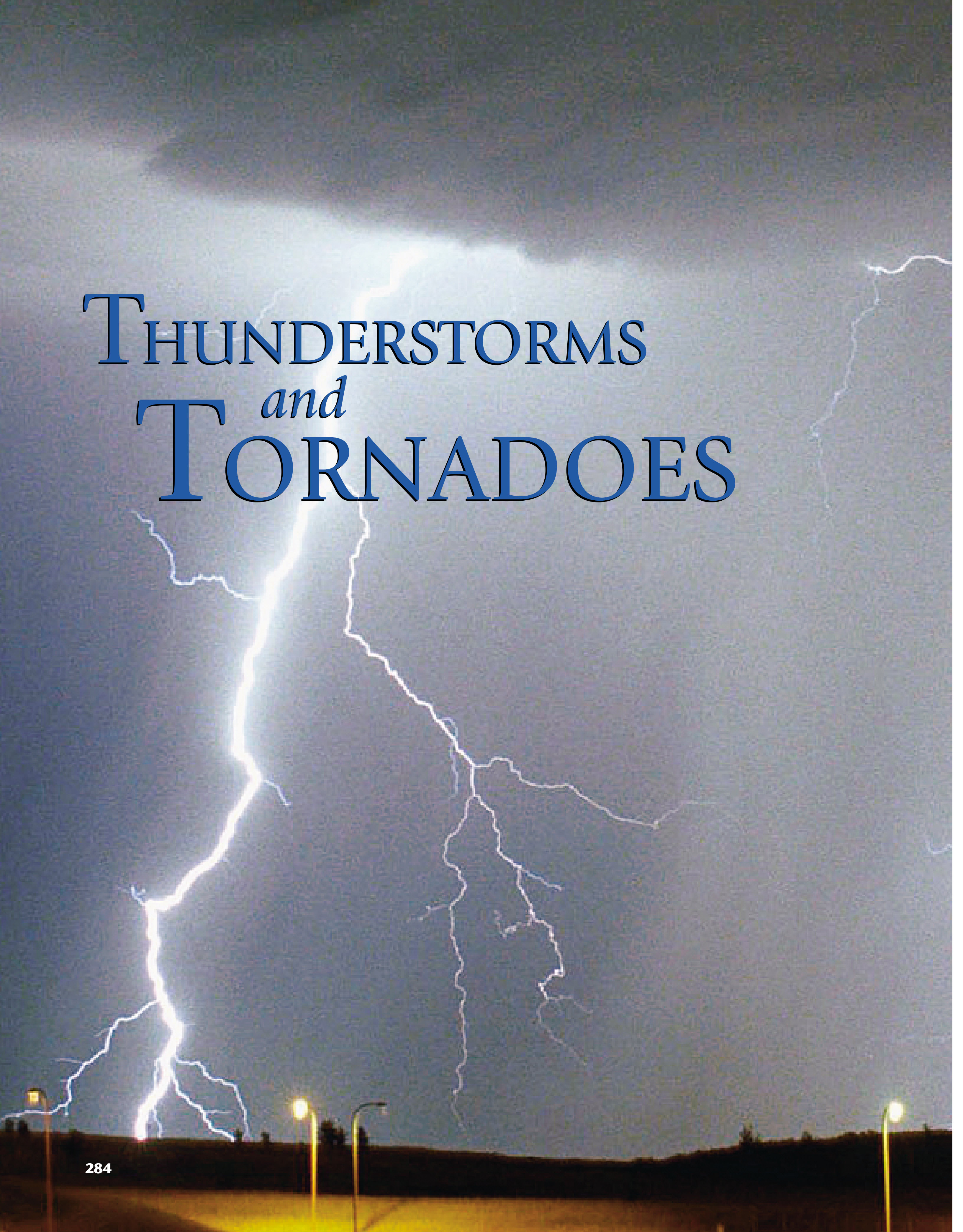
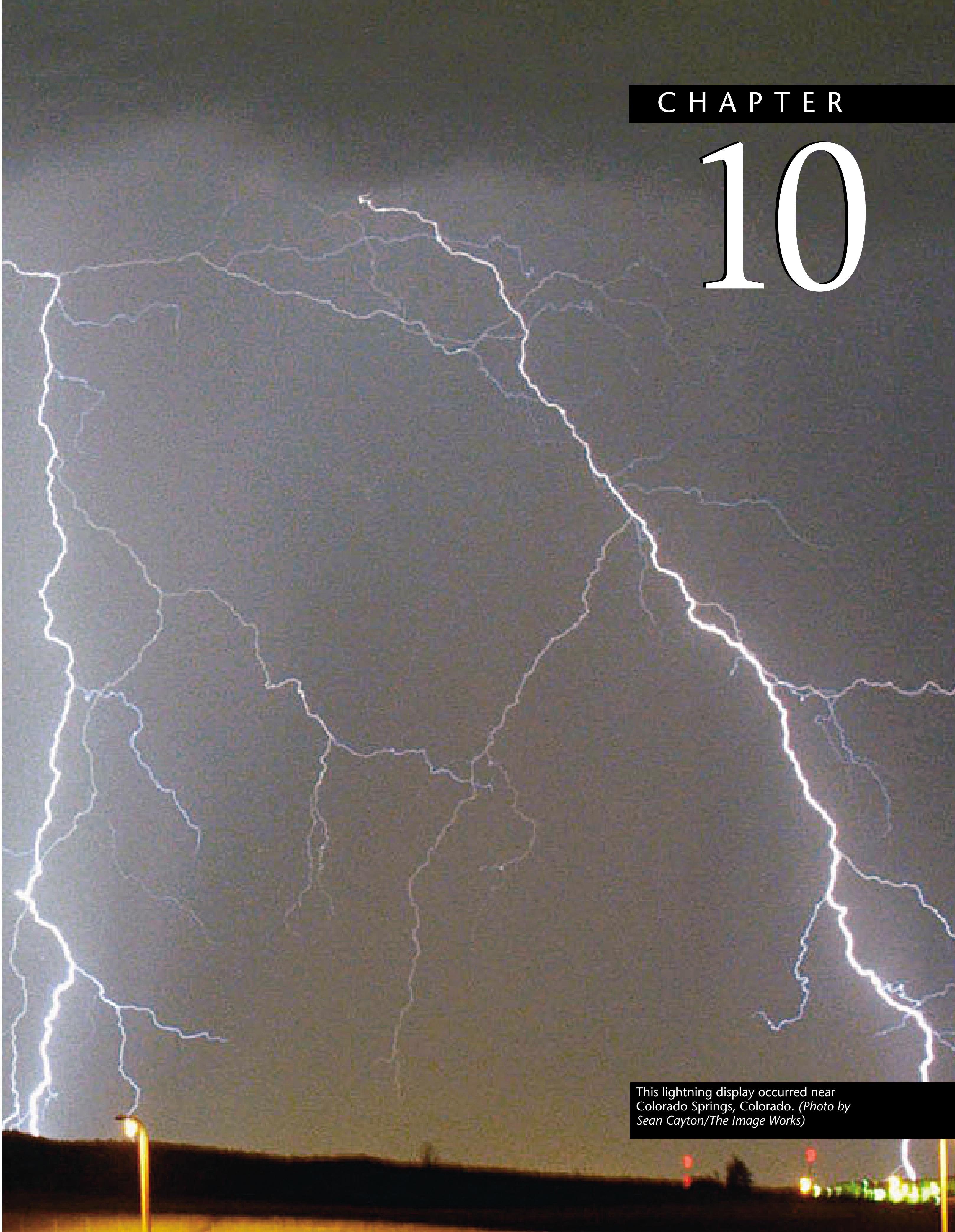
THUNDERSTORMS *and* TORNADOES



CHAPTER 10



This lightning display occurred near Colorado Springs, Colorado. *(Photo by Sean Cayton/The Image Works)*

The subject of this and the following chapter, is severe weather. In this chapter we will examine the severe local weather produced in association with cumulonimbus clouds—namely, thunderstorms and tornadoes (Figure 10–1). In Chapter 11 the focus will turn to the large tropical storms we call hurricanes.

Occurrences of severe weather have a fascination that ordinary weather phenomena cannot provide. The lightning display generated by a thunderstorm can be a spectacular event that elicits both awe and fear. Of course, hurricanes and tornadoes also attract a great deal of much deserved attention. A single tornado outbreak or hurricane can cause billions of dollars in property damage as well as many deaths.

What's in a Name?

In Chapter 9 we examined the middle-latitude cyclones that play such an important role in causing day-to-day weather changes. Yet the use of the term "cyclone" is often confusing. For many people the term implies only an intense storm, such as a tornado or a hurricane. When a hurricane unleashes its fury on India or Bangladesh, for example, it is usually reported in the media as a cyclone (the term denoting a hurricane in that part of the world).

Similarly, tornadoes are referred to as cyclones in some places. This custom is particularly common in portions of the Great Plains of the United States. Recall that in the *Wizard of Oz,* Dorothy's house was carried from her Kansas farm to the land of Oz by a cyclone. Indeed, the nickname for the athletic teams at Iowa State University is the *Cyclones.* Although hurricanes and tornadoes are, in fact, cyclones, the vast majority of cyclones are not hurricanes or tornadoes. The term "cyclone" simply refers to the circulation around any low-pressure center, no matter how large or intense it is.

Tornadoes and hurricanes are both smaller and more violent than middle-latitude cyclones. Middle-latitude cyclones may have a diameter of 1600 kilometers (1000 miles) or more. By contrast, hurricanes average only 600 kilometers (375 miles) across, and tornadoes, with a diameter of just 0.25 kilometer (0.16 mile), are much too small to show up on a weather map.

The thunderstorm, a much more familiar weather event, hardly needs to be distinguished from tornadoes, hurricanes, and midlatitude cyclones. Unlike the flow of air about these storms, the circulation associated with thunderstorms is characterized by strong up-and-down movements. Winds in the vicinity of a thunderstorm do not follow the inward spiral of a cyclone, but they are typically variable and gusty.

FIGURE 10-1 This tornado occurred over south central Kansas in May 2004. *(Photo by Weatherstock/Peter Arnold, Inc.)*

Although thunderstorms form "on their own" away from cyclonic storms, they also form in conjunction with cyclones. For instance, thunderstorms are frequently spawned along the cold front of a midlatitude cyclone, where on rare occasions a tornado may descend from the thunderstorm's cumulonimbus tower. Hurricanes also generate widespread thunderstorm activity. Thus, thunderstorms are related in some manner to all three types of cyclones mentioned here.

Thunderstorms

Almost everyone has observed various small-scale phenomena that result from the vertical movements of relatively warm, unstable air. Perhaps you have seen a dust devil over an open field on a hot day whirling its dusty load to great heights (see Box 7–1) or maybe you have seen a bird glide effortlessly skyward on an invisible thermal of hot air. These examples illustrate the dynamic thermal instability that occurs during the development of a *thunderstorm.* A **thunderstorm** is simply a storm that generates lightning and thunder. It frequently produces gusty winds, heavy rain, and hail. A thunderstorm may be produced by a single cumulonimbus cloud and influence only a small area, or it may be associated with clusters of cumulonimbus clouds covering a large area.

Thunderstorms form when warm, humid air rises in an unstable environment. Various mechanisms can trigger the upward air movement needed to create thunderstorm-producing cumulonimbus clouds. One mechanism, the unequal heating of Earth's surface, significantly contributes to the formation of *air-mass thunderstorms.* These storms are associated with the scattered puffy cumulonimbus clouds that commonly form *within* maritime tropical air masses and produce scattered thunderstorms on summer days. Such storms are usually short-lived and seldom produce strong winds or hail.

In contrast, thunderstorms in a second category not only benefit from uneven surface heating but are associated with the lifting of warm air, as occurs along a front or a mountain slope. Moreover, diverging winds aloft frequently contribute to the formation of these storms because they tend to draw air from lower levels upward beneath them. Some of the thunderstorms in this second category may produce high winds, damaging hail, flash floods, and tornadoes. Such storms are described as *severe.*

At any given time there are an estimated 2000 thunderstorms in progress. As we would expect, the greatest proportion occurs in the tropics, where warmth, plentiful moisture, and instability are always present. About 45,000 thunderstorms take place each day, and more than 16 million occur annually around the world. The lightning from these storms strikes Earth 100 times each second (Figure 10–2).

Annually the United States experiences about 100,000 thunderstorms and millions of lightning strikes. A glance at Figure 10–3 shows that thunderstorms are most frequent in Florida and the eastern Gulf Coast region, where activity is recorded between 70 and 100 days each year. The region on the east side of the Rockies in Colorado and New Mexico is next, with thunderstorms occurring 60 to 70 days annually. Most of the rest of the nation experiences thunderstorms 30 to 50 days a year. Clearly, the western margin of the United States has little thunderstorm activity. The same is true for the northern tier of states and for Canada, where warm, moist, unstable mT air seldom penetrates.

Air-Mass Thunderstorms

In the United States **air-mass thunderstorms** frequently occur in maritime tropical (mT) air that moves northward from the Gulf of Mexico. These warm, humid air masses contain abundant moisture in their lower levels and can be rendered unstable when heated from below or lifted along a front. Because mT air most often becomes unstable in spring and summer, when it is warmed from below by the heated land surface, it is during these seasons that air-mass thunderstorms are most frequent. They also have a strong preference for midafternoon, when surface temperatures are highest. Because local differences in surface heating aid the growth of air-mass thunderstorms, they generally occur as scattered, isolated cells instead of being organized in relatively narrow bands or other configurations.

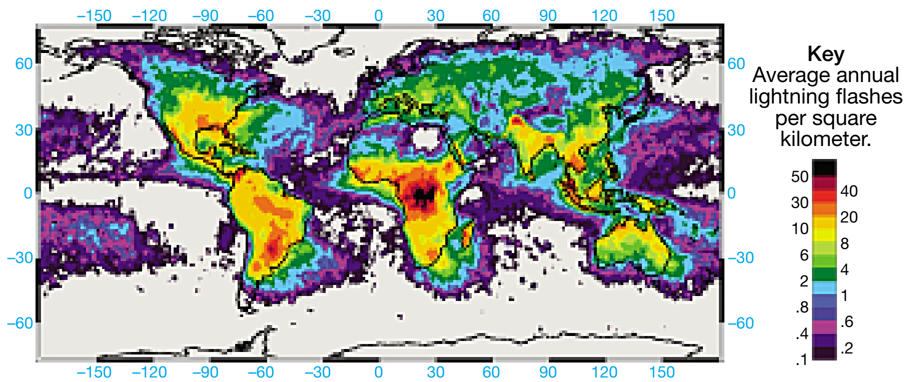


FIGURE 10-2 Data from space-based optical sensors show the worldwide distribution of lightning, with color variations indicating the average annual number of lightning flashes per square kilometer. The map includes data obtained from April 1995 to March 2000 from NASA's Optical Transient Detector, and from December 1997 to November 2000 from NASA's Lightning Imaging Sensor. Both are satellite-based sensors that use high-speed cameras capable of detecting brief lightning flashes even under daytime conditions. *(NASA image)*

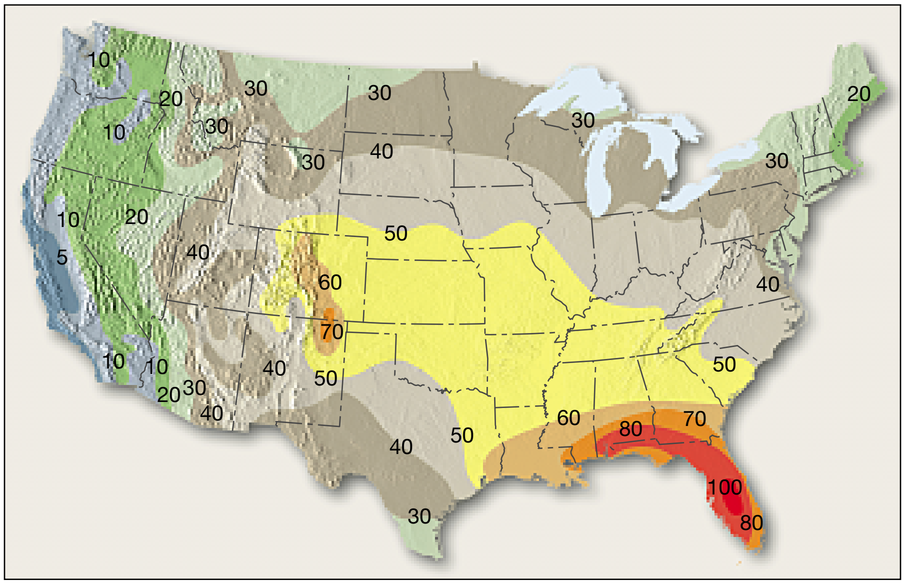


FIGURE 10-3 Average number of days each year with thunderstorms. The humid subtropical climate that dominates the southeastern United States receives much of its precipitation in the form of thunderstorms. Most of the Southeast averages 50 or more days each year with thunderstorms. *(Source: Environmental Data Service, NOAA)*

Stages of Development

Important field experiments that were conducted in Florida and Ohio in the late 1940s probed the dynamics of air-mass thunderstorms. This pioneering work, known as the *Thunderstorm Project,* was prompted by a number of thunderstorm-related airplane crashes. It involved the use of radar, aircraft, radiosondes, and an extensive network of surface instruments. The research produced a three-stage model of the life cycle of an air-mass thunderstorm that remains basically unchanged after more than 50 years. The three stages are depicted in Figure 10–4.

Cumulus Stage. Recall that an air-mass thunderstorm is largely a product of the uneven heating of the surface, which leads to rising currents of air that ultimately produce a cumulonimbus cloud. At first the buoyant thermals produce fair weather cumulus clouds that may exist for just minutes before evaporating into the drier, surrounding air (Figure 10–5a). This initial cumulus development is important because it moves water vapor from the surface to greater heights. Ultimately, the air becomes sufficiently humid that newly forming clouds do not evaporate, but instead continue to grow vertically.

The development of a cumulonimbus tower requires a continuous supply of moist air. The release of latent heat allows each new surge of warm air to rise higher than the last, adding to the height of the cloud (Figure 10–5b). This phase in the development of a thunderstorm, called the **cumulus stage,** is dominated by updrafts (Figure 10–4a).

Once the cloud passes beyond the freezing level, the Bergeron process begins producing precipitation. Eventually, the accumulation of precipitation in the cloud is too great for the updrafts to support. The falling precipitation causes drag on the air and initiates a downdraft.

The creation of the downdraft is further aided by the influx of cool, dry air surrounding the cloud, a process termed **entrainment.** This process intensifies the downdraft because the air added during entrainment is cool and therefore heavy; possibly of greater importance, it is dry. It thus causes some of the falling precipitation to evaporate

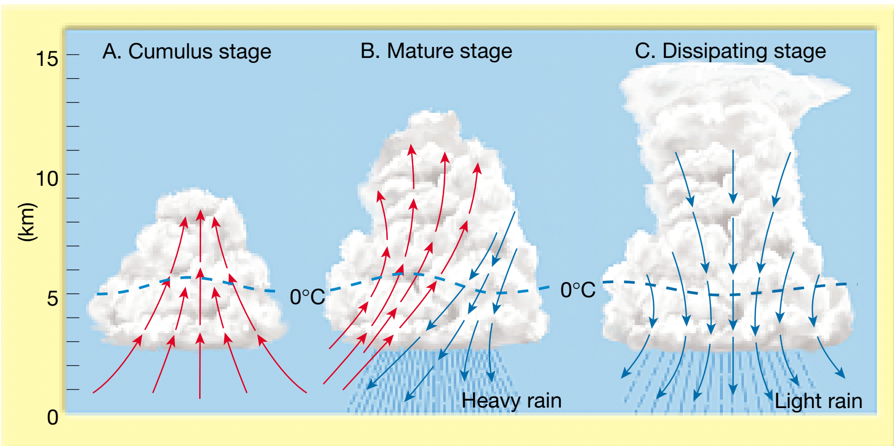
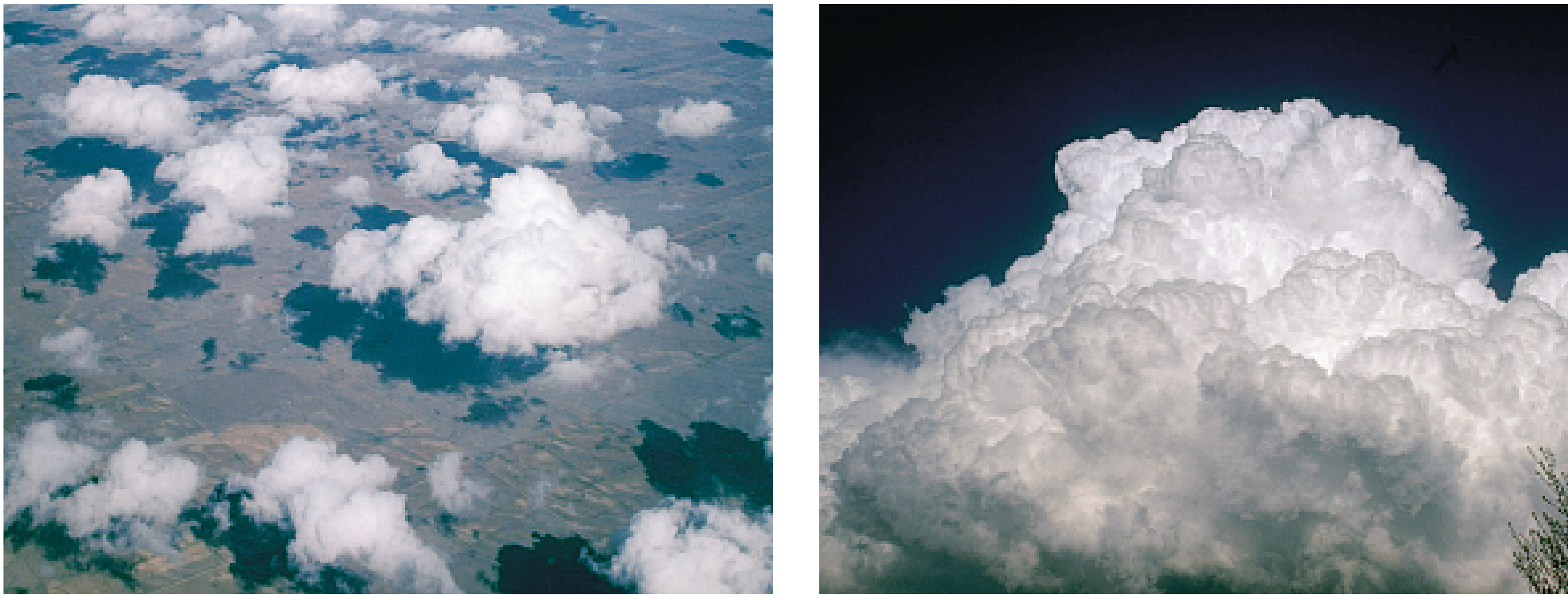


FIGURE 10-4 Stages in the development of a thunderstorm. During the cumulus stage, strong updrafts act to build the storm. The mature stage is marked by heavy precipitation and cool downdrafts in part of the storm. When the warm updrafts disappear completely, precipitation becomes light and the cloud begins to evaporate.



(a) (b)

FIGURE 10-5 (a) At first, buoyant thermals produce fair weather cumulus clouds that soon evaporate into the surrounding air, making it more humid. As this process of cumulus development and evaporation continues, the air eventually becomes sufficiently humid so that newly forming clouds do not evaporate but continue to grow. *(Photo by Henry Lansford/Photo Researchers, Inc.)* (b) This developing cumulonimbus cloud became a towering August thunderstorm over central Illinois. *(Photo by Henry Lansford)*

(a cooling process), thereby cooling the air within the downdraft.

Mature Stage. As the downdraft leaves the base of the cloud, precipitation is released, marking the beginning of the cloud's **mature stage** (Figure 10–4b). At the surface the cool downdrafts spread laterally and can be felt before the actual precipitation reaches the ground. The sharp, cool gusts at the surface are indicative of the downdrafts aloft. During the mature stage, updrafts exist side by side with downdrafts and continue to enlarge the cloud. When the cloud grows to the top of the unstable region, often located at the base of the stratosphere, the updrafts spread laterally and produce the characteristic anvil top. Generally, ice-laden cirrus clouds make up the top and are spread downwind by strong winds aloft. The mature stage is the most active period of a thunderstorm. Gusty winds, lightning, heavy precipitation, and sometimes small hail are experienced.

Dissipating Stage. Once downdrafts begin, the vacating air and precipitation encourage more entrainment of the cool, dry air surrounding the cell. Eventually, the downdrafts dominate throughout the cloud and initiate the **dissipating stage** (Figure 10–4c). The cooling effect of falling precipitation and the influx of colder air aloft mark the end of the thunderstorm activity. Without a supply of moisture from updrafts, the cloud will soon evaporate. An interesting fact is that only a modest portion—on the order of 20 percent—of the moisture that condenses in an air-mass thunderstorm actually leaves the cloud as precipitation. The remaining 80 percent evaporates back into the atmosphere.

It should be noted that within a single air-mass thunderstorm there may be several individual *cells*—that is, zones of adjacent updrafts and downdrafts. When you view a thunderstorm, you may notice that the cumulonimbus cloud consists of several towers (Figure 10–5b). Each tower may represent an individual cell that is in a somewhat different part of its life cycle.

To summarize, the stages in the development of an air-mass thunderstorm are as follows:

1. The *cumulus stage,* in which updrafts dominate throughout the cloud, and growth from a cumulus to a cumulonimbus cloud occurs.
2. The *mature stage,* the most intense phase, with heavy rain and possibly small hail, in which downdrafts are found side by side with updrafts.
3. The *dissipating stage,* dominated by downdrafts and entrainment, causing evaporation of the structure.

Occurrence

Mountainous regions, such as the Rockies in the West and the Appalachians in the East, experience a greater number of air-mass thunderstorms than do the Plains states. The air near the mountain slope is heated more intensely than air at the same elevation over the adjacent lowlands. A general upslope movement then develops during the daytime that can sometimes generate thunderstorm cells. These cells may remain almost stationary above the slopes below.

Although the growth of thunderstorms is aided by high surface temperatures, many thunderstorms are not generated solely by surface heating. For example, many of Florida's thunderstorms are triggered by the convergence associated with sea-to-land airflow (see Figure 4–22, p. 117). Many thunderstorms that form over the eastern two-thirds of the United States occur as part of the general convergence and frontal wedging that accompany passing mid-latitude cyclones. Near the equator, thunderstorms commonly form in association with the convergence along the equatorial low. Most of these thunderstorms are not severe, and their life cycles are similar to the three-stage model described for air-mass thunderstorms.

Severe Thunderstorms

Severe thunderstorms are capable of producing heavy downpours and flash flooding as well as strong, gusty straight-line winds, large hail, frequent lightning, and perhaps tornadoes (see Box 10–1). For a thunderstorm to be officially classified as *severe* by the National Weather Service, it must have winds in excess of 93 kilometers (58 miles) per hour (50 knots) or produce hailstones with diameters larger than 1.9 centimeters (0.75 inch) or generate a tornado. Of the estimated 100,000 thunderstorms that occur annually in the United States, about 10 percent (10,000 storms) reach severe status.

As you learned in the preceding section, air-mass thunderstorms are localized, relatively short-lived phenomena that dissipate after a brief, well-defined life cycle. They actually extinguish themselves because downdrafts cut off the supply of moisture necessary to maintain the storm. For this reason, air-mass thunderstorms seldom if ever produce severe weather. By contrast, other thunderstorms do not quickly dissipate but instead may remain active for hours. Some of these larger, longer-lived thunderstorms attain severe status.

Why do some thunderstorms persist for many hours? A key factor is the existence of strong vertical wind shear—that is, changes in wind direction and/or speed between different heights. When such conditions prevail, the updrafts that provide the storm with moisture do not remain vertical, but become tilted. Because of this, the precipitation that forms high in the cloud falls into the downdraft rather than into the updraft as occurs in air-mass thunderstorms. This allows the updraft to maintain its strength and continue to build upward. Sometimes the updrafts are sufficiently strong that the cloud top is able to push its way into the stable lower stratosphere, a situation called *overshooting* (Figure 10–6).

Beneath the cumulonimbus tower, where downdrafts reach the surface, the denser cool air spreads out along the ground. The leading edge of this outflowing downdraft acts like a wedge, forcing warm, moist surface air into the thunderstorm. In this way, the downdrafts act to maintain the updrafts, which in turn sustain the thunderstorm.

By examining Figure 10–6, you can see that the outflowing cool air of the downdraft acts as a "mini cold front" as it advances into the warmer surrounding air. This outflow boundary is called a **gust front.** As the gust front moves across the ground, the very turbulent air sometimes picks up loose dust and soil, making the advancing boundary visible. Frequently a *roll cloud* may form as warm air is lifted along the leading edge of the gust front (Figure 10–7). The

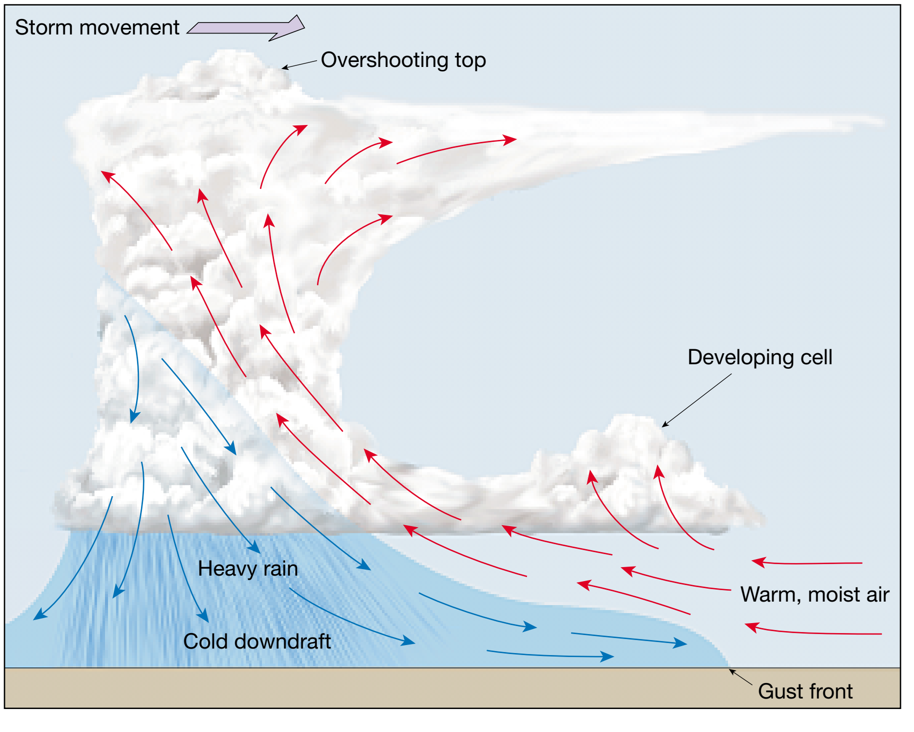


FIGURE 10-6 Diagram of a well-developed cumulonimbus tower showing updrafts, downdrafts, and an overshooting top. Precipitation forming in the tilted updraft falls into the downdraft. Beneath the cloud, the denser cool air of the downdraft spreads out along the ground. The leading edge of the outflowing downdraft acts to wedge moist surface air into the cloud. Eventually the outflow boundary may become a gust front that initiates new cumulonimbus development.

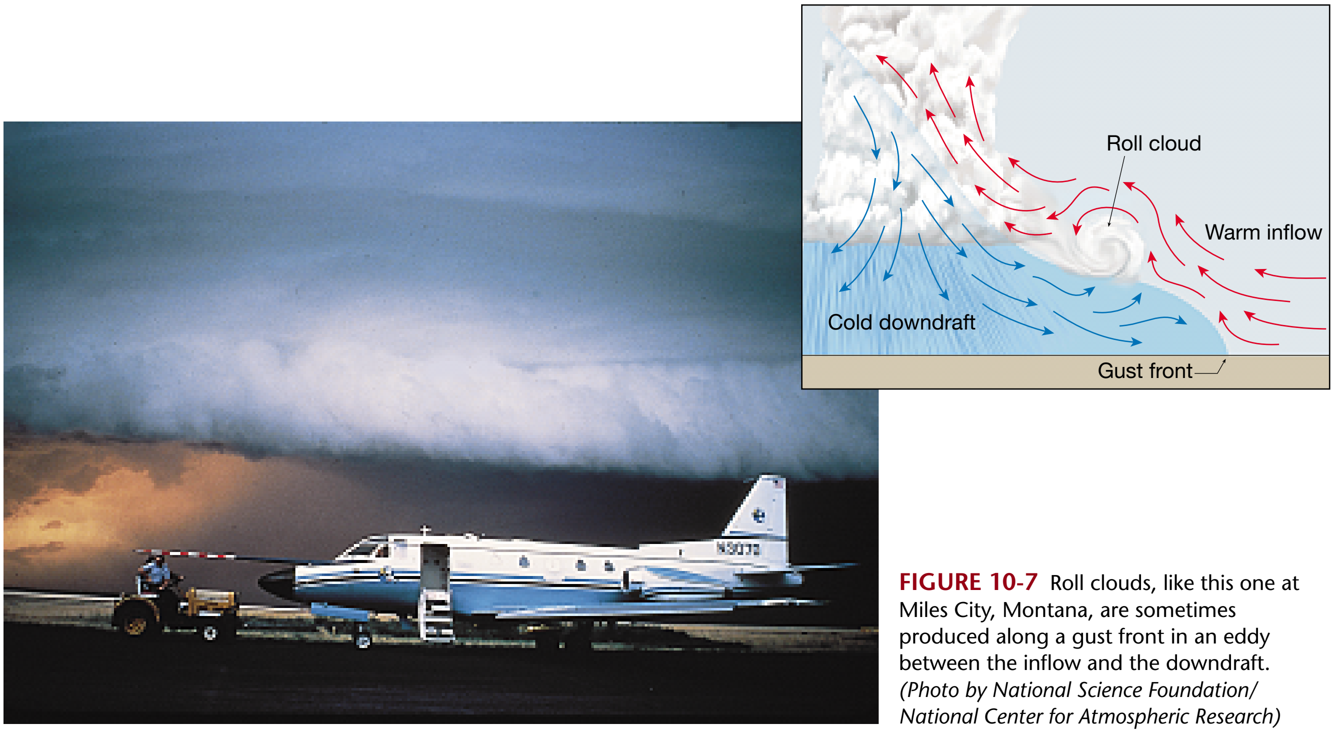


FIGURE 10-7 Roll clouds, like this one at Miles City, Montana, are sometimes produced along a gust front in an eddy between the inflow and the downdraft. *(Photo by National Science Foundation/ National Center for Atmospheric Research)*

advance of the gust front can provide the lifting needed for the formation of new thunderstorms many kilometers away from the initial cumulonimbus clouds.

Supercell Thunderstorms

Some of our most dangerous weather is caused by a type of thunderstorm called a **supercell.** Few weather phenomena are as awesome (Figure 10–8). An estimated 2000 to 3000 supercell thunderstorms occur annually in the United States. They represent just a small fraction of all thunderstorms, but they are responsible for a disproportionate share of the deaths, injuries, and property damage associated with severe weather. Less than half of all supercells produce tornadoes, yet virtually all of the strongest and most violent tornadoes are spawned by supercells.

A supercell consists of a single, very powerful cell that at times can extend to heights of 20 kilometers (65,000 feet) and that persists for many hours. These massive clouds have diameters ranging between about 20 and 50 kilometers (12 and 30 miles).

Despite the single-cell structure of supercells, these storms are remarkably complex. The vertical wind profile may cause the updraft to rotate. For example, this could occur if the surface flow is from the south or southeast and the winds aloft increase in speed and become more westerly with height. If a thunderstorm develops in such a wind environment, the updraft is made to rotate. It is within this column of cyclonically rotating air, called the **mesocyclone,** that tornadoes often form.*

*More on mesocyclones can be found in the section on "Tornado Development."

The huge quantities of latent heat needed to sustain a supercell require special conditions that keep the lower troposphere warm and moisture-rich. Studies suggest that the existence of an inversion layer a few kilometers above the surface helps to provide this basic requirement. Recall that temperature inversions represent very stable atmospheric conditions that restrict vertical air motions. The presence of an inversion seems to aid the production of a few very large thunderstorms by inhibiting the formation of many smaller ones (Figure 10–9). The inversion prevents the mixing of warm, humid air in the lower troposphere with cold, dry air above. Consequently, surface heating continues to increase the temperature and moisture content of the layer of air trapped below the inversion. Eventually, the inversion is locally eroded by strong mixing from below. The unstable air below "erupts" explosively at these sites, producing unusually large cumulonimbus clouds. It is from such clouds, with their concentrated, persistent updrafts, that supercells form.

Squall Lines and Mesoscale Convective Complexes

Because the atmospheric conditions favoring the formation of severe thunderstorms often exist over a broad area, they frequently develop in groups that consist of many individual storms clustered together. Sometimes these clusters occur as elongate bands called *squall lines.* At other times the storms are organized into roughly circular clusters known as *mesoscale convective complexes.* No matter how the cells are arranged, they are not simply clusters of unrelated individual storms. Rather, they are related by a common origin, or they occur in a situation in which some cells lead to the formation of others.

BOX 10-1 Atmospheric Hazard: Flash Floods—The Number One Thunderstorm Killer

Tornadoes and hurricanes are nature's most awesome storms. Because of this status, they are logically the focus of much well-deserved attention. Yet, surprisingly, in most years these dreaded events are not responsible for the greatest number of storm-related deaths. That distinction is reserved for flash floods. For the nine-year period 1995–2004, the number of storm-related deaths in the United States from flooding averaged 84 per year. By contrast, tornado fatalities averaged 65 annually and hurricanes, 15 (Figure 10–A).

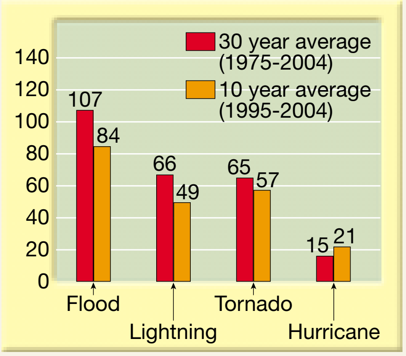


FIGURE 10-A Average annual storm-related deaths in the United States for two time spans. *(Data from National Weather Service)*

Flash floods are local floods of great volume and short duration. The rapidly rising surge of water usually occurs with little advance warning and can destroy roads, bridges, homes, and other substantial structures (Figure 10–B). Discharges quickly reach a maximum and diminish almost as rapidly. Flood flows often contain large quantities of sediment and debris as they sweep channels clean.

Several factors influence flash flooding. Among them are rainfall intensity and duration, surface conditions, and topography. Urban areas are susceptible to flash floods because a high percentage of the surface area is composed of impervious roofs, streets, and parking lots, where runoff is very rapid (Figure 10–C).

Frequently, flash floods result from the torrential rains associated with a slow-moving severe thunderstorm or take place when a series of thunderstorms repeatedly pass over the same location. Sometimes they are triggered by heavy rains from hurricanes and tropical storms. Occasionally, floating debris or ice can accumulate at a natural or artificial obstruction and restrict the flow of water. When such temporary dams fail, torrents of water can be released as a flash flood.

Flash floods can take place in almost any area of the country. They are particularly common in mountainous terrain, where steep slopes can quickly channel runoff into narrow valleys. The hazard is most acute

FIGURE 10-B Debris piled around the sign for a campground in Spain's Pyrenees Mountains on August 8, 1996, after a flash flood flowed through the campground killing at least 67 people and injuring another 180. *(AP Photo/Christophe Ena)*

when the soil is already nearly saturated from earlier rains or consists of impermeable materials. A disaster in Shadydale, Ohio, demonstrates what can happen when even moderately heavy rains fall on saturated ground with steep slopes.

> On the evening of 14 June 1990, 26 people lost their lives as rains estimated to be in the range of 3 to 5 inches fell on saturated soil, which generated flood waves in streams that reached tens of feet in height, destroying near-bank residences and businesses. Preceding months of above-normal rainfall had generated soil moisture contents of near saturation. As a result, moderate amounts of rainfall caused large amounts of surface and near-surface runoff. Steep valleys with practically vertical walls channeled the floods, creating very fast, high, and steep wave crests.*

Why do so many people perish in flash floods? Aside from the factor of surprise (many are caught sleeping), people do not appreciate the power of moving water. A glance at Figure 10–B helps illustrate the force of a flood wave. Just 15 centimeters (6 inches) of fast-moving flood water can knock a person down. Most automobiles will float and be swept away in only 0.6 meter (2 feet) of water. *More than half of all U.S. flash-flood fatalities are auto related!* Clearly, people should never attempt to drive over a flooded road. The depth of water is not always obvious. Also, the road bed may have been washed out under water. Present-day flash floods are calamities with potential for very high death tolls and huge property losses. Although efforts are being made to improve observations and warnings, flash floods remain elusive natural killers.

*"Prediction and Mitigation of Flash Floods: A Policy Statement of the American Meteorological Society." *Bulletin of the American Meteorological Society,* Vol. 74, No. 8 (Aug. 1993), p. 1586.

FIGURE 10-C Urban areas are susceptible to flash floods because runoff following heavy rains is rapid due to the high percentage of the surface that is impervious. Flash flooding in Las Vegas, Nevada, in August 2003. Parts of the city received nearly half the average annual rainfall in a matter of hours. Here firefighters are rescued from a fire truck that was caught in a torrent of water. *(Phot by John Locher/Las Vegas Review-Journal)*

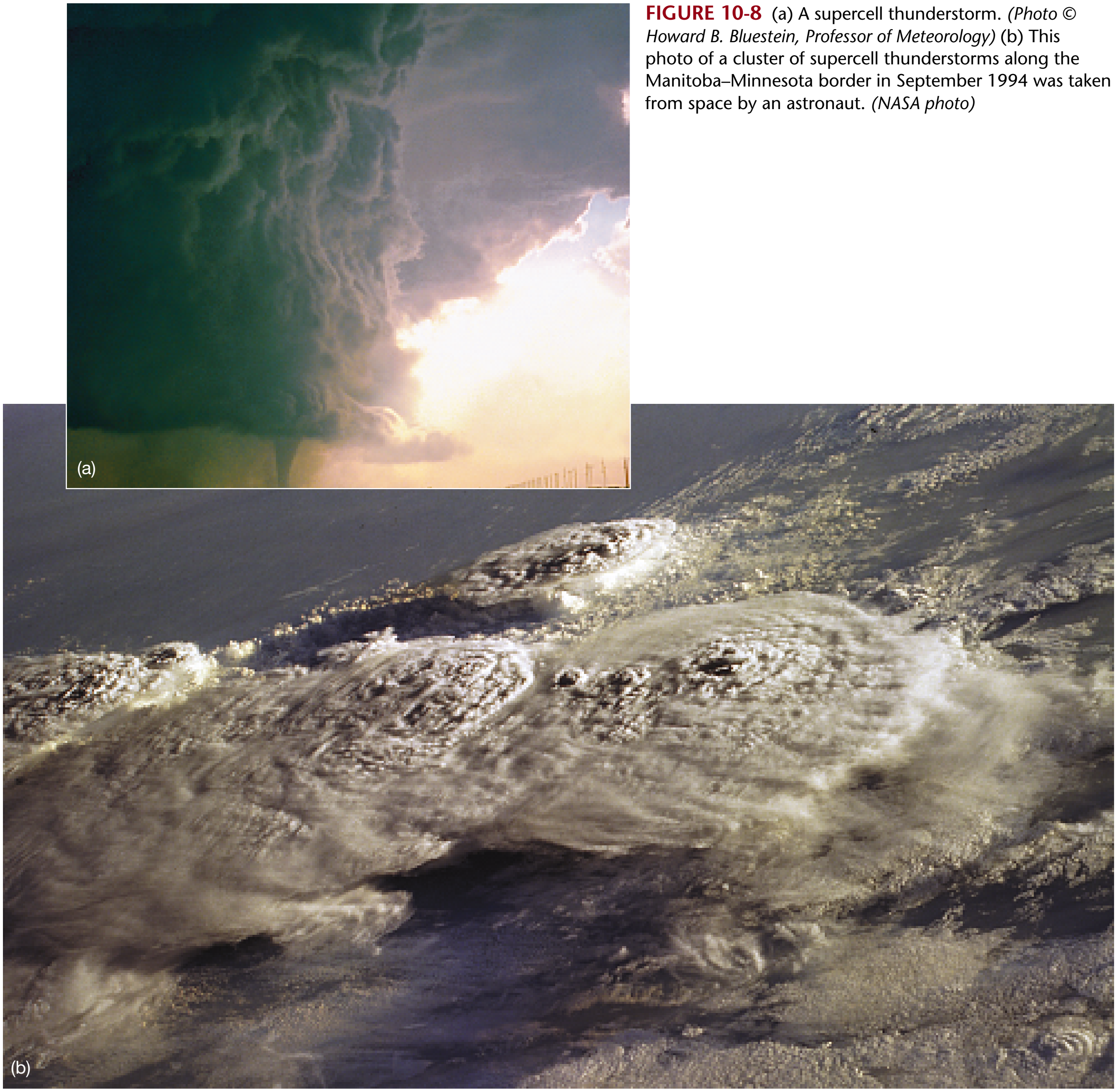


FIGURE 10-8 (a) A supercell thunderstorm. *(Photo © Howard B. Bluestein, Professor of Meteorology)* (b) This photo of a cluster of supercell thunderstorms along the Manitoba–Minnesota border in September 1994 was taken from space by an astronaut. *(NASA photo)*

Squall Lines. A **squall line** is a relatively narrow band of thunderstorms, some of which may be severe, that develops in the warm sector of a middle-latitude cyclone, usually 100 to 300 kilometers (60 to 180 miles) in advance of the cold front. The linear band of cumulonimbus development might stretch for 500 kilometers (300 miles) or more and consists of many individual cells in various stages of development. An average squall line can last for 10 hours or more, and some have been known to remain active for more than a day. Sometimes the approach of a squall line is preceded by a *mammatus sky* consisting of dark cloud rolls that have downward pouches (Figure 10–10).

Most squall lines are not the product of forceful lifting along a cold front. Some develop from a combination of warm, moist air near the surface and an active jet stream aloft. The squall line forms when the divergence and resulting lift created by the jet stream is aligned with a strong, persistent low-level flow of warm, humid air from the south.

A squall line with severe thunderstorms can also form along a boundary called a **dryline,** a narrow zone along which there is an abrupt change in moisture. It forms when continental tropical (cT) air from the southwestern United States is pulled into the warm sector of a middle-latitude cyclone, as shown in Figure 10–11. The denser cT air acts to lift the less dense mT air with which it is converging.* By contrast, both cloud formation and storm development along

*Warm, dry air is more dense than warm, humid air, because the molecular weight of water vapor (H_2O) is only about 62 percent as great as the molecular weight of the mixture of gases that make up dry air.

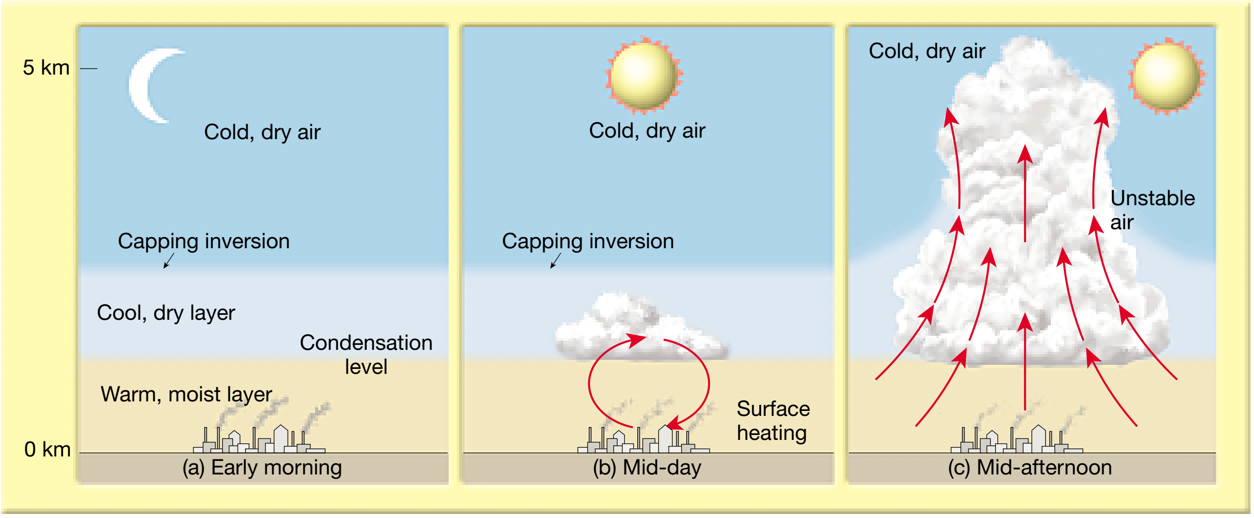


FIGURE 10-9 The formation of severe thunderstorms can be enhanced by the existence of a temperature inversion located a few kilometers above the surface.

the cold front are minimal because the front is advancing into dry cT air.

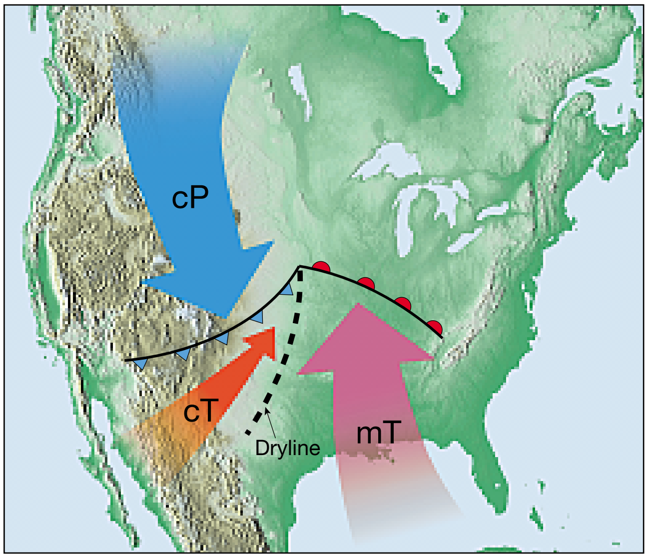
Drylines most frequently develop in the western portions of Texas, Oklahoma, and Kansas. Such a situation is illustrated by Figure 10–12. The dryline is easily identified by comparing the dew-point temperatures on either side of the squall line. The dew points in the mT air to the east are 30° to 45°F higher than those in the cT air to the west. Much severe weather was generated as this extraordinary squall line moved eastward, including 55 tornadoes over a six-state region.

Mesoscale Convective Complexes. A **mesoscale convective complex (MCC)** consists of many individual thunderstorms organized into a large oval to circular cluster. A typical MCC is large, covering an area of at least 100,000 square kilometers (39,000 square miles). The usually slow-moving complex may persist for 12 hours or more (Figure 10–13).

MCCs tend to form most frequently in the Great Plains. When conditions are favorable, an MCC develops from a group of afternoon air-mass thunderstorms. In the evening, as the local storms decay, the MCC starts developing. The transformation of afternoon air-mass thunderstorms into an MCC requires a strong low-level flow of very warm and moist air. This flow enhances instability, which in turn spurs convection and cloud development. As long as favorable conditions prevail, MCCs remain self-propagating as gust fronts from existing cells lead to the formation of new powerful cells nearby. New thunderstorms tend to develop near

FIGURE 10-10 The dark overcast of a mammatus sky, with its characteristic downward bulging pouches, sometimes precedes a squall line. When a mammatus formation develops, it is usually after a cumulonimbus cloud reaches its maximum size and intensity. Its presence is generally a sign of an especially vigorous thunderstorm. *(Photo by Annie Griffiths/DRK Photo)*

FIGURE 10-11 Squall-line thunderstorms frequently develop along a dryline, the boundary separating warm, dry continental tropical air and warm, moist maritime tropical air.



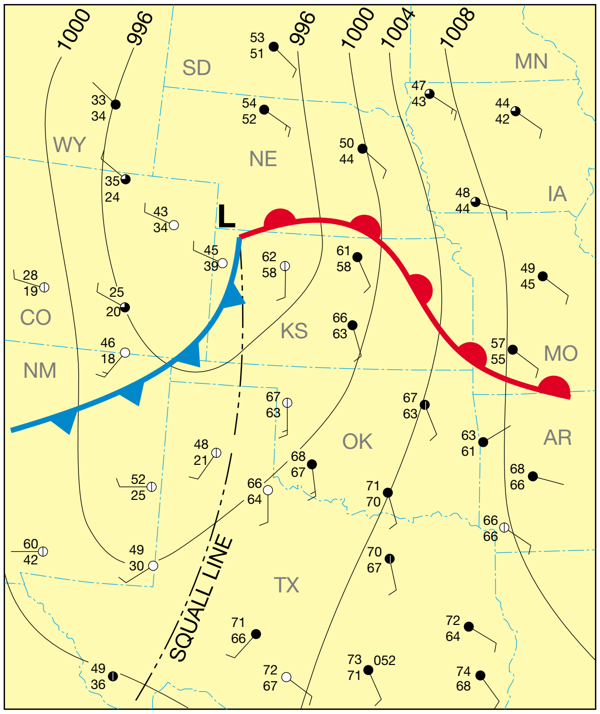


FIGURE 10-12 The squall line of this middle-latitude cyclone was responsible for a major outbreak of tornadoes. The squall line separates dry (cT) and very humid (mT) air. The dryline is easily identified by comparing dew-point temperatures on either side of the squall line. Dew point (°F) is the lower number at each station.

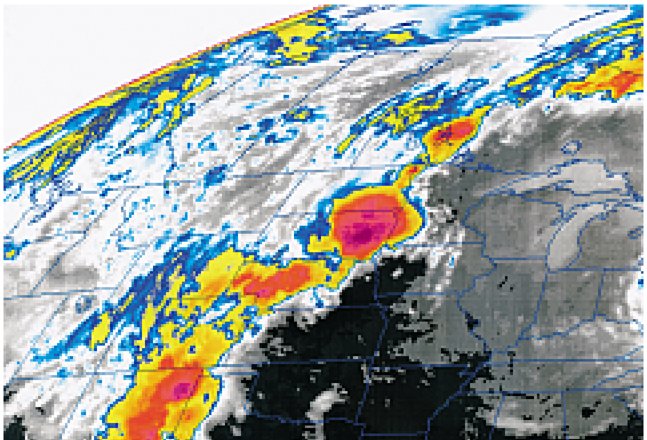
the side of the complex that faces the incoming low-level flow of warm, moist air.

Although mesoscale convective complexes sometimes produce severe weather, they are also beneficial because they provide a significant portion of the growing-season rainfall to the agricultural regions of the central United States.

Microbursts

Beneath some thunderstorms, strong localized downdrafts known as *downbursts* sometimes occur. When downbursts are small—that is, less than 4 kilometers (2.5 miles) across—they are called **microbursts.** These straight-line concentrated bursts of wind are often produced when downdrafts are accelerated by a great deal of evaporative cooling. (Remember, the colder the air, the denser it is, and the denser the air, the faster it will "fall.") Microbursts typically last just two to five minutes. Despite their small size and short duration, microbursts represent a significant atmospheric hazard.

FIGURE 10-13 This satellite image shows a mesoscale convective complex (MCC) over the eastern Dakotas. *(NOAA)*



Upon reaching the surface, the chilled air of the microburst pushes out in all directions from the center of the downdraft, similar to a jet of water from a faucet splashing in a sink. In this manner, microbursts can produce winds in excess of 160 kilometers (100 miles) per hour. Within minutes the source of the downdraft dissipates while the outflow at the ground continues to expand.

The violent winds of a microburst can cause a great deal of destruction. For example, in July 1993 millions of trees were uprooted by a microburst near Pak Wash, Ontario. In July 1984 11 people drowned when a microburst caused a 28-meter- (90-foot-) long sternwheeler boat to capsize on the Tennessee River. Sometimes the damage associated with these violent outflows is mistaken for tornado damage. However, wind damage from microbursts occurs in straight lines, whereas a rotational circulation pattern is usually detectable along the damage path created by a tornado.

The wind shear associated with microbursts has been responsible for a number of airplane crashes. Imagine an aircraft attempting to land and being confronted by a microburst, as in Figure 10–14. As the airplane flies into the microburst, it initially encounters a strong headwind, which tends to carry it upward. To reduce the lift, the pilot points the nose of the aircraft downward. Then, just seconds later, a tailwind is encountered on the opposite side of the microburst. Here, because the wind is moving with the airplane, the amount of air flowing over the wings and providing lift is dramatically reduced, causing the craft to suddenly lose altitude and crash.

The number of aviation deaths due to microbursts has declined significantly as understanding of the event has increased. Systems to detect the wind shifts associated with microbursts have been installed at most major airports in the United States. Moreover, pilots now receive training on how to handle microbursts during takeoffs and landings.

Lightning and Thunder

A storm is classified as a thunderstorm only after thunder is heard. Because thunder is produced by lightning, lightning must also be present (see chapter-opening photo and Figure 10–15). **Lightning** is similar to the electrical shock you may have experienced on touching a metal object on a very dry day. Only the intensity is different.

During the formation of a large cumulonimbus cloud, a separation of charge occurs, which simply means that part of the cloud develops an excess negative charge, whereas another part acquires an excess positive charge. The object of lightning is to equalize these electrical differences by producing a negative flow of current from the region of excess negative charge to the region with excess positive charge or vice versa. Because air is a poor conductor of electricity (good insulator), the electrical potential (charge difference) must be very high before lightning will occur.

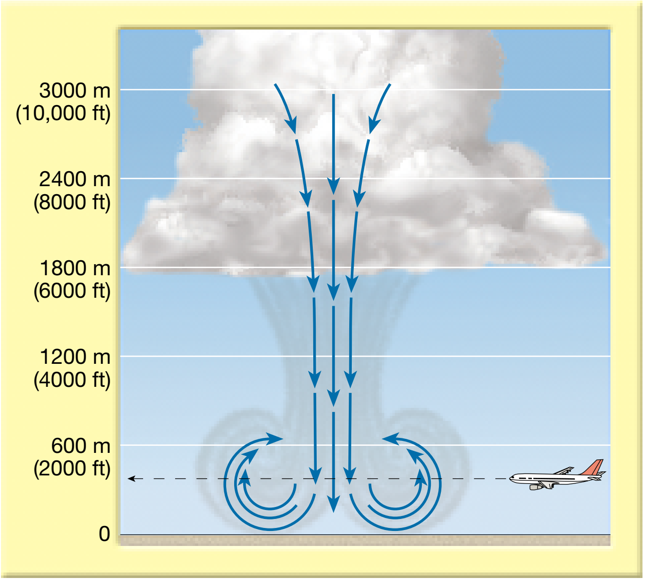


FIGURE 10-14 The arrows in this sketch represent the movement of air in a microburst, a concentrated intense downdraft formed by extraordinary evaporative cooling that creates an outward wind burst at the surface. If you could see it leave the cloud and strike the ground, it might resemble a narrow stream of water "splashing" into a sink. Because of the extremely abrupt changes in wind direction within microbursts, they are a threat to aircraft during landings and takeoffs.

The most common type of lightning occurs between oppositely charged zones *within* a cloud or between clouds. About 80 percent of all lightning is of this type. It is often called *sheet lightning* because it produces a bright but diffuse illumination of those parts of the cloud in which the flash occurred. Sheet lightning is not a unique form; rather, it is ordinary lightning in which the flash is obscured by the clouds. The second type of lightning, in which the electrical discharge occurs between the cloud and Earth's surface, is often more dramatic (see chapter-opening photo). This *cloud-to-ground lightning* represents about 20 percent of lightning strokes and is the most damaging and dangerous form.

FIGURE 10-15 Multiple lightning stroke of a single flash as recorded by a moving-film camera. *(Courtesy of E. J. Tarbuck)*

What Causes Lightning?

The origin of charge separation in clouds, although not fully understood, must hinge on rapid vertical movements within, because lightning occurs primarily in the violent mature stage of a cumulonimbus cloud. In the midlatitudes the formation of these towering clouds is chiefly a summertime phenomenon, which explains why lightning is seldom observed there in the winter. Furthermore, lightning rarely occurs before the growing cloud penetrates the 5-kilometer level, where sufficient cooling begins to generate ice crystals.

Some cloud physicists believe that charge separation occurs during the formation of ice pellets. Experimentation shows that as droplets begin to freeze, positively charged ions are concentrated in the colder regions of the droplets, whereas negatively charged ions are concentrated in the warmer regions. Thus, as the droplets freeze from the outside in, they develop a positively charged ice shell and a negatively charged interior. As the interior begins to freeze, it expands and shatters the outside shell. The small positively charged ice fragments are carried upward by turbulence, and the relatively heavy droplets eventually carry their negative charge toward the cloud base. As a result, the upper part of the cloud is left with a positive charge, and the lower portion of the cloud maintains an overall negative charge with small positively charged pockets (Figure 10–16).

As the cloud moves, the negatively charged cloud base alters the charge at the surface directly below by repelling negatively charged particles. Thus, the surface beneath the cloud acquires a net positive charge. These charge differences build to millions and even hundreds of millions of volts before a lightning stroke acts to discharge the negative region of the cloud by striking the positive area of the ground below, or, more frequently, the positively charged portion of that cloud, or a nearby cloud.

Students Sometimes Ask…

How frequently does lightning strike the ground in the United States?

Beginning in the late 1980s, it has been possible to detect cloud-to-ground lightning flashes in real time across the country. Since 1989 the *National Lightning Detection Network* has recorded an average of about 20 million cloud-to-ground flashes per year in the contiguous 48 states. In addition, about half of all flashes have more than one ground-strike point, so at least 30 million points on the ground are struck in an average year. Besides cloud-to-ground flashes, there are roughly 5 to 10 times as many flashes within clouds.

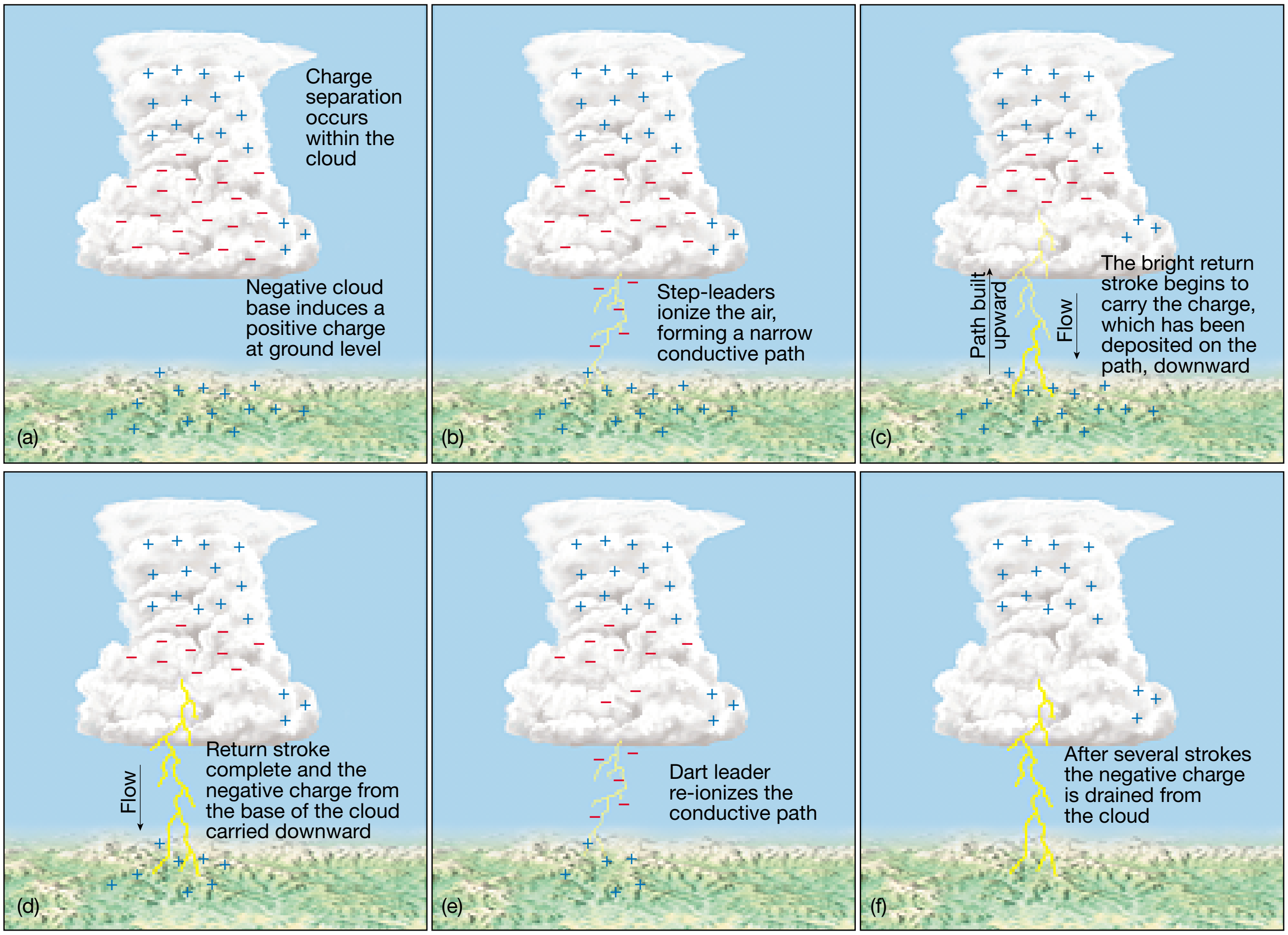


FIGURE 10-16 Discharge of a cloud via cloud-to-ground lightning. Examine this drawing carefully while reading the text.

The Lightning Stroke

Cloud-to-ground strokes are of most interest and have been studied in detail (see Box 10–2). Moving-film cameras have greatly aided in these studies (see Figure 10–15). They show that the lightning we see as a single flash is really several very rapid strokes between the cloud and the ground. We will call the total discharge—which lasts only a few tenths of a second and appears as a bright streak—the **flash.** Individual components that make up each flash are termed **strokes.** Each stroke is separated by roughly 50 milliseconds, and there are usually three to four strokes per flash.* When a lightning flash appears to flicker, it is because your eyes discern the individual strokes that make up this discharge. Moreover, each stroke consists of a downward propagating leader that is immediately followed by a luminous return stroke.

Each stroke is believed to begin when the electrical field near the cloud base frees electrons in the air immediately below, thereby ionizing the air (Figure 10–16). Once ionized, the air becomes a conductive path having a radius of roughly 10 centimeters and a length of 50 meters. This path is called a **leader.** During this electrical breakdown, the mobile electrons in the cloud base begin to flow down this channel. This flow increases the electrical potential at the head of the leader, which causes a further extension of the conductive path through further ionization. Because this initial path extends itself earthward in short, nearly invisible bursts, it is called a **step leader.** Once this channel nears the ground, the electrical field at the surface ionizes the remaining section of the path. With the path completed, the electrons that were deposited along the channel begin to flow downward. The initial flow begins near the ground.

As the electrons at the lower end of the conductive path move earthward, electrons positioned successively higher up the channel begin to migrate downward. Because the path of electron flow is continually being extended upward, the accompanying electric discharge has been appropriately named a **return stroke.** As the wave front of the return stroke moves upward, the negative charge that was deposited on the channel is effectively lowered to the ground. It is this intense return stroke that illuminates the conductive path and discharges the lowest

*One millisecond equals one one-thousandth ($\frac{1}{1000}$) of a second.

BOX 10-2 Atmospheric Hazard: Lightning Safety*

In the United States, lightning ranks second only to floods in the number of storm-related deaths each year. Although the number of reported lightning deaths in the United States annually averages about 70, many go unreported. About 100 people are estimated to be killed and more than 500 injured by lightning every year in the United States.

Warnings, statements, and forecasts are routinely issued for floods, tornadoes, and hurricanes, but not for lightning. Why is this the case? The answer relates to the wide geographic occurrence and frequency of lightning.

The magnitude of the cloud-to-ground lightning hazard is understood better today than ever before. Lightning occurs in the United States every day in summer and nearly every day during the rest of the year. Because lightning is so widespread and strikes the ground with such great frequency, it is not possible to warn each person of every flash. For this reason, lightning can be considered the most dangerous weather hazard that many people encounter each year.

Being aware of and following proven safety guidelines can greatly reduce the risk of injury or death. Individuals are ultimately responsible for their personal safety and should take appropriate action when threatened by lightning.

No place is absolutely safe from the threat of lightning, but some places are safer than others.

- Large enclosed structures (substantially constructed buildings) tend to be much safer than smaller or open structures. The risk for lightning injury depends on whether the structure incorporates lightning protection, the types of construction materials used, and the size of the structure.
- In general, fully enclosed metal vehicles, such as cars, trucks, buses, vans, and fully enclosed farm vehicles, etc., with the windows rolled up, provide good shelter from lightning. Avoid contact with metal or conducting surfaces outside or inside the vehicle.
- Avoid being in or near high places and open fields, isolated trees, unprotected gazebos, rain or picnic shelters, baseball dugouts, communications towers, flagpoles, light poles, bleachers (metal or wood), metal fences, convertibles, golf carts, and water (ocean, lakes, swimming pools, rivers, etc.).
- When inside a building, avoid use of the telephone, taking a shower, washing your hands, doing dishes, or any contact with conductive surfaces with exposure to the outside, such as metal doorframes or window frames, electrical wiring, telephone wiring, cable TV wiring, plumbing, and so forth.

Safety guidelines for individuals include the following:

- Generally speaking, if individuals can see lightning and/or hear thunder, they are already at risk. Louder or more frequent thunder indicates that lightning activity is approaching, thus increasing the risk for lightning injury or death. If the time delay between seeing the flash (lightning) and hearing the bang (thunder) is less than 30 seconds, the individual should be in, or seek, a safer location. Be aware that this method of ranging has severe limitations, in part due to the difficulty of associating the proper thunder to the corresponding flash.
- High winds, rainfall, and cloud cover often act as precursors to actual cloud-to-ground strikes, and these should motivate individuals to take action. Many lightning casualties occur in the beginning, as the storm approaches, because people ignore these precursors. Also, many lightning casualties occur after the perceived threat has passed. Generally, the lightning threat diminishes with time after the last sound of thunder but may persist for more than 30 minutes. When thunderstorms are in the area but not overhead, the lightning threat can exist even when it is sunny, not raining, or when clear sky is visible.
- When available, pay attention to weather-warning devices such as NOAA (National Oceanic and Atmospheric Administration) weather radio and/or credible lightning-detection systems; however, do not let this information override good common sense.

*Material in this box is based on "Updated Recommendations for Lightning Safety—1998," in *Bulletin of the American Meteorological Society,* Vol. 80, No. 10, October 1999, pp. 2035–39.

kilometer or so of the cloud. During this phase, tens of coulombs of negative charge are lowered to the ground.*

The first stroke is usually followed by additional strokes that apparently drain charges from higher areas within the cloud. Each subsequent stroke begins with a **dart leader** that once again ionizes the channel and carries the cloud potential toward the ground. The dart leader is continuous and less branched than the step leader. When the current between strokes has ceased for periods greater than 0.1 second, further strokes will be preceded by a step leader whose path is different from that of the initial stroke. The total time of each flash consisting of three or four strokes is about 0.2 second.

Students Sometimes Ask...

About how many people who are struck by lightning are actually killed?

According to the National Weather Service, only about 10 percent are killed, leaving 90 percent with various injuries. Lightning tends to injure the nervous system. When the brain is affected, the person may have difficulty with short-term memory, coding new information and accessing old information, multitasking, and being easily distracted. Lightning victims may also suffer personality changes because of frontal lobe damage and become irritable and easy to anger. In addition, some survivors complain of becoming more easily exhausted than before being struck.

Thunder

The electrical discharge of lightning superheats the air immediately around the lightning channel. In less than a second the temperature rises by as much as 33,000°C. When air is heated this quickly, it expands explosively and produces the sound waves we hear as **thunder.** Because lightning and thunder occur simultaneously, it is possible to estimate the distance to the stroke. Lightning is seen instantaneously, but the relatively slow sound waves, which travel approximately 330 meters (1000 feet) per second, reach us a little later. If thunder is heard five seconds after the lightning is seen, the lightning occurred about 1650 meters away (approximately 1 mile).

The thunder that we hear as a rumble is produced along a long lightning path located at some distance from the observer. The sound that originates along the path nearest the observer arrives before the sound that originated farthest away. This factor lengthens the duration of the thunder. Reflection of the sound waves by mountains or buildings further delays their arrival and adds to this effect. When lightning occurs more than 20 kilometers (12 miles) away, thunder is rarely heard. This type of lightning, popularly called *heat lightning,* is no different from the lightning that we associate with thunder.

*A coulomb is a unit of electrical charge equal to the quantity of charge transferred in 1 second by a steady current of 1 ampere.

Tornadoes

Tornadoes are local storms of short duration that must be ranked high among nature's most destructive forces. Their sporadic occurrence and violent winds cause many deaths each year. The nearly total destruction in some stricken areas has led many to liken their passage to bombing raids during war (Box 10–3).

Such was the case when devastating tornadoes hit parts of Oklahoma and Kansas on Monday evening, May 3, 1999 (Figure 10–17a). The estimated death toll was 49 people—44 in Oklahoma and five in the Wichita, Kansas, area. Altogether, 76 tornadoes occurred during this outbreak. Oklahoma officials estimated that nearly 8100 homes and businesses were damaged or destroyed. In Kansas the figure exceeded 1100. The insurance industry incurred losses that exceeded $1 billion. Oklahoma and Kansas are well known for tornadoes, but Maryland is not. Nevertheless, on April 28, 2002, towering thunderstorms spawned several tornadoes. The most powerful created a 39-kilometer (24-mile) path of destruction across southern Maryland (Figure 10-17b). Three people died and damages exceeded $100 million. It may have been the strongest tornado ever recorded along the eastern seaboard.

Tornadoes, sometimes called *twisters* or *cyclones,* are violent windstorms that take the form of a rotating column of air, or *vortex,* that extends downward from a cumulonimbus cloud. Pressures within some tornadoes have been estimated to be as much as 10 percent lower than immediately outside the storm. Drawn by the much lower pressure in the center of the vortex, air near the ground rushes into the tornado from all directions. As the air streams inward, it is spiraled upward around the core until it eventually merges with the airflow of the parent thunderstorm deep in the cumulonimbus tower.

Because of the rapid drop in pressure, air sucked into the storm expands and cools adiabatically. If the air cools below its dew point, the resulting condensation creates a pale and ominous-appearing cloud that may darken as it moves across the ground, picking up dust and debris (Figure 10–18). Occasionally, when the inward spiraling air is relatively dry, no condensation funnel forms because the drop in pressure is not sufficient to cause the necessary adiabatic cooling. In such cases, the vortex is only made visible by the material that it vacuums from the surface and carries aloft.

Some tornadoes consist of a single vortex, but within many stronger tornadoes are smaller intense whirls called *suction vortices* that orbit the center of the larger tornado circulation (Figure 10–19). The tornadoes in this latter category are called **multiple vortex tornadoes.** Suction vortices have diameters of only about 10 meters (30 feet) and usually form and die out in less than a minute. They can occur in all sorts of tornado sizes, from huge "wedges" to narrow "ropes." Suction vortices are responsible for most

BOX 10-3 Atmospheric Hazard: Surviving a Violent Tornado

About 11 A.M. on Tuesday, July 13, 2004, much of northern and central Illinois was put on a tornado watch.* A large supercell had developed in the northwestern part of the state and was moving southeast into a very unstable environment (Figure 10–D). A few hours later, as the supercell entered Woodford County, rain began to fall and the storm showed signs of becoming severe. The National Weather Service (NWS) issued a *severe thunderstorm warning* at 2:29 P.M. CDT. Minutes afterward a tornado developed. Twenty-three minutes later, the quarter-mile-wide twister had carved a 9.6-mile-long path across the rural Illinois countryside.

What, if anything, made this storm special or unique? After all, it was just one of a record-high 1819 tornadoes that were reported in the United States in 2004. For one, this tornado attained F4 status for a portion of its life.** The NWS estimated that maximum winds reached 240 miles per hour. Fewer than 1 percent of tornadoes attain this level of severity. However, what was most remarkable is that no one was killed or injured when the Parsons Manufacturing facility west of the small town of Roanoke took a direct hit while the storm was most intense. At the time, 150 people were in three buildings that comprised the plant. The 250,000-square-foot facility was flattened, cars were twisted into gnarled masses, and debris was strewn for miles (Figure 10–E).

*Watches and warnings are discussed later in this chapter on p. 308.

**F4 is a reference to the Fujita Scale of tornado intensity. See Table 10–1, p. 308.

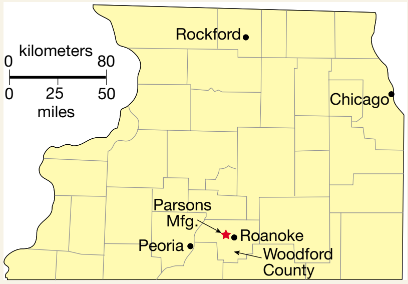


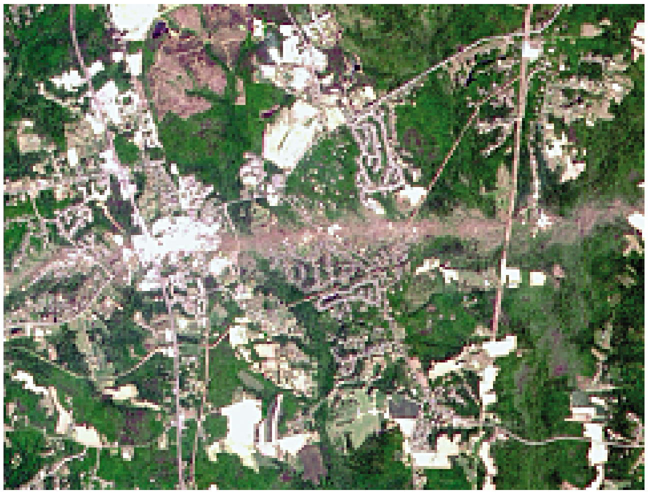
FIGURE 10-D On July 13, 2004, an F4 tornado cut a 23-mile path through the rural countryside near the Woodford County town of Roanoke, Illinois. The Parsons Manufacturing plant was just west of town.

How did 150 people escape death or injury? The answer is foresight and planning. More than 30 years earlier, company owner Bob Parsons was inside his first factory when a small tornado passed close enough to blow windows out. Later, when he built a new plant, he made sure that the restrooms were constructed to double as tornado shelters with steel-reinforced concrete walls and eight-inch-thick concrete ceilings. In addition, the company developed a severe weather plan. When the severe thunderstorm warning was issued at 2:29 P.M. on July 13, the emergency response team leader at the Parsons plant was immediately notified. A few moments later he went outside and observed a rotating wall cloud with a developing funnel cloud. He radioed back to the office to institute the company's severe weather plan. Employees were told to immediately go to their designated storm shelter. Everyone knew where to go and what to do because the plant conducted semi-annual tornado drills. All 150 people reached a shelter in less than four minutes. The emergency response team leader was the last person to reach shelter, less than two minutes before the tornado destroyed the plant at 2:41 P.M.

The total number of tornado deaths in 2004 for the entire United States was just 36. The toll could have been much higher. The building of tornado shelters and the development of an effective severe storm plan made the difference between life and death for 150 people at Parsons Manufacturing.

FIGURE 10-E The quarter-mile-wide tornado had wind speeds reaching 240 miles per hour. The destruction at Parsons Manufacturing was devastating. *(Photos courtesy of NOAA)*

(a)



(b)

FIGURE 10-17 (a) Aftermath of a violent (F5) tornado that struck Oklahoma City on May 3, 1999. The largest and most destructive of the 76 tornadoes formed about 72 kilometers (45 miles) southwest of Oklahoma City and cut a path about 0.8 kilometer (0.5 mile) wide as it moved north and east across the Oklahoma City area, staying on the ground for nearly four hours. The death toll was relatively low because of repeated warnings broadcast throughout the late afternoon and early evening. Yet, even with up to a half hour warning, many could not find adequate shelter from the tremendous power of the strongest storm. *(Photo by Sue Ogrocki/Reuters/Landov LLC)* (b) This satellite image shows the path of a tornado that struck Maryland on April 28, 2002. It was the strongest tornado ever recorded in the state and perhaps the strongest ever recorded along the Eastern Seaboard. The storm flattened everything in its 39-kilometer- (24-mile-) long path, including the historic downtown in the community of LaPlata. In all, nearly 1100 homes and businesses were damaged or destroyed, and damages exceeded $100 million. *(NASA image)*

of the narrow, short swaths of extreme damage that sometimes are through tornado tracks. It is now believed that most reports of several tornadoes at once—from news accounts and early-twentieth-century tornado tales—actually were multiple vortex tornadoes.

Because of the tremendous pressure gradient associated with a strong tornado, maximum winds can sometimes exceed 480 kilometers (300 miles) per hour. For example, using Doppler radar observations, scientists measured wind speeds of 510 kilometers (310 miles) per hour in one of the May 3, 1999, Oklahoma City tornadoes. Reliable wind-speed measurements using traditional anemometers are lacking. The changes that occur in atmospheric pressure with the passage of a tornado are largely estimates and are based on a few storms that happened to pass a nearby weather station. Thus, meteorologists have had to base their tornado models on a relatively scant observational foundation. Although additional data might be gathered if shelters and instruments capable of withstanding the fury of a tornado were placed in an area, such an effort would probably not be worthwhile. Tornadoes are highly localized and randomly distributed, and the probability of placing instruments at the right site would thus be infinitesimally small.

For instance, the probability of a tornado striking a given point in the region most frequently subject to tornadoes is about once in 250 years. The development of Doppler radar, however, has increased our ability to study tornado-producing thunderstorms. As we shall see, the development of this technology is allowing meteorologists to gather important new data from a safe distance.

Students Sometimes Ask...

What does a tornado sound like?

That depends on what it is hitting, its size, intensity, closeness, and other factors. The most common tornado sound is a continuous rumble, like a nearby train. Sometimes a tornado produces a loud whooshing sound, like that of a waterfall or of open car windows while driving very fast. Tornadoes that are tearing through densely populated areas may be producing all kinds of loud noises at once, which collectively may make a tremendous roar. Remember that just because you may have heard a loud roar during a damaging storm does not necessarily mean it was a tornado. Any intense thunderstorm wind can produce damage and cause a roar.

The Development and Occurrence of Tornadoes

Tornadoes form in association with severe thunderstorms that produce high winds, heavy (sometimes torrential) rainfall, and often damaging hail. Although hail may or may not precede a tornado, the portion of the thunderstorm adjacent to large hail is often the area where strong tornadoes are most likely to occur.

Fortunately, less than 1 percent of all thunderstorms produce tornadoes. Nevertheless, a much higher number must be monitored as potential tornado producers. Although meteorologists are still not sure what triggers tornado formation, it is apparent that they are the product of the interaction between strong updrafts in a thunderstorm and the winds in the troposphere.

Tornado Development

Tornadoes can form in any situation that produces severe weather, including cold fronts, squall lines, and tropical cyclones (hurricanes). Usually the most intense tornadoes are those that form in association with supercells. An important precondition linked to tornado formation in severe thunderstorms is the development of a mesocyclone. A *mesocyclone* is a vertical cylinder of rotating air, typically about 3 to 10 kilometers (2 to 6 miles) across, that develops in the updraft of a severe thunderstorm. The formation of this large vortex often precedes tornado formation by 30 minutes or so.

Mesocyclone formation depends on the presence of vertical wind shear. Moving upward from the surface, winds change direction from southerly to westerly and the wind speed increases. The speed wind shear (that is, stronger winds aloft and weaker winds near the surface) produces a rolling motion about a horizontal axis as shown in Figure 10–20a. If conditions are right, strong updrafts in the storm tilt the horizontally rotating air to a nearly vertical alignment (Figure 10–20b). This produces the initial rotation within the cloud interior.

At first the mesocyclone is wider, shorter, and rotating more slowly than will be the case in later stages. Subsequently, the mesocyclone is stretched vertically and narrowed horizontally causing wind speeds to accelerate in an inward vortex (just as ice skaters accelerate while spinning or as a sink full of water accelerates when it spirals down a drain).* Next, the narrowing column of rotating air stretches downward until a portion of the cloud protrudes below the cloud base to produce a very dark, slowly rotating *wall cloud.* Finally, a slender and rapidly spinning vortex emerges from the base of the wall cloud to form a *funnel cloud.* If the funnel cloud makes contact with the surface, it is then classified as a *tornado* (Figure 10–20).

The formation of a mesocyclone does not necessarily mean that tornado formation will follow. Only about half of all mesocyclones produce tornadoes. The reason for this is not understood. Because this is the case, forecasters cannot determine in advance which mesocyclones will spawn tornadoes.

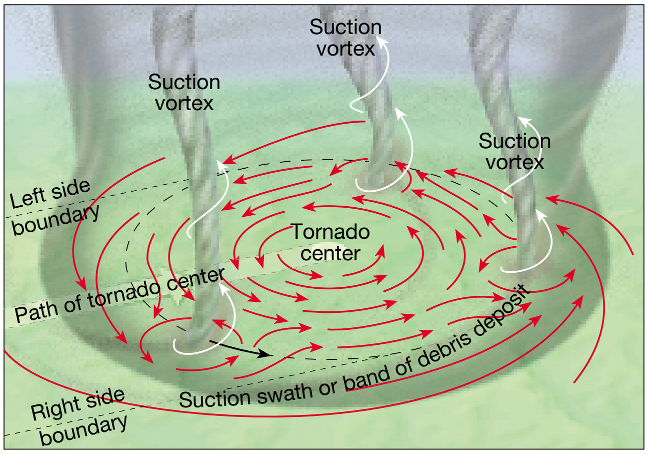
Tornado Climatology

Severe thunderstorms—and hence tornadoes—are most often spawned along the cold front or squall line of a middle-latitude cyclone or in association with supercell thunderstorms.

*For more on this concept, see Box 11–1 on the conservation of angular momentum.

FIGURE 10-18 A tornado is a violently rotating column of air in contact with the ground. The air column is visible when it contains condensation or when it contains dust and debris. Often the appearance is the result of both. When the column of air is aloft and does not produce damage, the visible portion is properly called a *funnel cloud.* This tornado in New Mexico near the Texas Panhandle touched down out of a rotating supercell thunderstorm. *(Photo by A.T. Willett/Alamy)*

FIGURE 10-19 Some tornadoes have multiple suction vortices. These small and very intense vortices are roughly 10 meters (30 feet) across and move in a counterclockwise path around the tornado center. Because of this multiple vortex structure, one building might be heavily damaged and another one, just 10 meters away, might suffer little damage. *(After Fujita)*



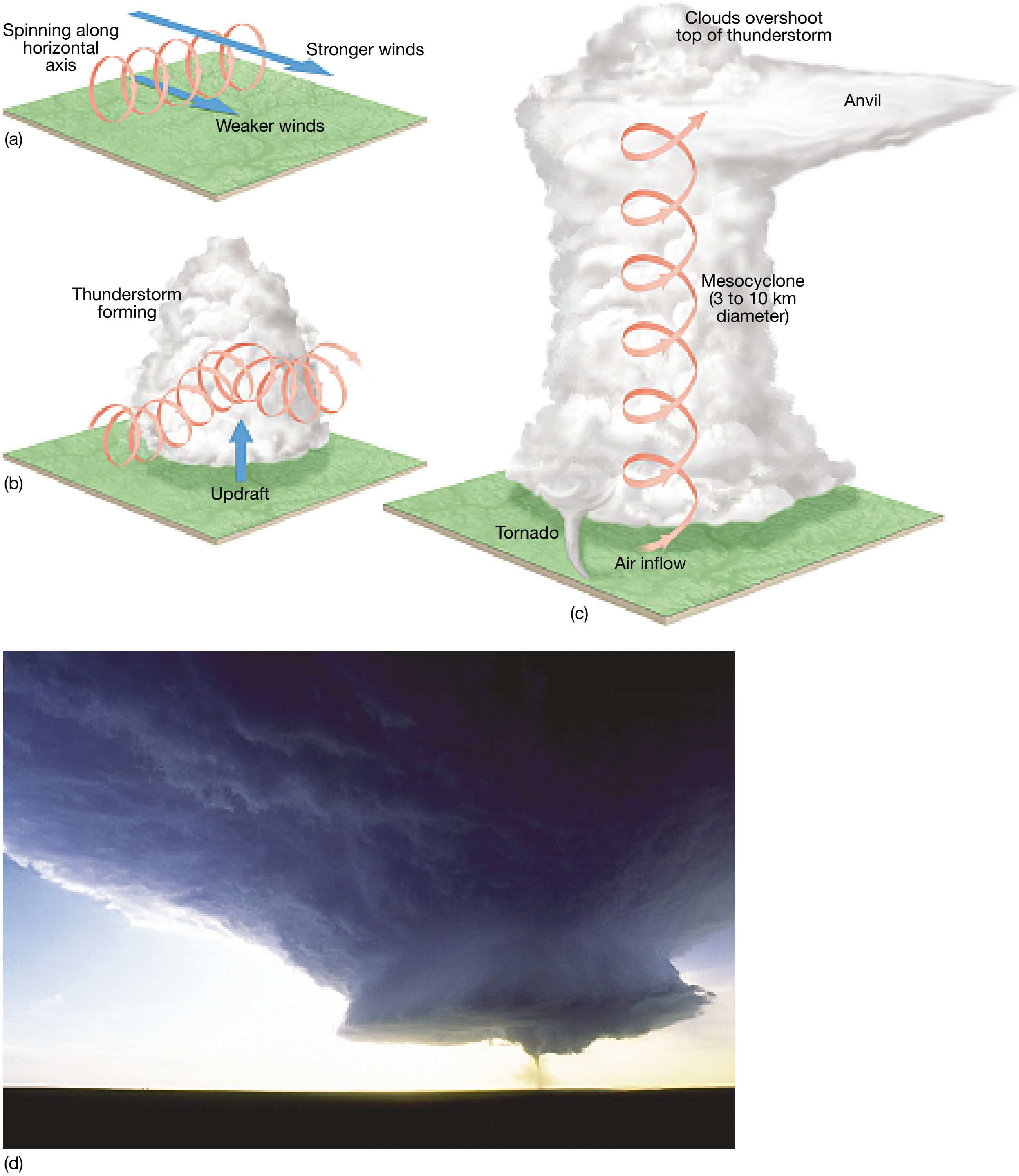


FIGURE 10-20 The formation of a mesocyclone often precedes tornado formation. (a) Winds are stronger aloft than at the surface (called *speed wind shear*), producing a rolling motion about a horizontal axis. (b) Strong thunderstorm updrafts tilt the horizontally rotating air to a nearly vertical alignment. (c) The mesocyclone, a vertical cylinder of rotating air, is established. (d) If a tornado develops it will descend from a slowly rotating wall cloud in the lower portion of the mesocyclone. This supercell tornado hit the Texas Panhandle in May 1996. *(Photo by Warren Faidley/Weatherstock)*

Throughout the spring, air masses associated with midlatitude cyclones are most likely to have greatly contrasting conditions. Continental polar air from Canada may still be very cold and dry, whereas maritime tropical air from the Gulf of Mexico is warm, humid, and unstable. The greater the contrast, the more intense the storm tends to be.

These two contrasting air masses are most likely to meet in the central United States because there is no significant natural barrier separating the center of the country from the arctic or the Gulf of Mexico. Consequently, this region generates more tornadoes than any other part of the country or, in fact, the world. Figure 10–21, which depicts the

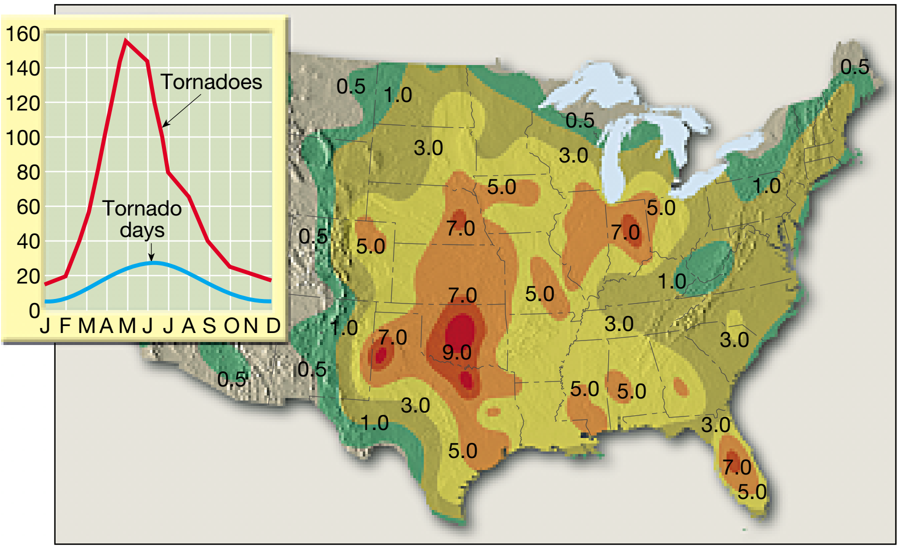


FIGURE 10-21 The map shows average annual tornado incidence per 10,000 square miles (26,000 square kilometers) for a 27-year period. The graph shows average number of tornadoes and tornado days each month in the United States for a 27-year period. *(After NOAA)*

average annual tornado incidence in the United States over a 27-year period, readily substantiates this fact.

An average of about 1200 tornadoes were reported annually in the United States between 1990 and 2004. Still, the actual numbers that occur from one year to the next vary greatly. During the 15-year span just mentioned, for example, yearly totals ranged from a low of 941 in the year 2002 to a high of 1819 in 2004. Tornadoes occur during every month of the year. April through June is the period of greatest tornado frequency in the United States, and December and January are the months of lowest activity. Of the nearly 40,522 confirmed tornadoes reported over the contiguous 48 states during the 50-year period 1950–1999, an average of almost six per day occurred during May. At the other extreme, a tornado was reported only about every other day in December and January.

More than 40 percent of all tornadoes take place during the spring. Fall and winter, by contrast, together account for only 19 percent (Figure 10–21). In late January and February, when the incidence of tornadoes begins to increase, the center of maximum frequency lies over the central Gulf states. During March this center moves eastward to the southeastern Atlantic states, with tornado frequency reaching its peak in April.

During May and June the center of maximum frequency moves through the southern Great Plains and then to the northern Plains and Great Lakes area. This drift is due to the increasing penetration of warm, moist air while contrasting cool, dry air still surges in from the north and northwest. Thus, when the Gulf states are substantially under the influence of warm air after May, there is no cold-air intrusion to speak of, and tornado frequency drops. Such is the case across the country after June. Winter cooling permits fewer and fewer encounters between warm and cold air masses, and tornado frequency returns to its lowest level by December.

Students Sometimes Ask…

What is "Tornado Alley"?

Tornado Alley is a nickname used by the popular media and others that refers to the broad swath of high tornado occurrence in the central United States (see Figure 10–21). The heart of Tornado Alley stretches from the Texas Panhandle through Oklahoma and Kansas to Nebraska. It's important to remember that violent (killer) tornadoes occur outside of Tornado Alley every year. Tornadoes can occur almost anywhere in the United States.

Profile of a Tornado

The average tornado has a diameter of between 150 and 600 meters (500 to 2000 feet), travels across the landscape at approximately 45 kilometers (30 miles) per hour, and cuts a path about 26 kilometers (16 miles) long. Because many tornadoes occur slightly ahead of a cold front, in the zone of southwest winds, most move toward the northeast. The Illinois example demonstrates this fact nicely (Figure 10–22). The figure also shows that many tornadoes do not fit the description of the "average" tornado.

Of the hundreds of tornadoes reported in the United States each year, over half are comparatively weak and short-lived. Most of these small tornadoes have lifetimes of three minutes or less and paths that seldom exceed 1 kilometer (0.6 mile) in length and 100 meters (330 feet) wide. Typical wind speeds are on the order of 150 kilometers (96 miles) per hour or less. On the other end of the tornado spectrum are the infrequent and often long-lived violent tornadoes. Although large tornadoes constitute only a small percentage of the total reported, their effects are often devastating. Such tornadoes may exist for periods in excess of three hours

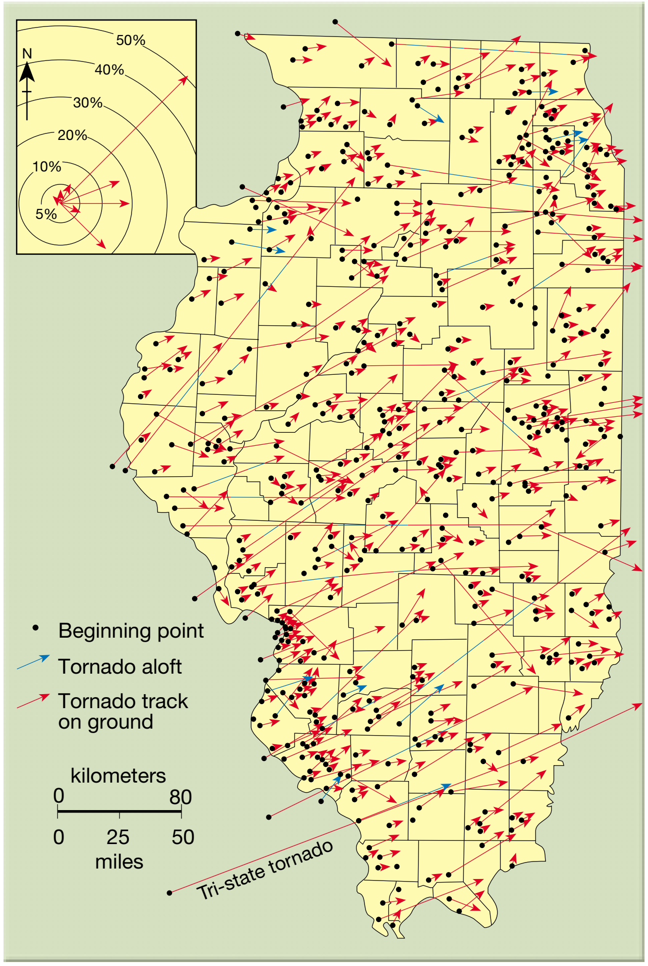


FIGURE 10-22 Paths of Illinois tornadoes (1916–1969). Because most tornadoes occur slightly ahead of a cold front, in the zone of southwest winds, they tend to move toward the northeast. Tornadoes in Illinois verify this. Over 80 percent exhibited directions of movement toward the northeast through east. *(After John W. Wilson and Stanley A. Changnon, Jr., Illinois Tornadoes, Illinois State Water Survey Circular 103, 1971, pp. 10, 24)*

and produce an essentially continuous damage path more than 150 kilometers (90 miles) long and perhaps a kilometer or more wide. Maximum winds range beyond 500 kilometers (310 miles) per hour (Figure 10–23).

Tornado Destruction

Because tornadoes generate the strongest winds in nature, they have accomplished many seemingly impossible tasks, such as driving a piece of straw through a thick wooden plank and uprooting huge trees (Figure 10–24). Although it may seem impossible for winds to cause some of the fantastic damage attributed to tornadoes, tests in engineering facilities have repeatedly demonstrated that winds in excess of 320 kilometers (200 miles) per hour are capable of incredible feats.

There is a long list of documented examples. In 1931 a tornado actually carried an 83-ton railroad coach and its 117 passengers 24 meters (80 feet) through the air and dropped them in a ditch. A year later, near Sioux Falls, South Dakota, a steel beam 15 centimeters (6 inches) thick and 4 meters (13 feet) long was ripped from a bridge, flew more than 300 meters (nearly 1000 feet), and perforated a 35-centimeter- (14-inch-) thick hardwood tree. In 1970 an 18-ton steel tank was carried nearly 1 kilometer (0.6 mile) at Lubbock, Texas. Fortunately, the winds associated with most tornadoes are not this strong.

Most tornado losses are associated with a few storms that strike urban areas or devastate entire small communities. The amount of destruction wrought by such storms depends to a significant degree (but not completely) on the strength of the winds. A wide spectrum of tornado strengths, sizes, and lifetimes are observed. One commonly used guide to tornado intensity was developed by the late T. Theodore Fujita at the University of Chicago and is appropriately called the **Fujita Intensity Scale,** or simply the **F-scale** (Table 10–1). Because tornado winds cannot be measured directly, a rating on the F-scale is determined by assessing the worst damage produced by a storm. Although widely used, the F-scale is not perfect. Estimating tornado intensity based on damage alone does not take into account the structural integrity of the objects hit by a tornado. A well-constructed building can withstand very high winds, whereas a poorly built structure can suffer devastating damage from the same or even weaker winds.

The drop in atmospheric pressure associated with the passage of a tornado plays a minor role in the damage process. Most structures have sufficient venting to allow for the sudden drop in pressure. Opening a window, once thought to be a way to minimize damage by allowing inside and outside atmospheric pressure to equalize, is no longer recommended. In fact, if a tornado gets close enough to a structure for the pressure drop to be experienced, the strong winds probably will have already caused significant damage.

Although the greatest part of tornado damage is caused by violent winds, most tornado injuries and deaths result from flying debris. On the average, tornadoes cause more deaths each year than any other weather events except lightning and flash floods. For the United States, the average annual death toll from tornadoes is about 75 people. However, the actual number of deaths each year can depart significantly from the average. On April 3–4, 1974, for example, an outbreak of 148 tornadoes brought death and destruction to a 13-state region east of the Mississippi River. More than 300 people died and nearly 5500 people were injured in this worst tornado disaster in half a century (see Box 10–4).

In one statistical study that examined a 29-year period, there were 689 tornadoes that caused loss of life. This figure represented slightly less than 4 percent of the total 19,312 reported storms. Although the percentage of tornadoes that result in death is small, every tornado is poten-

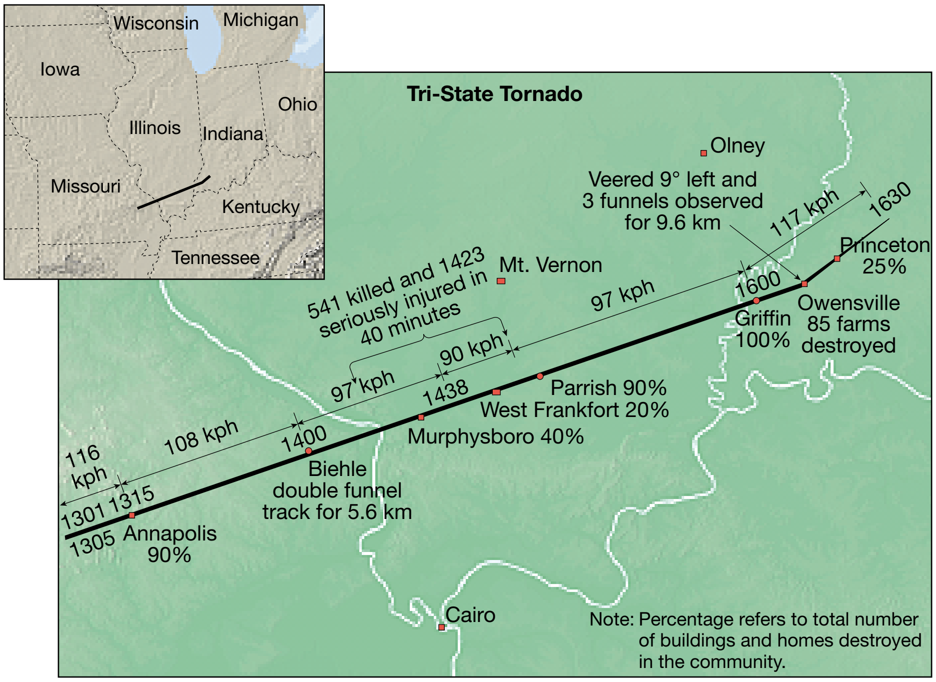


FIGURE 10-23 "One tornado among the more than 13,000 which have occurred in the United States since 1915 easily ranks above all others as the single most devastating storm of this type. Shortly after its occurrence on 18 March 1925, the famed Tri-State tornado was recognized as the worst on record, and it still ranks as the nation's greatest tornado disaster. The tornado remained on the ground for 219 miles. The resulting losses included 695 dead, 2027 injured, and damages equal to $43 million in 1970 dollars. This represents the greatest death toll ever inflicted by a tornado and one of the largest damage totals." *(Map and description from John W. Wilson and Stanley A. Changnon, Jr., Illinois Tornadoes, Illinois State Water Survey Circular 103, 1971, p. 32)*

tially lethal. If you examine Figure 10–25, which compares tornado fatalities with storm intensities, the results are quite interesting. It is clear from this graph that the majority (63 percent) of all tornadoes are weak and that the number of storms decreases as tornado intensity increases. The distribution of tornado fatalities, however, is just the opposite. Although only 2 percent of tornadoes are classified as violent, they account for nearly 70 percent of the deaths.

If there is some question about the causes of tornadoes, there certainly is none about the destructive effects of these violent storms. A severe tornado leaves the affected area stunned and disorganized and may require a response of the magnitude demanded in war.

Students Sometimes Ask…

How common are the most violent F5 tornadoes?

These strongest of all tornadoes are rare. During the 30-year span, 1970–1999, only 26 out of a total of 28,913 tornadoes were classified in the F5 category. That is just 0.09% (nine one-hundredths of one percent)! In many years, there were no F5 tornadoes reported. Nevertheless, during a single 16-hour span, April 3–4, 1974, there were seven F5 storms (for more on this, see Box 10–4).

FIGURE 10-24 The force of the wind during a tornado near Wichita, Kansas, in April 1991 was enough to drive this piece of metal into a utility pole. *(Photo by John Sokich/NOAA)*

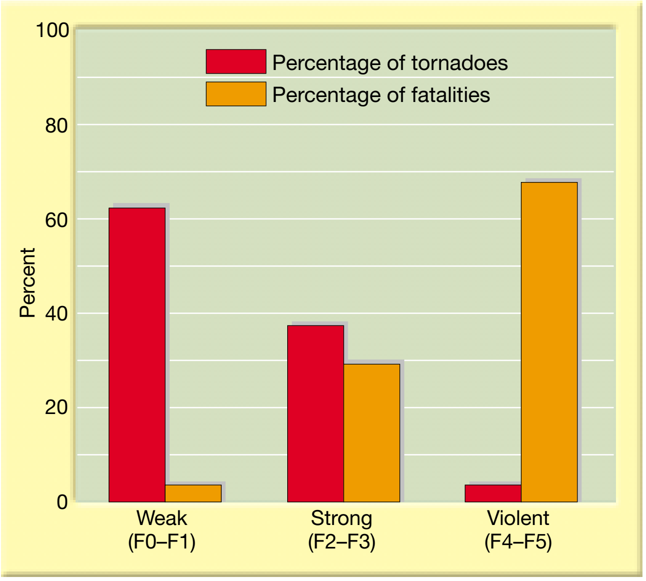
TABLE 10-1 Fujita Intensity Scale

	Wind speed		
Scale	**(KPH)**	**(MPH)**	**Expected damage**
F0	<116	<72	**Light Damage** Damage to chimneys and billboards; broken branches; shallow-rooted trees pushed over.
F1	116–180	72–112	**Moderate Damage** The lower limit is near the beginning of hurricane wind speed. Surfaces peeled off roofs; mobile homes pushed off foundations or overturned; moving autos pushed off the road.
F2	181–253	113–157	**Considerable Damage** Roofs torn off frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light-object missiles generated.
F3	254–332	158–206	**Severe Damage** Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off ground and thrown.
F4	333–419	207–260	**Devastating Damage** Well-constructed houses leveled; structures with weak foundations blown some distance; cars thrown and large missiles generated.
F5	>419	>260	**Incredible Damage** Strong frame houses lifted off foundations and carried considerable distance to disintegrate; automobile-sized missiles fly through the air farther than 100 m; trees debarked; incredible phenomena occur.

Tornado Forecasting

Because severe thunderstorms and tornadoes are small and short-lived phenomena, they are among the most difficult weather features to forecast precisely. Nevertheless, the prediction, the detection, and the monitoring of such storms are among the most important services provided by professional meteorologists. The timely issuance and dissemination of watches and warnings are both critical to the protection of life and property.

FIGURE 10-25 Percentage of tornadoes in each intensity category (blue) and percentage of fatalities associated with each category (red). *(From Joseph T. Schaefer et al., "Tornadoes—When, Where and How Often," Weatherwise, 33, no. 2 (1980), 57)*



The Storm Prediction Center (SPC) located in Norman, Oklahoma, is part of the National Weather Service (NWS) and the National Centers for Environmental Prediction (NCEP). Its mission is to provide timely and accurate forecasts and watches for severe thunderstorms and tornadoes.

Severe thunderstorm outlooks are issued several times daily. *Day 1* outlooks identify those areas likely to be affected by severe thunderstorms during the next six to 30 hours, and *day 2* outlooks extend the forecast through the following day. Both outlooks describe the type, coverage, and intensity of the severe weather expected. Many local NWS field offices also issue severe weather outlooks that provide a more local description of the severe weather potential for the next 12 to 24 hours.

Tornado Watches and Warnings

Tornado watches alert the public to the possibility of tornadoes over a specified area for a particular time interval. Watches serve to fine-tune forecast areas already identified in severe weather outlooks. A typical watch covers an area of about 65,000 square kilometers (25,000 square miles) for a four- to six-hour period. A tornado watch is an important part of the tornado alert system because it sets in motion the procedures necessary to deal adequately with detection, tracking, warning, and response. Watches are generally reserved for organized severe weather events where the tornado threat will affect at least 26,000 square kilometers

BOX 10-4 Atmospheric Hazard: The April 1974 Super Tornado Outbreak

The dates April 3–4, 1974, are important in the tornado history of the United States. In a span of just 16 hours, 148 tornadoes hit 13 states and Canada—the largest and costliest outbreak ever recorded (Figure 10–F). The storms killed 315 people and injured about 5500 more. Damages exceeded $600 million. Forty-eight tornadoes were killers, with seven rated F5 (the maximum possible on the Fujita Intensity Scale) and an additional 23 rated F4. The town of Xenia, in southwestern Ohio, was especially hard hit—more than 1000 homes were destroyed, 34 people were killed, and 1100 were injured. Property damages exceeded $100 million.

Following this record-breaking event, extensive studies and surveys were conducted. The results of this work provided meteorologists with the evidence they needed to demonstrate that many of the notions about tornadoes held by the general public were incorrect. Here are some of the myths that were disproved:

Myth: A tornado won't touch down at the confluence of major rivers. Fact: The town of Cairo, IL, located at the confluence of the Ohio and Mississippi Rivers was hit by a tornado that day.

Myth: Tornadoes don't go up and down steep or high hills. Fact: A tornado that hit Guin, AL, stayed on the ground as it climbed the 1640-foot Monte Sano Mountain and grew in intensity as it descended the northeast slope. The Blue Ridge tornado of that day formed in the mountains at 1800 feet just east of Mulberry Gap and crossed a 3000-foot ridge before moving down to the bottom of the canyon. The tornado finally climbed to the 3300-foot top of Rich Nob before dissipating.

Myth: Tornadoes will not follow terrain into steep valleys. Fact: The tornado that wiped out three schools in Monticello, IN, descended a 60-foot bluff over the Tippecanoe River as it moved out of the town and damaged homes at its base.*

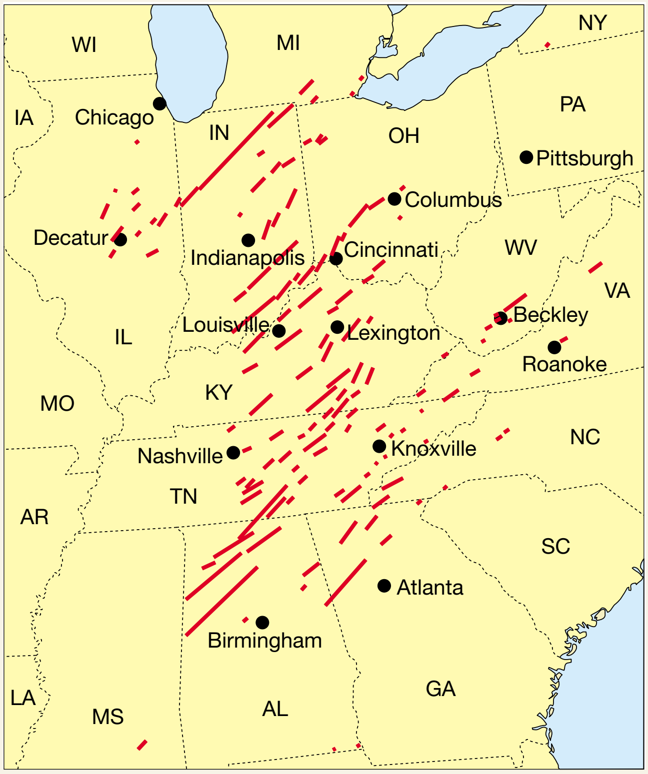


FIGURE 10-F Tracks of the 148 tornadoes that struck a 13-state area in the "super outbreak" of April 3–4, 1974. *(After NOAA)*

Engineering studies of damaged schools provided information that was later incorporated into construction designs that ensured greater safety. Evidence from damaged buildings showed that interior hallways provide the safest place and that classrooms with outside walls and gymnasiums with wide roof span were most dangerous.

What is the risk of another outbreak like the April 1974 event? We know such an occurrence is rare because it has only happened once since tornado records have been kept. However, there is no way to know if the odds are once in 50 years or once in 1000 years because we do not have a long enough record of accurate tornado statistics.

*NOAA "Tornado Outbreak 1974: The Worst in U.S. History." This publication was prepared to mark the twenty-fifth anniversary of the April 3–4, 1974, super tornado outbreak. http://www.publicaffairs.noaa.gov/storms/

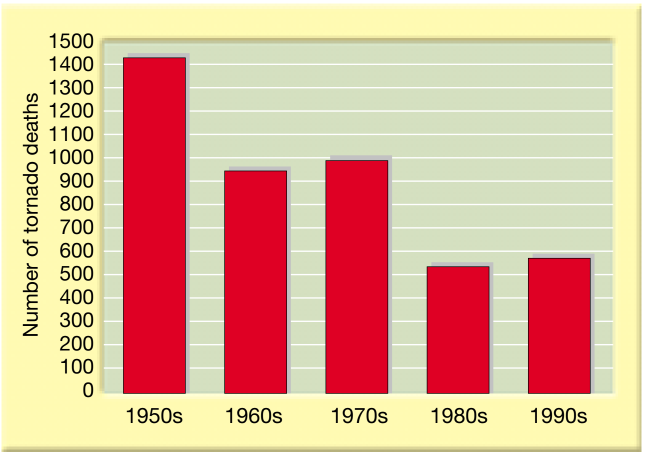
(10,000 square miles) and/or persist for at least three hours. Watches typically are not issued when the threat is thought to be isolated and/or short-lived.

Whereas a tornado watch is designed to alert people to the possibility of tornadoes, a **tornado warning** is issued by local offices of the National Weather Service when a tornado has actually been sighted in an area or is indicated by weather radar. It warns of a high probability of imminent danger. Warnings are issued for much smaller areas than watches, usually covering portions of a county or counties. In addition, they are in effect for much shorter periods, typically 30 to 60 minutes. Because a tornado warning may be based on an actual sighting, warnings are occasionally issued after a tornado has already developed. However, most warnings are issued prior to tornado formation, sometimes by several tens of minutes, based on Doppler radar data and/or spotter reports of funnel clouds or cloud-base rotation.

If the direction and the approximate speed of the storm are known, an estimate of its most probable path can be made. Because tornadoes often move erratically, the warning area is fan-shaped downwind from the point where the tornado has been spotted. Improved forecasts and advances in technology have contributed to a significant decline in tornado deaths over the last 50 years. Figure 10–26 illustrates this trend. During a span when the United States population grew rapidly, tornado deaths trended downward.

As noted earlier, the probability of one place being struck by a tornado, even in the area of greatest frequency, is slight. Nevertheless, although the probabilities may be small, tornadoes have provided many mathematical exceptions. For example, the small town of Codell, Kansas, was hit three years in a row—1916, 1917, and 1918—and each time on the same date, May 20! Needless to say, tornado watches and warnings should never be taken lightly.

FIGURE 10-26 Number of tornado deaths in the United States by decade 1950–1999. Even though the population has risen sharply since 1950, there has been a general downward trend in tornado deaths. *(Data from NOAA)*



Doppler Radar

The installation of **Doppler radar** across the United States has significantly improved our ability to track thunderstorms and issue warnings based on their potential to produce tornadoes (Figure 10–27). Conventional weather radar works by transmitting short pulses of electromagnetic energy. A small fraction of the waves that are sent out is scattered by a storm and returned to the radar. The strength of the returning signal indicates rainfall intensity, and the time difference between the transmission and return of the signal indicates the distance to the storm.

However, to identify tornadoes and severe thunderstorms, we must be able to detect the characteristic circulation patterns associated with them. Conventional radar cannot do so except occasionally when spiral rain bands occur in association with a tornado and give rise to a hook-shaped echo.

Doppler radar not only performs the same tasks as conventional radar but also has the ability to detect motion directly (Figure 10–28). The principle involved is known as the *Doppler effect* (see Box 10–5). Air movement in clouds is determined by comparing the frequency of the reflected signal to that of the original pulse. The movement of precipitation toward the radar increases the frequency of reflected pulses, whereas motion away from the radar decreases the frequency. These frequency changes are then interpreted in terms of speed toward or away from the Doppler radar unit. It is this same principle that allows police radar to determine the speed of moving cars. Unfortunately, a single Doppler radar unit cannot detect air movements that occur parallel to it. Therefore, when a more complete picture of the winds within a cloud mass is desired, it is necessary to use two or more Doppler units.

Doppler radar can detect the initial formation and subsequent development of the mesocyclone within a severe thunderstorm that frequently precedes tornado development. Almost all (96 percent) mesocyclones produce damaging hail, severe winds, or tornadoes. Those that produce tornadoes (about 50 percent) can sometimes be distinguished by their stronger wind speeds and their sharper gradients of wind speeds. Mesocyclones can sometimes be identified within parent storms 30 minutes or more before tornado formation, and if a storm is large, at distances up to 230 kilometers (140 miles). In addition, when close to the radar, individual tornado circulations may sometimes be detected. Ever since the implementation of the national Doppler network, the average lead time for tornado warnings has increased from less than 5 minutes in the late 1980s to nearly 11 minutes today.

Doppler radar is not without problems. One concern relates to the weak tornadoes that rank at or near the bottom of the Fujita Intensity Scale. The nature of this problem has been summarized as follows:

> Presently, all tornadoes are treated in the same manner by the NWS (National Weather Service); a tornado warning is issued, and local governments usually respond by

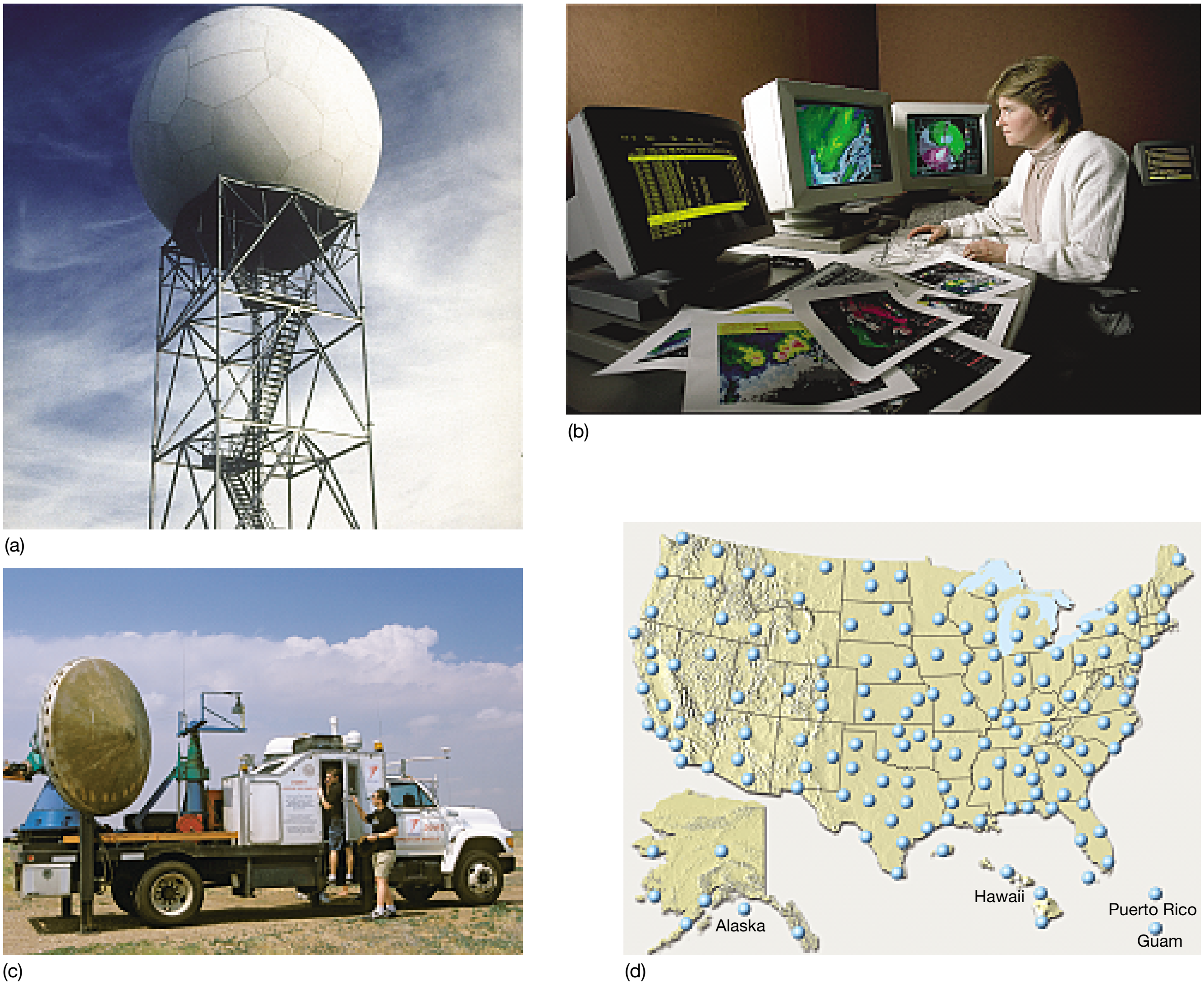


FIGURE 10-27 By using advanced Doppler radars, scientists are better able to estimate when and where thunderstorms will form, even in areas of seemingly clear air. Doppler radar installation (a) and advanced weather interactive processing system (b) at Sterling, Virginia, near Dulles International Airport. This is one of 115 state-of-the-art National Weather Service facilities shown on the map in (d). The equipment shown in (c), called *Doppler Radar on Wheels,* is scanning the skies of the Texas Panhandle on May 15, 2003. Portable units like this one are used by researchers to study severe weather events. *(Photos (a) and (b) by Brownie Harris/The Stock Market; map after National Weather Service; photo (c) © University Corporation for Atmospheric Research)*

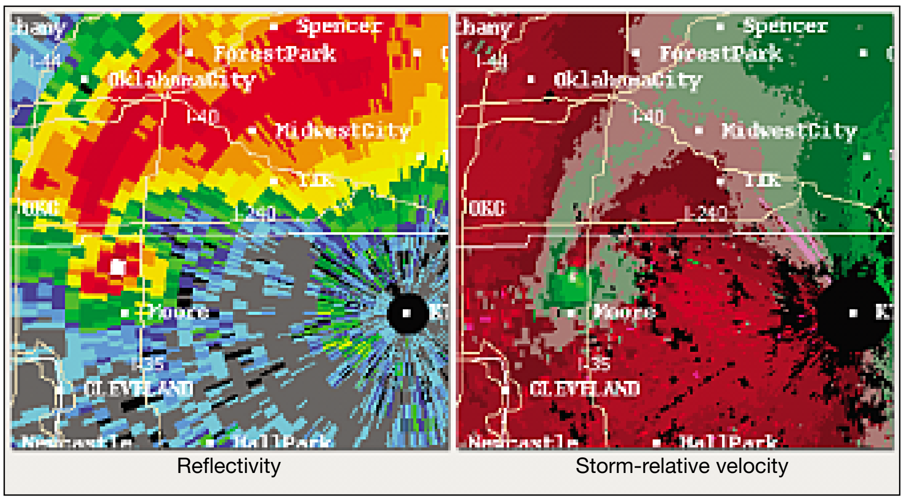


FIGURE 10-28 This is a dual Doppler radar image of an F5 tornado near Moore, Oklahoma, on May 3, 1999. The left image (reflectivity) shows precipitation in the supercell thunderstorm. The right image shows motion of the precipitation along the radar beam, that is, how fast rain or hail are moving toward or away from the radar. In this example, the radar was unusually close to the tornado—close enough to make out the signature of the tornado itself (most of the time only the weaker and larger mesocyclone is detected). *(After NOAA)*

BOX 10-5 The Doppler Effect

We have all heard the changes in the sounds that a car, truck, or train makes as it approaches and then passes by. As the vehicle moves toward us, the sound has a higher pitch, and after the vehicle passes, the pitch drops. The faster the car, truck, or train is moving, the more the pitch drops (Figure 10–G). This phenomenon occurs not only in association with sound waves but also with electromagnetic waves. Known as the *Doppler effect*, it is named for Christian Johannn Doppler, the Austrian physicist who first explained it in 1842.

Why does the wave frequency appear to shift when the wave source is moving? Figure 10–Ha shows the pattern of wave crests generated by a source that is not moving. The distance between wave crests (the wavelength) is identical for each successive wave. If this were a source emitting sound, the pitch would be the same no matter where the listener was located. However, if the source were moving, the wave crests would no longer make a concentric pattern. Rather, they would become more closely spaced in the direction the source was advancing. Therefore, the wave frequency would be greater ahead of the source and lower behind the source. Figure 10–Hb illustrates this pattern.

Astronomers apply this principle when they wish to determine whether a light source such as a star is approaching or retreating relative to Earth. When the lines in the star's

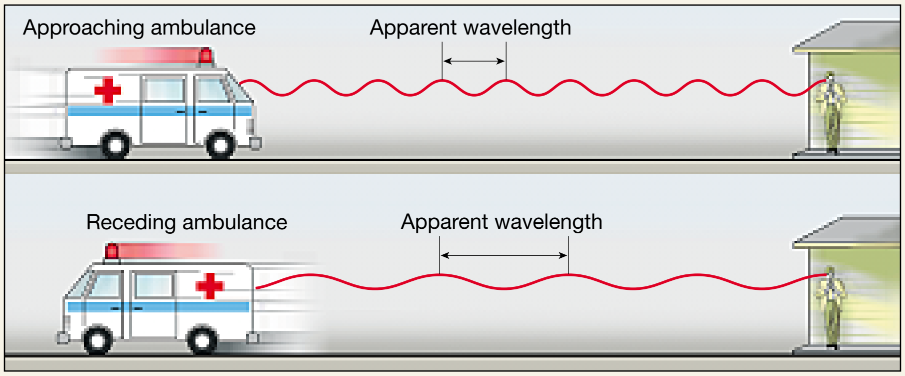


FIGURE 10-G This everyday example of the Doppler effect illustrates the apparent lengthening and shortening of wavelengths caused by the relative movement between a source and an observer.

activating their emergency procedures. Doppler radar makes forecasting and detection of these tornadoes possible in real-time operations. Thus, the potential exists for numerous warnings being issued for tornadoes which do little or no damage. This could desensitize the public to the dangers of more rare, life-threatening tornadoes. A future research goal should be the development of techniques that enable forecasting of tornado intensity.*

It should also be pointed out that not all tornado-bearing storms have clear-cut radar signatures and that other storms can give false signatures. Detection, therefore, is sometimes a subjective process and a given display could be interpreted in several ways. Consequently, trained observers will continue to form an important part of the warning system in the foreseeable future.

Although some operational problems exist, the benefits of Doppler radar are many. As a research tool, it is not only providing data on the formation of tornadoes but is also helping meteorologists gain new insights into thunderstorm development, the structure and dynamics of hurricanes, and air-turbulence hazards that plague aircraft. As a practical tool for tornado detection, it has significant advantages over a system that uses conventional radar.

*Lawrence B. Dunn, "Two Examples of Operational Tornado Warnings Using Doppler Radar Data," *Bulletin of the American Meteorological Society,* 71, no. 2 (February 1990), 152.

spectrum are shifted toward wavelengths that are shorter than those observed when such a source is at rest, the star is approaching. If the star is moving away from the observer, all of the spectral lines are shifted toward longer wavelengths. In meteorology, the new generation of weather radars use the Doppler principle to probe the circulation within a cloud by monitoring the movements of raindrops.

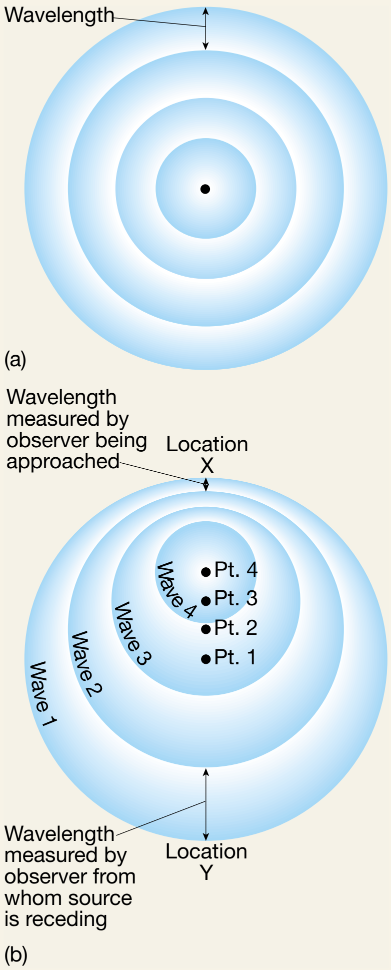


FIGURE 10-H The Doppler effect is the change in the observed frequency of waves produced by the motion of the wave source and/or the wave receiver. In both parts of the diagram, the circles represent wave crests that travel at a constant speed. (a) When the wave source is stationary, the distance between waves is identical for all waves that are produced. The wave frequency (the pitch of the sound) at any point in this diagram is the same. (b) Here the source is moving toward the top of the page. Whenever the source (or the receiver) moves, the wave pattern becomes distorted. Wave 1 was produced when the source was at point 1; wave 2 was created when the source was at point 2; and wave 3 was emitted at point 3. Notice that even though the frequency emitted by the source remains the same as in part (a), a listener at location *X* would experience a higher frequency (higher-pitched sound) because each wave has a shorter distance to travel and therefore arrives at location *X* more frequently than would occur if the source were not moving. Conversely, a listener at location *Y* would experience a lower frequency.

Chapter Summary

- Although tornadoes and *hurricanes* are, in fact, cyclones, the vast majority of cyclones are not hurricanes or tornadoes. The term "cyclone" simply refers to the circulation around any low-pressure center, no matter how large or intense it is. *Thunderstorms,* storms containing lightning and thunder, are related in some manner to tornadoes, hurricanes, and mid-latitude cyclones.
- Dynamic thermal instability occurs during the development of thunderstorms, which form when warm, humid air rises in an unstable environment. A number of mechanisms, such as unequal heating of Earth's surface or lifting of warm air along a front or mountain slope, can trigger the upward air movement needed to create thunderstorm-producing cumulonimbus clouds. Severe thunderstorms produce high winds, damaging hail, flash floods, and tornadoes.
- In the United States, *air-mass thunderstorms* frequently occur in maritime tropical (mT) air that moves northward from the Gulf of Mexico. During the spring and summer, when the air is heated from below by the warmer land surface, the warm, humid air mass becomes unstable and thunderstorms develop. Generally, three

stages are involved in the development of a thunderstorm. The *cumulus stage* is dominated by rising currents of air (updrafts) and the formation of a towering cumulonimbus cloud. Falling precipitation within the cloud causes drag on the air and initiates a downdraft that is further aided by the influx of cool, dry air surrounding the cloud, a process termed *entrainment.* The beginning of the *mature stage* is marked by the downdraft leaving the base of the cloud and the release of precipitation. With gusty winds, lightning, heavy precipitation, and sometimes hail, the mature stage is the most active period of a thunderstorm. Marking the end of the storm, the *dissipating stage* is dominated by downdrafts and entrainment. Without a supply of moisture from updrafts, the cloud soon evaporates. It should be noted that within a single air-mass thunderstorm there may be several individual *cells*—that is, zones of adjacent updrafts and downdrafts.

- Mountainous regions, such as the Rockies in the West and the Appalachians in the East, experience a greater number of air-mass thunderstorms than do the Plains states. Many thunderstorms that form over the eastern two-thirds of the United States occur as part of the general convergence and frontal wedging that accompany passing midlatitude cyclones.
- *Severe thunderstorms* are capable of producing heavy downpours and flash flooding as well as strong, gusty straight-line winds. They are influenced by strong vertical wind shear—that is, changes in wind direction and/or speed between different heights, and updrafts that become tilted and continue to build upward. Downdrafts from the thunderstorm cells reach the surface and spread out to produce an advancing wedge of cold air, called a *gust front,* which may form a *roll cloud* as warm air is lifted along its leading edge.
- Some of the most dangerous weather is produced by a type of thunderstorm called a *supercell,* a single, very powerful thunderstorm cell that at times may extend to heights of 20 kilometers (65,000 feet) and persist for many hours. The vertical wind profile of these cells may produce a *mesocyclone,* a column of cyclonically rotating air, within which tornadoes sometimes form. Supercells appear to form as inversion layers are eroded locally and unstable air "erupts" from below to form unusually large cumulonimbus clouds with concentrated, persistent updrafts.
- *Squall lines* are relatively narrow, elongated bands of thunderstorms that develop in the warm sector of a middle-latitude cyclone, usually in advance of a cold front. Some develop when divergence and lifting created by an active jet stream aloft is aligned with a strong, persistent low-level flow of warm, humid air from the south. A squall line with severe thunderstorms can also form along a boundary called a *dryline,* a narrow zone along which there is an abrupt change in moisture.
- A *mesoscale convective complex* (MCC) consists of many individual thunderstorms that are organized into a large oval to circular cluster. They form most frequently in the Great Plains from groups of afternoon air-mass thunderstorms. Although MCCs sometimes produce severe weather, they also provide a significant portion of the growing-season rainfall to the agricultural regions of the central United States.
- *Microbursts* are small, short-lived localized downdrafts of wind that occur beneath some thunderstorms and can reach speeds of 160 kilometers (100 miles) per hour. Microbursts are not only destructive, but the wind shear associated with them is a significant airport hazard.
- *Thunder* is produced by *lightning.* The object of lightning is to equalize the electrical difference associated with the formation of a large cumulonimbus cloud by producing a negative flow of current from the region of excess negative charge to the region with excess positive charge, or vice versa. The most common type of lightning, often called *sheet lightning,* occurs within and between clouds. The less common, but more dangerous, type of lightning is *cloud-to-ground lightning.*
- The origin of charge separation in clouds, although not fully understood, must hinge on rapid vertical movements within the cloud. The lightning we see as some single flashes are really several very rapid strokes between the cloud and the ground. When air is heated by the electrical discharge of lightning, it expands explosively and produces the sound waves we hear as thunder. The thunder we hear as a rumble is produced by a long lightning flash at some distance from the observer.
- *Tornadoes,* sometimes called twisters, or cyclones, are violent windstorms that take the form of a rotating column of air, or *vortex,* that extends downward from a cumulonimbus cloud. Some tornadoes consist of a single vortex. Within many stronger tornadoes, called *multiple vortex tornadoes,* are smaller intense whirls called *suction vortices* that rotate within the main vortex. Pressures within some tornadoes have been estimated to be as much as 10 percent lower than immediately outside the storm. Because of the tremendous pressure gradient associated with a strong tornado, maximum winds approach 480 kilometers (300 miles) per hour.
- Tornadoes form in association with severe thunderstorms that produce high winds, heavy rainfall, and often damaging hail. They form in any situation that produces severe weather including cold fronts, squall lines, and tropical cyclones (hurricanes). An important precondition linked to tornado formation in severe thunderstorms is the development of a mesocyclone that forms in the updraft of the thunderstorm. As the narrowing column of rotating air stretches downward, a rapidly spinning *funnel cloud* may emerge from a slowly rotating *wall cloud.* If the funnel cloud makes contact with the surface, it is then classified as a tornado.

- Severe thunderstorms, and hence tornadoes, are most often spawned along the cold front or squall line of a middle-latitude cyclone or in association with supercell thunderstorms. Although April through June is the period of greatest tornado activity, tornadoes occur during every month of the year. The average tornado has a diameter of between 150 and 600 meters, travels across the landscape toward the northeast at approximately 45 kilometers per hour, and cuts a path about 26 kilometers long.
- Most tornado damage is caused by tremendously strong winds. One commonly used guide to tornado intensity is the *Fujita Intensity Scale,* or simply *F-scale.* A rating on the F-scale is determined by assessing the worst damage produced by a storm. Whereas most tornado damage is done by violent winds, most tornado injuries and deaths result from flying debris.
- Because severe thunderstorms and tornadoes are small and short-lived phenomena, they are among the most difficult weather features to forecast precisely. When necessary, the Storm Prediction Center of the National Weather Service issues severe thunderstorm outlooks several times daily. When weather conditions favor the formation of tornadoes, a *tornado watch* is issued to alert the public to the possibility of tornadoes over a specified area for a particular time interval. A *tornado warning* is issued by local offices of the National Weather Service when a tornado has been sighted in an area or is indicated by weather radar. With its ability to detect the movement of precipitation within a cloud, *Doppler radar* technology has greatly advanced the accuracy of tornado warnings. Using the principle known as the *Doppler effect,* Doppler radar can identify the initial formation and subsequent development of the mesocyclone within a thunderstorm that frequently precedes tornado development.

Vocabulary Review

air-mass thunderstorm (p. 287)
cumulus stage (p. 288)
dart leader (p. 300)
dissipating stage (p. 289)
Doppler radar (p. 310)
dryline (p. 294)
entrainment (p. 288)
flash (p. 298)
Fujita Intensity Scale (F-scale) (p. 306)
gust front (p. 290)
leader (p. 298)
lightning (p. 296)
mature stage (p. 289)
mesocyclone (p. 291)
mesoscale convective complex (MCC) (p. 295)
microburst (p. 296)
multiple vortex tornado (p. 300)
return stroke (p. 298)
severe thunderstorm (p. 290)
squall line (p. 294)
step leader (p. 298)
stroke (p. 298)
supercell (p. 291)
thunder (p. 300)
thunderstorm (p. 287)
tornado (p. 300)
tornado warning (p. 308)
tornado watch (p. 308)

Review Questions

1. If you hear that a cyclone is approaching, should you immediately seek shelter?
2. Compare the wind speeds and the sizes of middle-latitude cyclones, tornadoes, and hurricanes.
3. Although tornadoes and hurricanes are dangerous storms, in most years they are not responsible for the greatest number of storm-related deaths in the United States. What is the deadliest storm phenomenon? (See Box 10–1.)
4. What are the primary requirements for the formation of thunderstorms?
5. Where would you expect thunderstorms to be most common on Earth? In the United States?
6. During what season and at what time of day is air-mass thunderstorm activity greatest? Why?
7. Why does entrainment intensify thunderstorm downdrafts?
8. Describe how downdrafts in a severe thunderstorm act to maintain updrafts. What is a *gust front?*
9. Briefly describe the formation of a squall line along a dry line.
10. How is thunder produced?
11. Which is more common, sheet lightning or cloud-to-ground lightning?
12. What is heat lightning?
13. Why do tornadoes have such high wind speeds?
14. What general atmospheric conditions are most conducive to the formation of tornadoes?

15. When is the "tornado season"? Can you explain why it occurs when it does? Why does the area of greatest tornado frequency migrate?

16. Violent (F4–F5) tornadoes are only about 2 percent of the total. What percentage of tornado fatalities is associated with these strongest storms? (See Figure 10–25.)

17. Distinguish between a tornado watch and a tornado warning.

18. A vehicle with its horn sounding moves away from an observer at point *A* and toward an observer at point *B*. Should the pitch of the horn at point *B* be higher or lower than at point *A*? What effect explains the difference in pitch experienced at points *A* and *B*? (See Box 10–5.)

19. What advantages does Doppler radar have over conventional radar?

Problems

1. If thunder is heard 15 seconds after lightning is seen, about how far away was the lightning stroke?

2. Examine the upper left portion of Figure 10–22 and determine the percentage of tornadoes that exhibited directions of movement toward the E through NNE.

3. Figures 10–29 and 10–30 represent two common ways that United States tornado statistics are graphically presented to the public. Which four states experience the greatest number of tornadoes? Are these the states with the greatest tornado threat? Which map is most useful for depicting the tornado hazard in the United States? Does the map in Figure 10–21 have an advantage over either or both of these maps?

4. Table 10–2 lists the total number of tornadoes reported in the United States by decade. Propose a reason that might explain why the total for the 1990s was so much higher than for the 1950s.

TABLE 10-2 Number of U.S. tornadoes reported by decade*

1950–59	4796
1960–69	6813
1970–79	8579
1980–89	8196
1990–99	12,138

*Data from Storm Prediction Center, NOAA

5. Figure 10–26 shows that the number of tornado deaths in the United States in the 1990s was less than half the number that occurred in the 1950s, even though there was a significant rise in the population during that span. To what can you attribute this decline in the death toll?

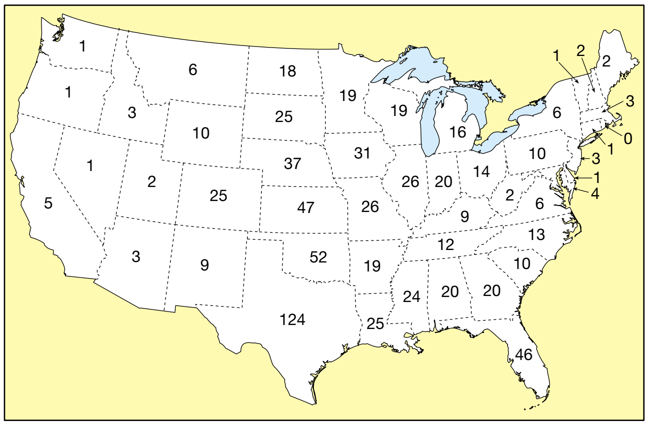


FIGURE 10-29 Annual average number of tornadoes by state for a 45-year period.

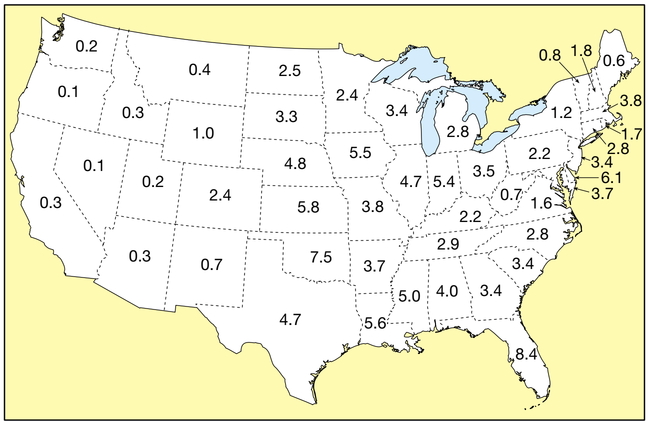


FIGURE 10-30 Annual average number of tornadoes per 10,000 square miles by state for a 45-year period.

Atmospheric Science Online

The Atmosphere 10e web site uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by meteorology instructors, this site will help improve your understanding of meteorology. Visit **http://www.prenhall.com/lutgens** and click on the cover of *The Atmosphere 10e* to find:

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