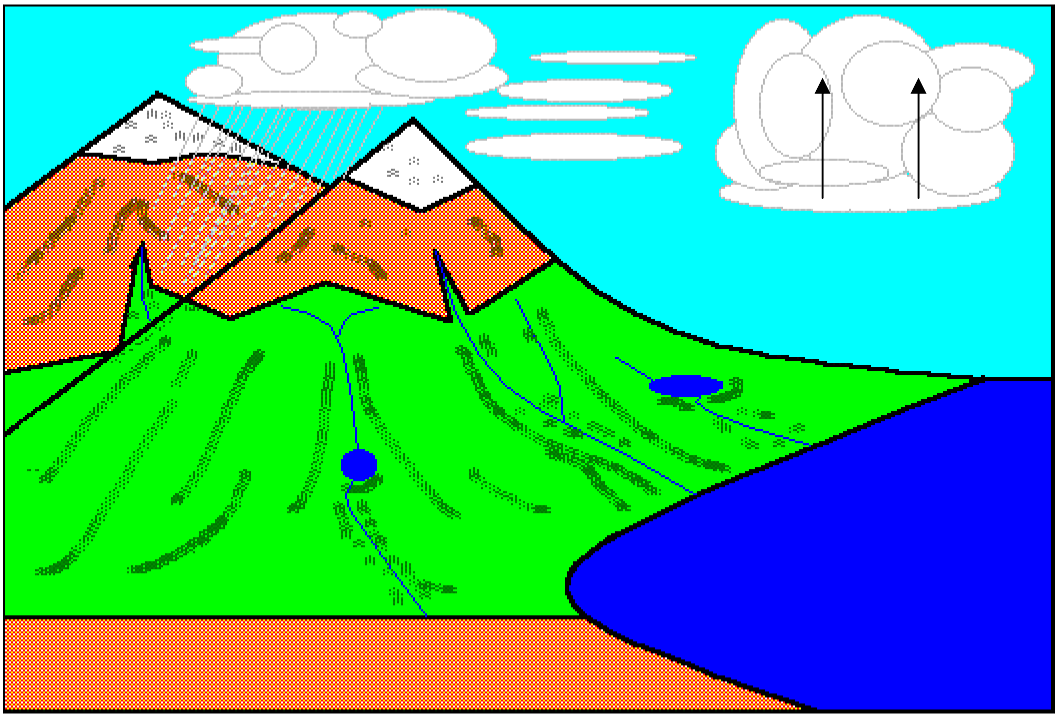


Image by: Globe

Most evaporated water exists as a gas outside of clouds and evaporation is more intense in the presence of warmer temperatures. This is shown in the image above, where the strongest evaporation was occurring over the oceans and near the equator (indicated by shades of red and yellow).

Condensation

the conversion of water from a gas into a liquid



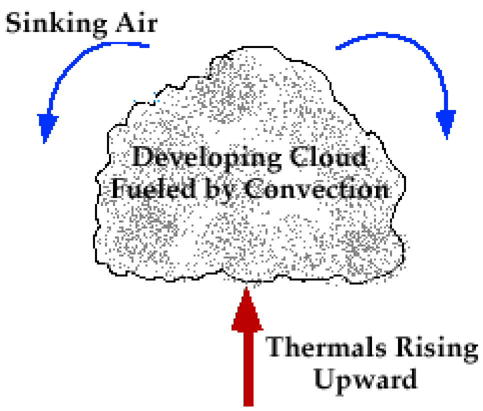
Animation by: Bramer

Condensation is the change of water from its gaseous form (water vapor) into liquid water. Condensation generally occurs in the atmosphere when warm air rises, cools and looses its capacity to hold water vapor. As a result, excess water vapor condenses to form cloud droplets. The upward motions that generate clouds can be produced by convection in unstable air, convergence associated with cyclones, lifting of air by fronts and lifting over elevated topography such as mountains.

Convection

atmospheric motions in the vertical direction

In meteorology, convection refers primarily to atmospheric motions in the vertical direction. As the earth is heated by the sun, different surfaces absorb different amounts of energy and convection may occur where the surface heats up very rapidly. As the surface warms, it heats the overlying air, which gradually becomes less dense than the surrounding air and begins to rise.



The bubble of relatively warm air that rises upward from the surface is called a "thermal".

A simple demonstration of condensation through convection can be performed by placing a pot of water on a heated stove. The burner represents the heating of the earth's surface by the sun, while the water and the air above it represent the atmosphere. As the bottom of the pot (earth's surface) begins to heat the water (lower atmosphere), warmer and less dense water evaporates and rises (thermal) into the drier, colder air above the pot (middle atmosphere). This causes the thermals to cool and water vapor within to condense, forming a small cloud, or steam, that is visible above the pot of heated water.

Photo by: Bramer

This same process occurs in the real atmosphere as the water vapor within rising thermals condenses to form a cloud, as occurred in the example shown above.

Convergence Associated With Cyclones

extra-tropical and tropical cyclones

Both extra-tropical and tropical cyclones, like this hurricane, can cause air to rise. This type of lifting is different from the lifting produced along frontal boundaries.

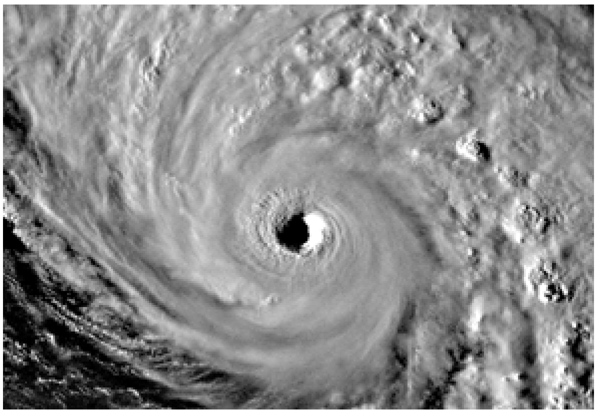
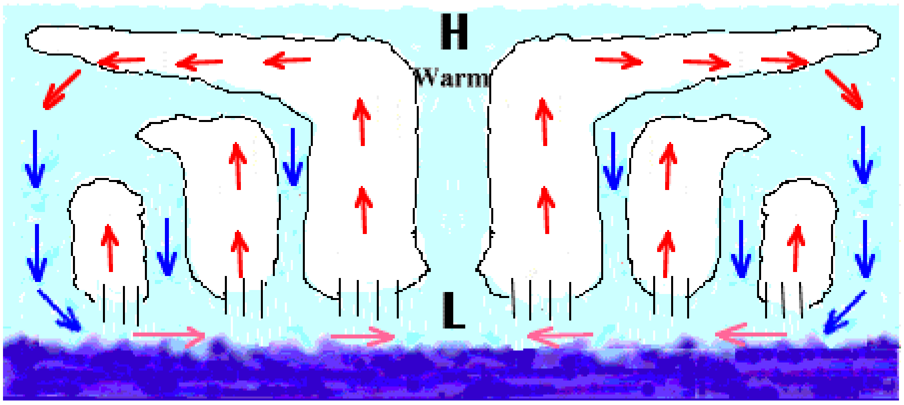


Image by: the GOES Project

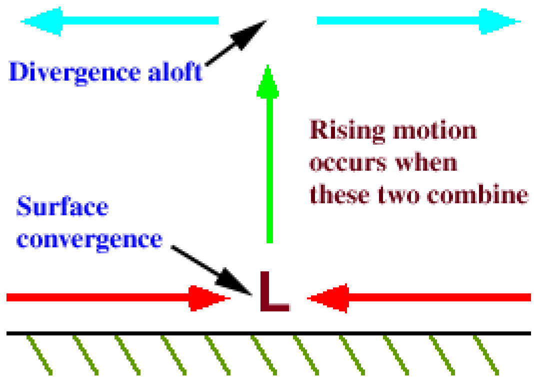
In hurricanes, condensation occurs through a process known as CISK (Convective Instability of the Second Kind). We will demonstrate CISK by referring to the animated cross-section through a mature hurricane given below. In CISK, surface convergence (pink horizontal arrows) causes rising motion around a surface cyclone (labeled as "L"). The air cools as it rises (red vertical arrows) and condensation occurs, which releases latent heat into the atmosphere. This heating causes air to expand, creating an area of high pressure aloft. The force resulting from the established pressure gradient causes air to diverge at upper levels (red horizontal arrows).



Animation by: Shao

Since pressure is a measure of the weight of the air above a unit area, removal of air at upper levels subsequently reduces pressure at the surface. A further reduction in surface pressure leads to increasing convergence (due to an intensified pressure gradient), which further intensifies the rising motion, latent heat release, and so on. Despite the absence of fronts, a tremendous amount of lifting occurs in hurricanes, with intense condensation leading to the development of deep clouds and heavy rainfall.

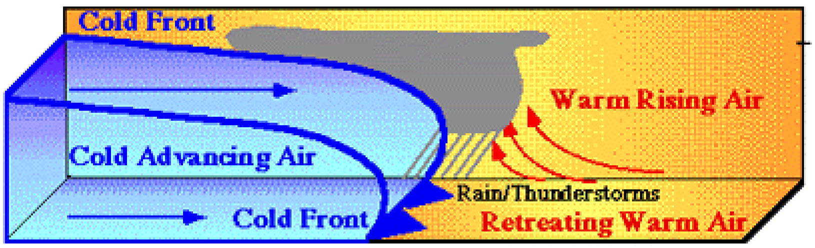
In extra-tropical cyclones, surface winds are deflected by friction towards the center of the low pressure system (red "L" below).



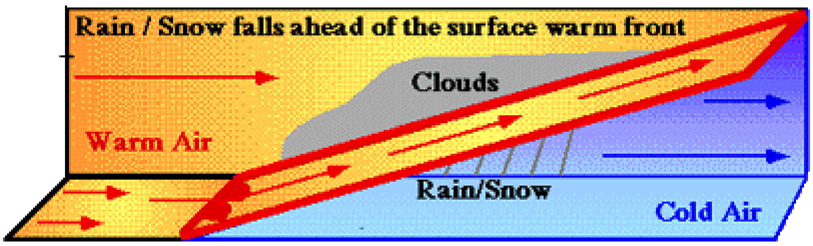
Coupled with divergence aloft, (blue arrows), surface convergence (red arrows) can generate rising motion (green arrow) that leads to the condensation of water vapor.

Fronts
boundaries between air masses

Fronts are boundaries between air masses. Depending on the air masses involved and which way the fronts move, fronts can be either warm, cold, stationary, or occluded.



In the case of a cold front, a colder, denser air mass lifts the warm, moist air ahead of it. As the air rises, it cools and its moisture condenses to produce clouds and precipitation. Due to the steep slope of a cold front, vigorous rising motion is often produced, leading to the development of showers and occasionally severe thunderstorms.

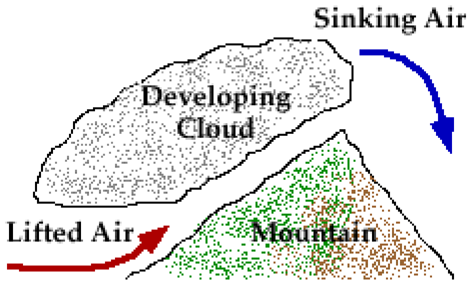


In the case of a warm front, the warm, less dense air rises up and over the colder air ahead of the front. Again, the air cools as it rises and its moisture condenses to produce clouds and precipitation. Warm fronts have a gentler slope and generally move more slowly than cold fronts, so the rising motion along warm fronts is much more gradual. Precipitation that develops in advance of a surface warm front is typically steady and more widespread than precipitation associated with a cold front.

Topography

forced lifting by the surface of the earth

Air is also lifted by the earth itself. When air encounters a mountain range, for example, air is forced to rise up and over the mountains and if enough lifting occurs, water vapor condenses to produce orographic clouds.



In the United States, the prevailing winds are generally from west to east, so most orographic clouds form on the western side of a mountain.

Why do orographic clouds appear to be stationary?

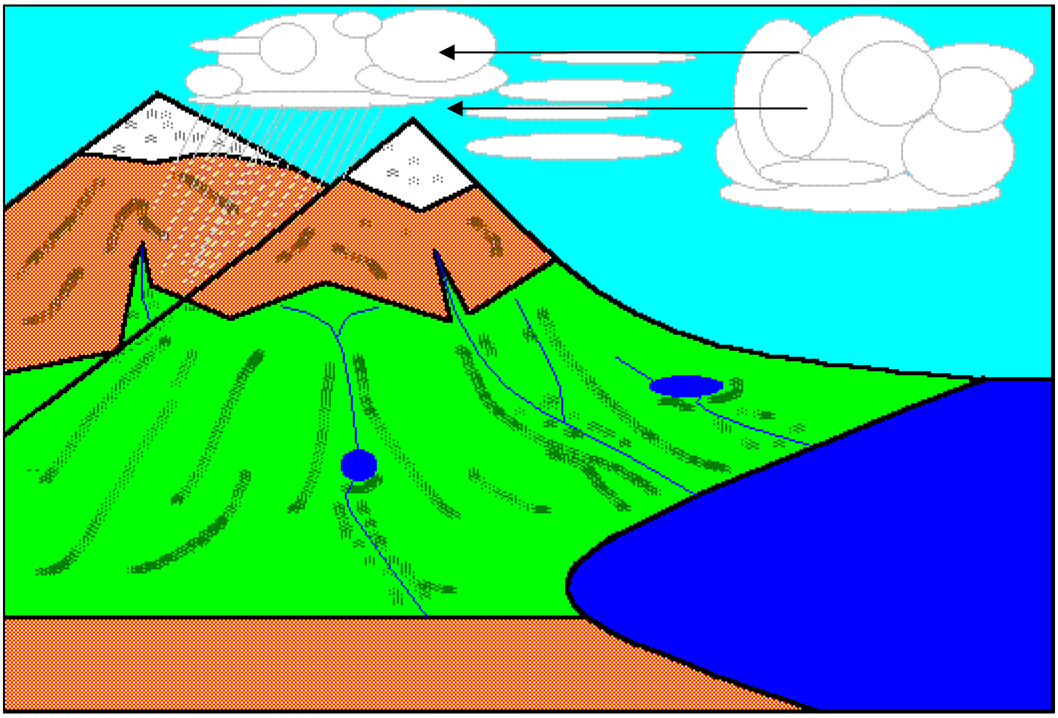
Air rises on a mountain's windward (upwind) side and sinks on the lee (downwind) side. This sinking motion warms the air and causes the cloud to evaporate, destroying the cloud. Therefore, even though the wind blows over the mountain, condensation processes and associated cloud droplets are confined to the windward side. This is why orographic clouds begin on the windward side of the mountain and end near the summit.

Photograph by: Holle

The Rocky and the Sierra-Nevada Mountains are examples of mountain ranges that produce orographic clouds. The large dark cloud in the upper right-hand corner of the picture above and the smaller cloud just above the mountain are both examples of orographic clouds.

Transport

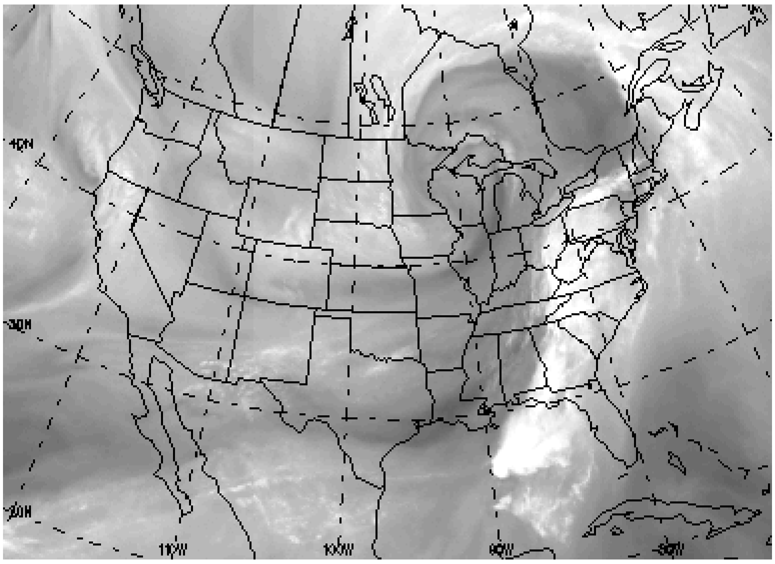
transport of water vapor around the globe



Animation by: Bramer

In the hydrologic cycle, **transport** is the movement of water through the atmosphere, specifically from over the oceans to over land. Some of the earth's moisture transport is visible as clouds, which themselves consist of ice crystals and/or tiny water droplets. Clouds are propelled from one place to another by either the jet stream, surface-based circulations like land and sea breezes, or other mechanisms. However, a typical 1 kilometer thick cloud contains only enough water for a millimeter of rainfall, whereas the amount of moisture in the atmosphere is usually 10-50 times greater.

Most water is transported in the form of water vapor, which is actually the third most abundant gas in the atmosphere. Water vapor may be invisible to us, but not to satellites, which are capable of collecting data about the moisture content of the atmosphere. From this data, visualizations like this water vapor image are generated, providing a visual picture of moisture transport in the atmosphere.

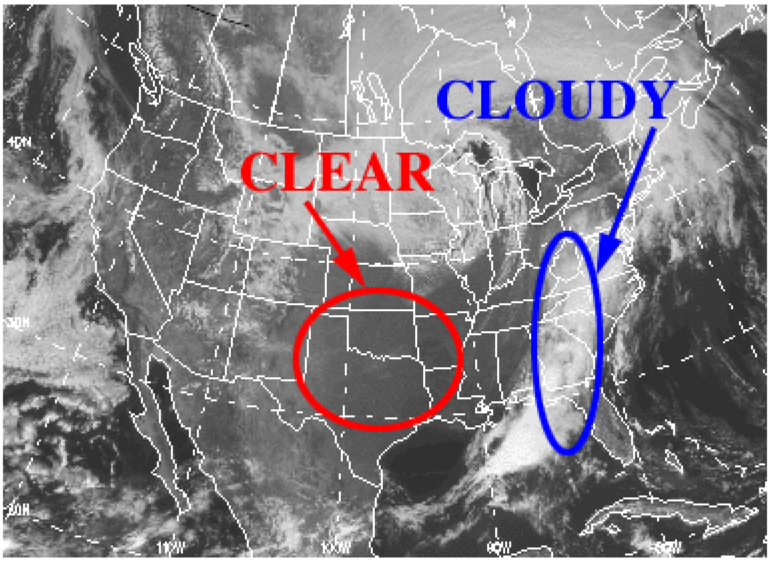


Bright areas indicate higher amounts of moisture and are often associated with clouds. Dark areas indicate less moisture, or relatively drier air. However, moist air does not always contain clouds.

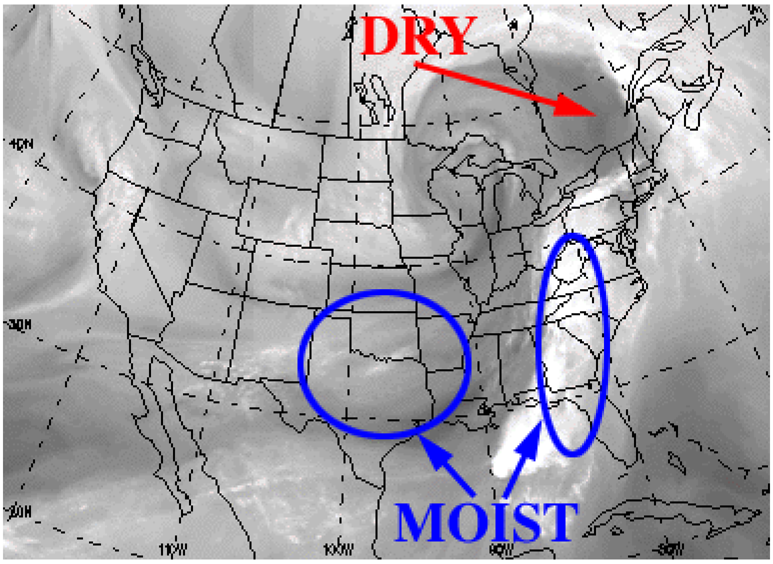
Satellite Images

detecting the presence of water vapor

Clouds are not the only indication of moisture in the atmosphere. In the visible satellite image below, there was considerable cloudiness associated with stormy activity over the the Eastern United States (circled in blue), while clear skies dominated the Southern Plains (circled in red).



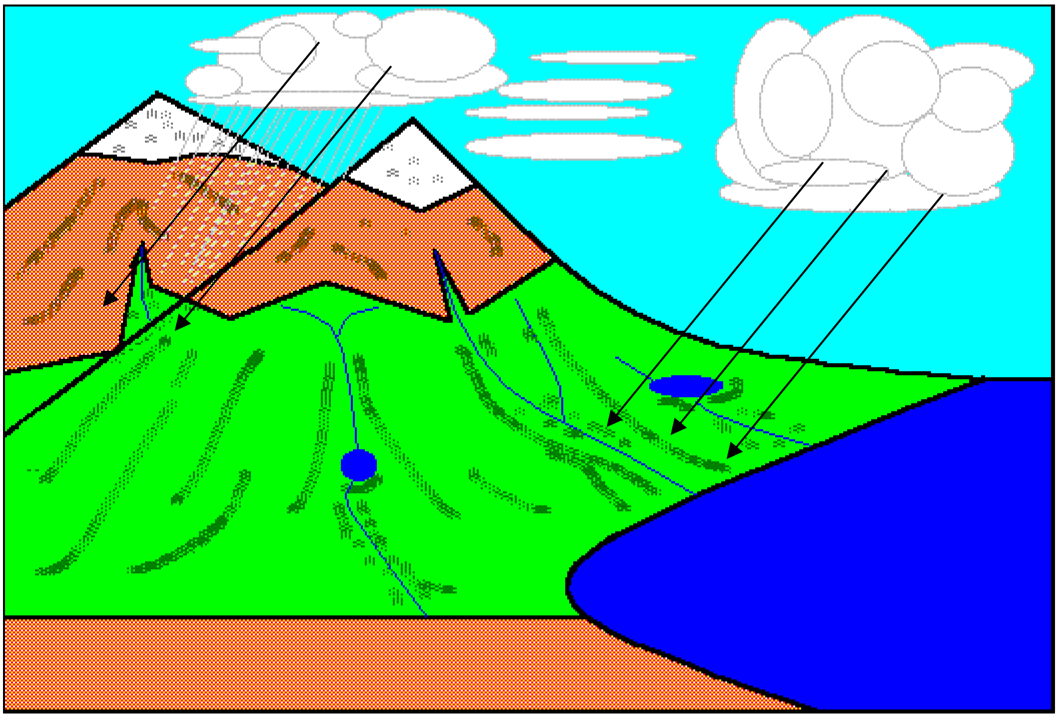
Now compare this image to the water vapor image for the same time. Bright white areas indicate higher amounts of moisture while darker areas indicate lesser amounts. The pronounced white areas in the water vapor image correlate almost exactly with the clouds circled above (in blue). However, the water vapor image indicates relatively high concentrations of moisture across the Southern Plains, while this same region appears cloud-free in the visible image. This is an example of water being transported through the atmosphere in its vapor form.



The area in the Southern Plains is not as bright as the area of clouds located in the Eastern U.S. because the clouds contain more water. Also observe that there is no black on this image, signifying the presence of at least small amounts of water vapor everywhere!

Precipitation

transfer of water from the atmosphere back to earth



Animation by: Bramer

Precipitation is the primary mechanism for transporting water from the atmosphere to the surface of the earth. There are several forms of precipitation, the most common of which for the United States is rain. Other forms of precipitation include; hail, snow, sleet, and freezing rain. A well developed extra-tropical cyclone could be responsible for the generation of any or all of these forms of precipitation.

Amounts of precipitation can vary by location. For example, deserts like this one in Nevada, average less than an inch of total precipitation per year.

Photograph by: Hall

The agricultural Midwest, however, receives approximately 15 inches per year, while tropical rain forests like this one in Hawaii, can receive more than 100 inches of precipitation per year!

Photograph by: Bramer

Amounts of precipitation also vary from year to year. In 1988, an intense drought gripped the Midwestern United States, disrupting agriculture because there was not enough rain to sustain crops. Five years later in 1993, the same area was subjected to severe flooding, greatly reducing the annual harvest because there was too much water for crops to grow.

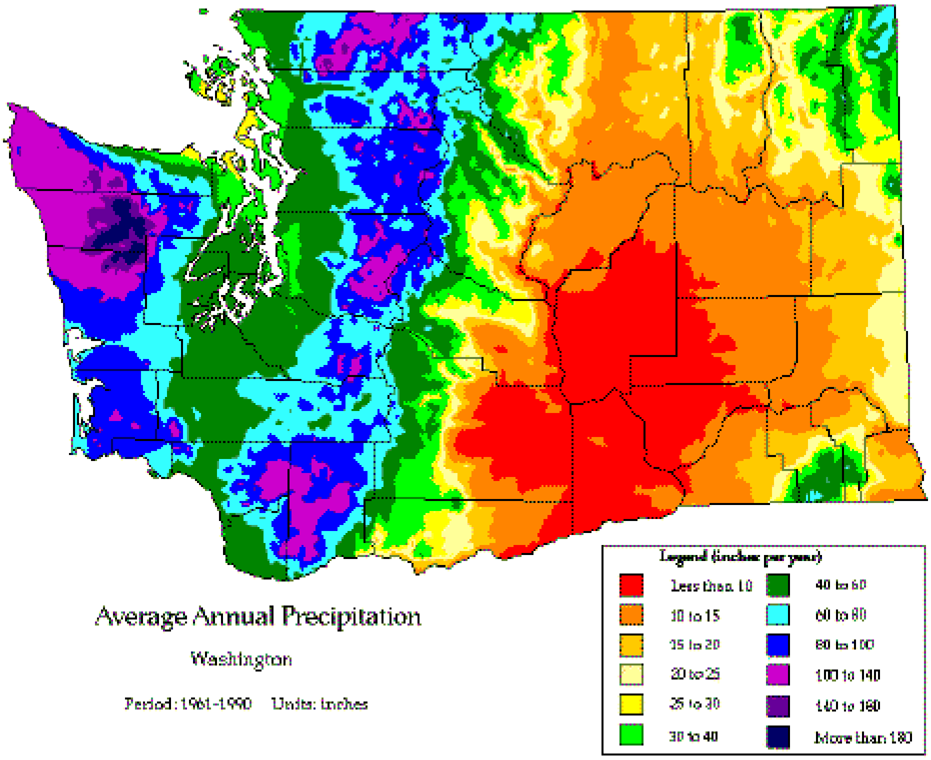
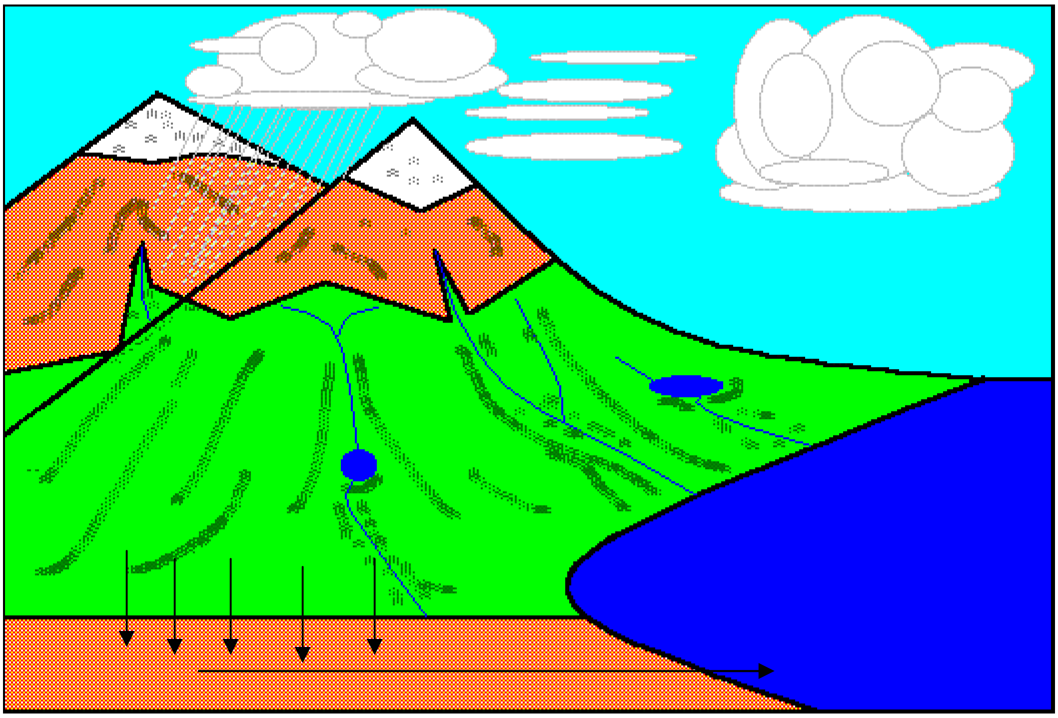


Image by: Northwest River Forecast Center

A good example of the geographical variability of precipitation is shown here in a plot of average annual precipitation for the state of Washington. Within a distance of 250 miles, annual precipitation totals change from more that 180 inches per year (deep purple) to less than 10 inches per year (bright red)! This distribution is a direct result of the topography of the land. The high precipitation totals are located on the western side of the Cascade mountains, while the extremely low precipitation totals are on the eastern, or lee side of the mountain range.

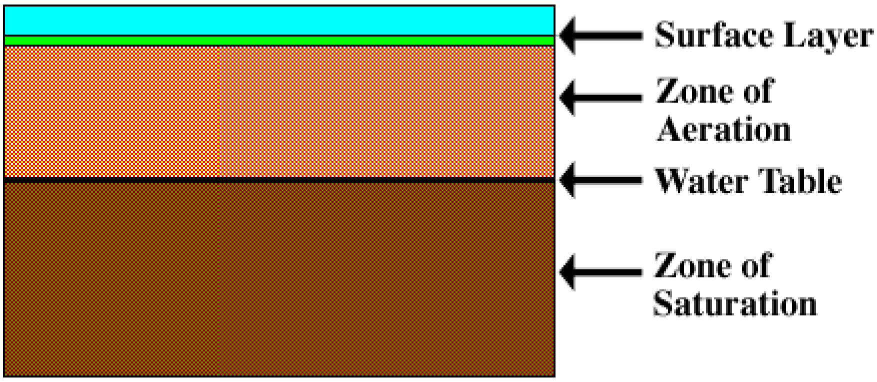
Groundwater

water that has penetrated the earth's surface

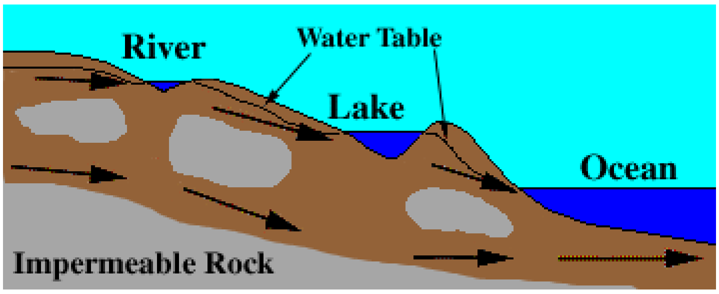


Animation by: Bramer

Groundwater is all the water that has penetrated the earth's surface and is found in one of two soil layers. The one nearest the surface is the "**zone of aeration**", where gaps between soil are filled with both air and water. Below this layer is the "**zone of saturation**", where the gaps are filled with water. The **water table** is the boundary between these two layers. As the amount of groundwater water increases or decreases, the water table rises or falls accordingly. When the entire area below the ground is saturated, flooding occurs because all subsequent precipitation is forced to remain on the surface.



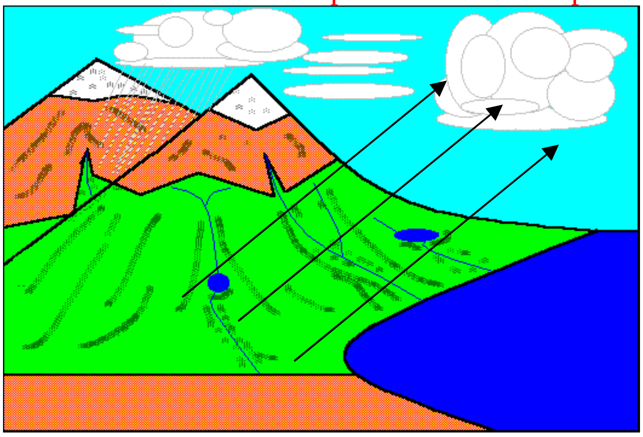
The amount of water that can be held in the soil is called "**porosity**". The rate at which water flows through the soil is its "**permeability**". Different surfaces hold different amounts of water and absorb water at different rates. Surface permeability is extremely important for hydrologists to monitor because as a surface becomes less permeable, an increasing amount of water remains on the surface, creating a greater potential for flooding. Flooding is very common during winter and early spring because the frozen ground has no permeability, causing most rainwater and meltwater to become runoff.



Water that infiltrates the soil flows downward until it encounters impermeable rock (shown in gray), and then travels laterally. The locations where water moves laterally are called "aquifers". Groundwater returns to the surface through these aquifers (arrows), which empty into lakes, rivers, and the oceans. Under special circumstances, groundwater can even flow upward in artesian wells. The flow of groundwater is much slower than runoff, with speeds usually measured in centimeters per day, meters per year, or even centimeters per year.

Transpiration

transfer of water from plants to the atmosphere



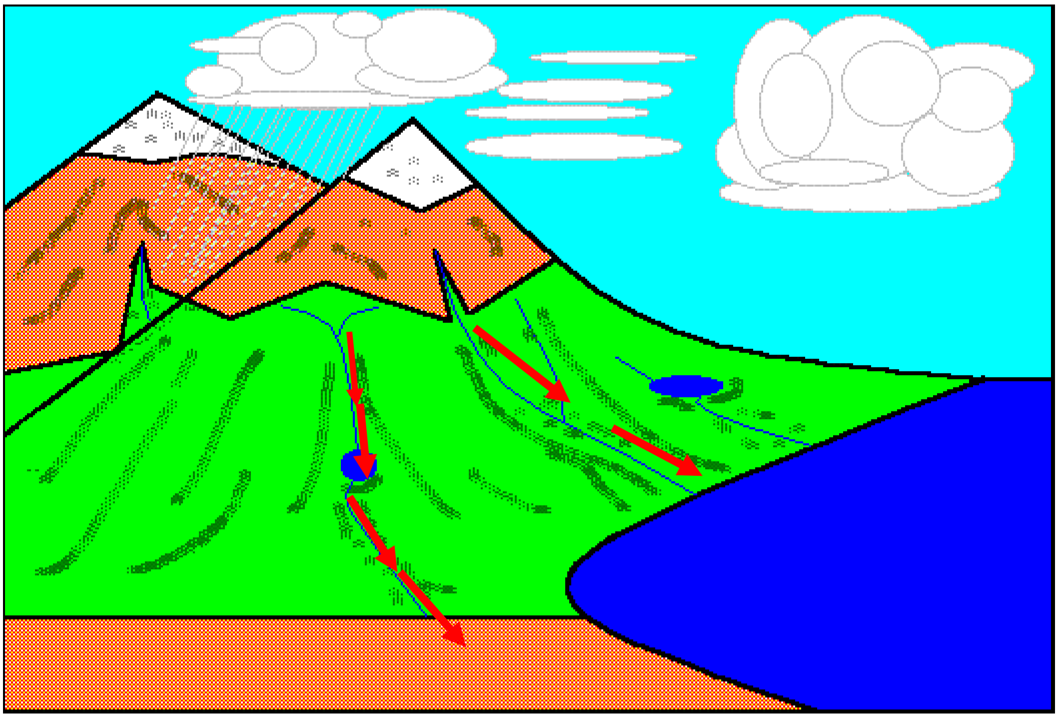
Animation by: Bramer

Transpiration is the evaporation of water into the atmosphere from the leaves and stems of plants. Plants absorb soilwater through their roots and this water can originate from deep in the soil. (For example, corn plants have roots that are 2.5 meters deep, while some desert plants have roots that extend 20 meters into the ground). Plants pump the water up from the soil to deliver nutrients to their leaves. This pumping is driven by the evaporation of water through small pores called "stomates", which are found on the undersides of leaves. Transpiration accounts for approximately 10% of all evaporating water.

Photo by: Bramer

Runoff

transfer of landwater to the oceans



Animation by: Bramer

Runoff is the movement of landwater to the oceans, chiefly in the form of rivers, lakes, and streams. Runoff consists of precipitation that neither evaporates, transpires nor penetrates the surface to become groundwater. Even the smallest streams are connected to larger rivers that carry billions of gallons of water into oceans worldwide.

Excess runoff can lead to flooding, which occurs when there is too much precipitation. Two recent events in the United States have caused major flooding.

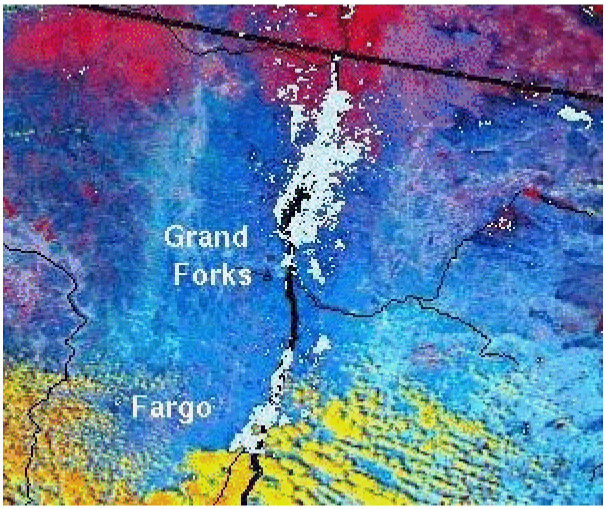


Image by: National Operational Hydrologic Remote Sensing Center

Northern Plains Flooding
March-May 1997

In early spring of 1997, the Northern Plains endured devastating floods. Towns along the Red River like Grand Forks, North Dakota were shut down due to flooding that completely paralyzed the city, leaving entire downtown areas underwater. Floodwater is shown here in white while unmelted snow is shaded red.

During the Fall of 1996, towns along the Red River received record amounts of rain. In the winter, a cold air outbreak froze the water before it could runoff, and the record rainfall was followed up by record amounts of snow. Snow continued to pile up during the long winter and once temperatures finally warmed up, the melting began. However, not only did the snow from the winter melt, but also the frozen rainwater from the previous Fall season. As it turned out, there was too much water for local streams and the Red River to handle, and consequently, the entire area flooded.

River levels rose to as much as 27 feet above flood stage! Large pieces of floating ice blocked the flow of the river, forcing it out of its banks and into nearby residences and businesses.

Photo by: Paul Thomson

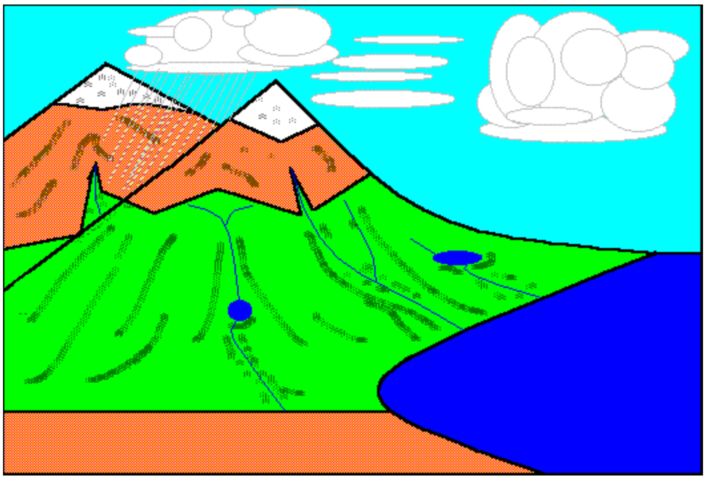
Midwest Flooding
June-August 1993

During the summer of 1993, over 20 inches of rain fell upon many locations in the Midwest, with localized amounts exceeding 33 inches. The excessive amounts of rain severely affected shipping, agriculture, and human lives. This photo was taken in Ames, Iowa when the flood waters reached their maximum.

An analysis of atmospheric conditions for the summer of 1993 showed a stationary high pressure system, also known as the Bermuda High, centered much closer to the United States than normally observed for that time of year. This allowed unusual amounts of warm moist air to be transported northward from the Gulf of Mexico and into the central portion of the country. This moisture-rich air fueled showers and thunderstorms that brought significant amounts of rain to many regions of the Midwest. Precipitation totals were so large and of such extended duration that normal means of surface water removal (transpiration, groundwater, and runoff) were inadequate. Rivers doubled, even quadrupled in size, as nearby towns succumbed to the floodwaters.

A Summary of the Hydrologic Cycle

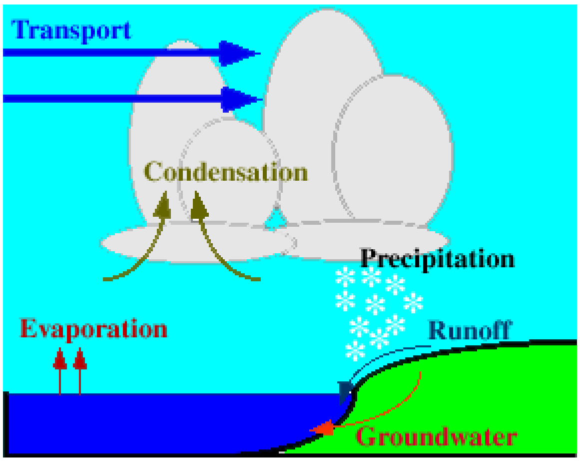
bringing all the pieces together



Animation by: Bramer
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hyd/smry.rxml

The hydrologic cycle begins with the evaporation of water from the surface of the ocean. As moist air is lifted, it cools and water vapor condenses to form clouds. Moisture is transported around the globe until it returns to the surface as precipitation. Once the water reaches the ground, one of two processes may occur; 1) some of the water may evaporate back into the atmosphere or 2) the water may penetrate the surface and become groundwater. Groundwater either seeps its way to into the oceans, rivers, and streams, or is released back into the atmosphere through transpiration. The balance of water that remains on the earth's surface is runoff, which empties into lakes, rivers and streams and is carried back to the oceans, where the cycle begins again.

Lake effect snowfall is good example of the hydrologic cycle at work. Below is a vertical cross-section summarizing the processes of the hydrologic cycle that contribute to the production of lake effect snow. The cycle begins as cold winds (horizontal blue arrows) blow across a large lake, a phenomena that occurs frequently in the late fall and winter months around the Great Lakes.



Evaporation of warm surface water increases the amount of moisture in the colder, drier air flowing immediately above the lake surface. With continued evaporation, water vapor in the cold air condenses to form ice-crystal clouds, which are transported toward shore.

By the time these clouds reach the shoreline, they are filled with snowflakes too large to remain suspended in the air and consequently, they fall along the shoreline as precipitation. The intensity of lake effect snowfall can be enhanced by additional lifting due to the topographical features (hills) along the shoreline. Once the snow begins to melt, the water is either absorbed by the ground and becomes groundwater, or goes returns back to the lake as runoff.

Lake effect snow events can produce tremendous amounts of snow. One such event was the Cleveland, Ohio Veteran's Day Snowstorm from November of 1996, where local storm snowfall totals exceeded 50 inches over two to three days.

Graphic by: Yiqi Shao

Rainbows, sunsets and halos; a spectacular display of colors and visuals in the sky called "atmospheric optics". As sunlight (or moonlight) enters the atmosphere, it is either absorbed, reflected, scattered, refracted or diffracted by atmospheric particles or air molecules. These processes, individually or in combination, are responsible for producing most optical effects. This module investigates these particle-light interactions and the assortment of optical effects they produce. The Light and Optics module has been organized into the following sections:

Sections
Last Update:
08/26/99

Mechanisms
Particle/Molecule-light interactions responsible for creating optical effects. These interactions include: reflection, scattering, refraction and diffraction.

Air, Dust, Haze
Optical effects resulting from the interaction of light with air, dust and haze particles. These effects include: crepuscular rays, blue skies, blue haze and sunsets.

Ice Crystals
Optical effects resulting from the interaction of light with ice crystals. These effects include: sundogs, sun pillars and halos.

Water Droplets
Optical effects resulting from the interaction of light with water droplets. These effects include: cloud iridescence, rainbows and a silver lining along the edge of clouds.

Acknowledgments
Those who contributed to the development of this module.

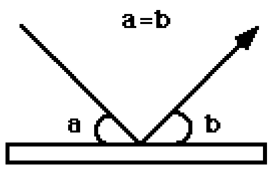
The type of optical effect that results greatly depends upon the type of particles the light encounters and on the wavelength of the light. For this reason, the optical effects discussed in this module have been grouped according to the following classifications of atmospheric particles: air, dust and haze, ice crystals, and water droplets.

The navigation menu (left) for this module is called "Light, Optics" and the menu items are arranged in a recommended sequence, beginning with this introduction. In addition, this entire web server is accessible in both "graphics" and "text"-based modes, a feature controlled by the blue "User Interface" menu (located beneath the black navigation menus). More information about the user interface options, the navigation system, or WW2010 in general is accessible from About This Server.

Reflection of Light

light bouncing off a surface

Light is said to be reflected when the angle at which light initially strikes a surface is equal to the angle at which light bounces off the same surface.

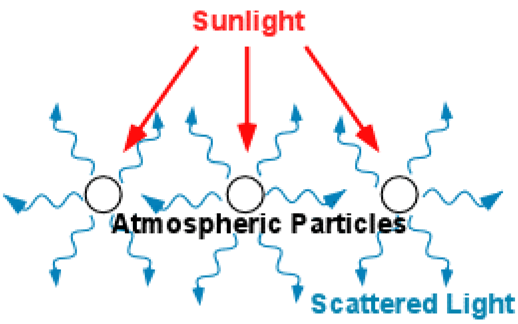


In the diagram above, light strikes a surface at an angle "a" and leaves at an angle "b" (relative to that surface). Because angle "a" is equal to angle "b", this is an example of reflected light.

Scattering of Light

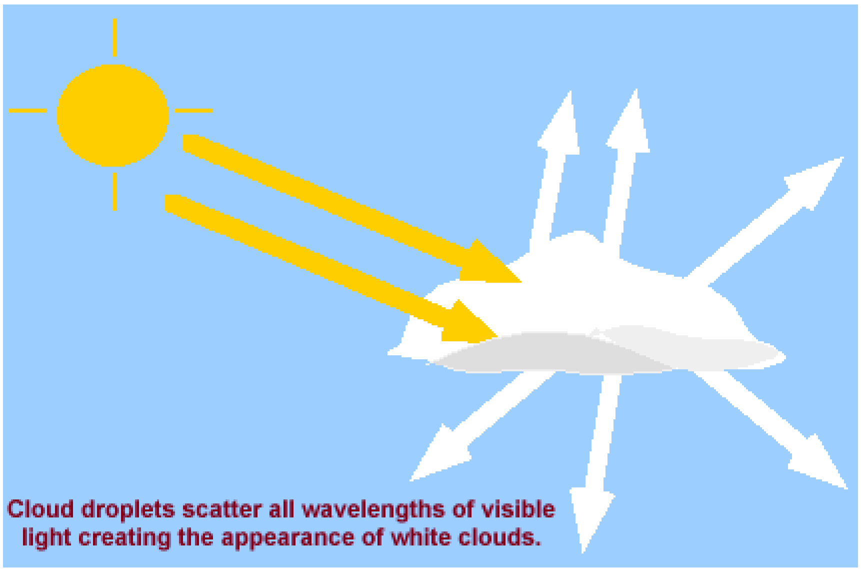
by small particles and molecules in the atmosphere

Different from reflection, where radiation is deflected in one direction, some particles and molecules found in the atmosphere have the ability to scatter solar radiation in all directions. The particles/molecules which scatter light are called scatterers and can also include particulates made by human industry.



Selective scattering (or Rayleigh scattering) occurs when certain particles are more effective at scattering a particular wavelength of light. Air molecules, like oxygen and nitrogen for example, are small in size and thus more effective at scattering shorter wavelengths of light (blue and violet). The selective scattering by air molecules is responsible for producing our blue skies on a clear sunny day.

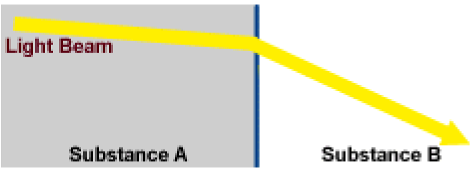
Another type of scattering (called Mie Scattering) is responsible for the white appearance of clouds. Cloud droplets with a diameter of 20 micrometers or so are large enough to scatter all visible wavelengths more or less equally. This means that almost all of the light which enters clouds will be scattered. Because all wavelengths are scattered, clouds appear to be white.



When clouds become very deep, less and less of the incoming solar radiation makes it through to the bottom of the cloud, which gives these clouds a darker appearance.

Refraction of Light

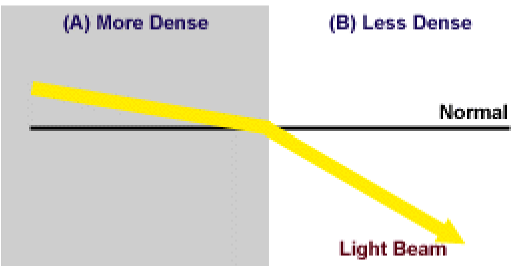
as it passes from more dense to less dense mediums



The bending of light as it passes from one medium to another is called refraction.

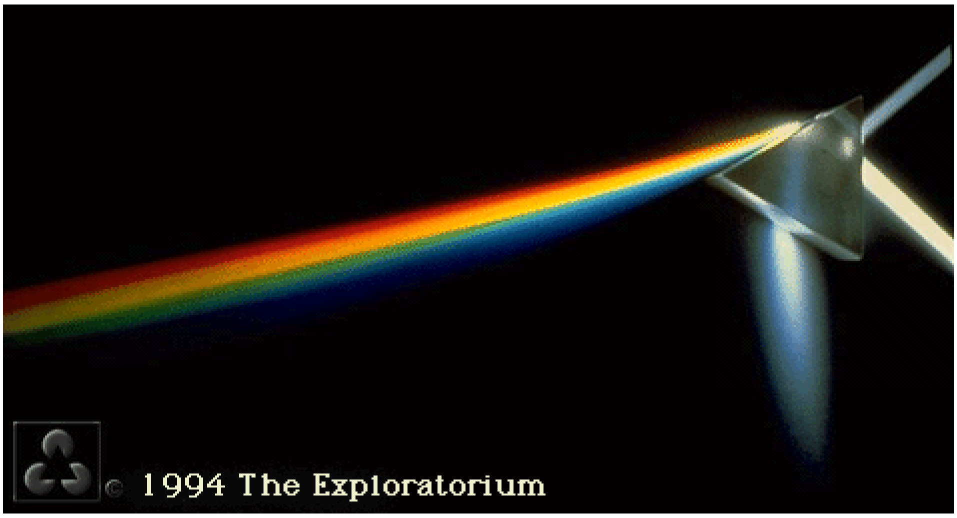
The angle and wavelength at which the light enters a substance and the density of that substance determine how much the light is refracted. The refraction of light by atmospheric particles can result in a number of beautiful optical effects like halos, which are produced when sunlight (or moonlight) is refracted by the pencil-shaped ice crystals of cirrostratus clouds.

When light passes from a more dense to a less dense substance, (for example passing from water into air), the light is refracted (or bent) away from the normal.



The normal is a line perpendicular (forming a 90 degree angle) to the boundary between the two substances. The bending occurs because light travels more slowly in a denser medium.

Another example of refraction is the dispersion of white light into its individual colors by a glass prism. As visible light exits the prism, it is refracted and separated into a magnificent display of colors.



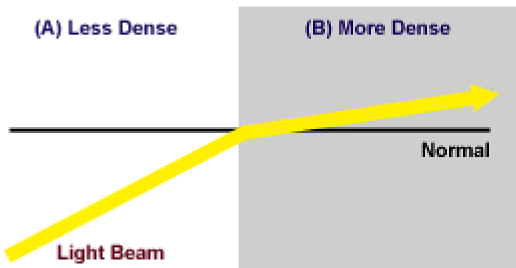
Photograph by: Susan Schwartzenberg (c)1997, The Exploratorium

Each color from the original beam of light has its own particular wavelength (or color) and each wavelength is slowed differently by the glass. The amount of refraction increases as the wavelength of light decreases. Shorter wavelengths of light (violet and blue) are slowed more and consequently experience more bending than do the longer wavelengths (orange and red).

Refraction of Light

as it passes from less dense to more dense mediums

When light passes from a less dense to a more dense substance, (for example passing from air into water), the light is refracted (or bent) towards the normal.



The normal is a line perpendicular (forming a 90 degree angle) to the boundary between the two substances. The bending occurs because light travels more slowly in a denser medium.

A demonstration of refraction can be conducted at home in a dark room. All that is needed is a flashlight, a clear glass filled with water and a small mirror.

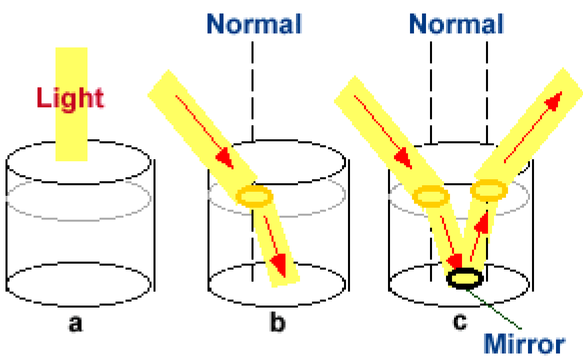


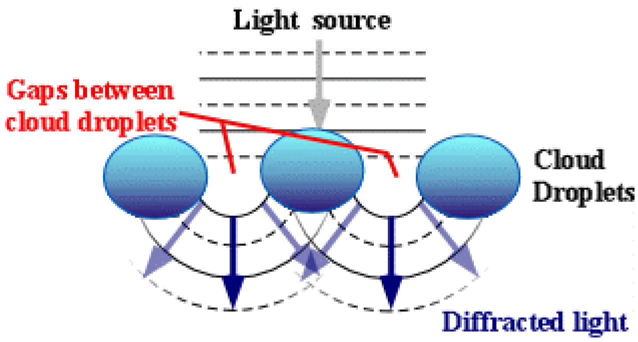
Figure adapted from Ahrens, 1994

- **Figure (a):** Shine the light directly into the glass. If the light strikes the water straight on (or parallel to the normal), no bending occurs and it simply passes directly into the water undisturbed, leaving only a straight beam of light all the way to the bottom of the glass.
- **Figure (b):** Shine the light into the glass at an angle. As the light enters the water, it is refracted. Since the light is passing from air (less dense) into water (more dense), it is bent towards the normal. The beam of light would appear to bend at the surface of the water.
- **Figure (c):** Place a mirror at the bottom of the glass of water and again shine the light into the glass of water at an angle. As light initially enters the water, it is refracted as in figure (b) and then reflected off the mirror (at the bottom of the glass). Upon exiting the water, the light is bent away from the normal as it passes from water (more dense) and into air (less dense). The light would leave the flashlight, bend at the surface of the water, reflect off the mirror at the bottom of the glass and move towards the surface, where it would bend outward at the same angle it bent in on the way in.

Diffraction of Light

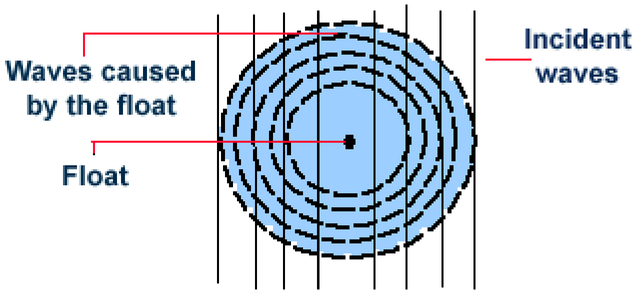
light bending around an object

Diffraction is the slight bending of light as it passes around the edge of an object. The amount of bending depends on the relative size of the wavelength of light to the size of the opening. If the opening is much larger than the light's wavelength, the bending will be almost unnoticeable. However, if the two are closer in size or equal, the amount of bending is considerable, and easily seen with the naked eye.



In the atmosphere, diffracted light is actually bent around atmospheric particles -- most commonly, the atmospheric particles are tiny water droplets found in clouds. Diffracted light can produce fringes of light, dark or colored bands. An optical effect that results from the diffraction of light is the silver lining sometimes found around the edges of clouds or coronas surrounding the sun or moon. The illustration above shows how light (from either the sun or the moon) is bent around small droplets in the cloud.

Optical effects resulting from diffraction are produced through the interference of light waves. To visualize this, imagine light waves as water waves. If water waves were incident upon a float residing on the water surface, the float would bounce up and down in response to the incident waves, producing waves of its own. As these waves spread outward in all directions from the float, they interact with other water waves. If the crests of two waves combine, an amplified wave is produced (constructive interference). However, if a crest of one wave and a trough of another wave combine, they cancel each other out to produce no vertical displacement (destructive interference).



This concept also applies to light waves. When sunlight (or moonlight) encounters a cloud droplet, light waves are altered and interact with one another in a similar manner as the water waves described above. If there is constructive interference, (the crests of two light waves combining), the light will appear brighter. If there is destructive interference, (the trough of one light wave meeting the crest of another), the light will either appear darker or disappear entirely.

Crepuscular Rays

sun rays converging on the horizon

Crepuscular rays occur when objects such as mountain peaks or clouds partially shadow the sun's rays. The name crepuscular means "relating to twilight" and these rays are observed at sunrise and sunset. Crepuscular rays appear to diverge outward from the setting sun, and are visible only when the atmosphere contains enough haze or dust particles so that sunlight in unshadowed areas can be scattered toward the observer.

Photograph by: Holle

The light rays are actually parallel, but appear to converge to the sun due to "perspective", the same visual effect that makes parallel railroad tracks appear to converge in the distance. Crepuscular rays are often red or yellow in appearance because blue light from the sun is selectively scattered out of the beam by air molecules.

Light rays scattered by dust and haze occasionally appear to converge toward the "antisolar" point, (the location on the horizon opposite the point where the sun is setting). These rays, called anti-crepuscular rays, originate at the sun, cross over the sky to the opposite horizon, and appear to converge toward the antisolar point because of perspective.

Photograph by: Mckee

In the photo above, the sun is near the horizon behind the observer and sunlight is reflecting off the small cloud in the top right corner of the picture. Mountains and clouds behind the observer are responsible for the shadows in between.

Blue Skies and Blue Haze

resulting from selective scattering by air molecules

Blue skies are produced as shorter wavelengths of the incoming visible light (violet and blue) are selectively scattered by small molecules of oxygen and nitrogen -- which are much smaller than the wavelength of the light. The violet and blue light has been scattered over and over by the molecules all throughout the atmosphere, so our eyes register it as blue light coming from all directions, giving the sky its blue appearance.

Photograph by: Holle

Blue haze is a phenomenon commonly observed in the Smoky Mountains of eastern Tennessee and the Blue Ridge Mountains of Virginia.

Photograph by: Young

As tiny hydrocarbon particles released by vegetation chemically react with ozone molecules, they produce particles that selectively scatter blue light, giving the mountains their blue appearance.

Sunsets

appear in a variety of colors

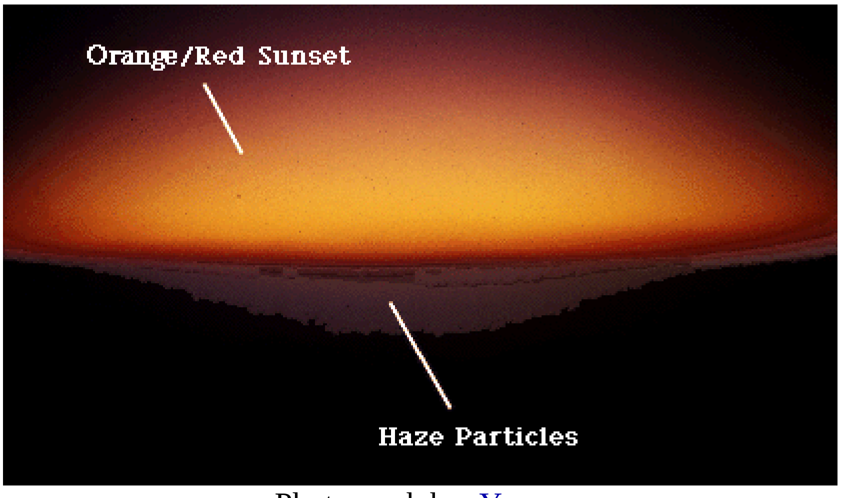
When the sun is high in the sky, it generally appears white because all wavelengths of visible light reach an observer's eyes with almost equal intensity. As the sun sinks toward the horizon, sunlight enters the atmosphere at a much lower angle and consequently must pass through much more atmosphere before being seen by an observer. Air molecules scatter away the shorter wavelengths of light (violet and blue) and the only light which penetrates through the atmosphere are the longer wavelengths of light (yellow, orange and red) which produce colorful sunsets. Because of the refraction of sunlight by the atmosphere itself, the sun will appear to be higher in the sky than it actually is. The combination of refraction and scattering of sunlight by atmospheric particles is responsible for producing twilight, the brightness in the sky we observe even though the sun is below the horizon.

Photograph by: Holle

The size and concentration of atmospheric particles in the path of incoming sunlight determine the type of sunset observed. When sunlight encounters very few particles in the atmosphere, most wavelengths of light reach the observer's eyes with almost equal intensity. The reduced scattering produces the white or yellow sunsets commonly observed in the Rocky Mountains, where the atmosphere typically contains fewer dust and assorted particles.

Photograph by: Holle

As incoming sunlight passes through a more dense atmosphere, shorter wavelengths of light (violet and blue) are efficiently scattered away by particles suspended in the atmosphere. This allows predominantly yellow and red wavelengths of light to reach the observer's eyes, producing a yellowish-red sunset.



Photograph by: Young

When there is a high concentration of particles in the atmosphere that are slightly larger than air molecules (like smoke, dust, and pollutants), shorter and intermediate wavelengths of light (violet, blue and yellow) are scattered away. Therefore, only the longer wavelengths (orange and red) reach the observer's eyes, giving the sun a orange-red appearance.

Photograph by: Holle

When incoming sunlight encounters a heavy concentration of particles in the atmosphere, the shorter wavelengths of light (violet and blue) are scattered away, resulting in a red sunset. Red sunsets are often observed from a beach because of the high concentration of salt particles suspended in the air over the oceans. These particles effectively scatter shorter wavelengths of light, producing red sunsets. Dust and ash particles injected into the atmosphere by volcanic eruptions can also cause red sunsets.

22 Degree Halo

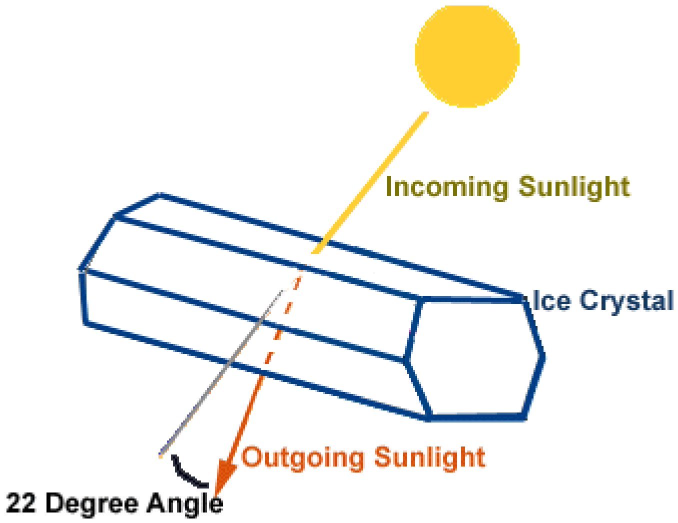
a ring of light 22 degrees from the sun or moon

A halo is a ring of light surrounding the sun or moon. Most halos appear as bright white rings but in some instances, the dispersion of light as it passes through ice crystals found in upper level cirrus clouds can cause a halo to have color.

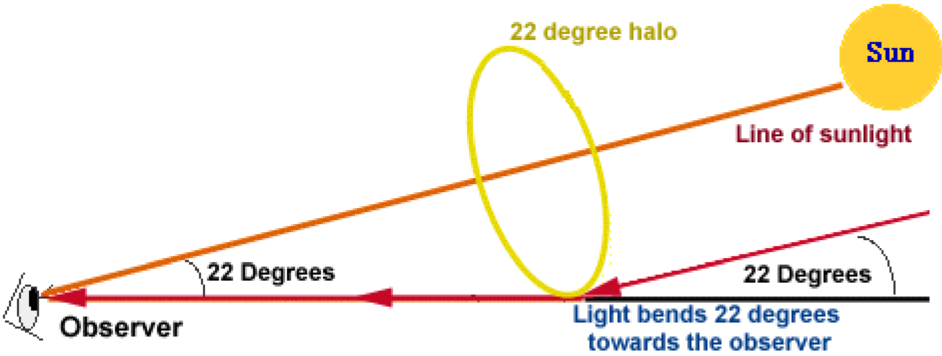
Photograph by: Rauber

Halos form when light from the sun or moon is refracted by ice crystals associated with thin, high-level clouds (like cirrostratus clouds). A 22 degree halo is a ring of light 22 degrees from the sun (or moon) and is the most common type of halo observed and is formed by hexagonal ice crystals with diameters less than 20.5 micrometers.

Light undergoes two refractions as it passes through an ice crystal and the amount of bending that occurs depends upon the ice crystal's diameter.



A 22 degree halo develops when light enters one side of a columnar ice crystal and exits through another side. The light is refracted when it enters the ice crystal and once again when it leaves the ice crystal.



The two refractions bend the light by 22 degrees from its original direction, producing a ring of light observed at 22 degrees from the sun or moon.

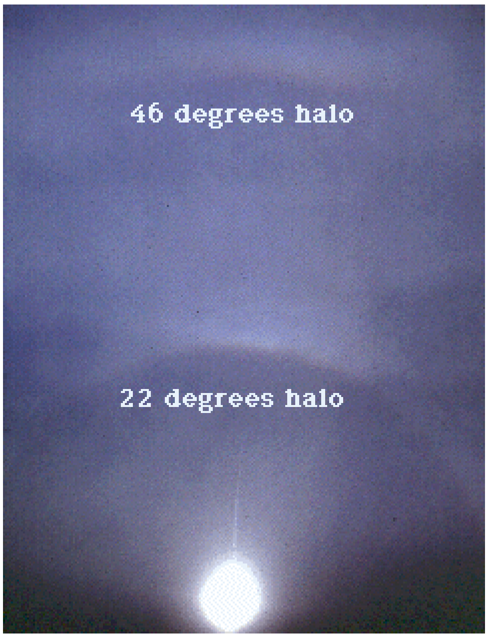
Photograph by: Knupp

A tangent arc is a patch of bright light that is occasionally observed along a halo. This occurs when sunlight is refracted by falling hexagonal "pencil-shaped" ice crystals whose long axes are oriented horizontally.

46 Degree Halo

a ring of light 46 degrees from the sun or moon

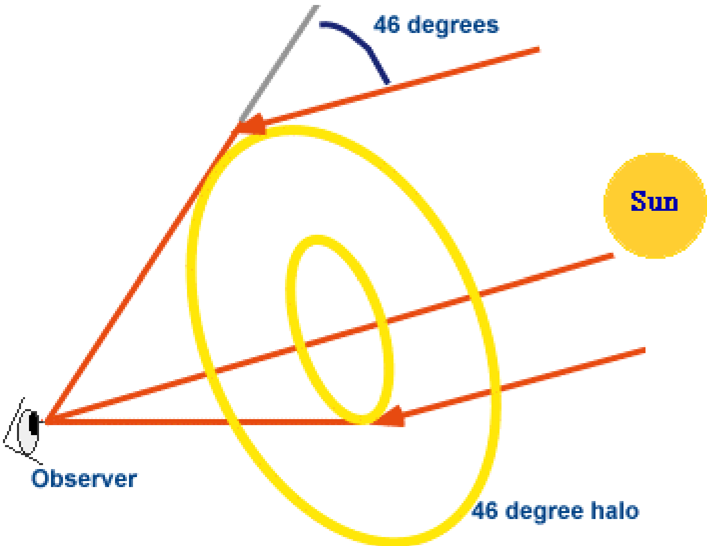
A 46 degree halo is a ring of light observed 46 degrees from the sun or moon. Although they are less common than 22 degree halos, the process by which they form is similar.



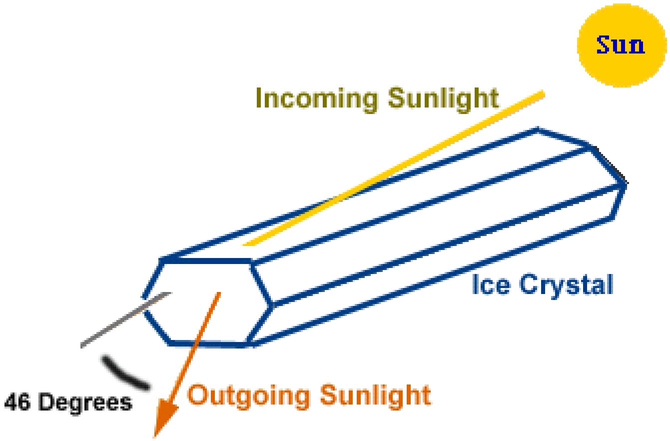
Photograph by: Rauber

What determines if a 46 degree halo or a 22 degree halo develops is the path of the light as it passes through hexagonal ice crystals. A 22 degree halo results from "in one side, out another side"; a 46 degree halo from "in one side, out the bottom".

The incoming light passes through ice crystals of thin, high-level clouds (like cirrostratus clouds) and is refracted by an angle of 46 degrees before being registered by the eye. Consequently, an observer sees a ring of light around the sun (or moon) at an angle of 46 degrees relative to the light source.



These ice crystals are hexagonal-shaped columns with diameters between 15 and 25 micrometers and have an appearance resembling tiny pencils.



A 46 degree halo develops when light enters one side of a columnar ice crystal and exits from either the top or bottom face of the crystal. The light is refracted twice as it passes through the ice crystal and the two refractions bend the light by 46 degrees from its original direction. This bending produces a ring of light observed at 46 degrees from the sun or moon.

Sundogs

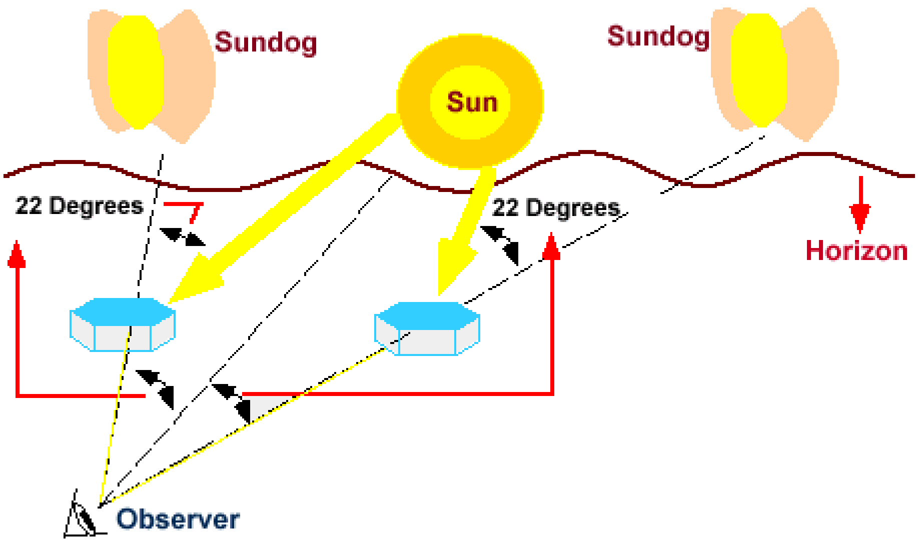
mock suns or parhelia

Sundogs, also known as mock suns or "parhelia", are a pair of brightly colored spots, one on either side of the sun.

Photograph by: Rauber

Sundogs form as sunlight is refracted by hexagonal plate-like ice crystals with diameters larger than 30 micrometers and their flat faces horizontally oriented.

Sundogs are visible when the sun is near the horizon and on the same horizontal plane as the observer and the ice crystals. As sunlight passes through the ice crystals, it is bent by 22 degrees before reaching our eyes, much like what happens with 22 degree halos. This bending of light results in the formation of a sundog.



The difference between sundogs and halos is the preferential orientation of the ice crystals through which the light passes before reaching our eyes. If the hexagonal crystals are oriented with their flat faces horizontal, a sundog is observed. If the hexagonal crystals are randomly oriented, a halo is observed.

Sun Pillars

vertical shafts of light

A sun pillar is a vertical shaft of light extending upward or downward from the sun. Typically seen during sunrise or sunset, sun pillars form when sunlight reflects off the surfaces of falling ice crystals associated with thin, high-level clouds (like cirrostratus clouds).

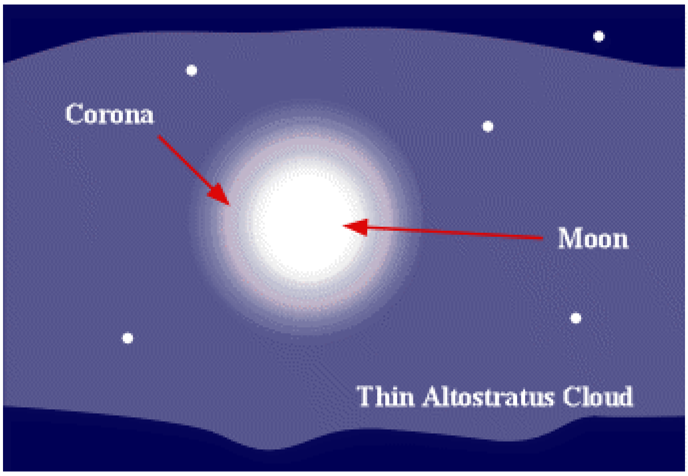
Photograph by: Rauber

The hexagonal plate-like ice crystals fall with a horizontal orientation, gently rocking from side to side as they fall.

When the sun is low on the horizon, an area of brightness appears in the sky above (or below) the sun as sunlight is reflected off the surfaces of these tipped ice crystals.

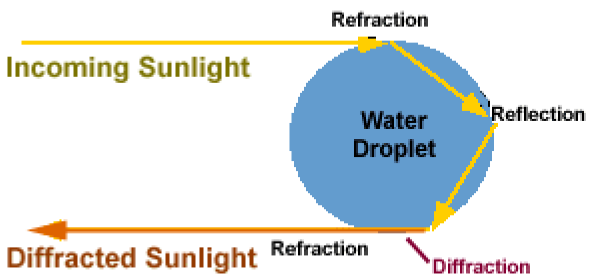
Coronas
produced by diffraction of light

When the distance between the drops is similar to the wavelength of visible light, the light that shines through the cloud droplets is diffracted and dispersed in the manner shown below. On a clear night, for example, the light you see coming from the moon is coning straight from the moon. However if a thin cloud layer is found between the observer and the moon, the diffraction and dispersion of the moonlight actually casts a light larger than the original light source. This 'crown' of light around the sun or moon is called the corona.



When the cloud droplets are very uniform in size, the diffracted light can cause the corona to be separated into its component colors, with blue light to the inside of the red light. These colors may repeat themselves, surrounding the moon with a series of colored rings, becoming fainter as each subsequent ring is located further from the moon.

Also, a combination of refraction, reflection and diffraction can combine to produce other optical effects such as glories and the "Heiligenschein" effect -- which is a bright area around the head of an observer's shadow on a surface containing spherical water droplets. Glories are the rings of illuminated light seen most commonly from plane's shadows as they fly over clouds of liquid water. In both phenomena, the light ultimately is bent close to 180° right back to the observer.



As a beam of light encounters a water droplet, it is refracted as it enters the droplet. Portions of the light are then internally reflected off the backside of the droplet. Before the light exits the droplet completely, it diffracts along the droplet's outer surface for just an instant as a surface wave before refracting as it leaves the droplet.

Silver Lining and Cloud Iridescence

produced through diffraction of sunlight

In the picture below, the sun is shining from behind the growing cumulus tower. This bright outline along the edge of the cloud is the silver lining, which occurs when light is diffracted by cloud droplets along the cloud's outer edge. Silver linings are observed around thicker clouds containing larger droplets.

Photograph by: Holle

Sometimes, diffraction of sunlight in clouds produce a multitude of colors. This optical effect is called cloud iridescence.

Photograph by: Knupp

These colors are usually observed within 20 degrees of the sun and are easier to look at through sunglasses.

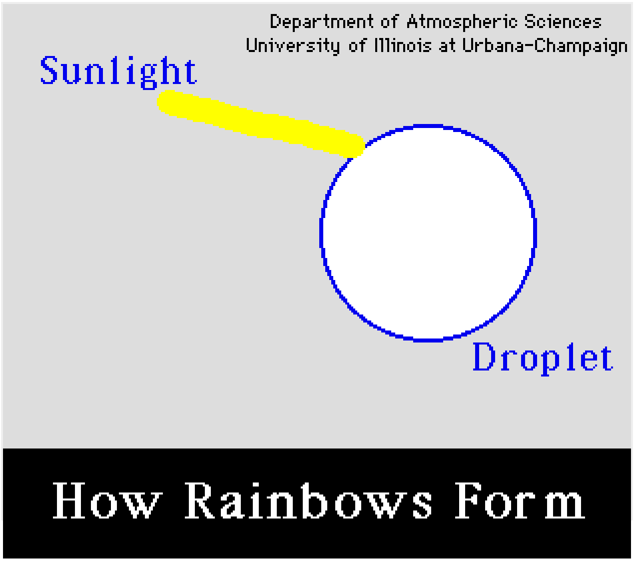
Rainbows

an arc of concentric colored bands

A rainbow is an arc of concentric colored bands that develops when sunlight interacts with rain drops.

Photograph by: Holle

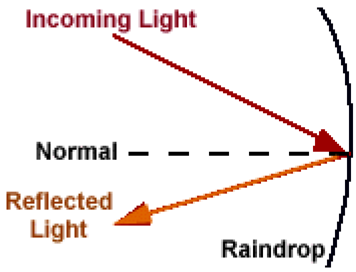
A rainbow occurs when rain is falling in one portion of the sky and the sun is shining in another. For a rainbow to be seen, the sun must be behind an observer who is facing falling rain.



Animation by: Hall

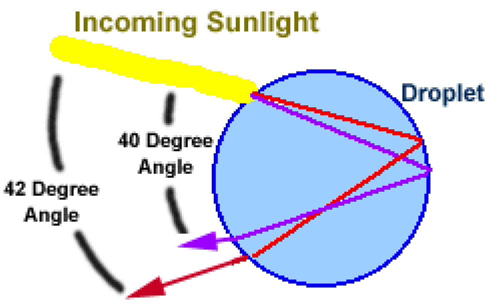
Sunlight is refracted as it enters a raindrop, which causes the different wavelengths (colors) of visible light to separate. Longer wavelengths of light (red) are bent the least while shorter wavelengths (violet) are bent the most.

If the angle between the refracted light and the normal to the drop surface is greater than a critical angle, the light reflects off the back of the drop.



The critical angle for water (which would apply to raindrops) is 48 degrees (relative to the normal). Therefore, if light strikes the back of a raindrop at an angle greater than 48 degrees, it will be reflected back. If the angle is smaller than 48 degrees, the light will simply pass on through.

The reflected light is refracted as it exits the drop. Violet light (bending the most) emerges at an angle of 40 degrees relative to the incoming sunlight while red light (bending the least) exits the drop at an angle of 42 degrees. Other colors of the rainbow leave a raindrop at angles somewhere in between. According to Descartes' calculations using laws of optics, the three stage refraction-reflection-refraction pattern that light undergoes when passing through a raindrop produces a concentration of outgoing rays along a line that is 42 degrees above the head of an observer's shadow. This concentration of light rays is the rainbow that we see.



Since only one color of light is observed from each raindrop, an incredible number of raindrops is required to produce the magnificent spectrum of colors that are characteristic of a rainbow.

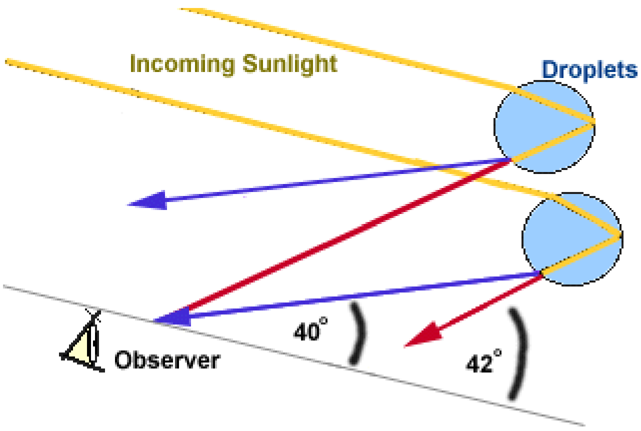
Primary Rainbows

brighter than a secondary rainbow

A primary rainbow is brighter than a secondary rainbow and has colors changing from red on the outside to violet on the inside.

Photograph by: Olthoff

We will focus on two raindrops to explain why this color pattern develops. Red light from the higher drop is directed toward the observer's eyes, while violet light is directed at a level above the observer.



From the lower drop, red light is directed to a level below the line of sight, while violet light is seen by the observer. This is why the colors of a primary rainbow change from red on the top of the arc to violet on the bottom.

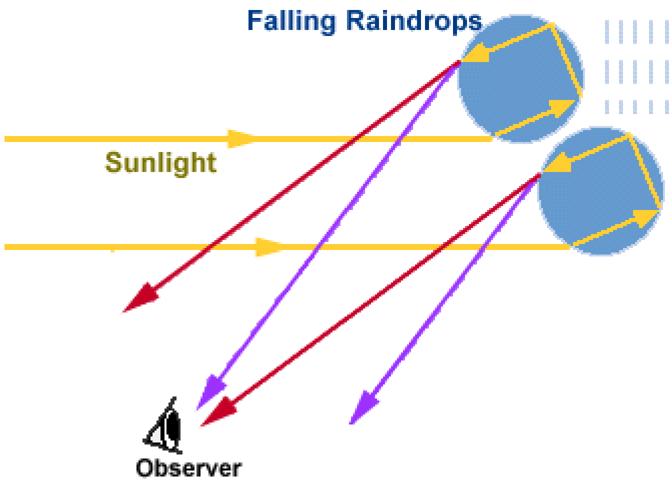
Secondary Rainbows

fainter than a primary rainbow

A secondary rainbow appears outside of a primary rainbow and develops when light entering a raindrop undergoes two internal reflections instead of just one (as is the case with a primary rainbow). The intensity of light is reduced even further by the second reflection, so secondary rainbows are not as bright as primary rainbows. Alternatively: fewer light rays go through the four-step sequence than the three-step sequence.

Photograph by: Olthoff

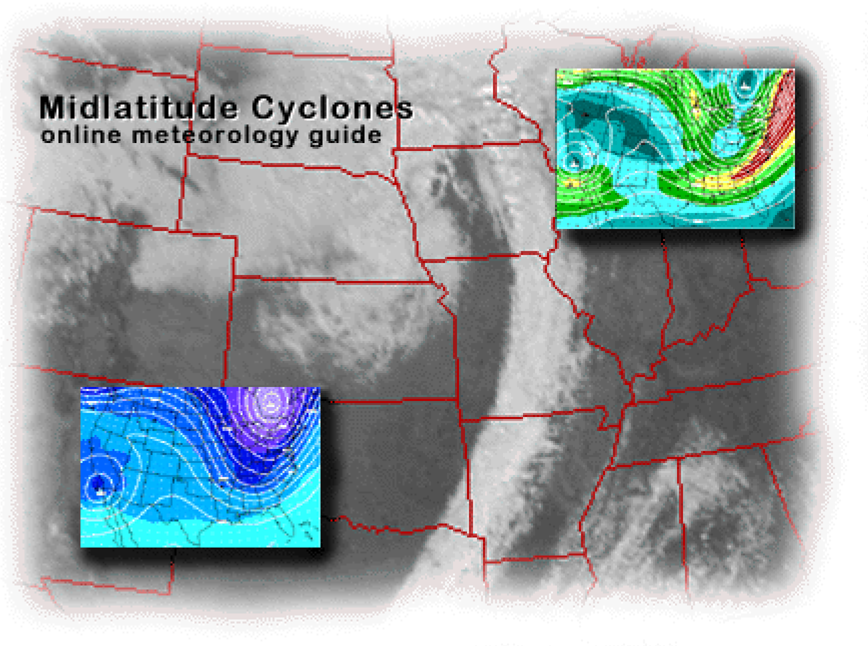
The color scheme of the secondary rainbow is opposite of the primary rainbow. Violet light from the higher drop enters the observer's eye, while red light from the same drop is incident elsewhere.



Simultaneously, red light from the lower drop enters the observer's eye and violet light is not seen. This is why the colors of a secondary rainbow change from violet on the top to red on the bottom.

Midlatitude Cyclones

bringing weather change



Graphic by: Ed Mlodzik

Midlatitude cyclones are the cause of most of the stormy weather in the United States, espeically during the winter season. Understanding the structure and evolution of midlatitude cyclones is crucial for predicting significant weather phenomena such as blizzards, flooding rains, and severe weather.

A midlatitude cyclone is an area of low pressure located between 30 degrees and 60 degrees latitude. Since the continental United States is located in this latitude belt, these cyclones impact the weather in the U.S.

This instructional module introduces the most important features of midlatitude cyclones. The module is divided into the following sections:

Sections
Last Update: 08/22/97

Definition of a Cyclone
The general structure of a cyclone and associated air masses and fronts is discussed.

Winds Associated With a Cyclone
A cyclone can be located simply using the wind barbs.

Air Masses and Cyclones
The movement of air masses associated with cyclone is discussed.

Cyclones on Satellite Images
A midlatitude cyclone looks very distinct on a satellite image.

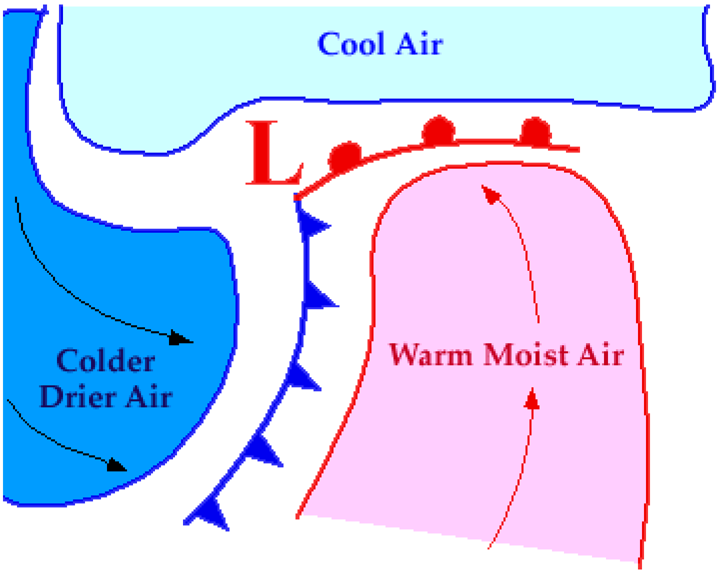
Upper Air Features
Cyclones develop as a result of upper air features discussed in this section, included troughs, wave amplification, and jet streaks.

Acknowledgements

Those who contributed to the development of this module.

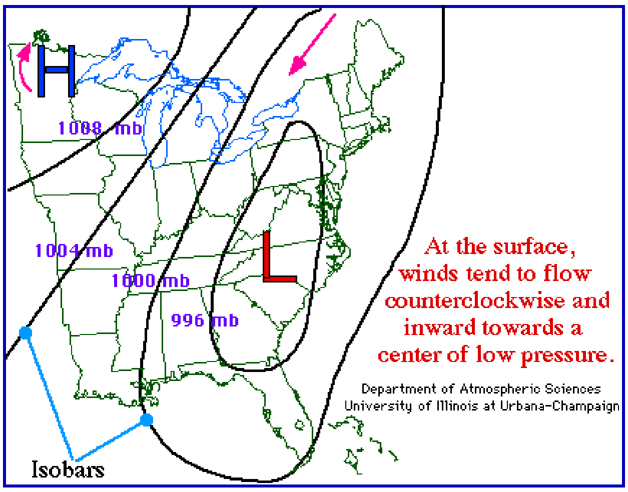
Cyclones
an idealized model

A **cyclone** is an area of low pressure around which the winds flow counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.



A developing cyclone is typically accompanied by a warm front pushing northward and a cold front pulling southward, marking the leading edges of air masses being wrapped around a center of low pressure, or the center of the cyclone.

The counterclockwise winds associated with northern hemisphere midlatitude cyclones play a significant role in the movement air masses, transporting warm moist air northward ahead of a low while dragging colder, drier air southward behind it.



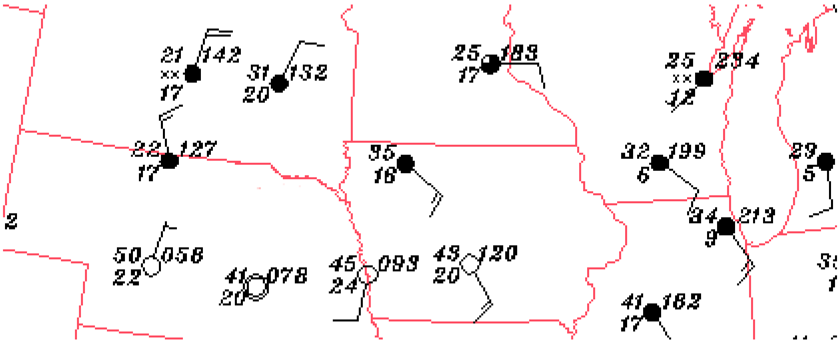
**** Press "Reload" to restart the animation ****

Rising air in the vicinity of a low pressure center favors the development of clouds and precipitation, which is why cloudy weather (and likely precipitation) are commonly associated with an area of low pressure. Cyclones are easily identifiable on certain types of weather maps by remembering some key signatures. For example, a cyclone can be found on a map of surface observations by recognizing a counterclockwise rotation of the wind barbs for a group of stations, while on satellite images, cyclones are identifiable by the trademark comma shaped configuration of cloud bands.

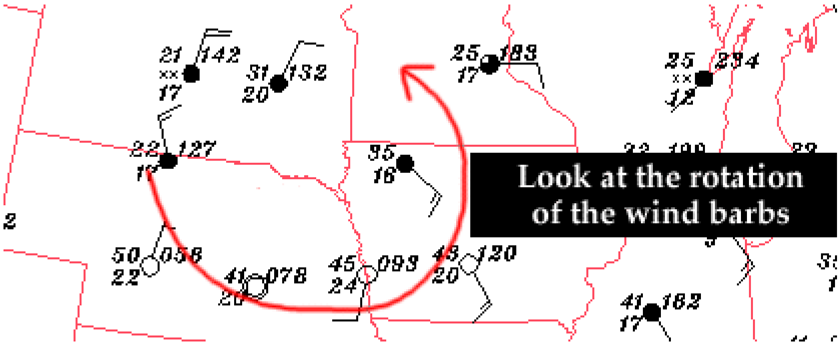
Winds Around Cyclones

flowing counterclockwise in the northern hemisphere

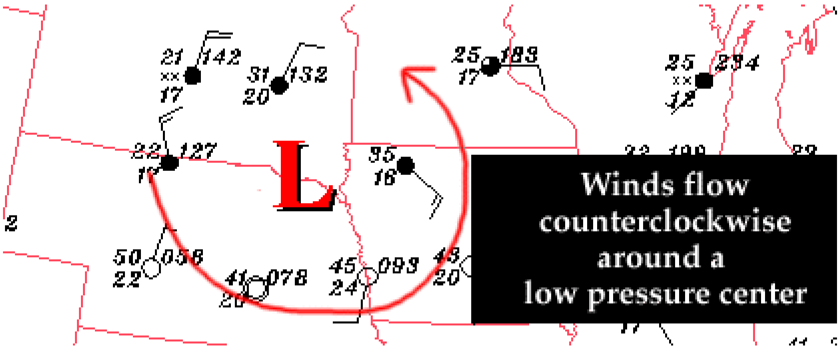
Wind barbs are useful for locating low pressure centers on surface weather maps.



Since winds flow in a counterclockwise direction around low pressure centers, look for a group of stations where the wind barbs reflect this type of wind pattern. For example, a counterclockwise wind pattern was observed in the states of Nebraska, Iowa, Minnesota and South Dakota (highlighted by the red arrow).



The low pressure center was located near the center (similar to the center of a whirlpool) with winds flowing counterclockwise around it.

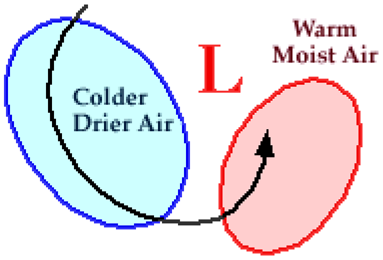


So when trying to find a low pressure center on a surface weather map, use the wind barbs to identify a counterclockwise wind pattern and the low pressure center will be found near the center of circulation.

The Movement of Air Masses

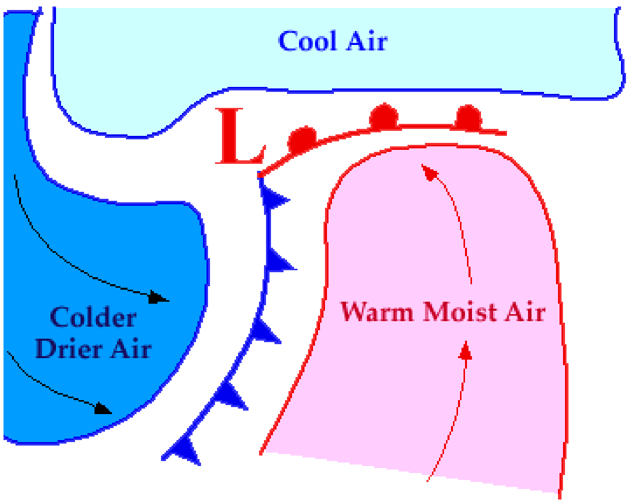
transporting warm air northward and colder air southward

Counterclockwise winds associated with cyclones transport heat and moisture from lower to higher latitudes and play a significant role in the movement of air masses.



As a cyclone intensifies, (the central pressure drops), counterclockwise winds around the low pressure center also intensify, transporting the air masses around the center of circulation.

By superimposing fronts over the low pressure center and the air masses, a top view of a midlatitude cyclone and accompanying air masses might resemble something like the diagram below:

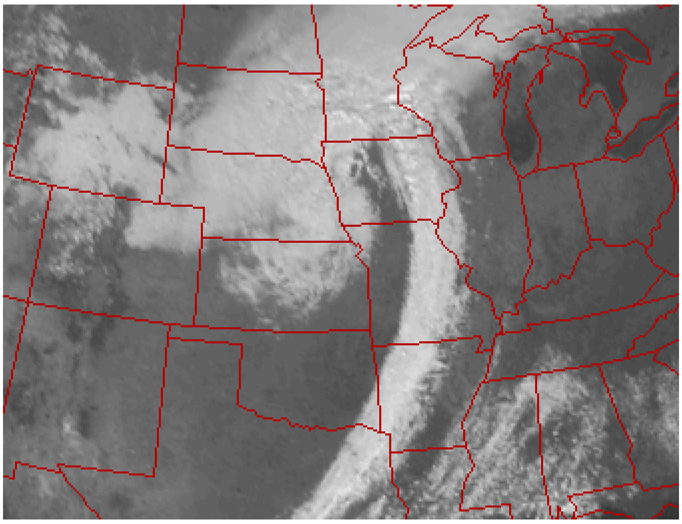


Southerly winds east of the low transport warm and moist air northward and this moisture often contributes to the development of precipitation. A warm front marks the leading edge of this warm, moist air mass. Behind the low, northerly winds transport colder and drier air southward, with a cold front marking the leading edge of this colder, drier air mass.

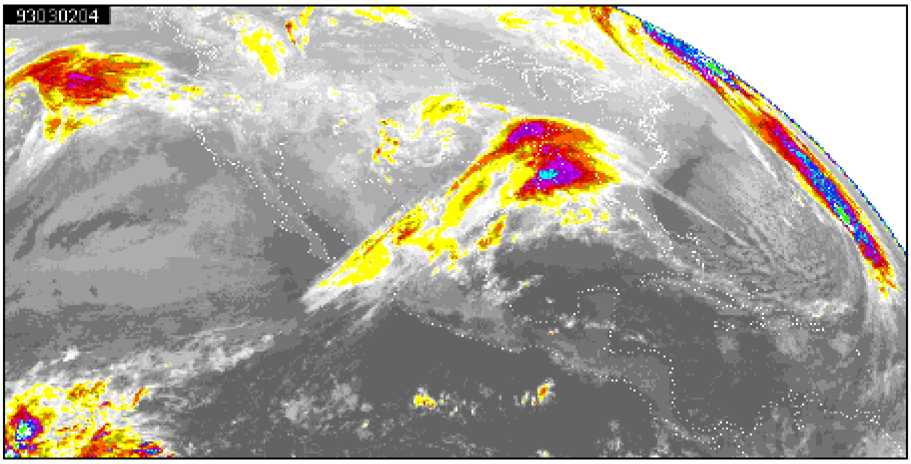
Cyclones on Satellite Images

comma-shaped cloud configuration

On satellite images, a midlatitude cyclone is often identifiable by a comma-shaped cloud mass.



A single cyclone can influence the weather over a large area, (in this case from Texas into Minnesota). This particular storm (in the satellite image above) left more than six inches of snow from Nebraska into Minnesota, while heavy rains occurred from Missouri into Texas.



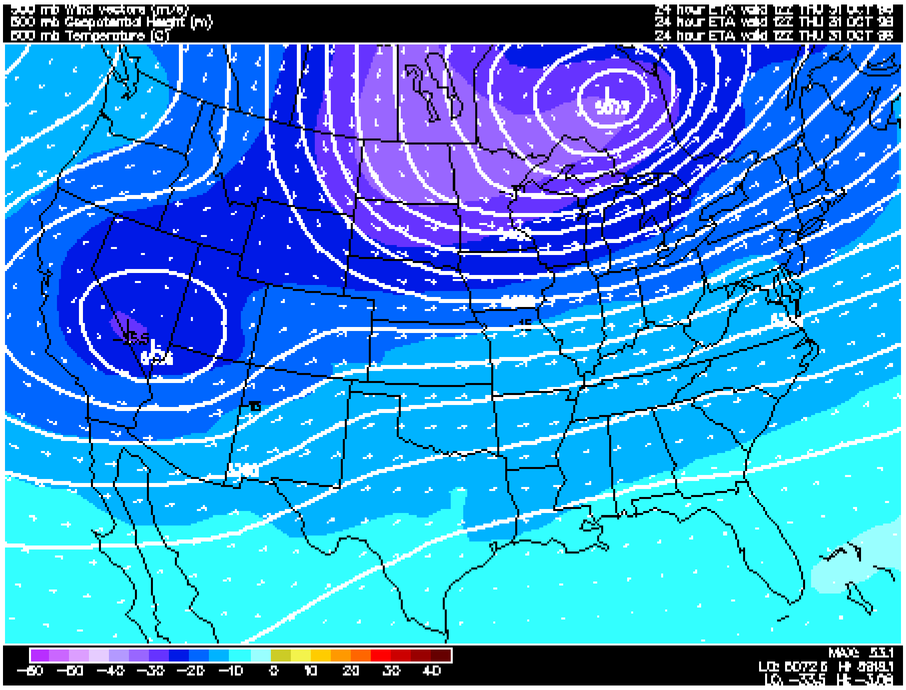
MOVIE (QuickTime 1.3MB): Infrared Satellite Loop
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/cyc/sat.rxml

Here is a movie loop of color enhanced infrared images spanning 18 hours. The center of the cyclone was initially located over the southcentral portions of the United States. As the cyclone evolved over time, notice the counterclockwise rotation of clouds around the cyclone center.

Geopotential Height

height of a given pressure

Geopotential height approximates the actual height of a pressure surface above mean sea-level. Therefore, a geopotential height observation represents the height of the pressure surface on which the observation was taken. A line drawn on a weather map connecting points of equal height (in meters) is called a height contour. That means, at every point along a given contour, the values of geopotential height are the same. An image depicting the geopotential height field is given below.

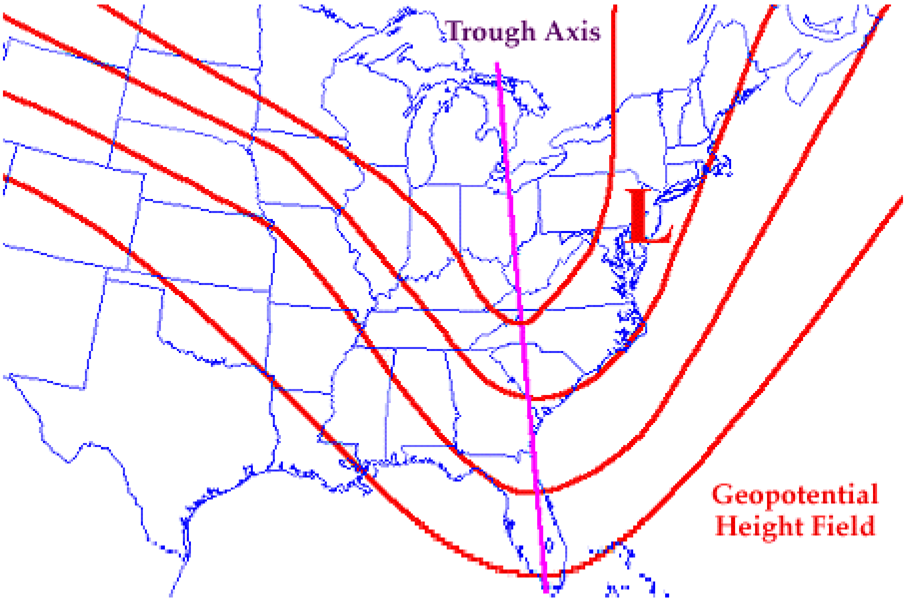


Height contours are represented by the solid lines. The small numbers along the contours are labels which identify the value of a particular height contour (for example 5640 meters, 5580 meters, etc.). This example depicts the 500 mb geopotential height field and temperatures (color filled regions). The height field is given in meters with an interval of 60 meters. Geopotential height is valuable for locating troughs and ridges which are the upper level counterparts of surface cyclones and anticyclones.

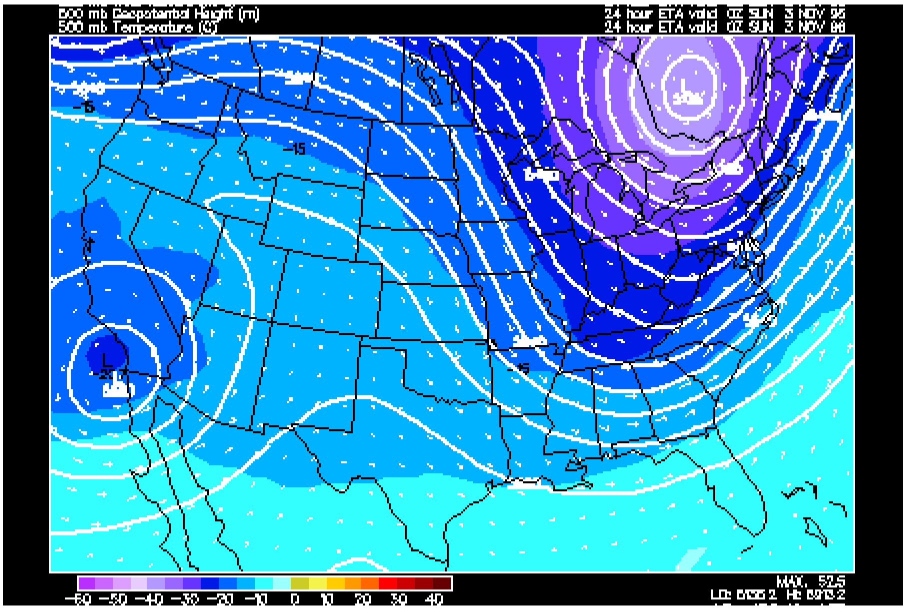
Troughs

upper level lows

When the height contours bend strongly to the south, (as in the diagram below), it is called a **TROUGH**. Strong troughs are typically preceded by stormy weather and colder air at the surface. Below is an example of a trough in an upper-level height field (red contours). The trough axis is denoted by the purple line.



The image below depicts geopotential height (solid white contours) and temperatures (colored regions) at 500 mb. Temperatures decrease with color from light blue to purple. A trough is located over the eastern United States and is indicated by the dip in the geopotential height field. This is the upper level extension of a surface low pressure center, which is why troughs are also called upper level lows.

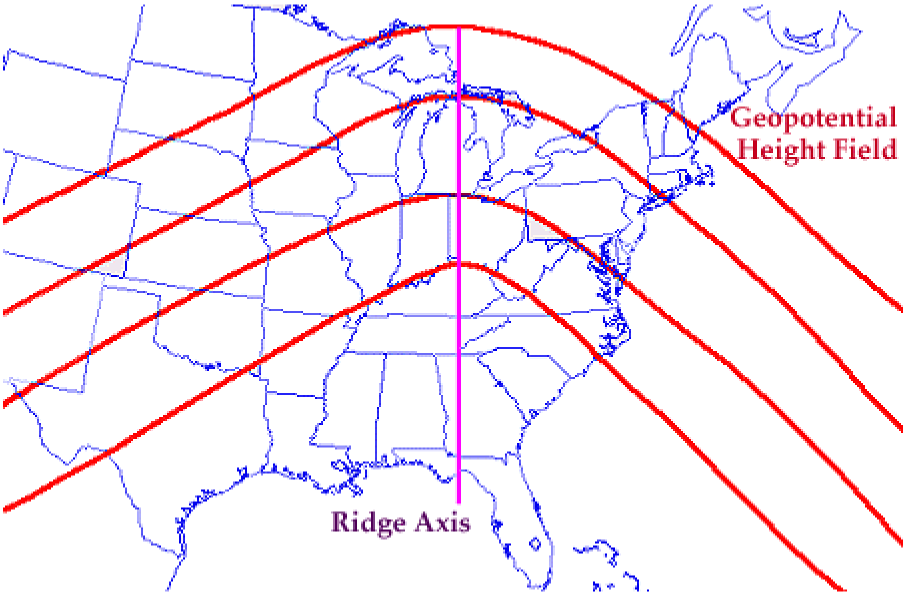


Notice the relatively cold temperatures associated with the trough. This is caused by the southward transport of colder air in the lower troposphere. The trough will intensify (deepen further southward) if cold air continues to move southward at low levels in the troposphere.

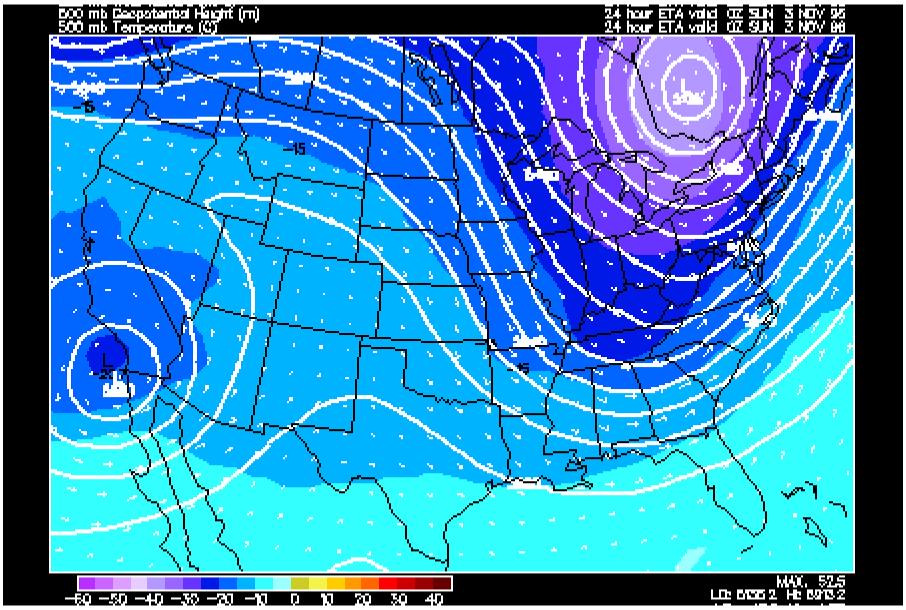
Ridges

upper level highs

When the height contours bend strongly to the north (as in the diagram below), this is known as a **RIDGE**. Strong ridges are accompanied by warm and dry weather conditions at the surface. Below is an example of a ridge in an upper-level height field (red contours). The purple line denotes the ridge axis.



The image below depicts geopotential height (solid white contours) and temperatures (colored regions) at 500 mb. Temperatures decrease with color from light blue to purple. A ridge is located from Texas into Montana and is indicated by the bulge in the geopotential height field. This is the upper level extension of a surface high pressure center, which is why ridges are also called upper level highs.

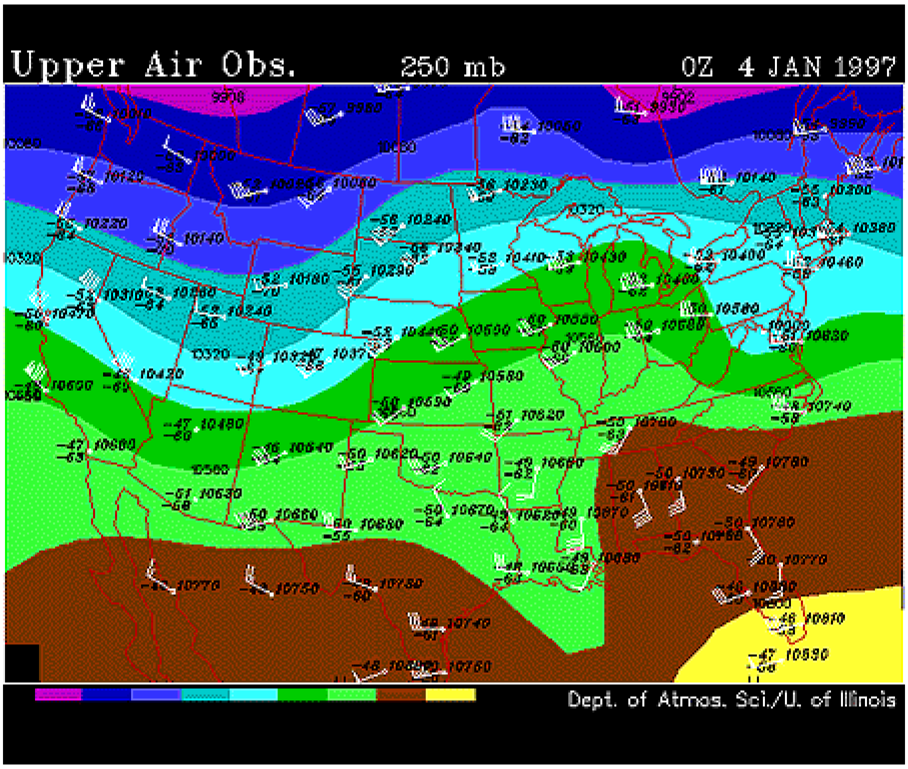


Notice the relatively warm temperatures associated with the ridge. This is caused by the northward transport of warmer air in the lower troposphere. The ridge will intensify (bulge further northward) if warm air continues to move northward at low levels in the troposphere.

Trough and Ridge Amplification

in response to lower level temperature advection

Warm advection beneath an upper level ridge causes it to build (increase in amplitude), while cold advection beneath an upper level trough will contribute to its deepening. The animation below highlights the amplification of ridge/trough system at 250 mb in response to intense thermal advection at 850 mb. The total time elapsed in the animation is 48 hours.



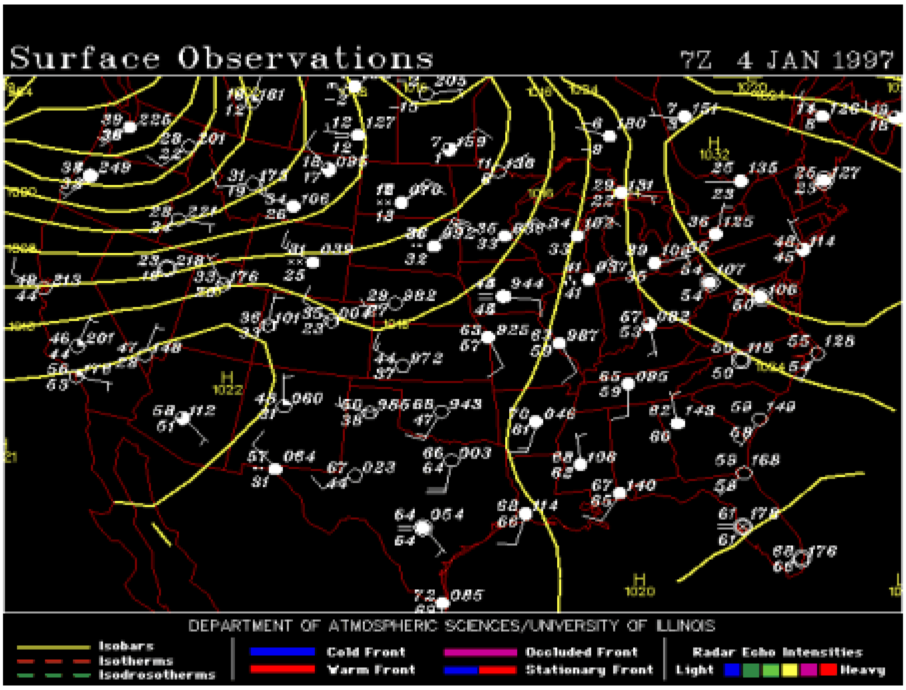
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/cyc/upa/amp.rxml

Observe how the ridge over the east gradually builds (raises northward) while the trough over the northern plains gradually deepens (sinks southward). While the entire ridge/trough system propagates eastward. Such amplification of upper level waves can increase the intensity of a cyclone at the surface.

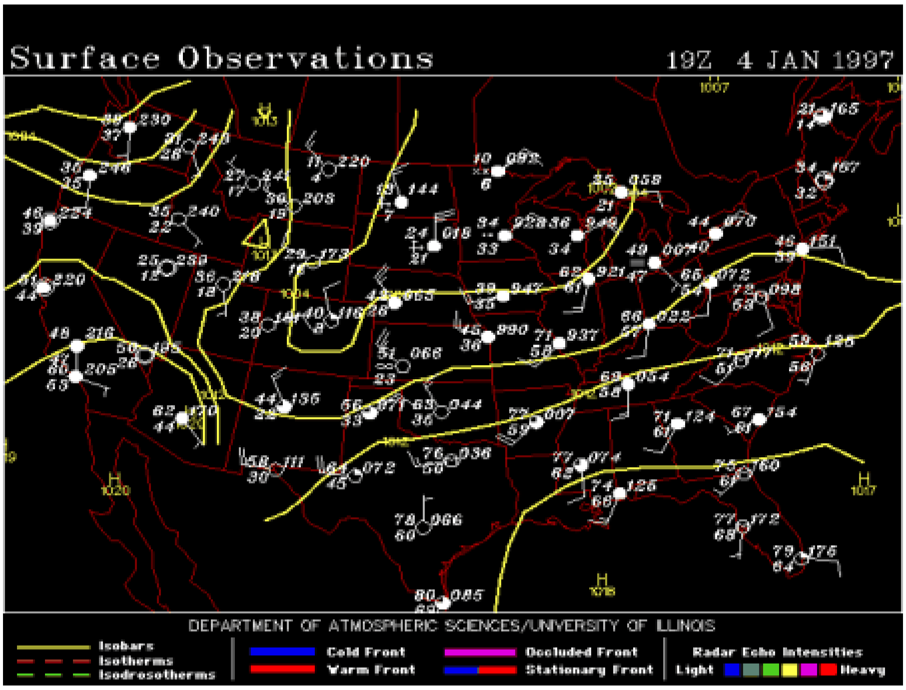
Rising Motion and Surface Pressure Falls

in response to warm and cold advections

Warm and cold advection influence vertical air motion. Warm advection results in rising motion which leads to falling pressures at the surface, while cold advection leads to sinking motion, causing pressures to rise at the surface. The sequence of surface maps below show the surface pressure fields (isobars) that resulted from the warm and cold advection patterns at 850 mb.



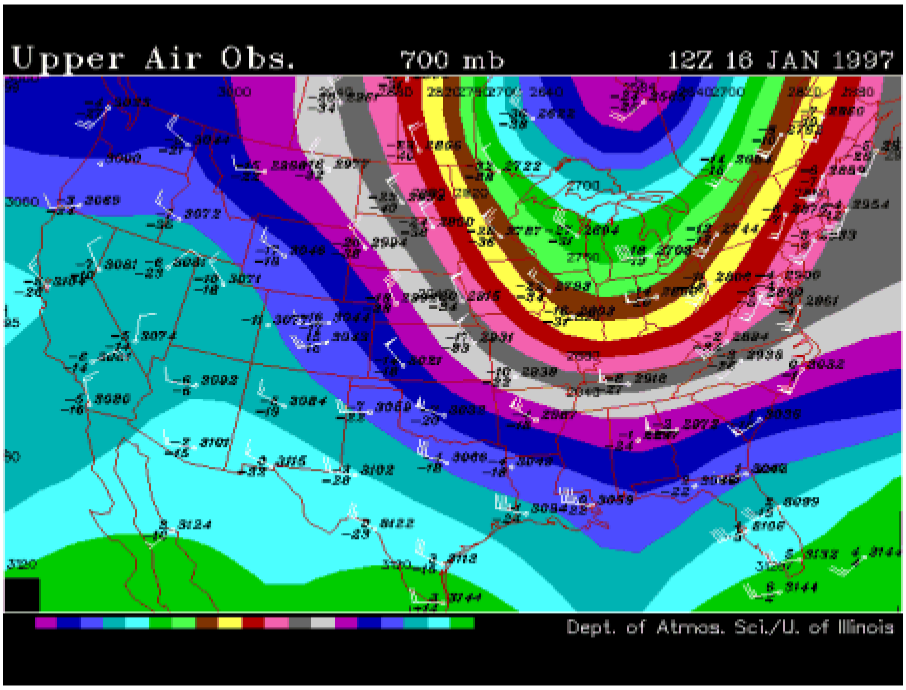
The top map shows an area of low pressure over the northwestern United States and an area of high pressure over the eastern U.S. 12 hours later, there is a noticeable decrease in pressure from Texas to Illinois (region of strongest warm advection at 850 mb) while surface pressures increased in regions where the strongest 850 mb cold advection was occurring.



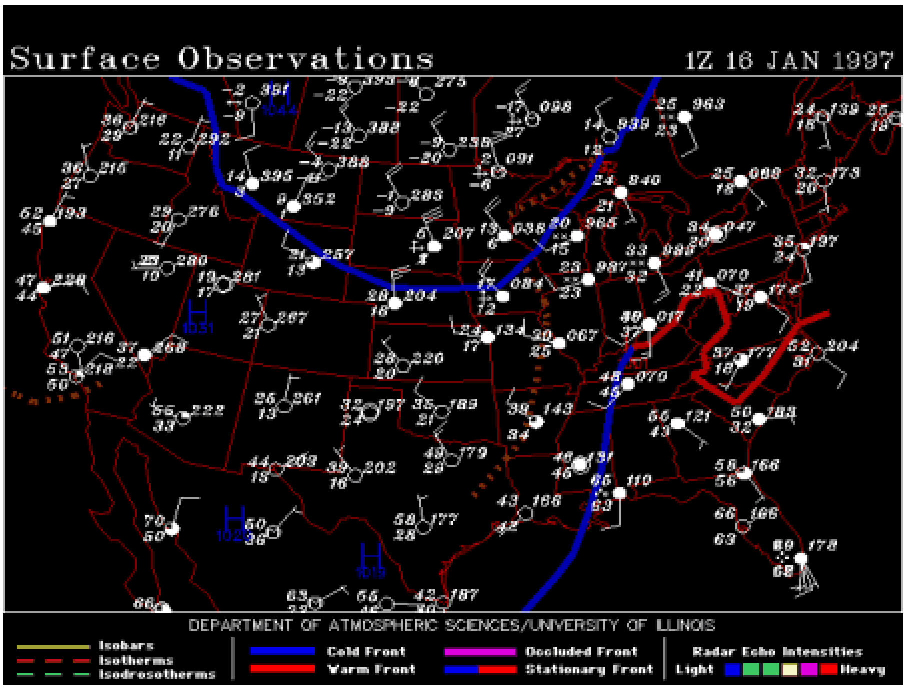
A cyclone at the surface that moves under an area of warm advection at 850mb is likely to deepen. For this reason, systems at the surface will tend to "phase lock" with systems aloft, and they will propagate more or less together.

Steering Level For Cyclones
guided by winds near 700 mb

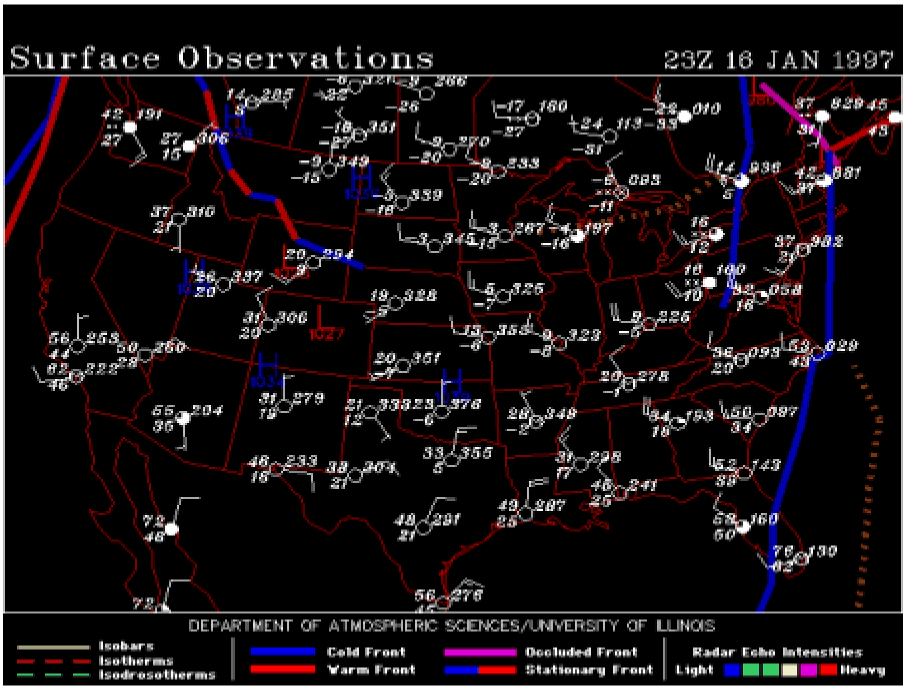
Surface systems often follow the prevailing airflow at this level. Therefore, the airflow at 700mb, inferred from the geopotential contours and geostrophic balance, can indicate the direction surface systems will take.



Notice that winds over the eastern U.S. are generally out of the south. At the same time, a surface cyclone was centered over the Ohio Valley.



24 hours later, the cyclone propagated northeastward (parallel to the winds at 700mb) and was centered over Eastern Canada.

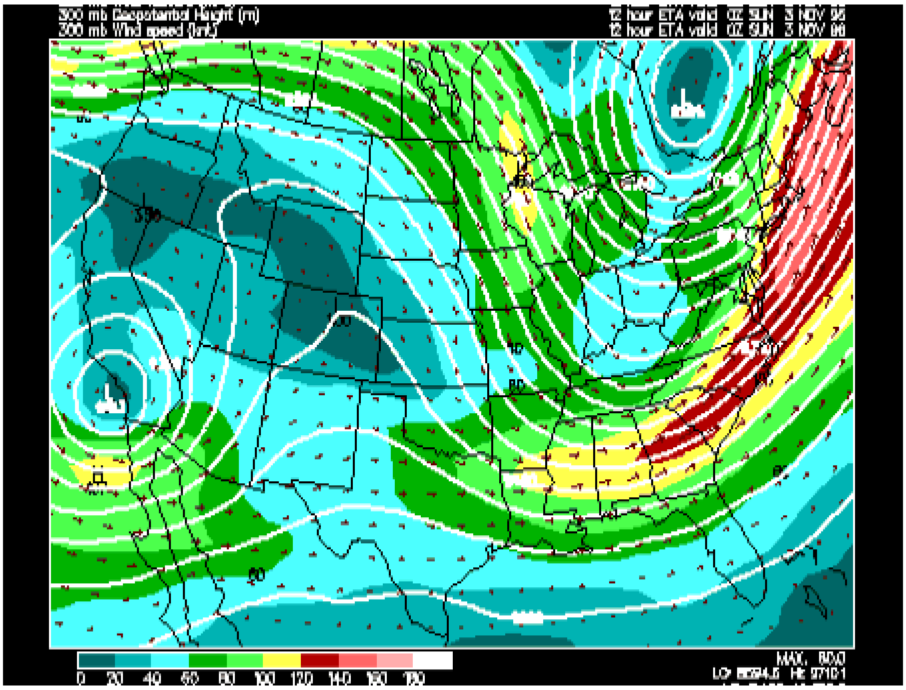


Jet Stream
current of rapidly moving air

The jet stream is a current of fast moving air found in the upper levels of the atmosphere. This rapid current is typically thousands of kilometers long, a few hundred kilometers wide, and only a few kilometers thick. Jet streams are usually found somewhere between 10-15 km (6-9 miles) above the earth's surface. The position of this upper-level jet stream denotes the location of the strongest SURFACE temperature contrast (as in the diagram below).

During the winter months, Arctic and tropical air masses create a stronger surface temperature contrast resulting in a strong jet stream. However, during the summer months, when the surface temperature variation is less dramatic, the winds of the jet are weaker.

Below is an ETA Model forecast panel for 300 mb winds and geopotential heights (white contours). The color filled regions indicate wind speed in knots and is color coded according to the legend at the bottom of the image. The shades of blue indicate winds less than 60 knots, while winds greater than 120 knots are given in shades of red.

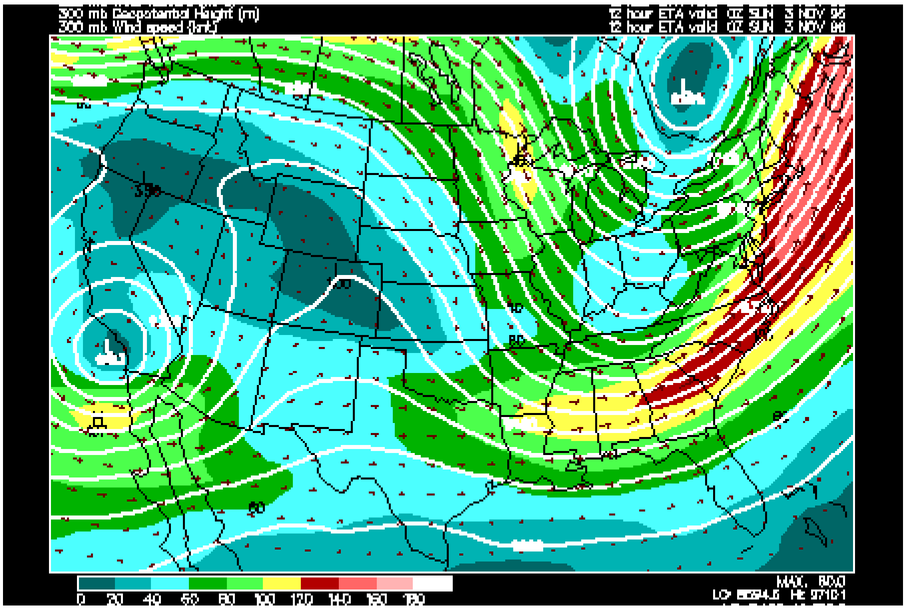


The yellow, green and red ribbon on the image above represents the jet stream, and along the East Coast, the region of strongest winds (shaded in red) is a jet streak.

Jet Streaks

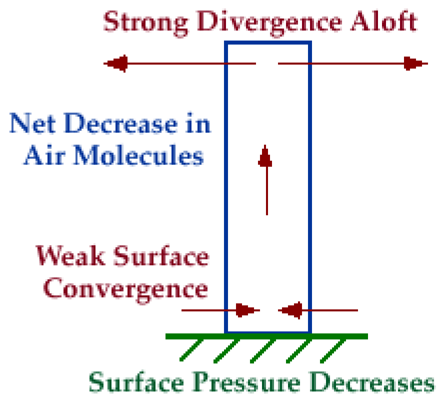
wind speed maxima within the jet stream

Jet streaks are localized regions of very fast winds embedded within the jet stream. Sometimes these local wind maxima reach speeds in excess of 160 knots. Below is an ETA Model forecast panel for 300 mb winds and geopotential heights (white contours). The color filled regions indicate wind speed in knots and is color coded according to the legend at the bottom of the image. The shades of blue indicate winds less than 60 knots, while winds greater than 120 knots are given in shades of red.



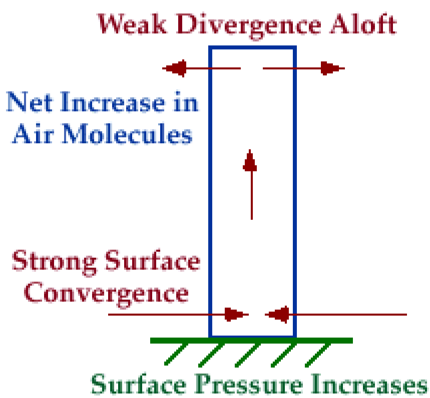
The yellow, green and red ribbon on the image above represent the jet stream, and along the East Coast, the region of strongest winds (shaded in red) is a jet streak.

As air enters a jet streak, it speeds up. When it leaves a jet streak, it slows down. These accelerations and decelerations, coupled with the curvature of the jet stream and strong wind shears, cause air to pile up in some areas (convergence) and spread out (divergence) in others. These regions of divergence and convergence have a significant influence on surface pressure features.



Intensifying Surface Cyclone:

For example, if a region of diverging winds at upper levels is stronger than the converging winds of a suface low pressure center below it, the low will deepen (intensify). This is because more air is being removed from the vertical column of air above the low than flowing into it, causing the pressure at the surface to decrease. A drop in pressure means an intensification of the low pressure center.



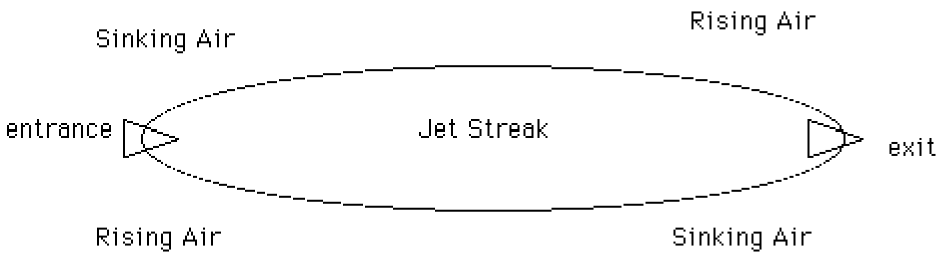
Weakening Surface Cyclone:

In contrast, if a region of diverging winds at upper levels is weaker than the converging winds of a suface low pressure center below it, the low begins to fill (weaken). This is because more air is flowing into the vertical column of air above the low than flowing out of it, causing the pressure at the surface to increase. An increase in pressure means a weakening of the low pressure center.

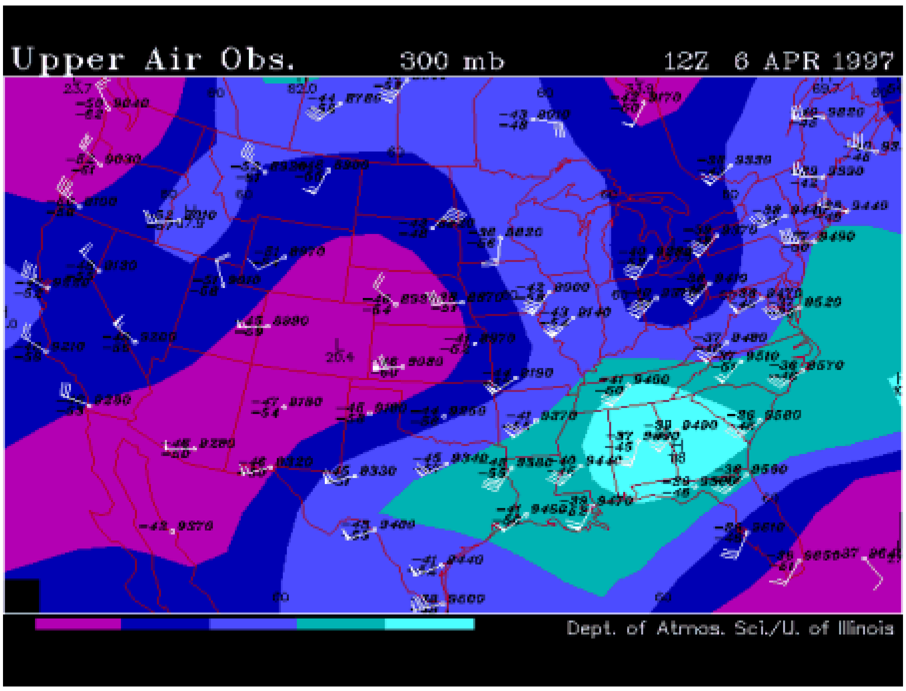
Vertical Motion and Jet Streaks

associated with different regions of a jet streak

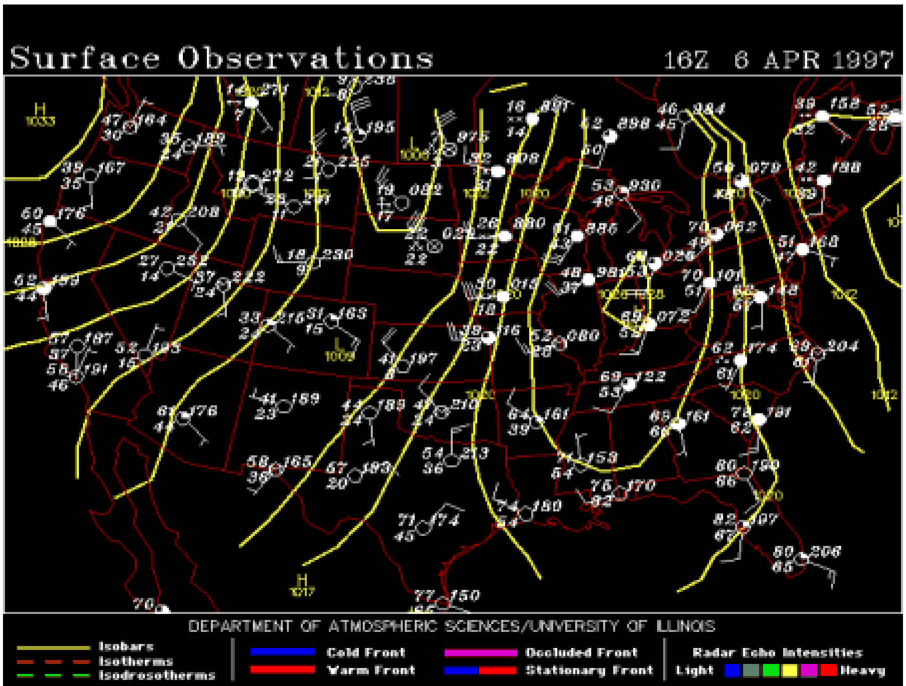
Jet streaks are important as they are indicative of rising motion/falling pressures at the surface. The figure below represents an idealized jet streak.

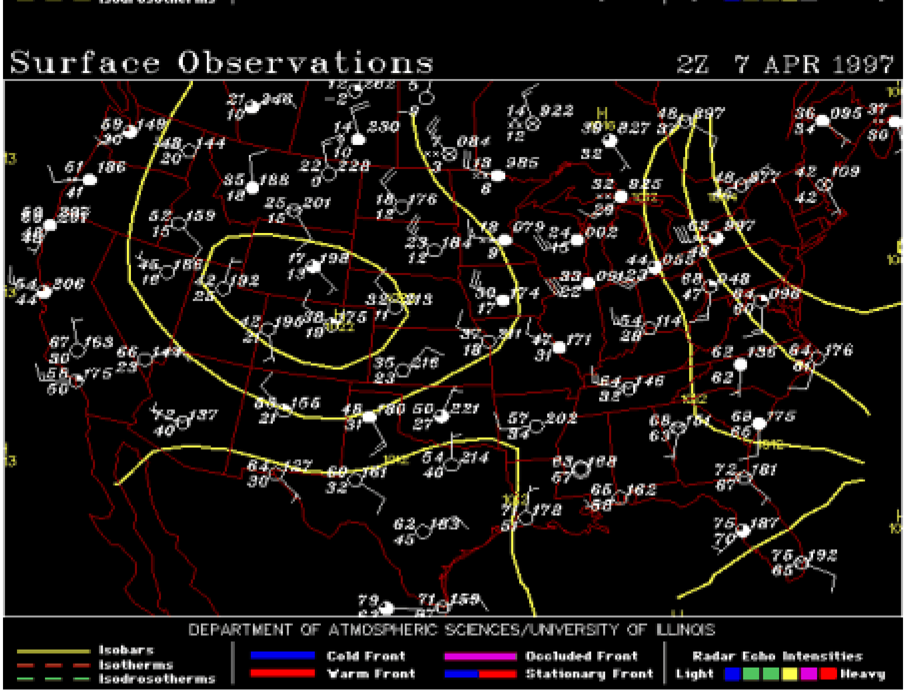


As air enters from the left, it must be accelerated. The force to do this is supplied by the Coriolis force as air flows from the south to the north near the jet entrance, leading to a force to the east (the right). This air motion results in a convergence to the north and a divergence to the south. As a result, air sinks in the northern 'quadrant', and rises in the southern quadrant, leading to pressure changes at the surface. In the jet exit region, the opposite happens, as air flows from north to south to create the force necessary to decelerate the air as it leave the jet streak. The vertical motion resulting from this leads to rising air in the north quadrant and sinking air in the south, also leading to surface pressure changes. Look at this 300mb map for 12Z, April 6,1997.



Notice the jet streak that lies along the southeastern U.S. Now look at the following surface pressure plots.



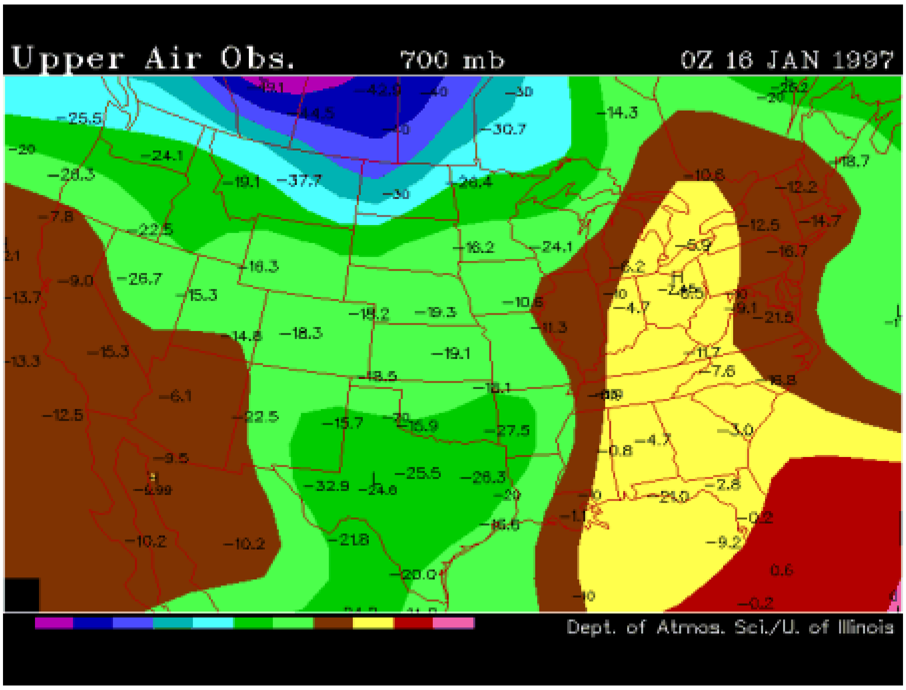


Notice how pressures have risen below the north entrance region, and fallen below the north exit region. This will intensify cyclones which tend to be located below the north exit quadrant.

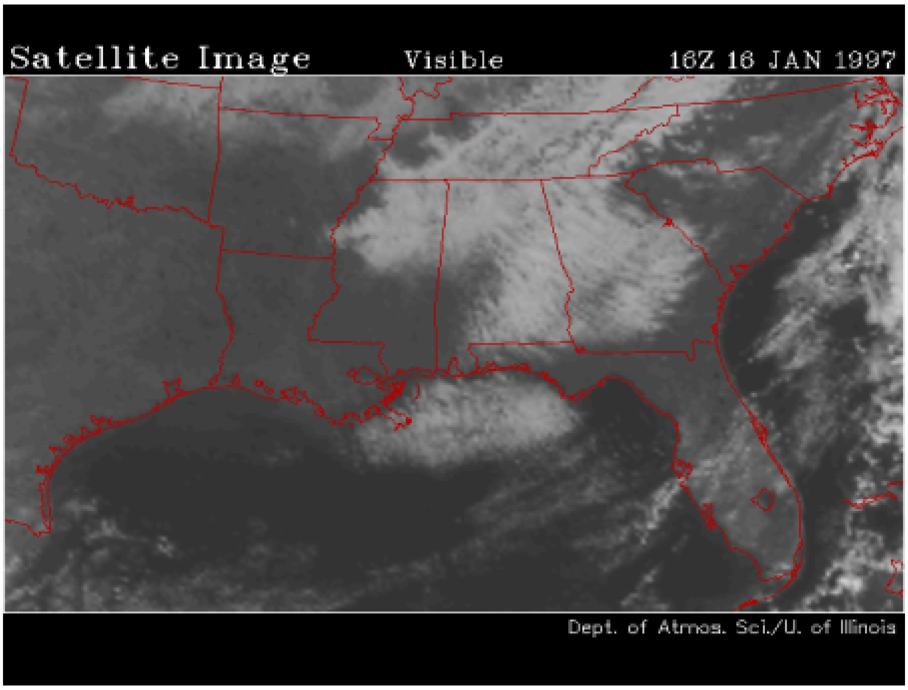
700 mb Dew Point Depression

important indicator for the presence of clouds

Dew point depression (DD) is useful indicator of how moist the air is and is calculated by taking the difference between the temperature of the air and the dew point temperature. Lower dew point depression values mean that the air is very moist, and an increased likelihood that clouds will develop. In the 700mb map below, the lowest DD values are located over the Southeast (shaded in yellow).



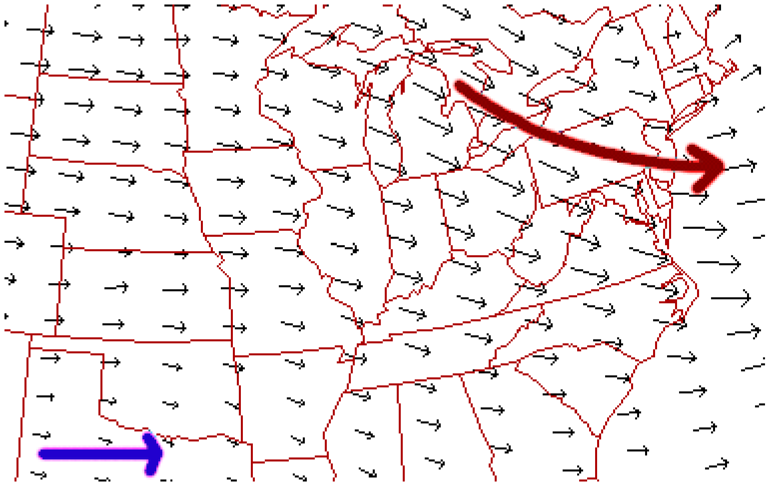
Examination of the [visible satellite image] from the same time reveals an extensive cloud deck present over the Southeast, corresponding very well with the low DD values identified above.



Also observe the lack of clouds over Texas and Louisiana, areas of much greater DD, indicating drier air.

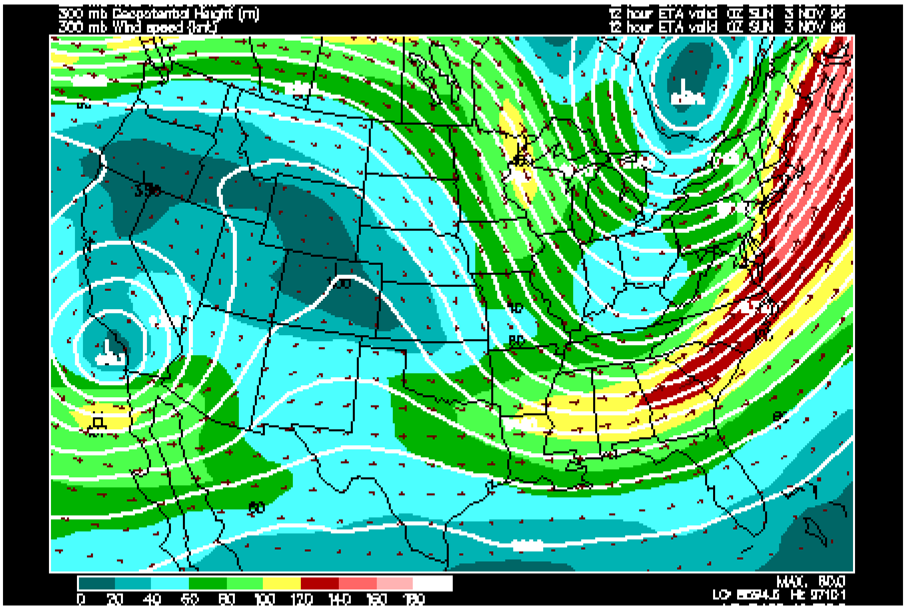
Wind Vectors
indicate wind direction and speed

The black arrows plotted on this image are wind vectors. These vectors indicate direction and intensity of the wind. The vectors point in the direction to which the wind is blowing and in this image, winds are primarily blowing from west to east. Intensity of the wind is conveyed through the size of the vector. The longer the arrows, the stronger the winds.



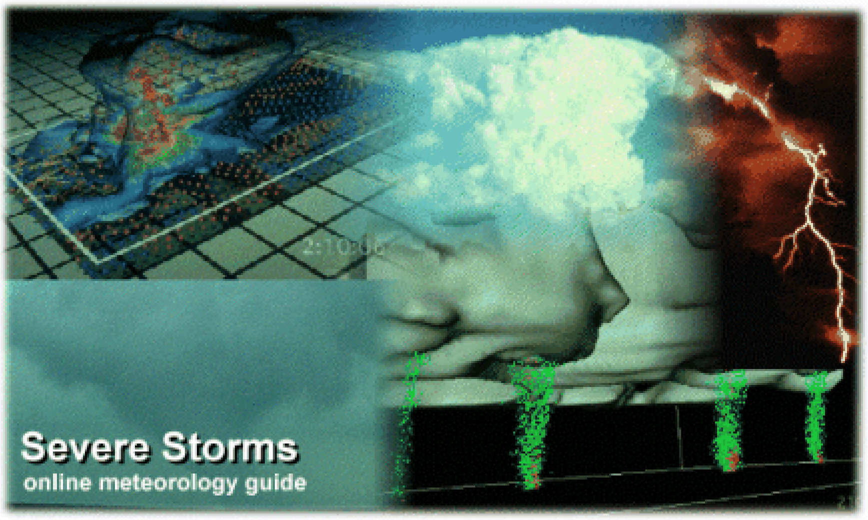
For example, wind vectors in the vicinity of the blue arrow are longer than those near the green arrow. This means that by the blue arrow, the winds are stronger, than by the green arrow. Wind vectors are also useful in finding regions of upper level convergence and divergence, which indicate regions of upward and downward motion. Upward motion is typically associated with clouds and precipitation.

Below is an ETA Model forecast panel for 300 mb winds and geopotential heights (white contours). The color filled regions indicate wind speed in knots and is color coded according to the legend at the bottom of the image. The shades of blue indicate winds less than 60 knots, while winds greater than 100 knots are given in shades of red.



The wind vectors (red arrows) are much smaller in the blue regions, where the winds are relatively weak, and largest in the red, which is the region of strongest winds. The ribbon of strongest winds (green, yellow and red colors) is called the jet stream with a jet maximum, or jet streak located along the east coast.

Notice how the wind vectors are aligned generally parallel to the geopotential height contours. Once high enough above the earth, the effects of surface friction on wind direction decrease dramatically and consequently, winds flow roughly parallel to the height contours.



Graphic developed by: Dan Bramer

The Severe Storms Module is a combination of two elements. The first is the NOAA Severe Storms Spotters Guide. The second is a section recently added to discuss the efforts and results of modeling severe storms. The Severe Storms Spotters Guide contains supplemental instructional resources and a program designed to familiarize meteorologists and advanced severe storm spotters with the basic "building blocks" of convective storm structure. The focus of the training series is the development of a thunderstorm "spectrum" and a discussion of the physical characteristics and severe weather potential of the various storm types in the spectrum.

Sections

Last Update:05/15/99

Dangers of Thunderstorms
Includes: lightning, floods, hail, winds and tornadoes.

Types of Thunderstorms
Single cells, multicell clusters, multicell lines (squall lines) and supercells.

Components of Thunderstorms
Updrafts and downdrafts, outflow phenomena, wall clouds and the effects of wind shear on thunderstorm development.

Tornadoes
Tornadoes, cyclic storms and low-level flow fields associated with tornadic thunderstorms.

Modeling
Supercells, squall lines, and other phenomena recreated inside computers for the benefit of forecasting and understanding.

Acknowledgments
Those who contributed to the development of this module.

The critical role of atmospheric dynamics and thermodynamics in determination of storm type is stressed. We will take a close look at the storms themselves; from the small, summer storms capable of producing dangerous "microbursts" to the large "supercell" storms which spawn destructive tornadoes.

Lightning

a visible electric discharge produced by thunderstorms

Let's review the destructive and deadly thunderstorm elements before introducing the thunderstorm spectrum. By definition, all thunderstorms contain lightning. This photograph shows lightning coming from the side of a cumulonimbus cloud.

Photograph by: Moller

In most years it is the thunderstorm's greatest killer. A possible contributing reason for this is that lightning victims frequently are struck before or just after the occurrence of precipitation at their location. Many people apparently feel safe from lightning when not experiencing rain.

Flash Floods and Hail

property and personal devastation

Cases involving either slow-moving thunderstorms or a series of storms which move repeatedly across the same area (sometimes called train-echo storms) frequently result in flash flooding. The total number of flash flood deaths has exceeded tornado fatalities during the last several decades.

Photograph by: NWS

Two factors seem to be responsible for this: public apathy regarding the flash flood threat and increased urbanization. When concrete replaces soil, rain water will run off rather than soak in.

Flash flood producing rainfall has made this type of dramatic rescue attempt (pictured above) all too familiar, especially in urban areas and popular mountain camping spots.

Another danger associated with thunderstorms, especially to personal property, is hail. This hailfall occurred in Altus, Oklahoma in 1982 and was accompanied by several tornadoes. Hail causes more monetary loss than any other type of thunderstorm-spawned severe weather.

Photograph by: NSSL

Annually, the United States alone suffers about one billion dollars in crop damage from hail. Hail rarely kills people, but these were hollow words in China in May, 1986 when 100 people were killed, 9,000 injured, and 35,000 homes destroyed by an intense hailstorm.

Outflow

winds flowing outward from thunderstorms

Thunderstorm winds also cause widespread damage and occasional fatalities. Thunderstorm "straight-line" winds originate from rain-cooled air that descends with accompanying precipitation. This central Texas windstorm, approaching from the west, was packing 80 MPH winds behind the spectacular appearing gust front. The same thunderstorm earlier produced several small tornadoes, grapefruit size hail, and flash flood rainfall. (Looking west from about 5 miles.)

Photograph by: Moller

After the thunderstorm gust front passes and before precipitation, if any, arrives, blowing dust often is kicked up by thunderstorm induced winds. The amount of dust depends on soil type, soil moisture content, and wind intensity.

Photograph by: Moller

Note the aviation "wind sock" in the photograph. Winds were estimated to be about 50 MPH at this time along the Texas-New Mexico border east of Hobbs, New Mexico. Severe thunderstorm winds are especially dangerous to aviation interests, particularly aircraft which are on final approach or taking off.

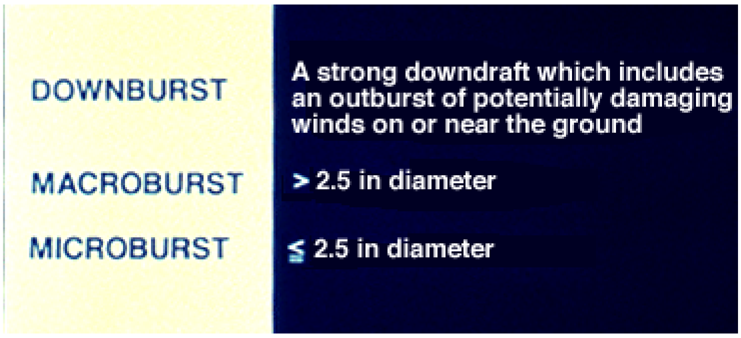
Many western US storms, such as this one in southern Colorado, have extremely high bases and low tops. Don't let the weak appearance fool you! Some of the "dry storms" can produce dangerous microbursts and copious amounts of fire-setting lightning.

Photograph by: Moller

Recent research has shown that microbursts, both "dry" ones such as this (actually some very light rain may fall with a dry microburst) and "wet" ones frequently are the cause of wind shear induced aircraft accidents.

Downbursts
severe localized downdrafts

Damaging thunderstorm winds have been termed downbursts by renowned severe storm researcher Dr. Ted Fujita. Dr. Fujita further classifies these events as macrobursts (greater than 2.5 miles in diameter) and microbursts (less than 2.5 miles in diameter).



Generally, a macroburst is on the scale of the entire cold air outflow field of a thunderstorm or a group of thunderstorms; whereas the microburst is a sub-thunderstorm scale outflow feature. This is a southward view from within one mile of a microburst embedded within a macroburst.


Photograph by: Moller

The transition line from ragged to smooth cloud texture, to the left and above the microburst, is where the right to left-advancing macroburst meets cloud base. This is the leading edge of the thunderstorm gust front ahead of a line of thunderstorms. Immediately behind the gust front and to the right side of the highway, the microburst has reached ground and is in the process of "curling" over the highway. Estimated wind speeds from moving dust parcels were 70 MPH. We will have more on the visual identification of microbursts later.

Tornadoes

violently rotating columns of air

The last severe weather element is the tornado. Defined as a violently rotating column of air in contact with the ground and pendent from a cumulonimbus cloud, tornadoes are capable of inflicting extreme damage.

Photograph by: Marshall

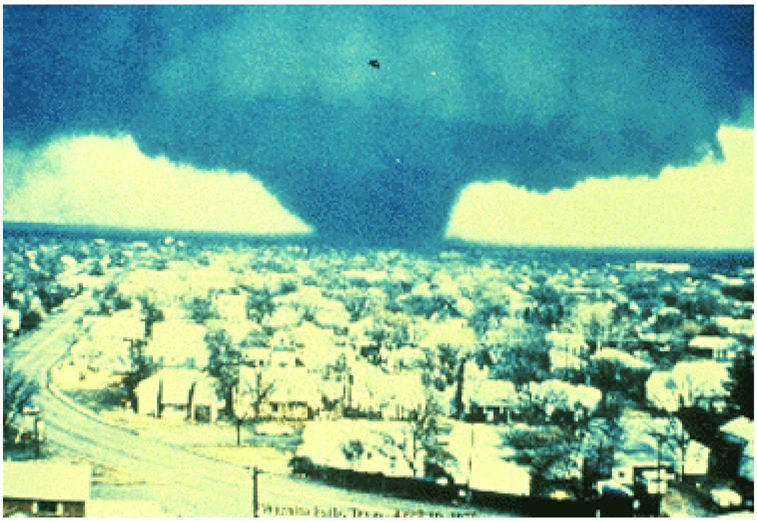
They can be categorized as "weak", "strong", and "violent"; with weak tornadoes often having a thin, rope-like appearance, as exhibited by this tornado near Dawn, Texas (looking west from about 1 mile). About 7 in 10 tornadoes are weak, with rotating wind speeds no greater than about 110 MPH.

The typical strong tornado often has what is popularly considered a more "classic" funnel-shaped cloud associated with the whirling updraft. Rotating wind speeds vary from 110 to 200 MPH.

Photograph by: NSSL

Nearly 3 in 10 tornadoes are strong, such as this twister on the plains of North Dakota. Looking northeast, note the spiraling inflow cloud, probably a tail cloud, feeding into the tornado. An important safety consideration is that weak and strong tornadoes, by definition, do not level well-built homes. Thus, a secure home will offer shelter from almost 100 percent of all direct tornado strikes.

Only violent tornadoes are capable of leveling a well-anchored, solidly constructed home. Fortunately, less than 2 percent of all tornadoes reach the 200+ MPH violent category. Furthermore, most violent tornadoes only produce home-leveling damage within a very small portion of their overall damage swath. Less than 5 percent of the 5,000 affected homes in Wichita Falls, Texas were leveled by this massive 1979 tornado. (Looking south from about 5 miles).



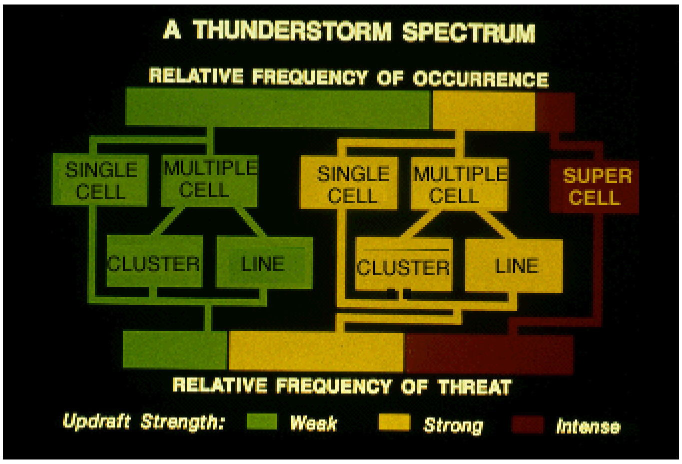
Photograph by: IDR

Note the huge, circular wall cloud above the tornado. This feature is probably close both in size and location to the parent rotating updraft (called a mesocyclone) which has spawned the violent tornado. Strong and violent tornadoes are usually associated with storms containing mesocyclones.

Types of Thunderstorms

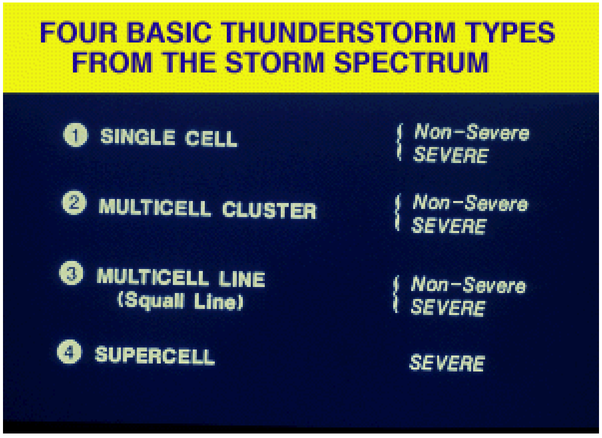
single cell, multicell clusters, multicell lines and supercells

The array of thunderstorms within the spectrum reflects our current scientific understanding. Thus, while the spectrum is very useful, it is neither perfect nor a final solution. Nevertheless, arrangement of storms within the spectrum is dependent on **updraft strength**, here represented by different colors; **relative frequencies of these updraft strength** categories, as indicated by differing lengths on the upper bar graph; **and relative threats of the updraft** categories, here represented by the lengths on the bottom bar graph.



Thus, while a "strong" updraft is less common than a "weak" updraft, the relative threat to life and property is greater with the "strong" updraft storm. Similarly, "intense" updraft storms are quite rare but inflict a disproportionate amount of damage and personal injury.

The breakdown into single cell, multicell, and supercell covers the major storm types within the spectrum. One "cell" denotes one updraft/downdraft couplet. Thus, there are several updrafts and downdrafts in close proximity with a multicell storm. Multicell storms can be broken down further into the categories of multicell line and multicell cluster storms. The "intense" updraft storm is almost invariably the supercell, a storm capable of producing the most devastating weather, including violent tornadoes.



With the two multicell storm categories, we have defined four basic storm types from the thunderstorm spectrum. The supercell is always severe, whereas the others can be non-severe or severe. We stress that a "severe" storm is a somewhat arbitrary National Weather Service definition of a storm with one or more of the following elements: 3/4 inch or larger diameter hail, 50 KT downbursts, and tornadoes.

Before reviewing these storms, it is important to emphasize that real thunderstorms do not always fit neatly into the categories we have just described. Research has suggested that the most basic distinction among storm types is between supercells and everything else, the so-called "ordinary" cells.

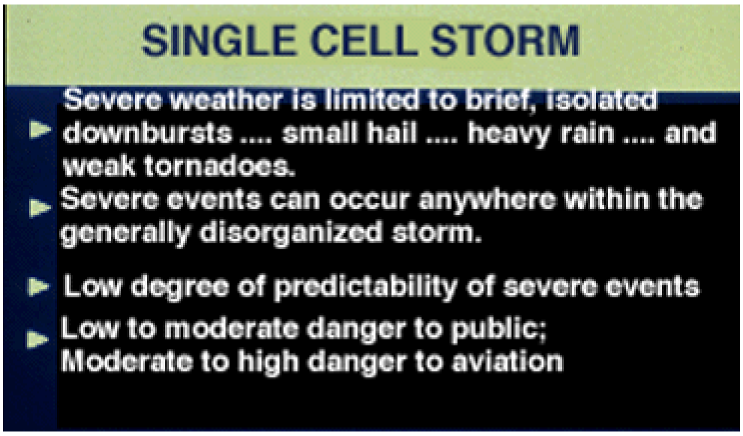
Non-supercell storms consist of one or more ordinary cells, and we have described three basic ways in which ordinary cells commonly occur: as **isolated cells**, as clusters of cells, and in lines of cells. Even though real storms can have physical traits that cross the boundaries of these categories, this classification scheme still has considerable value. This is because the intensity and type of weather events produced by a storm tends to be dependent on which category it fits most closely. We should also point out that a given storm may change its type one or more times during its existence.

Types Last Update: 7/23/97	**Single Cell Storms** Typically last 20-30 minutes. Pulse storms can produce severe weather elements such as downbursts, hail, some heavy rainfall and occasionally weak tornadoes. **Multicell Cluster Storms** A group of cells moving as a single unit, with each cell in a different stage of the thunderstorm life cycle. Multicell storms can produce moderate size hail, flash floods and weak tornadoes. **Multicell Line Storms** Multicell line storms consist of a line of storms with a continuous, well developed gust front at the leading edge of the line. Also known as **squall lines**, these storms can produce small to moderate size hail, occasional flash floods and weak tornadoes. **Supercells** Defined as a thunderstorm with a rotating updraft, these storms can produce strong downbursts, large hail, occasional flash floods and weak to violent tornadoes.

Single Cell Thunderstorms

also known as pulse thunderstorms

Single cell storms typically do not produce severe weather and usually last for 20-30 minutes. Also known as **pulse storms**, single cell storms seem quite random (perhaps because of our lack of understanding) in the production of brief severe events such as downbursts, hail, some heavy rainfall, and occasional weak tornadoes.



The "**degree of predictability**" is extremely low as forecasters are never quite sure which storm will produce severe weather and from which portion of that storm the severe events will occur. However, the microburst threat to aviation cannot be over-emphasized.

Photograph by: NSSL

This is a single cell storm, looking east from about 15 miles. The storm was moving east (into the photo). Some of the anvil cloud has been left behind the storm, but the greater portion of the anvil is blowing off in advance of the storm and is not observable from this perspective. (May storm in the Texas Panhandle near Amarillo.)

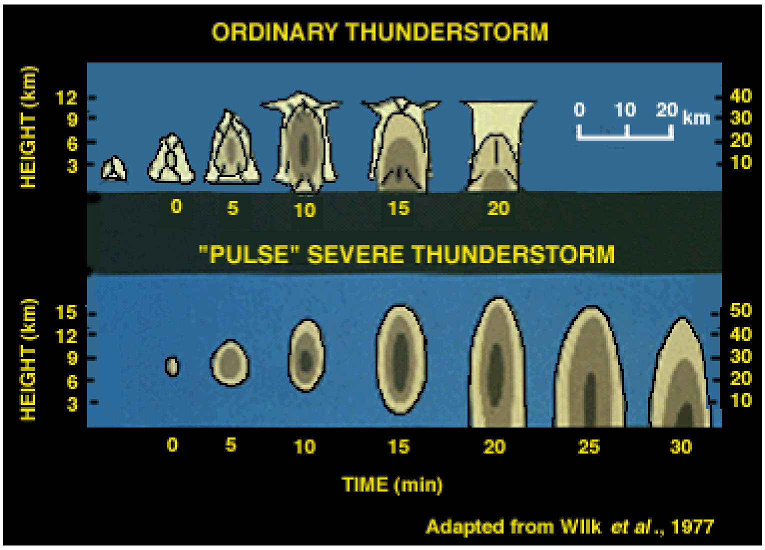
Photograph by: Moller

True single cell storms are relatively rare since even the weakest of storms usually occur as multicell updraft events. Some single cell thunderstorms are called "**air mass**" storms. This late May storm in Oklahoma, looking northeast from about 20 miles, occurred with weak to moderate vertical wind shear. It did not produce any severe weather.

Evolution of a Single Cell Storm

typical lifespan less than one hour

The upper sequence depicts the life cycle of a non-severe single cell storm in weak wind shear, with white cloud shapes and gray shades of progressively heavier radar reflectivity. Note the quick collapse of the rainy downdraft through the updraft. The bottom sequence depicts the radar history of the severe pulse storm. Note that the initial radar echo in the pulse storm develops at higher levels than in the non-severe single cell storms. Stronger radar reflectivities aloft with the pulse storm cascade down, resulting in a quick burst of severe weather, possibly hail but more likely downbursts, just before storm dissipation.



Rdar history of the severe pulse storm

Although both non-severe and severe single cell storms typically occur in weakly-sheared, summer atmospheres, the pulse storm usually occurs in a more unstable environment. Its stronger updraft allows for a slightly longer lifetime. Severe storm radar detection methods such as the Lemon Technique, developed for vertically-sheared environments, will not work very well with pulse storms. The exception to this is the case where the radar operator detects unusually strong mid-level reflectivities prior to updraft collapse.

Photograph by: Moller : Single cell storm

This is another single cell storm with tops near 40,000 feet, but on a day with virtually no vertical wind shear. Contrast the height of the cloud base with that in the previous photo. This storm had a much higher base, about 1/5 of the way to the storm top, or approximately 8,000 feet above the ground. The temperature and dew point temperature on this August day were 102 and 61, respectively. The low-based storm in the previous photo occurred with values of 94 and 74.

Storms that occur with 30 to 50 degree surface temperature/dew point spreads have relatively high microburst potential. (This is not to say that environments without such huge spreads will not produce microbursts!) This combination of surface observations and high-based Cbs should serve as "red flags" to pilots and aviation weather forecasters. Several short-lived storms that occurred in the Fort Worth area on this day produced microbursts.

Multicell Cluster Storms

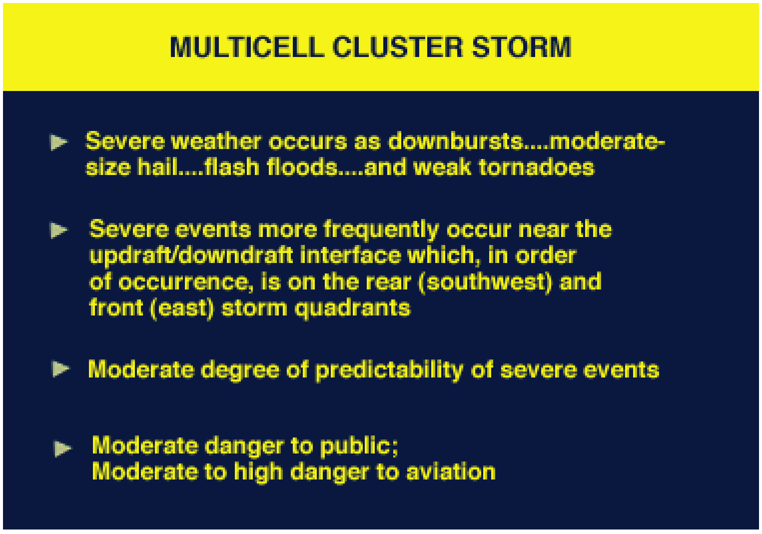
a cluster of storms in varying stages of development

A multicell cluster consists of a group of cells moving as a single unit, with each cell in a different stage of the thunderstorm life cycle. As the multicell cluster evolves, individual cells take turns at being the most dominant. New cells tend to form along the upwind (typically western or southwestern) edge of the cluster, with mature cells located at the center and dissipating cells found along the downwind (east or northeast) portion of the cluster.

Multicell cluster storms frequently look similar to the one pictured in the photograph below, (assuming that low visibilities and/or intervening clouds, trees, or hills do not obscure the view). Looking north from about 10 miles, note the three distinct updraft towers at the left (west) portion of the storm. The heaviest precipitation likely falls beneath the highest cloud top. The right (east) side of the complex is dominated by anvil outflow, moving with the storm from left to right.

Photograph by: Moller

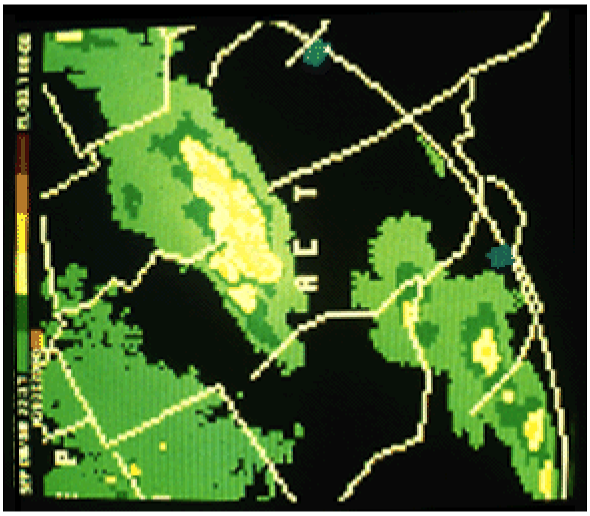
Multicell severe weather can be of any variety, and generally these storms are more potent than single cell storms, but considerably less so than supercells. Organized multicell storms have the higher severe weather potential, although unorganized multicells, which are simply conglomerates of single cells, can produce pulse storm-like bursts of severe events.



Actually, the distinction between multicell and single cell storms is not nearly as important as that between multicells and supercells. The multicell flash flood threat can be significant, in fact most flash floods probably occur with multicell complexes. As with all thunderstorms, the threat to the aviation community is quite high.

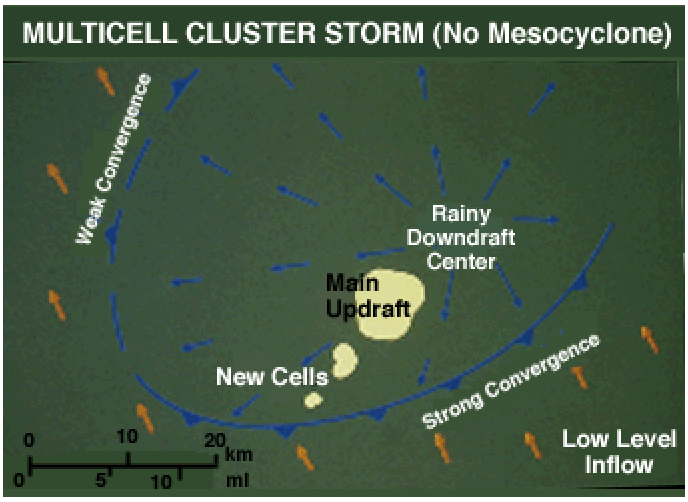
Components of Multicell Clusters

moderate dangers with some severe risk



Radar (PPI mode) often reflects the multicell nature of these storms, as seen with the central echo mass and its three light red (in this case VIP 5) cores in this photo. Occasionally, a multicell storm will appear unicellular in a low-level radar scan, but will display several distinct tops when a tilt sequence is used to view the storm in its upper extremities.

The close proximity of updrafts within the multicell cluster storm results in updraft competition for the warm, moist low-level air. Thus, updrafts never attain extremely strong vertical velocities and each has a short life span when compared to a supercell updraft. Naturally, multicell severe weather usually is less intense than that from supercells, but still can be quite potent, with marble to golf ball size hail and 60 to 80 MPH winds not uncommon.



This low-level, horizontal cross-section depicts a severe multicell storm or marginal supercell where the gust front typically has moved out ahead of and "undercut" the updraft area and possible wall cloud. Although the storm might well be severe, tornado production from the updraft/wall cloud area is unlikely.

Development of Multicell Cluster Storms

the flanking line and varying sheared environments

A multicell cluster storm, the most common of the four basic storm types, evolves as an organized sequence of cells in various stages of development and decay at any given time. When multicell storms form in environments with winds which veer from southerly to westerly and increase with height, new updraft development usually occurs in the upwind (usually southwest) quadrant of the complex, with older cells decaying in the downwind quadrant.

Photograph by: Doswell

The new development, called the **flanking line**, is at the left (southwest) side of the complex. The rain-free base disappears beneath the twin towers on the right-hand side of the photo, since precipitation is falling from these glaciated thunderstorm cells.

Glaciation refers to the transformation of cloud particles from water droplets to ice crystals. The visual cloud appearance often changes from rock-hard to soft during the glaciation process. The northeastward tilt of the multicell complex above indicates the presence of vertical wind shear (looking north from about 12 miles).

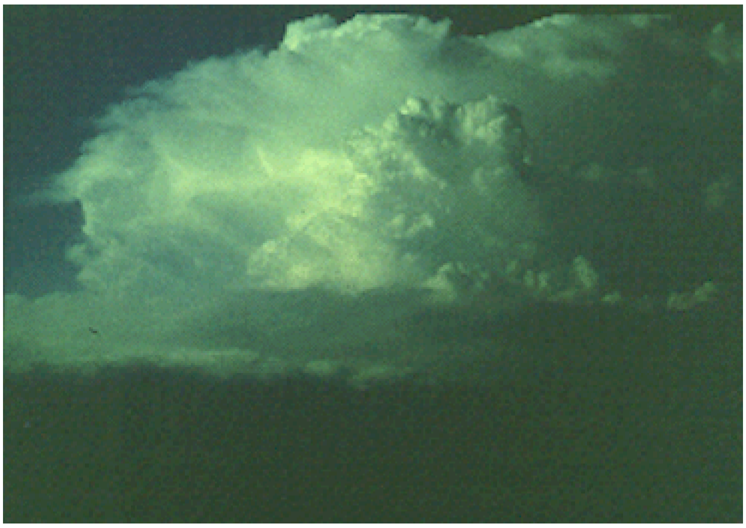
Photograph by: Doswell

Another multicell storm, this time looking south in an even more strongly sheared wind field. Precipitation is beginning to fall from the Cb top on the left (east) side of the complex. (Western Oklahoma storm, June 1980).

Multicell Clusters from Different Perspectives

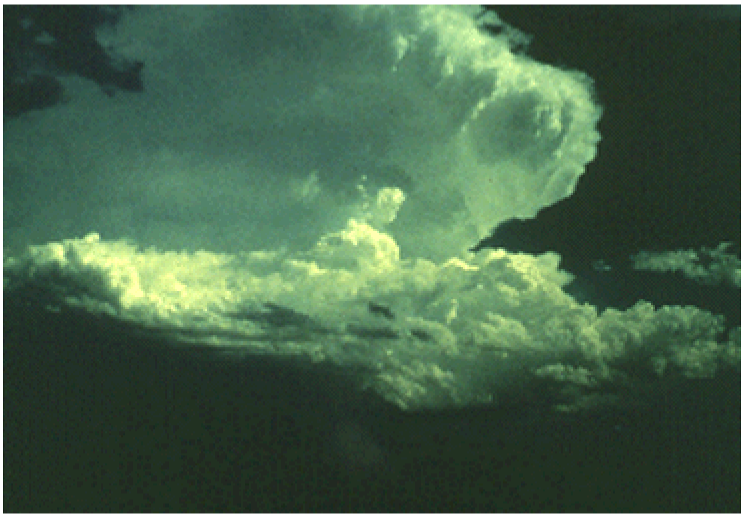
viewing from the northeast and southeast

We are looking northeast from about 15 miles, along the axis of the flanking line into this multicell storm. Note the several "humps" of multicellular Cb top embedded in the anvil.



Photograph by: NSSL

The soft or glaciated appearance of the Cb tops and anvil suggests little chance for updraft-dependent severe weather with this storm, as these visual clues strongly suggest a relatively weak or diminishing updraft.



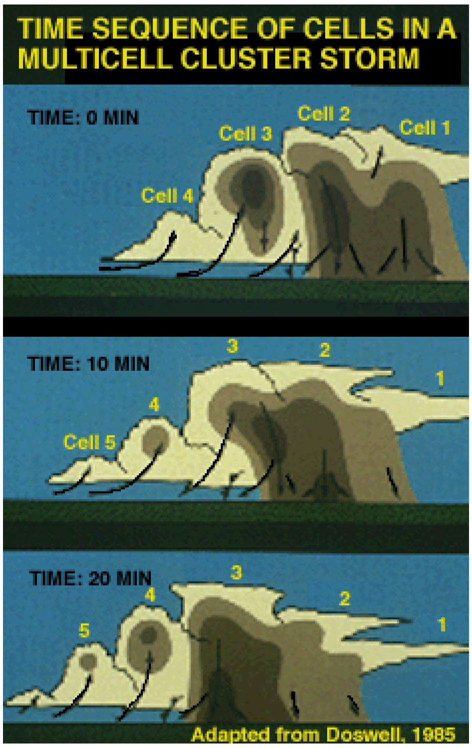
Photograph by: Doswell

This southeast view of another multicell storm, from about 12 miles, shows a much crisper appearing Cb top, with hard, cumuliform structure also seen in the anvil. Another clue that this is a strong updraft is the "back-sheared" anvil, overhanging the back flank of the right-to-left moving storm complex. This storm produced marginally-severe, one inch diameter hail in West Texas in 1977.

Life Cycle

evolution of cells in a multicell cluster

This illustration portrays a portion of the life cycle of a multicell storm. As cell 1 dissipates at time = 0, cell 2 matures and becomes briefly dominant. Cell 2 drops its heaviest precipitation about 10 minutes later as cell 3 strengthens, and so on.

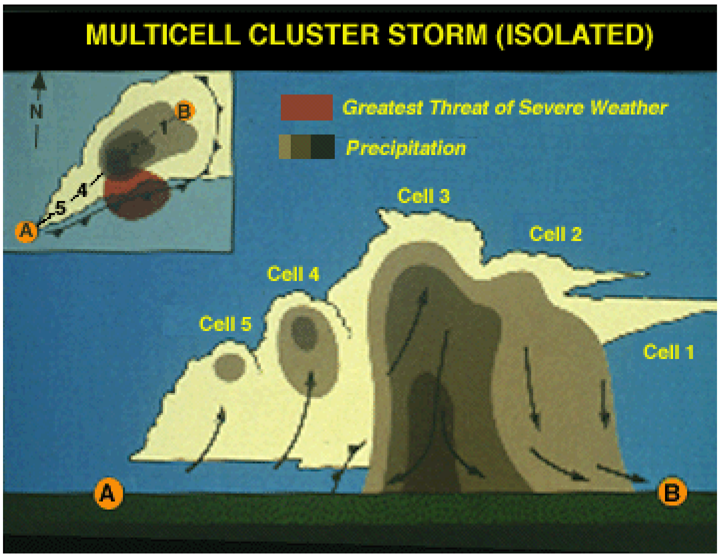


Thus, severe multicell storms characteristically produce a brief period of hail and/or downburst damage during and immediately after the strongest updraft stage. Later updraft resurgence may or may not result in further damage, leading to a spotty damage pattern.

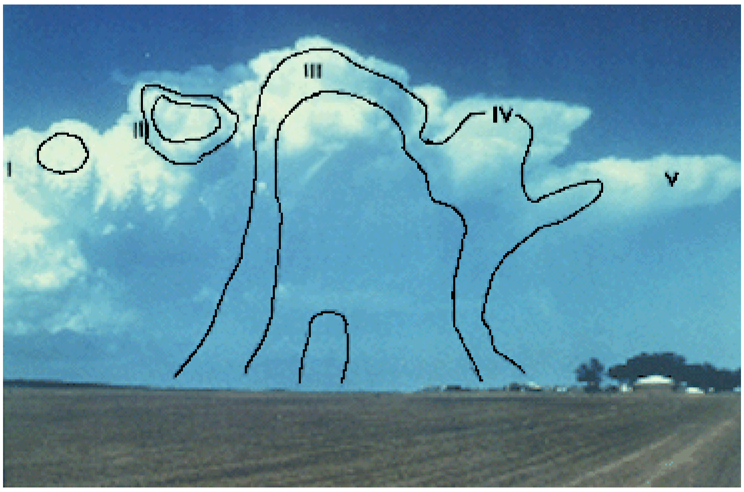
If the winds in the storm environment are blowing from left to right, it can happen that the storm motion arising from new cell development nearly cancels the motion arising from the environmental winds. Thus, new cells reach maturity over the same location, repeatedly.

This is the train-echo pattern of flash flood producing rainfall, although train echoes also may occur as different multicell thunderstorm complexes moving across an area with a greater time interval. Not having the benefit of radar, it will seem to citizens living in an area receiving repeated, short-term precipitation bursts that the storm is backing up and moving across again and again. This is a popular but erroneous notion.

A closer view at T = 20 minutes (from in the above slide) shows that cell 3 still has the highest top, but precipitation is undercutting the updraft in the lower levels. New echo development is occurring aloft in cells 4 and 5 in the flanking line, with only light rain falling from the dissipating cells 1 and 2 on the northeast side of the storm cluster.



The inset shows what the low-level PPI radar presentation might look like. This storm appears to be unicellular but the several distinct echo tops tell us otherwise. Note that the greatest risk of severe weather at this time extends from beneath the heavy precipitation areas of cell 3 (hail and downbursts) into the area of the leading gust front (downbursts and, on rare occasions, weak gust front tornadoes or gustnadoes).



Photograph by: Moller

Here is a real storm, with radar superimposed. Observe the physical similarities to the second slide. This Texas Panhandle storm was non-severe. Looking north-northeast from about 20 miles. Note that the updraft numbering is reversed.

Evolving Storm

an unusually severe multicell cluster storm

This is how some multicell cluster storms will appear as they approach, again assuming good visibility. The ominous shelf cloud, appearing like a mustache with this storm, is the leading edge of the storm outflow. Observe the rain-free updraft bases ahead of and above the shelf cloud. (Near Monahans, TX, 1977).

Photograph by: Moller

The storm was unusually severe, packing hail from 1 to 3 inches in diameter and 70 MPH winds. Most of the hail was from 1/2 to 1 inch in diameter. Looking east, note the steam fog arising from the fresh hailfall, as the storm ends.

Photograph by: Moller

From the backside we watch as the same storm cluster moves away to the east. Observe the southeastward-tilt of the clouds in the short flanking line and the precipitation area to the east. The flow aloft was from northwest to southeast (rather than southwest to northeast), influencing the tilt of the storm tops.

Photograph by: Moller

It is curious that this storm showed updrafts on the leading (east) edge as it approached, and on the back (northwest) side as it moved off. The storm was definitely multicellular, although not as "clear-cut" about preferred updraft locations as other multicell storms we have viewed. Again, nature does not always allow us to label and catalog everything neatly!

Concerning storms in northwest flow aloft, it has been observed that the updraft area frequently shifts to the southeast flank, when rain-cooled air keeps warm, southerly winds from providing a continual feed to the northwest flank updrafts. Thus, with this storm it is possible that the leading (southeast flank) updraft area became predominant once heavy precipitation began, with the northwest updraft area no longer benefiting from the "prime" air.

Multicell Lines

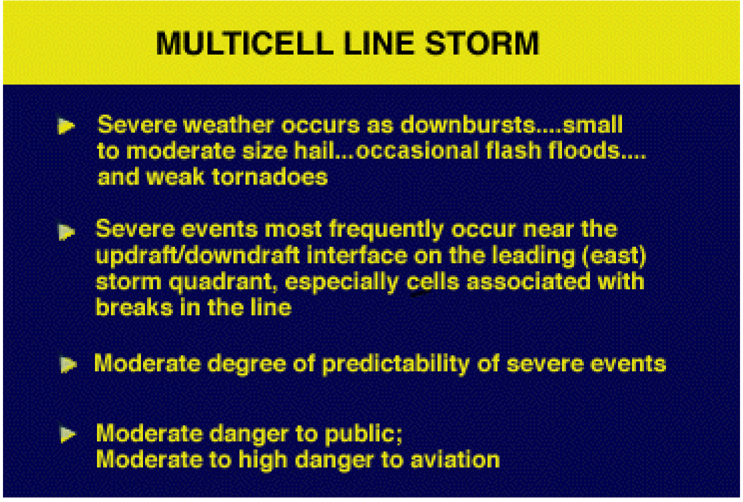
also known as **squall lines**

Multicell line storms consist of a line of storms with a continuous, well developed gust front at the leading edge of the line. An approaching multicell line often appears as a dark bank of clouds covering the western horizon. The great number of closely-spaced updraft/downdraft couplets qualifies this complex as multicellular, although storm structure is quite different from that of the multicell cluster storm.

Photograph by: Doswell

Multicell line storms are better known as **squall lines**, which is the term that we will use from here on. The former name is for positioning squall lines in the thunderstorm spectrum.

Squall lines most frequently produce severe weather near the updraft/downdraft interface at the storm's leading edge. Downburst winds are the main threat, although hail as large as golf balls and gustnadoes can occur. Flash floods occasionally occur when the squall line decelerates or even becomes stationary, with thunderstorms moving parallel to the line and repeatedly across the same area.



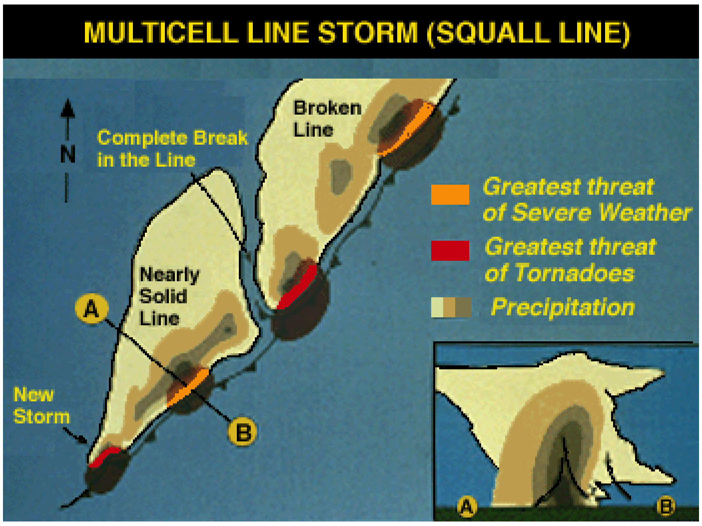
Squall lines with a confirmed severe weather history allow for the issuance of reliable warnings. Pilots should be extremely cautious, as they should for all thunderstorms, particularly near the squall line's leading updraft/downdraft interface.

Components
of multicell lines

This particular storm evolved from a supercell into a short line of storms at the time of the photograph. We are looking west from about 5 miles, as the storm approached. Wind damage and large amounts of small hail were occurring within the squall line at this time.

Photograph by: Moller

The squall line is a solid or broken line of thunderstorms with a continuous, well-developed gust front on the leading edge. Thus, updrafts and new updraft development occur on the downwind (east) side, where the squall line is moving into unstable inflow air. The gust front lifts warm moist air into the updraft, and the cool downdraft lowers mid-level air to the ground. Squall lines are common, especially in vertically sheared environments where the mid-level winds are moderate to strong.



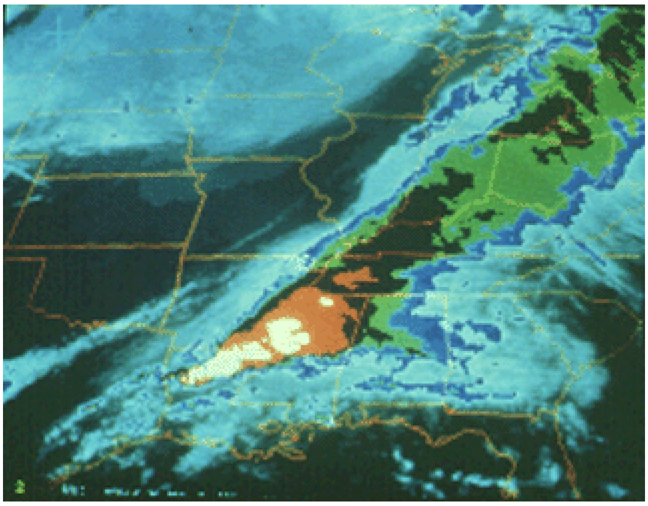
The most common severe weather element in squall lines, by far, is the downburst, with damaging winds possible from the time of gust front passage, into the period of heavy precipitation. Hail may occur with the rain, with the heaviest rain and largest hail adjacent to the updraft. Dissipating elements at the rear of the squall line often result in a period of light rain before cessation of precipitation.

Intense storms, in rare cases even tornadic supercells, periodically occur in squall lines. The most likely locations for these more powerful storms are at an eastward bend, on the south end, or north of a significant break in the line. Note that all of these positions allow a storm to compete better with its neighbors for the low-level inflow air.

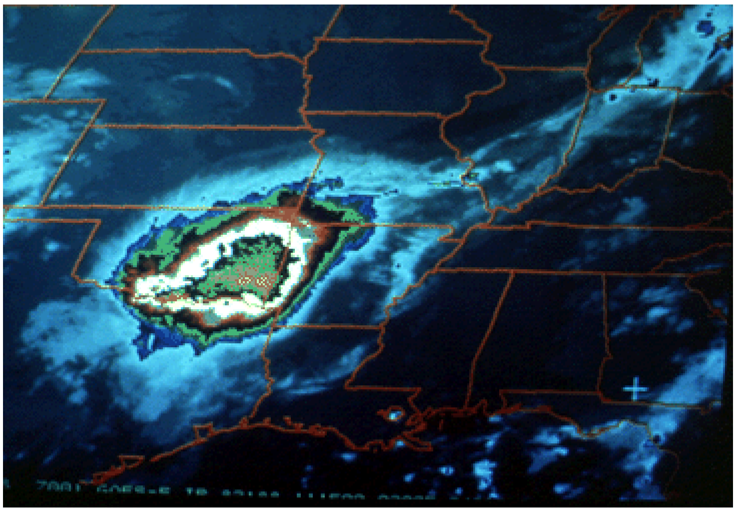
On Satellite Images

squall lines and mesoscale convective systems

This infrared satellite view of an eastward moving squall line, extending from the Ohio River Valley southwestward into Louisiana, shows the extreme lengths that thunderstorm lines can achieve. The lower, warmer anvils on the north end of the line and the colder, higher cloud tops at the south end reveal the tendency for older, weakening storms to be shed on the north side of the line with newer and stronger development near the south end.



The second satellite photo shows a huge anvil cloud arising from a large cluster of storms. This is called a **mesoscale convective system** or "**MCS**". An entire MCS cannot be viewed from the ground and in some cases not even by a single radar, so we use the satellite perspective. It is a group of multicell storms, often dominated by a vigorous squall line on the downwind (east) side and a number of weaker multicell cluster storms in the interior.



An MCS often will bring severe weather and heavy rain with the squall line, and additional heavy rainfall with the interior storms. A number of major flash floods have resulted from MCS passage, making this large storm complex an extremely important grouping of multicell thunderstorms to recognize.

Features Along The Leading Edge

shelf clouds and vaulted cloud structures

This rather innocuous appearing squall line probably is more typical in appearance than some of the spectacular squall lines we have been viewing. Note the subtle shelf cloud ahead of the dark precipitation area. This was a non-severe squall line in eastern Oklahoma in the fall, looking west from about 5 miles.

Photograph by: Doswell

Underneath the shelf cloud and looking north, note the change in appearance from the ragged, outflow-torn clouds to the smoother elements ahead of the line. The outflow winds had commenced at this time, and hail and heavy rain were to arrive in minutes.

Photograph by: Moller

This strong gust front (shown below) was accompanied by 40 and 50 MPH winds and a shelf cloud with a highly-sloped concave shape to the underside.

Photograph by: Moller

Near the light area on the southwest horizon, a downburst was resulting in damage at this time, as reported by Amateur Radio Spotters southwest of Fort Worth, Texas. The squall line was moving eastward (right to left).

Retreating Lines

an examination of backside features

After the precipitation has ended, a squall line is seen moving into the eastern horizon. Stable, stratiform clouds (those that develop in layers rather than clumps) predominate on the rear flank of a squall line.

Photograph by: Doswell

Mammatus often appear on the underside of the rear flank anvil (although they are also common on the front-flank anvil), as in the upper portions of the photograph. This upwind squall line anvil is not the same as a strongly back-sheared anvil, but consists of anvil refuse left behind as the advancing gust front moves rapidly eastward. The same phenomenon occurs when the squall line advances southeast or east, while upper winds blow anvil material north and northeast.

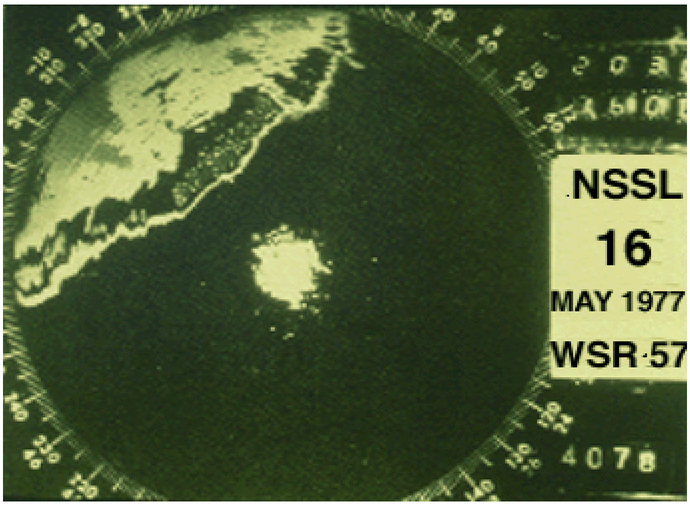
Photograph by: Doswell

Continuing its eastward movement, a squall line is pictured at sunset, looking to the distant southeast. The largest tops near the south end of the line graphically illustrate the tendency for fresh, strong convection to build southward with time, towards the area of strong inflow.

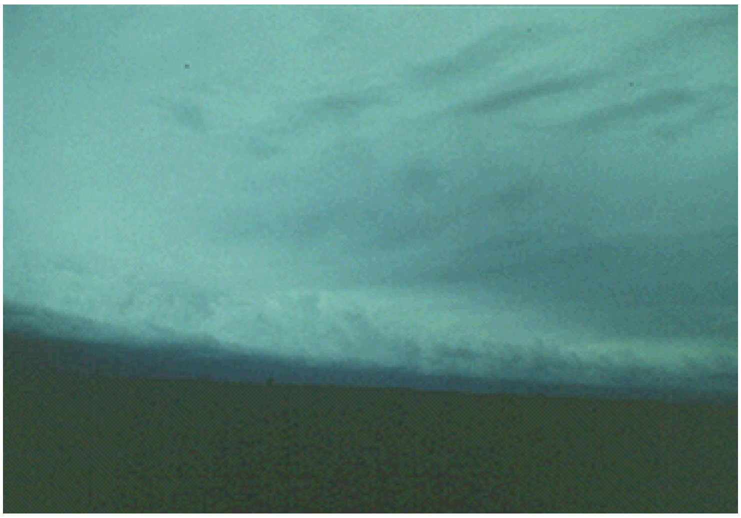
Linear Radar Echoes

squall lines on radar images

Radar indicates the linear nature of a squall line. The strongest radar reflectivity (VIP) levels on the leading edge reveal the locations of updrafts and adjacent regions of heavy precipitation.



From the eastern plains of Colorado we see a distant, approaching squall line, about 20 miles to the west. Further east from the High Plains, we would be less likely to have this unrestricted view because of haze and intervening clouds.



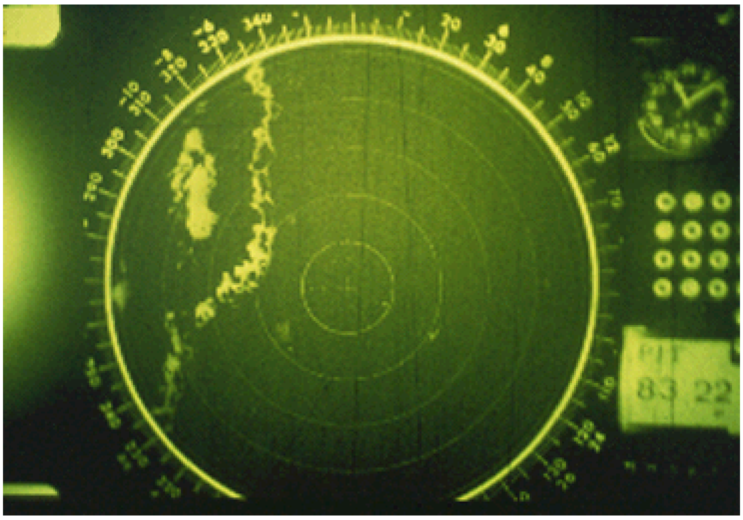
Photograph by: Moller

Nevertheless, similar storm structure, with new updrafts developing on the leading edge of the gust front, will be present regardless of location.

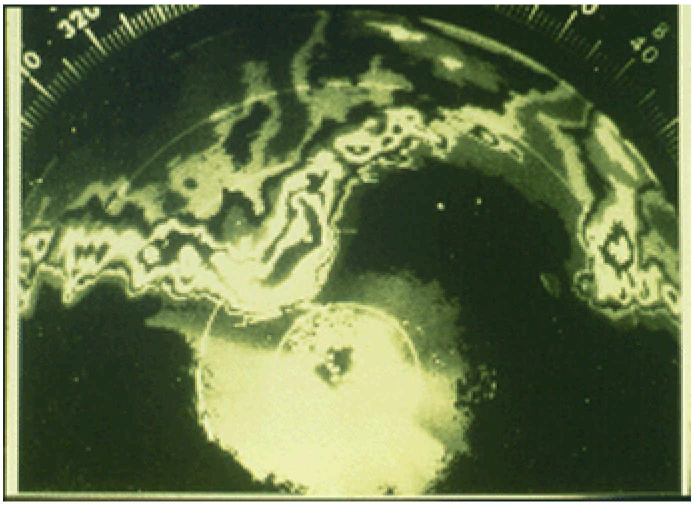
Bow Echoes on Radar

often accompanied by strong outflow winds

Large scale bow-shape squall lines sometimes are called line-echo wave patterns (LEWPs). Large areas of strong outflow winds, sometimes reaching strong downburst force, often occur. Tornadoes have been known to occur near and north of the apex of the bow. Widespread but scattered minor wind damage occurred along the eastward bow of this central Indiana squall line.



Below is a smaller scale bow echo. Short thunderstorm lines and multicell cluster storms can both evolve into bow echoes. Research indicates that these smaller scale bow echoes can be more dangerous than the large scale variety, with rotating comma head structures more likely to develop.

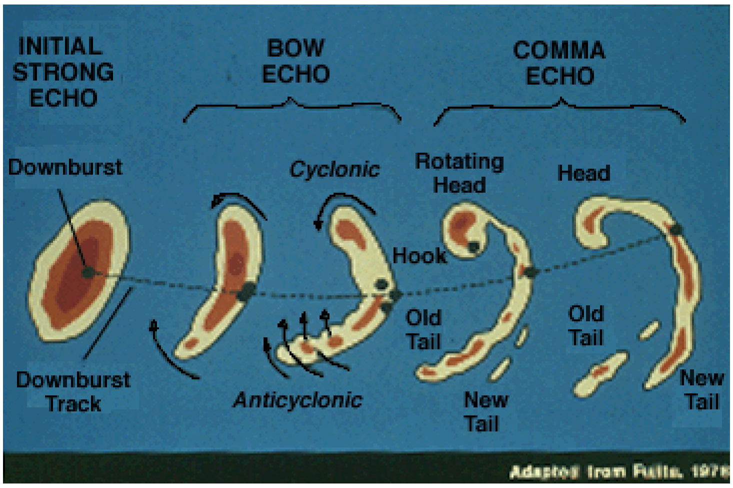


Bow echo storms occur in all parts of the country during unstable periods and with fairly strong vertical wind shear, but they seem to have a particular affinity for the area from the Northern and Central Plains eastward into the Ohio River Valley during strong northwest flow aloft in late spring and summer.

More About Bow Echoes

schematic radar view and observed events

Squall lines and multicell storms occasionally develop the appearance of a "bow echo" on radar. When the bow shape opens toward the strong mid-level winds (10 to 20 thousand foot level winds of 40 knots or greater), there is an excellent chance that the strong mid-level currents have been transported to the ground in a downburst, forcing a portion of the squall line or multicell storm to accelerate forward. Macroburst and microburst winds are common with these storms, and 100+ MPH winds have been reported in extreme cases.



Weak to occasionally strong tornadoes may occur with the comma head, while gustnadoes may form on the strong bow echo gust front.

Photograph by: Doswell

This is a northward view of a gustnado, a tornado that develops on a thunderstorm gust front with marked across-front horizontal shear. Gustnadoes typically are weak and short-lived as tornadoes go, since they are not associated with an intense deeply rotating updraft. They are also nearly impossible to warn for, because of their seemingly random occurrence along the gust front.

The bow echo weakens as the accelerating downburst outruns the storm complex. Those who operate radar should be aware that the rotating comma head occasionally has deceptively weak radar reflectivity while producing damaging winds and tornadoes.

Photograph by: Moller

Smaller scale bow echoes frequently can be detected from visual observations. This southward view shows the underside of a right to left (eastward) moving storm's shelf cloud, with the southern extent of the complex bowing radically eastward in the background. Damaging winds and a radar bow echo occurred within this area.

We need to stress that it is not the job of spotters to detect and report bow echoes, but spotters should know what they are dealing with and what the main severe weather threats are if Weather Service personnel ask them to check out a bow echo complex.

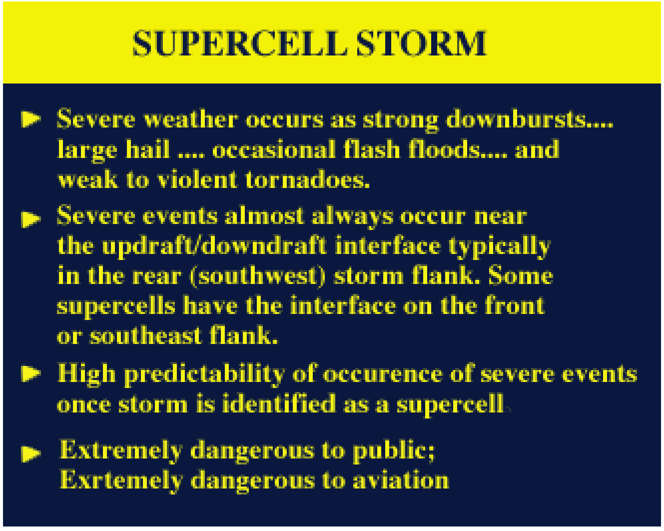
Supercell Thunderstorms

thunderstorms with deep rotating updrafts

The last of the four major storm types is the supercell. We define a **supercell** as a thunderstorm with a deep rotating updraft (mesocyclone). In fact, the major difference between supercell and multicell storms is the element of rotation in supercells. As we shall see, circumstances keep some supercells from producing tornadoes, even with the presence of a mesocyclone.

Photograph by: Moller

Even though it is the rarest of storm types, the supercell is the most dangerous because of the extreme weather generated. This storm was producing baseball hail east of Carnegie, Oklahoma, as it was photographed looking east from 30 miles. From right to left (south to north), we note the flanking line, main Cb, and downwind anvil above the precipitation area.



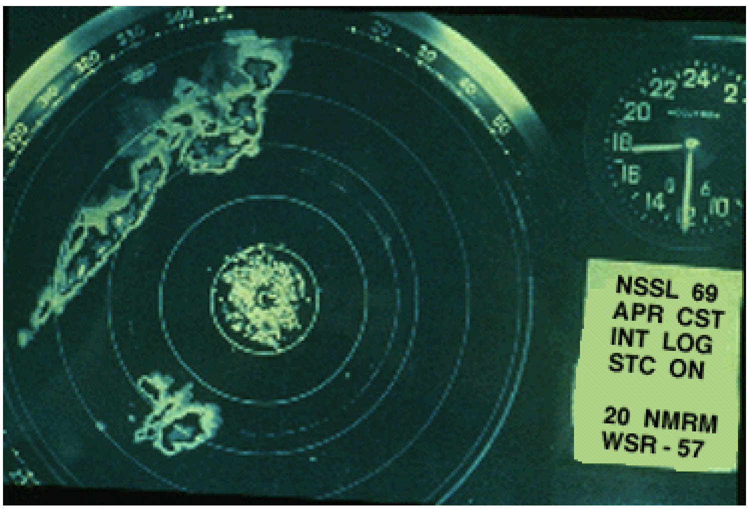
The flanking line of the supercell behaves differently than that of the multicell cluster storm, in that updraft elements usually merge into the main rotating updraft and then explode vertically, rather than develop into separate and competing thunderstorm cells. In effect, the flanking updrafts "feed" the supercell updraft, rather than compete with it.

In summary, supercells are extremely dangerous, but excellent warnings are possible once the storm has been properly identified. The demarcation between supercell and multicell storms is most important, obviously much more so than that between single cell and multicell storms, or between multicell and squall line storms. As mentioned earlier, it has been suggested that thunderstorms simply be classified as "supercells" and "ordinary" storms. A few supercells will have the updraft located on the leading southeast (or east) flank, as we shall see in the section, Supercell Variations.

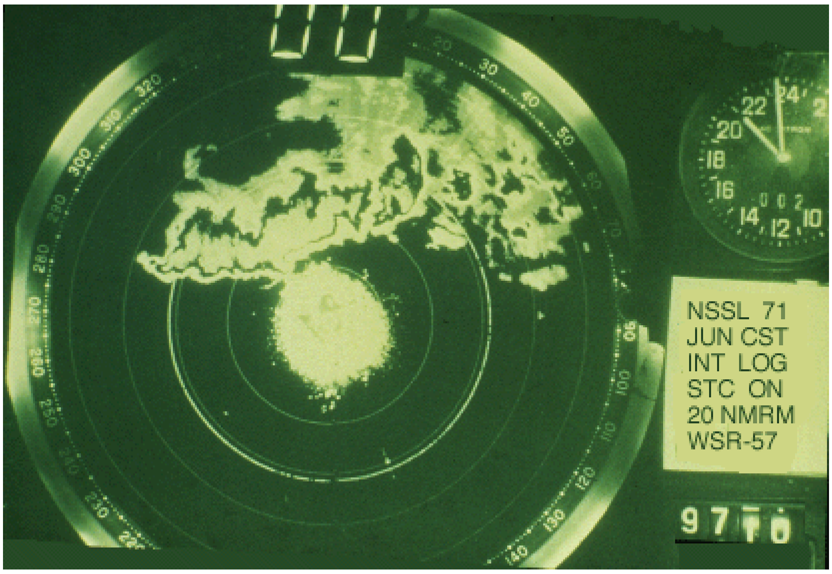
On Radar Images

supercells tend to develop in isolation

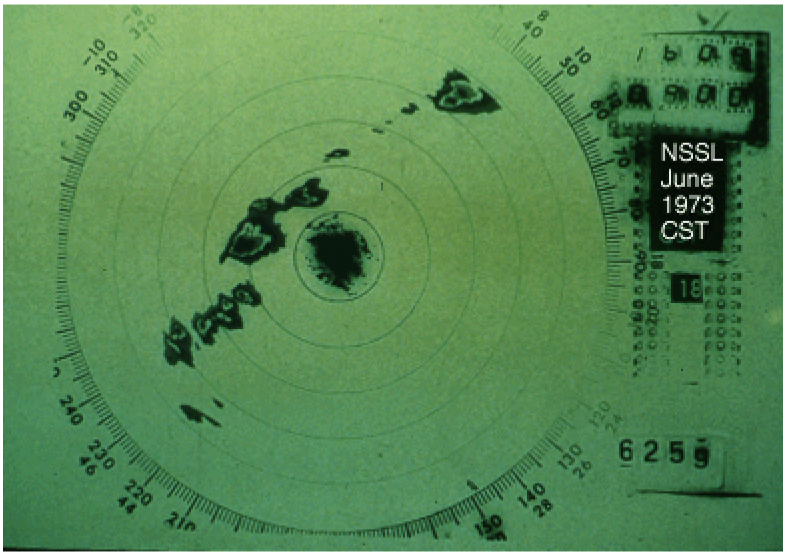
Supercells most frequently are isolated and often develop in the warm air ahead of a squall line. This supercell formed south-southwest of the radar site and produced large hail and tornadoes well ahead of a broken to solid squall line.



This supercell, north-northwest of the radar, developed within an east-west oriented solid squall line. It produced severe weather and funnel clouds, but no known tornadoes. Subjective experience suggests that such storms are not as likely to produce strong to violent tornadoes as are more isolated storms.



However, other evidence shows that storm spacing, which is necessary for significant tornado formation, is probably greater on the High Plains than that in the southeast U.S., possibly because of the abundant moisture near the Gulf of Mexico. Supercells frequently occur in "preferred" regions relative to other radar echoes. First, in this case of a scattered to broken line of thunderstorms, a supercell is evident due west of the radar site, positioned in a weakly-developed LEWP and north of a break in the line.

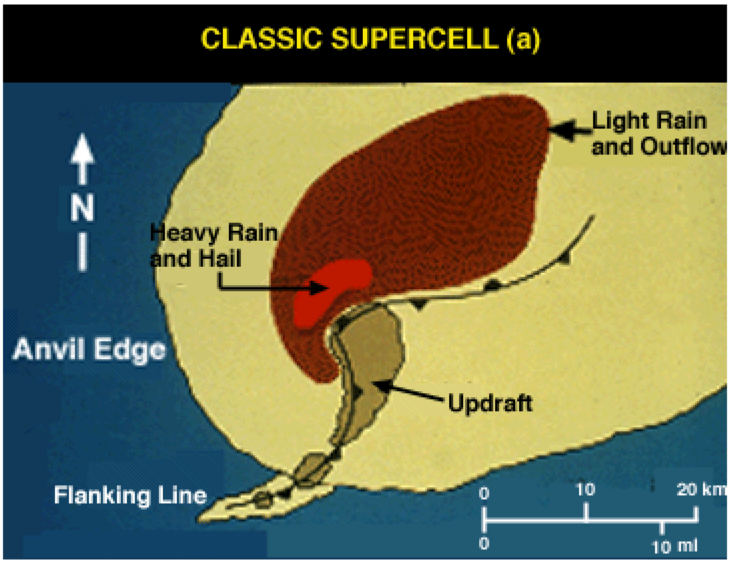


Surface data indicates that a small scale low pressure system, about 100 miles in diameter, probably accounted for the LEWP configuration. Supercells often form near or immediately northeast of such a low. The lack of other storms in the immediate vicinity of this supercell allowed the intense storm to produce tornadoes and large hail for several hours without interference. The slow-moving storm also produced flash flooding.

Schematic Diagrams

horizontal cross-section and westward view

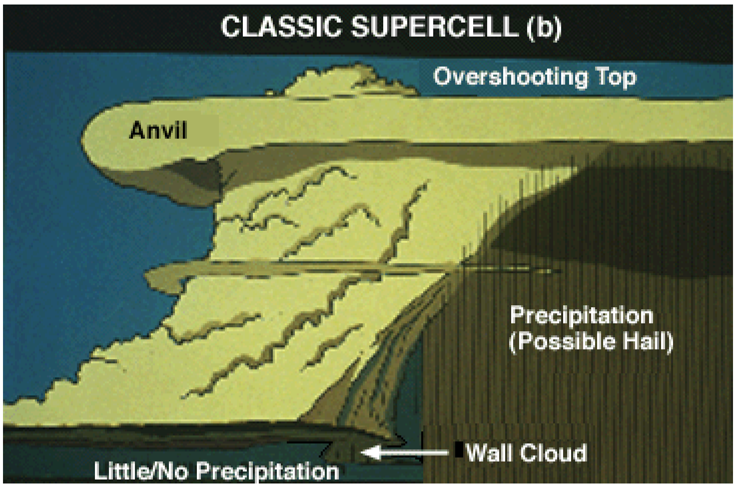
This is a horizontal, low-level cross-section of a "classic" supercell. The storm is characterized by a large precipitation area on radar, and a pendant or hook-shaped echo wrapping cyclonically around the updraft area. Note the position of the updraft and the gust front wave. The intense updraft suspends precipitation particles above it, with rain and hail eventually blown off of the updraft summit and downwind by the strong winds aloft. Updraft rotation results in the gust front wave, with warm surface air supplying a continual feed of moisture to the storm.



Updraft rotation occurs when winds through the troposphere are moderate to strong, and low-level turning is significant. As inflow air in the lowest 1-3 kilometers approaches the storm from the south or southwest, the low level turning results in the development of rotation about a horizontal axis. As the air is lifted into the updraft, the rotation is "tilted" to that about a vertical axis. To see this rotation about a horizontal axis caused by wind shear, imagine rolling a tube along a table-top with the palm of your hand.

The movement of your hand represents the strong winds above the surface, producing rotation because the winds near the ground are much weaker. This simple picture is complicated by the turning of the wind direction with height, but the concept remains similar. Lifting this "horizontal" vortex into the updraft results in cyclonic rotation.

A westward view of the classic supercell reveals the wall cloud beneath the intense updraft core and an inflow tail cloud on the rainy downdraft side of the wall cloud. Wall clouds tend to develop beneath the north side of the supercell rain-free base, although other configurations occur.



Observe the nearly vertical, "vaulted" appearance of the cloud boundary on the north side of the Cb and adjacent to the visible precipitation area. A sharp demarcation between downdraft and rotating updraft results in this appearance. Note the anvil overhang on the upwind (southwest) side of the storm and the overshooting top, both visual clues as to the intensity of the updraft.

Overshooting Tops

indicative of powerful updrafts

Looking east from about 40 miles away, we see a line of towering cumulus clouds and a large supercell storm in the background. Note the great amount of anvil overhang and the large overshooting dome at the summit of the updraft.

Photograph by: Doswell

Distant supercells frequently have this domed, "diffluent" anvil appearance, with the supercell's tremendous updraft velocities and outflow resulting in marked upper-level divergence. The visual clues are strong, although we cannot be sure that this is a supercell simply from appearance. By necessity, man and machine (i.e., spotters and radar) complement each other in the severe weather detection program. This storm produced hail but no known tornadoes in eastern Oklahoma.

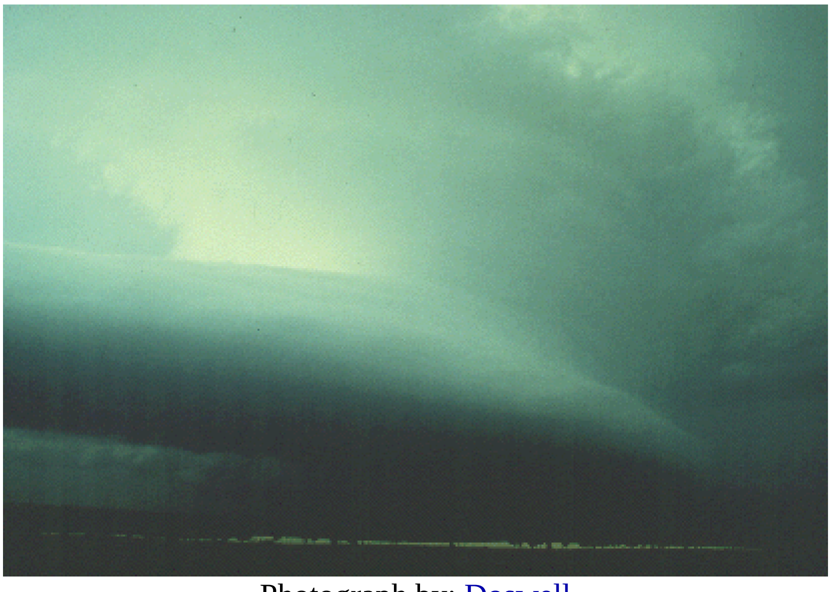
Photograph by: Bluestein

This supercell featured a rock-hard, overshooting Cb top and anvil overhang, looking southeast from about 40 miles away. Note that the supercell Cb is more vertically oriented than the weaker updraft of the neighboring towering cumulus cloud. This is a valuable clue in estimating the strength of updrafts on a day with strong vertical wind shear. This storm produced baseball hail, but no known tornadoes, along a track in southeast Oklahoma and southwest Arkansas.

Rotating Updrafts

visual clues

There are ample signatures of updraft rotation in this hazy, northeastward view of a very intense supercell from 40 miles away. The circular mid-level cloud bands and the smooth, cylindrical Cb strongly hint of updraft rotation. Above the mid-level cloud band, an extremely hard Cb top is barely visible (upper right) towering into the anvil. Note the smooth, "laminar" flanking line on the extreme left. A strong, "capping" temperature inversion in the low levels probably accounted for the laminar appearance of the flank.



Photograph by: Doswell

Cloud elements moved along the flank into the main Cb, with rapid vertical development occurring at the merger point. Close examination of the photo will reveal a wall cloud beneath the lower left edge of the Cb, with a relatively bright "clear slot" ahead of the wall cloud. Within 20 minutes, the storm produced two significant tornadoes near Alfalfa, Oklahoma.

Photograph by: NSSL

A close, westward view of a supercell updraft and adjacent precipitation cascade strikingly resembles the model we have just seen. Wall clouds frequently slope downward towards the precipitation area, as shown. If you are a mobile spotter and encounter a view such as this, turn around and out-run the storm by going eastward or, better yet, move away from the storm to the southeast. This is very close to the fall area of large hailstones, and moving north or waiting at this location will put you in danger from large hail and tornadic winds.

Backlighting

for better viewing of tornadoes

A view toward the west or northeast, often with revealing backlighting, typically offers the best view. This is the same Itaska, Texas storm, seen through a telephoto lens, looking west from about 15 miles!

Photograph by: NWS

Such spectacular distant views are relatively rare, especially in the east and southeast U.S. where low clouds, haze, precipitation, trees, and hills make spotting from a distance more difficult.

In this rare photograph we can see both the parent cumulonimbus cloud (Cb) and the tornado.

Photograph by: NWS

The indentation on the left side of the Cb in this photo seems to verify the presence of a rear flank downdraft (RFD), with a clear distinction between hard-textured updraft cloud and the ragged, dissipating cloud elements caught in the RFD. The tornado is at the intersecting point of the rotating updraft and RFD.

Variations

supercell storms come in a variety of shapes and sizes

Supercell storms come in different shapes and sizes, as observed on radar and by the human eye. Some are very prolific precipitation producers, whereas others produce very little precipitation that reaches the ground.

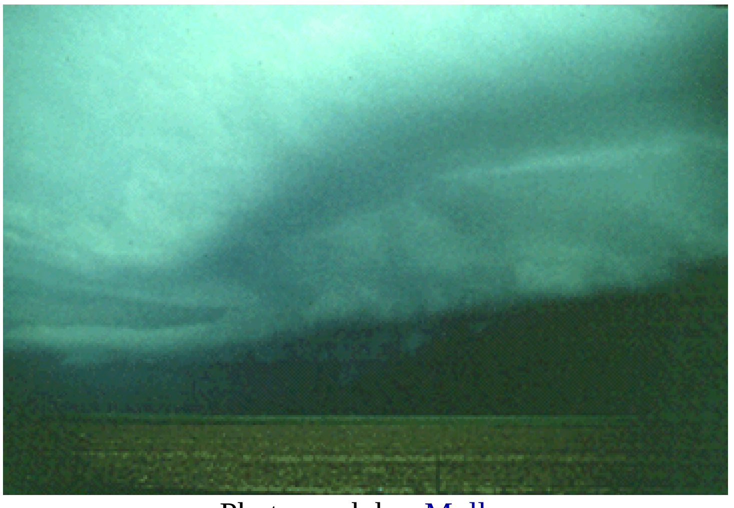
Photograph by: Moller

This is a westward view of a high precipitation (HP) supercell approaching in the evening light.

Hard, cumuliform anvil overhang, a vertical Cb edge, and flanking line are all visible in this southeastward view of a supercell storm. Mammatus can be seen on the underside of the north Texas supercell. Golf ball size hail, downbursts, flash flooding, and rotating wall clouds occurred without any known tornadoes.

Photograph by: Moller

This slide shows the problem that frequently arises in viewing a tornadic storm to the north -- lack of contrast. The dark precipitation area all too often blends in with wall clouds, tornadoes, etc. However, important clues as to the nature of this particular storm are visible, including the circular, mid-level cloud bands we saw in an earlier storm. These bands suggest rotation, and this storm did produce at least one tornado.



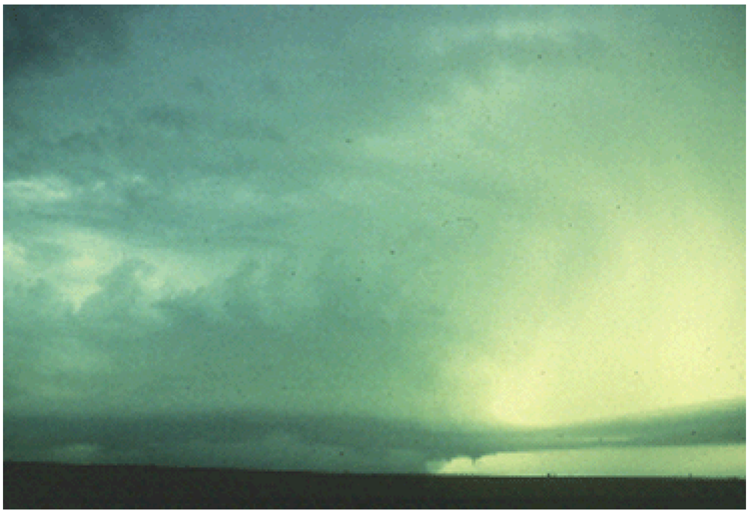
Photograph by: Moller

Also note the flat, elongated cloud on the right side of this photo. This is another type of "tail cloud," with the appearance of a beaver's tail. The east-west oriented cloud frequently is seen in the vicinity of the stationary gust front or "pseudo-warm front," which is northeast of the rotating updraft. The "beaver's tail" usually is at rain-free base level, slightly higher than the tail cloud associated with a wall cloud. Storm chase veterans consider these clues to be strong evidence of a supercell and suggestive of possible tornado formation, although not every tornadic supercell has pronounced mid-level rotating cloud bands and inflowing tail clouds.

High Precipitation (HP) Supercell

very heavy rainfall, possible large hail, downbursts and tornadoes

In this photograph, the typical HP storm visual appearance is present: beaver's tail inflow bands curling into the front-flank updraft, a gray area of anvil precipitation to the north, and a dark rain and hail core to the southwest, falling from what earlier had been the rain-free base.



Photograph by: Doswell

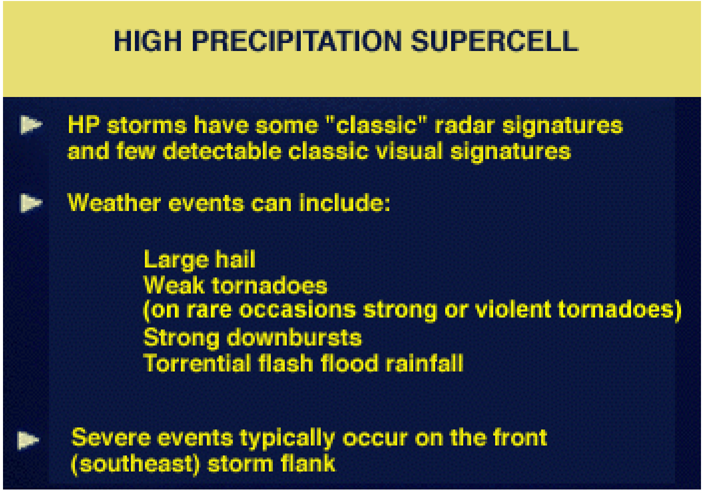
In the HP stage, this storm produced large hail, gusty winds, and extremely heavy rainfall, as well as several funnel clouds. One of these is visible where the inflow bands intersect the updraft. Continuous lightning occurred with this storm, much of it in-cloud, but a sizable percentage being cloud-to-ground strikes. Indeed, HP supercells seem to be especially prolific producers of lightning.

Photograph by: McGinley

Another HP supercell is pictured in the distant west. The characteristic inflow bands are present in front of a translucent, anvil-born precipitation area on the extreme right. Note the rotating, vaulted Cb adjacent to the anvil precipitation, and the dark precipitation shaft in the left-center, emanating from an area that would be visually rain-free in a classic supercell. This storm produced a 1/2 mile wide tornado shortly before this time. It later produced several smaller and weaker tornadoes. Many times when a tornado does form from an HP supercell, the southwest flank precipitation area literally wraps around the tornado, obscuring it from view.

Characteristics of (HP) Supercells
radar features, weather events and severe events

Heavy precipitation supercells have some identifiable radar features, including "broad hooks" and/or large inflow notches on the east and southeast storm flank. A lemon technique tilt sequence will indicate a weak echo region (WER), overhang, and highest top in alignment on the leading flank. These storms will be quite difficult for spotters to handle because of both the lack of contrast between the updraft and surrounding rainy-downdraft areas, and lack of past training about these storms.



HP supercells are prolific flash flood producers, and this threat should not be overlooked in light of the other severe weather elements being reported with such a storm.

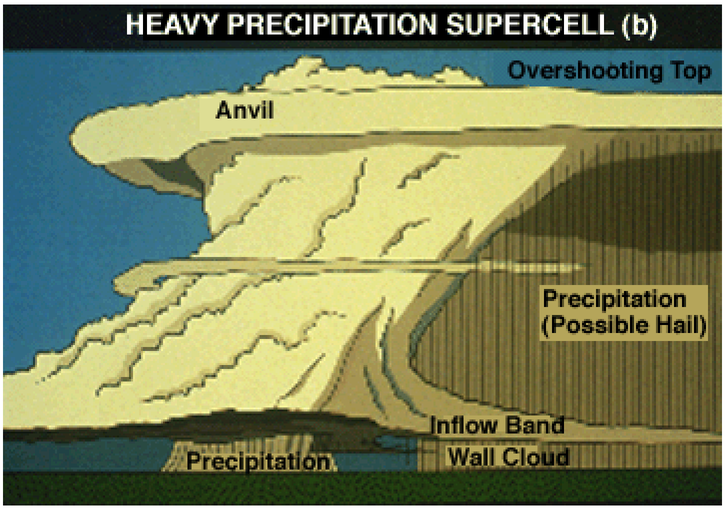
Photograph by: NWS

An HP storm in Fort Worth, Texas, produced almost 5 inches of rain within one hour, with most of the rain falling within 45 minutes. Some indications are that HP storms might be somewhat more frequent in the southeast U.S., but they do occur in most areas east of the Rockies. Quite important to storm spotters and severe weather forecasters is that HP supercells probably account for many of the "tornado embedded in rain" events, a phenomenon that occurs not only in the southeast but elsewhere, including the High Plains.

Westward View of HP Supercell

precipitation curtain wraps around the west and southwest flanks

A westward view of a composite HP storm model shows the position of an inflow cloud band, very similar to the previously mentioned beaver's tail cloud in the classic supercell. In fact, the HP storm has an appearance similar to the classic supercell, except for the opaque precipitation curtain wrapping around the west and southwest flanks of the wall cloud and/or updraft.

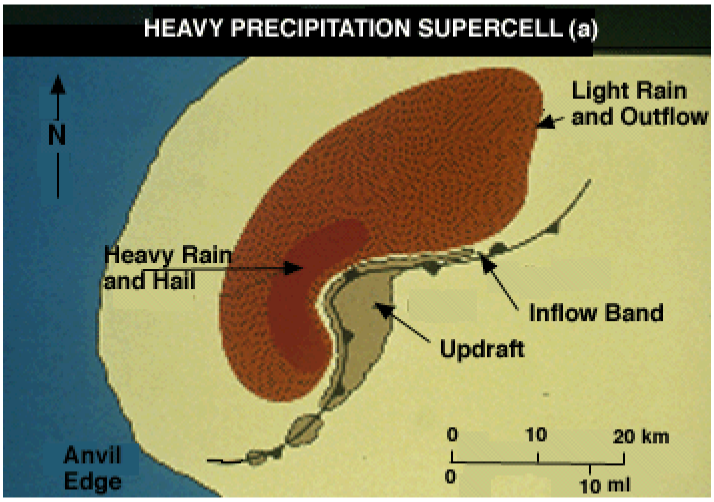


Sometimes the precipitation is a solid visual curtain, and at other times there is a distinct break, shown here, between the precipitation falling from the anvil area and that descending from the southwest flank. The southwest flank precipitation shaft is often visually dark and blue-green in color, indicative of unusually heavy rain and hail.

Photograph by: Neiman

This is a westward view of an HP storm in extreme northeast Colorado. Cyclonically-curving inflow bands are visible in the upper portions of the photo, feeding into the updraft area. The storm had a very well-developed wall cloud, with precipitation wrapping around the north, west, and southwest flanks of the lowered cloud base. Note the subtle gust front and shelf cloud extending southward from the wall cloud.

Spotters will have a difficult time with the HP supercell, since there can be poor visual contrast between the wall cloud and precipitation behind it. The strongest visual clues in identifying this type of supercell usually are the curving inflow bands and mid-level cloud bands which wrap around the updraft, both suggestive of storm-scale rotation. This dramatic storm produced large hail but no known tornadoes.



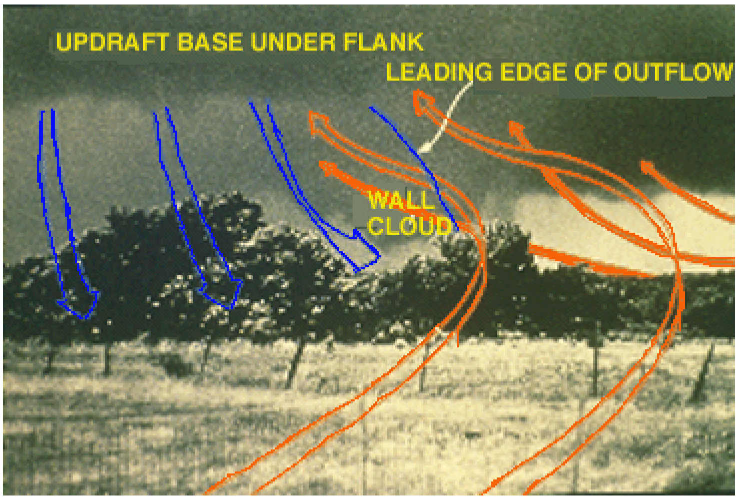
This is a low-level, horizontal cross section through a wet or heavy precipitation (HP) supercell. Basically, the HP supercell has a broad hook or pendant, usually with high radar reflectivities (VIP 5s or 6s). Occasionally, the HP supercell has an even more pronounced southwest flank precipitation area, with the radar echo taking the shape of a kidney bean or letter "C".

The inflow/rotating updraft notch will face east, and with nearly equal size precipitation areas northwest and southwest of the mesocyclone. Whichever is the case, the rotating updraft is on the leading storm flank, with heavy precipitation falling into the west and southwest flanks of the mesocyclone. Note the inflow band in the vicinity of the pseudo-warm front east of the updraft.

Flow Field of Tornadic HP Supercells

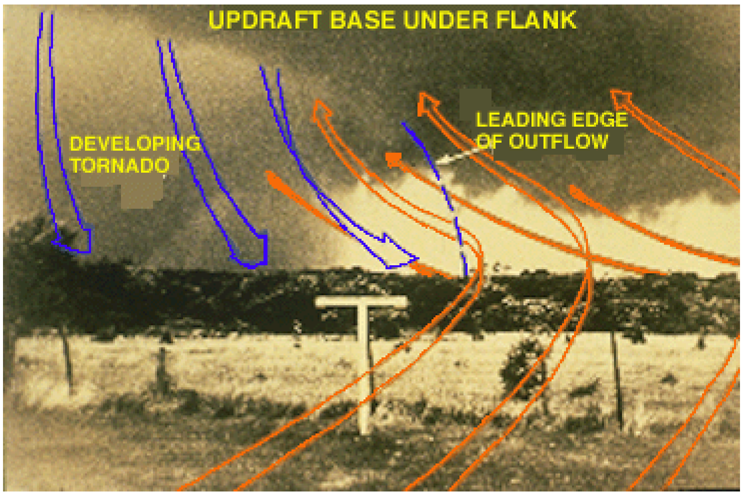
inflow and outflow

A few HP storms do produce violent tornadoes. When they occur, the tornadoes often will be wrapped in precipitation and quite difficult to observe. The photographer heard a roaring sound, and ran outside where he had this westward view. Behind the super-imposed inflow arrows is a wall cloud, with a rain area and RFD wrapping from left to right around the wall cloud's southeast flank. This rain shaft is visual manifestation of the radar hook (an unusually "fat" radar hook in this case) wrapping around the wall cloud and developing tornado.



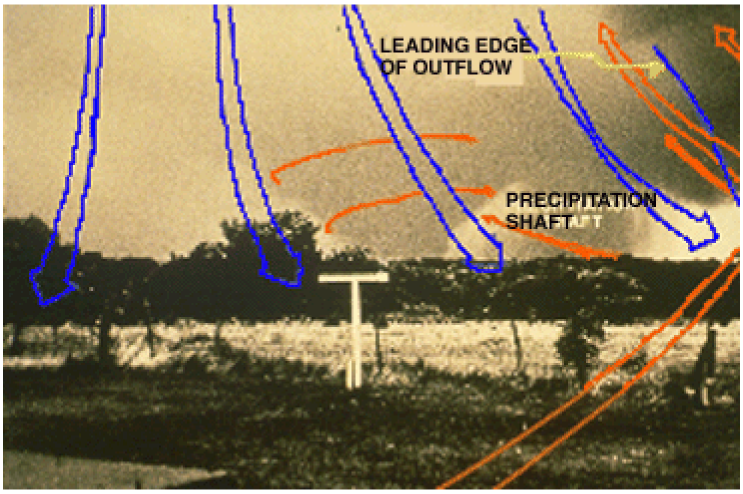
Photograph by: NSSL

We are in a position of strong inflow, as noted by the northward-bending trees (in the image below). However, a gust front (blue, descending arrows) is accompanying the precipitation and approaching the photographic position. The brunt of the HP storm's precipitation area is out of the photo and to the right (northeast of the wall cloud).



Photograph by: NSSL

Still hearing a roaring sound, the photographer shifted his view a bit towards the northwest. Almost hidden behind the advancing rotating rain curtain is a large and devastating tornado!



Photograph by: NSSL

The rain curtains that wrap around an HP supercell's tornado often change very quickly in appearance. Minutes later, the tornado is not quite as obscured by the precipitation. View these three slides a second time and observe the advance of the rain curtain and gust front. The tornado was continuing to receive a narrow corridor of inflow from the northeast at this time, as it approached Drumwright, Oklahoma. Fourteen people were killed by this violent 1974 tornado.

Developing Along Outflow Boundaries

from previous thunderstorms

HP supercells frequently have been observed to develop or intensify as they moved parallel to and along a stationary outflow boundary from previous thunderstorms. This is a northward view of such an outflow boundary, with several large thunderstorms in the distant and extreme right side of the photo moving away from our position. Note the long shelf cloud that has been left behind the storms and along the boundary.


Photograph by: Doswell

Looking southwest along the same outflow boundary, observe the distant thunderstorm at the end of the outflow line, with the Cb tower and anvil visible on the left hand side of the photo.

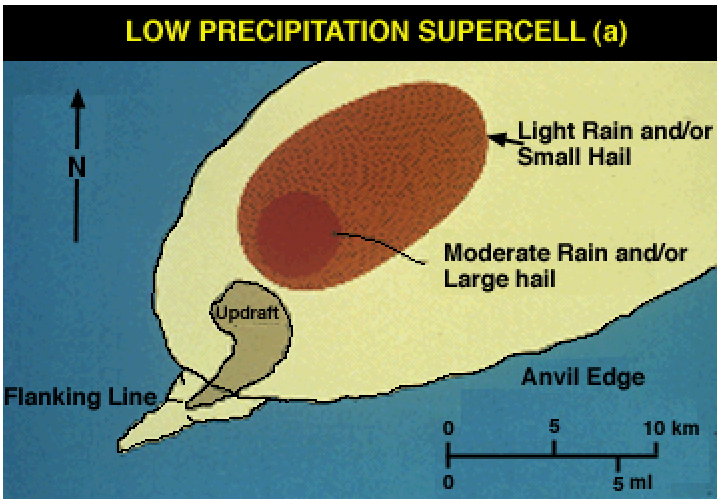
Photograph by: Doswell

A multiple-vortex tornado had just dissipated from beneath this distant updraft, and an opaque precipitation shaft was developing in the previously rain-free area where the tornado occurred.

Low Precipitation (LP) Supercells

lacking in liquid rainfall content

At the opposite end of the supercell scale is the Low Precipitation (LP) supercell. For years, storm chasers have observed LP storms in the Plains' states, usually in conjunction with a dry line or low pressure trough dividing dry, warm air to the west from very humid air to the east. These rotating storms typically are quite small and lacking in liquid rainfall content.

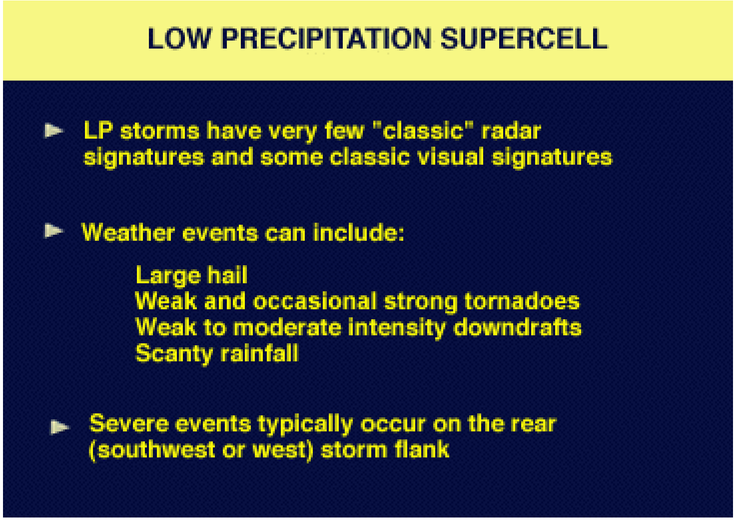


The radar echo rarely contains a pendant or hook, although the LP storm may have a tight reflectivity gradient at the southwest side. In many cases, the small size of the storm will not allow for adequate "beam filling", especially at moderate to long range from the radar. Therefore, the radar intensity of the small storm can be drastically underestimated.

This northward view of an LP storm in western Oklahoma shows both the small size and the powerful nature of the updraft. This storm was shrinking to an even smaller size at this time, which is how most LP storms meet their demise. Note that the updraft tower is scarcely any wider than the wall cloud. The storm earlier produced golf ball size hail and, although it rotated vigorously, it did not produce any tornadoes.

Photograph by: Doswell

Low-precipitation supercells probably rarely occur, if at all, east of the Mississippi River. They frequently produce large hail, funnel clouds, and wall clouds, and occasionally spawn weak or even strong tornadoes. Radar identification of the storm as a supercell is difficult, especially at great range, because of the relatively small size and dry nature of the storm. Similar to the classic supercell, but unlike the HP storm, severe weather usually occurs in the southwest quadrant of the LP storm.

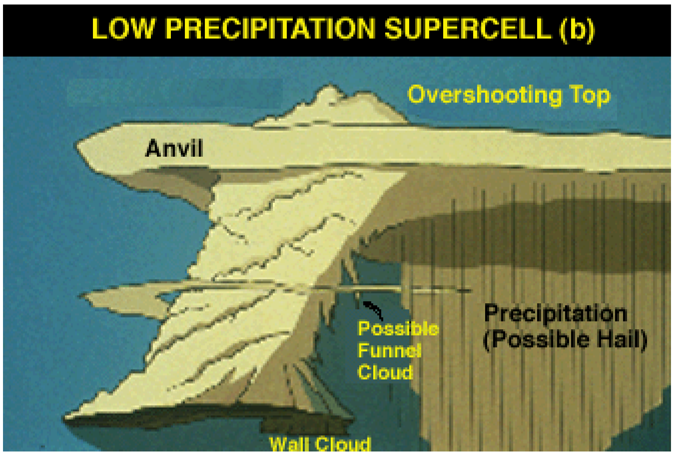


One last point of discussion for radar operators: spotters may report very wild visual sights and large hail with one of these storms while radar shows very little. Diplomacy, not disbelief, is important, for if you work severe weather in Texas, Oklahoma, Kansas, Nebraska, the Dakotas, or eastern portions of Colorado and Wyoming, you will encounter the LP supercell sooner or later.

LP Supercell With Tornado

plus rotating cloud bands and vaulted appearance

A westward view of the LP storm model's vertical cross-section shows the LP storm's undersized, rotating Cb and its small, nearly transparent precipitation area. Rotating cloud signatures are commonly visible in this supercell type, and wall clouds are frequently observed.



An oddity is that this bare-bones storm type occasionally fosters small funnel clouds that extend from the mid-levels of the Cb rather than from the Cb base! At times weak or even strong tornadoes develop from the vicinity of the wall cloud.

This LP storm did produce tornadoes -- two of them. The storm actually bordered between an LP and a classic supercell as it has a fairly large and intense radar echo (VIP 5), including a pendant. In this westward view, we note that the wall cloud was on the north side of the rain-free base, with spectacular rotating bands arranged much like barber pole stripes around the parent Cb.

Photograph by: Moller

This view gives us an excellent feel for the scale relationships between the rotating updraft and the tornado that occasionally develops beneath such an updraft. Remember, the radar hook echo is roughly equivalent in scale to the rotating Cb, whereas the tornado itself is much smaller.

Photograph by: Moller

The same storm is pictured looking northwest, as the tornado was lifting/weakening into a funnel cloud (extreme lower left). The storm has a spectacularly vaulted appearance adjacent to the precipitation area, which was nearly transparent. Scattered raindrops were falling in this precipitation area, along with 5 inch diameter hail! Thus, the lack of an opaque precipitation curtain does not preclude the possibility of very damaging hail.

This storm produced about 5 million dollars in hail damage in Borger, Texas, with one rain gauge that survived the hail fall showing only 1/4 of an inch of liquid rain. The tornado that we have witnessed in these photographs produced several hundred thousand dollars damage to an oil refinery, and several injuries.

Evolution From Multicell To Supercell

multiple updrafts merge into a single updraft

This late afternoon New Mexico storm has subtle indications of being multicellular. Can you see the two major updraft areas? You cannot always discern between storm types by visual observations. Radar usually is the best tool for that purpose, but in many cases the visual appearance will yield important clues.

Photograph by: Olthoff

This is the same storm complex less than one our later. The multicell complex apparently has evolved into a storm with one dominant updraft. The storm has become a supercell.

Photograph by: Olthoff

The storms we have seen lead us to ask several fundamental questions: What environmental factors influence the type or types of storms and the intensity of severe weather that occurs on a given day? And why does a storm sometimes evolve from one type to another?

Tornadic Supercell
produced six tornadoes

This supercell did produce tornadoes, six of them. About the time this photograph was taken, the last of the six tornadoes was occurring. From this vantage point about 20 miles north of the storm, near Itasca, Texas, we see a small portion of the rain-free base beneath the updraft area, but no tornado. Obviously, a spotter must have the right position relative to the storm to see tornadoes.

Photograph by: Moller

The same storm and its sixth tornado were photographed in a different location at about the time the last photo was taken. Looking northeast from 4 miles, we are on the other side of the precipitation seen in the last photo.

Photograph by: NWS

The left to right moving condensation funnel is partially illuminated by late afternoon lighting. Note the sharp-edged precipitation curtain on the right side. The combination of strong and adjacent vertical drafts often results in very heavy hail and rain curtains immediately downwind (usually northeast) of the updraft. Indeed, spotting position does make a difference, although the optimal view of a late afternoon supercell is not towards the northeast.

The following sections provide training in updraft/downdraft analysis, effects of wind shear on thunderstorm development, dangers of various outflow phenomena generated by thunderstorms and how to spot wall clouds.

Components

[Updrafts / Downdrafts]
Updraft and downdraft intensification and determining updraft strength using the Lemon Technique (LT).

[Wind Shear]
Wind shear and its impact on thunderstorm development.

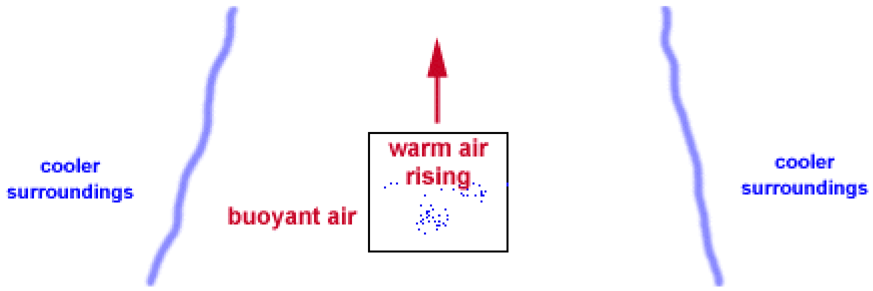
[Outflow Phenomena]
Outflow phenomena including: microbursts, macrobursts, gust fronts and virga.

[Wall Clouds]
Characteristics of wall clouds and common scenarios in which they occur.

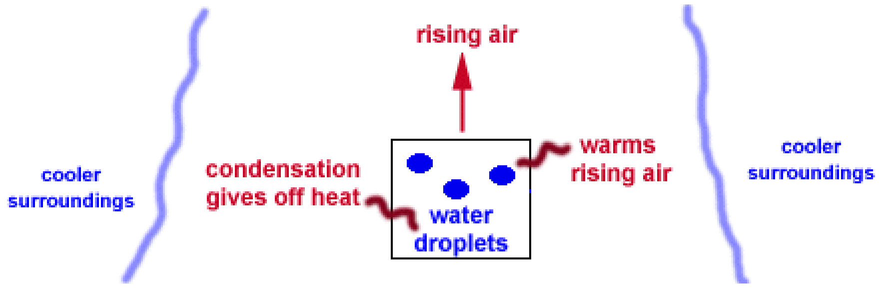
Updrafts/Downdrafts

rising and sinking air

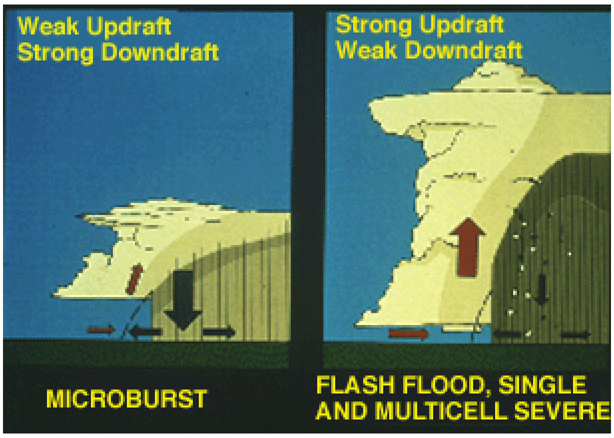
All thunderstorms require instability (potential) and lift. The lift is the mechanism that releases the instability. Lift is produced by such things as fronts and low pressure troughs, or by air rising upslope.



We say that the atmosphere is unstable when air rising in a cloud is warmer than its environment, like a hot-air balloon. It is the heat released by condensation within a cloud that permits the rising air to stay warmer than its surroundings, and thus to be buoyant through great depths.

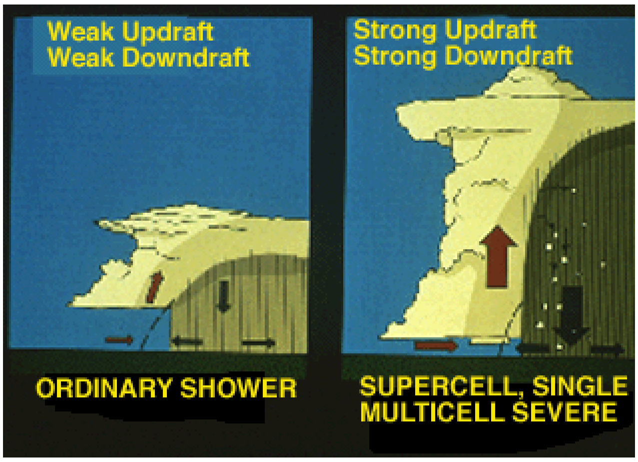


In the same way, air that is cooler than its environment tends to sink as long as it can stay cooler than its surroundings. The upward moving air in a thunderstorm is known as the updraft, while downward moving air is the downdraft. The atmosphere can be unstable for updrafts but stable for downdrafts, stable for updrafts but unstable for downdrafts, stable for both, or unstable for both. The degree of atmospheric instability is one of the two major factors in determining the strengths of thunderstorm updrafts and downdrafts. Furthermore, vertical draft strengths basically determine the degree of storm severity. If we consider a "generic" storm, there are four possible combinations of weak and strong draft strengths.



When the low-level air is unstable but relatively dry and adequate mid-level moisture is present, a storm may develop with a weak updraft but a strong downdraft with the latter the result of strong negative buoyancy and cooling through evaporation of precipitation into the dry air. This high-based storm resembles high terrain, western U.S. storms which occasionally produce dry microbursts. Significant hail and rain are unlikely.

A storm which contains a strong updraft and weak downdraft; will not produce wind damage, but can foster heavy rains and/or damaging hail. Single and multicell storms comprise this category. They include storms that dump heavy rain, but little or no hail because of warm conditions aloft, and multicell storms that are capable of producing hail because of lower environmental freezing levels. Strong updraft, weak downdraft storms often form in very moist atmospheres where there is little, if any, dry air and evaporational cooling to drive downdrafts.

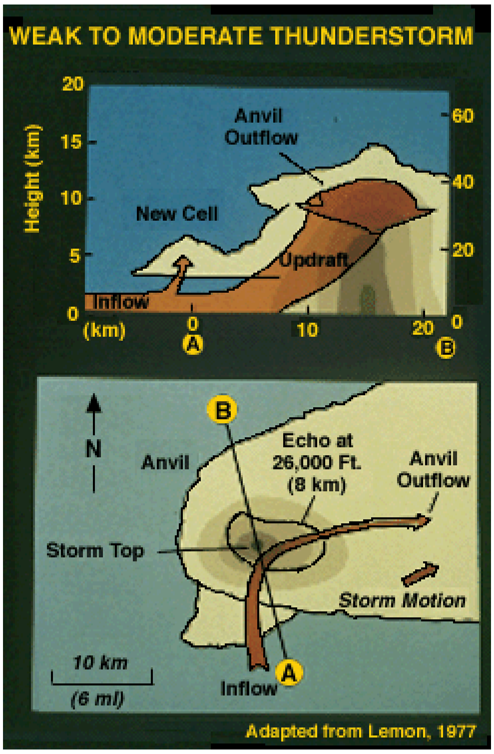


Relatively weak updrafts and downdrafts are found with non-severe showers and thunderstorms. The last possible combination is a storm with strong updrafts and downdrafts. These storms frequently produce destructive downbursts, hail, heavy rain, and tornadoes. As one would expect, the most severe storms, including supercells, have strong vertical drafts and occur in the most unstable atmospheres.

The Lemon Technique (LT)

to determine updraft strength

This section deals with the Lemon Technique of severe storm detection by radar, designed for environments with moderate to strong vertical wind shear. We have seen that strong shear causes weak updrafts to slope from the vertical, whereas stronger updrafts are able to withstand the shear and assume a more vertical character. The Lemon Technique, and modified versions such as the WRIST technique, allow the radar operator to infer the strength of the updraft through three-dimensional visualization of the radar-detectable rainy downdraft surrounding the updraft. We stress that the radar operator must perform the vertical tilt sequence employed in these techniques to determine storm structure and classification properly.



This diagram represents a weak, non-severe storm (most likely multicellular) in a sheared environment. The top figure is a westward view of a vertical cross section of the storm, whereas the bottom diagram is a horizontal, low-level cross section. (Note line A-B in the lower figure, which corresponds to the vertical cross section.) Precipitation and rainy downdraft descend downwind (usually northeast) from near the summit of the tilted cloud. The radar PPI echo, the bottom figure, has a concentric reflectivity configuration, with the highest top over the center of the low-level echo maximum. Note the orange arrow, which represents the trajectory that air parcels take into the storm, through the updraft, and out of the storm through the downwind anvil.

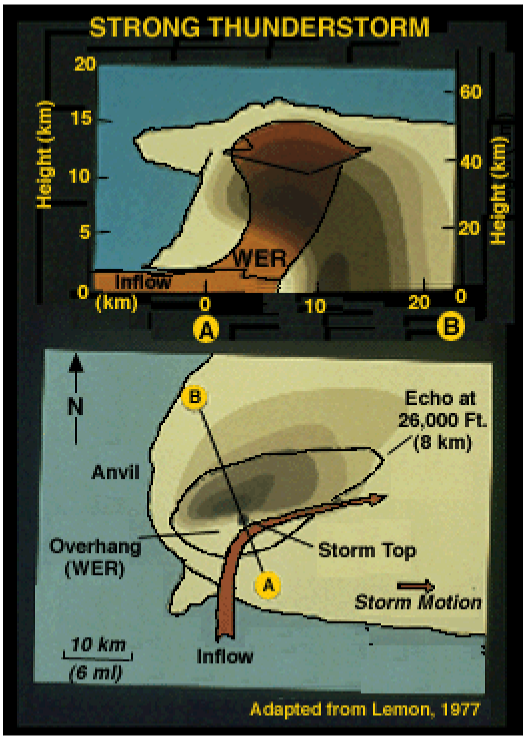
This thunderstorm was developing in a strongly-sheared environment in the northeast Texas Panhandle. The severe slope of both the updraft and its trailing flanking line towers is quite obvious in this view, looking north from about 30 miles.

Photograph by: Marshall

One of the tops, about half way along the flank and slightly behind the first row of flanking towers, had assumed a slightly more vertical appearance. The storm was a small VIP 4 on radar at this time with its top situated over the low-level echo.

Multicell Storm Analysis
using the lemon technique

As the multicell storm becomes severe, the stronger updraft becomes more vertical and the top shifts upwind over a tightening low-level reflectivity gradient on the updraft storm flank. This transformation is not the same updraft becoming more erect with time, but a new flanking line tower that is more powerful than earlier updrafts.



The precipitation downwind of the updraft becomes heavier, with moderately large hail (marble to golf ball size) falling near the updraft. Size separation of precipitation accounts for the increased VIP level gradient, with the lightest elements being blown the greatest downwind distance.

Tightening VIP gradient, shift in Cb top position, and development of mid-level echo overhang above a low-level weak echo region (WER) are all strong indicators of an intensifying updraft and increasing severe potential. As this intensification process proceeds, the strongest downbursts often shift from near the leading or east storm quadrant to near the southwest storm flank. This, in turn, enhances fresh convective development along the flanking line.

The same Texas Panhandle storm has intensified to the severe multicell stage at this time. The tower that was on the middle-back side of the flank in the previous photograph has developed vigorously and become much more vertical than its predecessors.

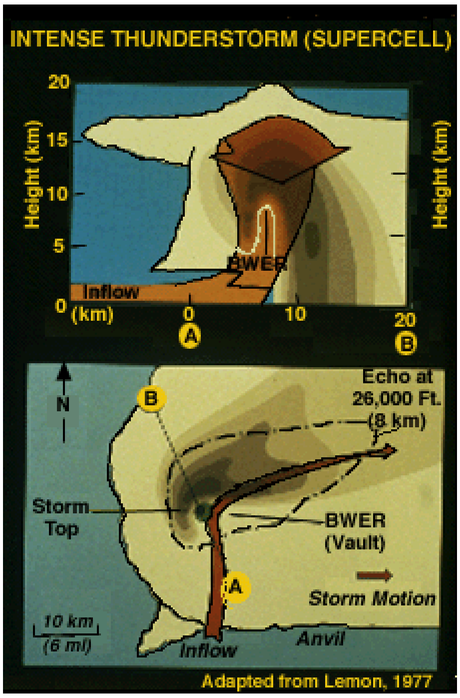
Photograph by: Marshall

The rock-hard nature of both the Cb and the downwind anvil are visual clues as to the updraft's strength. The storm was a much larger VIP 5 on radar at this time with an increasingly tight VIP level gradient on the southwest flank.

Supercell Analysis

using the lemon technique

A few storms take the intensification process further, to the supercell stage. The updraft becomes virtually erect and the storm top shifts off of the low-level echo gradient to the area above the developing pendent echo. Radar reflectivities continue to increase in both the low level and extensive mid-level overhang echoes. As mentioned earlier, evidence suggests that storm circulation associated with the mesocyclone holds the gust front in check. Therefore, rather than racing ahead of the updraft to eventually choke it off, the gust front remains quasi-stationary relative to the moving storm and aids in continued lifting of warm air into the updraft.



A bounded WER (BWER) develops where the intense updraft is surrounded by mid-level overhang. When a hook or pendant echo is not visible on radar, a BWER often is, provided that the radar operator searches for it with the suggested vertical tilt sequence rather than with the range-height indicator (RHI) mode.

The supercell in this illustration does have a pendant echo, with the top of the rotating updraft above the WER and just east of the pendant. The radar operator must be aware that spotters are likely to see a well-developed wall cloud, often with vigorous rotation, beneath the radar BWER.

Why is the supercell updraft so intense? Obviously, instability is one factor. Another contributor is rotation. Research has shown that the lowest pressures in the rotating updraft initially are in the mid-levels (20,000 feet or so) in a supercell, causing an acceleration of the updraft, because of the upward oriented pressure gradient. This can result in a 50 percent increase in updraft speeds!

Photograph by: NSSL

The Panhandle storm has become virtually erect, with an extremely crisp Cb top and anvil edge. We are still looking north, from about 30 miles, at the incipient supercell.

Supercell Matures

further analysis

The storm continued to grow, and assumed an extremely impressive appearance. We are looking northeast from about 20 miles.


Photograph by: NSSL

Was the storm really a supercell? Doppler Radar confirmed a mesocyclone. A storm chase team, looking northwest from about 10 miles, took this photograph. Note the circular banding wrapping around the low levels of the updraft.

Photograph by: NSSL

Again, this is visually suggestive of the rotation that Doppler Radar was indicating. The storm produced large hail and at least one tornado after this photograph was taken.

Vertical Wind Shear

change of winds with height

Vertical wind shear is the second critical factor in the determination of thunderstorm type and potential storm severity. Vertical shear, or the change of winds with height, interacts dynamically with thunderstorms to either enhance or diminish vertical draft strengths.

Photograph by: Moller

Looking north from about 15 miles, we see a storm embedded in strong vertical shear. Upper level winds near cloud summit were blowing from west to east (left to right) at 130 MPH. Surface winds were from the south at 20 MPH, indicating over 100 MPH of shear through the cloud layer! Such vertical shear often destroys all but the strongest storms by literally blowing the updraft away from its base. This nearly occurred in this case, as noted by the storm's severely tilted updraft. (It must be emphasized that cloud tilt is not always due to winds which increase in velocity with increasing height. Strong low-level winds beneath light upper-level winds will cause a cloud to slope over as the base is pushed away from the cloud tower.) Oddly, vertical shear, where winds increase or change direction with height serves to enhance rather than weaken the strongest storms, through wind removal of precipitation from the updraft summit, and in some cases introduction of updraft rotation.

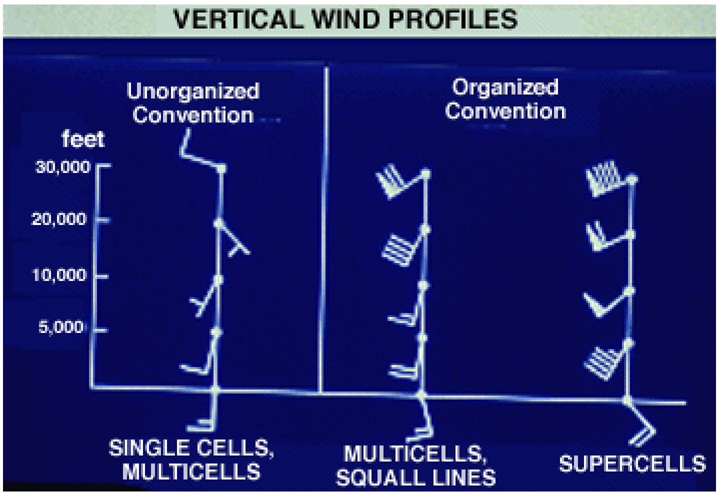
Photograph by: Moller

Thunderstorms which occur in weak vertical wind shear usually have an erect appearance. These storms don't last as long as strong storms in a sheared environment since the rainy downdraft quickly undercuts and chokes off the updraft. If any severe weather occurs with these weak-shear storms, it will be brief, occurring just prior to dissipation. Weak-shear severe storms are often called "pulse storms." (Looking southeast from 20 miles.)

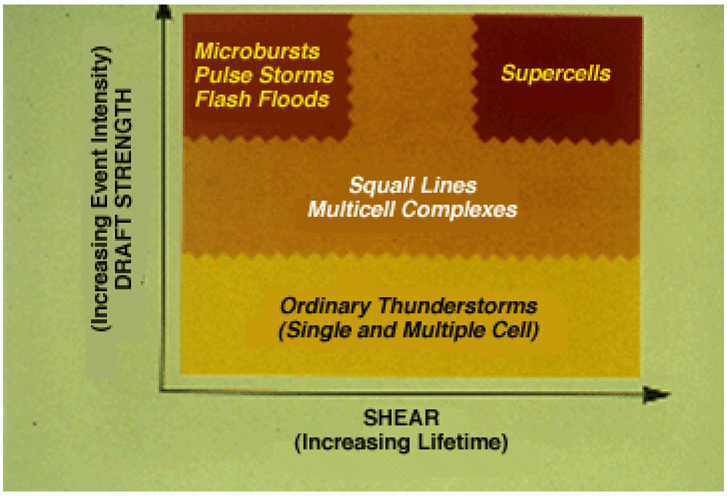
Wind Shear

organized and unorganized convection

For convenience, we refer to storms in unsheared and sheared environments as unorganized and organized convection, respectively. Organized storms are longer-lived, usually have preferred areas of new updraft development, and often allow for some predictability of periodic severe weather events. Unorganized storms appear to be more chaotic, because of their nature and, to some extent, because of our lack of knowledge about them.



The examples of vertical wind profiles are similar to those that have been observed with different storm types: from the chaotic, light winds of unorganized summer storms, to the veering and increasing winds typical of organized storms. Although wind profiles of multicells and supercells appear to be similar, note both the stronger 5 to 10 thousand foot level winds and the greater low-level directional turning with supercells. These are causative factors of supercell updraft rotation. We must caution that vertical wind profiles are subject to rapid space and time changes, and better observation systems such as profilers will be important in improving practical storm-type forecasting. Also, these specific wind profiles are not the only arrangements that can occur with the different storm types. For instance, supercell surface winds may be easterly, with 5,000 foot winds southerly, and so on.



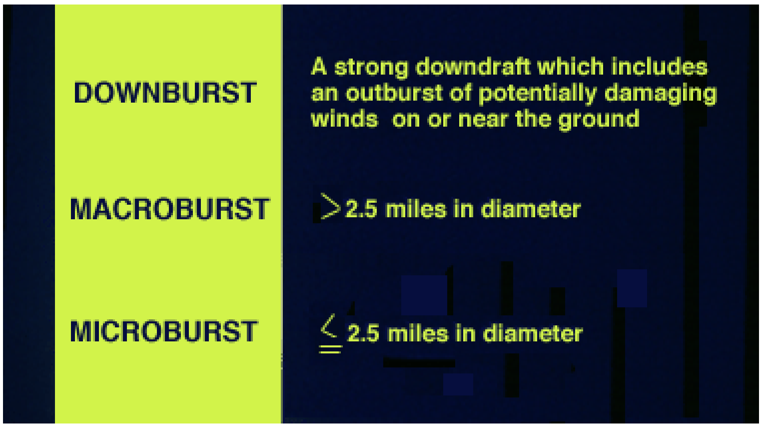
This diagram summarizes the combined effects of draft strength and vertical shear strength on storm type. Weak shears typically lead to short life cycles, although some severe weather can occur when instabilities and draft strengths are great (upper left). Stronger shears lead to longer storm life cycles, and repeated severe episodes. Note that supercells combine the strongest shears with the greatest instabilities. It is important to know that storm-relative winds are critical rather than absolute winds. Therefore, one must figure storm motion into the complex relationships concerning thunderstorm and vertical wind shear interactions.

We may think of this diagram as another form of the thunderstorm spectrum. In this case, the effects of ambient atmospheric dynamics and thermodynamics on storm type are included. The information in the diagram is subjective, and we cannot assign absolute shear and stability values as partitions between storm types. Instead, we must think of the boundary and near-boundary areas as the domains of hybrid thunderstorms.

Outflow Phenomena

downbursts

This section is on visual identification of macrobursts, microbursts, gust fronts and other outflow phenomena. Damaging thunderstorm winds have been termed downbursts by renowned severe storm researcher Dr. Ted Fujita. Dr. Fujita further classifies these events as macrobursts (greater than 2.5 miles in diameter) and microbursts (less than 2.5 miles in diameter).



The problems that aircraft have had with thunderstorm-induced wind shear, particularly microbursts, indicate that the spotting and reporting of microbursts is of paramount importance. Although some spotters will think that events such as microbursts and flash floods are less dramatic than tornadoes, in reality, they are just as lethal, if not more so, in some circumstances. Hopefully, pilots will find these slides beneficial in identifying outflow structures that could result in dangerous approach or take-off conditions, and delay their subsequent actions until danger has passed.

Photograph by: Moller

A downburst is a strong downdraft which includes an outburst of potentially damaging winds on or near the ground and if the diameter of the downburst is greater than 2.5 miles, then it is called a macroburst. As a macroburst or a non-severe gust front passes overhead, the ragged, concave-shaped underside of the shelf cloud accompanies the onset of cold outflow winds at the ground. Although some rotation may be visible in these clouds, it is likely to be short-lived and without vertical continuity, precluding a major tornado. Another clue for spotters as to the potential of any observed rotation would be the lack of warm and moist surface-based inflow to the feature.

Occasionally a cloud hole will appear behind, or in some cases immediately ahead of a gust front. The cause is frequently a small scale downdraft, possibly a microburst, which is resulting in rapid cloud dissipation.

Photograph by: Moller

There is little doubt about a small downdraft being the culprit in this particular case, as evidenced by the amount of blowing dust that has been kicked up beneath the cloud hole.

Gust Fronts

resembles the passage of a cold front

A gust front is a boundary that separates a cold downdraft of a thunderstorm from warm, humid surface air. Its passage at the surface resembles a cold front. A macroburst (damaging thunderstorm gust front) was advancing from northwest to southeast in this westward view across the West Texas prairie. Note the well-developed mammatus field under the leading anvil, and the new updrafts being lifted along the gust front.

Photograph by: Doswell

The question of whether or not new storms will form along a gust front is a difficult one to answer. If the gust front is moving quite fast and the atmospheric instability is marginal, new storms are not likely to develop. Research has indicated that low-level vertical shear profiles in the outflow field should be of equal but opposite sign of the shear in the low-level inflow air for the optimal redevelopment along the outflow boundary.

Photograph by: Doswell

A telephoto shot highlights the approach of the gust front. This complex had the appearance of a haboob, a dense sandstorm that occurs along the leading edge of outflow boundaries of desert thunderstorms in North Africa. Indeed, it was dust beneath the shelf cloud that resulted in this appearance, and the outflow was of downburst proportions.

Visual Clues to Gust Fronts

cloud lowering slopes downward and away from rain area

This is the first of four photographs of an approaching thunderstorm to help visualize the difference between gust front outflow "push" and wall cloud inflow "pull." To the distant west-southwest, note the suspicious cloud lowering at the south flank of an isolated severe thunderstorm. Is it a wall cloud or a portion of a shelf cloud?

Photograph by: Doswell

A subtle, but important clue is that the lowering slopes downward away from the rain area, rather than into the rain. This is the slope that a shelf cloud usually takes. As cold air is "pushed" out of the precipitation area by the downdraft, warm air slides up and over the gust front forming the concave-shaped shelf cloud. Within 20 minutes, the storm continued to approach. The ragged shelf structures has the same tilt, and although it is a bit easier to identify, there is still some question as to its nature.

Photograph by: Doswell

Another important clue is to discern whether or not the cloud element in question remains in one spot relative to the precipitation area, or moves away from the precipitation. When it moves away, as this cloud has, it signifies "push" and shelf cloud-producing outflow. Observe carefully, for there are signatures of strong outflow winds (a steep-sloped rain foot and a small gustnado). The storm was producing 70 MPH winds at this time.

More Clues to Gust Fronts

examining wall clouds

Still looking west from the same vantage point about 20 minutes later, the storm was moving off to the right (north) leaving a curving, weakening outflow boundary behind it. This boundary is visible as the darkest cloud base in the middle ground, arcing into the right background. Look to the right horizon. There is another rain area, and another cloud-base lowering to the south of the rain. Is this a repeat of what we have just observed? Note the subtle hint that the cloud is sloping into the rain area.

Photograph by: Doswell

The second storm is approaching, and the cloud lowering continues to slope into the precipitation. It is a wall cloud, exerting "pull" on the rain-cooled air and maintaining its distance from the visible precipitation shaft rather than being "pushed" away from it. We have witnessed the progression from severe multicell storm to supercell when a secondary updraft in the flanking line blossomed into a rotating updraft. This storm lasted for several hours after this stage, producing large hail and several weak tornadoes.

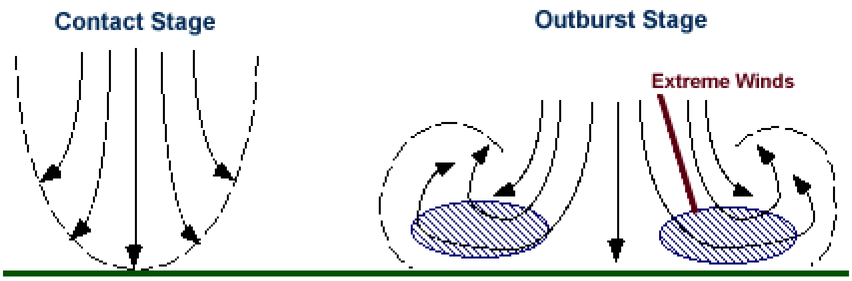
Photograph by: Doswell

A final word for spotters: when watching a potential wall cloud, have patience! Don't expect a quick tornado warning when you report the wall cloud, but watch for tornadic wall cloud characteristics. The forecaster and radar operator will also be scanning the storm for tornadic signatures.

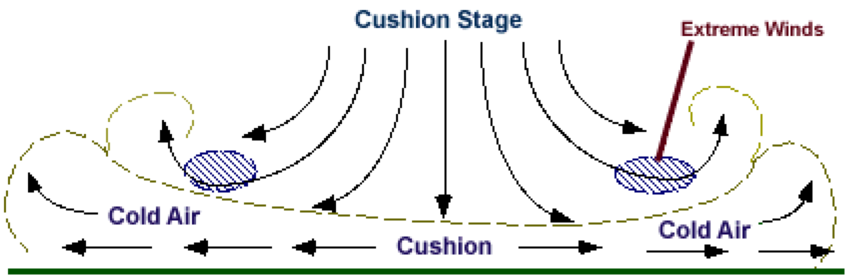
Microbursts

downburst less than 2.5 miles in diameter

A downburst is a strong downdraft which includes an outburst of potentially damaging winds on or near the ground. If the diameter of the downburst is less than 2.5 miles, it is called a microburst. The diagrams below depict the evolution of a microburst.



A microburst initially develops as the downdraft begins its descent from cloud base. The downdraft accelerates and within minutes, reaches the ground (contact stage). It is during the contact stage that the highest winds are observed. During the outburst stage (above), the wind "curls" as the cold air of the microburst moves away from the point of impact with the ground. During the cushion stage, winds about the curl continue to accelerate, posing a great threat to nearby aircraft.



These are very weak, high based showers without thunder, but with microbursts. Studies have shown that they predominantly occur in the High Plains and western U.S.: particularly in unstable, very dry low level environments with surface temperature-dew point spreads of 30 to 50 degrees and an area of mid-level moisture as a source for the weak showers.

Photograph by: Moller

The cloud on the left is developing, whereas the fuzzy anvil on the right has matured and is producing a trail of virga. Microbursts would be most likely to occur beneath the virga, when the downdraft reaches the ground. Several of these virga showers did produce microbursts in the Lubbock, Texas area.

Photograph by: Moller

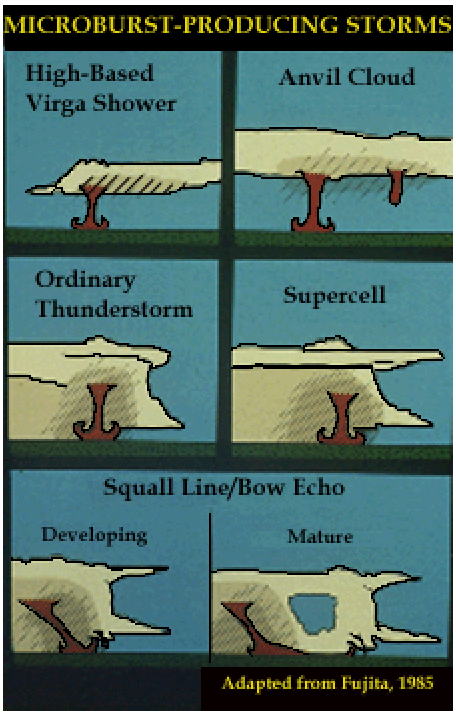
The same day, near the Lubbock Airport, we see several of the small microbursts which emanated from the virga patch in the upper right corner of the photograph. Wind shifts of 35 to 40 MPH were noted shortly after this time, with a rapid onset and cessation of the wind gusts.

Anatomy of Microbursts

and the dangers they pose to aircraft

The anatomy of a microburst shows that the highest wind speeds occur shortly after the cold air has impinged upon the ground. The spin-up of the microburst curl then results in an acceleration of wind velocities about the curl.

An aircraft entering a microburst will encounter strong headwinds, followed by strong tailwinds, as it flies from one side of the microburst to the other. If the pilot compensates for the headwind (to decrease lift) a bit too much, then the aircraft will lose lift in the tailwind and quickly strike the ground.



The end of microburst danger comes minutes after the air reaches ground, but other microbursts will follow in many cases, similar to repeated tornado events with a cyclic supercell. It was determined that one airliner crashed after it encountered three microbursts in rapid succession upon final approach.

Microbursts will occur with a plethora of thunderstorm types, even dissipating anvil clouds in some cases. The important message is that some thunderstorms or even weak convective showers which were regarded as harmless a few years ago are now recognized to be potential killers.

Microbursts

coupled with developing rain shaft

Photograph by: Doswell

Developing rain shafts often have a fuzzy, bulbous appearance as they descend. If a source of dry air is present and the air into which the rain is falling is sufficiently warm, then strong, and possibly damaging microbursts are possible.

Photograph by: Doswell

The precipitation continues to descend . . .

Photograph by: Doswell

. . . finally reaching ground within several minutes. The greatest threat of microbursts will be within 5 or 10 minutes either side of the precipitation "touchdown."

Extreme Mircroburst

associated with a supercell storm

Photograph by: Moller

This is an extreme microburst event in a supercell storm, looking west. Although no wall cloud was present, baseball hail was occurring in the precipitation shaft on the right, with a rotating updraft base in the center of the photograph. A very rapid right to left movement was visible with the rain foot. "Guesstimations" were that winds were above 80 MPH in the microburst.

Photograph by: Moller

A telephoto view of the previous microburst shows that although there was not a full rain foot curl, there was a curl of scud clouds above the diminishing rain foot. The microburst probably was peaking or had just peaked when this photograph was taken. Remember, supercell severe weather, tornado or otherwise, often is the most violent of thunderstorm phenomena.

Scud Clouds and Virga

minimal precipitation at the surface

Scud clouds are low, detached clouds caught in the outflow beneath the thunderstorm. As cold air first reaches the ground, it lifts relatively warm air, resulting in saturation through ascent. Thus, the presence of sub-thunderstorm base scud clouds almost always indicates the presence of outflow.

Photograph by Doswell

This is a dissipating multicell anvil cloud, looking northeast, late in the afternoon near Fort Morgan, Colorado. Note the lack of precipitation beneath the dissipating storm cell, except for the white virga streak behind the tree line.

Photograph by Moller

The area close to this virga could be quite dangerous for low-level aircraft operations. Microbursts that occur with virga are aptly called dry microbursts, even though a spattering of raindrops may reach the surface.

Rain Foot and Dust Foot

driven by microbursts

We are looking west at the south flank of a severe multicell storm that bordered on becoming a supercell at times. Some rotation and several wall clouds accompanied the bursts of large hail and microbursts with this southwest Texas storm.

Photograph by: Moller

A rain foot (below) was developing at this time, with rain-free base in the foreground and a small wall cloud southwest of the rain shaft.

Photograph by: Moller

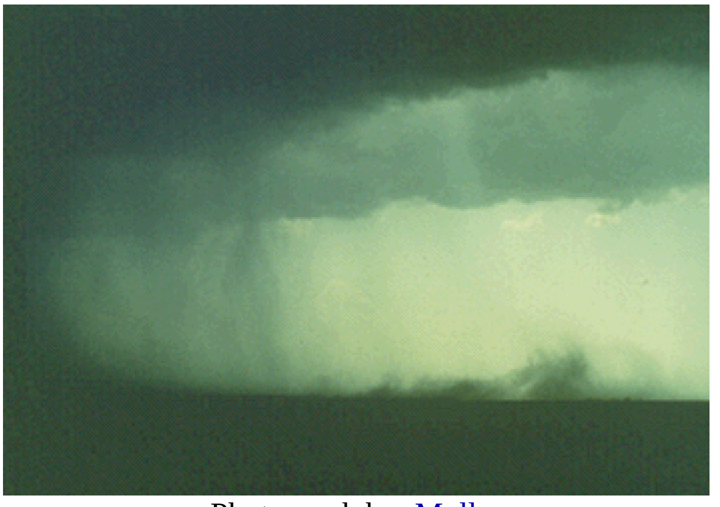
Several minutes later the rain foot was beginning to curl up towards the wall cloud. Even from this distance of about 10 miles, strong winds were evident from the motions of the laterally spreading precipitation.

Photograph by: Moller

This seems to verify that a microburst is occurring, and also that many wall clouds likely result from an injection of rain-cooled air into the severe storm updraft.

Photograph by: Moller

This is not a tornado, but a microburst with precipitation being pulled into the wall cloud and updraft of the multicell storm.



Photograph by: Moller

Similar to the rain foot is a "dust foot," seen here spreading and curling upwards from left to right. An aircraft engaged in low-level operations should not venture into these rain or dust feet! Spotters should check out the area that has been affected (if possible) for any sign of damage. This was a multicell storm that also produced heavy rain and small hail.

Wall Clouds

a lowering in the cloud base

Researchers have shown that wall clouds probably develop when some rain-cooled air is pulled upward, along with the more buoyant air, as the strengthening updraft attempts to replace ever-growing volumes of rising air. The rain-cooled air is very humid, and upon being lifted it quickly saturates to form the lowered cloud base. Thus, the wall and tail cloud probably develop sometime after an intense supercell or multicell storm begins to precipitate.

Photograph by: Moller

Looking to the northwest, we see a detached scud cloud which had just emerged from the precipitation area and was moving rapidly southwestward (from right to left).

About 5 minutes later, the scud cloud entered the updraft area and was lifted into the cloud base. This was the beginning of a wall and tail cloud that persisted for over 30 minutes.

Photograph by: Moller

Look closely at the center of the photo and near the north end of the tail cloud. A small, tornadic dust whirl is visible. This tornado circulation was relatively weak, but strong enough to overturn a mobile home. It was beneath the tail cloud and not the wall cloud! Events such as this have been observed more than once.

Numerous observations of wall clouds indicate these following items to be the main delineating characteristics between tornadic and non-tornadic wall clouds. Tornadic wall clouds usually persist for "tens of minutes" prior to tornadogenesis, whereas non-tornadic wall clouds often don't persist as long.

Photograph by: Moller

Tornadic wall clouds exhibit rapid and even violent rotational and vertical (predominantly ascending) motions, with non-tornadic wall clouds having less dramatic motions. Finally, tornadic wall clouds are characterized by strong, warm inflow from the southeast and east, usually much stronger inflow than that with non-tornadic storms. We will discuss these characteristics in more detail.

In review, tornadic wall clouds are persistent over tens of minutes, have surface-based inflow, and exhibit rapid rotational and vertical motions. Next we will view several non-tornadic wall clouds and discuss their "tornadic short-comings."

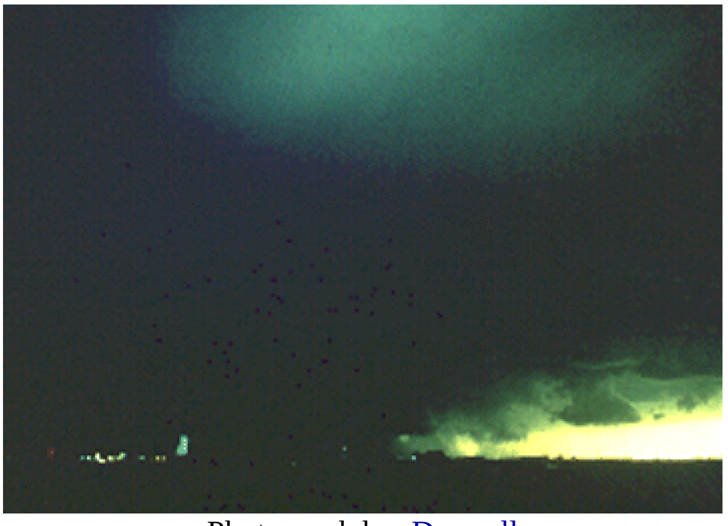
Wall Clouds Beneath CB Towers

visual clues of storm potential

Here we have a southward view of a supercell, with precipitation in the right middle-ground and a wall cloud beneath the cumulonimbus (Cb) tower and anvil overhang in the background. The wall cloud produced a tornado within 30 minutes in southwest Oklahoma City.

Photograph by: Doswell

Looking west from 5 miles away, note the supercell wall cloud. We have learned much about the nature of wall clouds in the last decade. For instance, persistent wall clouds signify a strong updraft which is capable of producing large hail, and if conditions are right, tornadoes. However, only a few cloud-base lowerings actually are wall clouds, and probably less than half of all legitimate wall clouds spawn tornadoes.



Photograph by: Doswell

This is not to minimize the importance of wall clouds, as they are a reasonable indicator of updraft strength. The most visually-impressive examples characteristically precede the most powerful tornadoes. This ominously dark wall cloud occurred with a very severe hailstorm and several weak tornadoes.

Interaction with Thunderstorm Outflow

a short-lived example

This fearsome looking wall cloud to our northwest did occur with a severe thunderstorm which produced golf ball size hail and strong winds. However, within 10 minutes the wall cloud began to break up as cold outflow undercut it.

Photograph by: Moller

Note the tendency for the same wall cloud to look more disorganized as it "gusted out," or was undercut by outflow.

Photograph by: Doswell

In addition to the lack of persistence, the wall cloud exhibited little if any rotation. It completely disappeared within another 5 minutes.

Dissipating and Redeveloping Wall Clouds

indicative of multicell or non-tornadic supercell storms

This small wall cloud, seen looking north-northwest from about 10 miles away, was moving south-southeast. At this time previously strong southeast winds had become near calm, and within several minutes the wind shifted to northerly. The wall cloud clearly was undercut by outflow.

Photograph by: Moller

About 10 minutes later, the same wall cloud was in the process of dissipating on the right side of the photograph. A second and equally small, unimpressive wall cloud was developing due southwest, or to the left of the first wall cloud. The second wall cloud also lasted less than 10 minutes. Once again significant rotation was not observed.

Photograph by: Moller

The quick dissipation and redevelopment of these wall clouds are suggestive of a multicell or non-tornadic supercell storm. This storm did produce sporadic hail up to golf ball size and a brief gustnado along the flanking line, but no significant tornadoes.

Rotating Wall Clouds

indicative of mesocyclones

Here is another wall cloud on another day, looking north-northeast from about 6 miles away. This wall cloud was rotating, but periodically seemed to become undercut by outflow and lose its rotational characteristics. The storm was severe, and Doppler radar near Norman, Oklahoma, did indicate a mesocyclone, but no tornadoes developed.

Photograph by: Doswell

We have emphasized that many thunderstorms are hybrids and contain characteristics of several of the storm classification groups that we have discussed. These storms will be difficult to warn for. The forecaster needs all the pertinent radar and spotter information that he/she can get to make an appropriate warning decision. In the case of this last storm, a tornado warning is quite probably justified, even though no tornadoes occurred. With some of the weaker wall cloud storms that we have shown, a severe thunderstorm warning likely would suffice.

Photograph by: Moller

Looking east from about 5 miles away, a furiously rotating wall cloud was moving northeast across the forests east of Logansport, Louisiana. Spotting in the southeast and east U.S. is more difficult because of trees, hills, and typically hazy conditions.

However, the basic building blocks of storms are the same in these areas as they are around the world, although some regional differences do exist in storm structure detail. In fact, the first study of a supercell was from England, with subsequent studies coming from the Soviet Union, Canada and the United States. This storm did produce large hail, but lack of access into the affected forest areas precluded positive identification of a tornado touchdown.

Tornadoes

violently rotating columns of air

A tornado is defined as a violently rotating column of air in contact with the ground and pendent from a cumulonimbus cloud.

Photograph by: Marshall

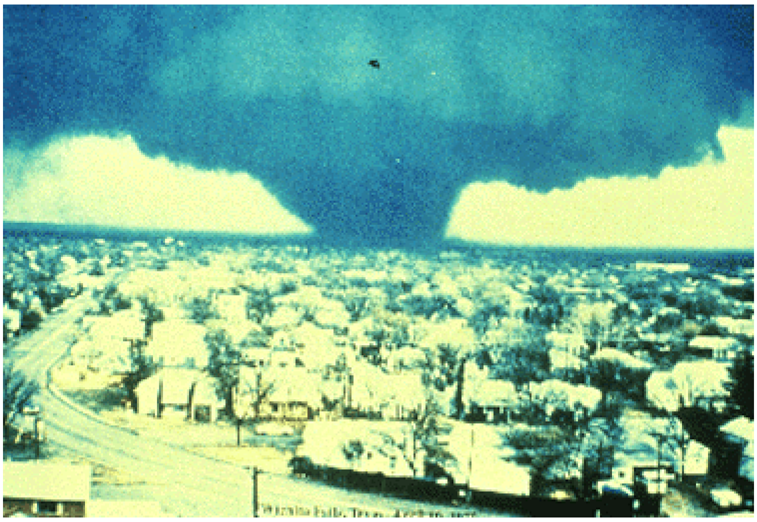
They can be categorized as "weak", "strong", and "violent"; with weak tornadoes often having a thin, rope-like appearance, as exhibited by this tornado near Dawn, Texas. About 7 in 10 tornadoes are weak, with rotating wind speeds no greater than about 110 MPH. (looking west from about 1 mile.)

The typical strong tornado often has what is popularly considered a more "classic" funnel-shaped cloud associated with the whirling updraft. Rotating wind speeds vary from 110 to 200 MPH.

Photograph by: NSSL

Nearly 3 in 10 tornadoes are strong, such as this twister on the plains of North Dakota. Looking northeast (from about 2 miles), note the spiraling inflow cloud, probably a tail cloud, feeding into the tornado. An important safety consideration is that weak and strong tornadoes by definition do not level well-built homes. Thus, a secure home will offer shelter from almost 100 percent of all direct tornado strikes.

Only violent tornadoes are capable of leveling a well-anchored, solidly constructed home. Fortunately, less than 2 percent of all tornadoes reach the 200+ MPH violent category. Furthermore, most violent tornadoes only produce home-leveling damage within a very small portion of their overall damage swath. Less than 5 percent of the 5,000 affected homes in Wichita Falls, Texas were leveled by this massive 1979 tornado. (Looking south from 5 miles).



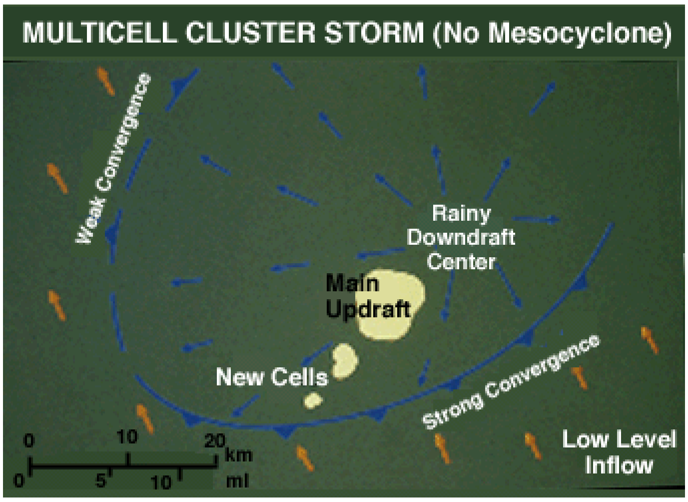
Photograph by: IDR

Note the huge, circular wall cloud above the tornado. This feature is probably close both in size and location to the parent rotating updraft (called a mesocyclone) which has spawned the violent tornado. Strong and violent tornadoes usually form in association with mesocyclones, which tend to occur with the most intense events in the thunderstorm spectrum.

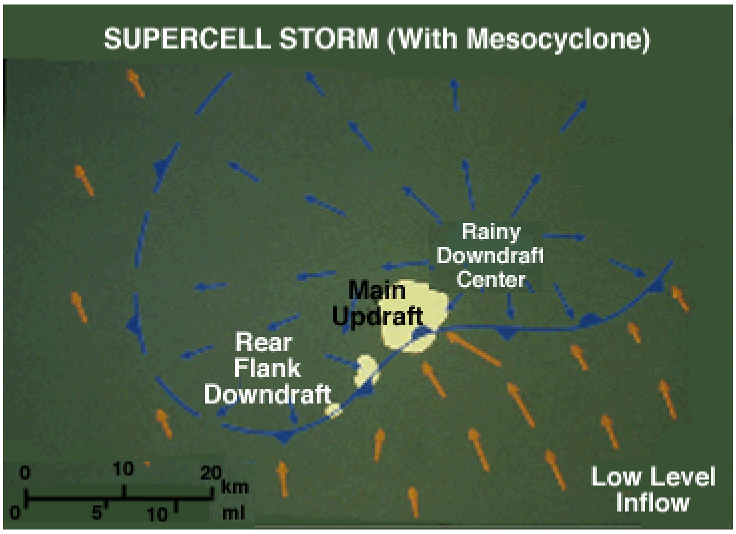
Schematic Diagrams

comparison of tornadic and non-tornadic supercells

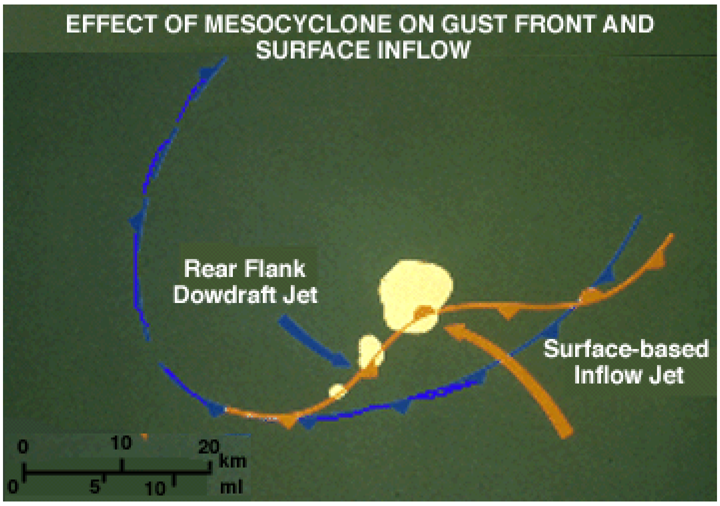
The difference between a non-tornadic thunderstorm



and a tornadic supercell is that the latter storm's vigorous rotation and surface low pressure field cause a wave to form on the gust front.



This allows warm, moist surface-based air to feed continually into the updraft and wall cloud. Cold air is "wrapped up" by the strong circulation and does not immediately undercut the wall cloud. Instead, the wall cloud becomes the location of extreme convergence of warm and rain-cooled air.



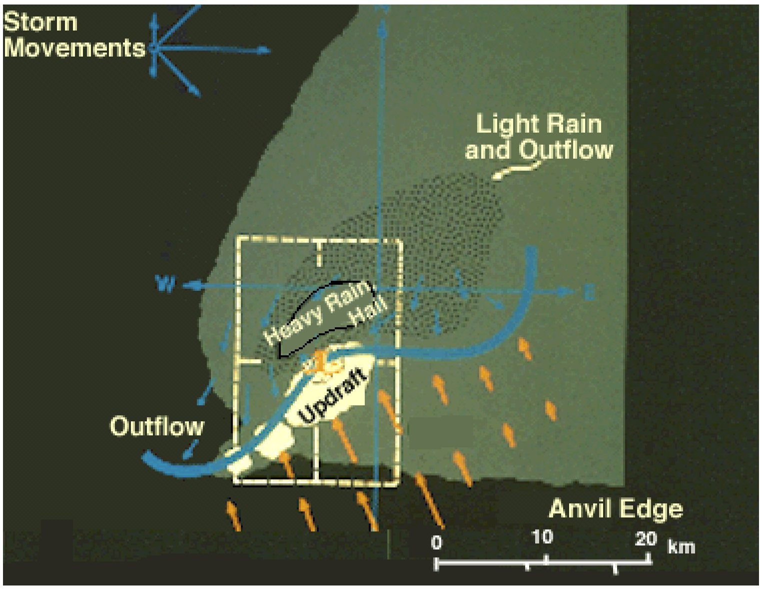
The two previous examples are combined for comparison's sake. If the "undercut" storm is a relatively weak supercell (rather than a severe multicell storm), then the circulation is not strong enough to prevent cold outflow undercutting.

Focusing on the Mesocyclone

of a tornadic supercell

To illustrate these points further, let us imagine that radar and spotters detect a possible supercell that is approaching a community. The spotter group's net controller first considers that the spotters must concentrate on that portion of the supercell which is most important: The quadrant with the updraft/downdraft interface.

If we center a coordinate axis and grid system on the storm's radar centroid, the "action" area typically is in the southwest quadrant as seen in this storm's horizontal cross-sectional view. Warm, ground-relative inflow winds are depicted by orange arrows and cold outflow is in blue, with the longest arrows suggestive of the strongest winds. The gust front is depicted by the thick, blue line, and the mesocyclone by the "L", or low pressure center in the gust front wave.



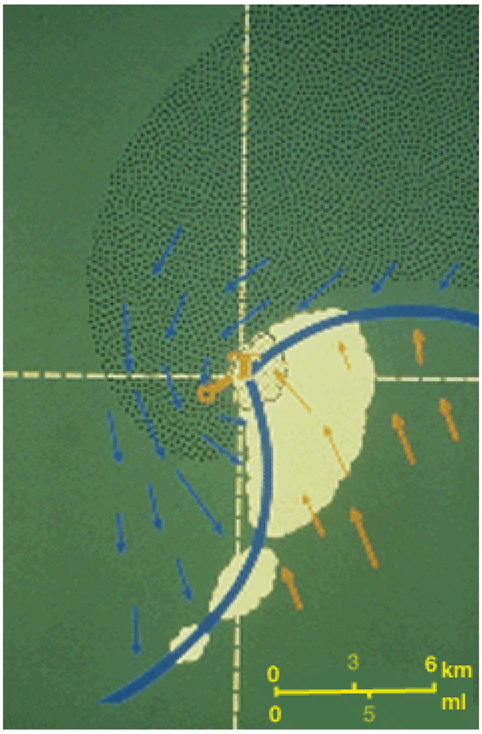
Note the storm motion vectors. Although a majority of these supercells move northeast or east, a significant number move southeast. Therefore, the heaviest precipitation usually either precedes the tornado (northeast movement) or falls immediately north of the tornado track (southeast movement), although brief bursts of large hail and/or rain often occur with the tornado.

Supercells frequently move to the "right" of non-supercell storms, even to the extreme of moving southeast on a day when winds aloft all blow from the southwest. Vigorous development on the south side of the main updraft apparently causes this rightward storm motion. Let us now concentrate on the storm flank where the most violent weather will occur.

Evolution of Tornadic Supercell

from early stages of tornado to dissipation

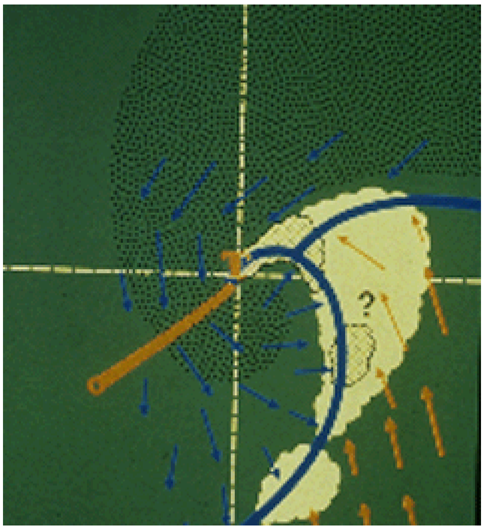
To do this, we "zoom in" and move the grid system to center it on the wall cloud and updraft area. The darkly-stippled precipitation area narrows to the radar pendant echo, that wraps around the white updraft area and the white-stippled wall cloud.



Spotter reports of strong, warm inflow winds southeast of the wall cloud suggest a higher tornado risk than the case where the wall cloud is undercut by outflow. Indeed, note the symbol "T", for tornado, and the incipient tornado track (solid orange line), indicating that a tornado has developed.

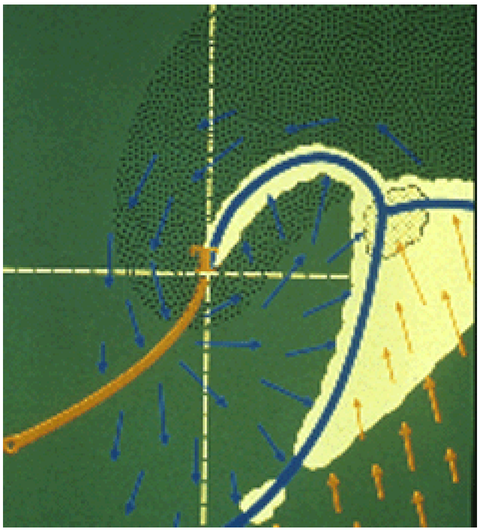
Knowledgeable spotters likely will have reported wall cloud persistence and rapid motions prior to tornado formation. We suggest that spotters have a county-wide grid system and compasses so that wall cloud positions can be readily triangulated, and that subsequent inflow and outflow circulation information can be solicited by the net controllers from spotters who are in the appropriate geographical locations.

During the mature stage of the tornado, the rear flank downdraft (RFD) air accelerates, causing the gust front and flanking line to surge rapidly eastward relative to the tornado. Damaging winds are possible along this flanking line gust front, and small gustnadoes often occur.



Note that radar-indicated precipitation is wrapping cyclonically around the tornado; and that the advancing gust front is cutting off warm air inflow to the tornado. Spotters south of the tornado probably would witness a sharp gust front passage.

The question mark on the accelerating gust front draws our attention to whether or not a second wall cloud is beginning to form several miles east or southeast of the existing tornado. It is extremely easy to miss such a feature with all eyes on the pre-existing tornado! The gust front has completely isolated the tornado from warm inflow and vortex dissipation is imminent.



As the RFD progressively wraps around the tornado, it frequently results in a visible "clear slot" of relatively cloud-free air wrapping cyclonically around the tornado's south and east sides.

Cold air downbursts impinging upon the tornado cause the visible funnel cloud to tilt increasingly from the vertical (usually away from the rain area). This vortex stretching is partially responsible for the tornado entering into the "shrinking" or "rope" stage. It is the most likely time for the tornado to make left or right turns from its path, depending on the angle of attack of cold downbursts on the vortex.

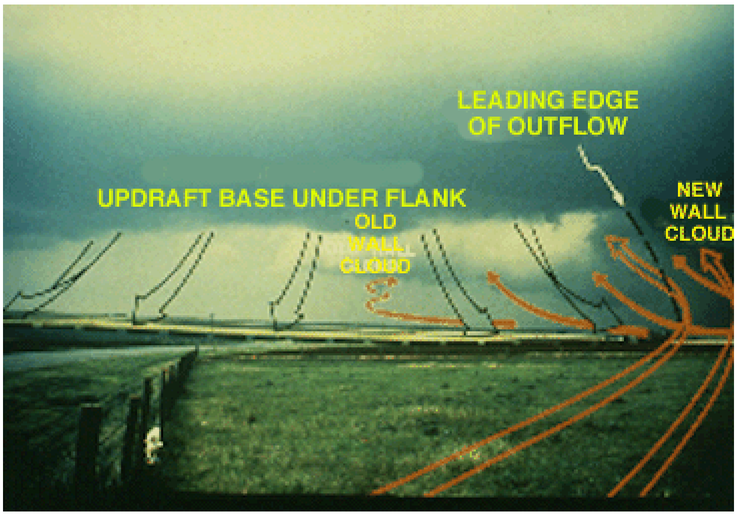
In this example, a new wall cloud has developed several miles to the inflow side (east or southeast) of the dissipating tornado. Storm spotters must be acutely aware of this possible development, which indicates a possible cyclic supercell storm, capable of producing more than one tornado. A repeat of the gust front evolution we have shown is likely if additional tornadoes develop.

Superimposed Low Level Flow Field

RFD outflow and inflow fields

Photograph by: Moller

We have superimposed inflow and RFD outflow arrows on these two slides, again to emphasize the advance of the RFD and the eventual occlusion of the gust front.



Photograph by: Moller

As tornado "A" lifts, inflow and outflow convergence rapidly increases into updraft and wall cloud "B".

A Developing Supercell Intensifies

precipitation and winds intensify, rotation develops

This was initially a small supercell, looking west from about 8 miles, that packed a very intense rotating updraft. The rain curtains extending beneath the storm base were rotating, and looked very much like the rain areas we have seen under HP supercell bases. Once again, note the vaulted appearance on the north (right) side of the updraft. The storm was producing baseball size hail at this time, and a low-pitched, subtle, and continuous roaring sound was heard. Storm chasers have heard this a number of times, particularly close to LP storms, and attribute it to hailfall.


Photograph by: Moller

Below is a northward view of the storm's main precipitation area. It has the nearly transparent look of an LP storm. The radar echo at this time showed a relatively small VIP 4 storm, although a small radar pendant was present. A VIP 4 with baseball hail! Indeed, it seemed to have mainly LP characteristics, except for the rotating rain curtains wrapping around the updraft base.


Photograph by: Moller

At this time and location, just west of Archer City, Texas, east surface winds were blowing into the supercell at 25 to 30 MPH. We are very close in position to the pseudo-warm front, separating cool outflow coming from this precipitation area to the north from warm air to the south...

A Tornado Develops

producing a 20 mile path of destruction

...About 15 minutes later, we have moved off to the east, but the storm is closer (relative to the photographic position) than before, about 4 miles to the west. The storm (below) was showing a dramatic visual increase in an opaque precipitation curtain northeastof the updraft at this time, which was verified by a much larger and more intense radar echo.


Photograph by: Moller

Note that the precipitation curtain extends fully around the back side of the vaulted updraft and the wall cloud lowering. From this position closer to the updraft, the easterly inflow has increased to 40 to 50 MPH! Not only was there strong inflow, it was becoming progressively stronger as it was "squeezed" into the mesocyclone. The radical increase in inflow, the increase in liquid (and likely frozen) precipitation, and the ominous appearance of the rotating storm led to an inescapable conclusion, that a tornado is about to form.

Photograph by: Moller

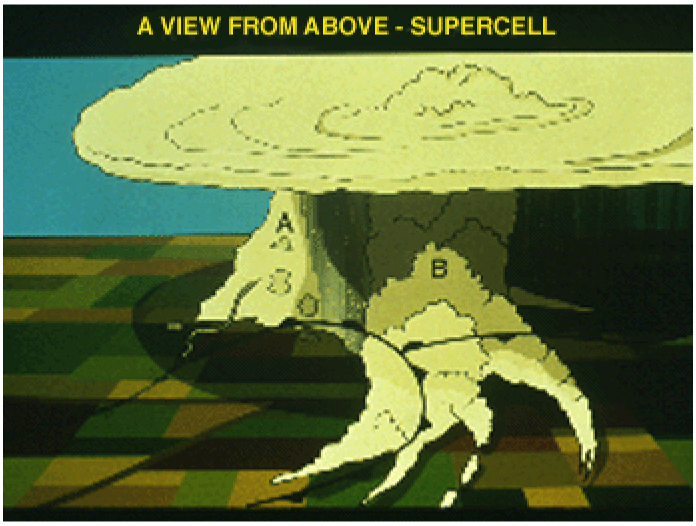
The tornado was buried in rotating rain curtains, but the rapidly-moving precipitation parted long enough to give the storm chasers this northwest view from about 3 miles. After about 6 minutes, the tornado became embedded in rain again, as it continued along a 20 mile path of destruction.

The parent storm had mainly LP traits early, then in quick succession swung into classic and finally HP storm modes. Clearly, these "variations" are spin-offs of one general storm classification, the supercell: the most dangerous of thunderstorms no matter which of the radar or visual appearances it assumes.

An Introduction to Cyclic Storms

one updraft weakens as a new one intensifies

Looking northwest from above, an artist's view of a cyclic supercell portrays the rope stage of the dissipating tornado, and the rapidly weakening updraft (A) associated with it. At the same time, a new rotating updraft (B) is developing several miles to the east along the intersection of the RFD gust front and the stationary front (referred to as a pseudo-warm front). The juxtaposition of the intersecting gust fronts make this a highly favored area for formation of a new rotating updraft.



The clear slot knifing between (A) and (B) and the new overshooting top indicates that (B) is now the dominant updraft. The cyclonically curving cloud bands inflowing to (B) and a "beaver's tail" oriented east-west in the cloud shadows near the pseudo-warm front are important visual supercell signatures that spotters are likely to observe.

From a meteorological view, as the cool and warm air on adjacent sides of the pseudo-warm front rush westward into the mesocyclone, there is a tendency for the north side cool air to slide beneath the warm air, which, in turn, rotates above the cool air. This "solenoidal" generation of horizontal vorticity and subsequent tilting of this vorticity into the vertical may be a vital component of the tornadogenesis process.

Photograph by: Moller

Looking in the same direction (northwest), but from beneath the storm, we observe another mature tornado with a clear slot RFD wedging in between the wall cloud and flanking line. A large area of rain-free base is apparent to the east of the tornado.

Photograph by: Moller

About 10 minutes later, the tornado lifts after its inflow has been cut off by the advancing RFD. A new wall cloud (extreme right) has formed from beneath the rain-free base, 3 or 4 miles east-southeast of the dying tornado. Within about 20 minutes this wall cloud fostered a violent, 1 mile wide tornado. These tornadoes occurred in the Alfalfa and Binger, Oklahoma. A limited amount of data indicates that 20 minutes is about average for periodicity of cyclic storm tornadoes.

More Tornadoes

produced by cyclic storms

Yet another cyclic storm, looking towards the northwest. Visibilities and contrast were low in this northern Kansas storm, but we can make out a distant, rope-like tornado just left of center (about 6 miles to our west-northwest, and a wall cloud and developing funnel on the extreme right, about 3 miles to the north-northwest.

Photograph by: Moller

Minutes later, tornado #2 has touched down to our north-northwest whereas tornado #1 has lifted. This second tornado was producing significant damage at this time.

Photograph by: Moller

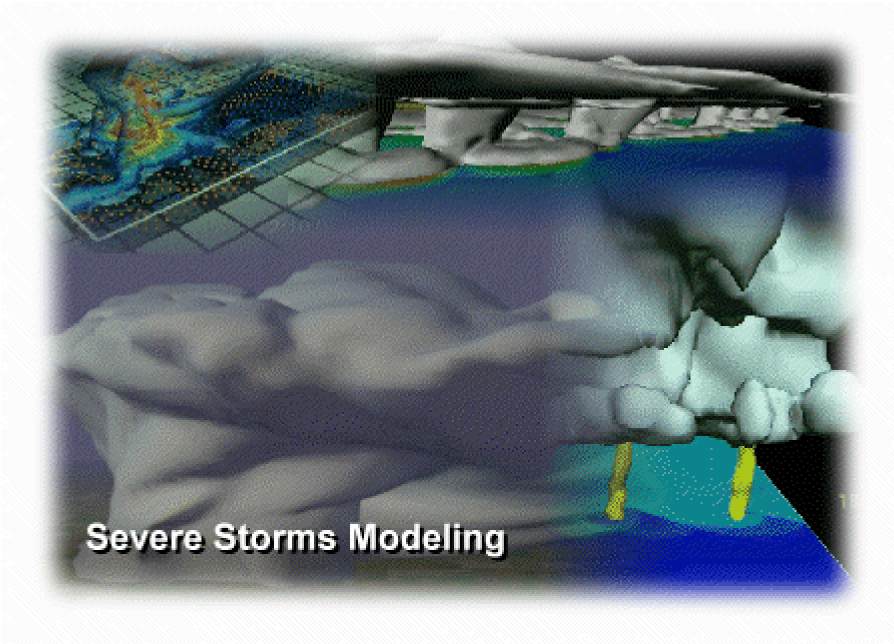
Moving closer, we are looking north from within 1/2 mile at tornado #2. It was changing rapidly in appearance as it quickly evolved into a large multiple vortex tornado. The huge vortex to the right of the road developed and dissipated within a minute, as another sub-vortex was forming to the left of the road. The tornado had become violent and leveled several farms. Early warnings were provided by excellent spotter reports.

Photograph by: Moller

Below is a storm which seemed to defy most of what we have said about cyclic storms! Looking north, note tornado #1 (with clear slot) at the south end of the precipitation area, tornado #2 east of the precipitation (extreme right), and wall cloud/developing tornado #3 in the visual distance between #1 and #2, and northeast of the precipitation area!

Photograph by: NSSL

Thus, instead of a 20 minute gap we have concurrent mesocyclones on three different thunderstorm flanks! There are always exceptions to just about any "rule of thumb" we can make about severe thunderstorms.



Since the early 1960's, meteorologists have studied severe storms with the aid of numerical models. These computer models are programmed to solve the mathematical equations describing the flow of air in the atmosphere including the development and evolution of storms. These equations describe changes in wind, temperature, pressure, water vapor amount, cloud water amount, etc. at selected points in the atmosphere. For example, a modeler might start solving the equations at some time T, calculating values at the selected points 10 seconds later. Using these new values, the solution can be computed at time T + 20 seconds. This process is often continued for hours as storms grow and decay within the modeled atmosphere.

Today scientists produce billions of numbers during a single storm simulation and this continues to increase as computer power grows. Visualization of this data is used to understand what these numbers are describing and why some storms are severe and others are not. In this module some of these visualizations are used in discussing the behavior of simulated storms and their relationship to storms seen in nature.

Sections Last Update:09/16/99	**Supercells** Illustrations and visualizations help explain these powerful storms which are the most likely to produce strong tornadoes. **Convective Lines** Convective line initiation, squall lines, and non-supercell thunderstorms which produce tornadoes will be discussed **Severe Storm Forecasting** How severe storm modeling has impacted weather forecasting.

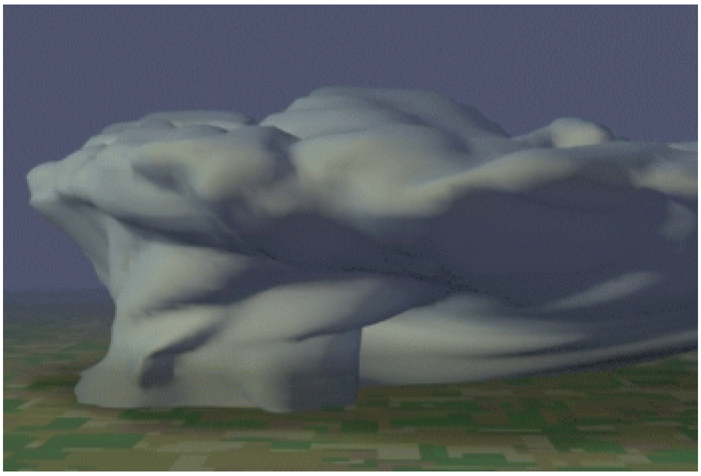
Supercells

Introduction

Supercells are long-lived thunderstorms which exhibit quasi-steady structure including a rotating updraft. These storms generally produce severe weather including heavy winds, large hail, heavy rainfall, and occasionally tornadoes. In fact it is these supercells that produce the strongest and longest-lived tornadoes.

Photo by Moller

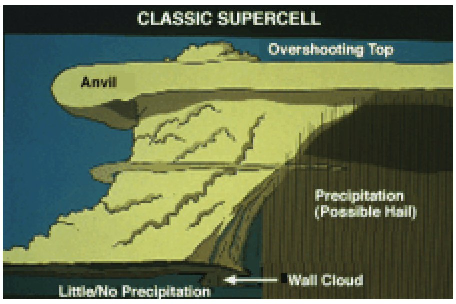
With the danger that supercells pose, it is wise to learn more about the nature of their origin and evolution. By discovering how supercell behavior is related to the surrounding environment, meteorologists can help predict when and where such storms will actually occur -- with the ultimate goal of saving lives. While real supercells like the one in the photograph above continue to occur, computer model visualizations like the one below are being used to advance our understanding and prediction of these terrible storms.



Visualization by NCSA/Wilhelmson
Click image for video (Must have RealPlayer G2)

Supercell Structure

Supercells have a common structure, as can be seen by the left diagram below. Computer model visualizations (below right) can capture most of this structure.



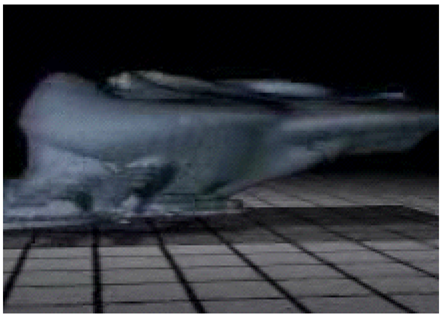
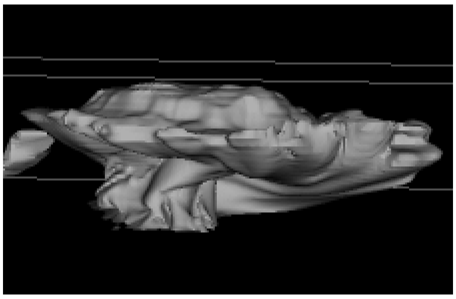
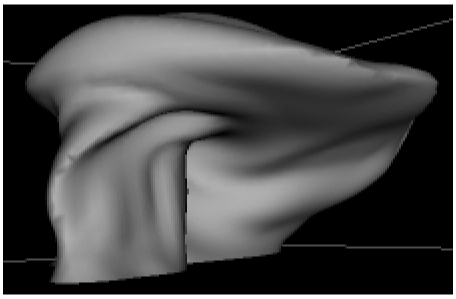


Image by NCSA/Wilhelmson
Click image for video (Must have RealPlayer G2)

Supercells are characteristically tall storms -- reaching way up into the stratosphere. The main updraft and downdraft mutually support one another leading to a long lasting storm. Click on the image below to explore a 3D severe storm through VRML.





Click to explore VRML Storm (11MB). Click to explore VRML Storm.

Often, if you can see the whole storm, you can see a large dome above the central updraft and a broad, flat region covering the entire storm and extending downwind of the updraft. This is called the anvil, and both features show up well in this model.

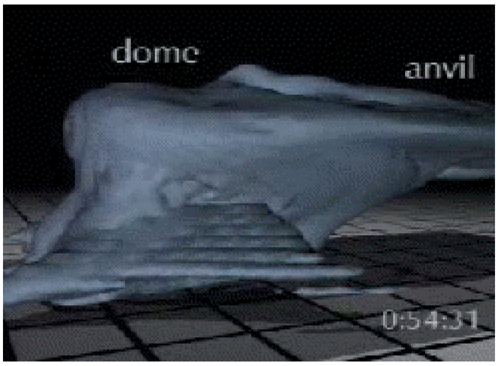


Image by NCSA/Wilhelmson

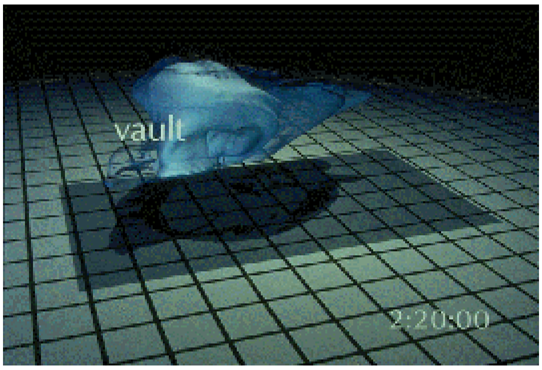


Image by NCSA/Wilhelmson

Another characteristic observable in both models and in nature is the large cloud free area above the base of the updraft known as the vault or Weak Echo Region. Rain and possibly hail fall to the ground outside this region, leaving the vault region relatively precipitation-free.

In some supercells, one can sometimes observe both a v-notch and a hook echo. In this modeled radar image, both are evident. A hook echo is a strong signal that a supercell thunderstorm is about to or already has produced a tornado.

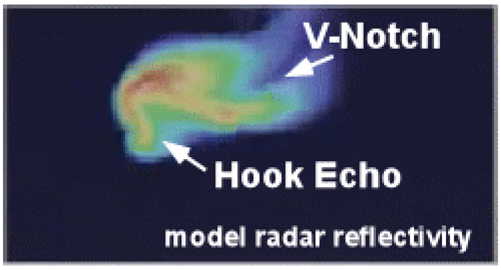
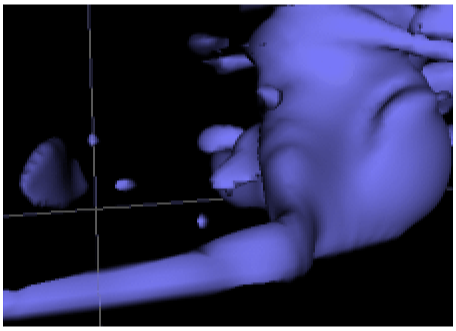


Image by NCSA/Wilhelmson


Click for VRML flanking line

Some supercell thunderstorms also possess a clearly visible flanking line. The flanking line separates cool storm outflow from warm moist storm inflow and sits above the gust front. New storms form along the flanking line as the moist inflow air rises as it approaches the cool surface air. In this VRML environment, the blue body represents areas of significant cloud development with the flanking line very evident (foreground of image).

Weightless particles are used to trace the air motion within a supercell. Blue balls are sinking and orange balls are rising.

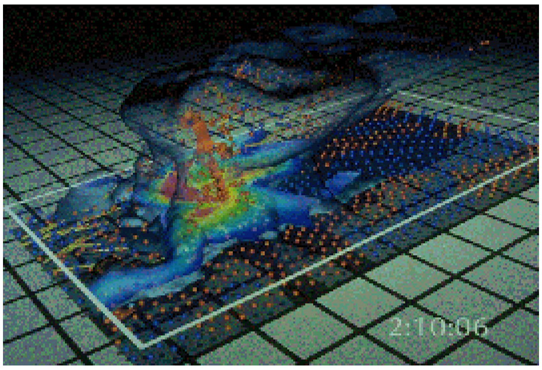


Image by NCSA/Wilhelmson

Supercells and Tornadoes

The strongest and most damaging tornadoes from within supercells. This is one of the primary reasons why researchers strive to understand them better. They want to be able to predict them (e.g. left figure) more accurately.

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/svr/modl/spr/torn.rxml

Video by Jewett

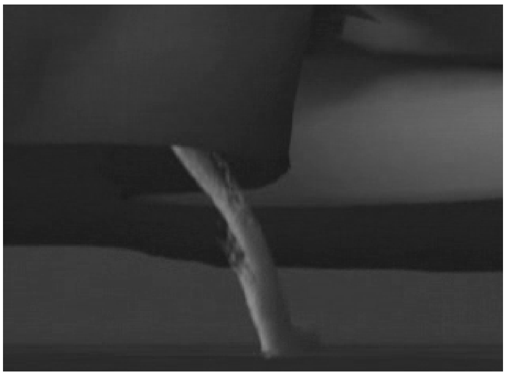
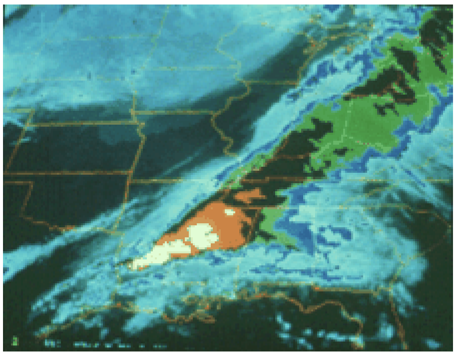


Image by NCSA/Wilhelmson

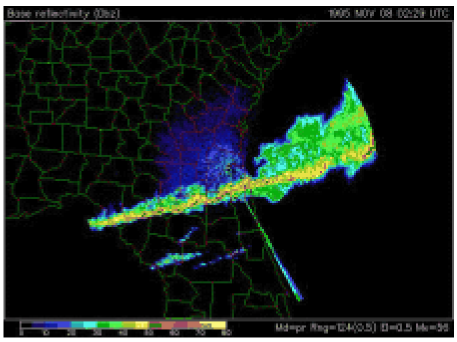
Computer models can now produce the general behavior of tornadoes like the one above on the right. Weightless tracer particles are used to define the tornado's flow. However, determining which supercells will produce tornadoes remains a challenging task that is still under investigation.

Convective Lines



Lines of convective cells can also produce severe weather and substantial damage.

Tornadic supercell thunderstorms can develop in squall lines. Tornadoes (non-supercell) can also appear in developing lines in which the parent storms exhibit little rotation.



Squall Lines

Squall lines generally form along or ahead of cold fronts and drylines and can produce severe weather in the form of heavy rainfall, strong winds, large hail, and frequent lightning.

Squall lines can extend to hundreds of miles in length, simultaneously affecting several states at a time. They also can travel quickly -- at speeds up to 60 mph.

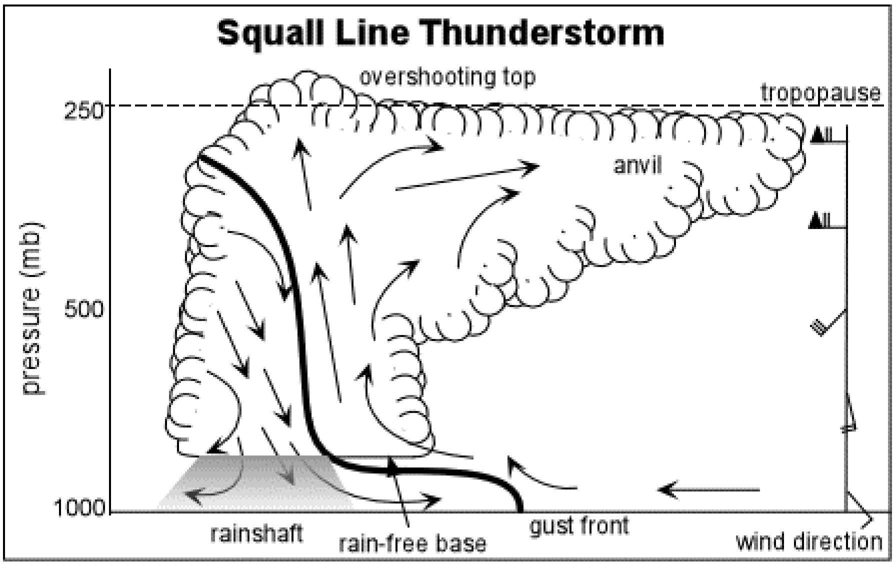
Photo by Doswell

Squall lines typically form in unstable atmospheric environments in which low-level air can rise unaided after being initially lifted (e.g., by a front) to the point where condensation of water vapor occurs. Heat is released during condensation, resulting in the rising air becoming lighter than nearby air at the same height. This leads to an increase in the speed of the rising air which sometimes reaches speeds above 30 mph. In models this initial lifting is specified through an idealization of the flow associated with the front or other lifting mechanism or through the use of observational flow information.

In this simulation, the clouds are shown in grey, and the surface color represents surface winds as seen by an observer moving with the line. Blue represents winds approaching the storm while greens and reds represent the winds in the cold air behind the storm outflow.

Video by Jewett
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/svr/modl/line/squall.rxml

The gust front is located along the line where these winds meet -- which extends from the surface well up into the the storm.



The schematic above is a depiction of the structure of a well-formed squall line. Such schematics are often a key result of a scientific investigation and can be based on observations, model and/or theory. They help communicate some of the key features in a simple and concise way. Note the similarity of the schematic to features in previous animation including the overshooting top, anvil, and gust front.

Nonsupercell Tornadoes

tornadoes produced from non-rotating storms

Even though supercell thunderstorms are responsible for the biggest and deadliest tornadoes, a significant number of tornadoes form under nonsupercell clouds and storms.

The left photograph below shows such an event. Notice that there are three tornadoes (there were actually five, but only three are pictured) that exist simultaneously. Modeling efforts to reproduce events like this have been successful as seen by the illustration below (right). Weightless tracer particles define the tornadoes.

Photo by Blottman

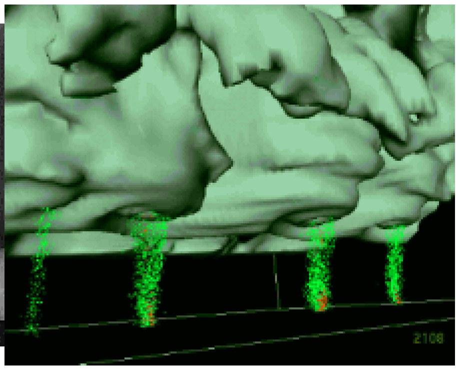


Image by Lee

These nonsupercell tornadoes (NST) are normally short-lived and weak, but from time to time can become strong enough to damage property and kill people. Because of this, researchers are investigating how a rotating entity like a tornado can be produced beneath clouds with non-rotating updrafts.

Video by Lee
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/svr/modl/line/torn.rxml

The visualization above shows the NST process. There is a strong change in the horizontal movement of air at the gust front located at the surface where the color changes. The resulting shearing instability leads to the formation of many tornadoes, some of which merge with one another. The yellow columns represent the rotation of the tornadoes.

Video by Lee
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/svr/modl/line/torn.rxml

Above is a closer look at the tornadoes produced in the previous animation. However, instead of marking the rotation regions in solid yellow, small weightless particles are introduced to show the wind field (red particles are sinking, green are rising).

These visualizations are from the first successful high resolution three-dimensional simulations of the NST generation process.

Severe Storms Forecasting

anticipating the danger

Severe storms modelers have performed many simulations over the years with the intention of helping to make more accurate forecasts.

Modelers can alter the environment that a storm starts and evolves in. Changes in storm behavior can then be assessed. An important characteristic of the atmospheric environment is vertical wind shear, a measure of the change in horizontal wind speed and direction with height. Researchers have found that different vertical distributions of wind speed and direction can make the difference between whether a storm becomes a harmless shower or a tornado producing supercell seen below. The time animation was created from a severe storm simulation by creating a "radar" view typical of the ones shown on television.

As a result of all of these studies, the research community has provided forecasters with information on the relationship between the storm environment and the type and behavior of storms that could possibly develop.

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/svr/modl/fcst/home.rxml

In addition, severe storm modelers have begun using high-resolution forecast models to predict severe weather. These models are initialized with a wide variety of observational data that reflect the character of the current atmosphere. Data includes surface and balloon data, aircraft data, and recently Doppler (NEXRAD) radar data. The benefits of this new direction in severe storm forecasting has already been demonstrated. Below is a forecast for the devastating tornadic storm in Oklahoma on May 3rd, 1999. The improvement in predicted storm location using NEXRAD data is seen.

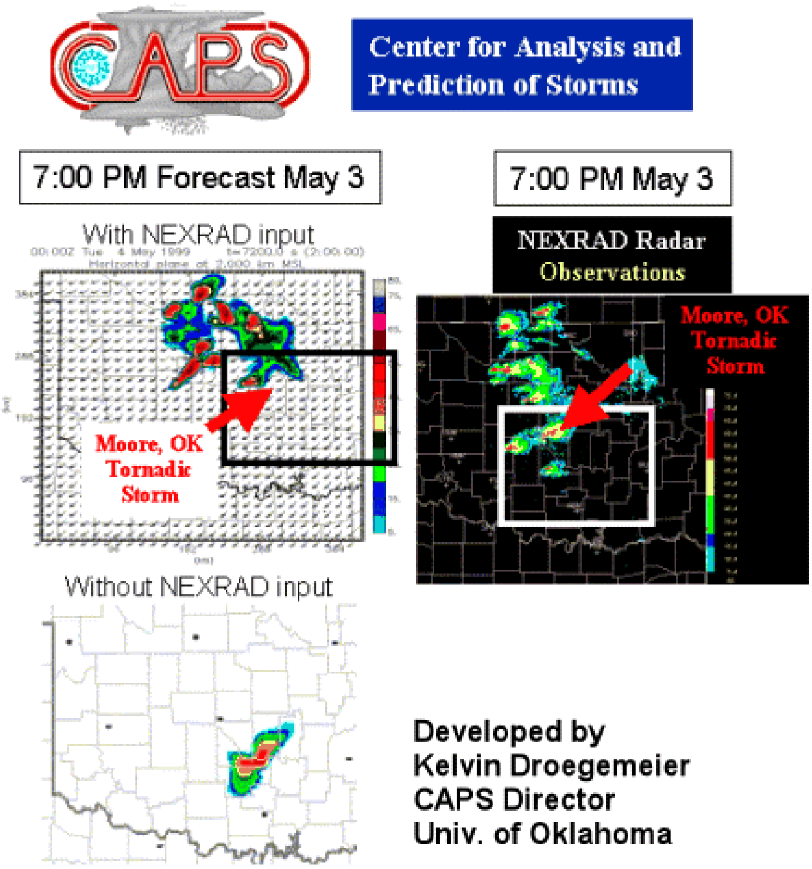
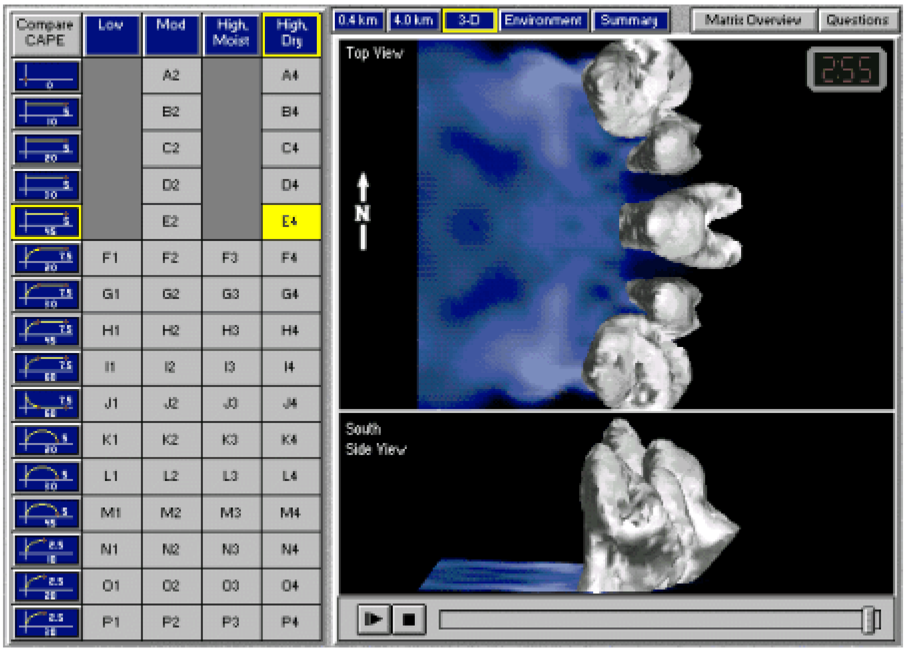


Image by CAPS

Forecast Matrix
developing a environment to storm relationship

Severe storm modeling has provided forecasters with a useful learning tool -- forecast (or convective) matrices. These matrices serve to practically condense years of modeling research results and give forecasters quick access to relationships between environment and storm type.

A forecast matrix is built by making many simulations using different combinations of wind shear and CAPE that are representative of actual storm environments. Different storm behavior is observed in these different environments. The matrix shows these results to the forecaster in the form of low level and mid level radar signatures, cloud visualizations, wind patterns, and sometimes, a brief explanation. For example, below is a 3-D view of thunderstorms that develop in a high CAPE, high speed shear (no directional shear) environment.



The original source of this image is the [Cooperative Program for Operational Meteorology, Education and Training (COMET®)](#) of the University Corporation for Atmospheric Research.

Forecasters always have estimates of wind shear and CAPE. With these, they can refer to the matrix and can get a first estimation about the potential for any developing storm to be severe.

Unfortunately, environments can change very quickly and once a storm develops, it can change its own environment. This means that the matrix is best used as a guide, and other factors -- observations, forecast models, spotters, and experience -- are vitally important.

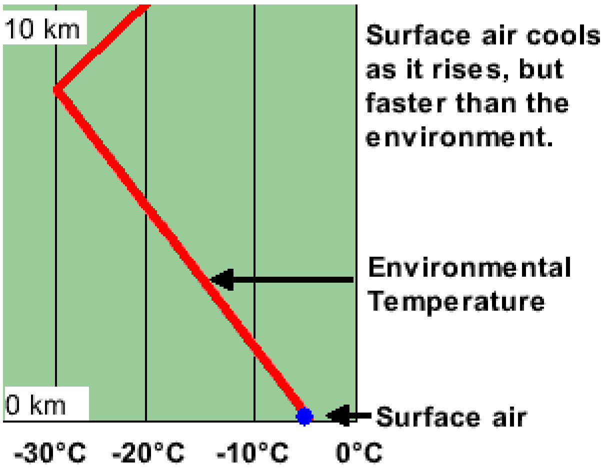
Stability

Storms developing in one environment can be different in character than those developing in another. Modelers can alter the stability of the atmosphere in which they simulate storms by changing the vertical distribution of temperature and moisture.

Thunderstorms develop when surface and low level air is allowed to rise without restriction into the upper troposphere. If air rises in an environment without restriction, the environment is said to be unstable. This means that stability is simply the resistance the atmosphere imposes on rising (or sinking) air.

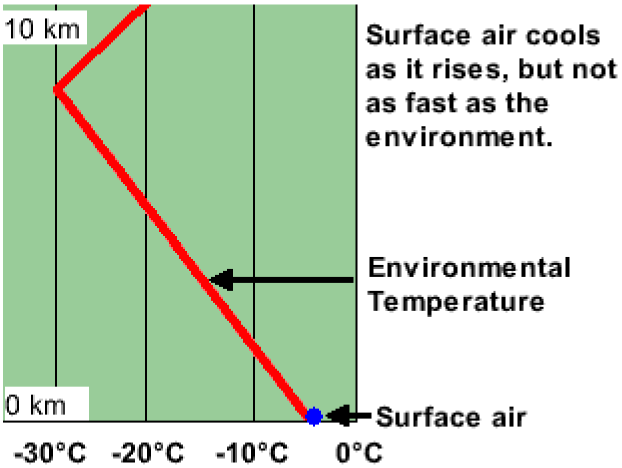
Stable Environments
Air temperature in the atmosphere generally decreases with height. However, when low level air rises, it cools at a rate that is often different from the air's surrounding environment. If, as it rises, the low level air becomes colder than its environment, it would be more dense than the environment and fall back toward its original level. This is a **stable** environment.

The only way air can rise in a stable environment is for a mechanical force such as a front to lift it.



Unstable Environments
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/svr/modl/fcst/params/stab.rxml

If, however, the rising air cools at a slower rate than the surrounding atmosphere, it will be warmer (and less dense) than its surroundings. Here, the rising air would continue rise.



The larger the temperature difference between the rising air and the environment, the more buoyant the rising air is. The more buoyant the air is, the faster it can rise, and the more severe the thunderstorm can become.

Sometimes, the environment is stable near the ground and must be forced to rise into unstable air by a front or other mechanism.
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/svr/modl/fcst/params/stab.rxml

Wind Shear

The environmental wind field is also very important in determining what type of a thunderstorm could develop. Severe weather usually occurs when the change in horizontal winds (wind shear) is significant. This includes the change in wind direction (directional shear) or speed (speed shear).

Speed Shear
In speed shear, the wind increases in speed from the surface to the upper levels, as shown in this diagram by the arrows. This vertical shear creates horizontal rotation which can best be visualized by placing a paddle wheel in the environment. Besides the rotation, the change in wind speed with

height lets the updraft separate from the downdraft, allowing the storm to survive longer and even become stronger.

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/svr/modl/fcst/params/shear.rxml

Illustration of vertical speed shear (arrows)
(paddlewheel inserted to demonstrate local vorticity)
The original source of this image is the Cooperative Program for Operational Meteorology, Education and Training (COMET®) of the University Corporation for Atmospheric Research.

Directional Shear
Directional shear refers to a change in the direction of the wind with height. Notice in this image there is both speed and directional shear as both the angle and the length of the wind vectors are changing with height. Two viewpoints are shown in the following figure. The length of the arrows represents the wind speed. The arrows point in the direction that the wind is blowing and are located at different heights in the column of air shown. Both speed and directional changes occur from one level to another.

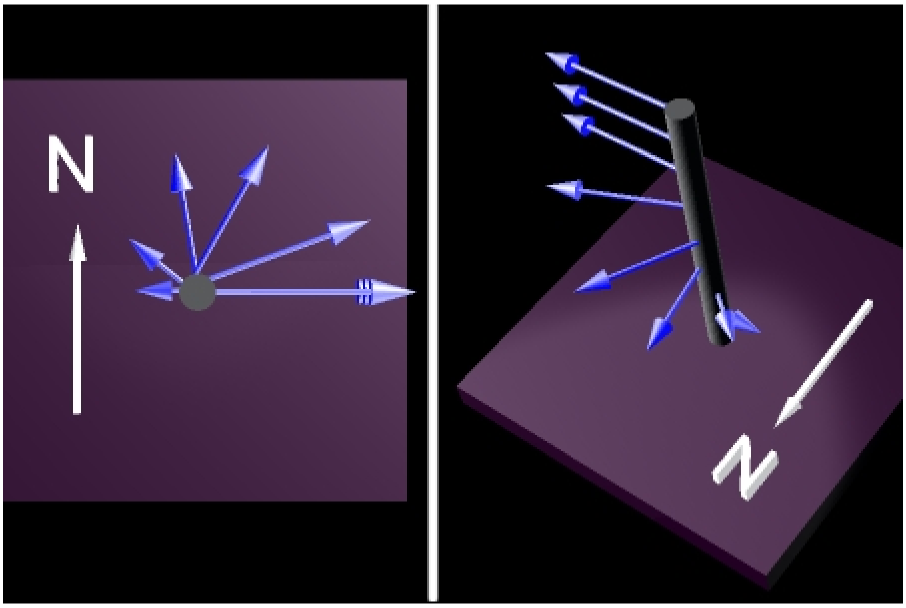


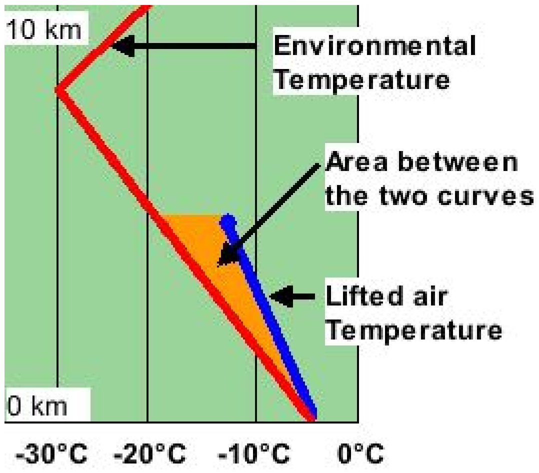
Illustration of both directional and speed shear
Image by Bramer

Modelers run experiments with storms developing in different amounts of wind shear. Differing amounts of wind shear can determine whether a storm remains small or becomes a supercell.

CAPE

In an unstable environment, the temperature of rising air can be traced and compared to the vertical profile of the environmental temperature.

The area between these two lines is representative of the available energy a storm could use to grow. This energy is call CAPE (Convective Available Potential Energy) and comes from the energy released when water condenses.



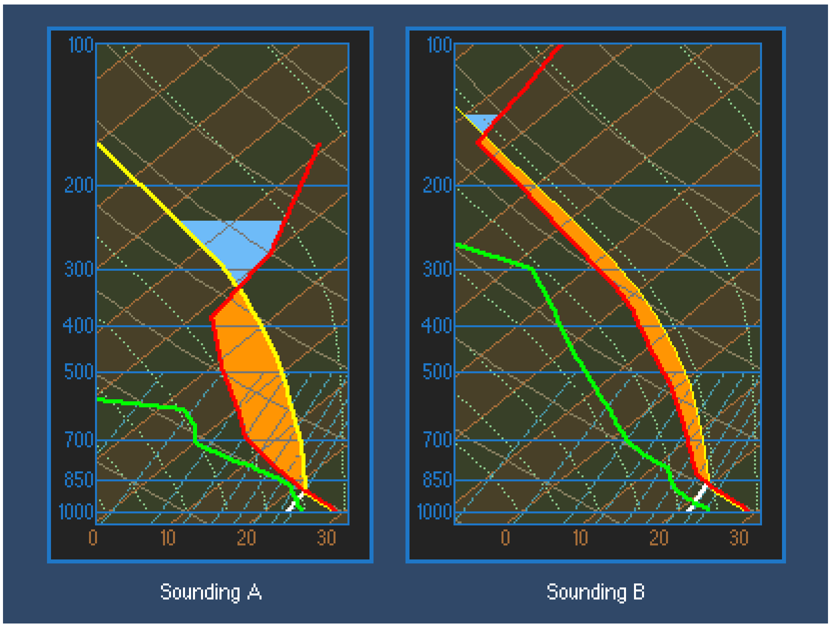
Meteorologists use more sophisticated diagrams (like the skew-T diagram below) to determine the relationship between the temperatures of the environment and the rising air. Here the red line still represents the environmental temperature.

This movie shows surface air which is lifted into unstable air. The thin yellow line is tracing the rising air's temperature. The orange area between these curves is related to the amount of CAPE present.

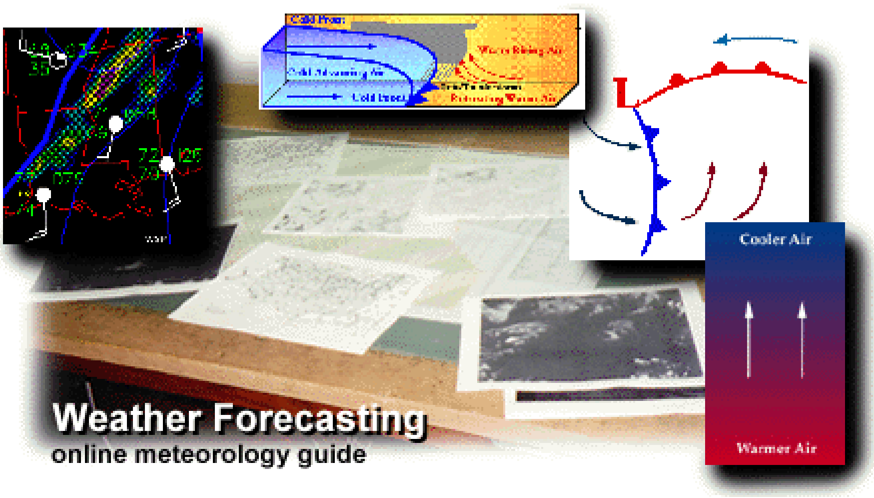
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/svr/modl/fcst/params/cape.rxml

The original source of this image is the Cooperative Program for Operational Meteorology, Education and Training (COMET®) of the University Corporation for Atmospheric Research.

There are two aspects of CAPE that meteorologists look at when diagnosing severe storm potential -- the size and the distribution of the orange area. The size (or magnitude) of CAPE is important as it describes the potential strength (e.g. updraft speeds) within storms. However the distribution of CAPE is just as important. This is because the same CAPE (orange area) could come from an environment with a large temperature difference over a shallow level or from a smaller temperature difference over a deeper level. The diagram below shows this. The orange areas (and therefore CAPEs) are identical.



Notice how in the sounding A, the difference in temperature between the environment and the rising air is much greater than in sounding B. This means that the rising air in sounding A is more buoyant with respect to its environment than that of the air rising in sounding B. Stronger updrafts and more severe storms are likely in sounding A.



Graphic developed by: Dan Bramer

"Look for hazy skies with afternoon thunderstorms and a high of 95 degrees." Weather forecasts, such as this one, provide critical information about the weather to come. In severe weather situations, short-term forecasts and warnings can help save lives and protect property. It is vital that weather forecasts be as accurate as possible because so many people depend upon them. This module introduces forecast methods and the numerous factors one must consider when attempting to make an accurate forecast. The Weather Forecasting module has been organized into the following sections:

Sections
Last Update:
07/21/97

Forecasting Methods
Different forecasting methods for different weather scenarios.

Surface Features
Important surface features to consider when making a forecast.

Forecasting Temperatures
Factors to consider when forecasting day and nighttime temperatures.

Forecasting Precipitation
Factors to consider when forecasting precipitation.

Acknowledgments
Those who contributed to the development of this module.

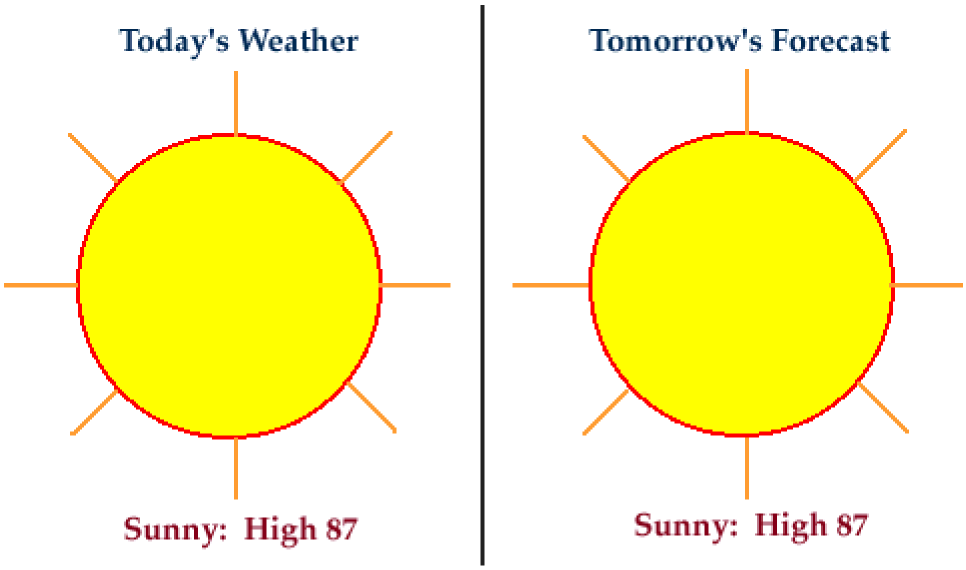
The navigation menu (left) for this module is called "Weather Forecasting" and the menu items are arranged in a recommended sequence, beginning with this introduction. In addition, this entire web server is accessible in both "graphics" and "text"-based modes, a feature controlled from the blue "User Interface" menu (located beneath the black navigation menus). More information about the user interface options, the navigation system, or WW2010 in general is accessible from About This Server.

Persistence Method

today equals tomorrow

There are several different methods that can be used to create a forecast. The method a forecaster chooses depends upon the experience of the forecaster, the amount of information available to the forecaster, the level of difficulty that the forecast situation presents, and the degree of accuracy or confidence needed in the forecast.

The first of these methods is the Persistence Method; the simplest way of producing a forecast. The persistence method assumes that the conditions at the time of the forecast will not change. For example, if it is sunny and 87 degrees today, the persistence method predicts that it will be sunny and 87 degrees tomorrow. If two inches of rain fell today, the persistence method would predict two inches of rain for tomorrow.



The persistence method works well when weather patterns change very little and features on the weather maps move very slowly. It also works well in places like southern California, where summertime weather conditions vary little from day to day. However, if weather conditions change significantly from day to day, the persistence method usually breaks down and is not the best forecasting method to use.

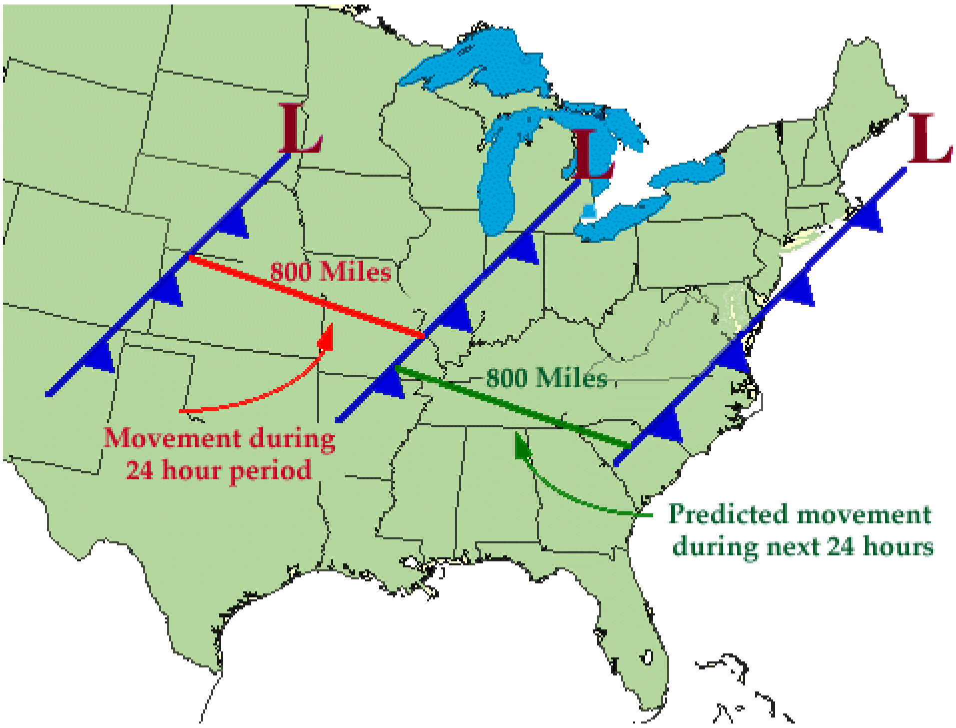
It may also appear that the persistence method would work only for shorter-term forecasts (e.g. a forecast for a day or two), but actually one of the most useful roles of the persistence forecast is predicting long range weather conditions or making climate forecasts. For example, it is often the case that one hot and dry month will be followed by another hot and dry month. So, making persistence forecasts for monthly and seasonal weather conditions can have some skill. Some of the other forecasting methods, such as numerical weather prediction, lose all their skill for forecasts longer than 10 days. This makes persistence a "hard to beat" method for forecasting longer time periods.

Trends Method
using mathematics

The trends method involves determining the speed and direction of movement for fronts, high and low pressure centers, and areas of clouds and precipitation. Using this information, the forecaster can predict where he or she expects those features to be at some future time. For example, if a storm system is 1000 miles west of your location and moving to the east at 250 miles per day, using the trends method you would predict it to arrive in your area in 4 days.

Mathematics
(1000 miles / 250 miles per day = 4 days)

Using the trends method to forecast only a few hours into the future is known as "Nowcasting" and this method is frequently used to forecast precipitation. For example, if a line of thunderstorms is located 60 miles to your northwest and moving southeast at 30 miles per hour, you would predict the storms to arrive in your area in 2 hours. Below is an example of using the trends method to forecast the movement of a cold front. Initially, the cold front moved 800 miles during the first 24 hours, from the central Plains to the Great Lakes.



Using the trends method, you would predict this weather system to move another 800 miles in the next 24 hours, reaching the East Coast of the United States. The trends method works well when systems continue to move at the same speed in the same direction for a long period of time. If they slow down, speed up, change intensity, or change direction, the trends forecast will probably not work as well.

Other Forecasting Methods

climatology, analogue and numerical weather prediction

Climatology:
The Climatology Method is another simple way of producing a forecast. This method involves averaging weather statistics accumulated over many years to make the forecast. For example, if you were using the climatology method to predict the weather for New York City on July 4th, you would go through all the weather data that has been recorded for every July 4th and take an average. If you were making a forecast for temperature and precipitation, then you would use this recorded weather data to compute the averages for temperature and precipitation.

If these averages were 87 degrees with 0.18 inches of rain, then the weather forecast for New York City on July 4th, using the climatology method, would call for a high temperature of 87 degrees with 0.18 inches of rain. The climatology method only works well when the weather pattern is similar to that expected for the chosen time of year. If the pattern is quite unusual for the given time of year, the climatology method will often fail.

Analog Method:
The Analog Method is a slightly more complicated method of producing a forecast. It involves examining today's forecast scenario and remembering a day in the past when the weather scenario looked very similar (an analog). The forecaster would predict that the weather in this forecast will behave the same as it did in the past.

For example, suppose today is very warm, but a cold front is approaching your area. You remember similar weather conditions one last week, also a warm day with cold front approaching. You also remember how heavy thunderstorms developed in the afternoon as the cold front pushed through the area. Therefore, using the analog method, you would predict that this cold front will also produce thunderstorms in the afternoon.

The analog method is difficult to use because it is virtually impossible to find a perfect analog. Various weather features rarely align themselves in the same locations they were in the previous time. Even small differences between the current time and the analog can lead to very different results. However, as time passes and more weather data is archived, the chances of finding a "good match" analog for the current weather situation should improve, and so should analog forecasts.

Numerical Weather Prediction:
Numerical Weather Prediction (NWP) uses the power of computers to make a forecast. Complex computer programs, also known as forecast models, run on supercomputers and provide predictions on many atmospheric variables such as temperature, pressure, wind, and rainfall. A forecaster examines how the features predicted by the computer will interact to produce the day's weather.

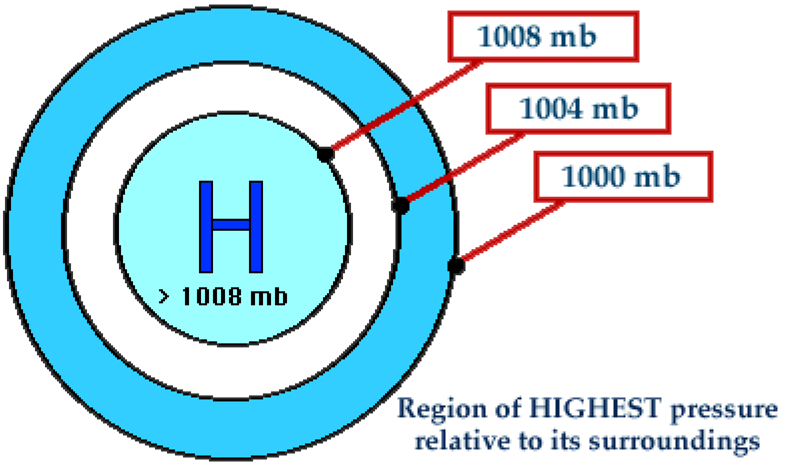
The NWP method is flawed in that the equations used by the models to simulate the atmosphere are not precise. This leads to some error in the predictions. In addition, the are many gaps in the initial data since we do not receive many weather observations from areas in the mountains or over the ocean. If the initial state is not completely known, the computer's prediction of how that initial state will evolve will not be entirely accurate.

Despite these flaws, the NWP method is probably the best of the five discussed here at forecasting the day-to-day weather changes. Very few people, however, have access to the computer data. In addition, the beginning forecaster does not have the knowledge to interpret the computer forecast, so the simpler forecasting methods, such as the trends or analogue method, are recommended for the beginner.

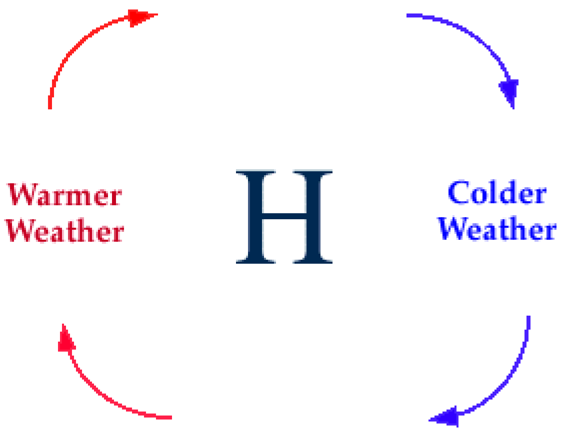
Anticyclones

bringing fairer weather

There are several key surface features to consider when making a forecast. We will begin this discussion with the anticyclone, which is a high pressure center where the pressure has been measured to be the highest relative to its surroundings. That means, moving any direction away from the "High" will result in a decrease in pressure. High pressure centers often represent the centers of anticyclones.



A high pressure center is represented on a weather map by a blue "H" and air diverges outward from a surface high. With air moving away from this region, air must sink from above to replace it. This sinking motion leads to generally fair skies and no precipitation near the high.

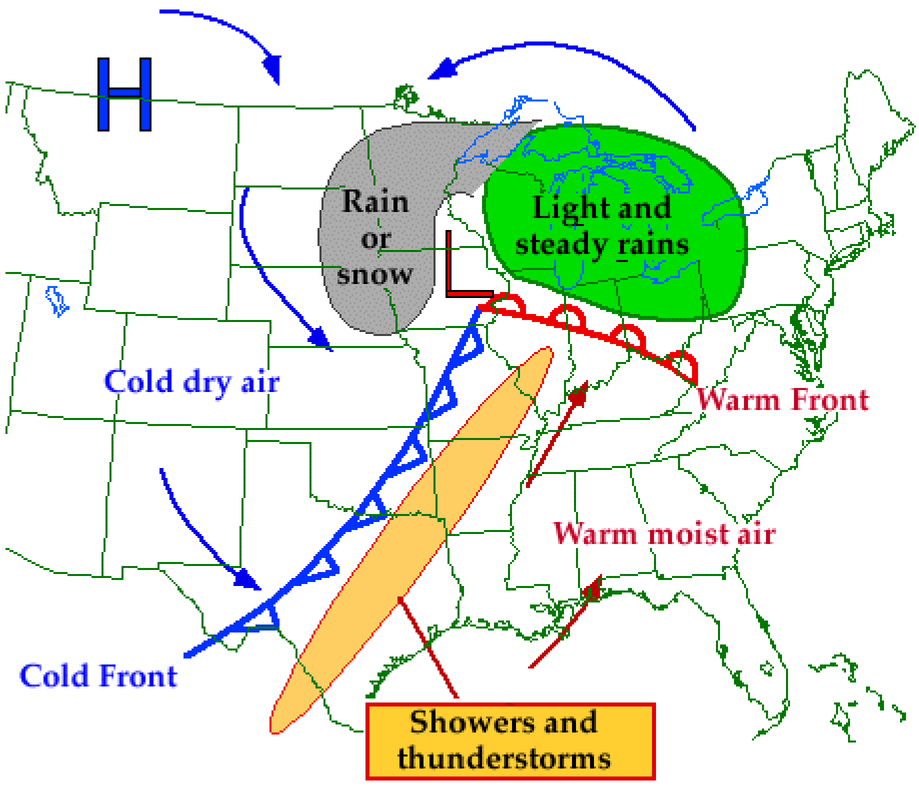


Winds flow clockwise around a high pressure center in the northern hemisphere (above). Temperatures are dependent upon the location relative to the high. Northerly winds associated with an approaching high are likely to result in colder temperatures while southerly winds found on the backside of a high, or once a high has passed through, typically result in a warming trend.

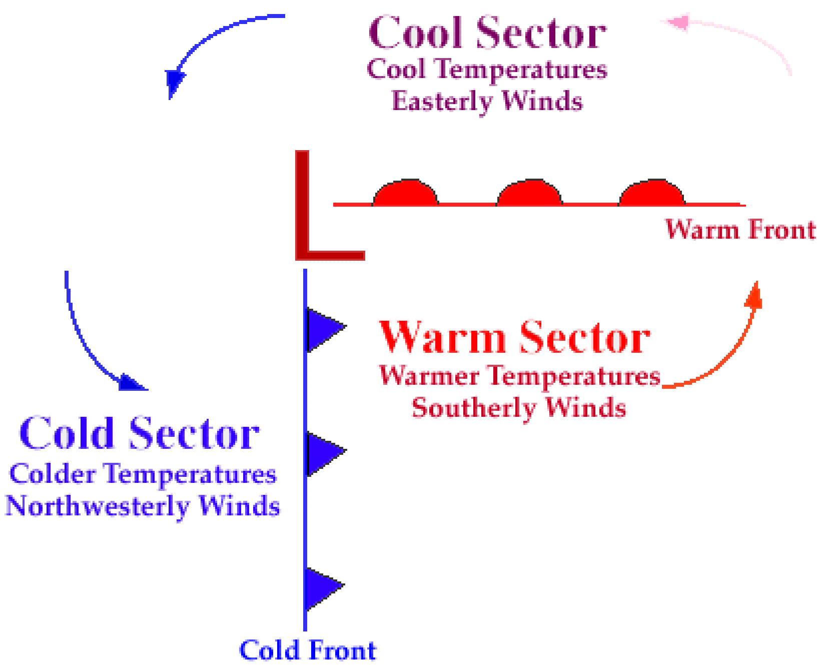
Cyclones

bringing clouds and precipitation

A cyclone is an area of low pressure around which the winds flow counterclockwise in the northern hemisphere. Since a cyclone is also known as a low pressure center, moving in any horizontal direction away from the "Low" will result in increasing pressure. Air converges into a low pressure center which causes air to rise. The rising motion may produce clouds and precipitation. Different precipitation types include rain and thunderstorms in the summer and fall seasons, to rain, thunderstorms, and even snow during the winter.



A low is represented on a weather map by a red "L". As a cyclone approaches, the likelihood of clouds and precipitation increases.

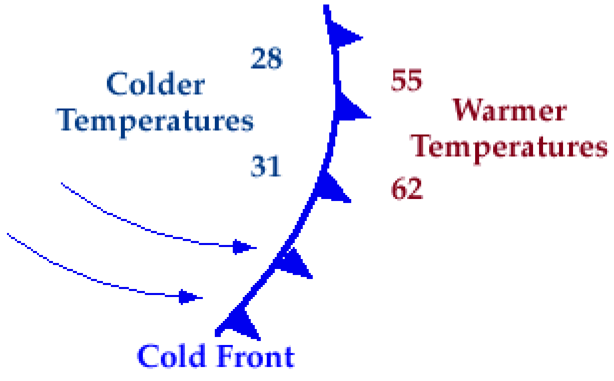


Winds flow counterclockwise around a low pressure center in the northern hemisphere and temperatures are dependent upon the location relative to the low. Southerly winds associated with an approaching cyclone are likely to result in warmer temperatures while northerly winds found on the backside of a low, or once a low has passed through, typically result in a cooling trend.

Cold Fronts

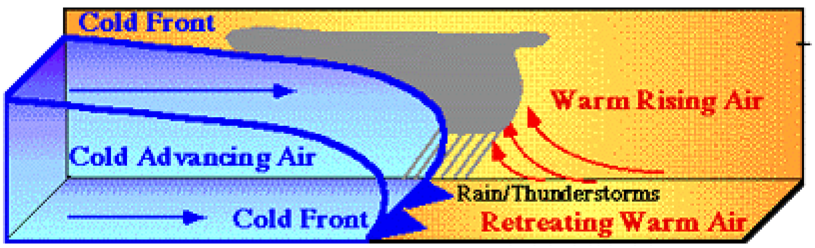
colder temperatures and possibly precipitation

A cold front is defined as the transition zone where a cold air mass is replacing a warmer air mass. In the example below, temperatures ahead of the cold front are 55 and 62 degrees while behind the front, the temperatures are lower, 31 and 28.



The air mass behind a cold front is likely to be cooler and drier than the one before the front. If a cold front is approaching, precipitation is possible just before and while the front passes. Behind the front, expect clearing skies, cooler temperatures, and lower relative humdities.

The picture below is a vertical cross-section depicting the development of precipitation ahead of and along cold front. The blue mass represents the colder air behind the cold front (solid blue line) and the yellow areas indicate the warm moist air mass ahead of the front.



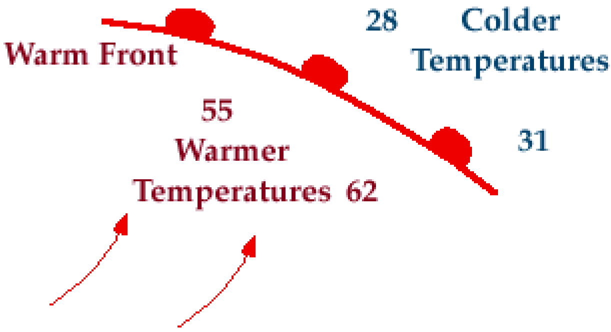
As the cold air mass propagates, it lifts the warmer less dense air ahead of it (red arrows). The air cools as it rises and the moisture condenses to produce clouds and precipitation ahead of and along the cold front. In contrast to lifting along a warm front, upward motions along a cold front are typically more vigorous, producing deeper clouds and more intense bands of showers and thunderstorms. However, these bands are often quite narrow (a couple hundred kilometers across) and move rapidly just ahead of the cold front.

+

Warm Fronts

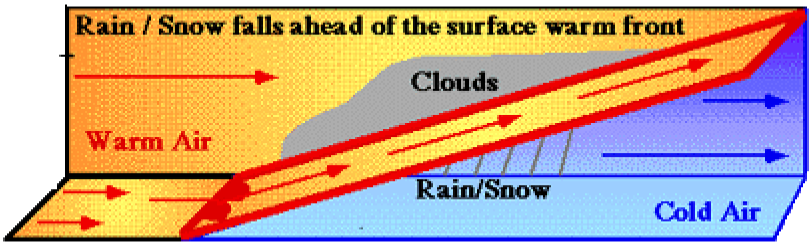
warm and more moist conditions

A warm front is the transition zone where a warm air mass is replacing a cold air mass. The air behind a warm front is generally warmer and more moist than the air ahead of it. A likely scenario has been depicted below, where temperatures ahead of the front are in the 20's and 30's while behind the front they are in the 50's and 60's.



The air mass behind a warm front is likely to be warmer and more moist than the one before the front. If a warm front is approaching, light rain or light winter precipitation is possible before and as the front passes. Behind the front, expect clearing skies, warmer temperatures and higher relative humdities.

The figure below is a vertical cross section depicting the development of precipitation ahead of and along a warm front. The region shaded in blue represents the colder air mass while the yellow areas indicate the warm moist air mass behind the warm front (solid red line).

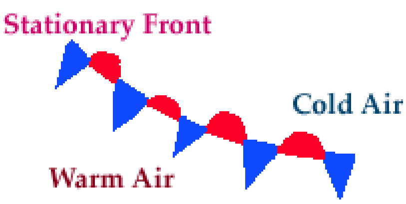


The surface of the warm front extends vertically into the atmosphere, sloping up and over the colder air ahead it. Warm air rides up and over the cold air mass, cooling as it rises, producing clouds and precipitation in advance of the surface warm front. Because the lifting is very gradual and steady, generally wide spread and light-intensity precipitation develops ahead of a warm front

Stationary Fronts

runway for cyclones

A stationary front is simply a front that is not moving. It is represented by alternating blue and red lines with blue triangles pointing towards the warmer air and red semicircles pointing towards the colder air.



Weather conditions greatly depend upon which side of the front a location is positioned. If a stationary front is nearby and a low pressure center is approaching along the front, heavy amounts of precipitation are possible.

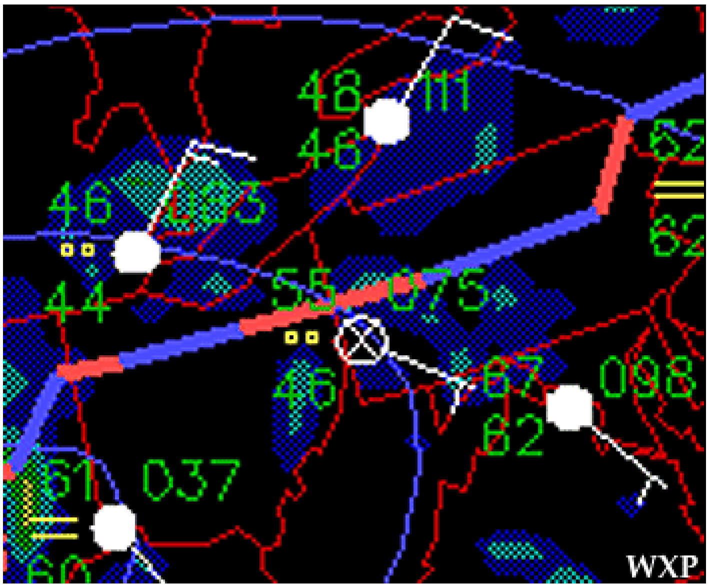


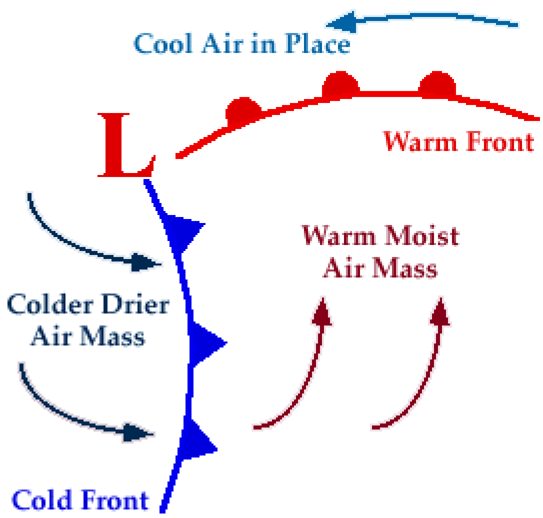
Image by: WXP Purdue

There is usually a noticeable change in temperature and wind shift crossing from one side of a stationary front to the other. Low pressure centers sometimes migrate along stationary fronts, dumping heavy amounts of precipitation in their path. Such a scenario has been depicted above. The alternating red and blue line is the stationary front and the blue and green swatches indicate precipitation.

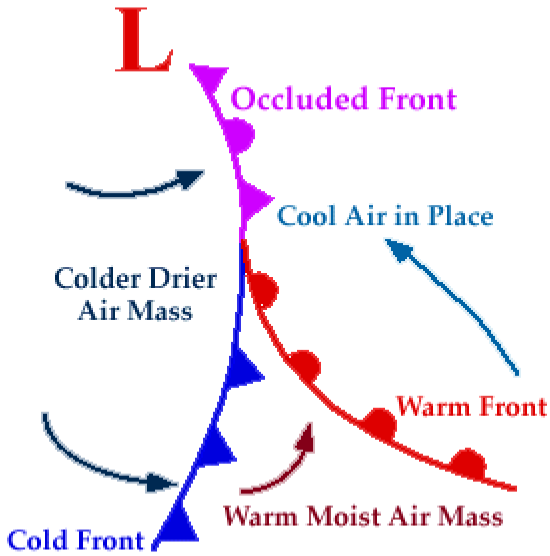
Occluded Fronts

when a cold front catches a warm front

An occluded front develops when a cold front catches a warm front. For a maturing cyclone, a warm front is progressing northward ahead of the storm center while a cold front is sweeping southeastward. The cool air mass north of the warm front is already in place.



As the storm intensifies, the cold front rotates around the storm and catches the warm front. This forms an occluded front, which is the boundary that separates the new cold air mass (to the west) from the older cool air mass already in place north of the warm front. Symbolically, an occluded front is represented by a solid line with alternating triangles and circles pointing the direction the front is moving. On colored weather maps, an occluded front is drawn with a solid purple line.



Ahead of the occluded front, temperatures were reported in the low 40's, while temperaturesbehind the front were in the 20's and 30's. The air mass behind the front is also drier as shown by the lower dew points. Wind direction reports to the east of the front are from the east or southeast, while winds behind the front are from the west or southwest. Convergence of the easterly winds ahead of the occluded front and the westerly winds behind it can result in showers of rain or snow.

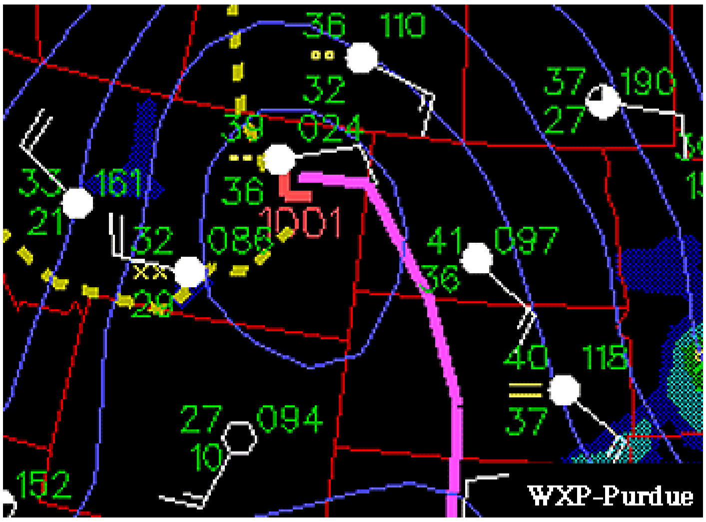


Image by: WXP Purdue

With the passage of an occluded front, weather conditions will likely turn from cool to cold. Winds will swing around from easterly to westerly or southwesterly with rain or snow showers possible, (depending upon how cold the temperatures are).

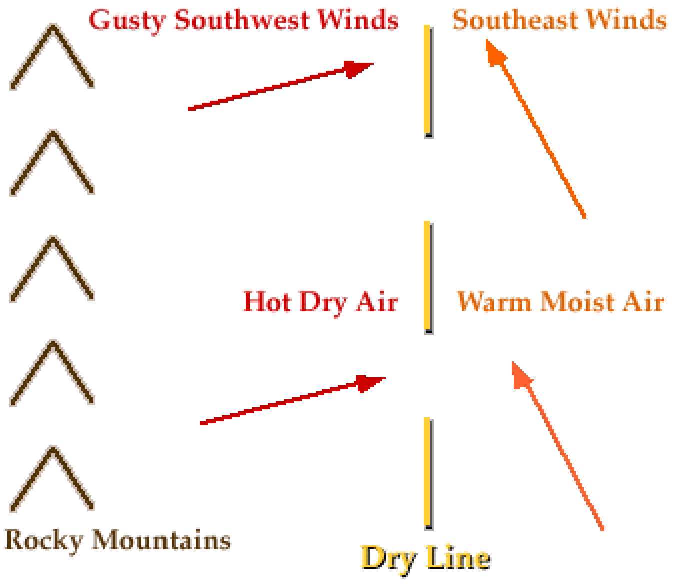
Dry Line

a moisture boundary

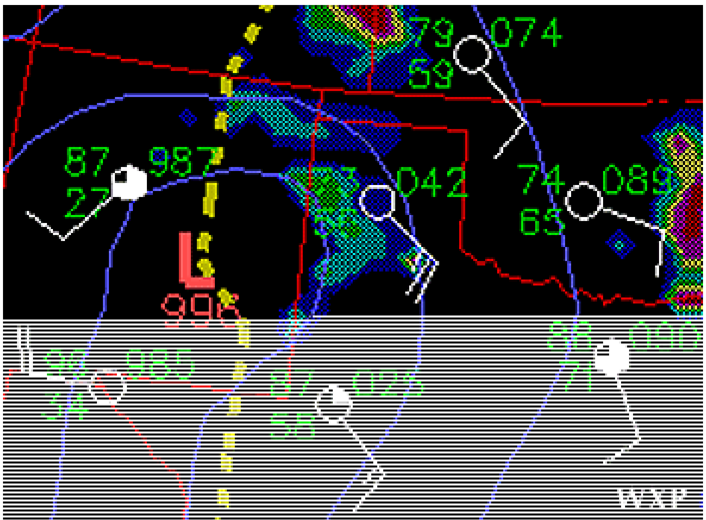
Forecast Tip:
If a dryline is approaching your region, predict that air will be much drier after the boundary moves

through. Storms are possible as the dryline approaches. The temperature may rise after the dryline passes through, since dry air heats up more quickly than moist air.

A dryline is a boundary that separates a moist air mass from a dry air mass. A dryline is also called a **Dew Point Front**. Sharp changes in dew point temperature can be found across a dryline (sometimes 9 degrees **Celsius** per kilometer). Drylines are most commonly found just east of the Rocky Mountains, separating a warm, moist air mass to the east from a hot, dry air mass to the west (see diagram below).



States like Texas, New Mexico, Oklahoma, Kansas, and Nebraska frequently experience drylines in the spring and summer, while east of the Mississippi River, drylines are extremely rare. The dryline is represented on surface maps by a dashed yellow line (see example below).



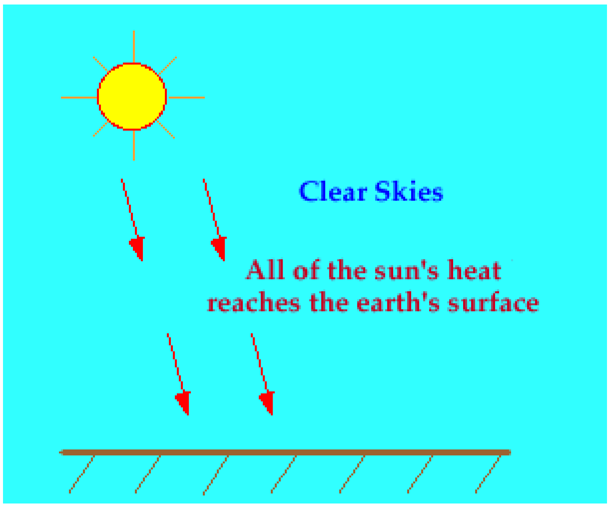
Dew points east of the dryline shown above range from the upper 50's to low 70's, with winds from the southeast. West of the dryline, dew points are much lower, in the 20's and 30's, which is almost 50 degrees less than those found east of the dryline.

Air temperature ahead of the dryline is generally in the 70's and 80's. Behind the dryline, temperatures are hotter, ranging from the mid 80's to mid 90's. The drier air behind the dryline lifts the moist air ahead of it as it advances, which could lead to the development of thunderstorms along and ahead of the dryline in a manner similar to how thunderstorms develop along cold fronts.

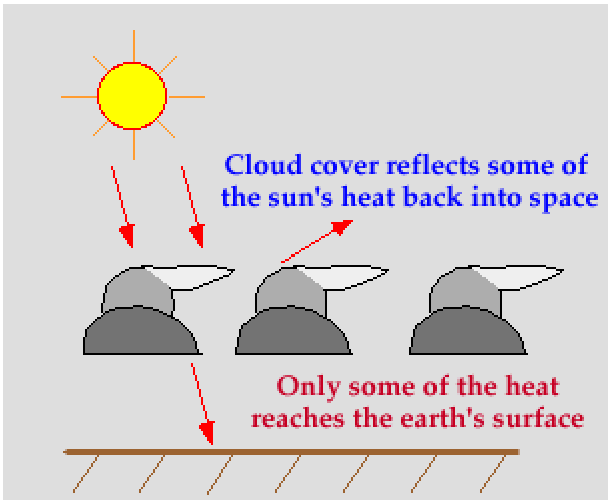
Effects of Cloud Cover

on forecasted temperatures

During the day, the earth is heated by the sun. If skies are clear, more heat reaches the earth's surface (as in the diagram below). This leads to warmer temperatures.

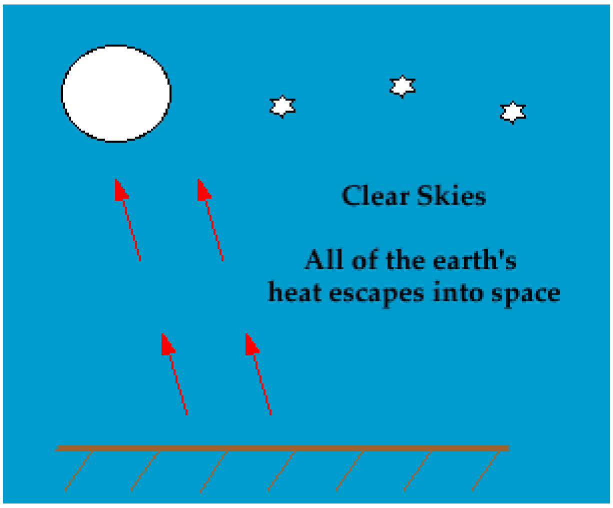


However, if skies are cloudy, some of the sun's rays are reflected off the cloud droplets back into space. Therefore, less of the sun's energy is able to reach the earth's surface, which causes the earth to heat up more slowly. This leads to cooler temperatures.

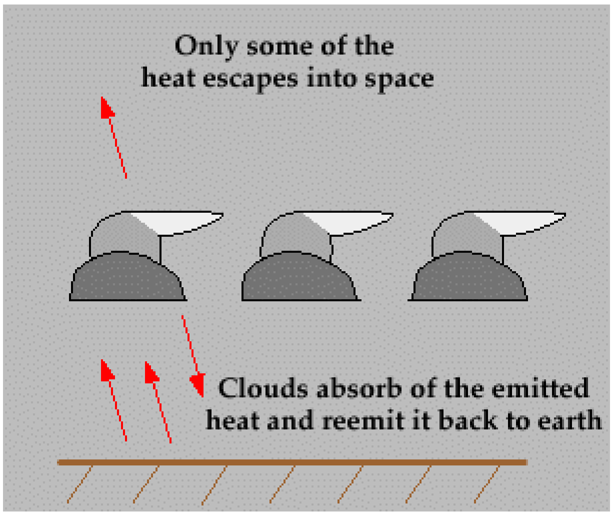


Forecast Tip:
When forecasting daytime temperatures, if cloudy skies are expected, forecast lower temperatures than you would predict if clear skies were expected.

At night cloud cover has the opposite effect. If skies are clear, heat emitted from the earth's surface freely escapes into space, resulting in colder temperatures.



However, if clouds are present, some of the heat emitted from the earth's surface is trapped by the clouds and reemitted back towards the earth. As a result, temperatures decrease more slowly than if the skies were clear.

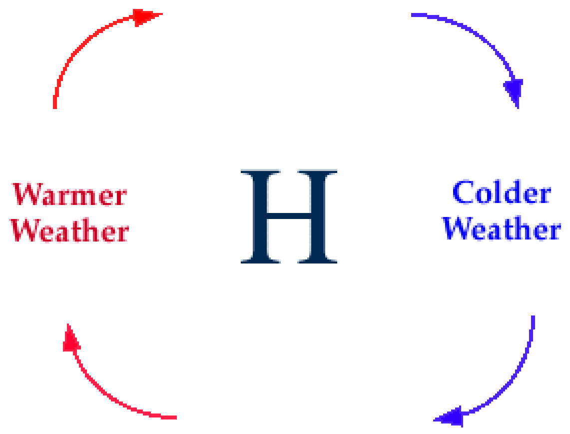


Forecast Tip:
When forecasting nighttime temperatures, if cloudy skies are expected, forecast warmer temperatures than you would predict if clear skies were expected.

High and Low Pressure Centers

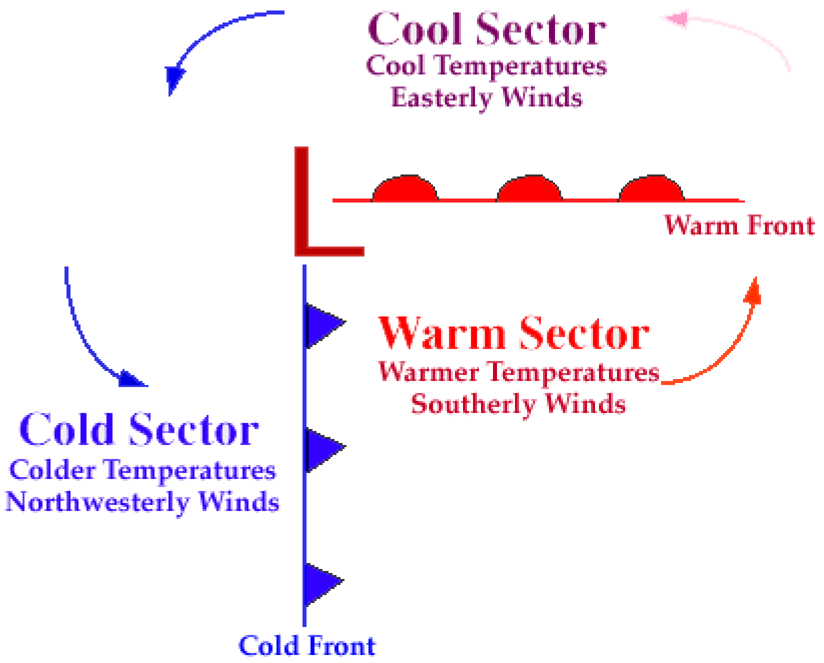
on forecasted temperatures

The positions of high and low pressure centers can greatly influence a forecast. Fair weather generally accompanies a high pressure center and winds flow clockwise around a high. This means that winds on the back (western) side of the high are generally from a southerly direction and typically mean warmer temperatures. On the front (eastern) side of a high, winds are generally from the north and this typically results in colder temperatures.



Forecast Tip:
If a city is expected to be located west of a high pressure center then warmer temperatures are likely. However, if the city is expected to be in the northerly winds of a high pressure center, then forecast colder temperatures. Cities under the influence of high pressure centers can expect generally fair weather with little or no precipitation.

In contrast, clouds and precipitation generally accompany a low pressure center and winds flow counterclockwise around lows. This means that winds on the back (western) side of the low are generally from a northerly direction and typically mean colder temperatures. On the front (eastern) side of a low, winds are generally from the south and this typically results in warmer temperatures.



Forecast Tip:

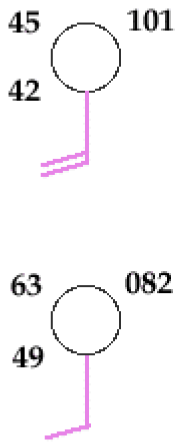
If a city is expected to be located west of a low pressure center then colder temperatures are likely. However, if the city is expected to be in the southerly winds of a high pressure center, then forecast warmer temperatures. Cities under the influence of low pressure centers can expect generally cloudy conditions with precipitation.

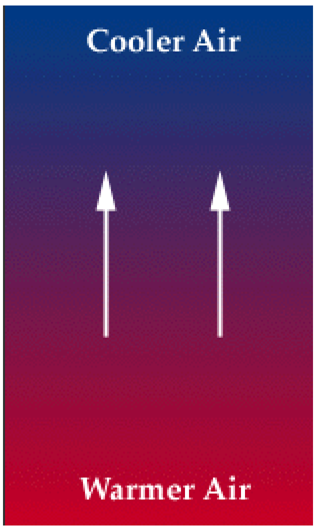
Effects of Temperature Advection

on forecasted temperatures

Forecast Tip:
When forecasting temperatures, look at the temperatures upstream from the station for which you making a forecast. If they are warmer, that means warmer air is being transported towards your station and the temperature should rise. Put in another way, if there is **warm advection** occuring at a given station, expect the temperatures to increase. In contrast, if cold advection is occurring at a given station, expect the temperatures to drop.

Temperature advection refers to change in temperature caused by movement of air by the wind. Forecasting temperatures using advection involves looking at the wind direction at your forecasting site and the temperatures upstream (in the direction from which the wind is blowing).



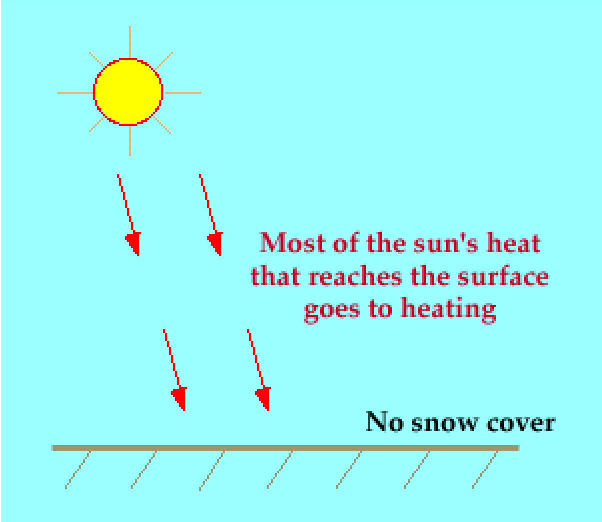


For example, consider the two cities below. Assume that a temperature forecast is being made for the northern station, which has a reported temperature of 45 degrees. The northern station is cooler than the southern station, but the wind directions are the same, out of the south. The wind is, in effect, blowing from the southern station towards the northern one. Over time, the wind will transport the warmer air located at the southern station towards the northern station (into a region of colder air), so expect the temperature at the northern station to rise. This process is called **warm advection**. When colder air is being transported by the wind into an area of warmer air, this is known as **cold advection**.

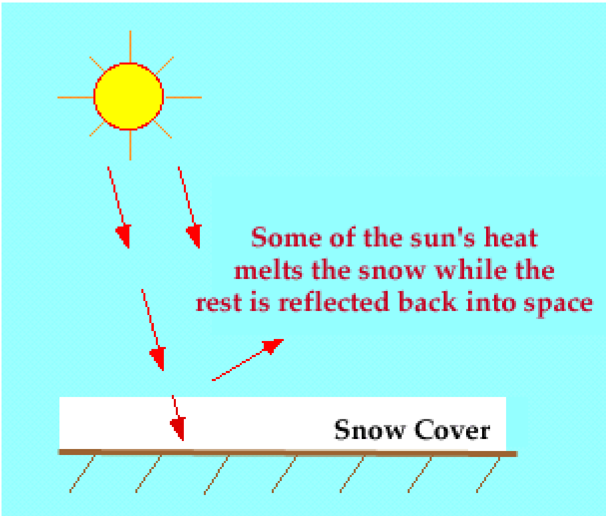
Effects of Snow Cover

on forecasted temperatures

As the sun's rays hit the surface of the earth, much of it is absorbed by the surface (as in the diagram below). This in turn warms the air near the earth's surface, causing the temperature to rise.



If there is snow on the ground, some of the sun's energy will be reflected away by the snow, and some of it will be used to melt the snow. This means that there is less energy available to heat the earth's surface and consequently, the temperatures rise more slowly than would occur with no snow on the ground.



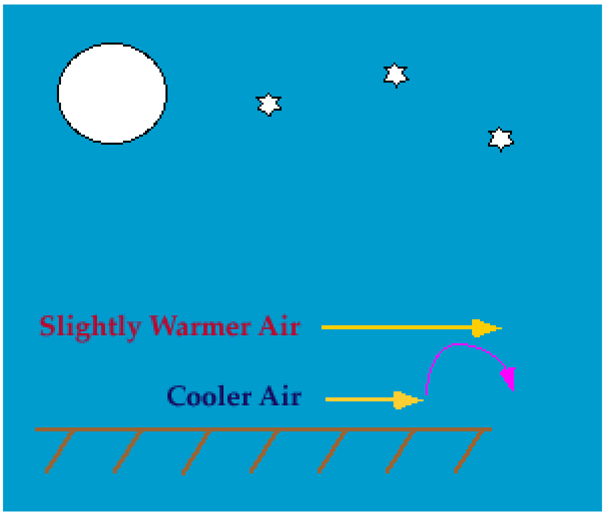
Forecast Tip:
When snow cover is present, forecast lower daytime temperatures than you would normally predict if there was no snow cover. At night, snow on the ground readily gives off heat. This causes rapid cooling. Forecast the overnight temperature to be lower than you would predict if there was no snow cover.

Effects of Wind

on forecasted temperatures

At night, the earth's surface cools by radiating heat off to space. The strongest cooling takes place right near the surface while temperatures at roughly 3000 feet are actually warmer than those at the surface. On a windy night, some of the warmer air aloft is mixed down towards the surface. This occurs because the winds are faster aloft than at the surface.

To visualize this, place one hand over the other about six inches apart. The bottom hand represents the air near the surface and the top hand represents the warmer wind higher up. Move the bottom hand slowly and the upper hand faster (to indicate the faster winds aloft). The faster air above and slower air below causes the air to overturn or spin (as in the picture below). This overturning motion is how warmer air from above is transported downward on windy nights.

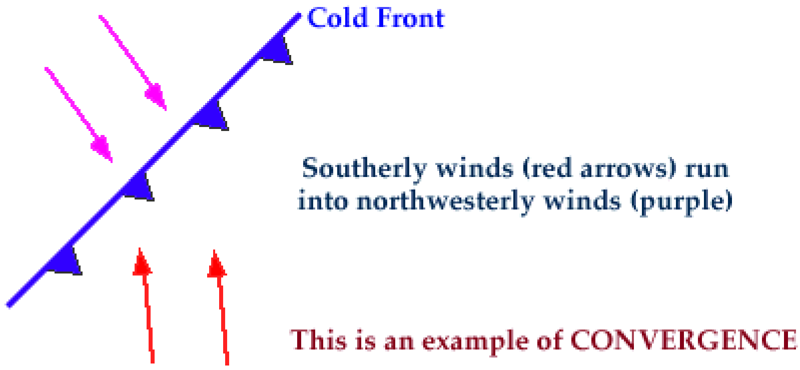


Forecast Tip:
On a calm night, the maximum surface cooling can take place. But on a windy night, some warmer air is mixed downward to the surface, which prevents the temperatures from droping as quickly as they would on a clear night. Therefore, forecast slightly warmer temperatures for a windy night than for a calm night.

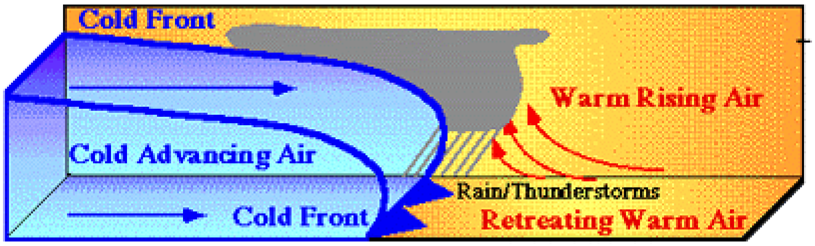
Effects of Frontal Lifting
on forecasted precipitation

Forecast Tip:
If there is sufficient moisture in the air and a forcing mechanism like a cold front (for example) is approaching the area, then there is an increased probability that precipitation will occur.

Clouds and precipitation are formed by the upward motion of air. Therefore, there must be a mechanism present to lift the air. Fronts often serve as such a mechanism. Air on one side of the front typically blows in a different direction from the wind on the other side, causing the air to converge, or pile up right along the frontal surface.



Since this air has to go somewhere, it rises. As air rises, the moisture in the rising air cools, condenses and forms clouds and precipitation. For example, a cold front lifts warm moist air ahead of it as it advances. The rising air cools and the water vapor condenses out to form clouds, most commonly ahead of and along the cold front (diagram below).



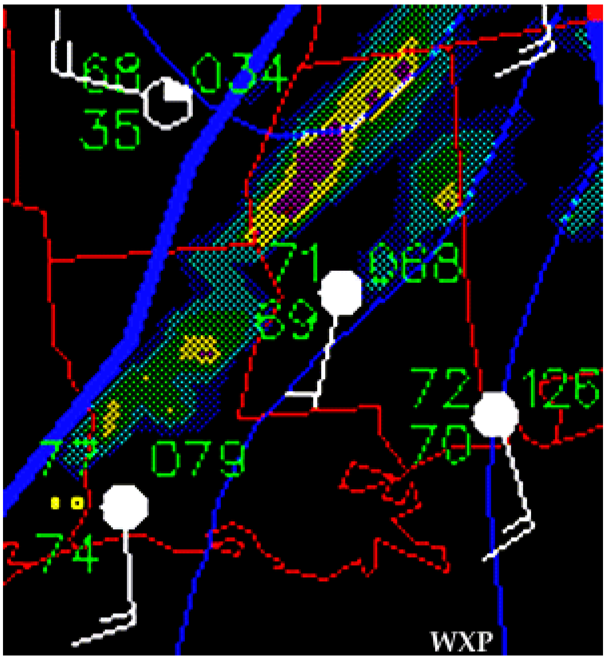
As the cloud droplets grow in size, they begin to fall back to the earth as precipitation. Vigorous upward motions often occur ahead of and along a cold front, resulting in more vertically developed clouds like cumulonimbus clouds, which themselves can produce heavy rains and powerful thunderstorms.

Forecast Tip:
If there is sufficient moisture in the air and a forcing mechanism like a cold front (for example) is approaching the area, then there is an increased probability that precipitation will occur.

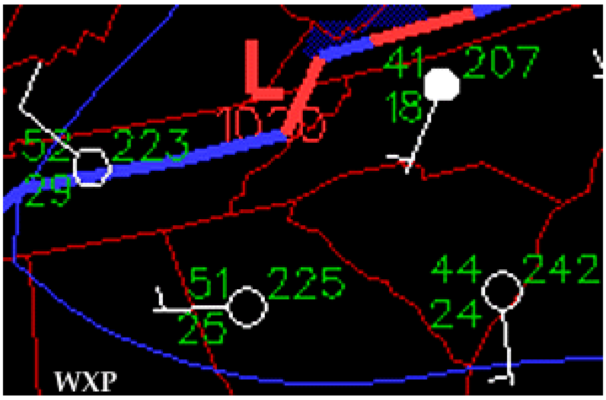
Effects of Moisture
on forecasted precipitation

Even if there is a mechanism to lift the air, clouds and precipitation may not occur if the low levels of the atmosphere do not contain sufficient moisture. The availability of moisture is revealed on a surface map through the dew point temperatures. If the dew point is close to the corresponding temperature, the air is nearly saturated, so precipitation is quite possible.

Consider the example below where a cold front was approaching the southeastern United States. The values of the temperatures and dew point temperatures at stations ahead of the front are close together, meaning the air is nearly saturated. Since the dew points are quite high, these factors indicate that there is sufficient moisture for precipitation to develop, and the radar echoes on the map reveal that precipitation occur.



Now consider a different example with a stationary front (depicted on the surface map below).

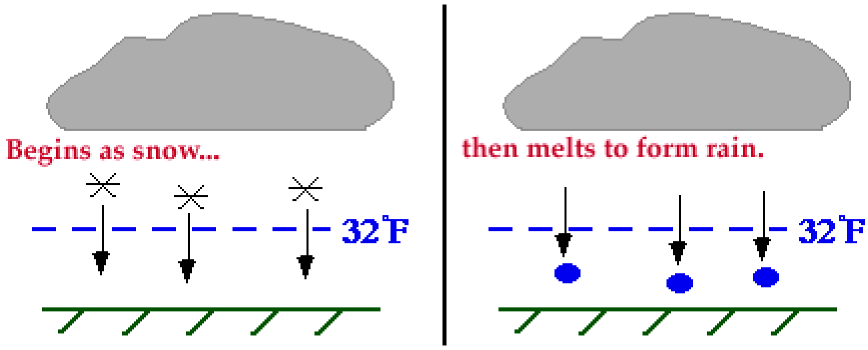


The values of the temperatures and dew points near the front are further apart, meaning the air is quite dry. Therefore, despite the lift provided by the convergence along the front, there is insufficient moisture for precipitation to develop.

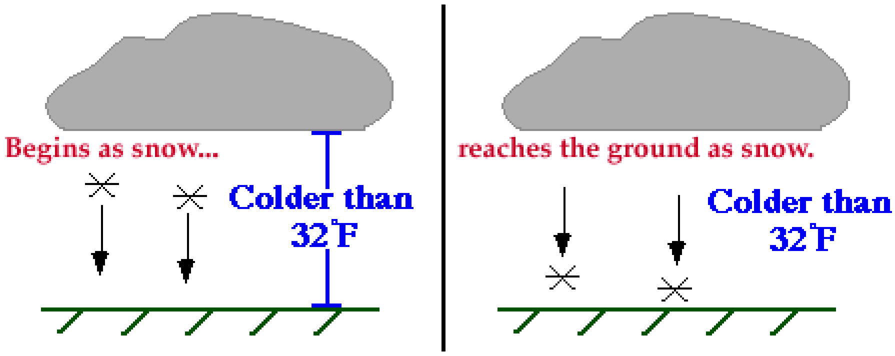
Rain or Snow?

dependent upon temperature

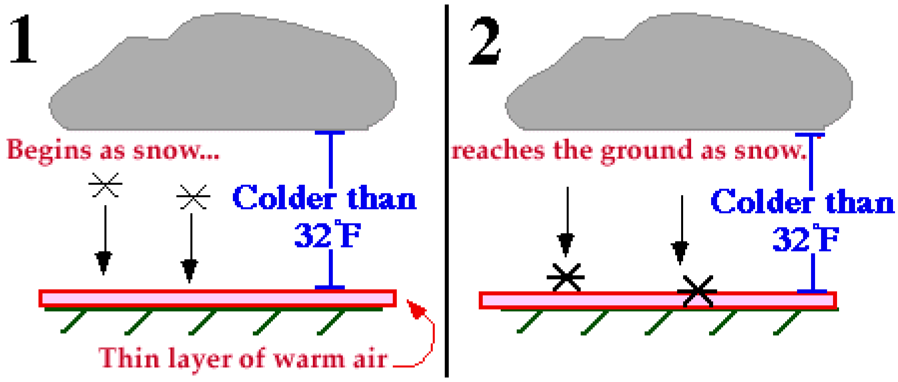
Most precipitation that reaches the ground actually begins as snow high in the atmosphere. These snow flakes develop somewhere above the freezing level where the air temperature is less than 32 F (the dashed blue line), and begin to fall toward the earth as snow. If ground temperature is above 32 F, the freezing level must be located somewhere above the ground. The falling snow passes through the freezing level into the warmer air, where it melts and changes to rain before reaching the ground.



When the air temperature at the ground is less than 32 F, the precipitation begins falling as snow from the clouds.

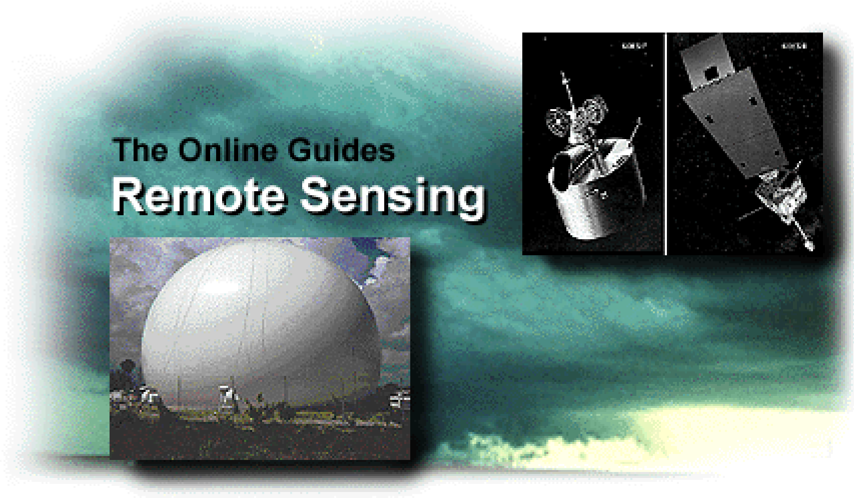


Since it is falling into cold air, the snow does not melt on the way down and reaches the ground as snow. This is why cold air is important for there to be snow.



Once in a while, a very thin layer of warm air is found near the surface and temperatures may be several degrees above freezing. However, since the layer of warm air is so shallow, the snow reaches the ground in tact before it has a chance to melt and become rain. This is how snow falls when the surface temperatures are above freezing.

Forecast Tip:
When forecasting precipitation type, if temperatures are expected to be above freezing, then rain is most likely. If temperatures are expected to be below freezing, then forecast for snow.



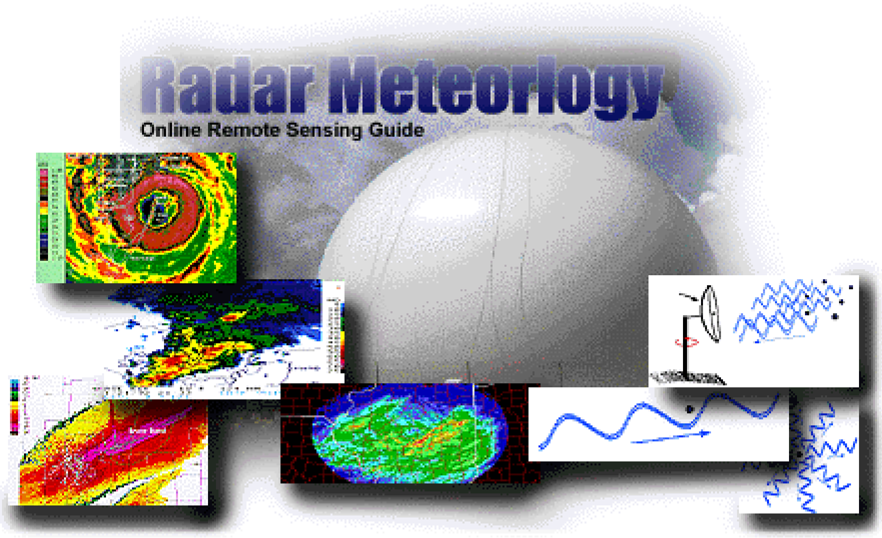
Graphic by: Steven E. Hall

The Online Remote Sensing Guide consists of two web-based instructional modules that use multimedia technology and the dynamic capabilities of the web. These resources incorporate text, colorful diagrams, and animations to introduce selected topics in the field of remote sensing. Selected pages link to (or will soon link to) relevant current weather products, allowing the user to apply what has been learned in the instructional modules to real-time weather data. Available modules include:

Modules Last Update: 08/28/99	**Radars** The basics of radars and target detection, interpreting radar imagery and exploring their applications in forecasting and severe weather prediction.
	Satellites GOES and POES satellites, the images they produce and how to interpret them.

The target audience for the Online Remote Sensing Guide is high school and undergraduate level students. However, these resources have been used by instructors throughout K-12, undergraduate and graduate level education. Contents of the Online Remote Sensing Guide were developed by graduate students and faculty through our efforts in the Collaborative Visualization Project (CoVis), which was funded by the National Science Foundation. These resources have been reviewed by faculty and scientists at the University of Illinois and the Illinois State Water Survey. Many of these resources were tested in a classroom environment and have been modified based upon teacher and student feedback.

The navigation menu (left) for this module is called "Remote Sensing" and the available modules are listed as menu items, beginning with this introduction. In addition, this entire web server is accessible in both "graphics" and "text"-based modes, a feature controlled from the blue "User Interface" menu (located beneath the black navigation menus). More information about the user interface options, the navigation system, or WW2010 in general is accessible from About This Server.



Graphic by: Steven E. Hall

Radars have an important role in the field of meteorology. These devices send out and receive signals providing valuable information about the location and intensity of precipitation. Advanced Doppler radar technology goes beyond simple detection to providing high resolution reflectivity and estimated velocity data, which is vital to short term forecasting and severe weather prediction. The purpose of this module is to introduce the basics of radar meteorology, features of WSR-88D and MDR radar imagery, and how to interpret Doppler velocity patterns. The Radar Meteorology module has been organized into the following sections:

Sections
Last Update:
07/23/97

Radar Basics
The sending and retrieving of signals, detecting a target and different scanning modes.

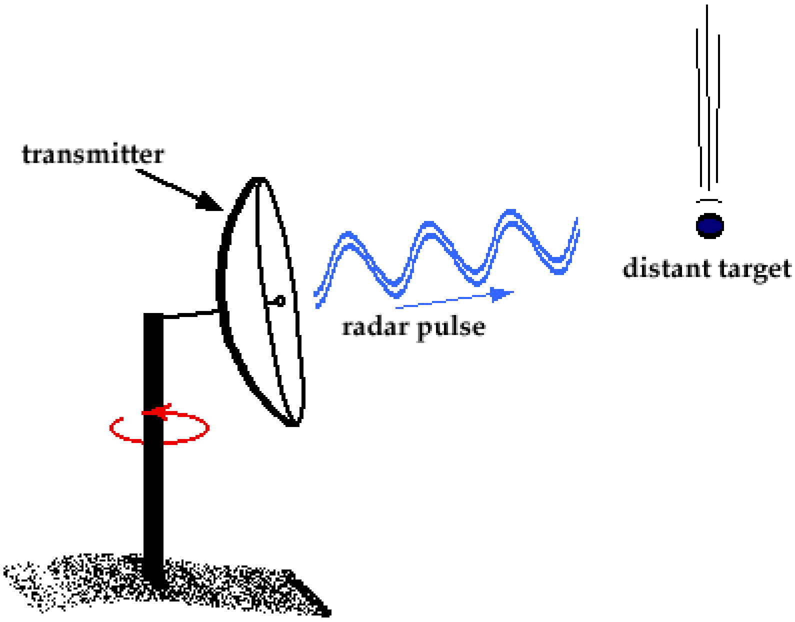
Radar Imagery
WSR-88D and MDR radar imagery.

Velocity Patterns
Various wind patterns depicted through Doppler radar estimated winds.

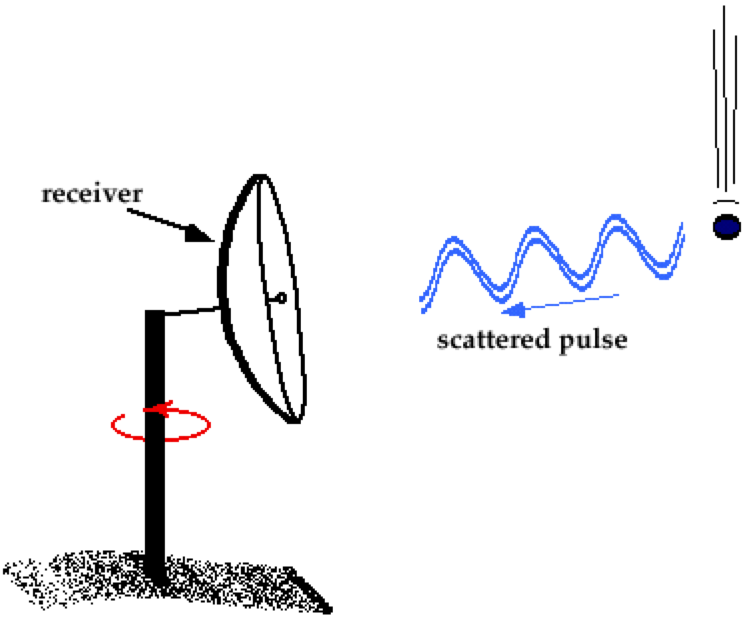
Applications
Applications in tornado and hurricane detection, short term forecasting and other areas.

Acknowledgments
Those who contributed to the development of this module.

The navigation menu (left) for this module is called "Radars" and the menu items are arranged in a recommended sequence, beginning with this introduction. In addition, this entire web server is accessible in both "graphics" and "text"-based modes, a feature controlled from the blue "User Interface" menu (located beneath the black navigation menus). More information about the user interface options, the navigation system, or WW2010 in general is accessible from About This Server.



The radar creates an electromagnetic energy pulse which is focused by an antenna and transmitted through the atmosphere. Objects in the path of this electromagnetic pulse, called targets, scatter the electromagnetic energy. Some of that energy is scattered back toward the radar.

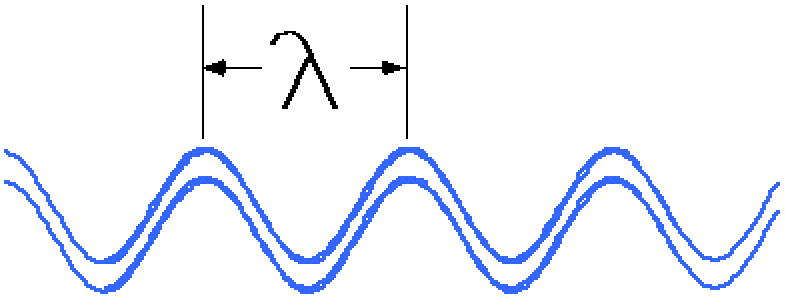


The receiving antenna (which is normally also the transmitting antenna) gathers this back-scattered radiation and feeds it to a device called a receiver.

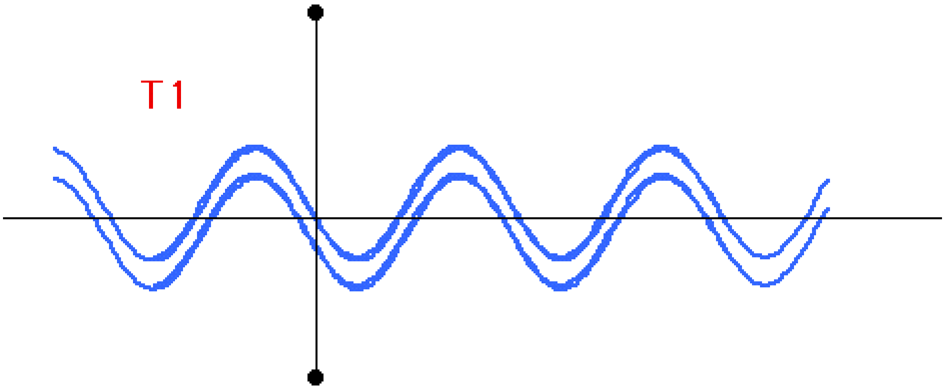
Wave Properties

wavelengths and phase shifts

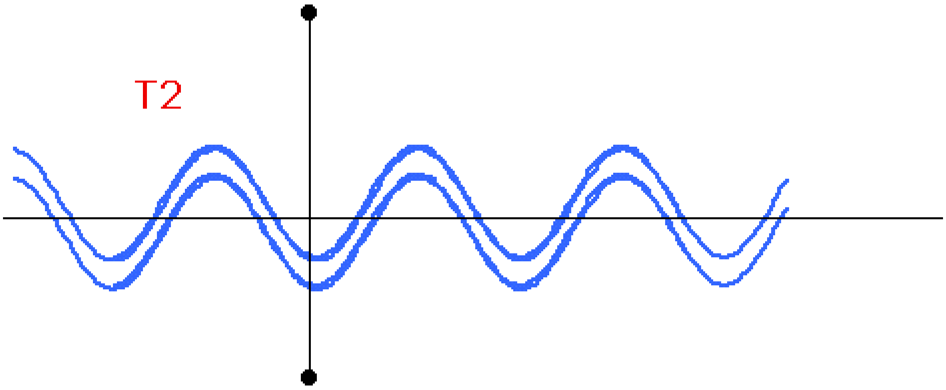
The wavelength (λ) of a wave is the distance from one crest to the next.



The phase of a wave, measured in degrees, where 360 degrees is one wavelength, indicates the current position of the wave relative to a reference position. For example, if at time T1 the position of the wave along the vertical line was:



while at time T2, the position of the wave was:

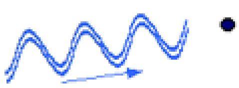


then the wavelength did not change from T1 to T2, but the wave's position relative to the vertical line changed 1/4 wavelength, or 90 degrees. This change is called a "phase shift".

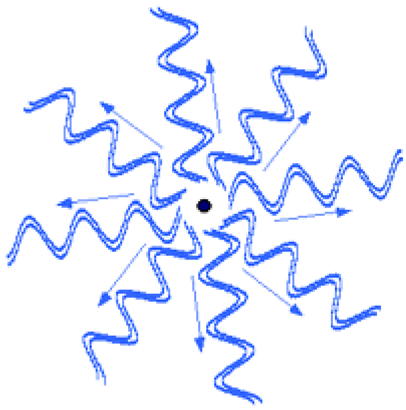
Scattering of a Radar Pulse

by a target back to the receiver

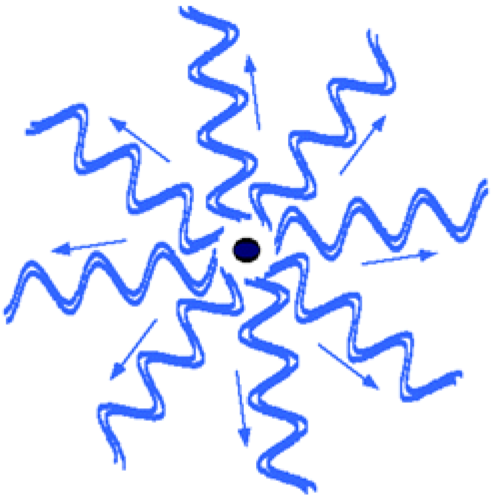
When a pulse encounters a target...



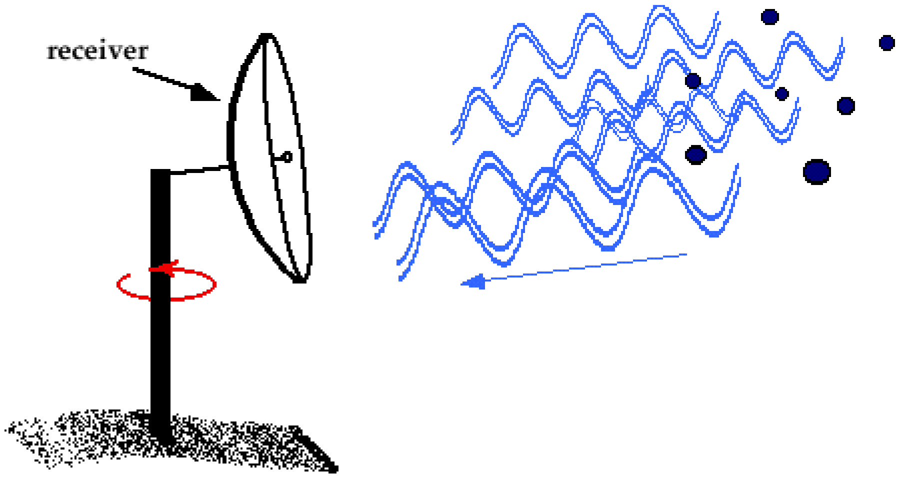
it is scattered in all directions. Of interest is the signal component received back at the radar. This signal is typically much weaker than the original sent from the transmitter and is called the "return signal".



The larger the target, the stronger the scattered signal.



The more targets there are to scatter the pulse, the stronger the return will be because the return signals from each target combine to produce a stronger signal. This means that many large raindrops will produce a stronger return than a few small raindrops. The quantity that a radar measures is the returned power which, with knowledge of other radar characteristics, is converted to a quantity called the reflectivity factor, or more simply, the "reflectivity".

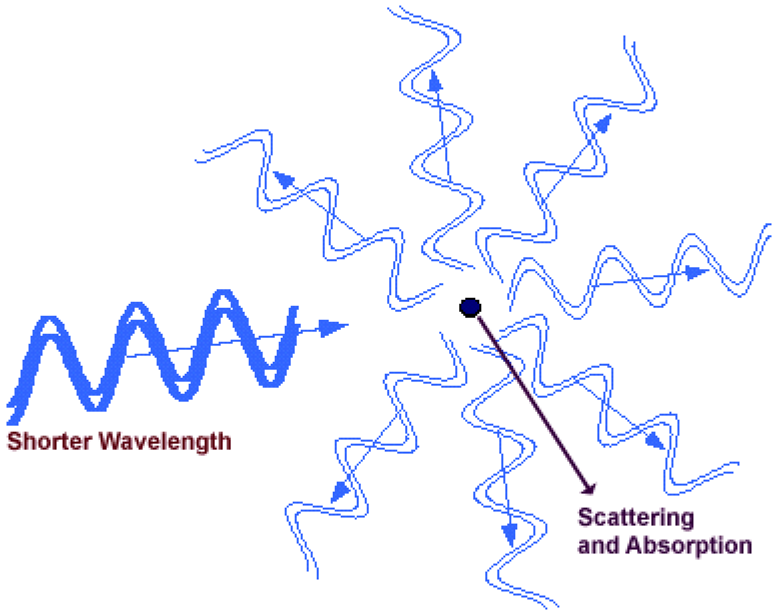


The magnitude of the reflectivity is related to the number and size of the drops encountered by the electromagnetic pulse. For this reason, high reflectivity generally implies heavy precipitation while low reflectivity implies lighter precipitation. Plots of the radar reflectivity, typically using colors to depict its magnitude, show both the location and intensity of precipitation. Extremely high reflectivities often indicate hail.

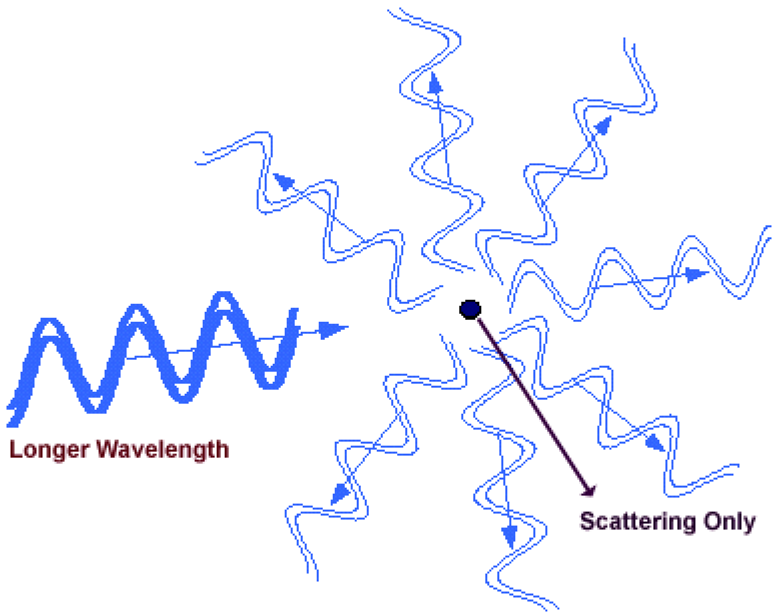
Effects of Wavelength

on the ability to detect an object

The factors which govern the choice of a wavelength to be used in a particular radar include its sensitivity, which is its ability to detect weak targets at long range, the radar's ability to resolve small features, the types of targets to be studied, and the effects of the intervening atmosphere on the transmitted energy. Other factors also must be considered such as the radar's size, weight and cost. Most weather radars have wavelengths that range between 0.8 centimeters (cm) and 10.0 cm. Generally short wavelengths mean smaller and less expensive equipment.



Short wavelength radars are more effective in detecting small particles such as cloud droplets and drizzle drops. However, the short wavelength electromagnetic energy is also partially absorbed by these same particles (a process called attenuation). This makes it difficult to accurately measure the intensity of back-scattered energy for more distant targets that lie beyond the range of closer targets.

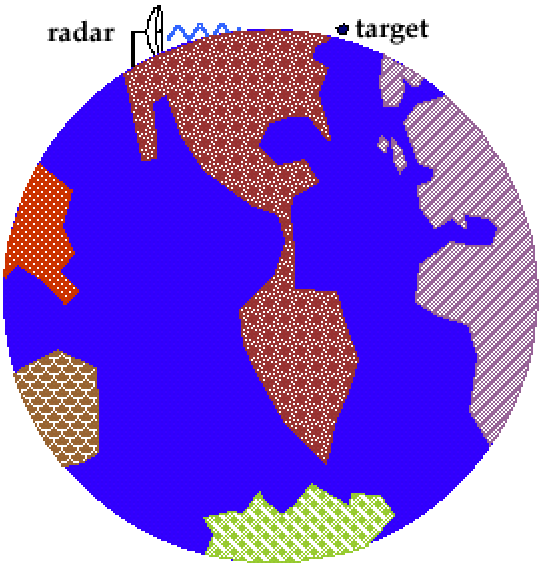


The main advantage of using longer wavelengths is that absorption by the intervening particles is drastically reduced. This means that a distant thunderstorm behind a closer thunderstorm will appear on the radar screen with its proper intensity. Since detecting severe weather is one of the most important missions of operational radars, such as the National Weather Service's WSR-88D Doppler radars, these radars typically use a long wavelength.

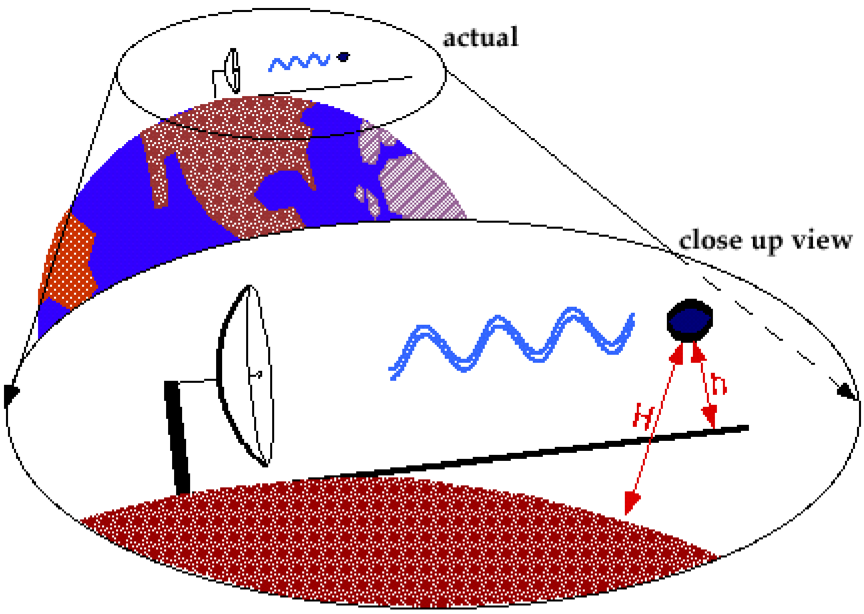
Effects of the Earth's Curvature and Atmospheric Refraction

on estimating a target's position

One must account for the curvature of the earth when determining the altitude of a target. Distant targets, which are close to the ground, cannot be seen by a radar because they will be below the horizon.



The height of a distant target that is above the horizon will be underestimated if the curvature of the earth is not taken into account. For example, the height of the target on the figure below would be underestimated as "h" rather than the actual height "H".



A second effect, called refraction, also affects the path the electromagnetic energy will take as it propagates through the atmosphere. Normally, because the atmosphere's density decreases rapidly with height, the radar beam will be deflected downward, much like light passing through a glass prism. In extreme cases, where temperature increases with height and dry air overlays warm air, (a condition often found along coastlines), the beam can bend down dramatically and even strike the ground. Meteorologists call this effect "anamolous propagation". Both the curvature of the earth and normal atmospheric refraction must be accounted for when determining the position of a target.

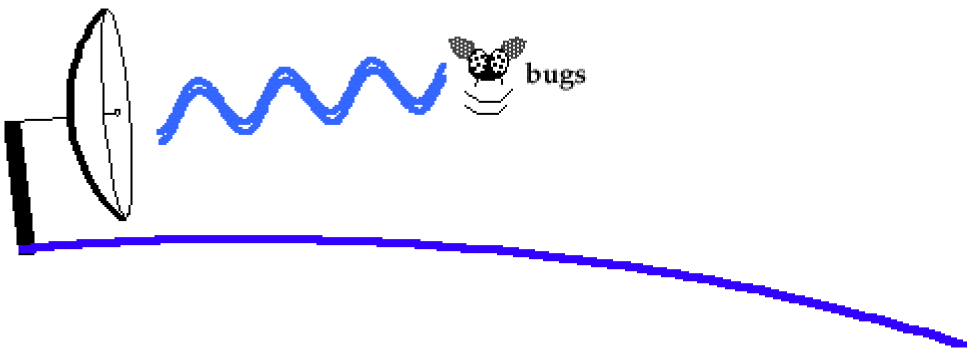
Clear Air Returns

insects and turbulence

When a radar transmits energy, part of it may be intercepted by targets on the ground, such as buildings, trees, cars, or other objects. The return signal from these objects is called "ground clutter". Ground clutter interferes with the detection of meteorological targets, such as raindrops, because ground targets are large and typically produce high reflectivity. Ground clutter can result even if the main radar beam is above ground targets because part of the energy radiated from the antenna is emitted off the beam axis in what are known as "sidelobes". Back-scattered energy from the sidelobes is interpreted by the radar processor to come from the main lobe, so ground targets hit by one of the sidelobes appear to a radar user in the same relative position in the main lobe.

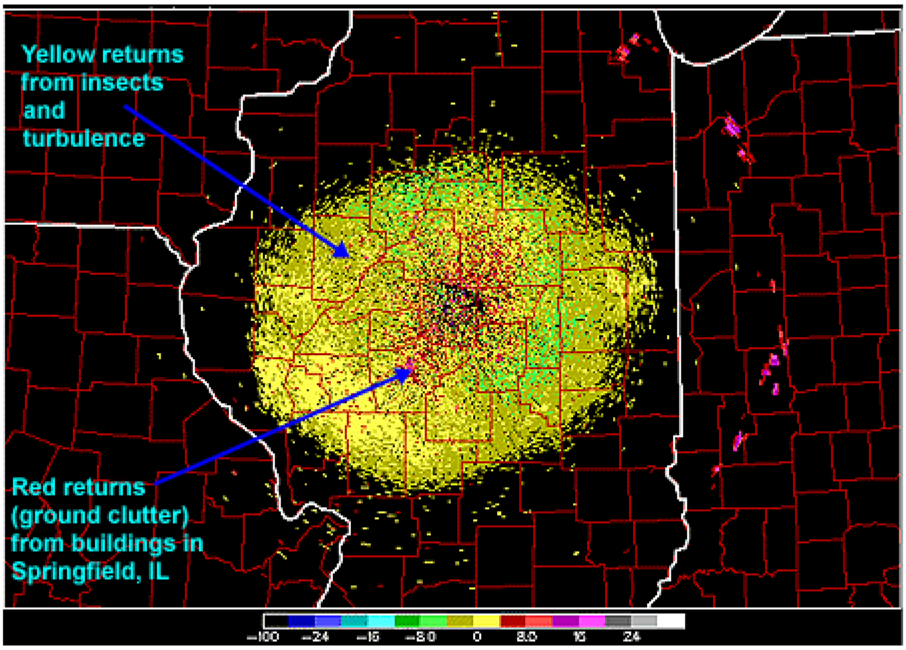
Ground clutter is usually the worst within about 20 kilometers of the radar site where the beam is still close to the earth's surface. Farther from the site, the beam is higher due to both its elevation angle and curvature of the earth away from the radar site. Ground clutter is easily identified with a Doppler radar because the radial velocity measured by the Doppler radar will approximately be zero since none of the ground targets are moving with respect to the radar. The radial velocity is not exactly zero because moving targets within the beam, such as birds, bugs, or even raindrops, also contribute to the total power return to the radar.

The Effect of Bugs:

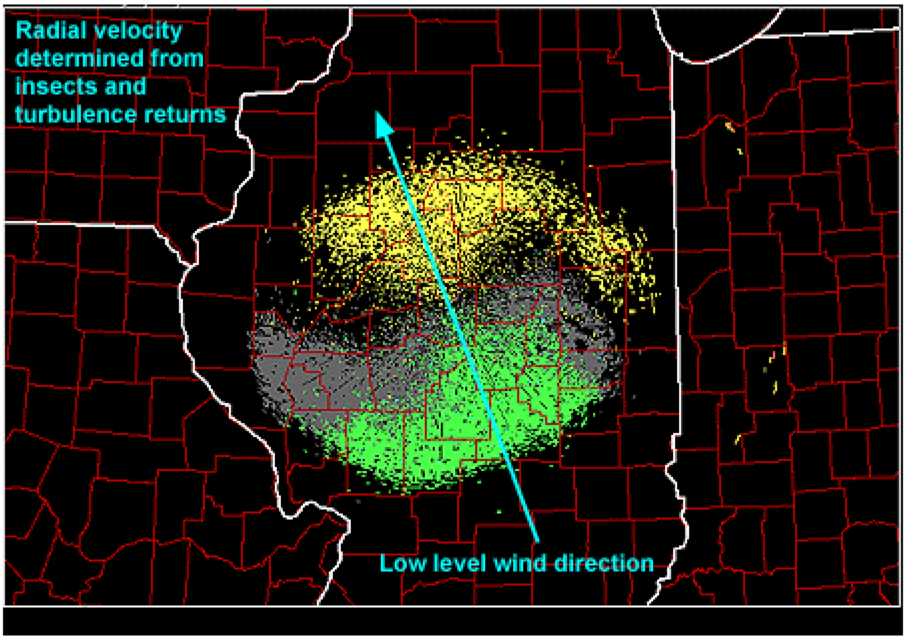


Insects present large targets to radar and they are always present during the warmer seasons. This actually is beneficial to meteorologists. Doppler radars require targets to determine the motion of the air. Outside of regions where precipitation is falling, there would be no targets if there were no insects. Airborne insects turn out to be very good tracers of air motion since, on average, they blow along with the wind. The returns from insects allow meteorologists to see air motions outside the storm circulation which in many cases is important for predicting where new storms are likely to occur.

Turbulence provides another way in which electromagnetic energy from a radar can be back-scattered. Turbulence is associated with variations in density in the atmosphere. When variations in density occur on a scale of half the wavelength of the radar, energy is scattered through a process called diffraction. Radar echoes in a clear atmosphere will be more common on days when the lower atmosphere is unstable, as when there are thermals present, or when the wind increases rapidly with height just above the ground, so that there is mechanical turbulence.



The picture above shows the radar reflectivity measured by the National Weather Service Doppler radar at Lincoln, IL (ILX) on a beautiful clear day. Radar returns are due to insects, turbulent motions, and ground targets. These echoes, which extend out to about 100 kilometers from the radar, allow the radar operator to see the air motion.



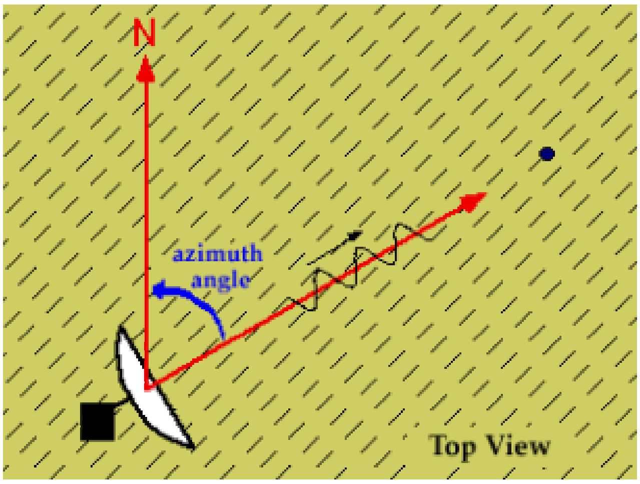
This second picture shows the corresponding radial velocity field. The distribution of inbound (green) and outbound (yellow) velocities indicate that the low level winds are out of the south-southeast.

Locating a Target

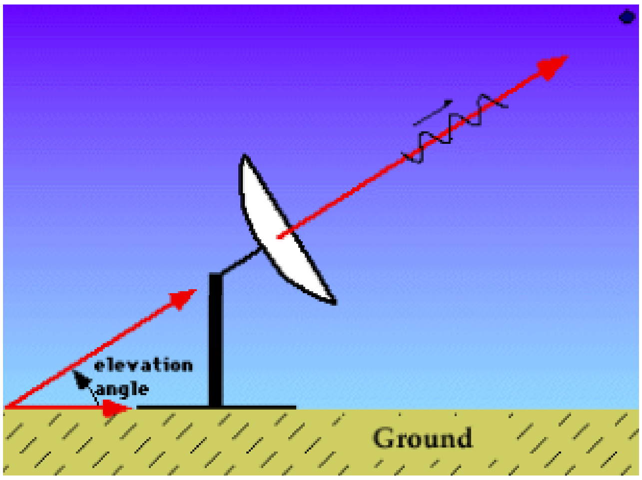
angles and distances used

The radar needs 3 pieces of information to determine the location of a target.

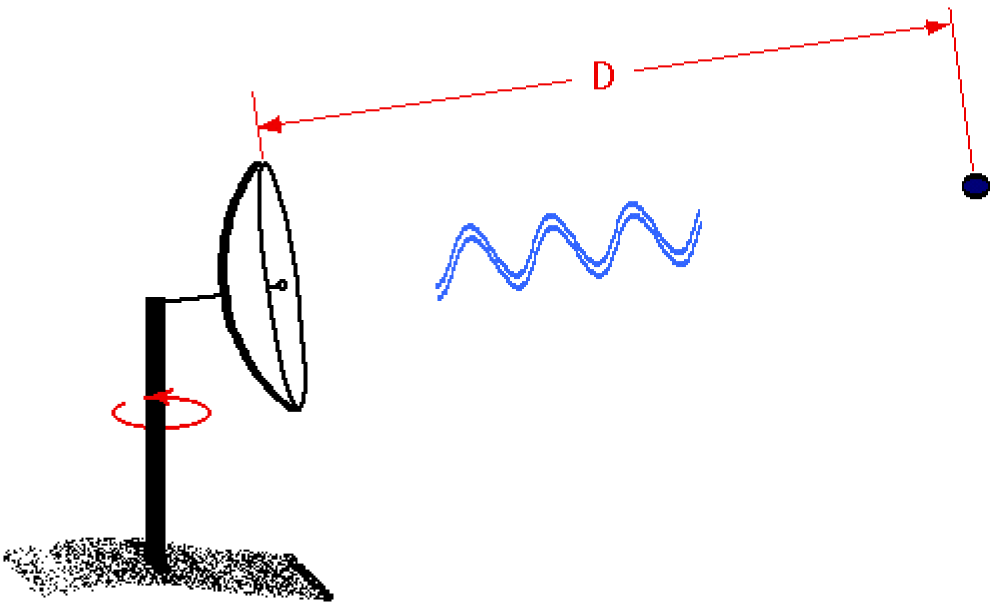
The first piece of information is the angle of the radar beam with respect to north; called the "azimuth angle".



The second is the angle of the beam with respect to the ground; called the "elevation angle".



The third piece of information needed is the distance (D) from radar to target.

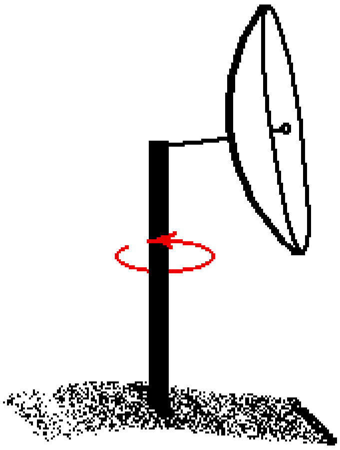


Distance is determined by measuring the time it takes for the pulse to make a round trip from the radar to the target and back using the relation *distance = (time) * (velocity)*. The velocity is the speed of light, the speed at which the pulse travels (c). Since the pulse has to travel to the target and back, the total distance is 2D. If **t** is the time it takes, then 2D = ct or D = ct/2. Using the calculated distance, azimuth angle and elevation angle, the exact location of the target can be determined.

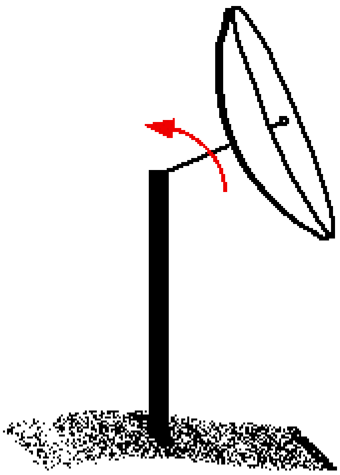
Scanning Modes

PPI and RHI

The two main types of scans used in meteorology are the Plan Position Indicator (PPI) and the Range Height Indicator (RHI) scans.



Plan Position Indicator (PPI):
When scanning in PPI mode, the radar holds its elevation angle constant but varies its azimuth angle. The returns can then be mapped on a horizontal plane. If the radar rotates through 360 degrees, the scan is called a "surveillance scan". If the radar rotates through less than 360 degrees, the scan is called a "sector scan".



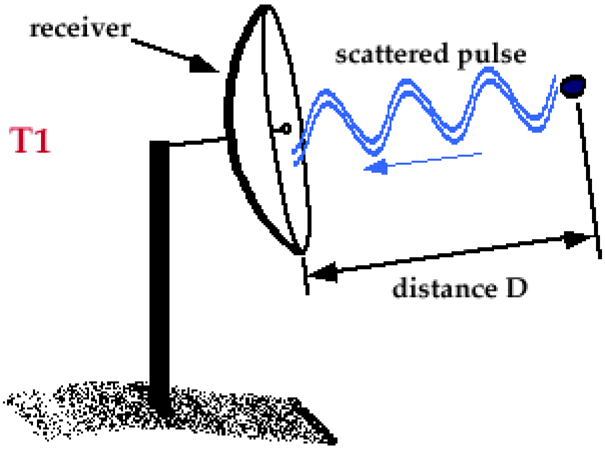
Range Height Indicator (RHI):
When scanning in RHI mode, the radar holds its azimuth angle constant but varies its elevation angle. The returns can then be mapped on a vertical plane. The elevation angle normally is rotated from near the horizon to near the zenith (the point in the sky directly overhead).

Radial Velocity

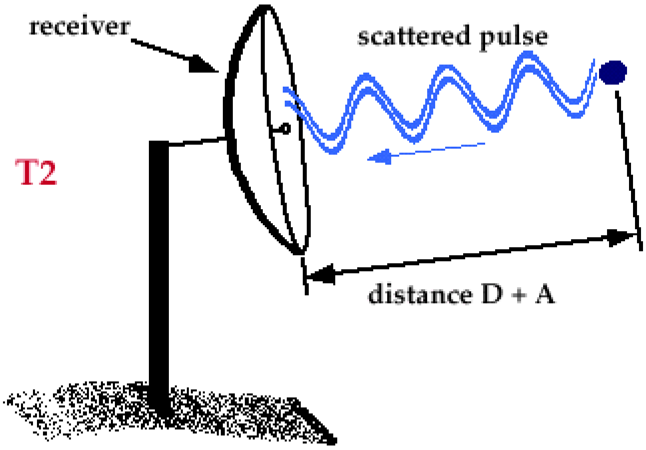
measured by Doppler radars

Doppler radars can measure the component of the velocity of targets toward or away from the radar. This component is called the "radial velocity".

For example, at time T1 a pulse is sent towards a target and it returns a target distance "D".



2) At time T2, another pulse is sent towards the same target and returns a target distance "D+A"

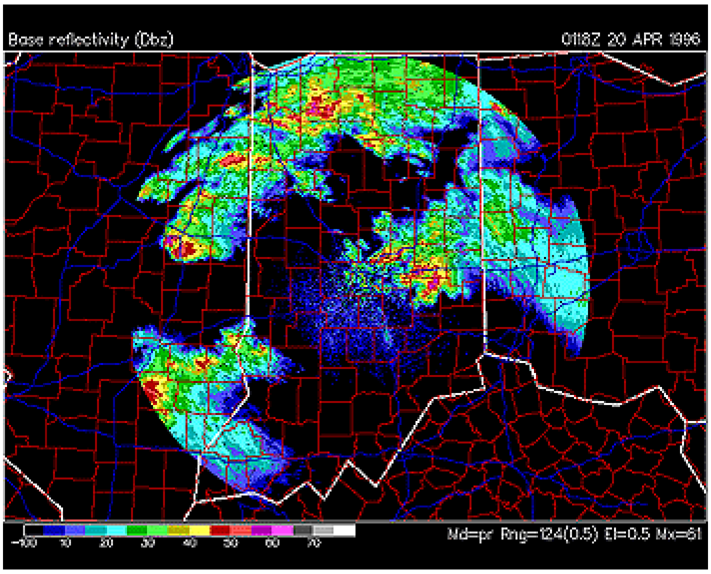


The distance to target has changed from times T1 to T2, resulting in a phase shift between the two return signals, which Doppler radars are capable of measuring. By knowing the phase shift, the wavelength and the time interval from T1 to T2, the velocity the target has moved toward or away from the radar can be computed. If the target is moving sideways so that its distance relative to the radar does not change, the radar will record zero radial velocity for that target.

WSR-88D Radar Imagery

detecting precipitation

The word radar is an acronym from "Radio Detection and Ranging". Radar images are useful for locating precipitation. As a Magnetic Resonance Imaging (MRI) scan examines the inside of a human body, a radar examines the inside of a cloud. A radar sends a pulse of energy into the atmosphere and if any precipitation is intercepted by the energy, part of the energy is scattered back to the radar. These returned signals, called "radar echoes", are assembled to produce radar images.



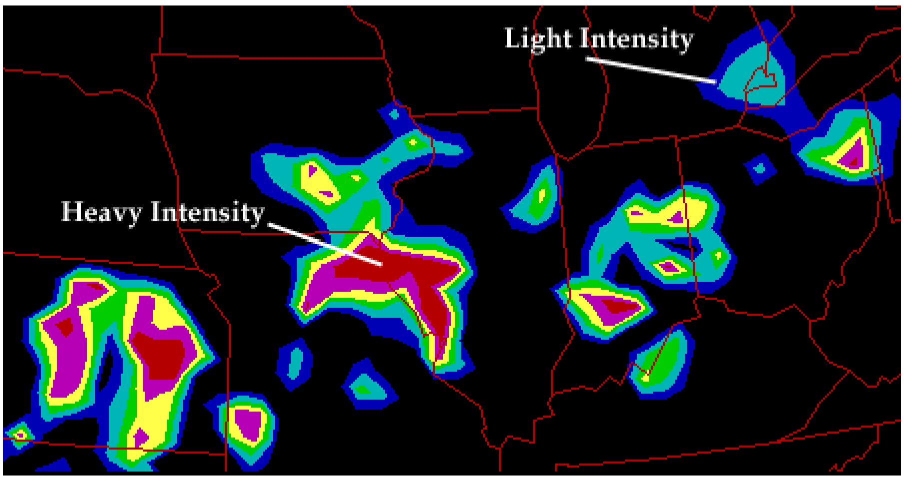
The location of the colored radar echoes indicate where precipitation is falling and the various colors indicate the intensity of the precipitation through the color code in the lower left corner of the image. The example radar image above shows several strong thunderstorms moving through Illinois and Indiana on April 20, 1996. Regions of light and dark blue indicate regions of lighter precipitation while areas of red and pink indicate strong, to occasionally severe thunderstorms.

Normally, it is difficult to distinguish precipitation type on the basis of the radar reflectivity alone. Snow and light drizzle both produce radar reflectivity with about the same value. Melting snow and moderate rain also have similar values. Very high reflectivities (the grays on the scale on the image above) are always associated with hail.

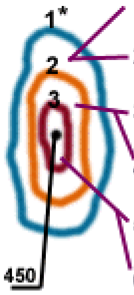
MDR Images

manually digitized radar

Manually Digitized Radar (MDR) images are low resolution radar depictions available from the National Weather Service. These images show the echo intensity in six categories. There also a number of symbols indicating precipitation type, cell movement, line movement, and echo coverage. Severe thunderstorm and tornado watches, line echo wave patterns, and hook echoes are also indicated. The height of cloud tops is also indicated in hundreds of feet above sea level. The figure below shows an example of an MDR image.



The table below summarizes the features of MDR images.



VIP** Level	Echo Intensity	Precipitation Intensity	Rainfall Rate (in/hr) Stratiform	Rainfall Rate (in/hr) Convective	Reflectivity in (dBZ)
1	Weak	Light	Less Than 0.1	Less Than 0.2	Min. Signal - 30
2	Moderate	Moderate	0.1 - 0.5	0.2 - 1.1	31 - 40
3	Strong	Heavy	0.5 - 1.0	1.1 - 2.2	41 - 45
4	Very Strong	Very Heavy	1.0 - 2.0	2.2 - 4.5	46 - 50
5	Intense	Intense	2.0 - 5.0	4.5 - 7.1	51 - 57
6	Extreme	Extreme	More Than 5.0	More Than 7.1	> 57

Highest precipitation top in area in hundreds of feet MSL (45,000 feet MSL).

* The numbers representing the intensity level do not appear on the chart. Beginning from the first contour line, bordering the area, the intensity level is 1-2, second contour is 3-4, and third contour is 5-6.

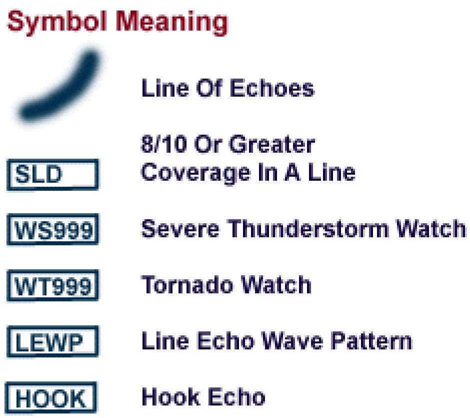
** DVIP stands for Digital Video Integrater and Processor. Often DVIP is represented by VIP.

Symbol	Meaning
R	Rain
RW	Rain Shower
HAIL	Hail
S	Snow
IP	Ice Pellets
SW	Snow Shower
L	Drizzle
T	Thunderstorm
ZR, ZL	Freezing Precipitation
NE	No Echoes Observed
NA	Observations Unavailable
OM	Out For Maintenance
STC	STC ON - all precipitation may not be seen
ROBEPS	Radar Operating Below Performance Standards
RHINO	Range Height Indicator Not Operating

These symbols represent various types of precipitation and status conditions.

Symbol	Meaning
+	Intensity Increasing Or New Echo
-	Intensity Decreasing
NO SYMBOL	No Change In Intensity
35	Cell Movement to NE At 35 Knots
	Line Or Area Movement To East At 20 Knots
LM	Little Movement
MA	Echoes Mostly Aloft
PA	Echoes Partly Aloft

These symbols indicate speed and direction of movement, plus changes in echo intensity.



Symbol	Meaning
	Line Of Echoes
SLD	8/10 Or Greater Coverage In A Line
WS999	Severe Thunderstorm Watch
WT999	Tornado Watch
LEWP	Line Echo Wave Pattern
HOOK	Hook Echo

These symbols indicate severe weather conditions.

Reflectivity Features

bright band

Precipitation typically forms high in the atmosphere where the temperature is below freezing. As ice crystals form aloft and fall toward the surface, they collect each other to form large snowflakes. As the snowflakes fall, they pass through a level where the temperature rises above freezing. When the snowflakes start to melt, they initially develop a water coating. Water is about 9X more reflective than ice at microwave wavelengths, so these large wet snowflakes produce a high reflectivity.

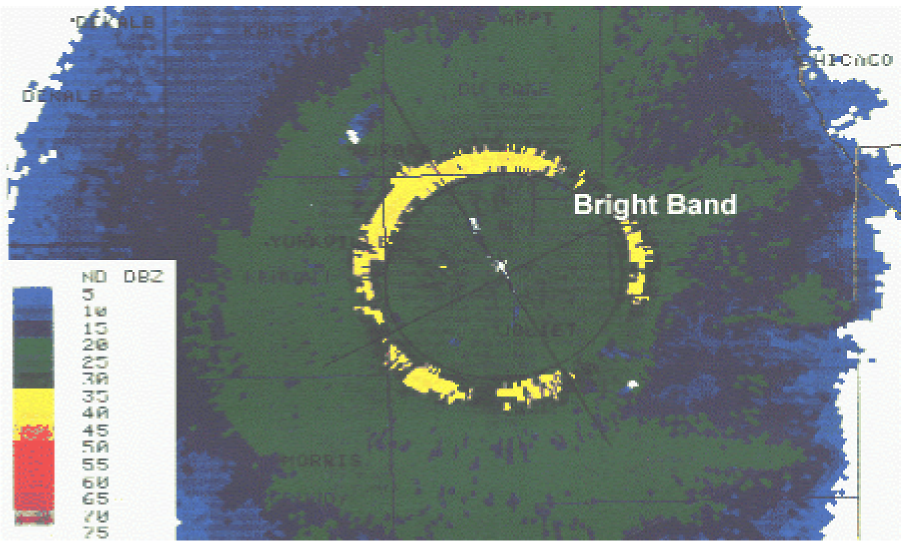


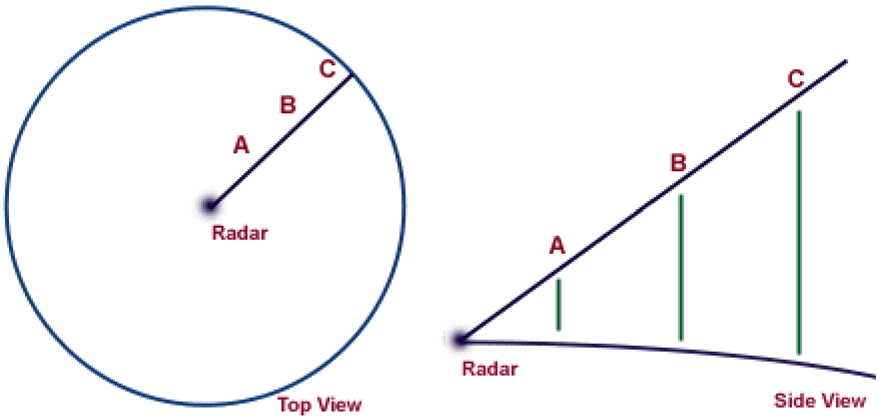
Image by: NWS

As the flakes continue to fall and melt, they collapse into rain drops. The rain drops are smaller and fall faster, so both the size of the particles and their concentration are reduced, reducing the radar reflectivity. All of these processes lead to the formation of a narrow ring of high reflectivity near the melting level. This ring, called the "bright band", can be seen on the image above.

Interpreting Doppler Radar Velocities

speed shear wind patterns

To understand Doppler radial velocity patterns, one first has to consider the geometry of a radar scan. Normally the radar beam is pointed at an elevation angle greater than zero so that the beam, as it moves away from the radar, moves higher and higher above the surface of the earth. Because of this geometry, radar returns originating from targets near the radar represent the low-level wind field, while returns from distant targets represent the wind field at higher levels.



On a radar [PPI](#) display, the distance away from the radar at the center of the display represents both a change in horizontal distance and a change in vertical distance. To determine the wind field at a particular elevation above the radar, one must examine the radial velocities on a ring at a fixed distance from the radar. The exact elevation represented by a particular ring depends upon the [elevation angle](#) of the radar beam.

In the examples below, idealized Doppler [radial velocity](#) patterns were constructed with a computer assuming simple vertical wind field patterns. These simplified radial velocity patterns can help us understand the more complicated patterns that are associated with storm motions. Doppler velocity patterns (right) correspond to vertical wind profiles (left), where the wind barbs indicate wind [speed](#) and [direction](#) from the ground up to 24,000 feet. Negative Doppler velocities (blue-green) are toward the radar and positive (yellow-red) are away. The radar location is at the center of the display.

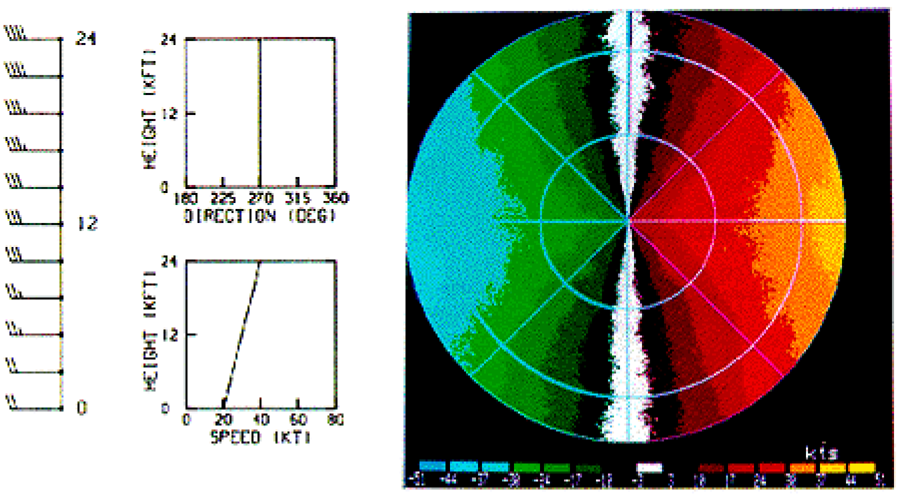


Image by: [Brown & Wood](#)

For this first example, [wind direction](#) is constant with height, but [wind speed](#) increases from 20 knots at the ground to 40 knots at 24,000 feet. Note on the [radial velocity](#) field that the maximum inbound velocity is to the west and maximum outbound to the east while to the north and south the radar measures zero radial velocity. This is because the winds are perpendicular to the radar beam when viewed to the north or south.

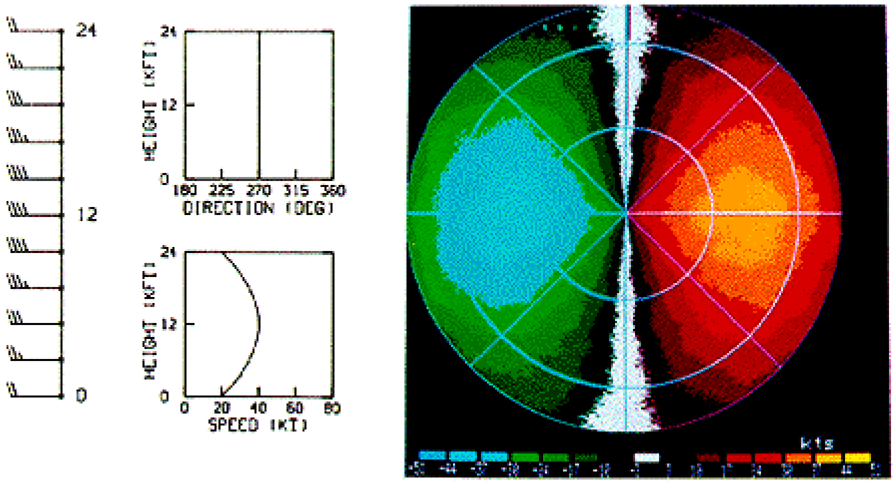


Image by: [Brown & Wood]

In the second example, the winds increase from 20 to 40 knots between zero and 12,000 feet and then decrease again to 20 knots at 24,000 feet. The [wind direction] again is constant. The radar beam intersects the 12,000 foot level along a ring half-way across the radar display. This is where we see the maximum inbound and outbound velocities.

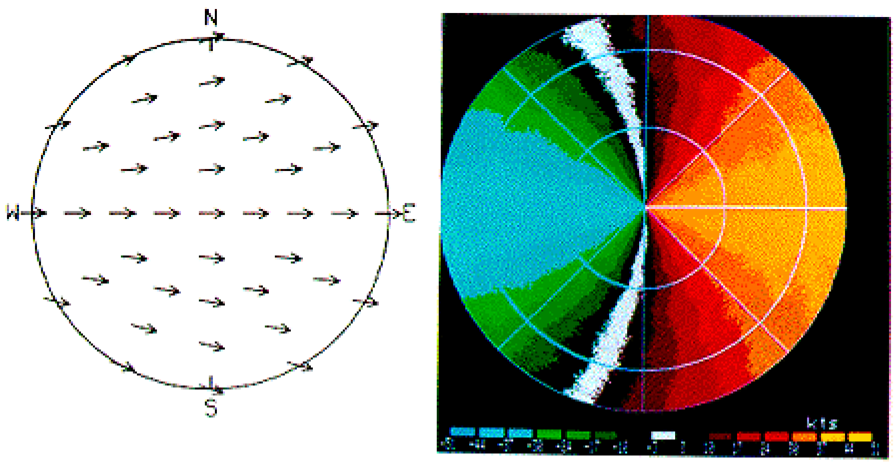


Image by: [Brown & Wood]

In the third example, we see a wind field which changes direction from north to south but has a constant speed at all heights. The zero radial velocity line now bends so that it is everywhere perpendicular to the wind field. The maximum [radial velocities] are observed where the radar beam points directly toward or away from the wind direction.

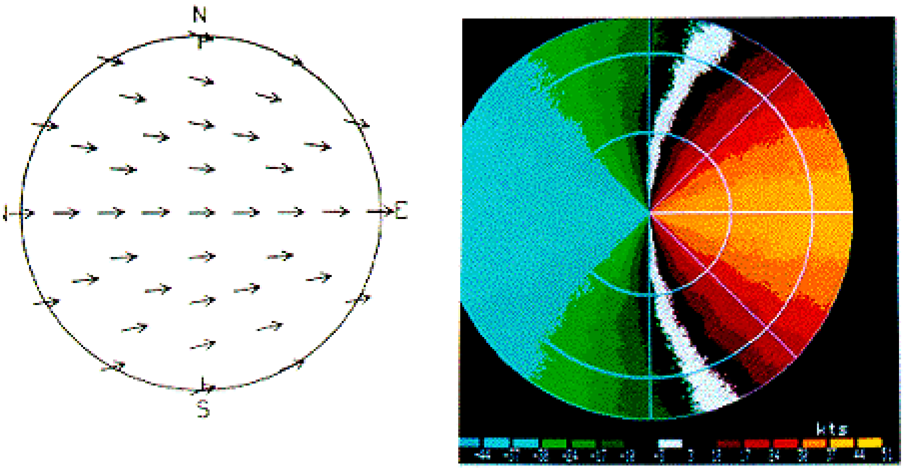


Image by: Brown & Wood

In our fourth example, we see the same effect but in this case, the flow is confluent instead of difluent.

Interpreting Doppler Radar Velocities

directional shear velocity patterns

The following examples showcase where the wind direction is changing.

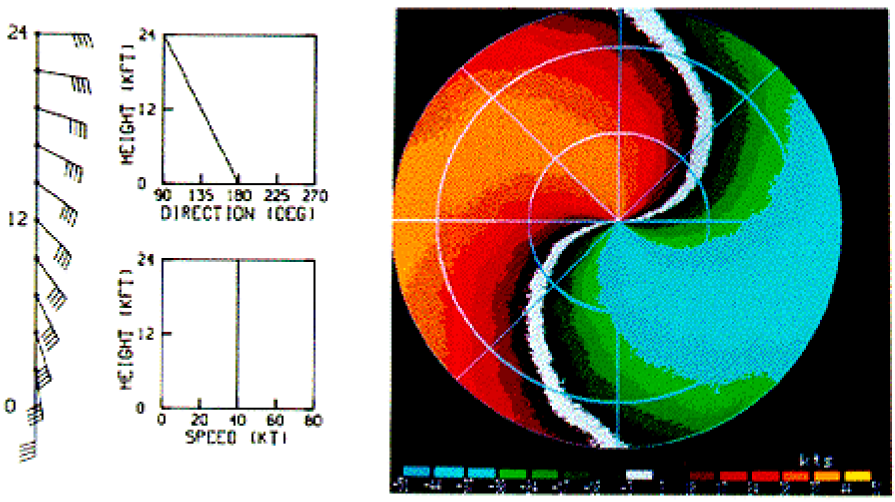


Image by: Brown & Wood

In the first case above, winds back from southerly at the ground to easterly at 24,000 feet. The wind speed does not change. The innermost rings on the radar screen show blue to the south and orange to the north representing a southerly wind. The outermost rings show blue to the east and orange to the west representing easterly winds. Intermediate rings show a progressive change from southerly to easterly as one moves farther from the center of the display. Note the characteristic backward "S" shape to the zero velocity line. This is characteristic of winds backing with height.

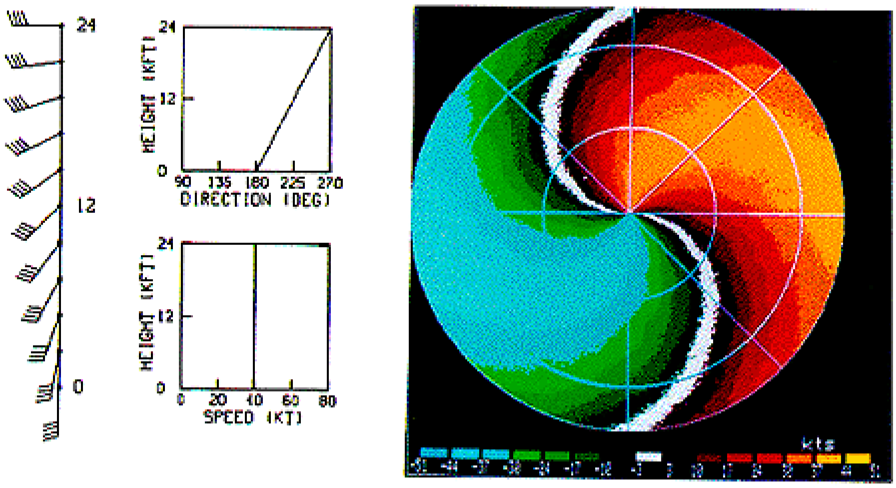


Image by: [Brown & Wood]

In the second example, the interpretation is exactly the opposite. The winds are veering with height and the zero line takes the shape of a normal "S"

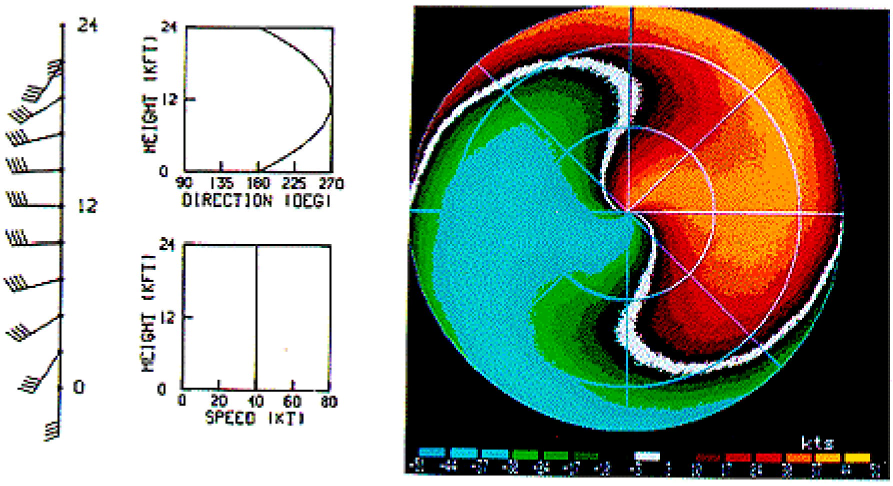
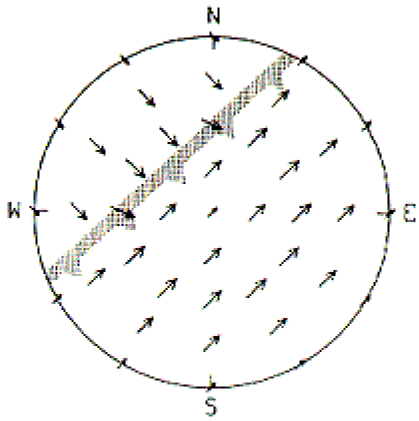


Image by: [Brown & Wood]

In our third example, winds veer with height to 12,000 feet and then back to 24,000 feet. The inner rings show the characteristic normal "S" pattern while the outer rings show the reverse.



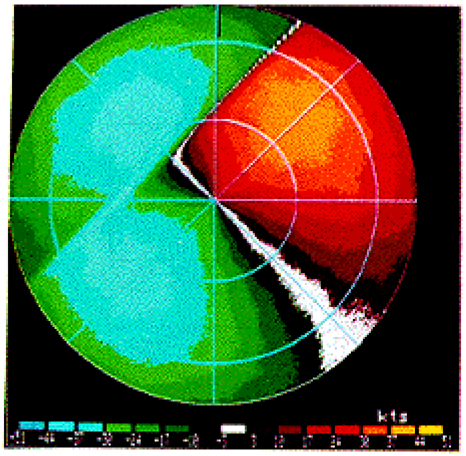


Image by: Brown & Wood

In our fourth example, a cold front is moving toward the radar from the northwest. East of the cold front, winds are from the southwest. The Doppler velocity pattern depicts the southwest winds. Behind the cold front where northwesterly winds are present, all of the winds are inbound toward the radar and appear with blue and green colors. The sharp boundary between the reds and greens on the north part of the display defines the cold front.

Interpreting Doppler Radar Velocities

straight line winds and rotation

We will now investigate how Doppler velocity patterns vary in a small area of the display where the flow field is uniform, rotating, and flowing outward from a point. These patterns would be similar to what an operator would see with uniform winds, when a mesocyclone associated with a severe thunderstorm was present, or when a downburst was present. We will view a small area located north of the radar as seen in the figure below.

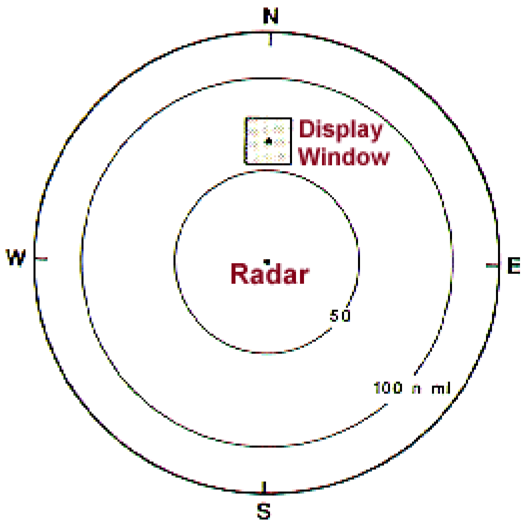


Image by: Brown & Wood

This diagram shows the location and size of the 27 x 27 nautical mile displaying window used for simulated Doppler velocity patterns of convective storm features. The window is 65 nautical miles due north of the radar located at the center of the overall display region.

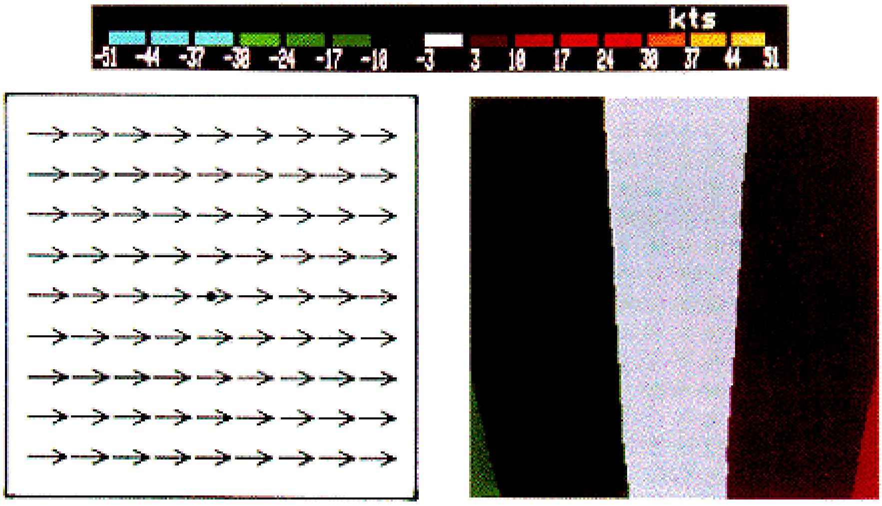


Image by: [Brown & Wood]

First, let's look at what a uniform flow field would look like in the small box. The [radial velocity] pattern on the right is what the radar would see if the wind speed was uniform at 50 knots and the wind was blowing from the west towards the east. Note the zero line goes down the center of the box because the winds are perpendicular to the beam along that line.

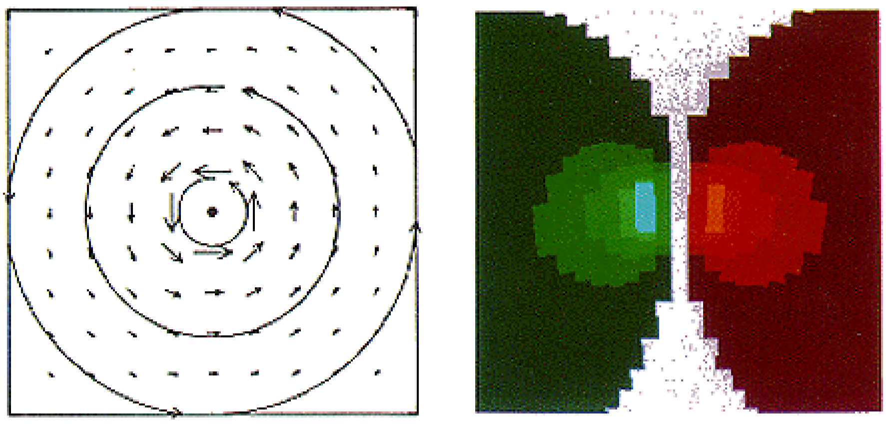


Image by: [Brown & Wood]

Next we look at a wind field which is rotating about a point at the center of the box. The wind speeds are 40 knots, 2.5 miles from the circulation center, and decrease outward to zero at the edge of the box. This crudely represents the mesocyclone circulation associated with a severe thunderstorm. The Doppler [radial velocity] display again shows the zero line down the middle of the box since winds along this line are perpendicular to the radar beam. However, to the left and right of the line, a sharp velocity couplet appears with strong outbound velocities just to the right and strong inbound velocities just to the left. This is the classic signature of rotation with strong inbound and outbound velocities flanking the beam axis.

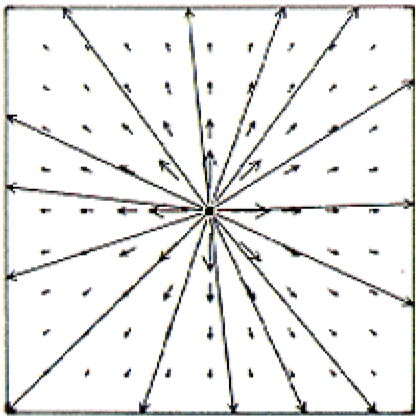
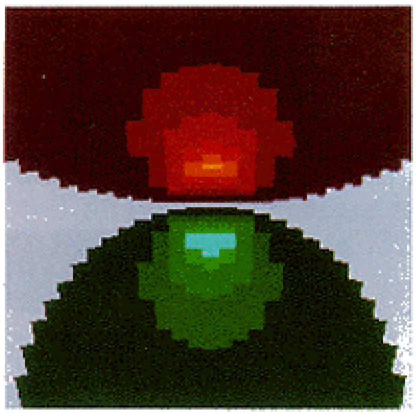
 

Image by: Brown & Wood

Straight line winds often originate in circulations called downbursts, in which cool descending air strikes the ground at high speed and spreads out in all directions. The leading edge of this cold outflow is called a gust front. The image above shows the Doppler radial velocities associated with an idealized downburst. This Doppler velocity pattern corresponds to an axisymmetric divergent flow where the center of the downburst is in the center of the box 65 nautical miles north of the radar. Note the strong velocity couplet, with the zero line perpendicular to the beam axis and strong inbound and outbound velocities along the beam axis.

Interpreting Doppler Radar Velocities

velocity patterns associated with tornado vortex signatures

The most important phenomena associated with severe convection are tornadoes. When a tornado is present, it is usually small enough that it fits within one or two beam widths. Depending upon the geometry of the beam, the distance of the tornado from the radar, and the location of the beam relative to the tornado, the strong winds of the tornado will typically occupy one or two pixels. Adjacent pixels will have sharply different velocities, typically with one inbound and one outbound. In the picture below, the mesocyclone and tornado are in the middle of the radar beam so that the gray zero Doppler velocity band separates the two halves of the display.

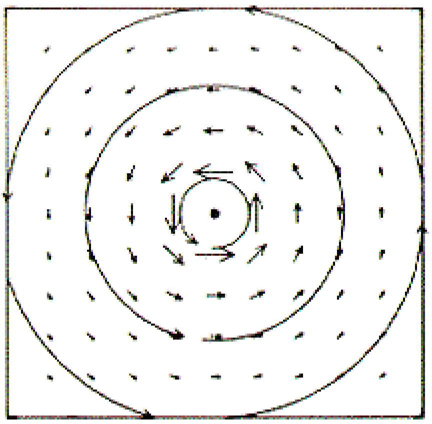
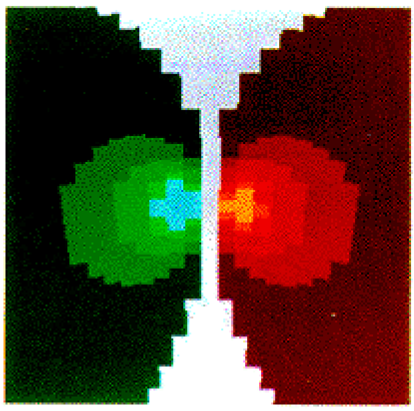
 

Image by: Brown & Wood

Doppler radars have a limited range of radial velocities that they can observe. Velocities beyond that range will be "folded" back into that range such that a strong outbound velocity, just beyond the observable range, will be interpreted as a strong inbound velocity within the observable range. Oftentimes the winds will be so strong in a tornado that the velocities observed by the radar will be folded in the pixel containing the tornado. Tornado Vortex Signatures (TVS) take on different characteristics depending on the geometry and whether or not the velocities are folded. The two figures below show examples of tornado vortex signatures. In the top figure, the circulation has been moved one half beam width to the right. The radar velocities are folded.

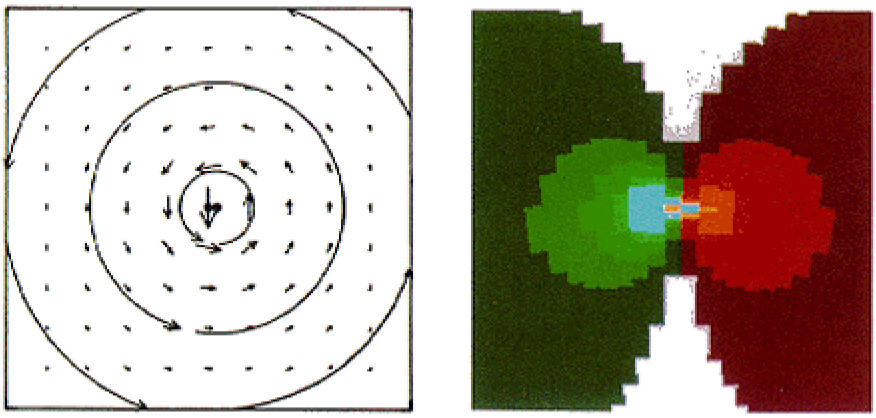


Image by: Brown & Wood

In the following figure, the tornado vortex signature is located 2.5 miles northeast of the cyclone center.

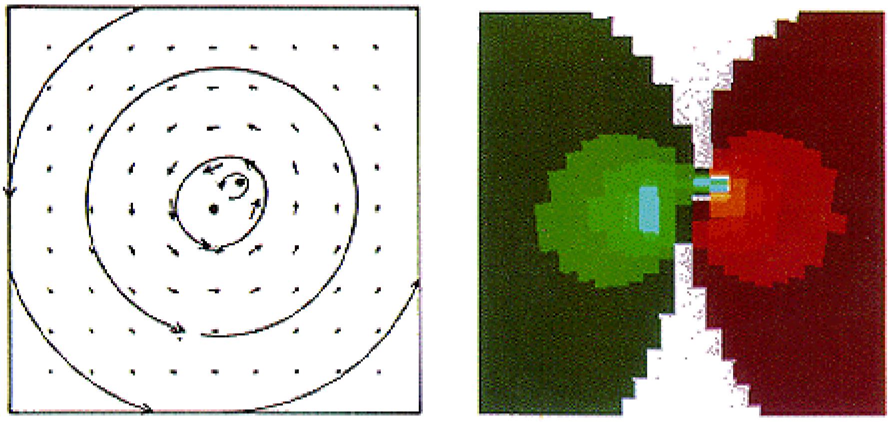
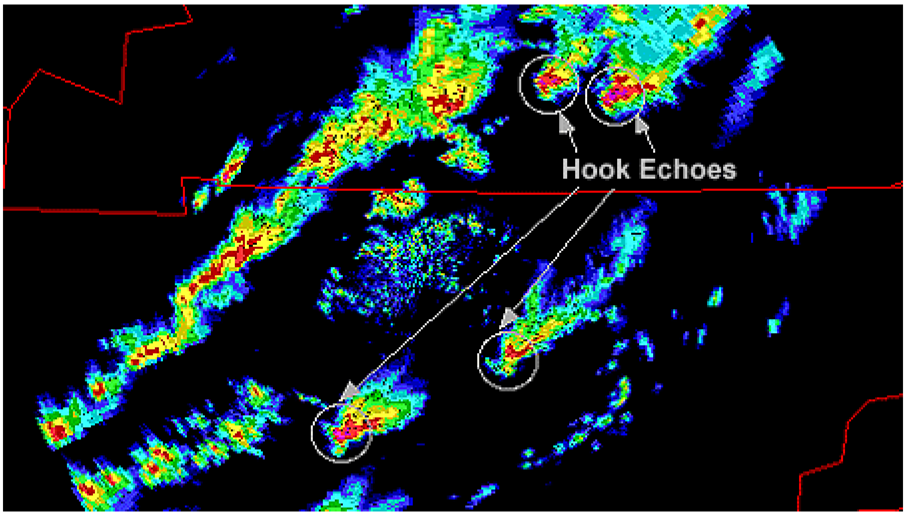


Image by: Brown & Wood

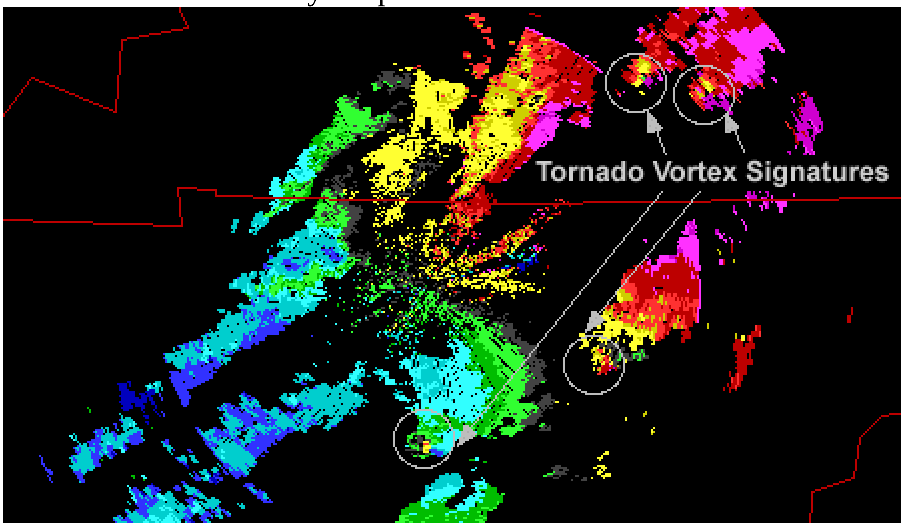
Locating Tornadoes

hook echoes and velocity couplets

Tornadoes are often located at the center of a hook-shaped echo on the southwest side of thunderstorms. The hook is best observed in the reflectivity field. This image shows a reflectivity field containing several hook echoes associated with thunderstorms that occurred in Tennessee and Kentucky on May 18, 1995.



Another way to determine if a storm is tornadic is to examine the radial velocity field. A mesocyclone, the small rotating circulation with its center beneath the updraft of a supercell thunderstorm, is detectable as a velocity couplet.



The couplet is oriented so that a concentrated area of radial winds moving away from the radar appears on one side of the beam axis, while a concentrated area of radial winds moving toward the radar appears on the opposite side of the beam axis. When the central pixels near the beam axis show exceptionally strong winds, this signature is called a tornado vortex signature (TVS). This image shows the TVS in the velocity field from the same Tennessee and Kentucky storms. Negative values (blue-green) denote movement toward the radar and positive values (yellow-red) represent movement away from the radar.

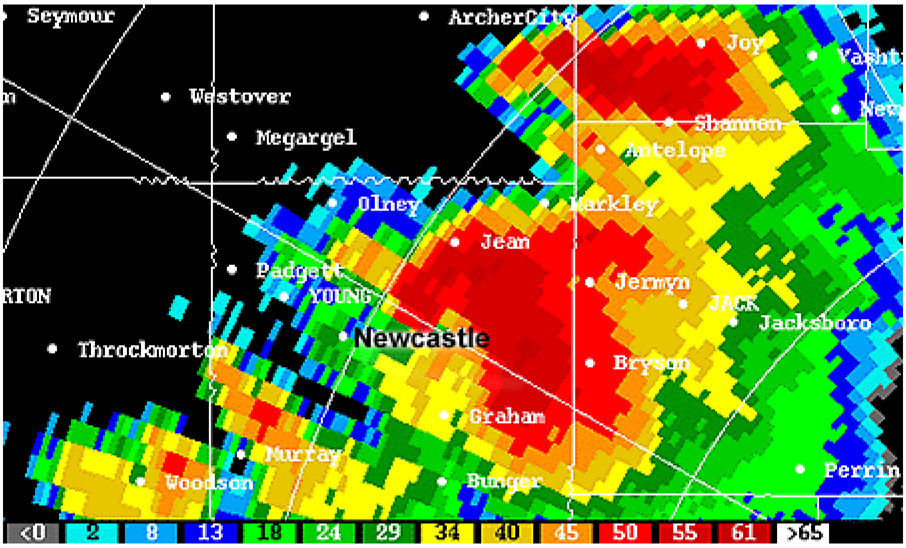


Image provided by: [NSSL]

Here is the reflectivity field from a storm which produced a tornado in Texas on May 29, 1995. The hook echo in the reflectivity field is located near Newcastle.

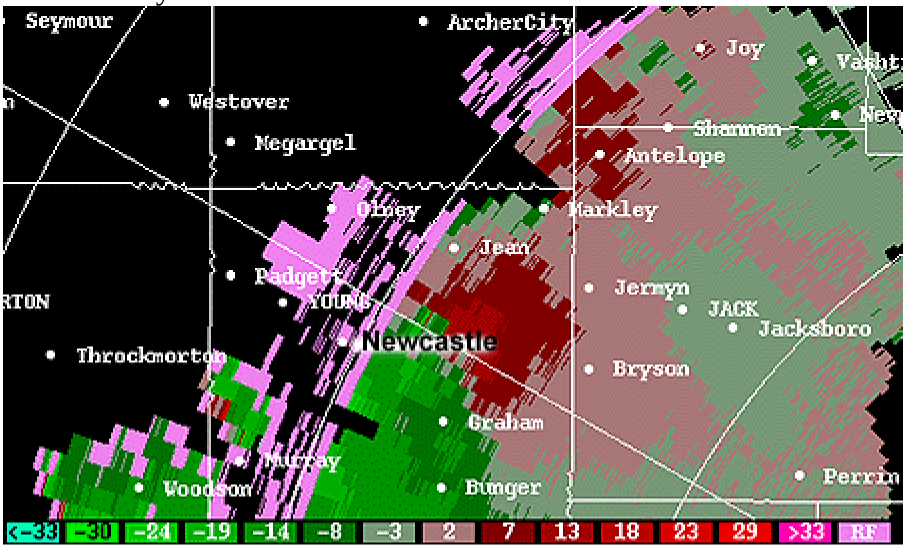


Image provided by: [NSSL]

Here is the velocity couplet associated with the Newcastle hook echo (red and green pixels adjacent to each other).

Hurricanes on Radar

circular areas of moderate to high reflectivity

[Hurricanes] show up clearly on radar as circular areas of moderate to high reflectivity, often surrounding a low reflectivity center.

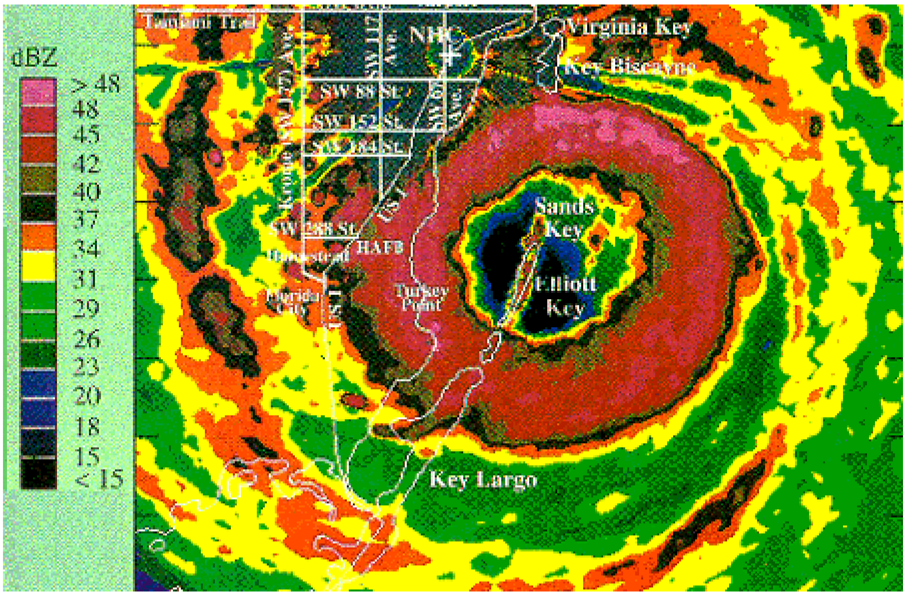
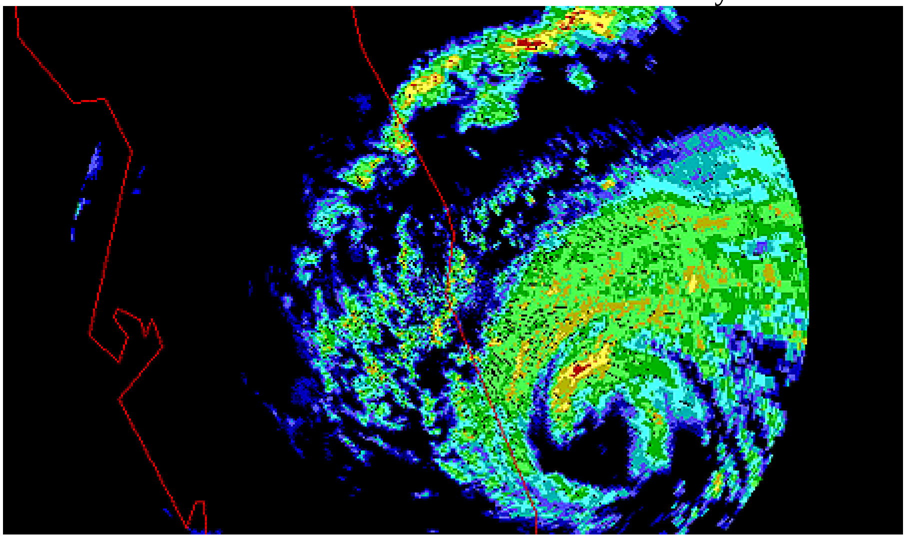
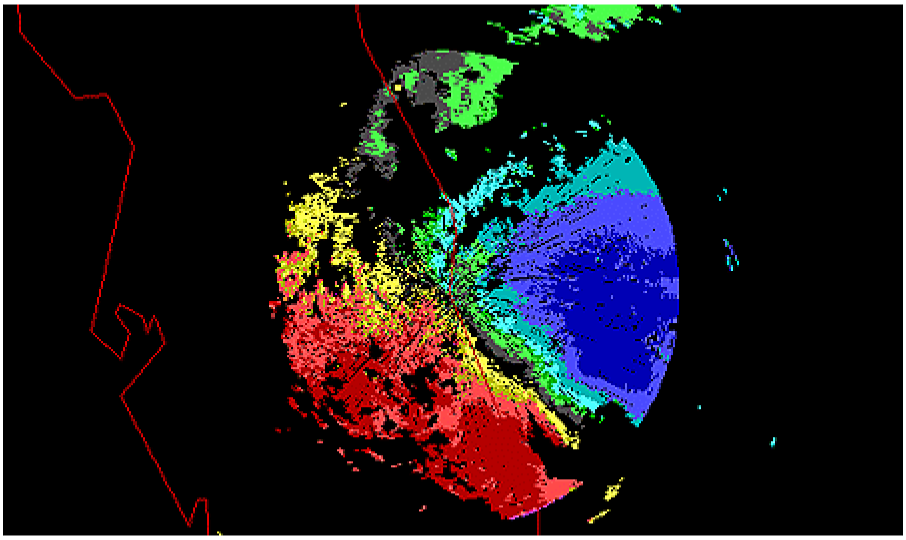


Image by: NHC

This image shows the reflectivity field from the eye wall of Hurricane Andrew. The symmetry shown in this image indicates that Andrew was a very well developed hurricane. The ring of orange are the high reflectivities associated with the convection found in the eye wall.



This image shows the reflectivity field from a scan of Hurricane Erin on August 2, 1995. The lack of symmetry indicates that Erin was a rather weak hurricane, especially compared to Andrew.



The velocity field of Hurricane Erin reveals the strong counterclockwise rotation responsible for the inward flow on the storm's north side and the outward flow on the south side. Negative values (blue-green) denote movement toward the radar and positive values (yellow-red) represent movement away from the radar.

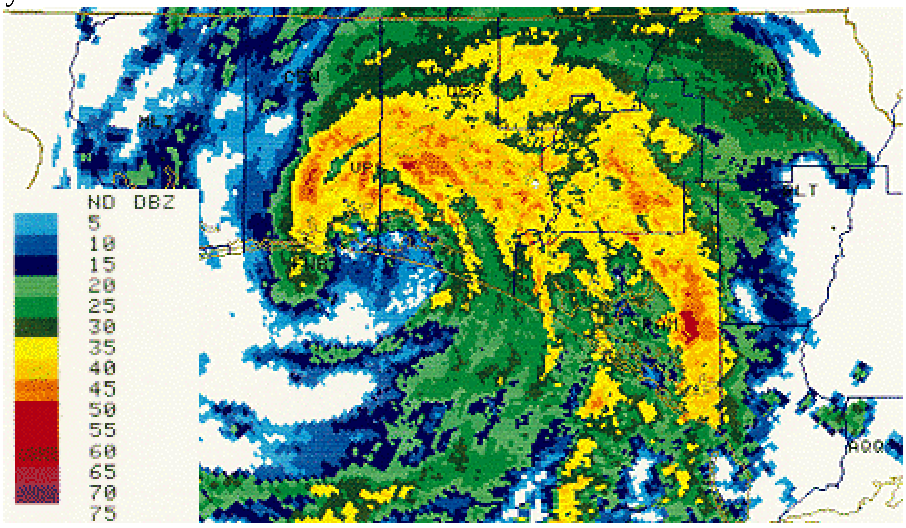


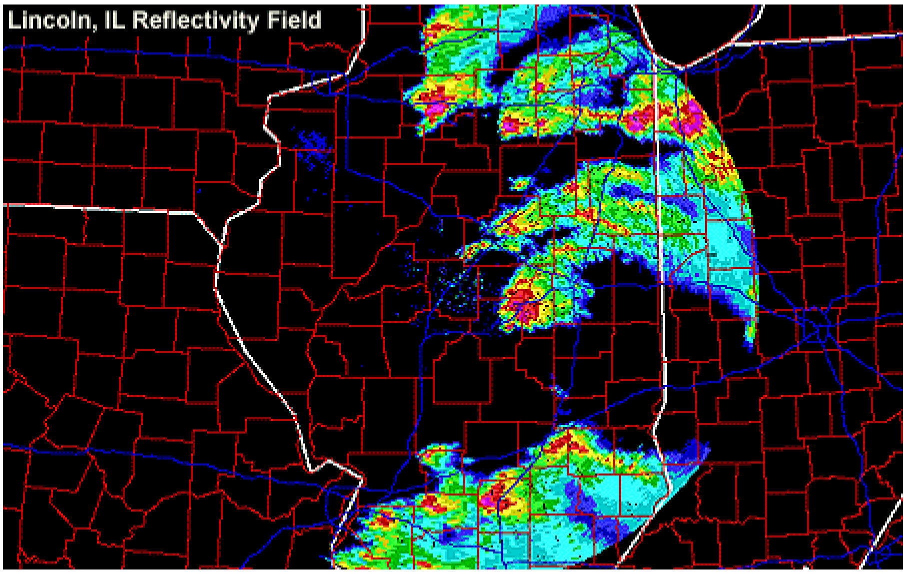
Image by: NWS

This image shows the reflectivity field from a scan of hurricane Roxanne on October 19, 1994. High reflectivities north and east of the eye are associated with strong convection present in the eye wall.

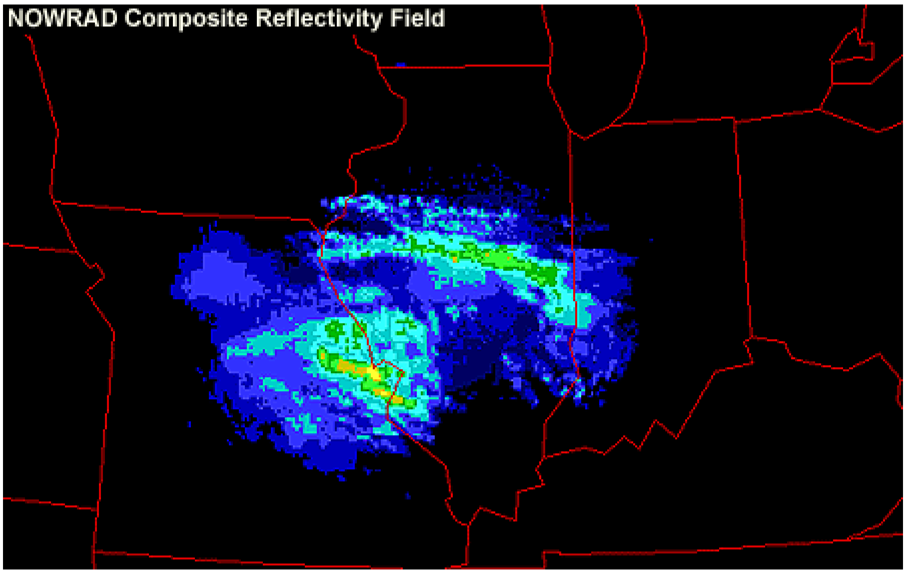
Short Term Forecasting

advantages of radar data

Using radar data, a forecaster can determine the nature of any existing weather systems and follow their movement and evolution. This is a valuable tool for making short term weather predictions.



This QuickTime movie (964k) shows severe thunderstorms moving across Illinois. By analyzing radar loops such as this, forecasters can determine the intensity and movement of thunderstorms, helping them to issue advanced warnings and advisories to cities which lie in the paths of the storms.

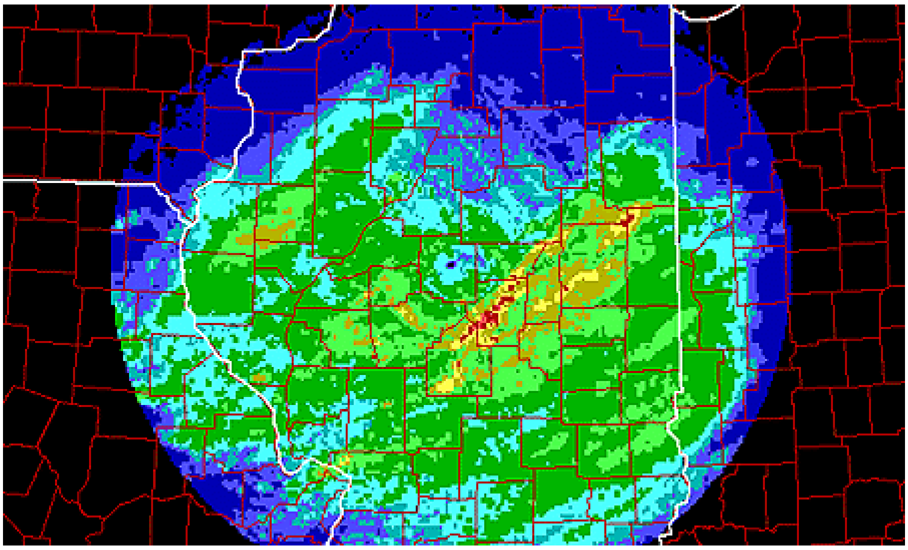


This QuickTime movie (803k) shows a large area of heavy rain developing around St. Louis. After seeing this area develop on radar, meteorologists issued flood watches for Missouri and southern Illinois.

Flash Floods

radar data is used to issue special weather statements

This image shows a map of radar-estimated precipitation totals for a 12 hour period. Since the radar reflectivity is closely related to the precipitation rate, the total amount of precipitation falling on a region over a fixed period of time can be determined by analyzing reflectivity field over that period.



The heaviest amounts are indicated in yellow and red. Flash flood warnings would be issued for the stream and river basins which drain these areas.

Snow Storms

radar data is used to identify bands of heavy snow

This image shows the different scales on which snow can occur. The large snow band extending across the figure is associated with a large storm system moving across the country.

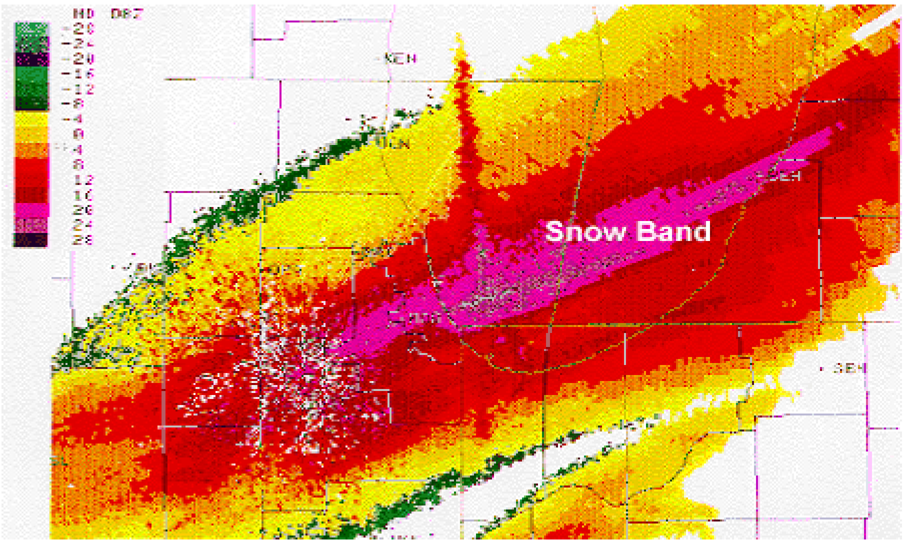


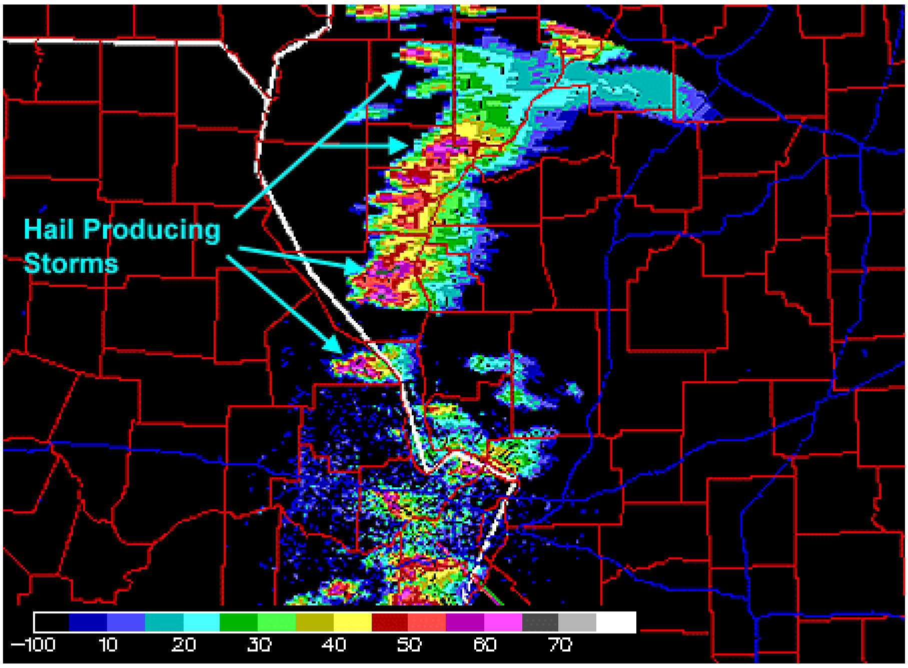
Image by: NWS

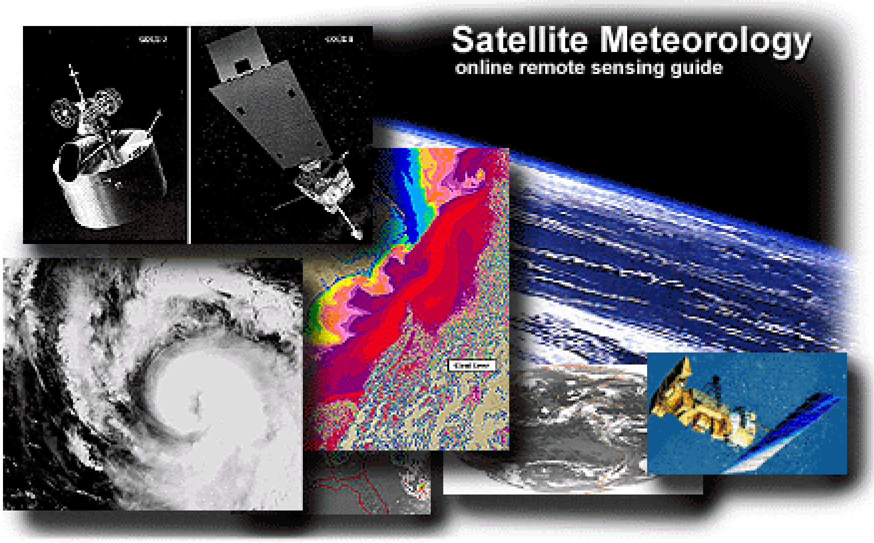
Superimposed on the large system, is a smaller scale snow band located off the west shoreline of Lake Michigan. Each of these bands individually produced heavy snow and where they intersected near Chicago, the snow was particularly intense.

Hail

indicated by regions of very high reflectivity

This image shows some severe thunderstorm cells in western Illinois and eastern Missouri on April 19, 1996. The small regions of high reflectivity (shades of purple and gray) located near the edges of these storms are likely to be regions where large hail is falling. Typically, radar reflectivities associated with hail have values exceeding 60 dBZ.





Graphic developed by: Steven E. Hall

The Webster dictionary defines a satellite as a man-made object put into orbit around a celestial body, like the earth or the moon. Satellites serve a wide variety of purposes from transmission of television signals via communication satellites to guidance and tracking systems of defense satellites. For meteorologists, satellites provide a comprehensive view of the world's weather by observing weather and the environment on a scale not possible by other means.

On April 1, 1960, the nation's first weather satellite, "TIROS I" was launched into orbit. Soon after, meteorologists saw the first pictures of a midlatitude cyclone over the northeastern United States. A new era had begun. Since then, weather satellites have been launched into orbit and their capabilities have improved significantly. Today, not only do satellites observe clouds, but measure other non- visible radiation from the earth and atmosphere. This helps us to estimate such aspects as crop and soil conditions as well as monitor concentrations of atmospheric ozone and many other global characteristics.

The purpose of this module is to examine Earth observing satellites and their capabilities in greater detail, focusing on two satellite orbital groups in particular; Geostationary Operational Environmental Satellites (GOES) and Polar Orbiting Environmental Satellites (POES). Finally, this module will demonstrate how to interpret visible, infrared and water vapor channel satellite images.

Sections Last Update: 08/28/99	**GOES Satellites** Orbital coverage, architecture, equipment and the types of products they produce.

POES Satellites
Orbital coverage, architecture, equipment and the types of products they produce.

Interpreting Satellite Images
Introduces visible, infrared, enhanced infrared and water vapor images, plus how to interpret them.

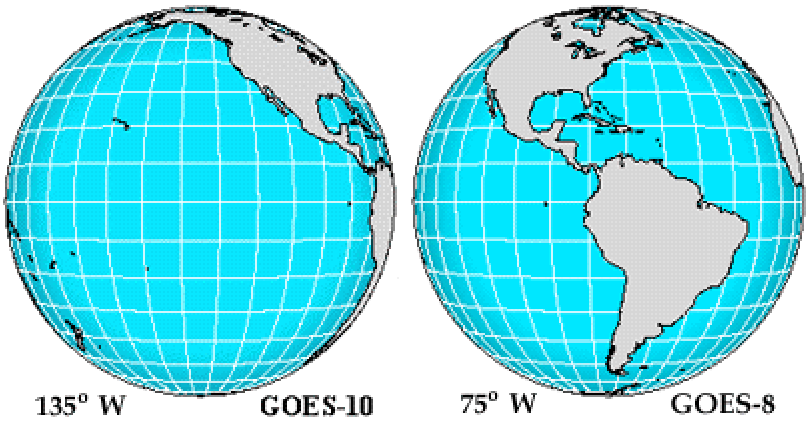
Acknowledgments
Those who contributed to the development of this module.

The navigation menu (left) for this module is called "Satellites" and the menu items are arranged in a recommended sequence, beginning with this introduction. Click on the menu item of interest to go to that particular section. More details about the navigation system or the WW2010 web server in general are available from About This Server.

GOES Satellites

geostationary operational environmental satellites

Geostationary Operational Environmental Satellites (GOES) circle the Earth in a geosynchronous orbit over the equator. This means they observe the Earth from the exact same place all the time. This allows the GOES satellites to continuously monitor a single position on the earth's surface. From 35,800 kilometers (22,300 miles) above the earth, GOES satellites provide half-hourly observations of the earth and its environment. Earth coverage of the GOES-8 and GOES-10 satellites has been depicted below.



Images provided by: Satellite Coverages and Orbits (NCAR)

GOES satellites are owned and operated by the National Oceanic and Atmospheric Administration (NOAA) while the National Aeronautics and Space Administration (NASA) manages the design, development and launch of the spacecraft. Once launched, NOAA once again resumes responsibility for the satellites. There are other geostationary satellites operated by other countries wihich contribute to cover the rest of the Earth.

The first geostationary weather satellite (GOES-1) was launched on October 16, 1975 and quickly became a critical part of the National Weather Service operations. For the past 30 years, environmental service agencies have stated the need for continuous, dependable, timely, and high-quality observations of the earth and its environment. The new generation of GOES satellites, do just that. These satellites have instruments on board that measure Earth-emitted and reflected radiation from which atmospheric temperature, winds, moisture and cloud cover can be derived. GOES-8 and GOES-9 were the first members of this new satellite generation to be launched, replacing the older GOES-6 and GOES-7 orbiters.

The GOES data, which is vital to weather monitoring and short-term forecasting, is then distributed by the National Environmental Satellite and Information Service (NESDIS) to a variety of operational and research centers. Today, GOES data products are used by a wide variety of users; the National Weather Service, commercial weather services, universities, the Department of Defense, and the global research community.

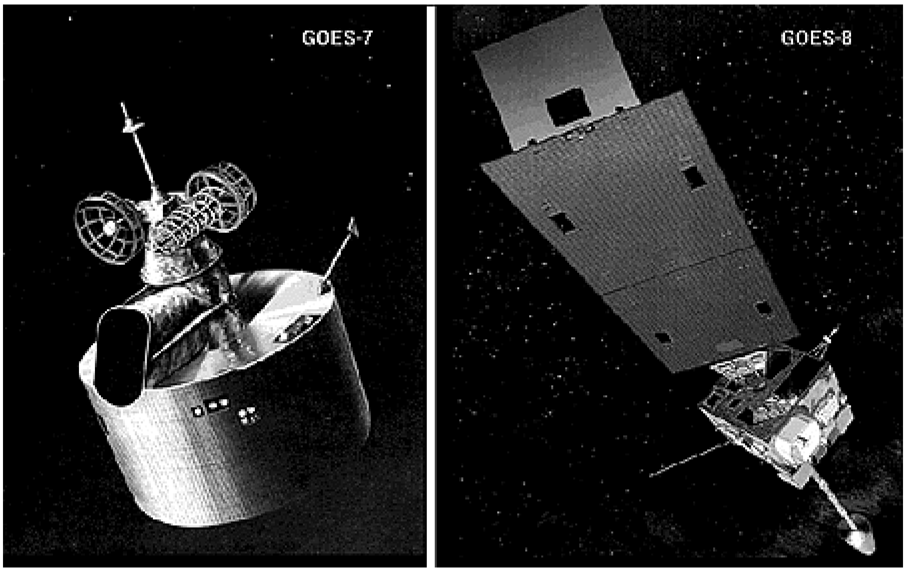
Selected Text and Image Provided By: GOES Mission Overview

History of GOES

GOES-1 through GOES-7

The first satellite in the GOES program (GOES-1) was launched on October 16, 1975 and quickly became an essential component of services provided by the National Weather Service. From the earliest days of the GOES program, implementing satellite imagery to perform such tasks as tracking hurricanes and volcano ash, as well as deriving cloud drift winds and their temperatures, were (and still are today) used by operational forecast centers to help with analyses in data sparse areas.

The newer satellites have benefited from the experiences of the other seven (GOES-1 through GOES-7) and results are shown through their improved capabilities. GOES-7 (pictured below) was only recently discontinued in 1995 and replaced by the more advanced GOES-9.



Resource: GOES-8 Tutorial of the NOAA-NESDIS RAMM Group

To date, a total of ten GOES satellites have been launched into orbit. Over the years as new technologies became available, the design of the GOES satellites changed accordingly to best make use of these new innovations. Below is a table that reconstructs the history of the GOES Program.

Information about GOES-1 through GOES-7 (no longer in use.)

Name	Launch dates	Significant milestones
GOES-1	Oct. 16,1975	Geosynchronous satellites dedicated to meteorology. GOES data became a critical part of National Weather Service
GOES-2	June 6,1977	
GOES-3	June 16,1978	
GOES-4	Sept. 9,1980	Added Atmospheric Sounder to the VISSR; however, imaging and sounding could not be done at the same time.
GOES-5	May 22,1981	
GOES-6	April 28, 1983	
GOES-7	Feb. 26, 1987	

GOES-1, GOES-2, and GOES-3 were constructed by Aeronautics Ford, and the remaining four were built by the Hughes Aircraft Company.

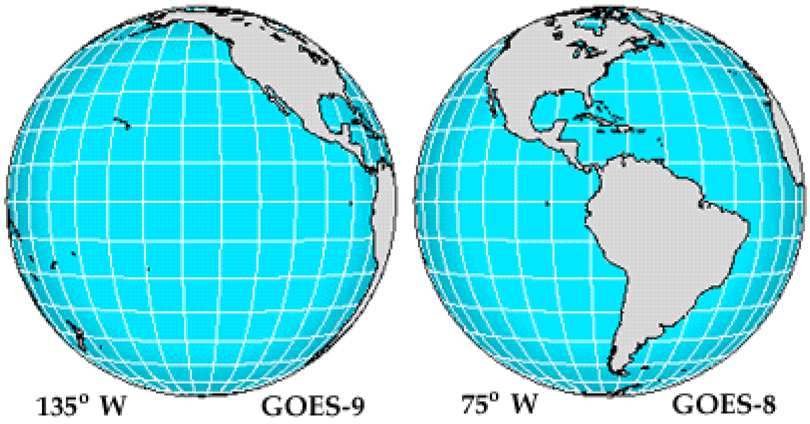
GOES-8 and GOES-10

fully operational

Image provided by GOES Mission Overview

Currently the US operates two geostationary satellites (GOES-8 and GOES-10) in geostationary orbit over the equator.

The GOES-8 is located at 75 west longitude above the equator and it covers North and South America and most of the Atlantic Ocean. The GOES-10 is also located above the equator at 135 west longitude and it monitors North America and the Pacific Ocean basin.



Images provided by: Satellite Coverages and Orbits (NCAR)

Both satellites carry imager and sounder instruments. The three-axis, body stabilized spacecraft design enables the sensors to image clouds, monitor earth's surface temperature and water vapor fields, and sound the atmosphere for its vertical thermal and vapor structures. GOES-8 and GOES-10 also introduce two new features: flexible scanning that allows small-area imaging *plus simultaneous and independent imaging and sounding*, allowing continuous gathering of data from both instruments.

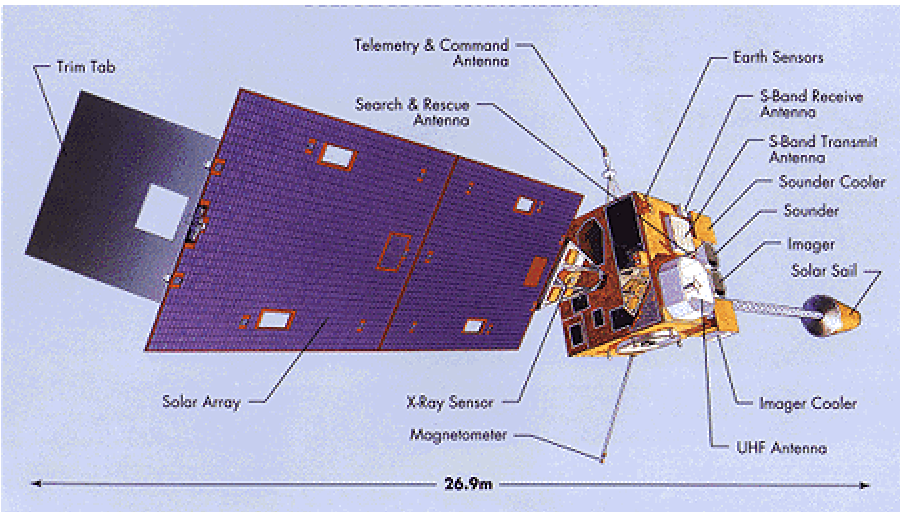


Image provided by: GOES-I/M Brochure

The components of a deployed GOES satellite are labeled in the diagram above. The main body has dimensions of 2.0 x 2.1 x 2.3 meters (m) and when the solar array deployed, the satellite is 26.9 meters long. The craft weighs 2104.7 kilograms (kg) and has a minimum lifetime of 5 years. GOES-8 was launched on April 13, 1994 and GOES-10 followed on May 23, 1995. GOES-10 launched on April 25, 1997 and has replaced GOES-9.

GOES Imager

multi-channel energy sensor

The GOES Imager is a multi-channel instrument designed to sense radiant and solar-reflected energy from sampled areas of the Earth. The multi-element spectral channels simultaneously sweep east-west and west-east along a north-to-south path by means of a two-axis mirror scan system. An imager schematic is given below.

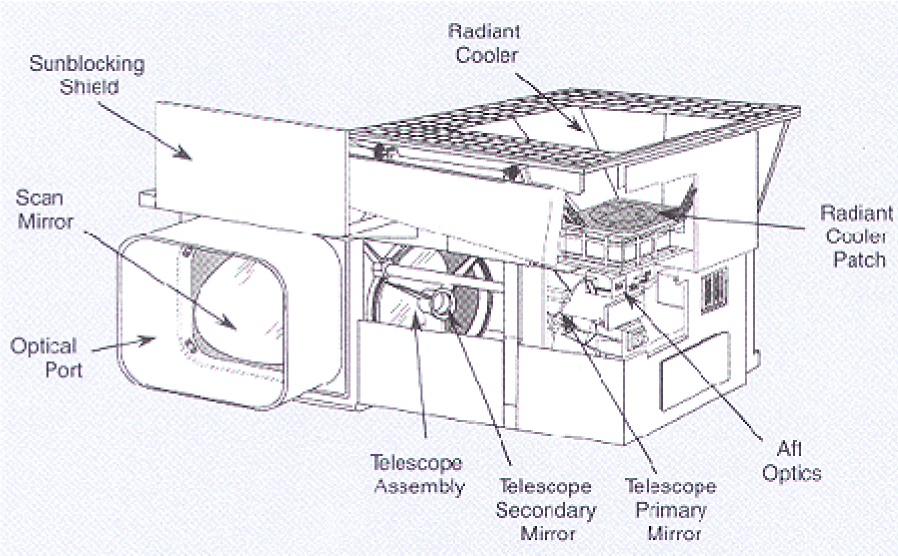


Image provided by: GOES Mission Overview

The instrument can produce full-Earth disc images, sector images containing the edges of the Earth, and various sizes of area scans completely enclosed within the Earth scene using a new flexible scan system. A five-channel monitoring system makes it possible to produce a wide variety of image products from imager data.

Text Provided By: GOES Mission Overview

Image provided by: GOES-8 Results (NASA-Goddard)

One such example is this visible full-Earth disc image taken by GOES-8.

GOES Imager Products

products generated from imager data

The imager detects different wavelengths of energy through different channels. This allows the imager to capture visible light, emitted long wave radiation and other radiation wavelengths. The imager has five "channels" which monitor radiation at a specific wavelength per given channel. Channel and product descriptions are given below:

0.52 - 0.72 micrometers (visible) - at 1 km, useful for cloud, pollution, and haze detection and severe storm identification.

Image provided by GOES-8 Results (NASA-Goddard)

3.78 - 4.03 micrometers (short wave infrared window) - at 4 km, useful for identifying fog at night, discriminating between water clouds and snow or ice crystal clouds, detecting fires and volcanoes, and determining sea surface temperatures.

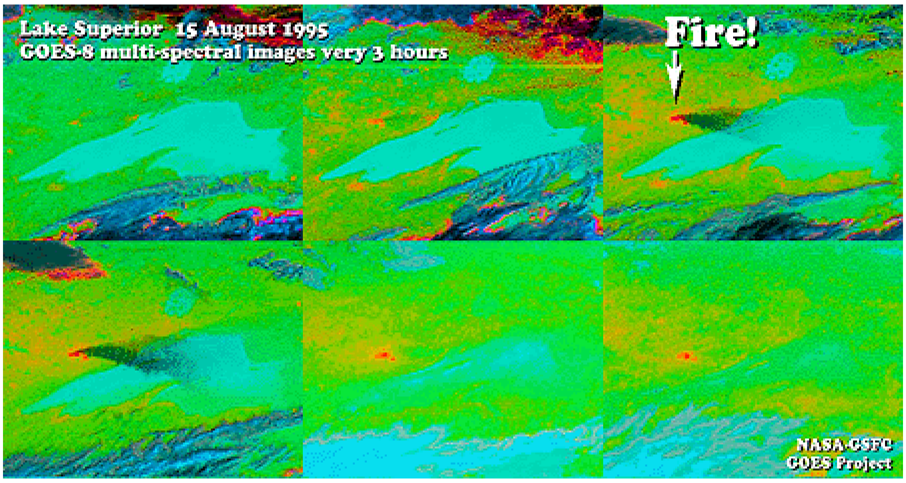


Image provided by GOES-8 Results (NASA-Goddard)

6.47 - 7.02 micrometers (upper level water vapor) - at 4 km, useful for estimating regions of mid-level moisture content and advection plus tracking mid-level atmospheric motions.

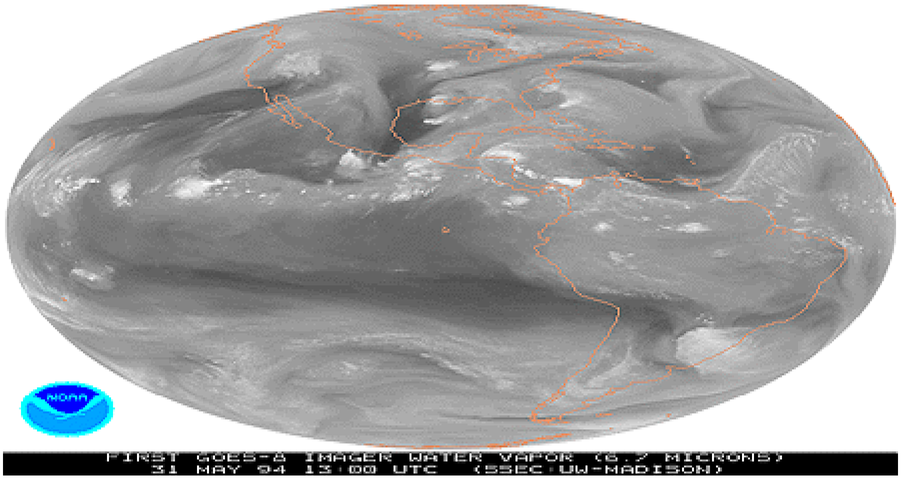


Image provided by GOES-8 Results (NASA-Goddard)

10.2 - 11.2 micrometers (long wave infrared window) - at 4 km, familiar to most users for cloud-drift winds, severe storm identification, and location of heavy rainfall.

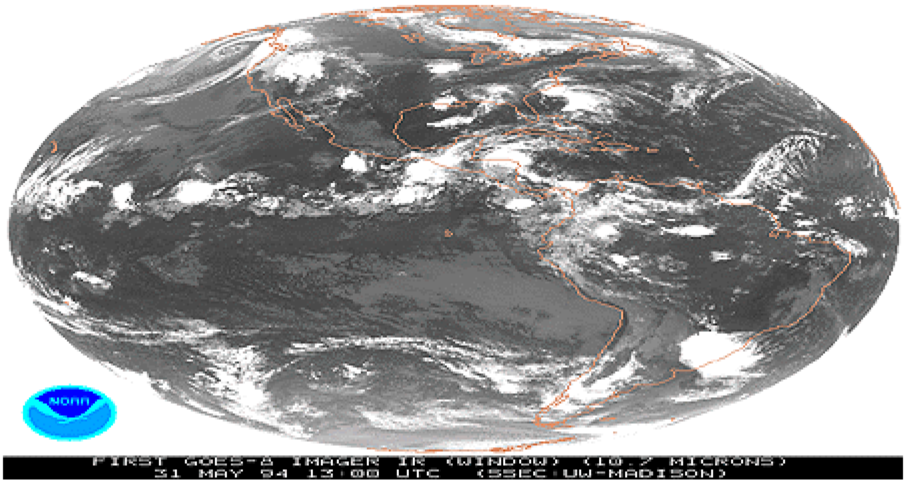


Image provided by GOES-8 Results (NASA-Goddard)

11.5 - 12.5 micrometers (infrared window more sensitive to water vapor) - at 4 km, useful for identification of low-level moisture, determination of sea surface temperature, and detection of airborne dust and volcanic ash.

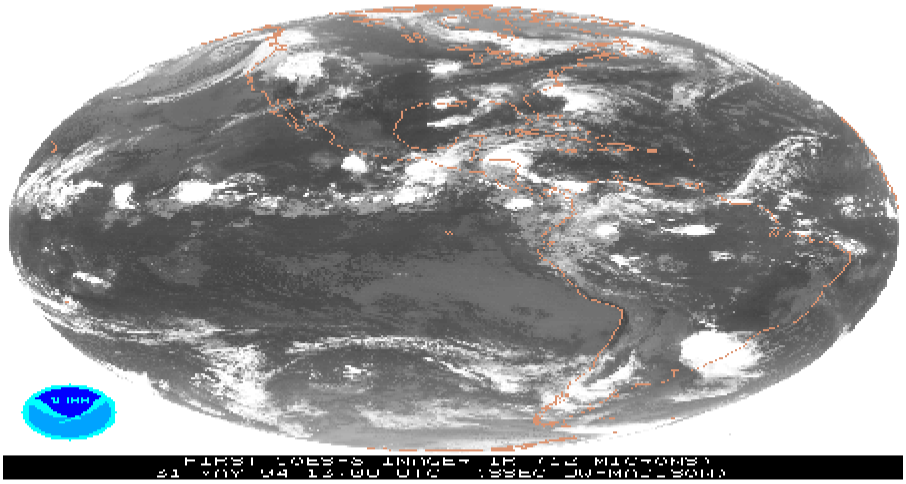


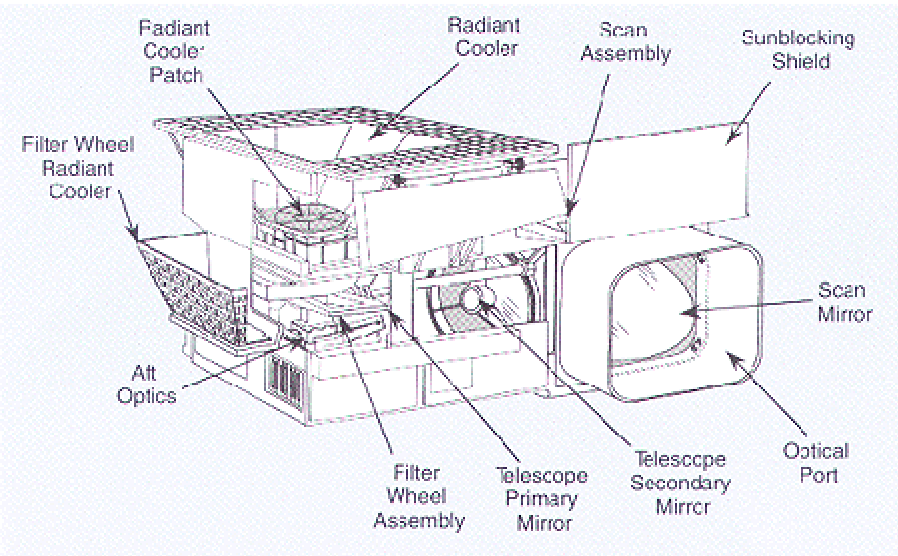
Image provided by GOES-8 Results (NASA-Goddard)

Selected text provided by: Space Science and Engineering Center (UW Madison).

GOES Sounder

radiometer for producing atmospheric vertical profiles

The GOES Sounder is a 19-channel discrete-filter radiometer covering the spectral range from the visible channel wavelengths to 15 microns. It is designed to provide data from which atmospheric temperature and moisture profiles, surface and cloud-top temperatures and pressures, and ozone distribution can be deduced by mathematical analysis.



GOES Mission Overview

It operates independently of and simultaneously with the Imager, using a similarly flexible scanning system. The sounder's multi-element detector array assemblies simultaneously sample four separate fields or atmospheric columns. A rotating filter wheel, which brings spectral filters into the optical path of the detector array, provides the infrared channel definition.

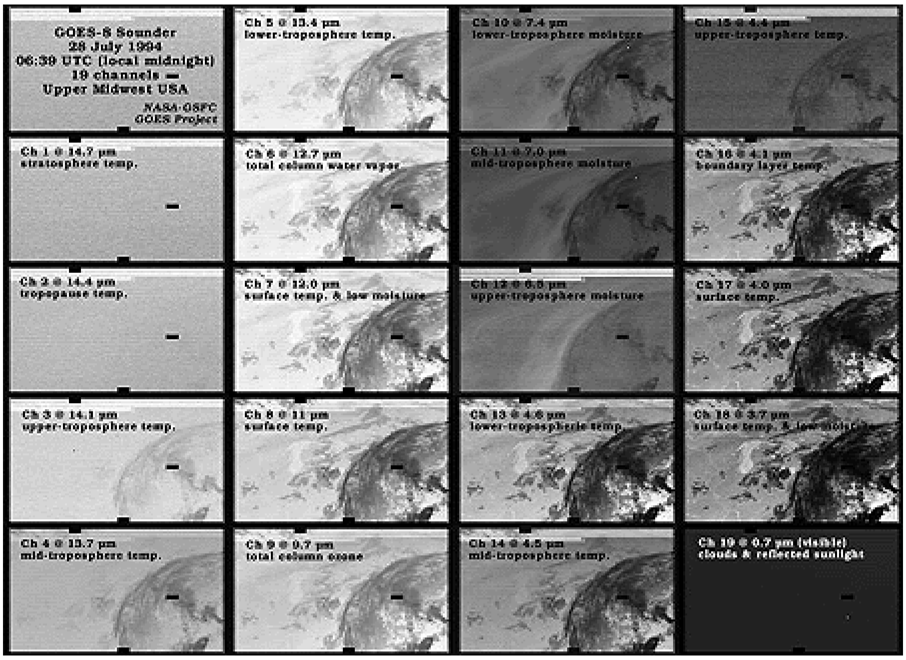


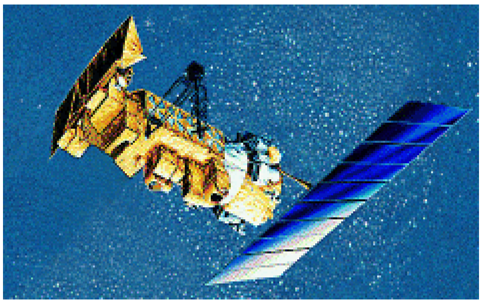
Image provided by: GOES-8 Results (NASA Goddard)

Above is a collection images from sounder data of the midwestern United States on 28 July 1994 at 0630 UTC, as viewed through the various sounder channels.

Text Provided By: GOES Mission Overview

Polar Orbiting Satellites

the POES program



Polar Orbiting Environmental Satellites (POES) are placed in circular sun-synchronous (see below) orbits and their altitudes usually range from 700 to 800 kilometers, with orbital periods of 98 to 102 minutes.

Image provided by: National Climatic Data Center

POES satellites include: Defense Meteorological Satellite Program (DMSP), Landsat, SPOT and NOAA Polar-orbiting Operational Environmental Satellites (NPOES). The DMSP and NPOES satellites are operational meteorological satellites. Imagery from successive orbits overlay each other, providing global daily coverage from each satellite. Commercial polar orbiters like Landsat and SPOT, on the other hand, are intended for geophysical remote sensing, with an emphasis on high-resolution and multispectral imagery, at the cost of daily global coverage.

POES have meteorological and geophysical importance because of their high-resolution global coverage and well calibrated channels. They are designed to stay in a low earth orbit and reach high latitudes. The POES program began in 1960 with the launch of TIROS-1. Later satellites in the

Improved TIROS Operational Satellite (ITOS) program were expanded to capture concurrent multiple-channel data on a daily basis.

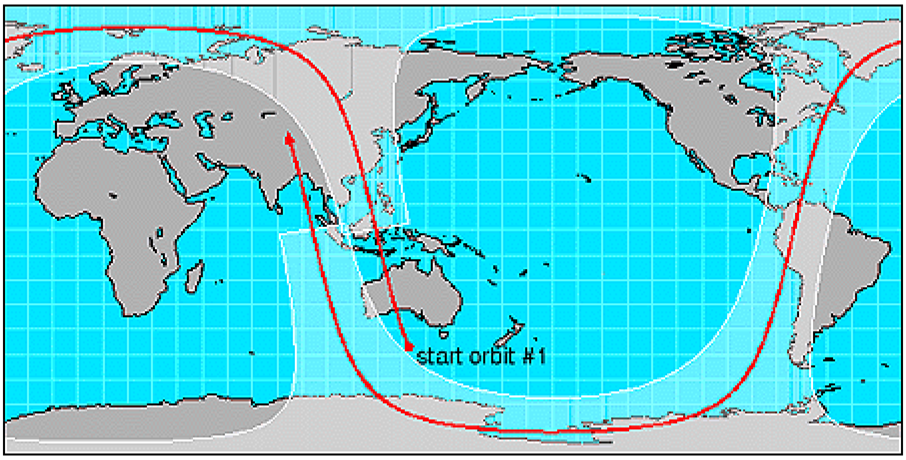


Image provided by: Satellite Coverages and Orbits (NCAR)

The POES orbit (above) relative to the Earth's surface is sun-synchronous. Its track is due to a combination of the orbital plane of the satellite coupled with the rotation of the Earth beneath the satellite. The orbit is slightly tilted towards the northwest and does not actually go over the poles. The red path follows the earth track of the satellite, the transparent overlay indicates the coverage area for the Advanced Very High Resolution Radiometer (AVHRR) imaging instrument carried by NOAA/POES satellites. This instrument scans a swath roughly 3000 kilometers wide.

Text Provided By: Satellite Coverages and Orbits (NCAR)

DMSP POES

run by the department of defense

The Defense Meteorological Satellite Program (DMSP) is run by the Air Force Space and Missile Systems Center (SMC).

Image provided by: DMSP Homepage

The DMSP program designs, builds, launches, and maintains several near polar orbiting, sun synchronous satellites monitoring the meteorological, oceanographic, and solar-terrestrial physics environments.

DMSP satellites are in a near polar, sun synchronous orbit approximately 830 kilometers above the earth. Each satellite crosses any point on the earth twice a day and has an orbital period of about

101 minutes, thus providing complete global coverage every six hours. Each DMSP satellite monitors the atmospheric, oceanographic and solar-geophysical environment of the Earth.

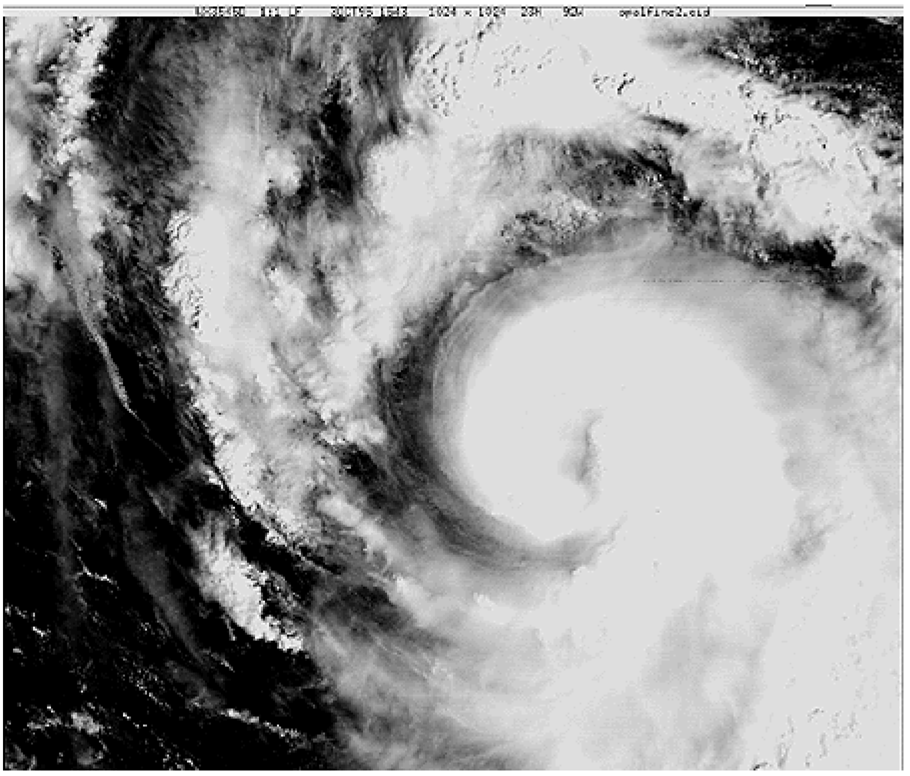


Image provided by: DMSP Homepage

These satellites have capabilities to zoom in close to atmospheric phenomena (like hurricanes). Other capabilities of DMSP satellites include the detection of: lightning, biomass burning, aurora, snow, ice and even city lights.

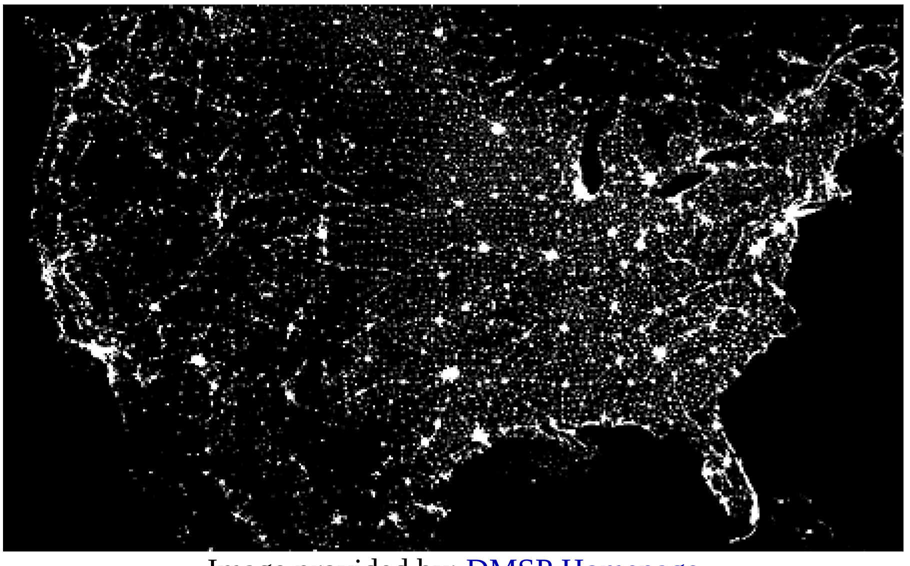


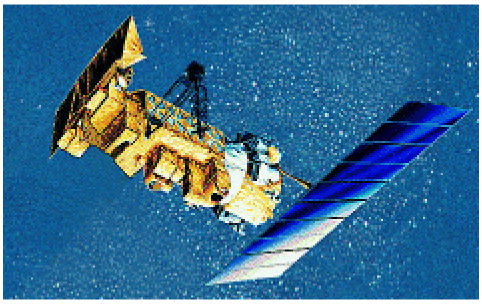
Image provided by: DMSP Homepage

The image above reveals where the lights are in the US when the sun goes down. The data from the DMSP satellites are received and used at operational centers on a continual basis. The data are sent daily to the National Geophysical Data Center (NGDC) and Solar Terrestrial Physics Division (STPD) for creation of an archive.

Text Provided By: DMSP at NGDC

NOAA POES

run by noaa



NOAA Polar-orbiting Operational Environmental Satellites (POES) are three-axis-stabilized spacecrafts that are launched into an orbit 830-870 kilometers high, constantly circling the Earth in an almost north-south orbit, passing close to both poles. POES satellites from NOAA-6 offer 4 or 5 channel multispectral daily repetitive global coverage.

Image provided by: National Climatic Data Center

The NOAA-12 -14 belong to the TIROS series known as the advanced Television Infrared Observing System satellite (The first meteorological satellite was one of the TIROS family).

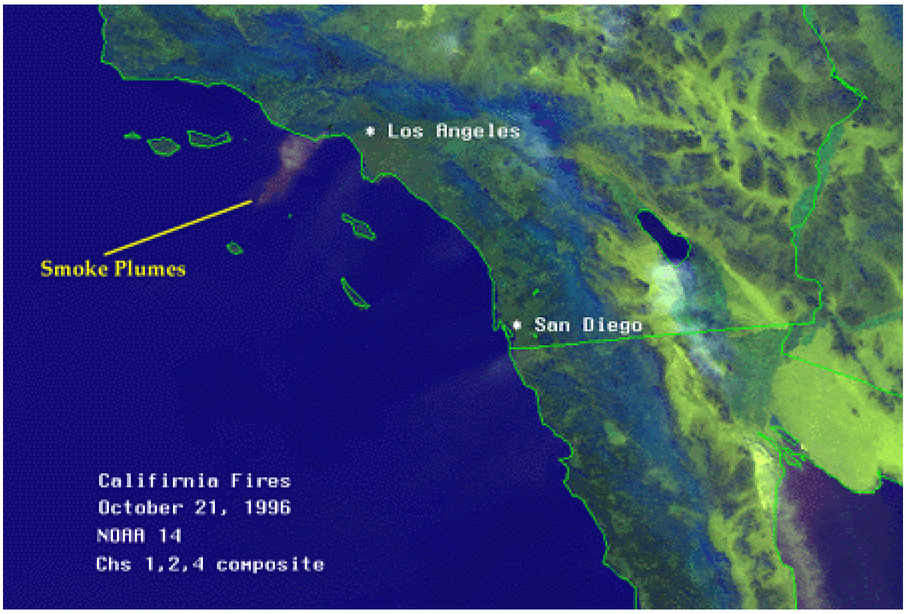


Image provided by: NOAA Satellite Active Archive

They operate as a pair to ensure that data for any region of the Earth is no more than six hours old. More than 16,000 global measurements are sent daily to NOAA's Command and Data Acquisition areas and are used for forecasting models. Additional capabilities of these satellites include fire plume detection (above) and sea surface temperatures (image below).

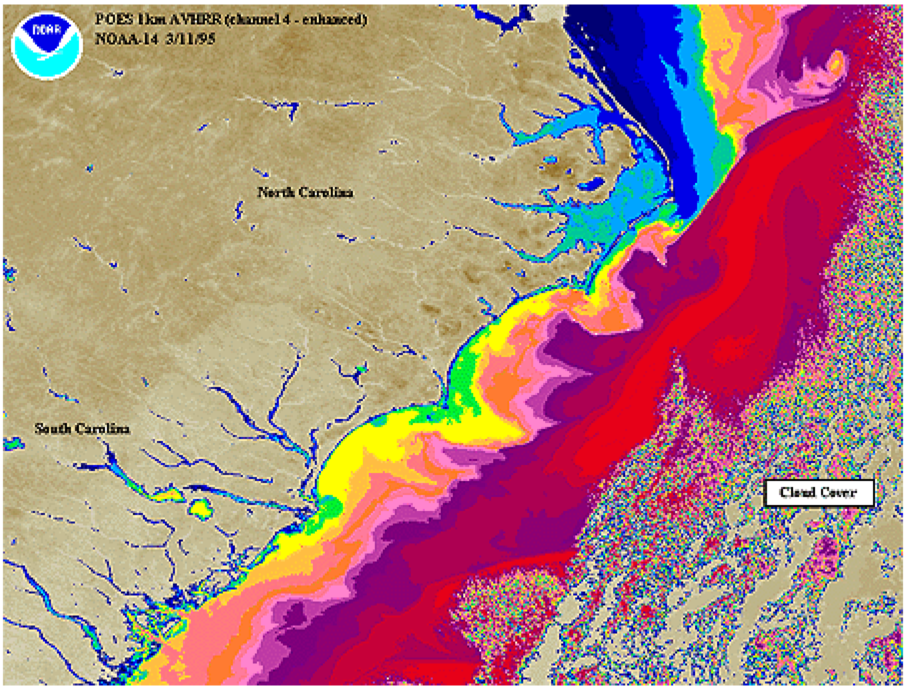


Image provided by: NOAA Satellite Active Archive

NOAA's POES satellites continue to carry the Advanced Very High Resolution Radiometer (AVHRR) which is a four or five channel scanner (depending on the model). AVHRR data are acquired in three formats:

High Resolution Picture Transmission (HRPT)
Full resolution (1.1 km) image data transmitted to a ground station as they are collected.

Local Area Coverage (LAC)
Full resolution data, but recorded with an on-board tape recorder for subsequent transmission during a station overpass.

Global Area Coverage (GAC)
Daily subsampled (4 out of 5 samples included) global coverage recorded on tape recorders then transmitted to a ground station.

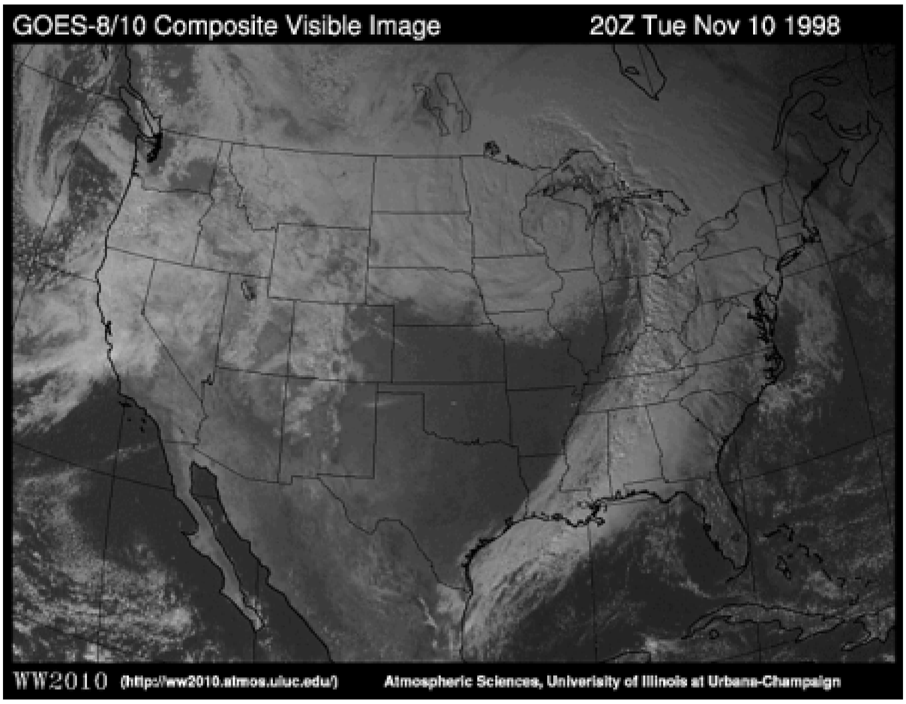
A new series of polar orbiters, with improved sensors, will began with the launch of NOAA-k (NOAA-15) in early 1998.

Text Provided By: NOAA Polar Orbiter Data User's Guide.

Visible Satellite Images

a picture of the earth

Visible satellite images are photographs of the earth that provide information about cloud cover. Areas of white indicate clouds while shades of gray indicate generally clear skies. In the example below (a composite of data from GOES-8 and GOES-10 satellites), scattered clouds are found across much of the eastern United States with clearer skies from North Dakota south to Oklahoma.

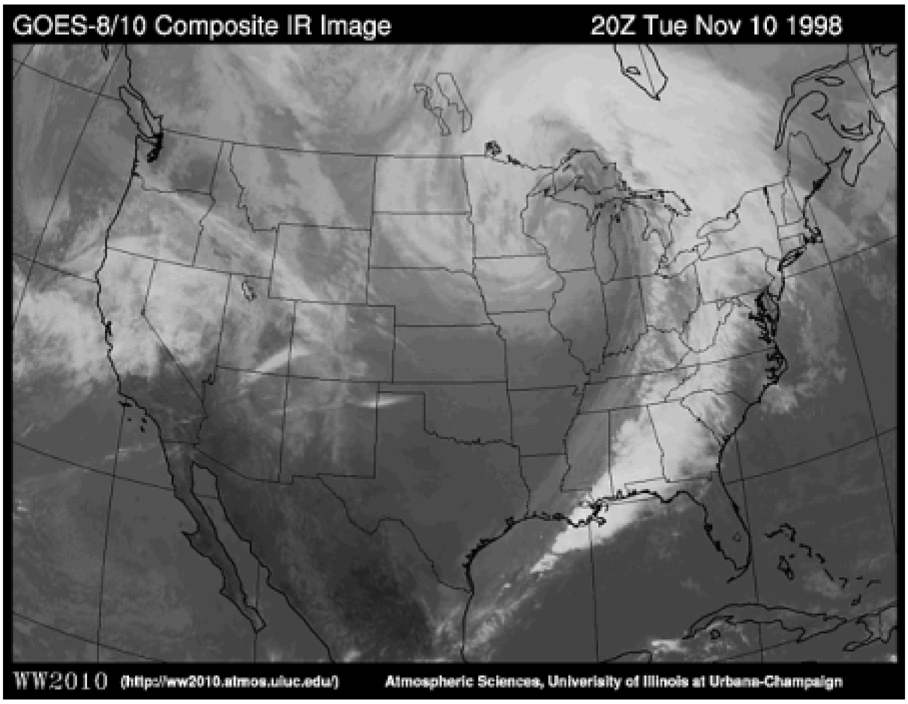


Visible images represent the amount of sunlight being scattered back into space by the clouds, aerosols, atmospheric gases, and the Earth's surface. Thicker clouds have a higher reflectivity (or albedo) and appear brighter than thinner clouds on a visible image. However, it is difficult to distinguish among low, middle, and high level clouds in a visible satellite image, since they can all have a similar albedo and for this distinction, infrared satellite images are useful.

Infrared Satellite Images

estimating temperature

Infrared satellite measurements are related to the brightness temperature. For an infrared picture, warmer objects appear darker than colder objects, as in the example below (a composite of data from GOES-8 and GOES-10 satellites).

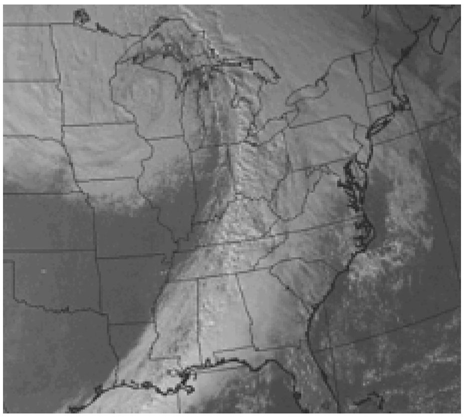


Since temperature in the troposphere decreases with height, high level clouds are colder than low level clouds. Therefore, low clouds (like those found over North Carolina and Virginia) appear darker on an infrared image and higher clouds (like those found throughout the eastern U.S.) appear brighter. The very dark shades of gray in parts of the Rocky Mountains and in the deserts of the Southwest indicate regions where the ground is being heated by the sun.

Visible -vs- Infrared Images

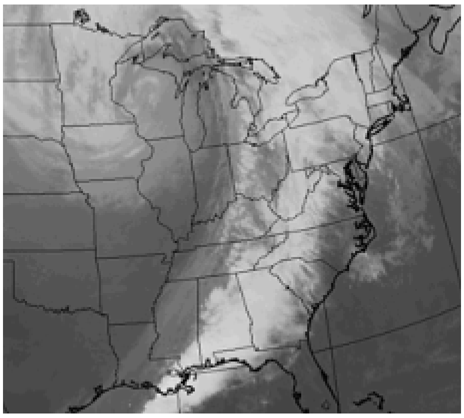
comparison and contrast

Images (a) and (b) are examples of visible and infrared satellite images respectively (valid for the same time).



(a)

Visible images measure scattered light and the example here depicts a wide line of clouds stretching across the southeastern United States and then northward into Ontario and Quebec.



(b)

In contrast, infrared images are related to brightness. Therefore, the clouds over Louisiana, Mississippi, and western Tennessee in image (a) appear gray in the infrared image (b) because of they are lower and have relatively warm cloud tops. The warmer the temperature, the lower the clouds, the darker the color.

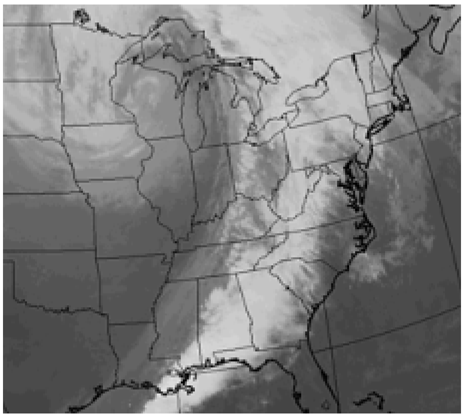
From Alabama northeastward into New York is a region of deep convective clouds that appear bright white in both pictures. Because of their higher cloud tops, these clouds are bright white in both images because of their high reflectivity and extremely cold cloud top temperatures.

The clouds in Canada probably high thinner cirrus and cirrostratus clouds. They have lower reflectivities and therefore appear somewhat darker in the visible image (a) but because of their higher altitudes and colder cloud tops, they appear bright white in the infrared image (b).

Color Enhanced Infrared Images

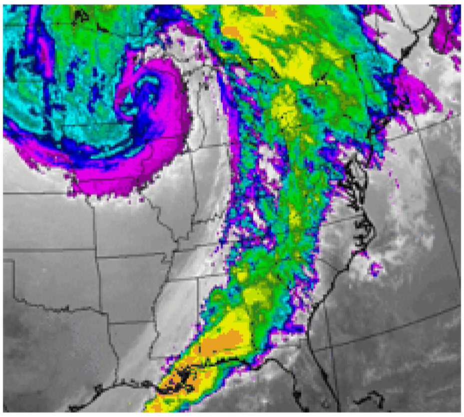
color enhancement of colder temperatures

Images (a) and (b) are examples of gray scale and color enhanced infrared satellite images respectively (valid for the same time).



(a)

In this infrared image (a), the thunderstorms erupting from the Gulf of Mexico into New York appear to be roughly the same height.



(b)

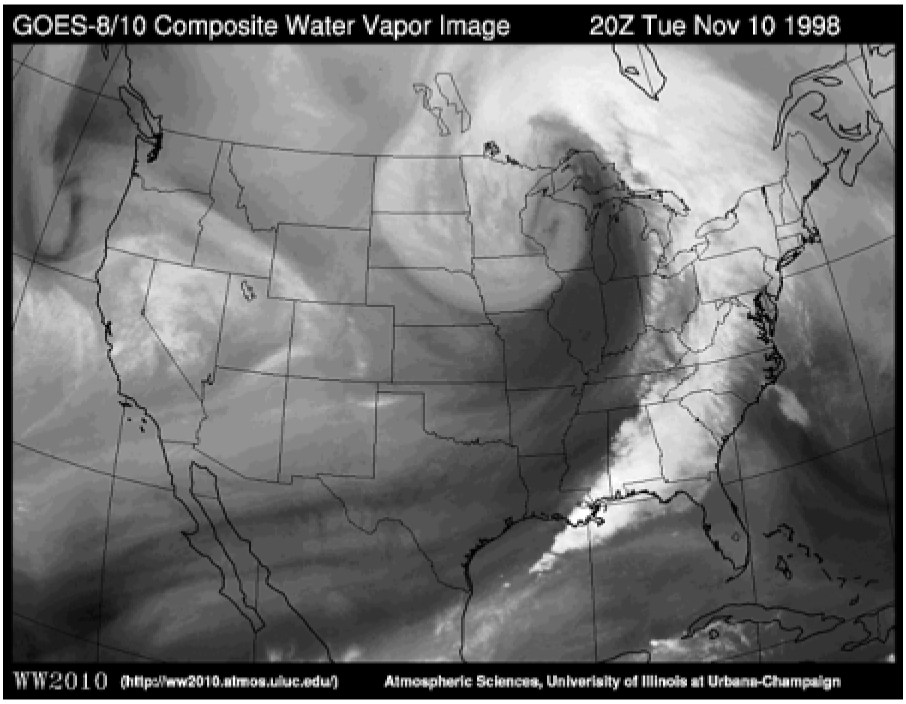
Color enhancement is a procedure where specified levels of energy -- in this example, infrared energy -- are given a specific color. this makes locations with the desired energies easier to locate. In this example (b), shades of yellow and orange represent infrared energy emissions consistent with strong thunderstorms. This is because infrared energy is proportional to brightness temperature, and the highest cloud tops are colder than those at lower altitudes (the highest cloud tops are typically associated with the strongest thunderstorms).

These images have been extracted from the same data, however color enhancement uses colors ranging from purple to red to make certain features stand out. Such features are not as easily observed in gray scale images.

Water Vapor Images

estimating moisture

Water vapor images are useful for pointing out regions of moist and dry air, which also provides information about the swirling middle tropospheric wind patterns and jet streams. The example below is a composite of data from GOES-8 and GOES-10 satellites.

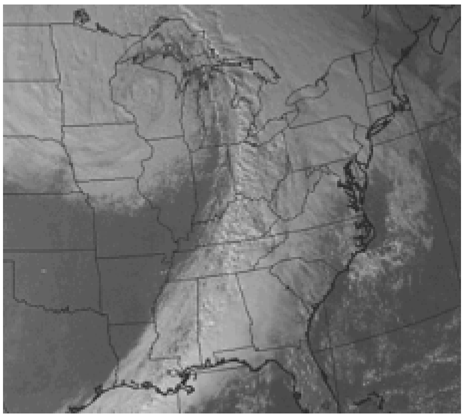


Darker colors indicate drier air while the brighter the shade of white, the more moisture in the air. In the image above, very dry air was present from Oklahoma into Illinois (indicated by the dark colors). Bright white plumes stretching from Missouri to South Carolina indicate the very moist air associated with thunderstorms occurring in the area.

Visible -vs- Infrared -vs- Water Vapor

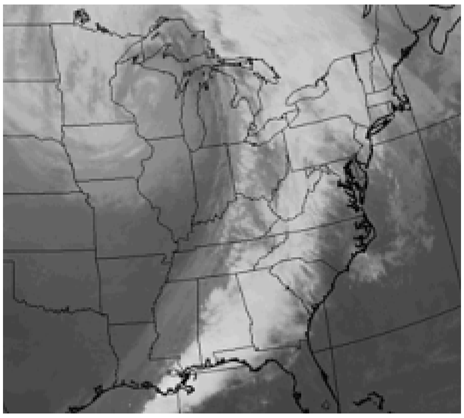
reflectivity -vs- temperature -vs- moisture

Images (a), (b) and (c) are examples of visible and infrared and water vapor satellite images respectively (valid for the same time).



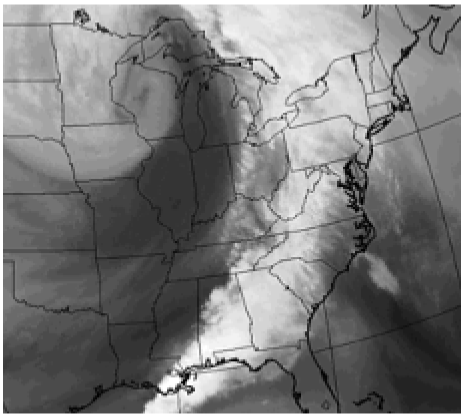
(a)

The visible image depicts clouds stretching from the Gulf of Mexico northeastward into Canada.



(b)

The clouds over Louisiana, Mississippi, and western Tennessee appear gray in the infrared image because of their low and relatively warm cloud tops. The warmer the cloud top temperature, the darker the color.



(c)

These clouds are associated with a large area of moist air covering most of the eastern third of the United States visible in the water vapor image as the extensive area of white.

The thunderstorms (areas of bright white) that broke out from Missouri to South Carolina stand out more vividly in the infrared and water vapor images than in the visible. Drier air filtering in behind the thunderstorms across Illinois, Indiana and Missouri stands out very well in the water vapor image (c), however is not as noticeable in the infrared (b) and visible (a) images.

"Look for hazy skies with afternoon thunderstorms and a high of 95 degrees." Weather forecasts, such as this one, provide critical information to many people, including farmers, construction workers, and those planning a trip to the beach. In severe weather situations, short-term forecasts and warnings can help save lives and protect property. But how does one take the wealth of weather information that is available and make a prediction from it?

In the sections that follow, we examine features to look for on weather maps to make a forecasts, general methods of preparing a forecast, and more specific tips for specific scenarios.

Sections
Last Update: 2/26/99

Coordinated Universal Time
Learn to convert your local time to the standard used by all meteorologists.

Temperatures
See how temperatures measured in Kelvin, Celsius and Farernheit are related.

Surface Observations
Learn how to read maps containing weather observation information for the surface.

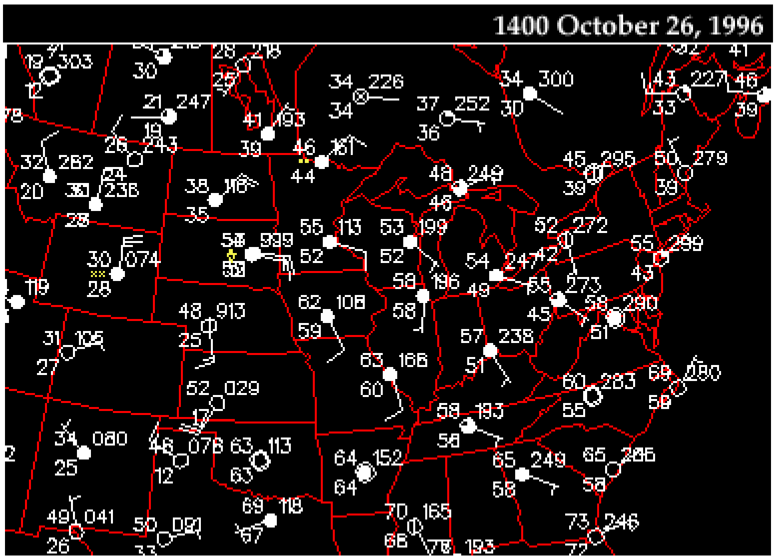
Surface Maps
Learn how to interpret the WW2010 surface weather maps.

Upper Air Observations
Learn how to read weather data observed above the surface.

Coordinated Universal Time

converting between UTC and AM/PM time

Coordinated Universal Time (UTC) can be considered equivalent to Greenwich Mean Time (GMT) (when fractions of a second are not important). UTC is the system used to indicate time in meteorology and is recommended for all general timekeeping applications. Time on most weather maps is given given in Coordinated Universal Time, (as in the example below).



Resources are available to demonstrate the conversions from AM/PM time to UTC and also from UTC to AM/PM time.

Converting Between AM/PM and 24 Hour Clock

making the conversion

Converting from AM/PM to 24 hour clock:

between 12:00 AM and 12:59 AM, subtract 12 hours:
12:59 AM --> 0059

between 1:00 AM and 12:59 PM, a straight conversion:
10:00 AM --> 1000

between 1:00 PM and 11:59 PM, add 12 hours:
10:59 PM --> 2259

Converting from 24 hour clock to AM/PM:

between 0000 and 0059, add 12 hours:
0059 --> 12:59 AM

between 0100 and 1159, straight conversion to AM:
0100 --> 1:00 AM

between 1200 and 1259, straight conversion to PM:
1259 --> 12:59 PM

between 1300 and 2359, subtract 12 hours:
1559 --> 3:59 PM

Converting from AM/PM to UTC

for both standard and daylight saving time

Standard Time:
When converting to Coordinated Universal Time (UTC), the local AM/PM time must be converted to a 24-hour clock. Then, use the chart below to convert to UTC.

From Local Time to UTC:

Eastern Standard Time (EST)	EST + 5 hours = UTC
Central Standard Time (CST)	CST + 6 hours = UTC
Mountain Standard Time (MST)	MST + 7 hours = UTC
Pacific Standard Time (PST)	PST + 8 hours = UTC

Some Examples:

Local Date	AM/PM Time	24 Hour Clock		UTC Time	UTC Date
May 2nd	9:59 AM (EST)	959 (EST)		1459	May 2nd
May 2nd	1:00 PM (EST)	1300 (EST)		1800	May 2nd
May 2nd	6:00 PM (EST)	1800 (EST)		2300	May 2nd
If the UTC time is greater than 2359, then you have crossed over to the next day. So for example, 2430 becomes 0030 the day after.					
May 2nd	6:00 PM (CST)	1800 (CST)		0000	May 3rd
May 2nd	6:00 PM (MST)	1800 (MST)		0100	May 3rd
May 2nd	6:00 PM (PST)	1800 (PST)		0200	May 3rd

Daylight Saving Time:
When converting from Daylight Saving Time to UTC, the conversions are similar but the UTC Time is one hour less than when converting than its Standard Time counterpart. Local AM/PM time must be converted to a 24-hour clock. Then, use the chart below to convert to UTC.

From Local Daylight Saving Time to UTC:

Eastern Daylight Time (EDT)	EDT + 4 hours = UTC
Central Daylight Time (CDT)	CDT + 5 hours = UTC
Mountain Daylight Time (MDT)	MDT + 6 hours = UTC
Pacific Daylight Time (PDT)	PDT + 7 hours = UTC

Some Examples:

Local Date	AM/PM Time	24 Hour Clock		UTC Time	UTC Date
May 2nd	9:59 AM (EDT)	959 (EDT)		1359	May 2nd
May 2nd	1:00 PM (EDT)	1300 (EDT)		1700	May 2nd
May 2nd	6:00 PM (EDT)	1800 (EDT)		2200	May 2nd
May 2nd	6:00 PM (CDT)	1800 (CDT)		2300	May 2nd
If the UTC time is greater than 2359, then you have crossed over to the next day. So for example, 2430 becomes 0030 the day after.					
May 2nd	6:00 PM (MDT)	1800 (MDT)		0000	May 3rd
May 2nd	6:00 PM (PDT)	1800 (PDT)		0100	May 3rd

Converting from UTC to AM/PM

for both standard and daylight saving time

Standard Time:
When converting from Coordinated Universal Time (UTC), first use the conversion table below.

From UTC to Local Time:

Eastern Standard Time (EST)	UTC - 5 hours = EST
Central Standard Time (CST)	UTC - 6 hours = CST
Mountain Standard Time (MST)	UTC - 7 hours = MST
Pacific Standard Time (PST)	UTC - 8 hours = PST

Next, the local time is converted from a 24 Hour Clock to an AM/PM time.

Some Examples:

UTC Date	UTC Time	Local Time -->	24 Hour Clock	AM/PM Time	Local Date
May 2nd	1459		959 (EST)	9:59 AM (EST)	May 2nd
May 2nd	1800		1300 (EST)	1:00 PM (EST)	May 2nd
May 2nd	2300		1800 (EST)	6:00 PM (EST)	May 2nd
If the local time on the 24 hour clock is less than 0000, then you have crossed over to the previous day. So for example, -0400 becomes 2000 the day before.					

May 3rd	0000		1800 (CST)	6:00 PM (CST)	May 2nd
May 3rd	0100		1800 (MST)	6:00 PM (MST)	May 2nd
May 3rd	0200		1800 (PST)	6:00 PM (PST)	May 2nd

Daylight Saving Time:
When converting from UTC to Daylight Saving Time, the conversions are similar but the UTC Time is one hour less than when converting than its Standard Time counterpart. First use the conversion table below.

From UTC to Local Time:

Eastern Daylight Time (EDT)	UTC - 4 hours = EDT
Central Daylight Time (CDT)	UTC - 5 hours = CDT
Mountain Daylight Time (MDT)	UTC - 6 hours = MDT
Pacific Daylight Time (PST)	UTC - 7 hours = PDT

Next, the local time is converted from a 24 Hour Clock to an AM/PM time.

Some Examples:

UTC Date	UTC Time	Local Time -->	24 Hour Clock	AM/PM Time	Local Date
May 2nd	1459		1059 (EDT)	10:59 AM (EDT)	May 2nd
May 2nd	1800		1400 (EDT)	2:00 PM (EDT)	May 2nd
May 2nd	2300		1900 (EDT)	7:00 PM (EDT)	May 2nd
If the local time on the 24 hour clock is less than 0000, then you have crossed over to the previous day. So for example, -0400 becomes 2000 the day before.					
May 3rd	0000		1900 (CDT)	7:00 PM (CDT)	May 2nd
May 3rd	0100		1900 (MDT)	7:00 PM (MDT)	May 2nd
May 3rd	0200		1900 (PDT)	7:00 PM (PDT)	May 2nd

Units of Temperature

from fahrenheit to celsius to kelvin and back

Degrees **Fahrenheit**, (developed in the early 1700's by G. Daniel Fahrenheit), are used to record surface temperature measurements by meteorologists in the United States. However, since most of the rest of the world uses degrees **Celsius** (developed in the 18th Century), it is important to be able to convert from units of degrees Fahrenheit to degrees Celsius:

Fahrenheit to Celsius:

$$°C = (°F - 32) / 1.8$$

Kelvin is another unit of temperature that is very handy for many scientific calculations, since it begins at **absolute zero**, meaning it has no negative numbers. (Note...the word "degrees" is NOT used with Kelvin.) The way to convert from degrees Celsius to Kelvin is:

Celsius to Kelvin:

$$K = °C + 273.$$

The three different temperature scales have been placed side-by-side in the chart below for comparison.

Temperature Scales

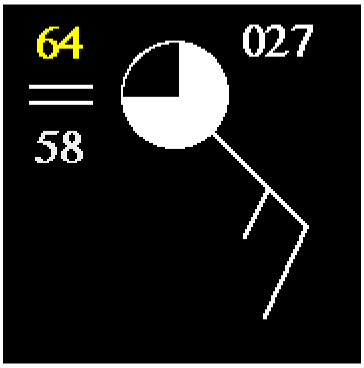
Fahrenheit	Celsius	Kelvin	
212	100	373	Boiling point of water at sea-level
194	90	363	
176	80	353	
158	70	343	
140	60	333	
122	50	323	
104	40	313	
86	30	303	
68	20	293	Average room temperature
50	10	283	
32	0	273	Melting (freezing) point of ice (water) at sea-level
14	-10	263	
-4	-20	253	
-22	-30	243	
-40	-40	233	
-58	-50	223	
-76	-60	213	
-94	-70	203	
-112	-80	193	-89°C (-129 °F) Lowest recorded temperature. Vostok, Antarctica July, 1983
-130	-90	183	
-148	-100	173	

Reference: Ahrens (1994) — Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign

Image adapted from: Ahrens

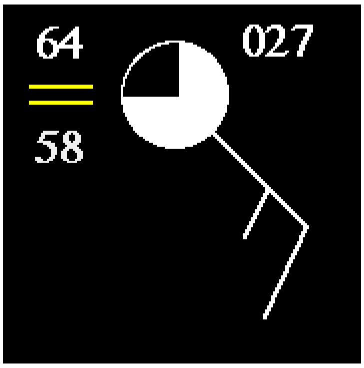
Interpreting Surface Observation Symbols

a quick overview



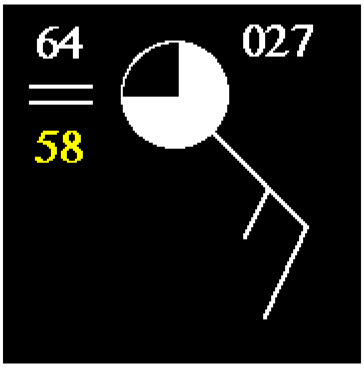
Temperature:

The value highlighted in yellow located in the upper left corner is the temperature in degrees **Fahrenheit**. In this example, the reported temperature is 64 degrees.



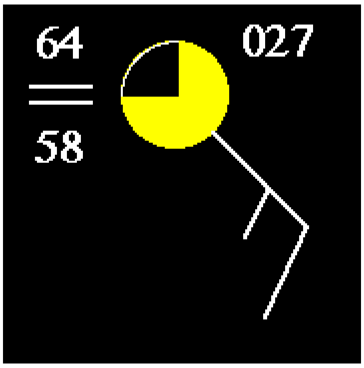
Weather Symbol:

The weather symbol highlighted in yellow indicates the type of weather occurring at the time the observation is taken. In this case, fog was reported. If there were thunderstorms occurring when the observation was taken, then the symbol for thunderstorms would have appeared instead.



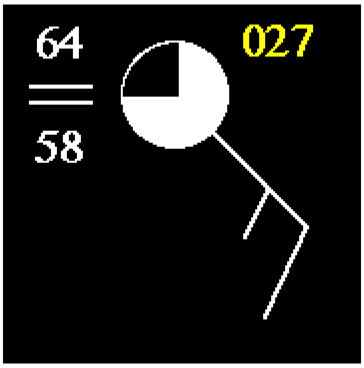
Dew Point Temperature:

The value highlighted in yellow located in the lower left corner is the dew point temperature in degrees **Fahrenheit**. In this example, the reported dew point temperature is 58 degrees.



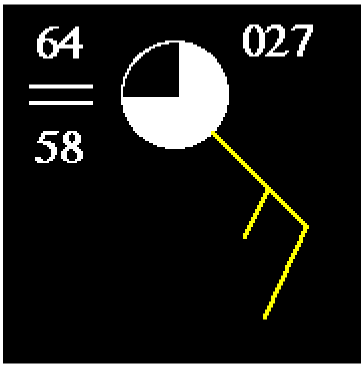
Cloud Cover:

The symbol highlighted in yellow indicates the amount of cloud cover observed at the time the observation is taken. In this case, broken clouds were reported.



Sea Level Pressure:

The value highlighted in yellow located in the upper right corner represents the last three digits of the sea level pressure reading in **millibars (mb)**.



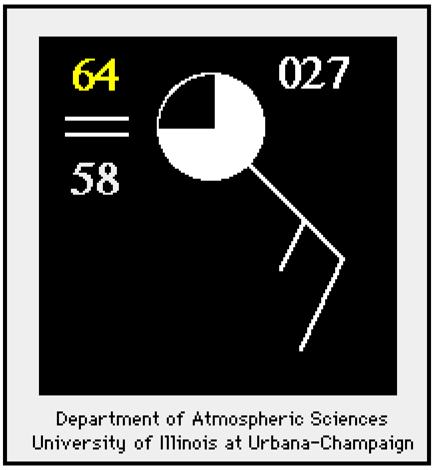
Wind Barb:

The symbol highlighted in yellow is known as a wind barb. The wind barb indicates wind direction and wind speed.

Observed Temperature

station reporting symbol

The value highlighted in yellow located in the upper left corner (in the diagram above) is the temperature in degrees **Fahrenheit**. In this example, the reported temperature is 64 degrees.

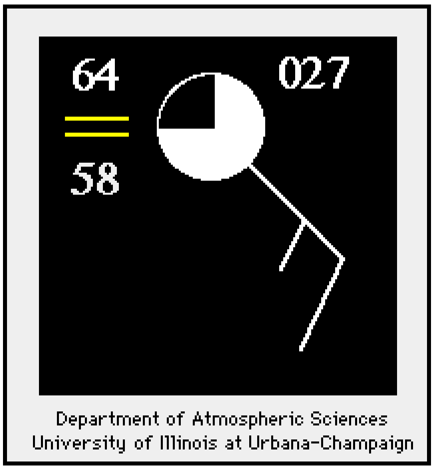


Temperature:
is defined as a measure of the average kinetic energy (or speed) of the molecules in the air.

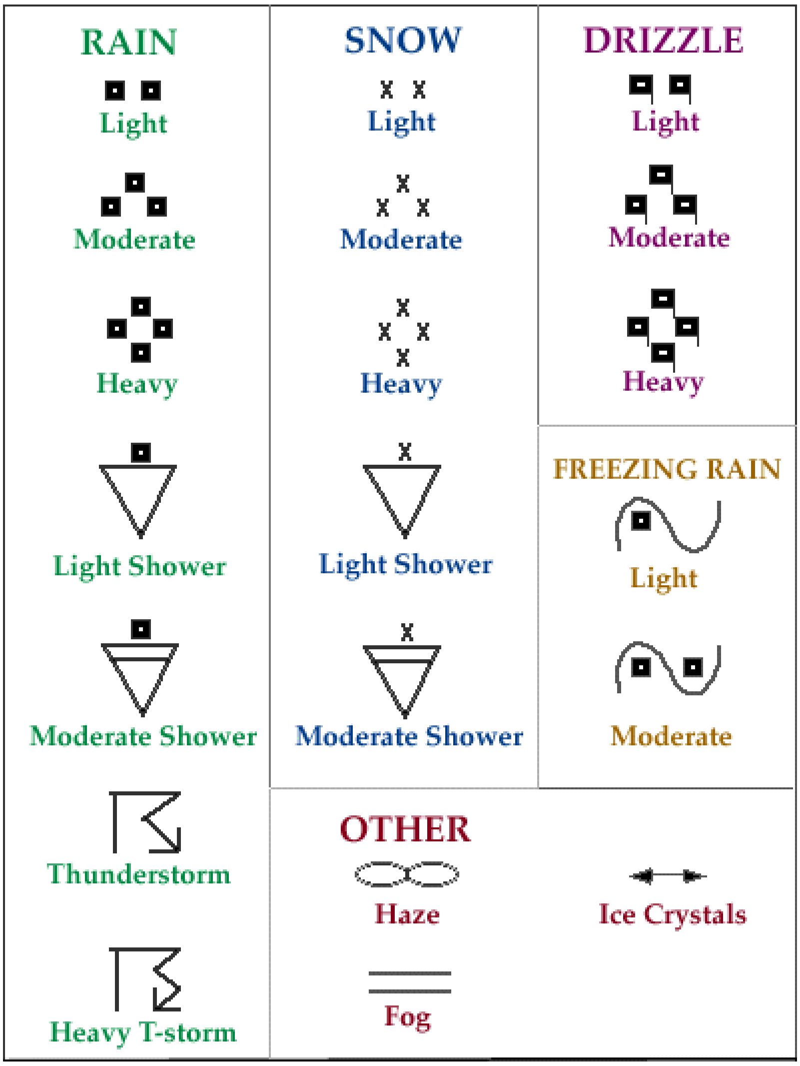
Observed Weather

station reporting symbol

The symbol highlighted in yellow indicates the type of weather occurring at the time the observation is taken. In this case, fog was reported. If there were thunderstorms occurring when the observation was taken, then the symbol for thunderstorms would have appeared instead.



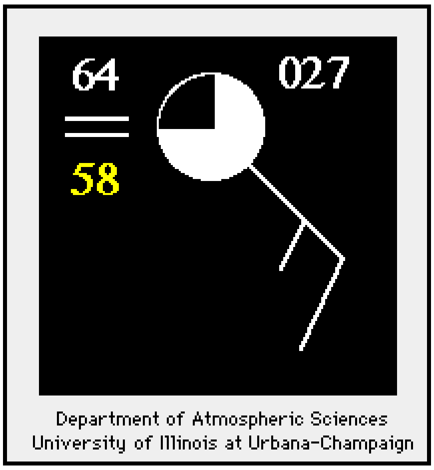
Common Weather Symbols:
The chart below identifies some the most commonly used weather symbols and the type of weather they represent. For example, the first row of weather symbols (from left to right) identify Light Rain, Light Snow and Light Drizzle.



Observed Dew Point Temperature

indicates the amount of moisture in the air

The value highlighted in yellow located in the lower left corner (in the diagram above) is the dew point temperature in degrees Fahrenheit. In this example, the reported dew point temperature is 58 degrees.



Dew points indicate the amount moisture in the air. The higher the dew points, the higher the moisture content of the air at a given temperature. Dew point temperature is defined as the temperature to which the air would have to cool (at constant pressure and constant water vapor content) in order to reach saturation. A state of saturation exists when the air is holding the maximum amount of water vapor possible at the existing temperature and pressure.

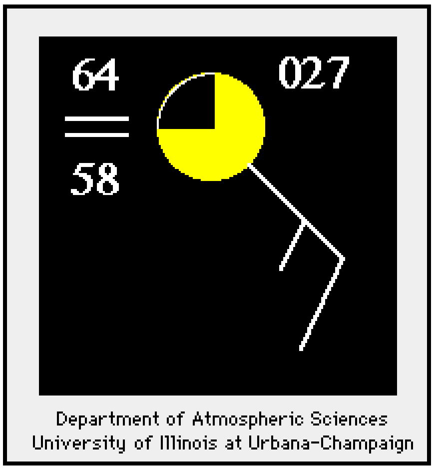
When the dew point temperature and air temperature are equal, the air is said to be saturated. Dew point temperature is NEVER GREATER than the air temperature. Therefore, if the air cools, moisture must be removed from the air and this is accomplished through **condensation**. This process results in the formation of tiny water droplets that can lead to the development of fog, frost, clouds, or even precipitation.

Relative Humidity can be inferred from dew point values. When air temperature and dew point temperatures are very close, the air has a high relative humidity. The opposite is true when there is a large difference between air and dew point temperatures, which indicates air with lower relaitve humidity. Locations with high relative humidities indicate that the air is nearly saturated with moisture; clouds and precipitation are therefore quite possible. Weather conditions at locations with high dew point temperatures (65 or greater) are likely to be uncomfortably humid.

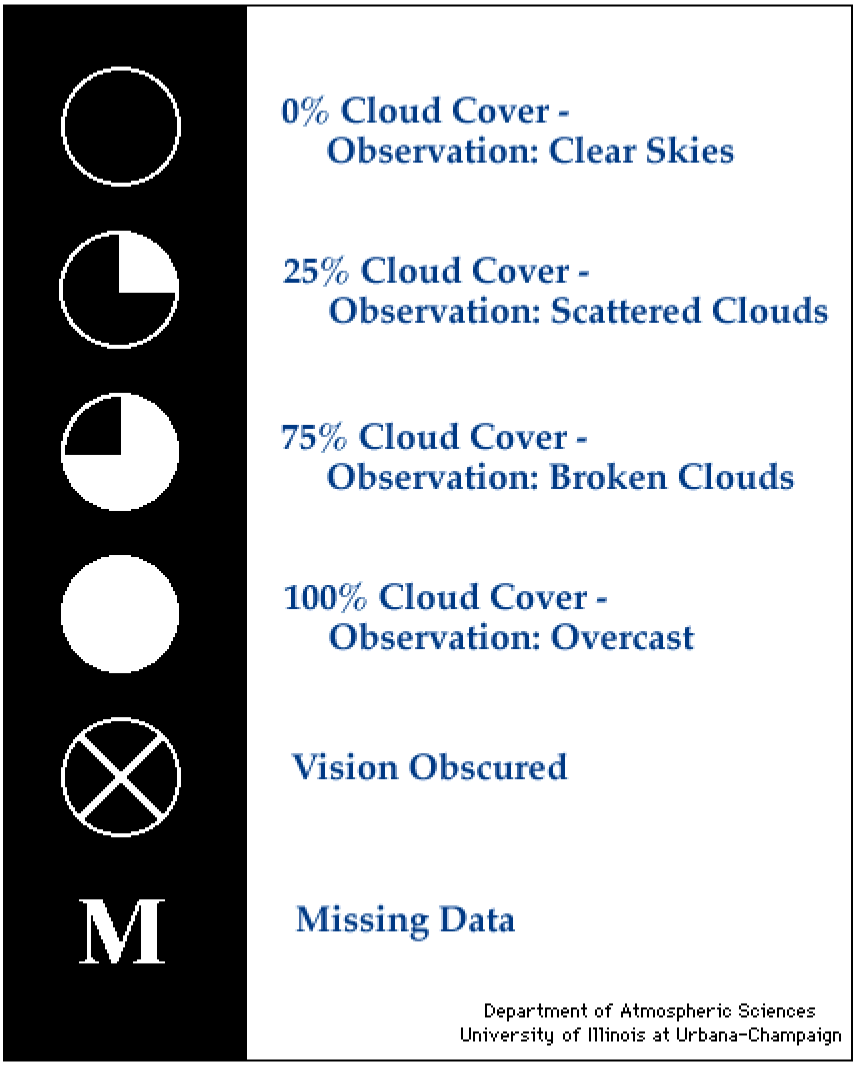
Observed Cloud Cover

station reporting symbol

The symbol highlighted in yellow indicates the amount of cloud cover observed at the time the observation is taken. In this case, broken clouds were reported.



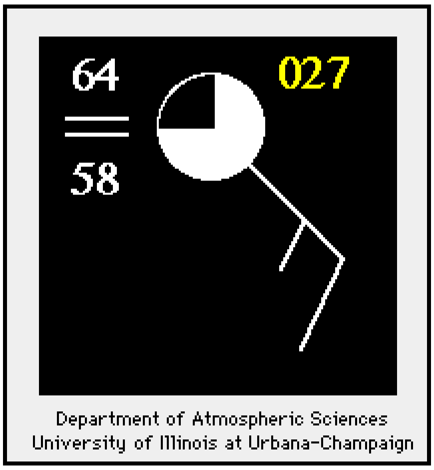
The chart below spans the entire spectrum of cloud cover reports, from clear to overcast skies.



Observed Sea Level Pressure

station reporting symbol

The value highlighted in yellow located in the upper right corner (in the diagram above) represents the last three digits of the observed pressure reading in **millibars (mb)**.



Interpreting Pressure Reports:

If reported value greater than 500:

Initial 9 is missing. Place it on left, then divide by 10.
For example: **827** becomes **982.7 mb**.

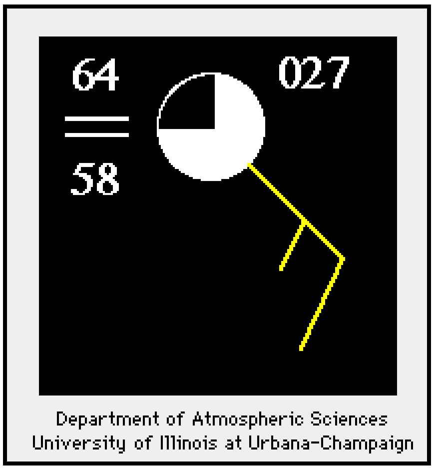
If reported value less than 500:

Initial 10 is missing. Place it on left, then divide by 10.
For example (as in above diagram): **027** becomes **1002.7 mb**.

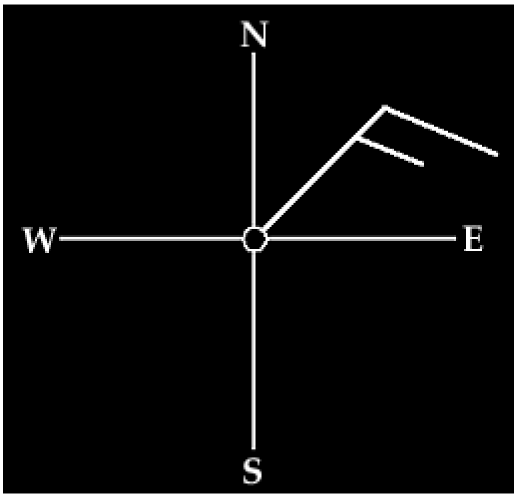
Observed Winds

represented by wind barbs

The symbol highlighted in yellow (in the diagram above) is known as a **"Wind Barb"**. The wind barb indicates the wind direction and wind speed.



Wind barbs point in the direction "from" which the wind is blowing. In the case of the diagram below, the orientation of the wind barb indicates winds from the Northeast.



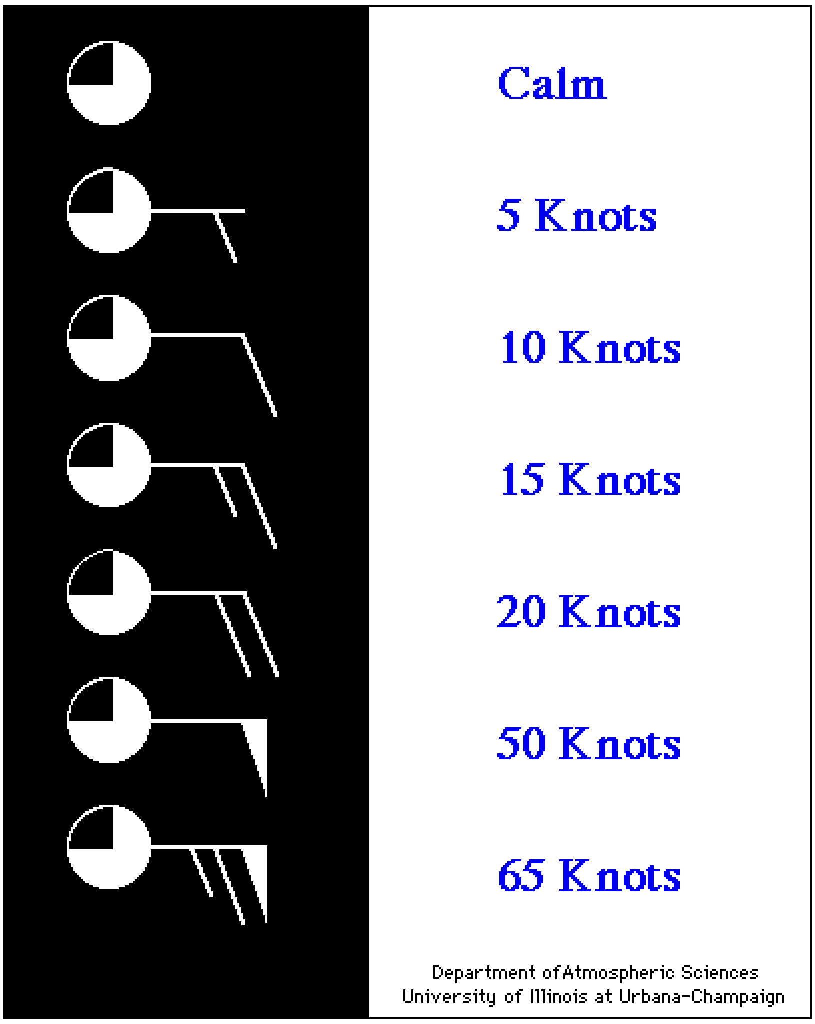
The term easterly means that the winds are from the east. In the example above, the winds are out of the northeast, or northeasterly. On the otherhand, the term "eastward" means that the winds are blowing towards the east.

Wind speed is given here in the units of "knots" (knt). A "Knot" is a nautical mile per hour.

1 Knot = 1.15 Miles Per Hour (MPH)

1 Knot = 1.9 Kilometers Per Hour (KM/HR)

Each short barb represents 5 knots, each long barb 10 knots. A long barb and a short barb is 15 knots, simply by adding the value of each barb together (10 knots + 5 knots = 15 knots). If only a station circle is plotted, the winds are calm.



Pennants are 50 knots. Therefore, the last wind example in the chart below has a wind speed of 65 knots. (50 knots + 10 knots + 5 knots).

Surface Contours
surface maps

The various contours available for surface images include:

- **isobars** (lines of constant pressure)
- **isotherms** (lines of constant temperature)
- **isodrosotherms** (lines of constant dew point temperature)

This section has been designed to explain what each feature represents and how to interpret them on weather maps.

The Following Options Are Available:

- [**What are Isobars?**]
- **Wind Direction and Isobars**
- **What are Isotherms?**
- **What are Isodrosotherms?**
- **For more on Contouring**

More Extensive Resources Include:

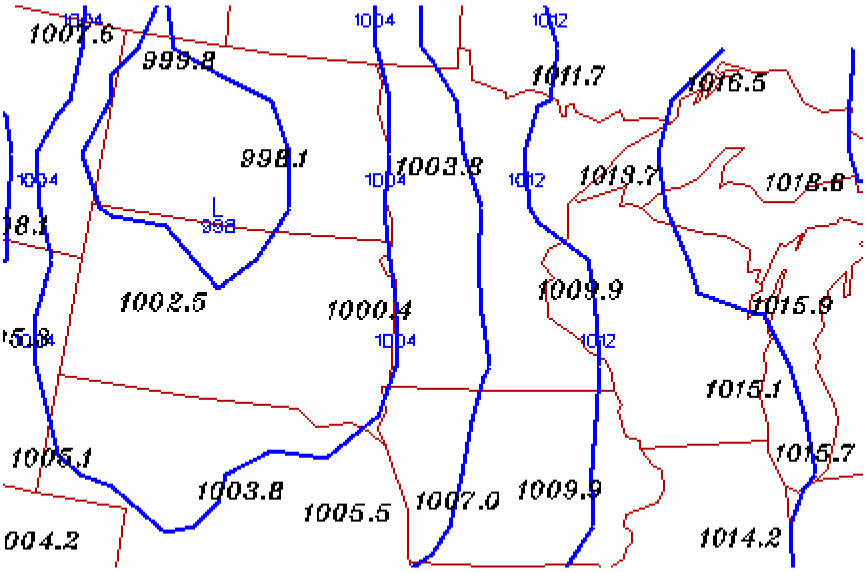
- **For much more on Isobars**

The Pressure Module - An Online Guide To Meteorology

Isobars
surface maps

A line connecting points of equal pressure is called an **isobar**. That means, that at every point along a given isobar, the values of pressure are the same.

Isobars are represented by solid blue contours. An image of sea-level pressure reports and isobars has been given below.



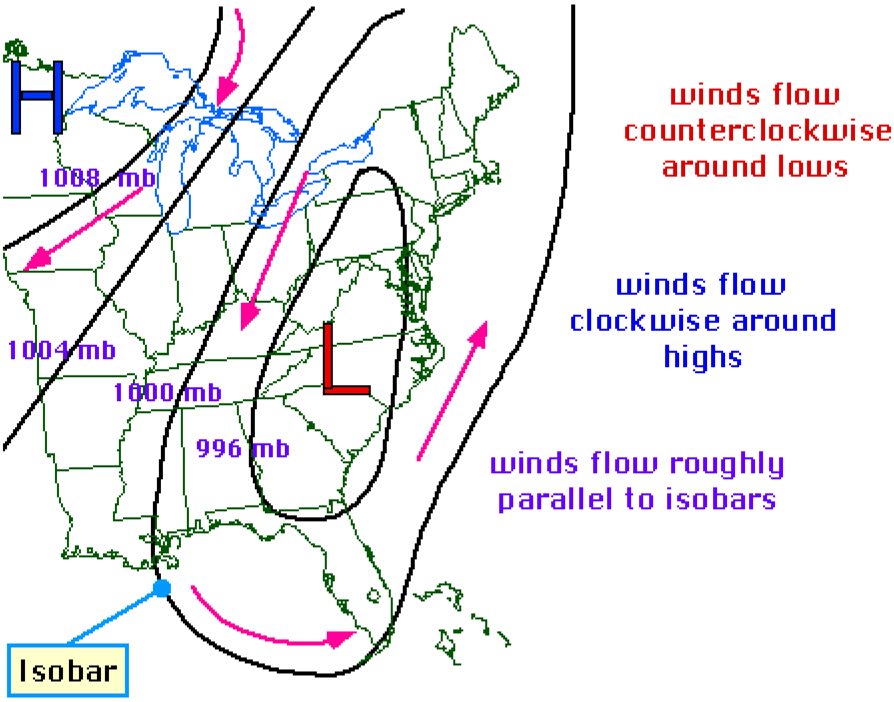
The black numbers are station reports of sea-level pressure in millibars. Isobars are normally drawn at 4 mb intervals, with 1000 mb being the base value. The small blue numbers are contour labels, which identify the value of an isobar (for example 1004 mb, 1012 mb, etc.).

The isobars displayed here have been generated from these pressure observations. For example, pressure reports in South Dakota are 1002.5 mb and 1000.4 mb respectively, and notice that they are contained within the region bound by the 1000 mb and 1004 mb contours.

An area of relatively lower pressure is centered in western North Dakota, while the pressure increases outward from this region.

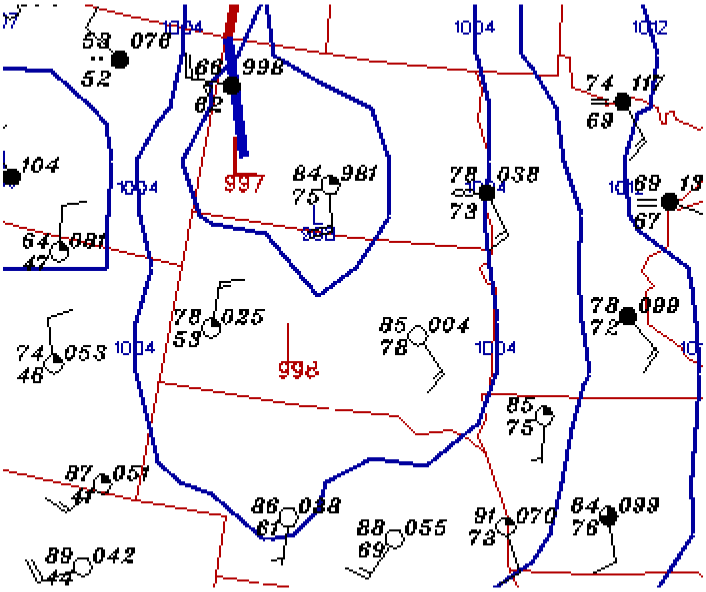
Wind Direction and Isobars
surface maps

Winds flow roughly parallel to the isobars, as depicted in the schematic below.



This relationship is observed on real surface maps.

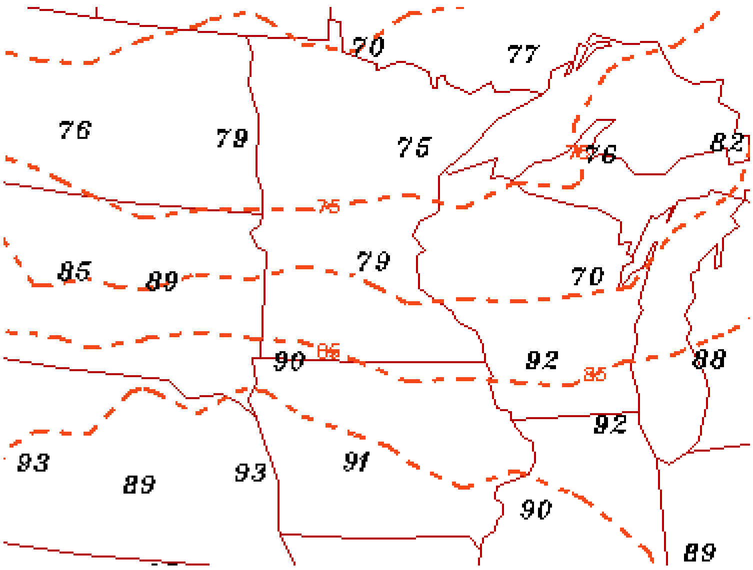
In the example below, surface observations and isobars (yellow contours) have been plotted. Reports of wind direction from Nebraska into Minnesota, show that the observed wind direction is nearly parallel to the isobars.



Isotherms
surface maps

A line connecting points of equal temperature is called an **isotherm.** That means, at every point along a given isotherm, the values of temperature are the same.

Isotherms are represented by dashed orange contours in the Weather Visualizer. An image of surface temperature reports and isotherms has been given below.

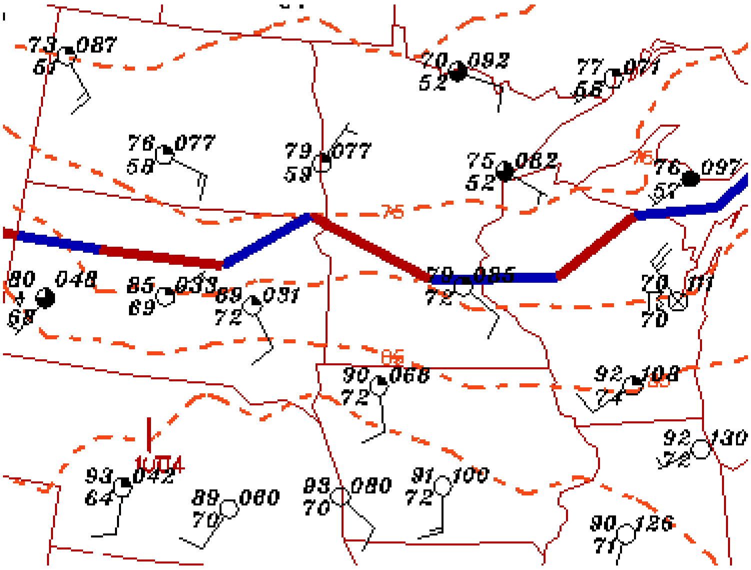


The black numbers are station reports of surface temperature in degrees [Fahrenheit](), which is the unit for temperature in the U.S.. Most other nations of the world use [Celsius]().

The isotherms displayed were generated from the observed values of temperature, and have been plotted at intervals of 5 degrees Fahrenheit. The small orange numbers are contour labels, which identify the value of an isotherm (75, 85 degrees Fahrenheit).

For example, reported temperature values in Nebraska, southern Iowa and Illinois are generally 90 or above, and are therefore located south of the 90 degree contour.

In the image below, this surface temperature information has been incorporated into a more complex surface map generated for the same time.

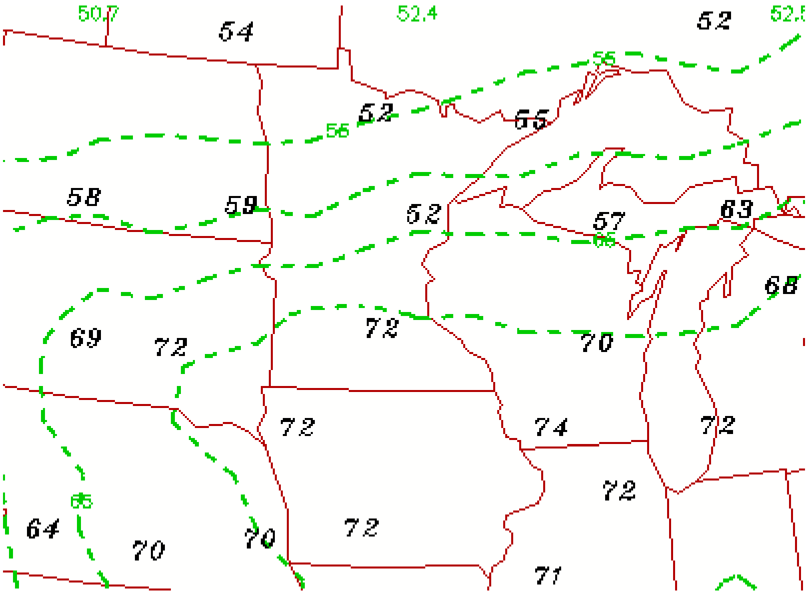


Reported temperatures show that a dome of very warm air has pushed its way into Nebraska, where temperatures are above 90. More pleasant weather is found across North Dakota and Minnesota, where temperatures are in the 70's.

Isodrosotherms
surface maps

A line connecting points of equal Dew Point Temperature is called an **isodrosotherm**. That means, at every point along a given isodrosotherm, the values of dew point temperature are the same.

Isodrosotherms are represented by dashed green contours. An image of reported dew point temperatures and isodrosotherms has been given below.

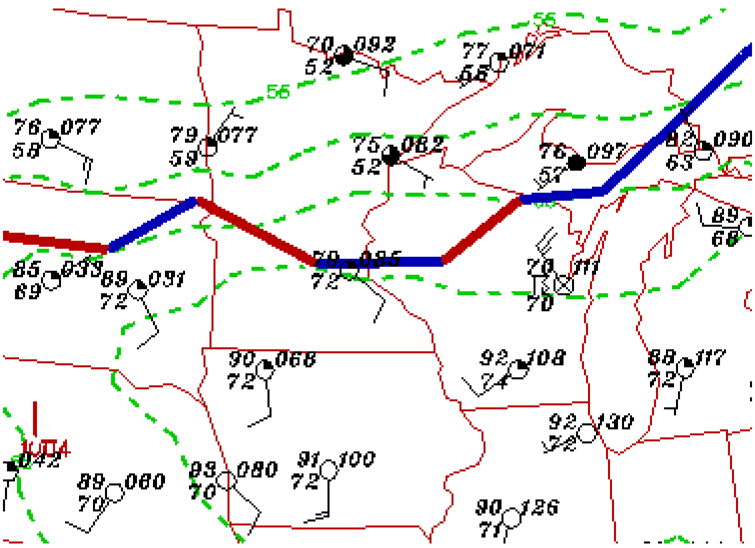


The black numbers are station reports of surface dew point temperature in degrees Fahrenheit, which is the unit for dew point temperature in the U.S.. Most other nations of the world use Celsius

The isodrosotherms were generated from the observed values of dew point temperature, and have been plotted at intervals of 5 degrees Fahrenheit. The small green numbers are contour labels, which identify the value of an isodrosotherm (55, 65 degrees Fahrenheit).

For example, high dew point values of greater than 70 have been reported in Iowa, Illinois and southern Michigan and are therefore located south of the 70 degree contour.

In the image below, this surface dew point temperature information has been incorporated into a more complex surface map generated for the same time.



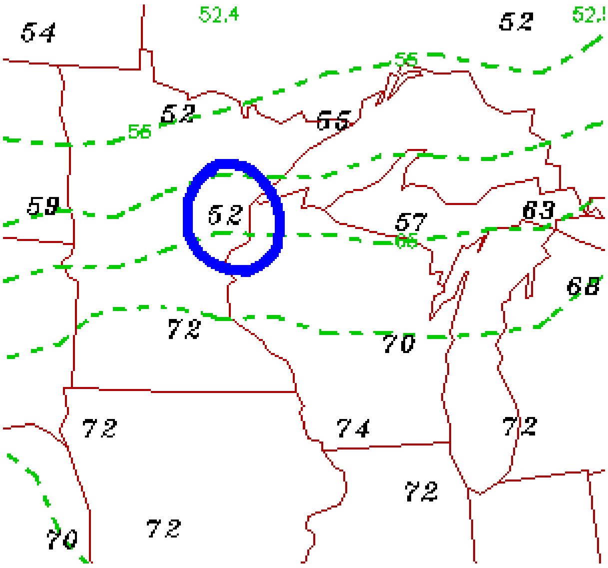
Reported dew points show that a dome of very moist air has pushed its way into Iowa, Illinois, and southern Michigan where dew point temperatures are above 70. Such high dew points usually mean humid and sticky weather conditions.

On the other hand, pleasant weather is found across North Dakota and Minnesota, where dew points are in the 50's and the air is much drier.

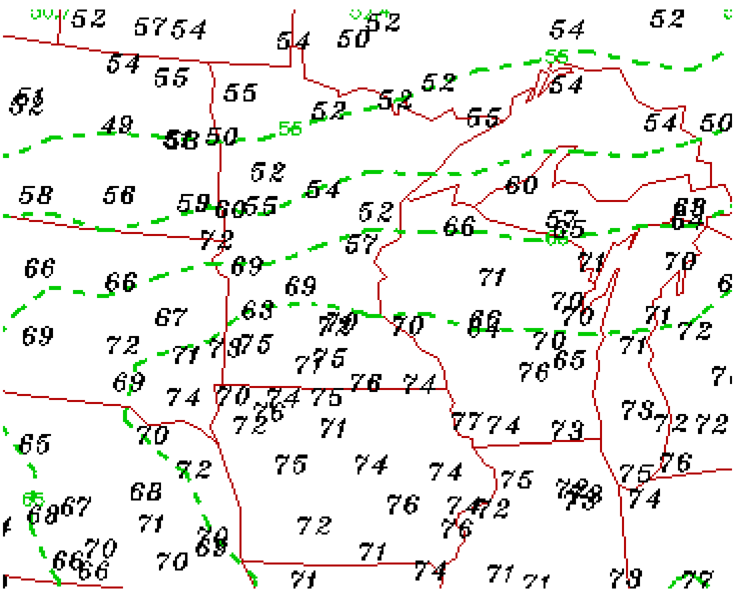
Contouring

surface maps

Sometimes the reported values (black numbers) are not always located between the correct contours. For example, in the dew point temperature map below, a station in Minnesota (circled in blue) reported a dew point temperature of 52 degrees, but it is located between the 60 and 65 degree contours.



Why is this so? Because contours are plotted to provide a "best-fit" for all reports, which include a very large number of stations. To give you an idea, I've increased the number of reporting stations in the image below.

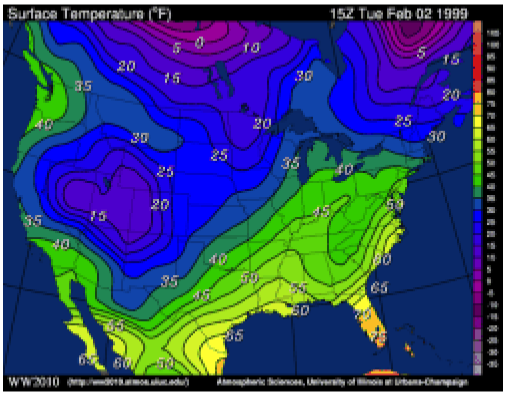


This is the exact same dew point map, but with many more station reports (black numbers). And this still doesn't include all of them!

In order for every station to be within the correct contours, lines would be zigging and zagging everywhere, making the map unreadable. Fortunately, contour lines are smoothed to make the map readable.

Therefore, it is important to remember that although the contours may not be 100% accurate for every single reporting station, contouring provides READABLE information, as accurately as possible, for a HUGE number of reporting stations.

Temperature Contours



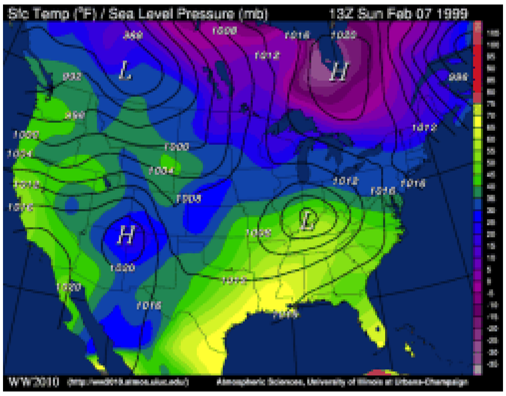
Reference Weather Map *Current Weather Map*

This surface meteorological chart shows the temperature pattern (in degrees Fahrenheit) over the continental United Sates and is updated every hour.

Surface temperature reported at each station are contoured every five degrees Fahrenheit. Areas of warm and hot temperatures are depicted by orange and red colors and cold temperatures (below freezing) are shaded blue and purple. Areas of sharp temperature gradients (several contours close to each other) tend to be associated with the position of surface fronts. Fronts separate airmasses of different temperature and moisture (and therefore density) characteristics.

In the example above on the left, there is a large change in temperature from western Oklahoma to central Texas. This suggests that a front is somewhere in the area. You can check the current map (above right) to see is there are areas that also appear to be affected by fronts.

Pressure and Temperature



Reference Weather Map *Current Weather Map*

This panel depicts temperature and sea-level pressure contours. This chart is useful for finding fronts and high and low pressure systems.

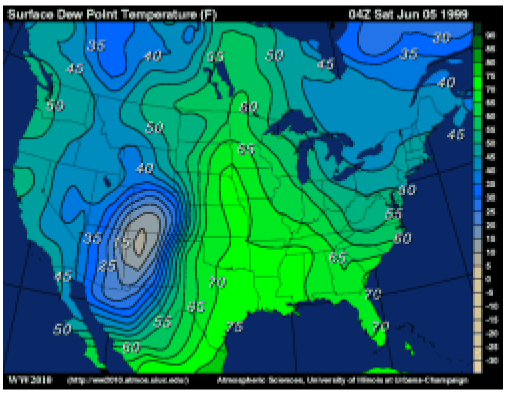
The solid black contours represent pressure contours (isobars) in millibars. The isobars have a contour interval of four millibars. The wind speed is directly related to the distance between the isobars. The closer the isobars are together, the stronger the pressure gradient, and the stronger the wind.

The colored regions represent the surface temparature. The contour interval of the isotherms is 5 degrees Fahrenheit. From the chart above you can sometimes find warm and cold fronts. Fronts are usually located where temperature changes drastically over a short distance.

When pressure contours are perpendicular to isotherms it means it is either getting warmer or colder. By knowing that winds flow counter-clockwise around a low and clockwise around a high, one can usually see whether there is warming or cooling going on. Usually when the winds are from the south, and you have isotherms (temperature lines) perpendicular to the isobars (pressure lines) you have warm air advection (warm air moving up from the south). The opposite is true if you have winds from the north and isotherms perpendicular to isobars. In that case you have cold air advection (cold air coming in from the north) going on.

For more information on how pressure affects the weather go to our pressure module

Dew Point Reports and Contours



Reference Weather Map *Current Weather Map*

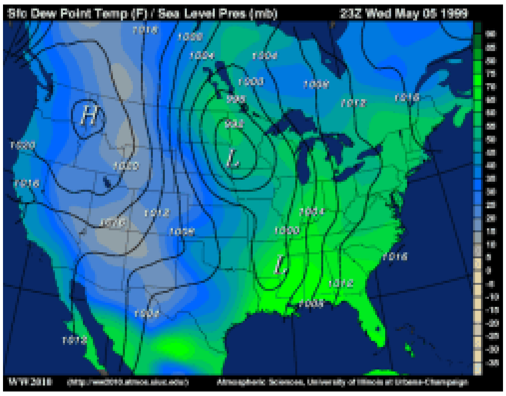
This surface meteorological chart shows the dew point temerature pattern (in degrees Fahrenheit) over the continental United States and is updated every hour. Dew point temperature is a measure of moisture in the air and is contoured here every 5 degrees.

When the dew point temperature is close to the temperature of the air, the air is nearly saturated. However, nearly saturated air is not always humid. Only when the temperatures reach above 70 degrees Fahrenheit and dew points rise nearly as high does the air feel "muggy" and uncomfortable. Humidity of the air generally increases southward, similarly to the temperatures. During the summer dark green shading (dew points in the 60s or higher) indicate humid air. Dew points in the 40s or lower (light green, yellow or white) are considered dry. In the winter the dew points are on average 30-40 degrees lower, similarly to the temperatures (except the southern coastal regions where the fluctuations are a little smaller).

In the example above on the left, there is a large change in dew point temperature from New Mexico to central Texas. This suggests that a dry line is somewhere in the area. You can check the current map (above right) to see is there are areas that also appear to be affected by dry lines.

Humidity decreases the **convective stability** of the air. Since the density of moist air is lower it tends to rise over colder, denser air. This can happen along a frontal boundary or if air becomes **convectively unstable** and rises to form clouds and precipitation. This is why thunderstorms and convective showers often form in a warm, moist airmass. Sharp gradients (closely packed dew point contours) are often indicative of frontal boundaries or dry lines. During the warm season intense precipitation often occurs along those boundaries.

Pressure and Dew point



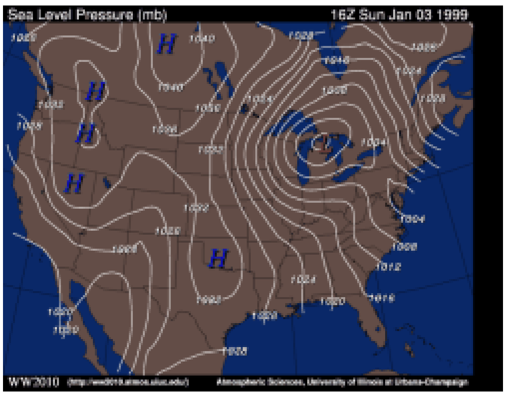
Reference Weather Map *Current Weather Map*

This panel depicts sea-level pressure and dew point temperature. This chart is useful for finding fronts and high and low pressure systems.

The solid black contours represent pressure contours (isobars) in millibars. The isobars have a contour interval of four millibars. The wind speed is directly related to the distance between the isobars. The closer the isobars are together, the stronger the pressure gradient, and the stronger the wind.

The dashed color filled regions represent areas of equal dew point (isodrosotherms). The contour interval of the dew point contours is five degrees Fahrenheit. From the map above you can sometimes find warm fronts, cold fronts, and drylines. Fronts are usually located where the dew point changes drastically over a short distance.

Sea Level Pressure



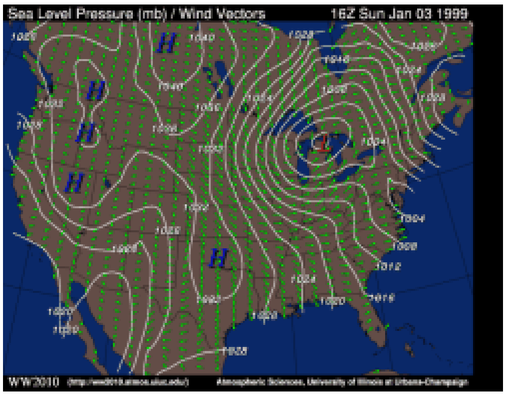
Reference Weather Map *Current Weather Map*

This panel depicts sea-level pressure across the United States. This chart is useful for finding regions of high and low pressure systems.

The solid white contours represent pressure contours (isobars) in millibars. The isobars have an interval of 4 millibars. The wind speed is directly related to the distance between the isobars. The closer they are together, the stronger the pressure gradient, and the stronger the wind. Low and high pressure systems can also be located from the map above. Low pressure systems are located in the regions of the lowest pressure, while high pressure systems are located in the regions of highest pressure.

For more information on how pressure affects the weather go to our forces and winds module.

Pressure and Wind Vectors



Reference Weather Map *Current Weather Map*

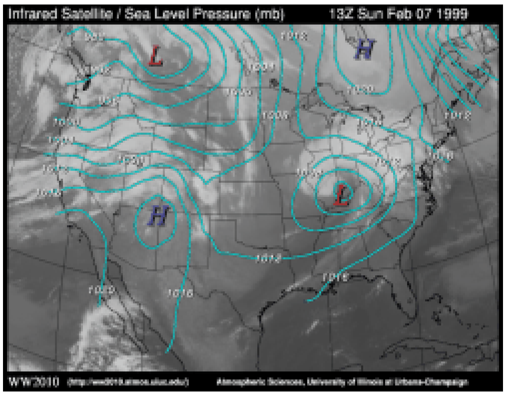
This panel depicts sea-level pressure and surface wind vectors. This chart is useful for finding fronts and high and low pressure systems.

The green arrows represent wind vectors. Wind vectors show wind direction and wind speed. The arrows point in the direction the wind is blowing and the longer the wind vector the stronger the wind. From the map above you can easily find warm, cold, occluded, and stationary fronts. Fronts are usually located in areas where winds come together and change direction. Low and high pressure systems can also be located from the map above. Winds around a low pressure system move counter-clockwise (cyclonic) and in towards the center. While winds in high pressure move clockwise (anticylonic) and out away from the center.

The solid white contours represent pressure contours (isobars) in millibars. The isobars have an interval of 4 millibars. The wind speed is directly related to the distance between the isobars, The closer they are together, the stronger the pressure gradient, and the stronger the wind.

For more information on how pressure affects the weather go to our forces and winds.

Pressure and Infrared Satellite



Reference Weather Map *Current Weather Map*

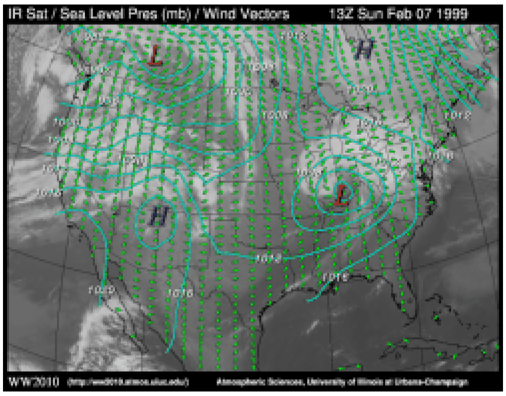
This panel depicts sea-level pressure across the United States. This chart is useful for finding regions of high and low pressure systems.

The solid white contours represent pressure contours (isobars) in millibars. The isobars have an interval of 4 millibars. The wind speed is directly related to the distance between the isobars. The closer they are together, the stronger the pressure gradient, and the stronger the wind.

In the background, infrared satellite data shows the cloud patterns over North America. The brightness of the cloud images is inversely proportional to the temperature of cloud tops, therefore the deep clouds with high (and thus cold) cloud tops typically indicating areas of intense rain and/or hail associated with deep convection appear brightest on this image. However high cirrus clouds will often also appear very bright, but these clouds do not produce precipitation. Low and high pressure systems can also be located from the map above. Low pressure systems are located in the regions of the lowest pressure, while high pressure systems are located in the regions of highest pressure.

For more information on how pressure affects the weather go to our forces and winds module.

Pressure, Infrared Satellite, and Wind



Reference Weather Map *Current Weather Map*

This panel depicts sea-level pressure and surface wind vectors. This chart is useful for finding fronts and high and low pressure systems.

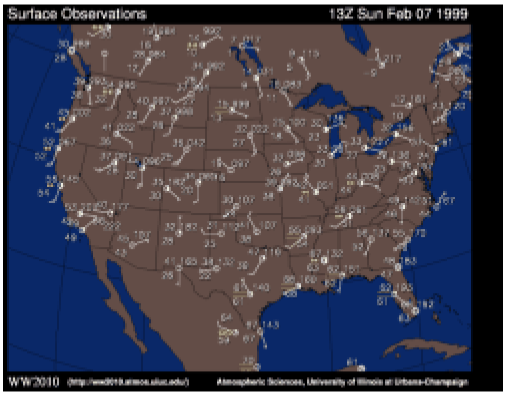
The green arrows represent wind vectors. Wind vectors show wind direction and wind speed. The arrows point in the direction the wind is blowing and the longer the wind vector the stronger the wind. From the map above you can easily find warm, cold, occluded, and stationary fronts. Fronts are usually located in areas where winds come together and change direction. Low and high pressure systems can also be located from the map above. Winds around a low pressure system move counter-clockwise (cyclonic) and in towards the center. While winds in high pressure move clockwise (anticylonic) and out away from the center.

The solid cyan contours represent pressure contours (isobars) in millibars. The isobars have an interval of 4 millibars. The wind speed is directly related to the distance between the isobars, The closer they are together, the stronger the pressure gradient, and the stronger the wind.

In the background, infrared satellite data shows the cloud patterns over North America. The brightness of the cloud images is inversely proportional to the temperature of cloud tops, therefore the deep clouds with high (and thus cold) cloud tops typically indicating areas of intense rain and/or hail associated with deep convection appear brightest on this image. However high cirrus clouds will often also appear very bright, but these clouds do not produce precipitation.

For more information on how pressure affects the weather go to our forces and winds module.

Surface Observations

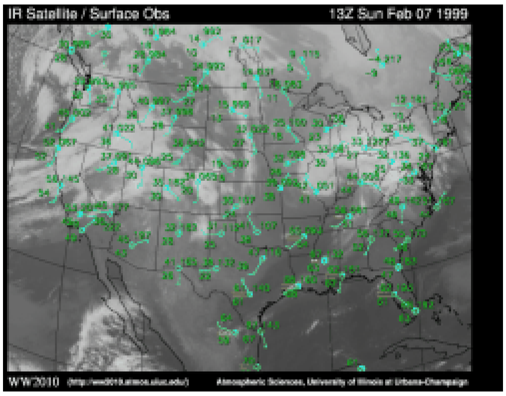


Reference Weather Map *Current Weather Map*

The surface meteorological charts above depict the current surface conditions at chosen sites across North America.

The hourly observations (updated every hour) contain information about surface temperature and dew point temperature in degrees Fahrenheit, sea level pressure, wind speed and direction, cloud cover and type of weather conditions occurring at each surface station during the last hour. The hourly observations link provides detailed information on how to decode and interpret the numbers and symbols at each station.

Surface Obs with Infrared Satellite



Reference Weather Map *Current Weather Map*

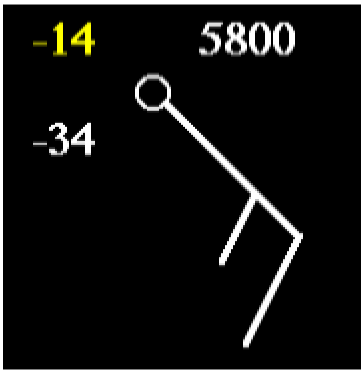
The surface meteorological chart above depicts the current surface conditions at chosen sights across North America. This map, updated shortly after each hour, illustrates the present weather patterns and the location of storm systems over the continental United States.

The hourly observations (updated every hour) contain information about surface temperature and dew point temperature in degrees Fahrenheit, sea level pressure, wind speed and direction, cloud cover and type of weather conditions occurring at each surface station during the last hour. The hourly observations link provides detailed information on how to decode and interpret the numbers and symbols at each station.

In the background, infrared satellite data shows the cloud patterns over North America. The brightness of the cloud images is inversely proportional to the temperature of cloud tops, therefore the deep clouds with high (and thus cold) cloud tops typically indicating areas of intense rain and/or hail associated with deep convection appear brightest on this image. However high cirrus clouds will often also appear very bright, but these clouds do not produce precipitation.

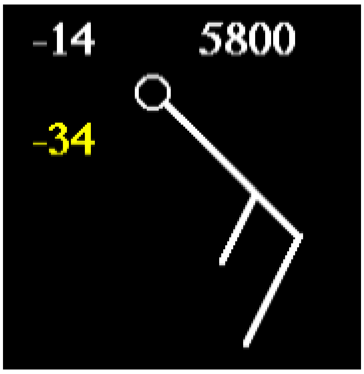
Interpreting Upper Level Observation Symbols

a quick overview



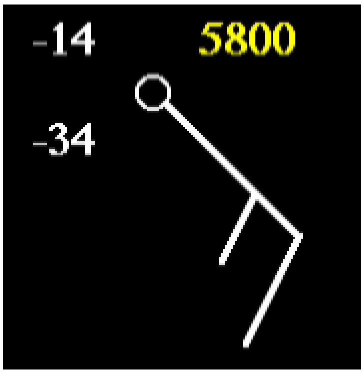
Temperature:

The value highlighted in yellow located in the upper left corner is the temperature in degrees Celsius. In this example, the reported temperature is -14 degrees.



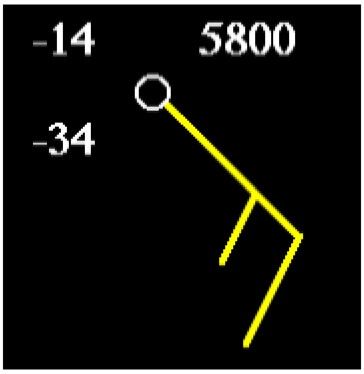
Dew Point Temperature:

The value highlighted in yellow located in the lower left corner is the dew point temperature in degrees Celsius. In this example, the reported dew point temperature is -34 degrees.



Geopotential Height:

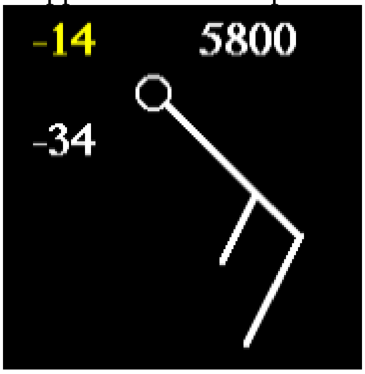
The value highlighted in yellow located in the upper right corner represents the geopotential height in meters (m).



Wind Barb:

The symbol highlighted in yellow is known as a wind barb. The wind barb indicates wind direction and wind speed.

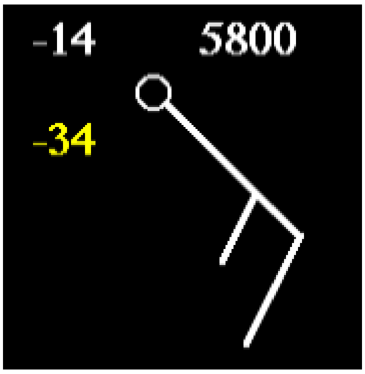
Temperature
upper air station reports



The value highlighted in yellow located in the upper left corner (in the diagram above) is the temperature in degrees Celsius. In this example, the reported temperature is -14 degrees.

Temperature is defined as a measure of the average kinetic energy (or speed) of the molecules in the air.

Dew Point Temperature
upper air station reports



The value highlighted in yellow located in the lower left corner (in the diagram above) is the dew point temperature in degrees Celsius. In this example, the reported dew point temperature is 58 degrees.

Dew Point Temperature is defined as the temperature at which air would have to cool (at constant pressure and constant water vapor content) in order to reach **saturation.** Dew points provide insight into the amount of moisture in the air. The higher the dew point temperature, the higher the moisture content for air at a given temperature.

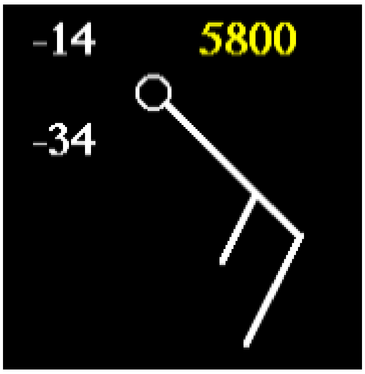
When the dew point temperature and air temperature are equal, the air is said to be saturated. Dew point temperature is NEVER GREATER than the air temperature. Therefore, if the air cools, moisture must be removed from the air and this is accomplished through condensation. This process results in the formation of tiny water droplets that can lead to the development of fog, frost, clouds, or even precipitation.

Other upper air observation maps may actually report **dew point depression** instead of dew point temperature. Dew point depression is the difference in degrees Celsius between the temperature and the dew point. In the example above the dew point depression would be 20 degrees.

What to Look For in Dew Point Observations:

- Relative Humidity can be inferred from dew point values. When the air and dew point temperatures are very close, this indicates that the air has a **high relative humidity**. The opposite is true when there is a large difference between air and dew point temperatures, which points to air with a **low relaitve humidity**.

Geopotential Height
upper air station reports

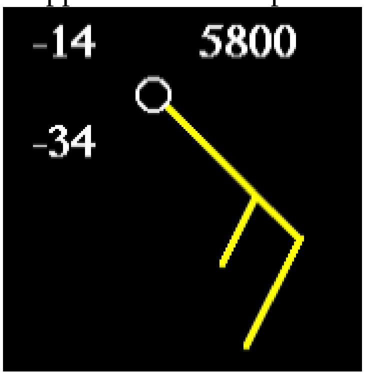


The value highlighted in yellow located in the upper right corner (in the diagram above) represents the geopotential height of a given pressure surface in meters (as reported by weather balloons).

Geopotential Height approximates the actual height of a pressure surface above mean sea-level. Therefore, for the example given above, the height of the pressure surface on which the observation was taken is 5800 meters.

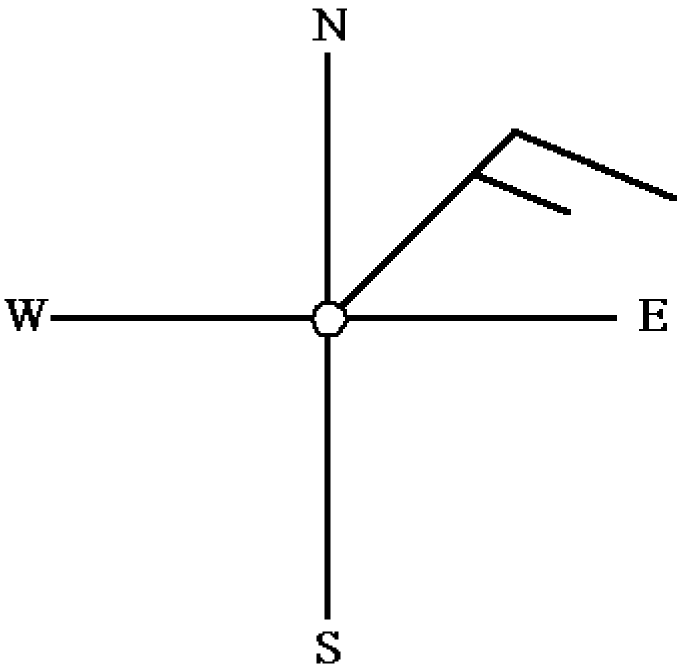
When a collection of geopotential height reports are contoured on a given pressure surface, we are able to identify upper air troughs and ridges, which are very important influences on surface weather conditions.

Wind Barbs
upper air station reports



The symbol highlighted in yellow (in the diagram above) is known as a **"Wind Barb"**. The wind barb indicates the wind direction and wind speed.

Wind barbs always point in the direction the wind is blowing **"from"**. As is the case of the diagram below, the orientation of the wind barb indicates winds from the Northeast.



Terminology:

The term **"easterly"** means that the winds are **from** the east, as in the example above. So if you hear someone say, "Generally easterly winds are found across much of the state of... ", they are describing winds from the east.

On the otherward, winds blowing in an **"eastward"** direction are winds that are blowing **towards** the east (from the west).

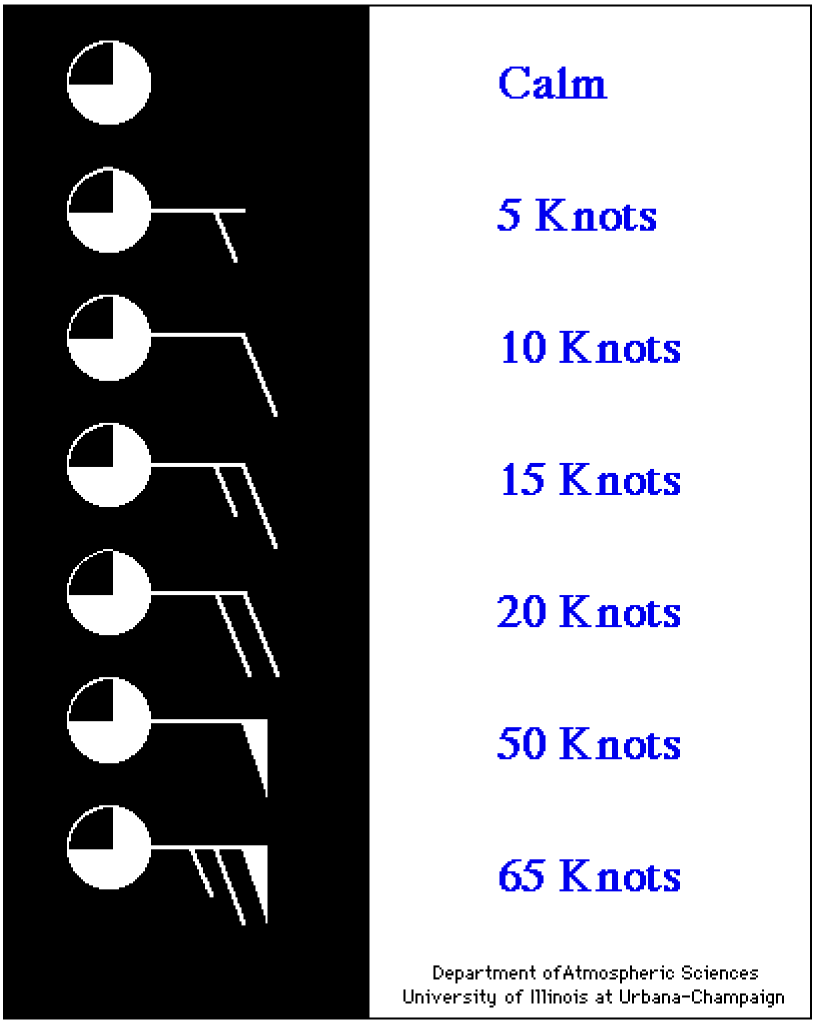
Wind speed is given here in the units of "knots" (knt). A **Knot** is a nautical mile per hour.

1 Knot = 1.15 Miles per Hour (mi/hr)

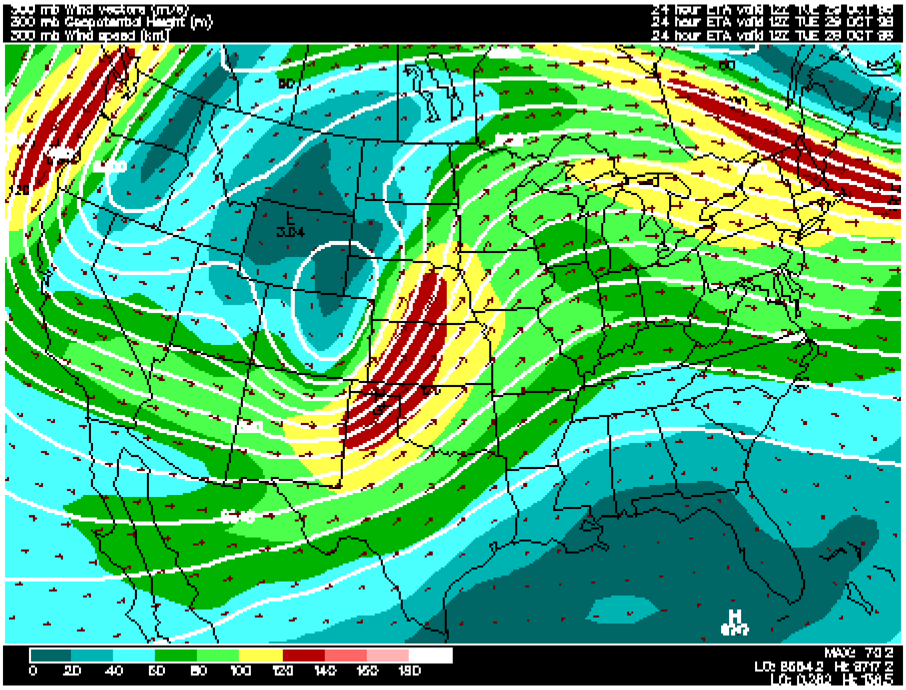
1 Knot = 1.9 Kilometers per Hour (km/hr)

Using the table below, each short barb represents 5 knots, while each long barb represents 10 knots. A single long barb and a short barb is 15 knots, simply by adding the value of each barb together (10 knots + 5 knots = 15 knots).

Pennants are 50 knots. Therefore, the last wind barb in the chart below has a wind speed of 65 knots. (50 knots + 10 knots + 5 knots). If only a station circle is plotted, the winds are calm.



300 mb Winds and Heights
eta model forecast



Latest ETA Model 12 HR Forecast Panel

300 mb forecasted fields for geopotential height, wind speed and wind vectors. 300 mb charts depict conditions in the upper troposphere (roughly 9000 meters) where most of the weather producing phenomena occur, otherwise known as the jet stream level.

Geopotential height approximates the actual height of a pressure surface above mean sea-level and is represented by the solid white contours. The geopotential height field is given in meters with an interval of 120 meters between height lines. The 300 mb height field encircling the globe consists of a series of troughs and ridges, which are the upper air counterparts of surface cyclones and anticyclones. The distance from trough to trough (or ridge to ridge) is known as a longwave. Embedded within the longwaves are shortwaves, which are smaller disturbances often responsible for triggering surface cyclone development.

Wind vectors provide information about wind direction and wind speed and are drawn here as tiny red arrows. Wind vectors point towards the direction in which the wind is blowing and the longer the wind vector, the stronger the wind. The unit of magnitude for wind speed as depicted by the wind vectors is meters per second.

Wind speed is represented by the color filled regions and the intensity is indicated by the color code located in the lower left corner of the forecast panel. Wind speeds are given in knots with an interval of 20 knots between wind speed contours, also called isotachs. Wind speeds of less than 60 knots are represented by shades of blue while winds exceeding 120 knots are depicted in shades of red.

This information is useful in locating the jet stream, a narrow band of relatively strong winds encircling the earth in the upper troposphere. Wind speed maxima embedded within the jet stream, called jet streaks, are localized regions of high atmospheric energy that play a vital role in the development of surface low pressure centers. The closer together the height contours, the stronger the wind speed, which is why jet streaks are found where height contours are packed closely together.