A thunderstorm, also known as an electrical storm or a lightning storm, is a storm characterized by the presence of lightning[1] and its acoustic effect on the Earth's atmosphere, known as thunder.[2] Relatively weak thunderstorms are sometimes called thundershowers.[3] Thunderstorms occur in a type of cloud known as a cumulonimbus.[4] They are usually accompanied by strong winds[1] and often produce heavy rain[1] and sometimes snow, sleet, or hail,[1] but some thunderstorms produce little precipitation or no precipitation at all. Thunderstorms may line up in a series or become a rainband, known as a squall line. Strong or severe thunderstorms include some of the most dangerous weather phenomena, including large hail, strong winds, and tornadoes. Some of the most persistent severe thunderstorms, known as supercells, rotate as do cyclones. While most thunderstorms move with the mean wind flow through the layer of the troposphere that they occupy, vertical wind shear sometimes causes a deviation in their course at a right angle to the wind shear direction.

Thunderstorms result from the rapid upward movement of warm, moist air, sometimes along a front.[5] However, some kind of cloud forcing, whether it is a front, shortwave trough, or another system is needed for the air to rapidly accelerate upward. As the warm, moist air moves upward, it cools, condenses,[5] and forms a cumulonimbus cloud that can reach heights of over 20 kilometres (12 mi). As the rising air reaches its dew point temperature, water vapor condenses into water droplets or ice, reducing pressure locally within the thunderstorm cell. Any precipitation falls the long distance through the clouds towards the Earth's surface. As the droplets fall, they collide with other droplets and become larger. The falling droplets create a downdraft as it pulls cold air with it, and this cold air spreads out at the Earth's surface, occasionally causing strong winds that are commonly associated with thunderstorms.

Thunderstorms can form and develop in any geographic location but most frequently within the mid-latitude, where warm, moist air from tropical latitudes collides with cooler air from polar latitudes.[6] Thunderstorms are responsible for the development and formation of many severe weather phenomena, which can be potentially hazardous. Damage that results from thunderstorms is mainly inflicted by downburst winds, large hailstones, and flash flooding caused by heavy precipitation. Stronger thunderstorm cells are capable of producing tornadoes and waterspouts.

There are three types of thunderstorms: single-cell, multi-cell, and supercell.[7] Supercell thunderstorms are the strongest and most severe.[7] Mesoscale convective systems formed by favorable vertical wind shear within the tropics and subtropics can be responsible for the development of hurricanes. Dry thunderstorms, with no precipitation, can cause the outbreak of wildfires from the heat generated from the cloud-to-ground lightning that accompanies them. Several means are used to study thunderstorms: weather radar, weather stations, and video photography. Past civilizations held various myths concerning thunderstorms and their development as late as the 18th century. Beyond the Earth's atmosphere, thunderstorms have also been observed on the planets of Jupiter, Saturn, Neptune, and, probably, Venus.

Life cycle

Stages of a thunderstorm's life

See also: Cloud

Warm air has a lower density than cool air, so warmer air rises upwards and cooler air will settle at the bottom[8] (this effect can be seen with a hot air balloon).[9] Clouds form as relatively warmer air, carrying moisture, rises within cooler air. The moist air rises, and, as it does so, it cools and some of the water vapor in that rising air condenses.[10] When the moisture condenses, it releases energy known as latent heat of condensation, which allows the rising packet of air to cool less than the cooler surrounding air[11] continuing the cloud's ascension. If enough instability is present in the atmosphere, this process will continue long enough for cumulonimbus clouds to form and produce lightning and thunder. Meteorological indices such as convective available potential energy (CAPE) and the lifted index can be used to assist in determining potential upward vertical development of clouds.[12] Generally, thunderstorms require three conditions in order to form:

Moisture

An unstable airmass

A lifting force (heat)

All thunderstorms, regardless of type, go through three stages: the developing stage, the mature stage, and the dissipation stage.[13][14] The average thunderstorm has a 24 km (15

mi) diameter. Depending on the conditions present in the atmosphere, each of these three stages take an average of 30 minutes.[15]

Developing stage

A cumulus congestus' transformation into a mature cumulonimbus incus

The first stage of a thunderstorm is the cumulus stage or developing stage. During this stage, masses of moisture are lifted upwards into the atmosphere. The trigger for this lift can be solar illumination, where the heating of the ground produces thermals, or where two winds converge forcing air upwards, or where winds blow over terrain of increasing elevation. The moisture carried upward cools into liquid drops of water due to lower temperatures at high altitude, which appear as cumulus clouds. As the water vapor condenses into liquid, latent heat is released, which warms the air, causing it to become less dense than the surrounding, drier air. The air tends to rise in an updraft through the process of convection (hence the term convective precipitation). This process creates a low-pressure zone within and beneath the forming thunderstorm. In a typical thunderstorm, approximately 500 million kilograms of water vapor are lifted into the Earth's atmosphere.[16][failed verification]

Mature stage

Anvil-shaped thundercloud in the mature stage

In the mature stage of a thunderstorm, the warmed air continues to rise until it reaches an area of warmer air and can rise no farther. Often this 'cap' is the tropopause. The air is instead forced to spread out, giving the storm a characteristic anvil shape. The resulting cloud is called cumulonimbus incus. The water droplets coalesce into larger and heavier droplets and freeze to become ice particles. As these fall, they melt to become rain. If the updraft is strong enough, the droplets are held aloft long enough to become so large that they do not melt completely but fall as hail. While updrafts are still present, the falling rain drags the surrounding air with it, creating downdrafts as well. The simultaneous presence of both an updraft and a downdraft marks the mature stage of the storm and produces cumulonimbus clouds. During this stage, considerable internal turbulence can occur, which manifests as strong winds, severe lightning, and even tornadoes.[17]

Typically, if there is little wind shear, the storm will rapidly enter the dissipating stage and 'rain itself out',[14] but, if there is sufficient change in wind speed or direction, the downdraft will be separated from the updraft, and the storm may become a supercell, where the mature stage can sustain itself for several hours.[18]

Dissipating stage

A thunderstorm in an environment with no winds to shear the storm or blow the anvil in any one direction

Flanking line in front of a dissipating cumulonimbus incus cloud

In the dissipation stage, the thunderstorm is dominated by the downdraft. If atmospheric conditions do not support super cellular development, this stage occurs rather quickly, approximately 20–30 minutes into the life of the thunderstorm. The downdraft will push down out of the thunderstorm, hit the ground and spread out. This phenomenon is known as a downburst. The cool air carried to the ground by the downdraft cuts off the inflow of the thunderstorm, the updraft disappears and the thunderstorm will dissipate. Thunderstorms in an atmosphere with virtually no vertical wind shear weaken as soon as they send out an outflow boundary in all directions, which then quickly cuts off its inflow of relatively warm, moist air, and kills the thunderstorm's further growth.[19] The downdraft hitting the ground creates an outflow boundary. This can cause downbursts, a potential hazardous condition for aircraft to fly through, as a substantial change in wind speed and direction occurs, resulting in a decrease of airspeed and the subsequent reduction in lift for the aircraft. The stronger the outflow boundary is, the stronger the resultant vertical wind shear becomes.[20]

Classification

Conditions favorable for thunderstorm types and complexes

There are four main types of thunderstorms: single-cell, multi-cell, squall line (also called multi-cell line) and supercell.[7] Which type forms depends on the instability and relative

wind conditions at different layers of the atmosphere ("wind shear"). Single-cell thunderstorms form in environments of low vertical wind shear and last only 20–30 minutes.

Organized thunderstorms and thunderstorm clusters/lines can have longer life cycles as they form in environments of significant vertical wind shear, normally greater than 25 knots (13 m/s) in the lowest 6 kilometres (3.7 mi) of the troposphere,[21] which aids the development of stronger updrafts as well as various forms of severe weather. The supercell is the strongest of the thunderstorms,[7] most commonly associated with large hail, high winds, and tornado formation. Precipitable water values of greater than 31.8 millimetres (1.25 in) favor the development of organized thunderstorm complexes.[22] Those with heavy rainfall normally have precipitable water values greater than 36.9 millimetres (1.45 in).[23] Upstream values of CAPE of greater than 800 J/kg are usually required for the development of organized convection.[24]

Single-cell

Main article: Air-mass thunderstorm

A single-cell thunderstorm over Wagga Wagga

This term technically applies to a single thunderstorm with one main updraft. Also known as air-mass thunderstorms, these are the typical summer thunderstorms in many temperate locales. They also occur in the cool unstable air that often follows the passage of a cold front from the sea during winter. Within a cluster of thunderstorms, the term "cell" refers to each separate principal updraft. Thunderstorm cells occasionally form in isolation, as the occurrence of one thunderstorm can develop an outflow boundary that sets up new thunderstorm development. Such storms are rarely severe and are a result of local atmospheric instability; hence the term "air mass thunderstorm". When such storms have a brief period of severe weather associated with them, it is known as a pulse severe storm. Pulse severe storms are poorly organized and occur randomly in time and space, making them difficult to forecast. Single-cell thunderstorms normally last 20–30 minutes.[15]

Multi-cell clusters

Main article: Multicellular thunderstorm

A group of thunderstorms over Brazil photographed by the Space Shuttle Challenger

This is the most common type of thunderstorm development. Mature thunderstorms are found near the center of the cluster, while dissipating thunderstorms exist on their downwind side. Multicell storms form as clusters of storms but may then evolve into one or more squall lines. While each cell of the cluster may only last 20 minutes, the cluster itself may persist for hours at a time. They often arise from convective updrafts in or near mountain ranges and linear weather boundaries, such as strong cold fronts or troughs of low pressure. These type of storms are stronger than the single-cell storm, yet much weaker than the supercell storm. Hazards with the multicell cluster include moderate-sized hail, flash flooding, and weak tornadoes.[15]

Multicell lines

Main article: Squall line

See also: List of derecho events

A squall line is an elongated line of severe thunderstorms that can form along or ahead of a cold front.[25][26] In the early 20th century, the term was used as a synonym for cold front.[27] The squall line contains heavy precipitation, hail, frequent lightning, strong straight line winds, and possibly tornadoes and waterspouts.[28] Severe weather in the form of strong straight-line winds can be expected in areas where the squall line itself is in the shape of a bow echo, within the portion of the line that bows out the most.[29] Tornadoes can be found along waves within a line echo wave pattern, or LEWP, where mesoscale low pressure areas are present.[30] Some bow echoes in the summer are called derechos, and move quite fast through large sections of territory.[31] On the back edge of the rain shield associated with mature squall lines, a wake low can form, which is a mesoscale low pressure area that forms behind the mesoscale high pressure system normally present under the rain canopy, which are sometimes associated with a heat burst.[32] This kind of storm is also known as "Wind of the Stony Lake" (simplified Chinese: 石湖风; traditional Chinese: 石湖風; shi2 hu2 feng1) in southern China.[33]

Supercells

Main article: Supercell

A drone photograph of a supercell from Chamberlain, South Dakota on 18 July 2023.

The setting sun illuminates the top of a classic anvil-shaped thunderstorm cloud in eastern Nebraska, United States.

Supercell storms are large, usually severe, quasi-steady-state storms that form in an environment where wind speed or wind direction varies with height ("wind shear"), and they have separate downdrafts and updrafts (i.e., where its associated precipitation is not falling through the updraft) with a strong, rotating updraft (a "mesocyclone"). These storms normally have such powerful updrafts that the top of the supercell storm cloud (or anvil) can break through the troposphere and reach into the lower levels of the stratosphere. Supercell storms can be 24 kilometres (15 mi) wide. Research has shown that at least 90 percent of supercells cause severe weather.[18] These storms can produce destructive tornadoes, extremely large hailstones (10 centimetres or 4 inches diameter), straight-line winds in excess of 130 km/h (81 mph), and flash floods. In fact, research has shown that most tornadoes occur from this type of thunderstorm.[34] Supercells are generally the strongest type of thunderstorm.[15]

Severe thunderstorms

In the United States, a thunderstorm is classed as severe if winds reach at least 93 kilometres per hour (58 mph), hail is 25 millimetres (1 in) in diameter or larger, or if funnel clouds or tornadoes are reported.[35][36][37] Although a funnel cloud or tornado indicates a severe thunderstorm, a tornado warning is issued in place of a severe thunderstorm warning. A severe thunderstorm warning is issued if a thunderstorm becomes severe, or will soon turn severe. In Canada, a rainfall rate greater than 50 millimetres (2 in) in one hour, or 75 millimetres (3 in) in three hours, is also used to indicate severe thunderstorms.[38] Severe thunderstorms can occur from any type of storm cell. However, multicell, supercell, and squall lines represent the most common forms of thunderstorms that produce severe weather.[18]