Thunderstorms
Teachers Guide

Slide 1: Introduction

Slide 2: Course outline

Slide 3: The sun heats the entire Earth, but where the sun is more directly overhead it heats the Earth and atmosphere more. The result would be the equator becomes very hot with the hot air rising into the upper atmosphere. That air would then move toward the poles where it would become very cold and sink, then return to the equator (right). One large area of high pressure would be at each of the poles with a large belt of low pressure around the equator.

Slide 4: Jet streams are relatively narrow bands of strong wind in the upper levels of the atmosphere. The winds blows from west to east in jet streams but the flow often shifts to the north and south. Jet streams follow the boundaries between hot and cold air. Since these hot and cold air boundaries are most pronounced in winter, jet streams are the strongest for both the northern and southern hemisphere winters.

Why does the jet stream winds blow from west to east? Recall what the global wind patterns would be like if the earth was not rotating. (The warm air rising at the equator will move toward both poles.) We saw that the earth's rotation divided this circulation into three cells. The earth's rotation is responsible for the jet stream as well.

The motion of the air is not directly north and south but is affected by the momentum the air has as it moves away from the equator. The reason has to do with momentum and how fast a location on or above the Earth moves relative to the Earth's axis.

Your speed relative to the Earth's axis depends on your location. Someone standing on the equator is moving much faster than someone standing on a 45° latitude line. In the graphic (left) the person at the position on the equator arrives at the yellow line sooner than the other two. Someone standing on a pole is not moving at all (except that he or she would be slowly spinning). The speed of the rotation is great enough to cause you to weigh one pound less at the equator than you would at the north or south pole.

The momentum the air has as it travels around the earth is conserved, which means as the air that's over the equator starts moving toward one of the poles, it keeps its eastward motion constant. The Earth below the air, however, moves slower as that air travels toward the poles. The result is that the air moves faster and faster in an easterly direction (relative to the Earth's surface below) the farther it moves from the equator.

In addition, with the three-cell circulations mentioned previously, the regions around 30°

N/S and 50°-60° N/S are areas where temperature changes are the greatest. As the difference in temperature between the two locations increase, the strength of the wind increases. Therefore, the regions around 30° N/S and 50°-60° N/S are also regions where the wind, in the upper atmosphere, is the strongest.

The 50°-60° N/S region is where the polar jet located with the subtropical jet located around 30°N. Jet streams vary in height of four to eight miles and can reach speeds of more than 275 mph. The actual appearance of jet streams result from the complex interaction between many variables - such as the location of high and low pressure systems, warm and cold air, and seasonal changes. They meander around the globe, dipping and rising in altitude/latitude, splitting at times and forming eddies, and even disappearing altogether to appear somewhere else.

Jet streams also "follow the sun" in that as the sun's elevation increases each day in the spring, the jet streams shifts north moving into Canada by Summer. As Autumn approaches and the sun's elevation decreases, the jet stream moves south into the United States helping to bring cooler air to the country.

Slide 5: All thunderstorms require three ingredients for their formation: Moisture, Instability, and a lifting mechanism.

Slide 6: One of the ingredients needed for thunderstorm development is moisture, preferably in the lower and mid levels. The main source of moisture for the Four State area is the Gulf of Mexico. (There is a reason we experience more thunderstorms than does Arizona, moisture is plentiful here.)

Slide 7: When two air masses collide such as a warm or cold front, there is vertical transport of moisture which can result in thunderstorm development assuming other factors are met. Other examples of lifting mechanisms include a sea breeze.

Differential Heating

This heating of the ground and lower atmosphere is not uniform. For example, a grassy field will heat at a slower rate than a paved street. The warmest air, called thermals, tends to rise. In the image (right) a wildfire provided the differential heating for a cumulus cloud to form over the smoke plum.

Fronts, Drylines and Outflow Boundaries

Fronts are the boundary between two air masses of different temperatures. Fronts lift warm moist air. Cold fronts lift air the most abruptly. If the air is moist and unstable thunderstorms will form along the cold front.

Drylines are the boundary between two air masses of different moisture content and separate warm moist air from hot dry air. While the temperature may be different across the dryline, the main difference is the rapid decrease in moisture behind the dryline. It is the lack of moisture which allows the temperatures to occasionally be higher than ahead of the dryline. However, the result is the same as the warm moist air is lifted along the dryline forming thunderstorms. This is common over the plains in the spring and early summer.

Outflow boundaries are a result of the rush of cold air as a thunderstorm moves overhead. The rain-cooled air acts as a "mini cold front", called an outflow boundary. Like fronts, this boundary lifts warm moist air and can cause new thunderstorms to form.

Slide 8: Terrain
As air encounters a mountain it is forced up the slope of the terrain. Upslope thunderstorms are common in the Rocky Mountain west during the summer.

Slide 9: Instability
We generally think of west to east or north to south movement of air masses, that is fronts. We need to think in the vertical as well. Think of the atmosphere heating up during a summer day. Air parcels in the boundary layer will begin to rise into the atmosphere as heating takes place. **The greater the contrast in temperature between two air masses the greater the instability.** As you look at the lava lamp, imagine the colored parcels that are rising and sinking as air parcels in the atmosphere. The greater the instability, the faster these parcels will move.

Slide 10: A thunderstorm is simply a rain shower with lightning. Sounds simple, but it really isn't. Thunderstorms are a fairly complex entity. In order to develop, a thunderstorm needs moisture, instability, and a lifting or trigger mechanism.

During the **initial stage**, a developing thunderstorm begins as a cumulus cloud with upward air motion (the **updraft**) throughout most of the cloud. This is called the cumulus or towering cumulus stage. If the air temperature in this cloud is warmer or more buoyant than the surrounding atmosphere, it can continue to rise, produce precipitation, and grow into a thunderstorm. The cumulus or towering cumulus cloud can grow vertically, perhaps to a height of 20,000 feet. Air within the cloud is dominated by updraft with some turbulent eddies around the edges.
A thunderstorm reaches its **mature stage** when the updraft develops a counterpart; sinking rain-cooled air. This is known as the **downdraft**. The storm has considerable depth, often reaching 40,000 to 60,000 feet This is usually when the thunderstorm is strongest and has the highest potential to produce severe weather.

When the downdraft begins to dominate the thunderstorm, it has reached its **dissipating stage**. A thunderstorm needs a supply of fuel (relatively warm and moist air) to survive. When the cool downdraft begins to spread out and cut off this fuel supply, the thunderstorm will dissipate. It should be noted that severe weather can still occur in the dissipating stage. The life cycle for an individual thunderstorm cell is about 30 minutes. During its life cycle, the two main components of a thunderstorm are the updraft and downdraft.

Slide 11: Multi-cell
Although there are times when a thunderstorm consists of just one ordinary cell that

transitions through its life cycle and dissipates without additional new cell formation, thunderstorms often form in clusters with numerous cells in various stages of development merging together. Unlike ordinary single cells, cluster storms can last for several hours producing large hail, damaging winds, flash flooding, and isolated tornadoes.

Slide 12: Squall Lines
Squall lines are simply a continuous or nearly continuous line of thunderstorms. The are common along, or in advance, of cold fronts. All types of severe weather can occur with squall lines. However, they are particularly known for producing strong straight-line winds. In the above illustration, storm motion is from left to right. Warm moist air flows up into the updraft (as represented by the red arrows) while rain-cooled air (blue arrows) descends through the downdraft. The leading edge of this rain cooled air is called the **gust front** and is often times accompanied by an abrupt wind change and sharp temperature drop. Along the gust front a distinct cloud formation often times occurs. This is called a **shelf cloud**. It demarks that area where the warm moist air meets and is lifted over the rain cooled gust front air.

These "squall lines" can persist for many hours and produce damaging winds and hail.

Slide 13: **Supercell Thunderstorms**
Supercell thunderstorms are a special kind of single cell thunderstorm that can persist for many hours. They are responsible for nearly all of the significant tornadoes produced in the U.S. and for most of the hailstones larger than golf ball size. Supercells are also known to produce extreme winds and flash flooding.

They are characterized by a rotating updraft (usually cyclonic - above left) which results from a storm growing in an environment of significant vertical wind shear. Wind shear occurs when the winds are changing direction and increasing with height. The most ideal conditions for supercells occurs when the winds are veering or turning clockwise with height. For example, in a veering wind situation the winds may be from the south at the surface and from the west at 15,000 feet (4500 m). Beneath the supercell, the rotation of the storm is often visible as well (above right).

Most tornadoes are spawned from supercell thunderstorms. Supercell thunderstorms are characterized by a persistent rotating updraft and form in environments of strong vertical wind shear.

Slide 14: Knowing the difference of shear vs. rotation is vital when determining whether or not a thunderstorm will produce a tornado or another hazard such as damaging straight line winds. The difference in motion with shear and rotation can, at times, be difficult to assess. **Shear** is simply a rapid variation in wind speed or direction over a short distance. Most shear can be determined by observing cloud motion that is in different directions. These different cloud motions can occur at the same height (horizontal shear) or at different heights (vertical shear). **Rotation** is a **circular** motion (***usually* counterclockwise** motion in thunderstorms). Some types of rotation can occur in all thunderstorms. However, if the rotation occurs in a non-supercell thunderstorm, it is usually very shallow and short-lived. Shear is very common in all thunderstorms. Often times shear will be very evident as a thunderstorm approaches. Lower level clouds moving with the mean low level wind into the storm will have a different motion than those clouds attached to, or directly associated with, the thunderstorm. To determine whether or not cloud motion is rotation or shear, one needs to carefully watch the clouds for a few minutes. Pick a few distinctive cloud elements and watch long enough to assess if the motion is circular. Do the cloud elements revolve around a central point? If so, its rotation. If clouds are seen moving in two different directions but no circular motion is observed, it is just shear. **A storm must be rotating in order for a tornado to occur.**

Slide 15: Lightning

Slide 16: At any given moment, there can be as many as 2,000 thunderstorms occurring across the globe. This translates to more than 14.5 MILLION storms each year. NASA satellite research indicated these storms produce lightning flashes about 40 times a second worldwide.

Lightning is the **MOST UNDERRATED** weather hazard. On average, only floods kill more people. **Lightning makes every single thunderstorm a potential killer**, whether the storm produces one single bolt or ten thousand bolts.

In the United States, lightning routinely kills more people each year than tornadoes and hurricanes **COMBINED**. Tornadoes, hail, and wind gusts get the most attention, but only lightning can strike outside the storm itself. Lightning is the first thunderstorm hazard to arrive and the last to leave.

Slide 17: Thunderstorms have very turbulent environments. Strong updrafts and downdrafts occur with regularity and within close proximity to each other. The updrafts transport small liquid water droplets from the lower regions of the storm to heights between 35,000 and 70,000 feet, miles above the freezing level.

Meanwhile, downdrafts transport hail and ice from the frozen upper regions of the storm. When these collide, the water droplets freeze and release heat. This heat in turn keeps the surface of the hail and ice slightly warmer than its surrounding environment, and a "soft hail", or "graupel" forms.

When this graupel collides with additional water droplets and ice particles, *a critical phenomenon occurs*: Electrons are sheared off of the ascending particles and collect on the descending particles. Because electrons carry a negative charge, the result is a storm cloud with a negatively charged base and a positively charged top.

Slide 18: In the world of electricity, opposites attract and insulators inhibit. As the charges separate within the cloud, an electric field is generated between its top and base. The greater the magnitude of separation, the stronger the field, and the stronger the attraction between the charges.

However, the atmosphere is a very good insulator that inhibits electric flow, so a TREMENDOUS amount of charge has to build up before lightning can occur. When that charge threshold is reached, the strength of the electric field overpowers the atmosphere's insulating properties, and lightning results.

The electric field within the storm is not the only one that develops. Below the negatively charged storm base, positive charge begins to pool within the surface of the earth (see image left). This positive charge will shadow the storm wherever it goes, and is responsible for cloud-to-ground lightning. However, the electric field within the storm is much stronger than the one between the storm base and the earth's surface, so most lightning (~75-80%) occurs within the storm cloud itself.

A moving thunderstorm gathers another pool of positively charged particles along the ground that travel with the storm (image 1). As the differences in charges continue to increase, positively charged particles rise up taller objects such as trees, houses, and telephone poles.

A channel of negative charge, called a "stepped leader" will descend from the bottom of the storm toward the ground (image 2). It is invisible to the human eye, and shoots to the ground in a series of rapid steps, each occurring in less time than it takes to blink your eye. As the negative leader approaches the ground, positive charge collects in the ground and in objects on the ground.

This positive charge "reaches" out to the approaching negative charge with its own channel, called a "streamer" (image 3). When these channels connect, the resulting electrical transfer is what we see as lightning. After the initial lightning stroke, if enough charge is leftover, additional lightning strokes will use the same channel and will give the bolt its flickering appearance.

Slide 19: Thunder is the acoustic shock wave resulting from the extreme heat generated by a lightning flash. Lightning can be as hot as 54,000°F, a temperature that is five times the surface of the sun! When lightning occurs, it heats the air surrounding its channel to that same incredible temperature in a fraction of a second.

Like all gases, when air molecules are heated, they expand. The faster they are heated, the faster their rate of expansion. But when air is heated to 54,000°F in a fraction of a second, a phenomenon known as "explosive expansion" occurs. This is where air expands so rapidly that it compresses the air in front of it, forming a shock wave similar to a sonic boom. Exploding fireworks produce a similar result.
When lightning strikes a shock wave is generated at each point along the path of the lightning bolt. With nearby lightning strikes the thunder will sound like a loud bang, crack or snap and its duration will be very short.

As the shock wave propagates away from the strike center, it stretches, diminishes, and becomes elongated. Then other shock waves from more distance locations arrive at the listener.

At large distances from the center, the shock wave (thunder) can be many miles across. To the listener, the combination of shock waves gives thunder the continuous rumble we hear.

Slide 20: Hail

Slide 21: Baseball size hail did considerable damage to the car on the left. Realize that updraft speeds of 80 mph are required in a thunderstorm to sustain hail this size aloft. **Rule: The Stronger the updraft the larger the hail stones.**

Slide 22: Hail is precipitation that is formed when updrafts in thunderstorms carry raindrops upward into extremely cold areas of the atmosphere. Hail can damage aircraft, homes and cars, and can be deadly to livestock and people.

While Florida has the most thunderstorms, New Mexico, Colorado, and Wyoming usually have the most hail storms. Why? The freezing level in the Florida thunderstorms is so high, the hail often melts before reaching the ground.

Hailstones grow by collision with supercooled water drops. (Supercooled drops are liquid drops surrounded by air that is below freezing which is a common occurrence in thunderstorms.) There are two methods by which the hailstone grows, wet growth and dry growth, and which produce the "layered look" of hail.

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

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

Multi-cell thunderstorms produce many hail storms but usually not the largest hailstones. The reason is that the mature stage in the life cycle of the multi-cell is relatively short which decreases the time for growth. However, the sustained updraft in supercell thunderstorms support large hail formation by repeatedly lifting the hailstones into the very cold air at the top of the thunderstorm cloud.

In all cases, the hail falls when the thunderstorm's updraft can no longer support the weight of the ice. **The stronger the updraft the larger the hailstone can grow.**

Slide 23: Tornadoes and Downburst

Slide 24: A tornado is a violently rotating (usually counterclockwise in the northern hemisphere) column of air descending from a thunderstorm and in contact with the ground. Although tornadoes are usually brief, lasting only a few minutes, they can sometimes last for more than an hour and travel several miles causing considerable damage.

In a typical year about 1000 tornadoes will strike the United States. The peak of the tornado season is April through June and more tornadoes strike the central United States than any other place in the world. This area has been nicknamed "tornado alley."

Most tornadoes are spawned from supercell thunderstorms. Supercell thunderstorms are characterized by a persistent rotating updraft and form in environments of strong vertical wind shear. Wind shear is the change in wind speed and/or direction with height.

Tornadoes are natures most destructive weather hazard.

Slide 25: The Fujita scale is a measure of tornado intensity quantified through a subjective analysis of relating tornadic damage to wind speed.

-Weak tornadoes are F0 - F1, winds 60 to 115 mph.
-Strong tornadoes are F2 - F3, winds 115 - 205 mph.
-Violent tornadoes are F4 - F5, winds > 205 mph.

The size and/or shape of a tornado is no measure of its strength. Occasionally, small tornadoes do major damage and some very large tornadoes, over a quarter-mile wide, have produced only light damage.

Slide 26: Damaging wind from thunderstorms is much more common than damage from tornadoes. In fact, many confuse damage produced by "straight-line" winds and often erroneously attribute it to tornadoes. Wind speeds can reach up to 100 mph with a damage path extending for hundreds of miles.

Several factors contribute to damaging winds at the surface. As precipitation begins to fall, it drags some of the air with it. This *precipitation drag* initiates a downdraft. The downdraft is intensified by evaporative cooling as drier air from the edges of the storm mix with the cloudy air within the storm.

Also some of the strong winds aloft are carried down with the downdraft by a process called "momentum transfer". These processes lead to a rapid downward rush of air. As the air impacts the ground it is forced to spread out laterally causing the gusty and sometimes damaging winds associated with thunderstorms.

Derechos
Derechos are the result of the combination of several outflow boundaries, which are set

up by the precipitation downdraft. The word "derecho" is of Spanish origin, and means straight ahead. Derechos result from particularly strong downdrafts and can travel many hundreds of miles before dissipating.

There are two dangers associated with derechos: The duration of the damaging winds and widespread coverage of such winds,

Damaging winds are classified as those winds exceeding 50-60 mph. In derecho situations it is not uncommon for winds of this magnitude to last for over 30 minutes, with occasional gusts of 100 mph and cover up to 1250 square miles or about the size of Rhode Island.

Slide 27: Downbursts can create hazardous conditions for pilots and these events have been responsible for several disasters.
1. As aircraft descend into the airport they follow an imagery line called the "glide slope" to the runway (solid light blue line).

2. Upon entering the downburst, the plane encounters a "headwind", an increase in wind speed over the aircraft. The faster wind creates lift causing the plane to rise above the glide slope. To return the plane to the proper position, the pilot lowers the throttle to decrease the plane's speed thereby causing the plane to descend.

3. As the plane flies to the other side of the downburst, the wind direction shifts and is now from behind the aircraft. This decreases the wind over the wing reducing lift. The plane sinks below the glide slope.

4. However, the "tailwind" remains strong and even with the pilot applying full throttle trying to increase lift again, there is little, if any, room to recover from the rapid descent causing the plane to crash short of the runway.

Since the discovery of this effect in the early to mid 1980's, pilots are now trained to recognize this event and take appropriate actions to prevent accidents. Also, many airports are now equipped with equipment to detect downbursts and warn aircraft of their location.

Slide 28: Flooding

Slide 29: Except for heat related fatalities, more deaths occur from flooding than any other thunderstorm hazard. Why? Most people fail to realize the power of water. For example, **six inches of fast-moving flood water can knock you off your feet.**

National Weather Service data also shows:
- Nearly half of all flash flood fatalities are vehicle-related,
- The majority of victims are males, and
- Flood deaths affect all age groups.

Most flash floods are caused by slow moving thunderstorms, thunderstorms that move repeatedly over the same area or heavy rains from tropical storms and hurricanes. These floods can develop within minutes or hours depending on the intensity and duration of the rain, the topography, soil conditions and ground cover.
Flash floods can roll boulders, tear out trees, destroy buildings and bridges, and scour out new channels. Rapidly rising water can reach heights of 30 feet or more. Furthermore, flash flood-producing rains can also trigger catastrophic mud slides.

Occasionally, floating debris or ice can accumulate at a natural or man-made obstruction and restrict the flow of water. Water held back by the ice jam or debris dam can cause flooding upstream. Subsequent flash flooding can occur downstream if the obstruction should suddenly release.

Slide 30: Acknowledgements

Slide 31: The End