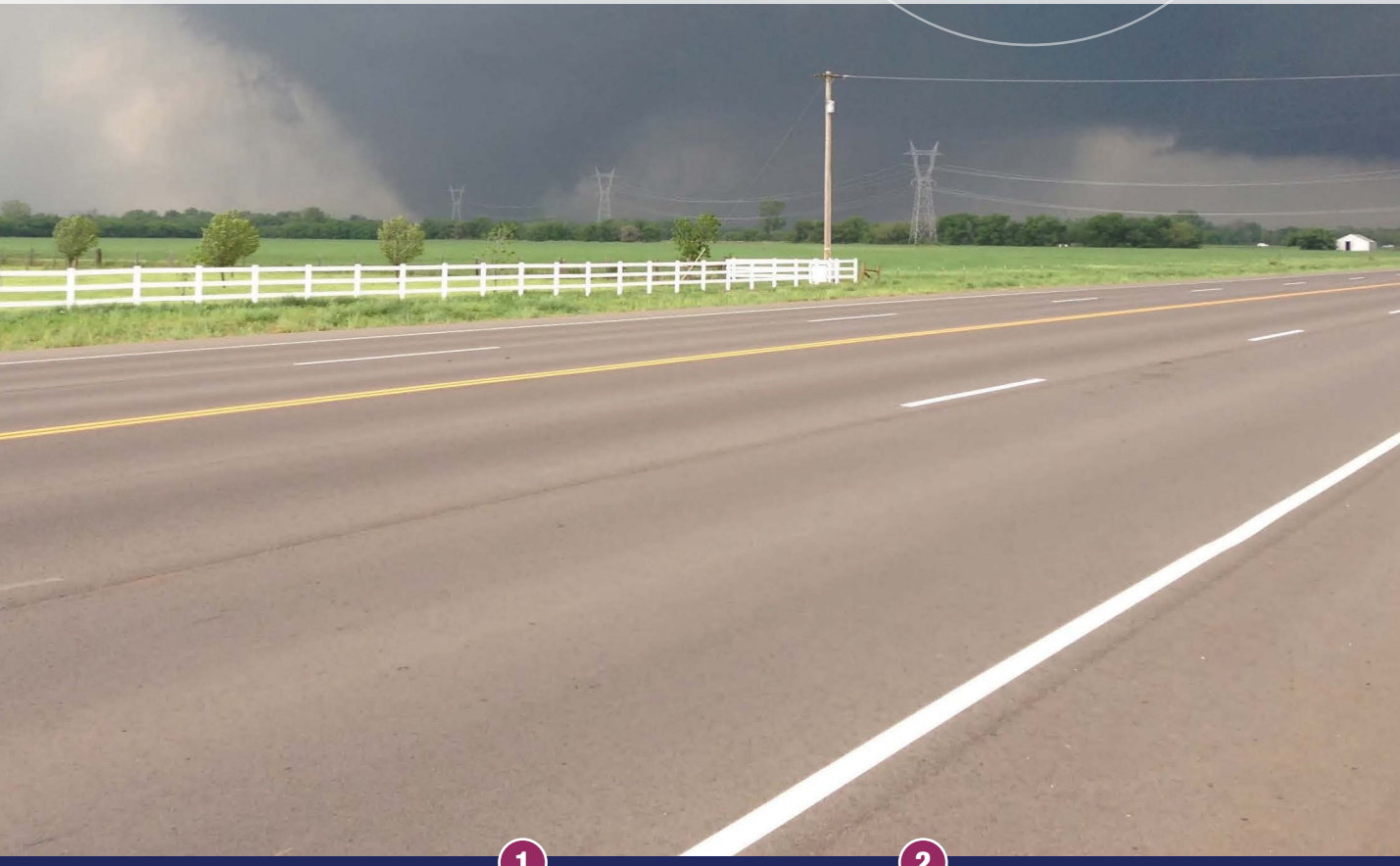
Anything in the direct path of the tornado . . . was completely obliterated

9



APPLYING the 5 fundamental concepts 1999 and 2013 Tornadoes of Moore, Oklahoma

1

Science helps us predict hazards.

As you will see when we return to Moore, Oklahoma, advances in weather satellites and ground-based monitoring equipment over the past decade have enhanced prediction of tornado formation and extended the lead time for tornado warnings.

2

Knowing hazard risks can help people make decisions.

The frequency of severe weather events, such as tornadoes, for a particular region is fairly well known and, therefore, most severe weather phenomena are amenable to risk analysis.

Atmospheric Processes and Severe Weather

1999 and 2013 Tornadoes of Moore, Oklahoma

Although the majority of weather-related deaths are caused by blizzards and heat waves, it is the tornado that strikes fear in the hearts of many people living in the midcontinental United States. This fear is well founded—a **tornado**, simply defined as a violently rotating column of air associated with extreme horizontal winds, can cause tremendous property damage and loss of life. Having been struck by extremely powerful tornadoes in both 1999 and 2013, the city of Moore, Oklahoma, is an excellent example of the frightening power of tornadoes and the human interaction with and adjustment to severe weather.

The "1999 Oklahoma tornado outbreak" included 152 tornadoes spread throughout the U.S. Great Plains over a seven-day period,[1]

< 2013 MOORE, OKLAHOMA, TORNADO
An extremely powerful tornado devastates the City of Moore just south of metropolitan Oklahoma City, Monday, May 20, 2013. *(Ks0stm/Wikimedia Commons)*

LEARNING Objectives

Atmospheric processes and energy exchanges are driven by Earth's energy balance and linked to climate and weather. Hurricanes, thunderstorms, tornadoes, blizzards, ice storms, dust storms, and heat waves, as well as flash flooding resulting from intense precipitation, are all natural processes that are hazardous to people. These severe hazards affect considerable portions of North America and cause significant death and destruction each year.

After reading this chapter, you should be able to:

LO:1 Differentiate the three different ways in which heat is transferred in the atmosphere.

LO:2 Discuss how Earth's energy balance and energy exchanges produce climate and weather.

LO:3 Compare and contrast the different layers of Earth's atmosphere.

LO:4 Explain the different types of severe weather events and discuss the local weather conditions that cause these events.

LO:5 Explain how movement of air masses control the distribution of different severe weather hazards.

LO:6 Discuss how humans interact with severe weather.

LO:7 Summarize the effects of severe weather events, as well as their linkages to other natural hazards.

LO:8 Recognize some natural service functions of severe weather.

LO:9 Identify how we can minimize the effects of severe weather hazards.

3

Linkages exist between natural hazards.

Similar to the linkage between severe thunderstorms and tornadoes, other severe weather phenomena, such as blizzards, ice storms, mountain windstorms, heat waves, and dust storms share linkages.

4

Humans can turn disastrous events into catastrophes.

Tornadoes have long been a menace to agricultural lands of the midcontinental United States, but as metropolitan suburbs like Moore expand, the risk grows.

5

Consequences of hazards can be minimized.

About the time of the 1999 Moore tornado, new standards for aboveground shelters were released. At the end of this chapter you can evaluate how successful these standards were for saving lives during the 2013 Moore tornado.



▲ FIGURE 9.1 Neighorbood Flattened by 1999 Moore, Oklahoma, Tornado
A tossed motor vehicle trailer lies among the wreckage of countless homes that were completely demolished by the high winds generated by the 1999 tornado. *(Staff Sgt. Caroline Hayworth)*

with the most noteworthy tornado striking Moore. On the morning of May 3, the storm prediction center in Norman, Oklahoma, issued a warning for a slight risk of severe thunderstorms from Kansas to Nebraska. By late afternoon, mobile weather tracking systems indicated thunderstorm conditions were favorable for tornado formation. With the highest-ever recorded wind speed of 484 km (~301 mi.) per hour, the 1999 Moore tornado touched down at 6:23 P.M. and ripped a path 61 km (~38 mi.) long and, in places, 1.6 km (~1 mi.) wide through the city. In less than 90 minutes, the 1999 Moore tornado killed 36 people, injured 295, and damaged or destroyed about 10,000 homes.[1] Anything in the direct path of the tornado that was not below ground was completely obliterated (Figure 9.1).

On average about 1,000 tornadoes strike the United States each year, and of those only about one per year is close to the power of the 1999 Moore tornado. Although the probability of the same town being hit by a similarly large tornado less than 15 years later might seem unlikely, that is exactly what happened. On May 20, 2013, Moore was devastated by a tornado of comparable destructiveness (see chapter-opener photograph) that followed a remarkably similar path.

We will revisit Moore at the end of this chapter and evaluate the 2013 tornado within the context of the five fundamental concepts.

9.1 Energy

The concept of *energy* is fundamental to understanding severe weather. Energy is an abstract concept because we cannot see or feel it. We can, however, experience the part of energy referred to as *force*. Many people experience force by either pushing or pulling an object. For example, when we pull a box along the floor or push our car when it has stalled, we are exerting a force in a specific direction. The strength or magnitude of this force can be measured by how much the force accelerates the motion of the box or car. In the metric system, force is measured in newtons. A *newton* (N) is defined as the force necessary to accelerate a 1 kg (~2.2 lb) mass 1 m (~3.3 ft.) per second each second that it is in motion.

Another important concept in understanding energy is *work*. Work is done when energy is expended. In physics, work is done when a force is applied to an object and that object moves a given distance in the direction of the applied force. Work is thus calculated by multiplying the force times the distance over which it is applied. In the metric system, work is measured in joules. A *joule* is defined as a force of 1 N applied over a distance of 1 m (~3.3 ft.). To relate this concept to weather, the amount of work that is taking place in a typical thunderstorm is approximately 10 trillion joules, whereas an average hurricane expends approximately 100,000 times that amount of work.

The rate at which work is done is its *power*. Another way of stating this is that power is energy divided by time. In the metric system, power is expressed as joules per second, or *watts* (W), and 1 joule per second is equal to 1 W. Many people associate the latter unit of measurement with the power used by appliances and lightbulbs.

When we look at atmospheric processes, we are often concerned with large amounts of energy. For example, when we discuss global energy consumption, the amounts are so large that they are often expressed in exajoules (EJ). One EJ is 1 quintillion (10^8) joules. U.S. Department of Energy statistics indicate that global energy consumption is more than 440 EJ per year, a little more than 1.2 EJ each day. For comparison, the internal heat energy of Earth that reaches the surface is three times human global energy consumption, whereas solar energy reaching the surface of Earth is nearly 10,000 times more energy than humans consume each year.[2] Thus, it is primarily solar energy that heats the surface of our planet, evaporates water, and produces the differential heating that causes air masses to move across our landscape.

TYPES OF ENERGY

We must expend energy to do work; another way of stating this concept is to define energy as the "ability to do work." Three main types of energy are potential energy, kinetic energy, and heat energy. *Potential energy* is stored energy. For example, the water held behind a dam contains gravitational potential energy that, if released, would flow downward. *Kinetic energy* is the energy of motion. From the previous example, the water flowing from the dam loses potential energy but gains kinetic energy as it accelerates downward. In the case of a hydroelectric dam, the kinetic energy of the flowing water is used to turn turbines (doing *work*) to generate electricity.

Heat energy is the energy of random motion of atoms and molecules. Heat itself may then be defined as the kinetic energy of atoms or molecules within a substance. Heat may also be thought of as the energy that is transferred from one object to another due to a difference in temperature.[3] Two types of heat that are important in atmospheric processes are sensible heat and latent heat. As the name suggests, *sensible heat* is heat that may be sensed or measured by a thermometer. It is sensible heat that we feel in the air on a warm day. **Latent heat** is a more difficult concept to comprehend; it is the amount of heat that is either absorbed or released when a substance changes phase (from solid to liquid, for example). In the atmosphere, latent heat is related to the three phases of water: ice, liquid water, and water vapor (Figure 9.2). For example, the evaporation of water involves a phase change from liquid to water vapor, a gas. The energy required for this transformation is known as the *latent heat of vaporization*. This energy is recoverable when water vapor changes back to a liquid through condensation in the atmosphere, when moist air cools and water droplets form.[3]

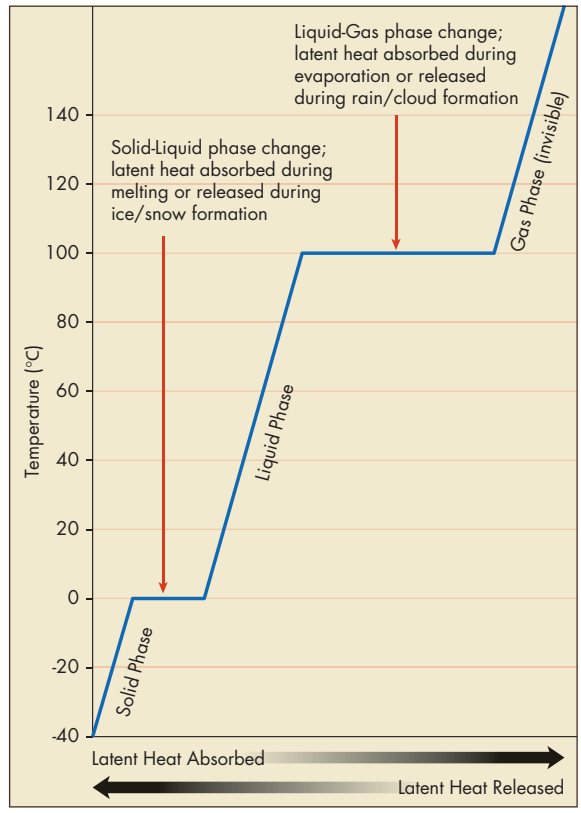


FIGURE 9.2 Latent Heat
Generalized graph showing how latent heat is either absorbed or released during phase changes of water. As you move from left to right—melting ice to water then vaporizing water to gas—heat is absorbed by the water. When the process is reversed, the previously absorbed heat is given off as water changes from gas, to liquid, to ice.

HEAT TRANSFER

To complete our discussion of energy, work, and power, we need to consider how heat energy is transferred in the atmosphere. Three major heat-transfer processes are conduction, convection, and radiation. A pot of boiling water on an electric range illustrates these three processes at work (Figure 9.3).

Conduction is the transfer of heat through a substance by means of atomic or molecular interactions. The process of conduction relies on temperature differences, causing heat to flow through a substance from an area of greater temperature to an area of lesser temperature. In our example, conduction of heat through the metal pot causes the handle to heat up. Although conduction also occurs in the atmosphere, on land, and in bodies of water such as the ocean, it is least important in the atmosphere. Air is actually a poor conductor of heat. This is why trapped

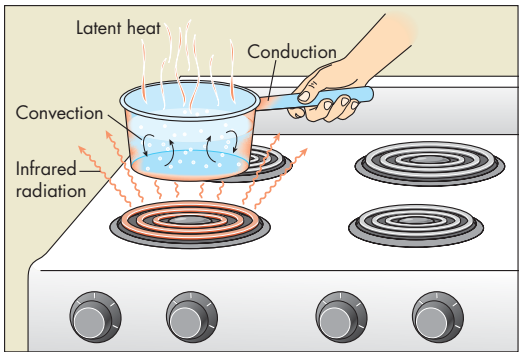


FIGURE 9.3 Heat Transfer Processes
Idealized heat transfer for a pan of boiling water on an electric range. Conduction is taking place in the metal of the pan and its handle; circulating water is transferring heat by convection, and visible and invisible electromagnetic radiation is being transferred through the air from the glowing coil. Latent heat is being absorbed by water vapor as liquid water evaporates. *(Based on Christopherson, R. W.,* Geosystems: An Introduction to Physical Geography, *6th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2006)*

air is used to increase the insulation value of goose-down comforters, double-paned windows, and plastic foam. In the atmosphere, significant conduction is generally limited to very thin layers of air in contact with Earth's surface.

Convection is the transfer of heat by the mass movement of a fluid, such as water or air. In our example, water in the bottom of the pot is heated and rises upward to displace the cooler water at the surface. The cooler water then sinks downward to the bottom of the pot. This physically mixes the water by moving the heat energy and creates a circulation loop known as a *convection cell.* Convection is an important process for the transfer of atmospheric heat in thunderstorms and in the large-scale circulation of warm air away from the equator.

Finally, **radiation** refers to wavelike energy that is emitted by any substance that possesses heat. The transfer of energy by radiation occurs by oscillations in an electric field and a magnetic field, and thus the waves are generally called *electromagnetic waves.* In our example, the red glow from the heating element of the electric range transmits visible electromagnetic radiation as red light and nonvisible infrared radiation. Most electromagnetic waves are not visible to us.

Our example is summarized as follows: The heat transfer from the electric range includes electromagnetic radiation from the glowing heating coil on the stove, conduction through the solid metal pot, and finally convection bringing warm water bubbling upward from the bottom to the top of the pot.

9.1 CHECK your understanding

1. Describe the differences between force, work, and power.
2. What are the three types of energy? How do they differ from one another?
3. What is the difference between sensible heat and latent heat?
4. What are the three types of heat transfer? How do they differ from one another?

9.2 Earth's Energy Balance

The energy that Earth receives from the sun affects the atmosphere, oceans, land, and living things before being radiated back into space. This process creates *Earth's energy balance*—a general equilibrium between incoming and outgoing energy (Figure 9.4). In the shift from incoming to outgoing energy, some of the energy changes form, but as stated in the first law of thermodynamics, it is neither created nor destroyed.

Although Earth intercepts only a tiny fraction of the total energy emitted by the sun, the intercepted energy is adequate to sustain life. The sun's energy also drives the hydrologic cycle, ocean waves and currents, and global atmospheric circulation. Although Earth's energy balance or budget contains several important components, nearly all of the energy that is available at Earth's surface comes from the sun (Figure 9.4).

ELECTROMAGNETIC ENERGY

Much of the energy emitted from the sun is *electromagnetic energy.* This energy, a type of radiation, travels through the vacuum of space at the speed of light, a velocity close to 300,000 km (~186,000 mi.) per second. Electromagnetic radiation is commonly described as a wave, and the distance between the tops of two successive waves is referred to as the *wavelength.* The various types of electromagnetic radiation are distinguished by their wavelengths, and the collection of all possible wavelengths is known as the *electromagnetic spectrum* (Figure 9.5). Longer wavelengths, those greater than 1 m (~3.3 ft.), include radio waves and microwaves, whereas the shortest wavelengths are X-rays and gamma rays. Visible electromagnetic radiation, referred to as light, makes up only a very small fraction of the total electromagnetic spectrum. Other types of electromagnetic radiation with environmental significance include infrared (IR) and ultraviolet (UV) radiation. Infrared radiation is involved in global warming, and

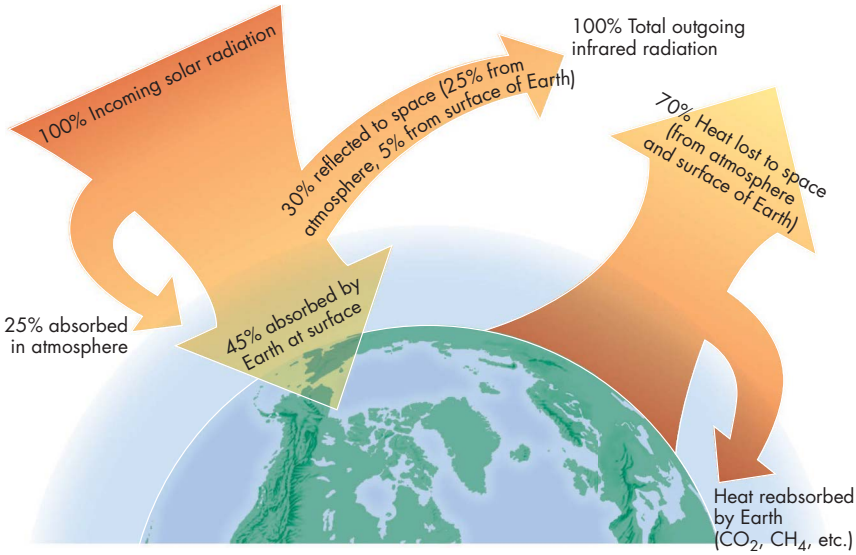


FIGURE 9.4 Earth's Energy Balance

Most of the annual energy flow to Earth from the sun is either reflected or reradiated back into outer space. Only a small component of Earth's heat is actually coming from its interior. *(Based on Pruitt, N. L., Underwood, L. S., and Surver, W.,* Bioinquiry, Learning System 1.0, Making Connections in Biology. *New York: John Wiley & Sons, 1999)*

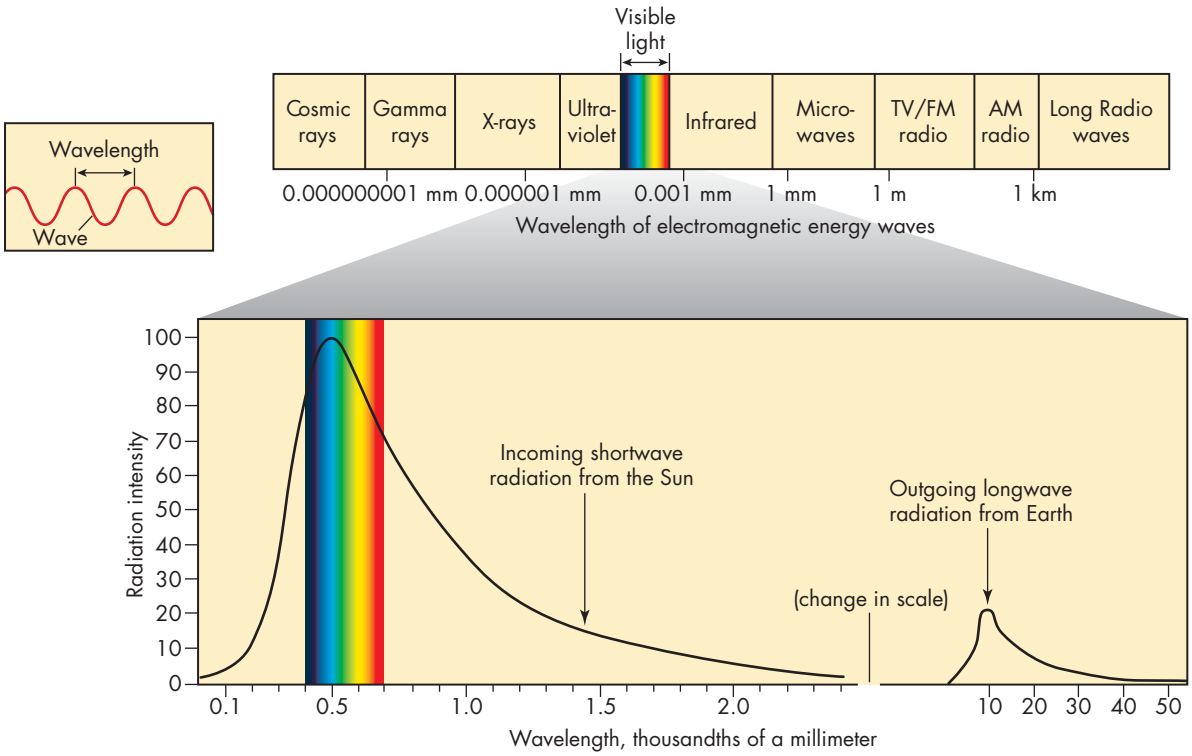


FIGURE 9.5 The Electromagnetic Spectrum

Wavelength is the distance between one wave crest and the next. Values for wavelength in the electromagnetic spectrum have an enormous range from billionths of a meter for X-rays to thousands of meters for long radio waves. The incoming energy from the sun has shorter wavelengths than the radiation emitted from Earth. Only a small amount of the electromagnetic spectrum is visible light that can be seen by the human eye.

levels of UV radiation at Earth's surface are influenced by the depletion of ozone in the upper atmosphere (see Chapter 12).

ENERGY BEHAVIOR

Once electromagnetic energy from the sun reaches Earth, it is redirected, transmitted, or absorbed by the atmosphere, ocean, or land. In redirection, the energy is either reflected like a light bouncing off a mirror or scattered in different directions. Reflection—from the tops of clouds, the water, and the land—is one of two ways that solar energy returns to outer space (see Chapter 12). Scattering disperses the energy in many directions, with scattered energy generally weaker than reflected or transmitted energy. Transmission involves the energy passing through the atmosphere, like light passing directly through window glass. On a clear day, the atmosphere transmits most of the energy it receives from the sun. Absorption of electromagnetic energy either alters the structure of molecules or causes them to vibrate and emit energy. Alteration of molecular structure can take place with penetrating shortwave radiation, such as UV radiation. Emitted energy can take the form of heat or electromagnetic radiation. For many gases, the emitted electromagnetic energy is at the same wavelength as the absorbed energy, whereas in many solids, the emitted energy is at a longer wavelength, such as IR energy. Emission is the second way that solar energy returns to outer space; Earth absorbs shortwave energy from the sun, heats up, and then emits energy in longer wavelengths (see Figures 9.4 and 9.5).

The relative amount of energy reflected and absorbed is important in determining the temperature of the air and land. For example, the color of the land surface determines its reflectivity to visible light. This reflectivity is referred to as the *albedo* of the surface. In general, darker-colored surfaces have lower albedo than lighter-colored surfaces. Darker-colored coniferous woodland, such as pine or spruce forests, reflects 5 percent to 15 percent of solar radiation compared to lighter-colored grasslands that reflect up to 25 percent of the incoming solar radiation.[4] Much of the energy that is not reflected is absorbed, causing darker surfaces to heat up more than lighter surfaces. Many atmospheric gases are selective absorbers; that is, they absorb some wavelengths of energy and are transparent to others. For example, carbon dioxide and water vapor selectively absorb IR wavelengths and contribute to the warming of the lowest layer of the atmosphere (see Chapter 12).

Absorbed energy that is not emitted as heat is emitted as electromagnetic radiation. The temperature of the object emitting the radiation also affects the wavelength of the electromagnetic radiation that it emits. Hotter objects radiate energy more rapidly and at shorter wavelengths. This fact explains why the sun emits mainly short-wave-length radiation, such as gamma rays and X-rays, and visible and UV light (Figure 9.5). In contrast, Earth's land surface, oceans, and clouds are so cool that they emit predominantly longer-wavelength IR radiation.

9.2 CHECK your understanding

1. Describe how Earth's energy balance works.
2. What is electromagnetic energy? How are the different types of electromagnetic energy distinguished?
3. List the following types of electromagnetic energy in order from shortest wavelength to longest wavelength: radio waves, ultraviolet radiation, gamma radiation, visible light, infrared radiation, X-rays, and microwaves.
4. Explain why incoming solar radiation does not overheat the Earth, using the energy balance diagram (Figure 9.4).
5. How is color related to energy absorption?

9.3 The Atmosphere

Now that we have finished our brief discussion of energy and Earth's energy balance, we will discuss the various components of Earth's atmosphere, along with atmospheric circulation. These concepts are fundamental to the understanding of weather processes and weather-related hazards.

The **atmosphere** is the thin gaseous envelope that surrounds Earth (Figure 9.6). It is made up of gas molecules, suspended particles of solid and liquid, and falling precipitation. The atmosphere causes the weather we experience every day and is responsible for trapping the heat that keeps the Earth warm enough to be habitable. Knowledge of the structure and dynamics of the atmosphere is critical to understanding severe weather, as well as the mechanisms and causes of global warming that will be discussed in Chapter 12.

COMPOSITION OF THE ATMOSPHERE

The atmosphere is mainly composed of nitrogen and oxygen; it contains smaller amounts of argon, water vapor, and carbon dioxide. Other trace elements and compounds exist in still lesser amounts. We will discuss



< FIGURE 9.6 Earth's Thin Atmosphere
Viewed from space, the atmosphere appears as a thin layer surrounding Earth. *(NASA)*

these gases in greater detail in Chapter 12. The behavior and content of water vapor in the atmosphere is an important part of cloud formation and atmospheric circulation. We use the term *humidity* to describe the amount of water vapor. Humidity is largely a function of temperature; warm air has the capacity to hold more water vapor than does cold air. The amount of moisture in the air is commonly given as the **relative humidity**, the ratio of the water vapor present in the atmosphere to the maximum amount of water vapor that could be there for a given temperature. Relative humidity is expressed as a percentage and varies from a few percent to 100 percent.

Natural changes in relative humidity occur each day without significant changes in the amount of water vapor in the atmosphere. Relative humidity increases at night because of the cooler temperature and decreases with daytime heating. Changes in the actual water vapor content of the atmosphere take place where water evaporates from Earth's surface or where air masses mix, either vertically or horizontally.

Virtually all the water vapor in the air is derived from evaporation of water from Earth's surface. Water is constantly being exchanged between the atmosphere and the various parts of the Earth. Sleet, snow, hail, and rain remove water from the atmosphere and deposit it on Earth where it may enter groundwater, rivers, lakes, oceans, and glaciers. Eventually this water will evaporate and return to the atmosphere to begin the cycle again. This constant cycling of water between the atmosphere and Earth's surface is a major part of the hydrologic cycle (see Chapter 1).

STRUCTURE OF THE ATMOSPHERE

The water vapor content and temperature of the atmosphere vary from Earth's surface to its upper limits. Images from orbiting spacecraft show that our atmosphere is very thin when compared to the size of Earth and that it is not easy to identify its upper limits (see Figure 9.7). Although the atmosphere has no well-defined upper boundary, most of the gas molecules are concentrated below a height of 100 km (~62 mi.).

Earth's atmosphere has a structure consisting of four major layers or spheres (Figure 9.7). The lowest layer, the **troposphere**, extends about 8 to 16 km (~5 to 10 mi.) above the surface of Earth. With the exception of some jet airplane travel, we spend our entire lives within the troposphere. Not even the highest mountains breach the upper boundary of the troposphere, known as the *tropopause*. The defining characteristic of the troposphere is a rapid upward decrease in temperature that results from decreasing air pressure with increasing altitude. However, the most visible characteristic of the troposphere is abundant condensed water vapor in the form of clouds. Most of the clouds and weather that directly affect us are found in the troposphere.

The formation and development of clouds are particularly important. Clouds develop when very small water droplets or ice crystals condense from the atmosphere. Without clouds there would be no rain, snow, thunder, lightning, or rainbows. You are probably familiar with two of the most common types of clouds—puffy, fair-weather *cumulus* clouds that may look like pieces of floating cotton, and the towering *cumulonimbus* thunderstorm clouds (Figure 9.8). Keep in mind that the formation of these large cumulonimbus clouds is associated with tremendous release of latent heat energy due to condensation of water vapor (see Figure 9.2).

Most of the atmospheric water vapor condenses in the troposphere, leaving little water in the upper layers of the atmosphere. In addition to water vapor, the

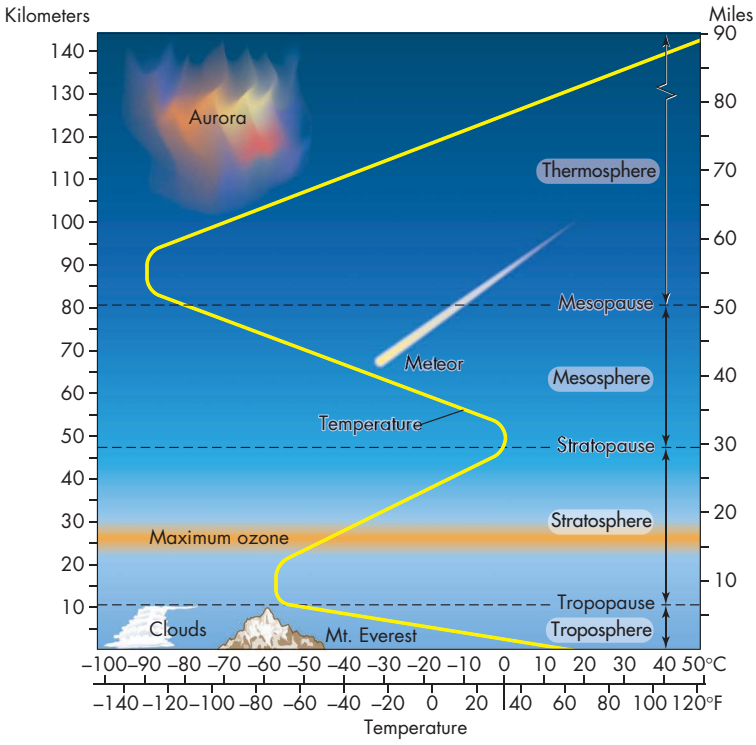


FIGURE 9.7 Atmospheric Structure

Earth's atmosphere has a structure based on changes in air temperature from the surface upward. The curving yellow line shows the average change in air temperature with height. Weather develops in the lowest layer, the troposphere, where temperatures fall with height. Temperatures rise in the stratosphere due to the presence of ozone molecules that absorb solar radiation. The rising temperatures act as a "lid," keeping air from rising and condensing past the tropopause. *(Based on Lutgens, F. K., and Tarbuck, E. J.,* The Atmosphere: An Introduction to Meteorology, *10th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2007)*

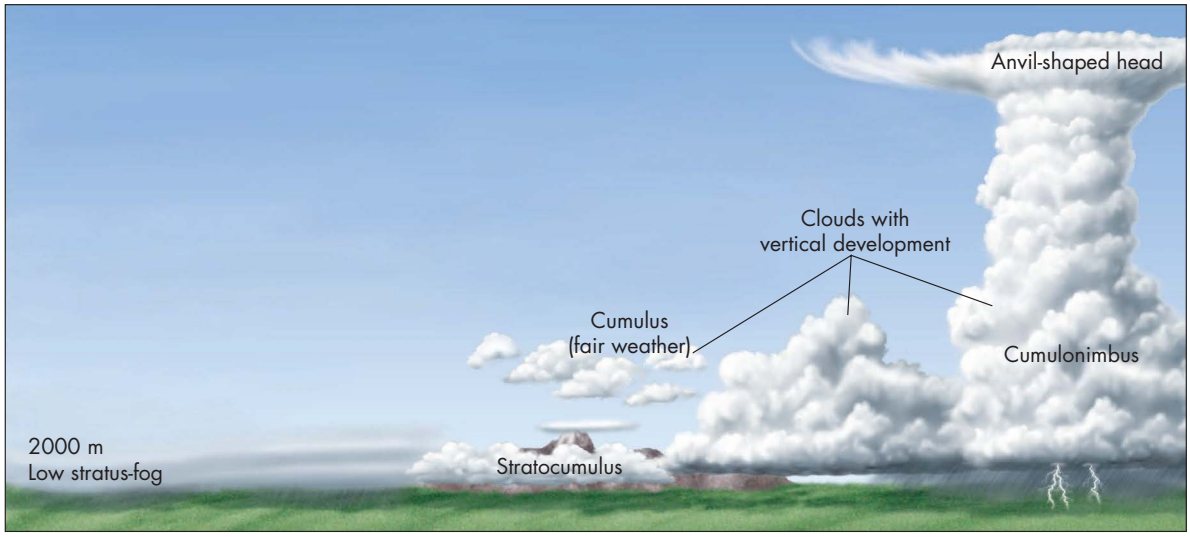


FIGURE 9.8 Cloud Types Associated with Severe Weather

Clouds consist of small water droplets and are classified on the basis of altitude (low, middle, and high) and form (cirriform, cumuliform, and stratiform). Cumulonimbus clouds are associated with severe thunderstorms and tornadoes. Stratus clouds in contact with the ground form fog. *(Based on Christopherson, R. W.,* Geosystems: An Introduction to Physical Geography, *6th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2006)*

troposphere contains most of the atmospheric carbon dioxide and methane, two gases that are important in global warming (Chapter 12). Only ozone, a gas composed of oxygen atoms (O_3), is significantly less abundant in the troposphere when compared with the upper atmosphere (see Figure 9.7).

9.3 CHECK your understanding

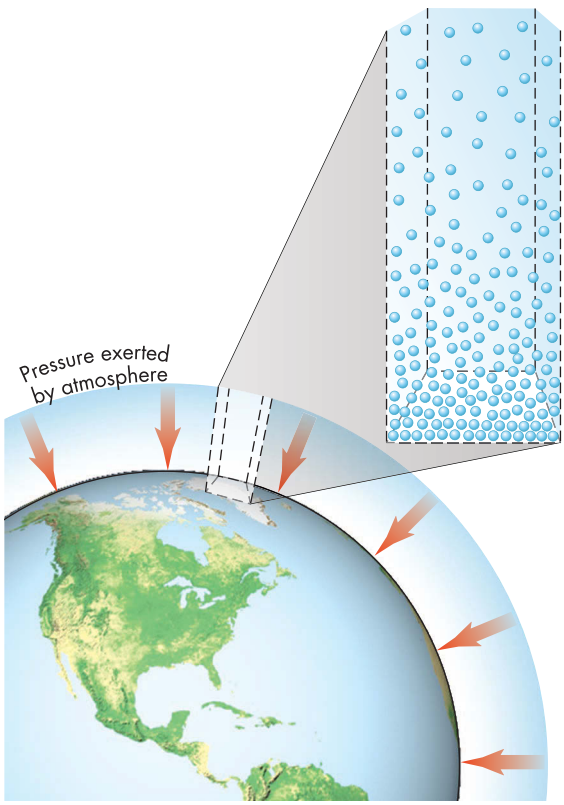
1. Describe the characteristics of the troposphere. How do meteorologists identify the top of the troposphere?
2. What is the tropopause? How high is it above Earth's surface?
3. How do clouds form?

9.4 Weather Processes

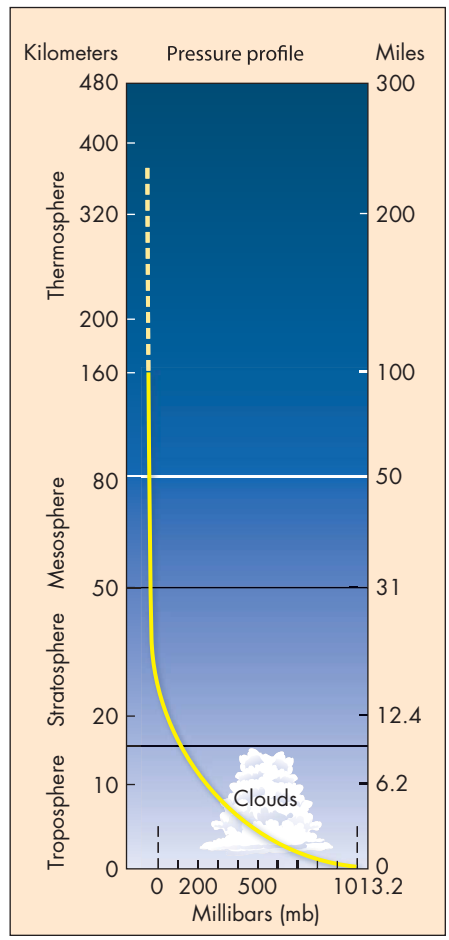
A complete discussion of the atmospheric conditions and processes associated with severe weather is beyond the scope of this book. Students who find this topic especially interesting should pursue coursework in meteorology, the scientific study of weather. Instead, we will focus on four aspects of the atmosphere that are directly related to severe weather: atmospheric pressure and circulation patterns, the vertical stability of the atmosphere, the Coriolis effect, and the interaction of different air masses.

ATMOSPHERIC PRESSURE AND CIRCULATION

Weather forecasters often talk about areas of low or high pressure. The pressure that they are referring to is *atmospheric pressure*. Also called *barometric pressure*, atmospheric pressure is the weight of the column of air that is above any given point (Figure 9.9a). This point



(a)



(b)

▲ FIGURE 9.9 Atmospheric Air Pressure Changes
Idealized diagram showing Earth and its atmosphere. Both the (a) density and (b) pressure of Earth's atmosphere decrease with increasing altitude. Air pressure at points on the Earth's surface also varies because the mass of overlying air varies from place to place. Variations in the mass of overlying air are caused by differences in the temperature and density of air masses. Air pressure can be expressed as atmospheric force per unit area. At sea level, average air pressure is about 1 kg per square centimeter (~14.7 pounds per square inch). *(Based on Lutgens, F. K., and Tarbuck, E. J.,* The Atmosphere: An Introduction to Meteorology, *10th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2007)*

may be on Earth's surface or above it, such as in an airplane. Atmospheric pressure can also be thought of as the force exerted by the gas molecules on a surface. As you might expect, atmospheric pressure is greater at sea level than at the top of a high mountain where there is less air (fewer gas molecules) above the surface (Figure 9.9b). Nearly all of the weight of the atmosphere and, thus, nearly all the pressure are in the lower atmosphere below an elevation of 50 km (~31 mi.). Atmospheric density and pressure decrease rapidly as one goes to higher elevations. You may have noticed this pressure change if your ears have ever "popped" while driving up or down a mountain or flying in an airplane when changing altitude.

Changes in air temperature and air movement are responsible for most of the horizontal variation in atmospheric pressure. Temperature change influences pressure because cold air is denser than warm air and exerts a higher pressure on the underlying surface. The density of cold air is higher because its gas molecules have lower kinetic energy and stay more closely packed together. Because air pressure and temperature are related, air pressure varies geographically, and this variation has a strong effect on the weather and global atmospheric circulation patterns.

Solar heating and evaporation of seawater at low latitudes near the equator creates warm air masses that have high relative humidity. This warm, low-density air near Earth's surface creates low-pressure zones at equatorial latitudes that convect upward in the atmosphere (Figure 9.10). The air masses cool as they rise; their relative humidity increases and water vapor within the

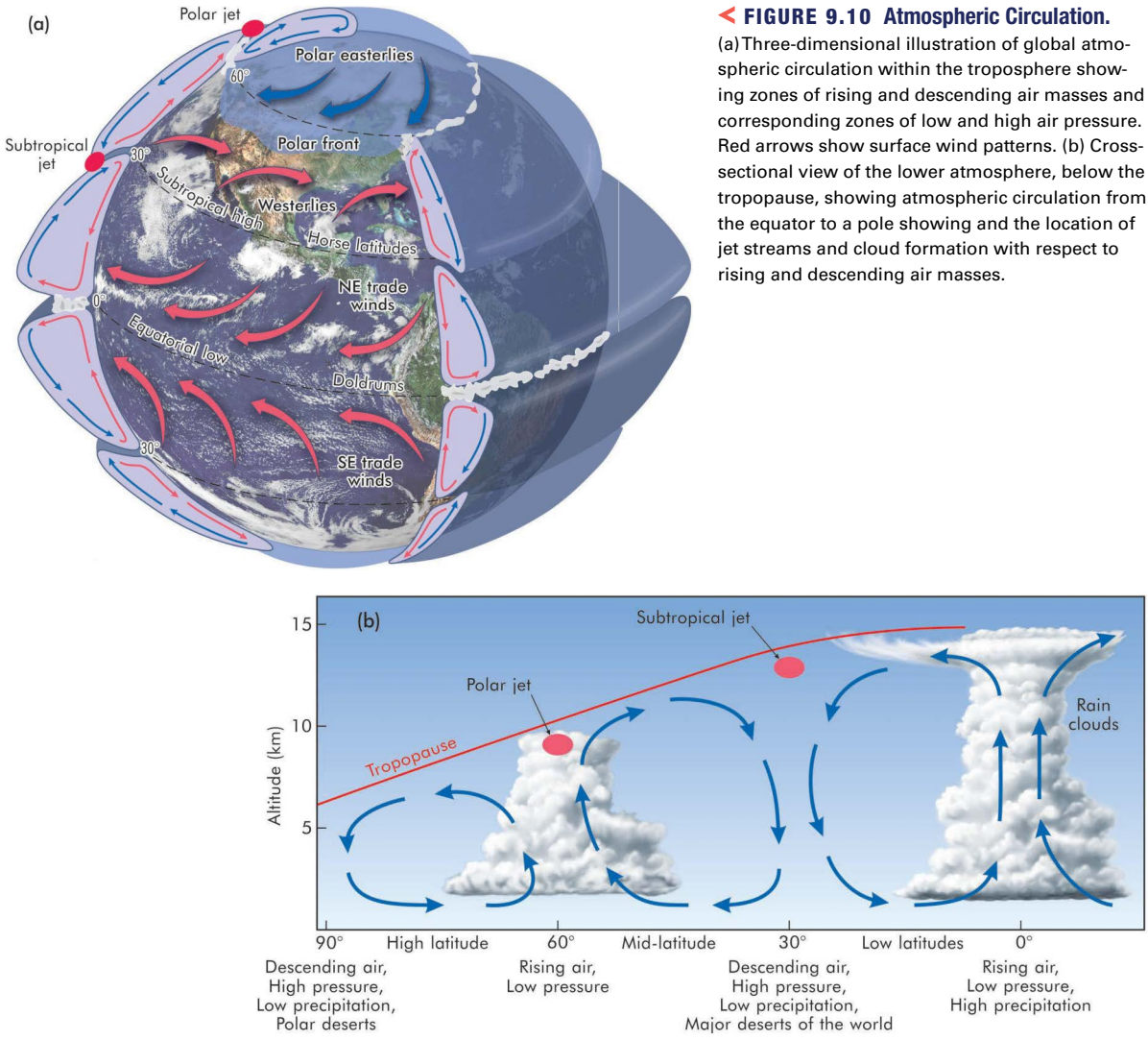


FIGURE 9.10 Atmospheric Circulation.
(a) Three-dimensional illustration of global atmospheric circulation within the troposphere showing zones of rising and descending air masses and corresponding zones of low and high air pressure. Red arrows show surface wind patterns. (b) Cross-sectional view of the lower atmosphere, below the tropopause, showing atmospheric circulation from the equator to a pole showing and the location of jet streams and cloud formation with respect to rising and descending air masses.

air masses condenses to form clouds and the abundant precipitation characteristic of the low latitude tropics (Figure 9.10b). Having dropped the rain, the now dry, cold, and dense air in the upper troposphere moves toward the poles and sinks at 30° north and south latitude. The subtropical midlatitude deserts of the world, such as the Sahara, Arabian, and Mojave, are, in fact, the result of these dry descending air masses. Similar vertical circulation cells are observed at middle and high latitudes, where low-pressure zones at 60° north and south latitude are characterized by rising humid air that spreads out at the tropopause and descends at the poles and 30° latitude (Figure 9.10b). Where midlatitude air masses of different temperatures collide near the tropopause, narrow fast-flowing jets of air occur. **Jet streams**, as they are called, are westerly winds (flowing from west to east) that encircle the globe and play an important role in creating severe weather and controlling the path of storms (Figure 9.11). Their westerly flow is due to the Coriolis effect (see Case Study 9.1: A Closer Look), and the greater the temperature difference between the colliding air masses, the faster the jet stream will flow.

Each hemisphere has two jet streams: one at an average altitude of 10 km (32,800 ft.) called the *polar jet stream*, and the other at an average altitude of 13 km (~42,660 ft.) referred to as the *subtropical jet stream* (Figure 9.11).[5] These jet streams vary from less than 100 km (~60 mi.) to more than 500 km (~310 mi.) in width and are typically several kilometers thick.[6] The Northern Hemisphere polar jet streams cross North America from west to east at an average speed of 180 km (~110 mi.) per hour in the winter and 90 km (~50 mi.) per hour in the summer, with peak flow within the jet streams being twice the average wind speed.[7] Because the jet streams flow at an altitude similar to that of commercial air traffic, you have likely interacted directly with these fast-moving jets of air. Next time you take a round-trip flight between the east and west coasts, notice that the length of the flight is almost always longer when flying westward. This is due to strong jet stream headwinds while traveling westward and tailwinds while flying eastward.

The polar jet stream is the stronger of the two jets because it occurs along the boundary between cold arctic polar air masses to the north and warm subtropical and tropical air masses to the south (Figure 9.11). The polar jet stream shifts from a path crossing the conterminous United States in the winter to one crossing southern Canada in the summer (Figure 9.12). This migration in its path causes a northward shift in the location of severe thunderstorm and tornado activity in the United States during the late winter, spring, and early summer. The subtropical jet stream that normally

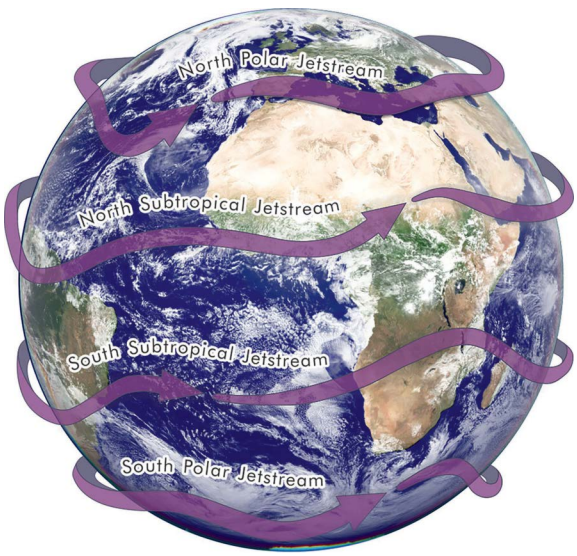


FIGURE 9.11 Polar and Subtropical Jet Streams
Strong winds near the boundary between the troposphere and stratosphere are concentrated in jet streams. The strongest winds are in the polar jet stream at around 10 km (~32,815 ft.), and generally less intense winds form the subtropical jet stream at about 13 km (~42,660 ft.). *(Based on Lutgens, F. K., and Tarbuck, E. J.,* The Atmosphere: An Introduction to Meteorology, *10th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2007)*

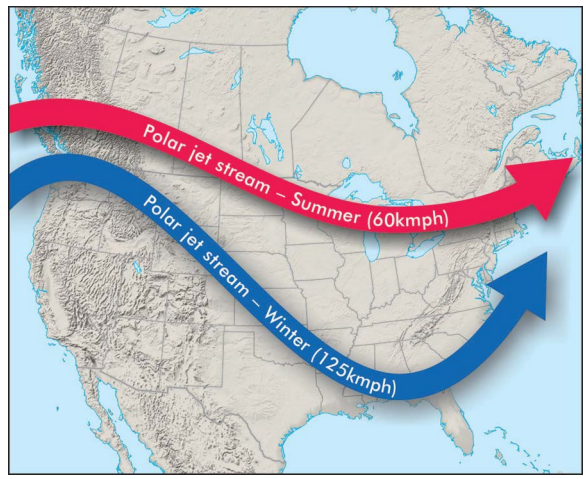


FIGURE 9.12 Polar and Subtropical Jet Streams
The position of the polar jet stream shifts from about 30° latitude in the winter months to about 70° latitude in the summer months. Because the temperature difference between midlatitude and polar air masses is lower during the summer months, the velocity of the polar jet is also decreased. *(Based on Lutgens, F. K., and Tarbuck, E. J.,* The Atmosphere: An Introduction to Meteorology, *12th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2010)*

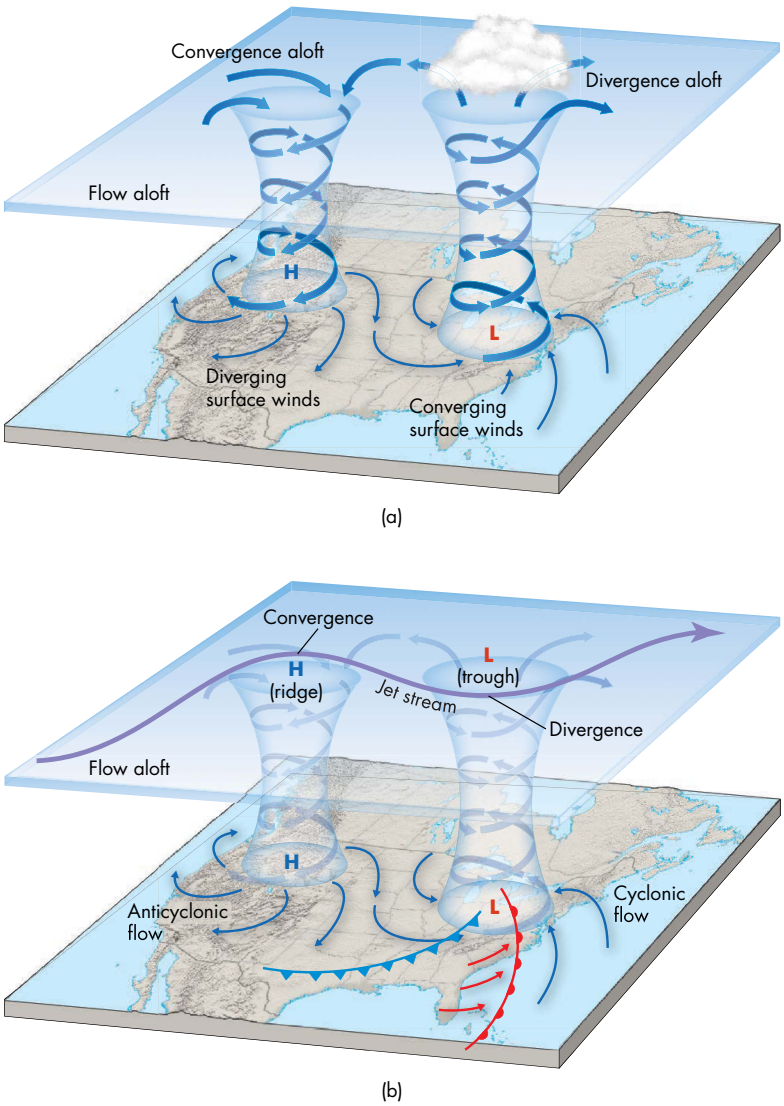
crosses Mexico and Florida is weak during summer months and strongest in the winter when the temperature gradient between low-latitude and midlatitude air masses is greatest.

Air movement can also cause changes in atmospheric pressure. If there is an overall flow of air into a region, *convergence* of the air occurs, and the air piles up to increase atmospheric pressure. In contrast, if there is an overall flow of air out of a region, then *divergence* occurs, and the loss of air lowers atmospheric pressure (Figure 9.13a).

The combined effects of temperature and air movement produce the *low-pressure centers* (L) and *high-pressure centers* (H) that you see on weather maps. At the surface and aloft, air flows from areas of high pressure to areas of low pressure. Where elongate regions of high and low pressure develop aloft—known as *ridges* and *troughs*, respectively—the jet stream is forced to meander northward and southward along its westerly path (Figure 9.13b). As the jet stream travels along the ridges and troughs, it causes local flow convergence and divergence aloft leading to sinking and rising air, which can affect near-surface atmospheric pressure conditions and weather patterns (Figure 9.13b).

UNSTABLE AIR

As stated in the previous section, air movement can also be caused by vertical differences in temperature and pressure in the atmosphere. We can understand how



< FIGURE 9.13 Low- and High-Pressure Centers
This diagram illustrates airflow near low- and high-pressure centers in the Northern Hemisphere. (a) Horizontal changes in atmospheric pressure and temperature at Earth's surface causes areas of low (L) and high (H) pressure. In areas of low pressure, cyclonic surface winds converge causing air to rise and clouds to develop. Whereas diverging anticyclonic surface winds in high-pressure areas cause air to descend, resulting in clear skies. (b) Similar pressure conditions and wind patterns also result from convergence and divergence of air flowing in the upper troposphere due to high- and low-pressure ridges aloft. *(Based on Lutgens, F. K., and Tarbuck, E. J.,* The Atmosphere: An Introduction to Meteorology, *12th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2010)*

Coriolis Effect

9.1 A Closer Look

CASE study

The unequal distribution of solar energy that reaches the surface of Earth inevitably leads to temperature and pressure gradients that drive atmospheric circulation. You might expect air moving from a high-pressure area to a low-pressure area to follow a straight path; yet, when wind patterns are traced across Earth's surface, they appear to curve (Figure 9.1.A). This is because Earth, our frame of reference, rotates beneath the flowing air masses, causing a deflection of the wind to the right or to the left. This apparent change in motion or deflection is known as the **Coriolis effect**.

In order to understand the Coriolis effect, we must first step off our planet and get some perspective on our rotating home. As Figure 9.1.B shows, Earth rotates from west to east and, when viewed from the Northern Hemisphere, rotates in a counterclockwise manner. Conversely and perhaps surprisingly, when viewed from above the South Pole, the west to east rotation of Earth results in a clockwise rotation. Because of the different rotation directions, the Coriolis effect behaves differently in the Northern Hemisphere than in the Southern Hemisphere. Specifically, in the Northern Hemisphere the deflection will be to the right, and in the Southern Hemisphere the deflection will be to the left (Figure 9.1.A).

Let us now examine what causes the Coriolis deflection. Notice in Figure 9.1.B that the rotation speed of Earth varies with latitude, increasing from zero at the poles to 1675 km (~1041 mi.) per hour at the equator. It is this variability in the rotation speed that causes the apparent deflection of anything that flows or flies north or south above the rotating surface of Earth, including airplanes, oceans, and air masses. The Coriolis force acts at a right angle to the direction of motion, causing an object moving above the surface to have a curved path (Figure 9.1.C). A good way to visualize the Coriolis effect is to vizualize an airplane flight to explain how Earth's rotation could cause air masses to be deflected across the surface of the Earth. The pilot plots a course due south along a straight path from the North Pole to Quito, Ecuador (Figure 9.1.B). Departing from the North Pole (the axis of Earth's rotation), the plane has zero eastward rotation. Although the plane flies along a straight path

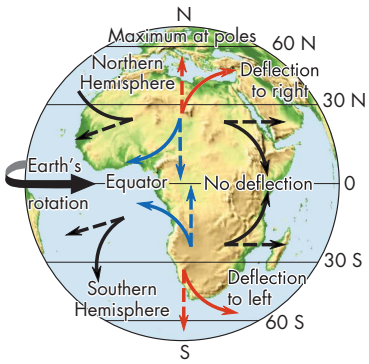


FIGURE 9.1.A Surface Wind Patterns Resulting from the Coriolis Effect
Air masses moving across the surface of Earth (dashed lines) are deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere (solid lines) due to the Coriolis effect. *(Based on Christopherson, R. W.,* Geosystems, *7th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2009)*

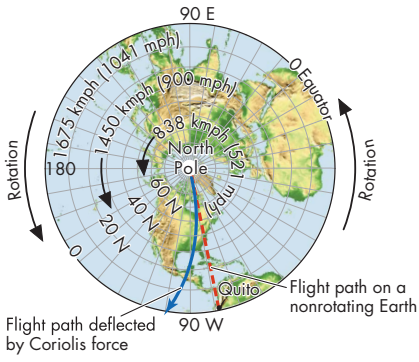


FIGURE 9.1.B Earth's Rotation
Apparent deflection of an airplane traveling along a straight path between the North Pole and Quito, Ecuador, which is on the equator. *(Based on Christopherson, R. W.,* Geosystems, *7th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2009)*

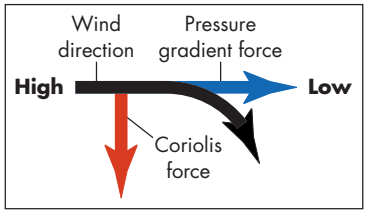


FIGURE 9.1.C Forces Involved in Wind Patterns
The path of an air mass is controlled by the pressure gradient and the Coriolis forces. On a nonrotating Earth, air masses would flow along the pressure gradient (blue arrow). However, on a rotating Earth, the Coriolis force exerts a force to the right in the Northern Hemisphere (red arrow) perpendicular to the horizontal wind direction, which causes the path of an air mass to curve (black arrow).

toward Quito, the greater rotation speed of Earth near the equator carries the city eastward. Upon arriving at the latitude of Quito, the pilot would be at a location over the Pacific Ocean. To an observer in Quito watching the airplane, the land surface would feel stationary, yet the airplane would appear to turn toward the west and head out over the sea, even though its path was straight. On the return flight from Quito, the greater eastward rotation at the equator compared to more northern latitudes would cause the airplane to be deflected toward the east. In both cases, when viewed from above, the plane appears to have been deflected to the right.

Let's now return to Figure 9.1.A to see how the Coriolis effect can be used to explain the predominant wind directions on Earth. Wind traveling southward from the Northern Hemisphere's subtropical high-pressure zone (30°N latitude) will be deflected toward the west, producing easterly winds, whereas winds moving toward the north will produce westerly winds. In contrast, air moving southward from the Southern Hemisphere's subtropical high-pressure zone (30°S latitude) will be deflected toward the west, producing easterly winds, whereas wind moving toward the north will produce westerly winds.

this occurs by examining the behavior of a small volume or *parcel* of air. You can visualize a parcel of air as an imaginary balloon similar to a small blimp circling over an outdoor stadium during a football game.

The tendency of a parcel of air to remain in place or change its vertical position is referred to as *atmospheric stability*. An air mass is stable if parcels of air within it resist vertical movement or return to their original position after they have moved. Alternatively, an air mass is considered unstable if parcels within it are rising until they reach air of similar temperature and density.[8] The atmosphere commonly becomes unstable when lighter warm or moist air is overlain by denser cold or dry air. Under these conditions, the instability causes some parcels of air to sink and others to rise like hot-air balloons. Severe weather, such as thunderstorms and tornadoes, is associated with unstable atmospheric conditions. Upper atmosphere winds can cause air masses to move over colder or warmer surfaces, increasing or decreasing atmospheric stability.

FRONTS

Weather forecasters refer to the boundary between a cooler and warmer air mass as a **front**. This boundary is called a cold front when cold air is moving into a mass of warm air and a warm front when the opposite occurs (Figure 9.14). Regardless of which air mass is advancing on the other, the warmer air will always be lifted by the colder, denser air mass. In addition to having different temperatures, the air masses may also have different humidity levels, densities, wind patterns, and stability. As a result of friction with the ground, high-density cold fronts are slowed at lower levels, compared to higher up in the air mass, causing the front to become steeper (Figure 9.14a). As the cold front advances, warm air is driven rapidly up the steep cold front causing localized cloud formation, strong updrafts, and, often, heavy precipitation. In contrast, warm fronts tend to be gentler as they override the receding cold air mass, and, therefore, updrafts and cloud formation are more scattered (Figure 9.14b). Fronts may remain stationary for a few hours or even days. A boundary between cooler and warmer air that shows little movement is called a *stationary front*. A fourth type of front, called an *occluded front*, develops when rapidly moving cooler air overtakes another cooler air mass and warm air is wedged above the frontal boundary. Each of these four types of fronts can cause inclement weather. The positions of fronts, as well as areas of high and low pressure, are shown on standard weather maps of surface atmospheric conditions (Figure 9.15).

9.4 CHECK your understanding

1. Why does atmospheric pressure decrease with increasing altitude?
2. What is the difference between stable and unstable air?
3. Explain the Coriolis effect. How does it influence weather?
4. Why is the polar jet stream stronger than the subtropical jet stream?

9.5 Hazardous Weather and Geographic Regions at Risk

The basic principles of atmospheric physics described earlier can help us understand severe weather and its associated hazards. Severe weather refers to events such as thunderstorms, tornadoes, hurricanes (see

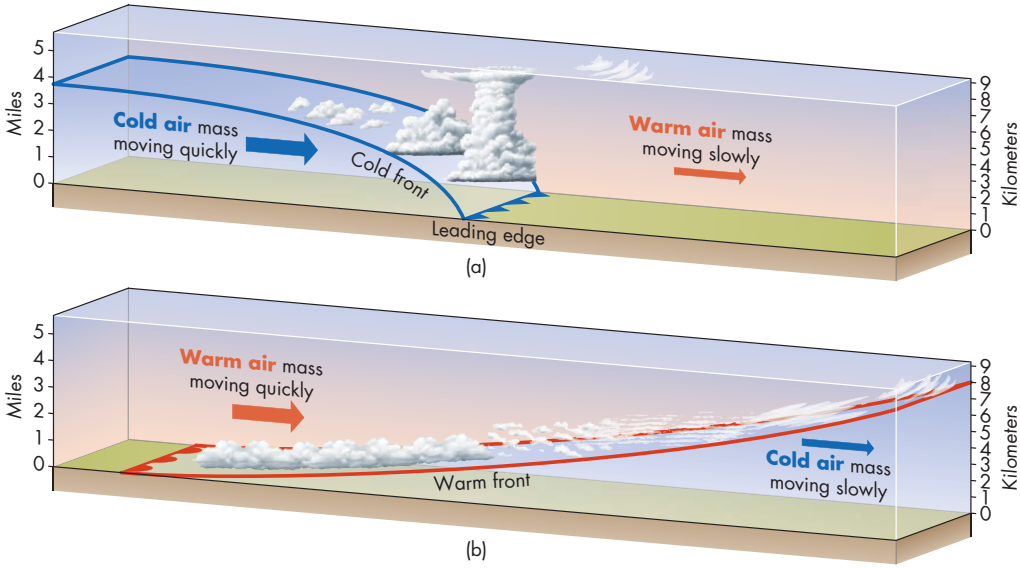


FIGURE 9.14 Fronts

Weather fronts mark the boundary of air masses that have different densities, generally as the result of differences in temperature. (a) Advancing cold front forces warm air upward. The rising warm air can create clouds and heavy precipitation. (b) Advancing warm front forces warm air to rise over cooler air. Clouds and precipitation may develop. *(Based on McKnight, T. L., and Hess, D.,* Physical Geography, *8th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2004)*

Chapter 10), blizzards, ice storms, mountain windstorms, heat waves, and dust storms. These events are considered hazardous because of the energy they release and damage they are capable of causing.

THUNDERSTORMS

At any one time, thousands of thunderstorms are in progress on Earth. Most occur in the equatorial regions. For example, the city of Kampala, Uganda, near the equator in East Africa, holds the world record for thunderstorm frequency; it has thunderstorms nearly seven out of every ten days. In North America, the regions with the highest annual number of days with thunderstorms are in an area along the Front Range of the Rocky Mountains in Colorado and New Mexico and in a belt that encompasses all of Florida and the southern parts of Georgia, Alabama, Mississippi, and Louisiana (Figure 9.16).

Most readers are likely to have experienced at least one thunderstorm, because they occur in virtually every part of the United States and Canada. Although they can form at any time, thunderstorms are most common during afternoon and evening hours, especially in the spring and summer. Their abundance at this time of

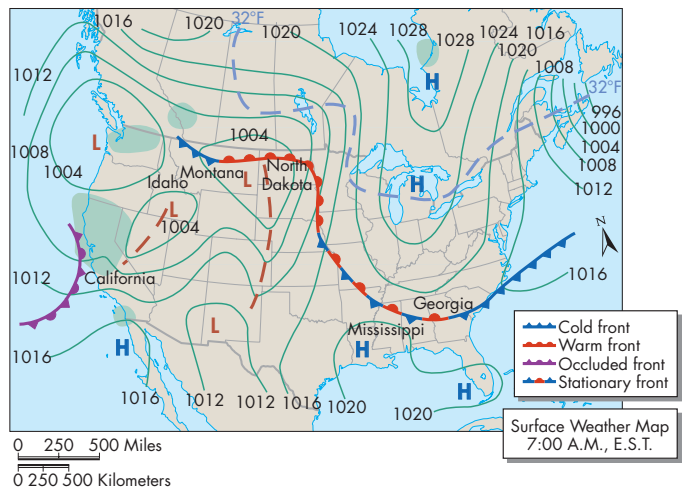
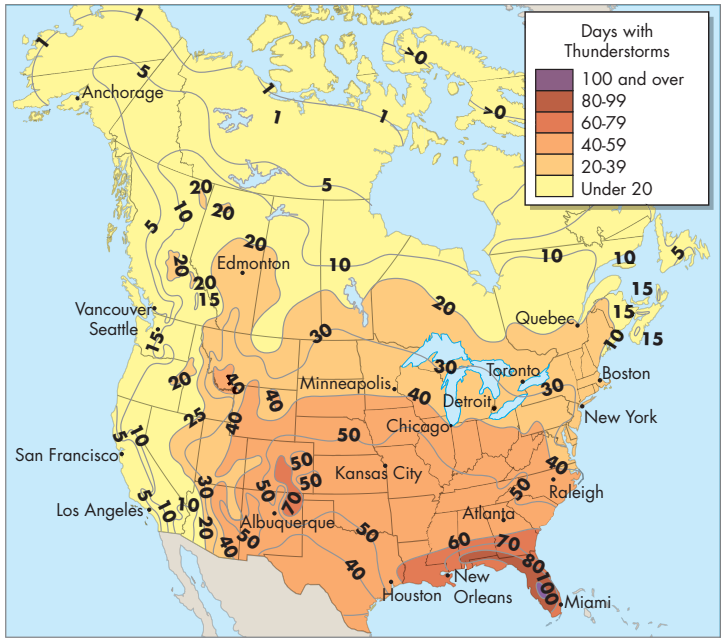


FIGURE 9.15 Weather Map

The weather showing surface atmospheric conditions for the United States and southern Canada on April 13, 2003. Map shows positions of surface high- (H) and low- (L) pressure centers, two low-pressure troughs (reddish brown dashed lines), a cold front extending east from Georgia into the Atlantic Ocean (blue line with triangles), a warm front in North Dakota (red line with half circles), a stationary front in the lower Mississippi Valley, an occluded front off the California coast, the line marking freezing temperature (curving dashed blue line), and areas of precipitation (solid green). The green contour lines show atmospheric pressure in millibars (e.g., 1016). *(From the National Weather Service, NOAA)*



< FIGURE 9.16 Thunderstorm Occurrence in North America

Average number of days per year with thunderstorms in the United States and Canada. South-central Florida has the greatest number of days with thunderstorms, and Baffin Island in the Canadian Arctic has the least. *(From the National Weather Service, NOAA)*

maximum daytime heating is related to three basic atmospheric conditions that are required to produce a thunderstorm:

1. Warm humid air must be available in the lower atmosphere to feed clouds and precipitation and provide energy to the storm as it develops.
2. A steep vertical temperature gradient must exist in the environment such that the rising air is warmer than the air through which it is moving. This gradient places colder air over warmer, moist air.
3. An updraft must force moist air up to colder levels of the atmosphere.

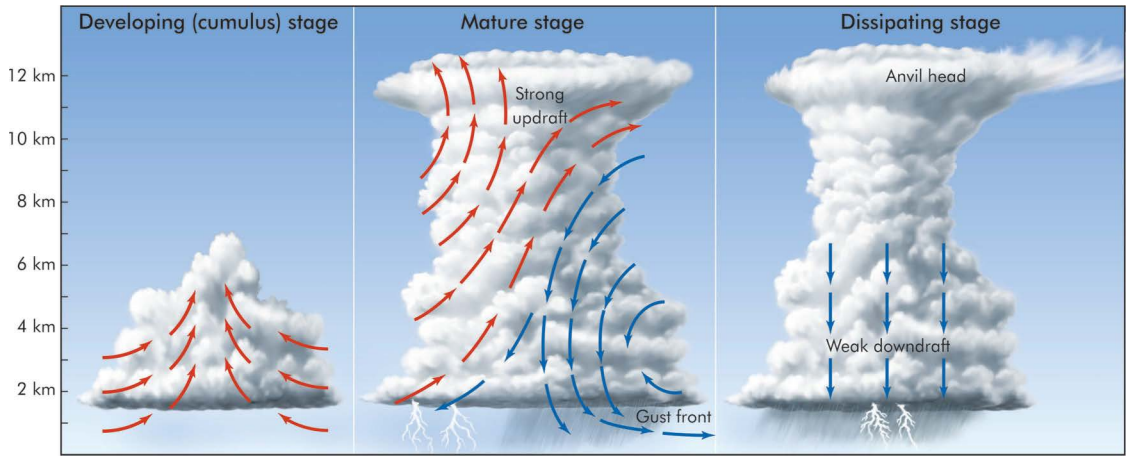
These three conditions are common along cold fronts where the warm humid air is forced upward along the relatively steep front of the cold air mass (see Figure 9.14a).

Thunderstorm formation starts as moist air is forced upward and cools, and water vapor condenses to form a puffy cumulus cloud. Initially the cloud will form and then evaporate with little increase in height. If the moisture supply and updraft continue, the relative humidity increases in the air surrounding the cloud and it grows in size instead of evaporating. The upward growth in size of a cumulus cloud begins the *cumulus stage* (Figure 9.17) of thunderstorm development. In this stage, the cumulus cloud becomes a cumulonimbus cloud with the growth of domes and towers that look like a head of cauliflower. This growth requires a continuous release of latent heat from water vapor condensation to warm the surrounding air and cause the air to rise farther.

As the domes and towers grow upward, precipitation starts by one of two mechanisms. First, growth of the cloud into colder air causes water droplets to freeze into ice crystals and snowflakes. The larger snowflakes fall until they enter air that is above freezing and melt to form raindrops. Second, in warm air in the lower part of the cloud, large cloud droplets collide with smaller droplets and coalesce to become raindrops. Once raindrops are too large to be supported by updrafts in the cloud, they begin to fall, creating a downdraft.

The *mature stage* of thunderstorm development begins when the downdraft and falling precipitation leave the base of the cloud (Figure 9.17). At this stage, the storm has both updrafts and downdrafts, and it continues to grow until it reaches the top of the unstable atmosphere. Commonly this upper limit of growth is the tropopause. At this point, the updrafts may continue to build the cloud outward to form a characteristic anvil shape (Figure 9.17). During the mature stage, the storm produces heavy rain, lightning and thunder, and occasionally large chunks of ice, known as *hail*.

The final or *dissipating* stage begins when the upward supply of moist air is blocked by downdrafts at the lower levels of the cloud (Figure 9.17). Downdrafts incorporate cool, dry air surrounding the cloud and cause some of the falling precipitation to evaporate. This evaporation further cools the downdraft and limits the updraft of warm humid air. Deprived of moisture, the



▲ FIGURE 9.17 Life Cycle of a Thunderstorm
Idealized diagram showing stages of development and dissipation (disappearance) of a thunderstorm. Red arrows show updrafts of warm air, and thin blue arrows show downdrafts of cold air, which are responsible for powerful gusts of wind (gust front) often felt in advance of an approaching storm. *(Based on Aguado, E., and Burt, J. E.,* Understanding Weather and Climate, *4th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2007)*

thunderstorm weakens, precipitation decreases, and the cloud dissipates. Most individual thunderstorms, sometimes called *air-mass thunderstorms*, last less than an hour and do little damage.

Severe Thunderstorms The scenario just described is typical of most thunderstorms, which never reach severe levels. However, under the right conditions, these storms can become severe. In the United States, the National Weather Service classifies a thunderstorm as *severe* if it has wind speeds exceeding 93 km (~58 mi.) per hour, or hailstones larger than 1.9 cm (~0.75 in.), or generates a tornado.[7] Severe thunderstorms, which rely on favorable atmospheric conditions over a large area, are able to self-perpetuate. They often appear in groups and can last from several hours to several days.

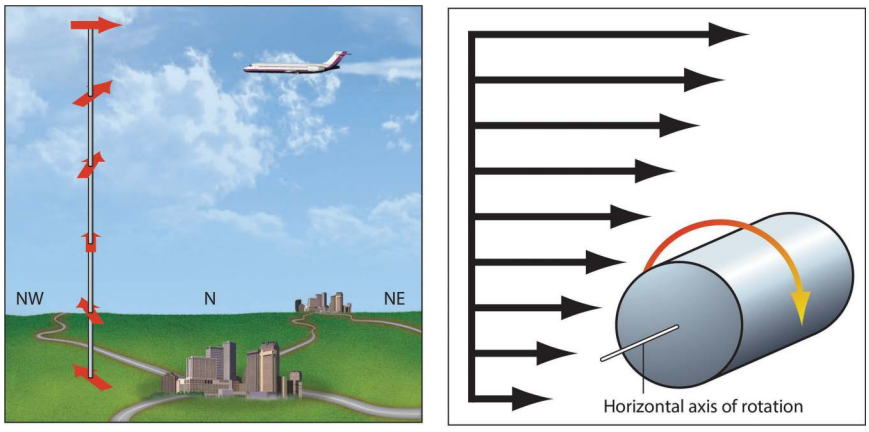
Conditions necessary for the formation of a severe thunderstorm include large changes in wind shear, high water vapor content in the lower troposphere, updraft of air, and the existence of a dry air mass above a moist air mass.[7] Of these four conditions, vertical wind shear is especially important. **Vertical wind shear** is produced by an increase in wind velocity with altitude, or change in the horizontal direction of wind with altitude, which causes a rolling motion—horizontal axis rotation—of the air in the lower troposphere (Figure 9.18). In general, the greater the vertical wind shear, the more severe a thunderstorm will become.[9]

Three types of severe thunderstorms have been identified on the basis of their organization, shape, and size. They include roughly circular clusters of storm cells called mesoscale convective systems (MCS), linear belts of thunderstorms called squall lines, and large cells with single updrafts called supercells.

The MCS is the most common of the three types. These systems are large clusters of self-propagating storms in which the downdraft of one cell leads to the formation of a new cell nearby. Unlike many single-cell, air-mass thunderstorms that last for less than an hour, these complexes of storms can continue to grow and move for periods of 12 hours or more.

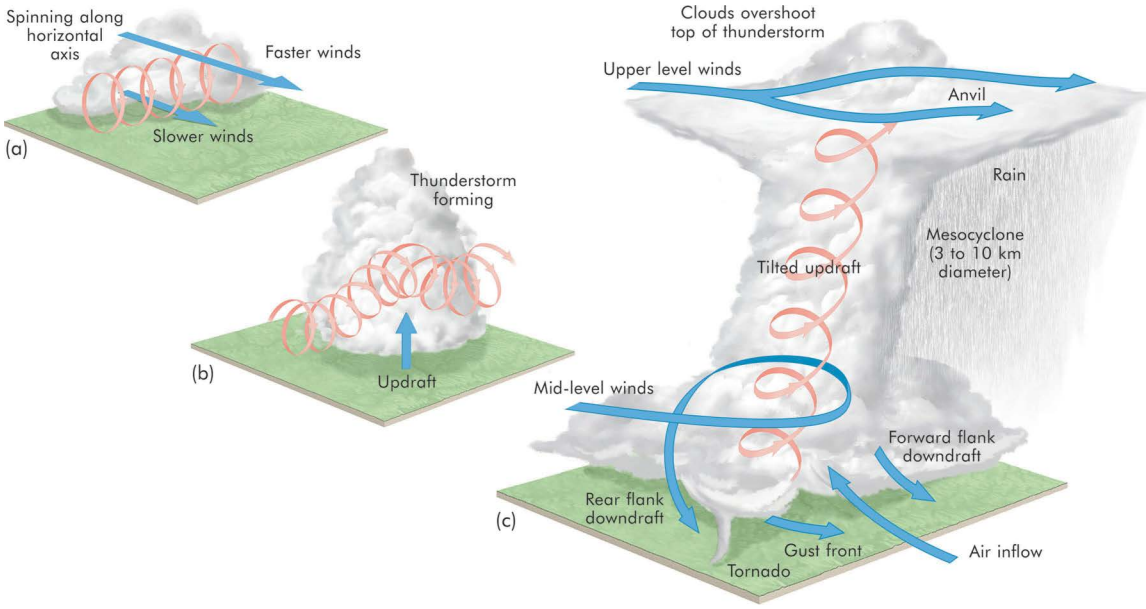
Squall lines, which average 500 km (~310 mi.) in length, are long lines of individual storm cells. These lines commonly develop parallel to cold fronts at a distance of 300 to 500 km (~180 to 310 mi.) ahead of the front.[9] Updrafts in the advancing line of storms typically form anvil-shaped clouds whose tops extend ahead of the line. Downdrafts originating on the back side of the storms often surge forward as a *gust front* of cold air that arrives ahead of precipitation (see Figure 9.17). Squall lines can also develop along *drylines*, an air-mass boundary similar to a front, but in which the air masses differ in moisture content rather than air temperature. Drylines develop in the southwestern United States during the spring and summer, sometimes producing daily squall lines.

The most damaging of all severe thunderstorms is the **supercell storm**. A supercell thunderstorm is defined by the presence of an upward spiraling column of air—vertical axis rotation—known as a *mesocyclone*. This rotation is detectable with Doppler radar, which



< FIGURE 9.18 Vertical Wind Shear
(a) Vertical wind shear resulting from changes in the wind direction with increasing altitude. (b) Vertical wind shear resulting from changes in the velocity of wind with increasing altitude.

is a primary tool used for identifying and predicting severe weather (see Section 9.9 and Case Study 9.2: Professional Profile). In the initial formation stage, vertical wind shear causes rotation to develop within the thunderstorm (Figure 9.19a). Strong updrafts develop ahead of the advancing cold front as the warm moist air is lifted. These updrafts, which are strengthened due to additional heating within the rising air caused by the latent heat of condensation, tilt the horizontally rotating air vertically (Figure 9.19b). At this point in the storm's development, vertical wind shear causes the rotating mesocyclone to tilt and the rain and forward downdraft to shift downwind, which stabilizes the updraft (Figure 9.19c). Although smaller than an MCS or a squall line, supercell storms are extremely violent and are the breeding ground for most large tornadoes. They usually range from 20 to 50 km (~12 to 30 mi.) in diameter, last from 2 to 4 hours, and are capable of doing significant damage in that time.



∧ FIGURE 9.19 Supercell Storm and Tornado Formation
(a) Vertical wind shear creates a horizontal axis rotation or rolling of air. (b) Updrafts produced by rising warm air lift the horizontally rolling air toward the vertical. (c) A vertical rotating mesocyclone develops. If conditions are right, a tornado will develop from the slowly rotating wall cloud toward the rear of the storm. *(Based on McKnight, T. L., and Hess, D.,* Physical Geography, *10th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2004)*

CASE study

9.2 Professional Profile

Sarah Tessendorf, Severe Storm Meteorologist

Sarah Tessendorf (Figure 9.2.A) has been a storm watcher for long as she can remember. "My favorite thing as a child was being woken up in the middle of the night by a really bright flash of lightning. I was scared to death of it—but it got my blood running every time," she said.

Tessendorf's fascination with extreme weather has never faltered. While still an undergraduate, she began studying tornadoes at SOARS (Significant Opportunities in Atmospheric Research and Science), a summer internship program at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado.

Working with Jeffrey Trapp of Purdue University, Tessendorf studied two types of storms known to trigger tornadoes. Supercells—severe thunderstorms containing rotating updrafts—were considered responsible for the most severe tornadoes. Squall lines—storms that travel in one long line—were thought to spawn only weak twisters. Using radar data, Tessendorf and Trapp discovered that squall lines birth up to 20 percent of tornadoes, some of which can be violent. Their results sent atmospheric scientists scrambling to learn how to spot squall line tornadoes in time to warn the public.

"It was exciting to have my first project lay the groundwork that there is a threat from this type of storm," Tessendorf said.

Building on this expertise, Tessendorf went on to study lightning for her Ph.D. The high plains of Colorado are struck by unusual, positive cloud-to-ground lightning. To find out why, dozens of scientists from the federal government, universities, and private industry combined forces in 2000 to observe high plains storms with three radars, instrumented balloons, and even a chase plane. "We wanted to figure out what made these storms unique," Tessendorf said.

Tessendorf and her colleagues confirmed that these odd storms have what is known as inverted charge structures—a midlevel positively charged layer sandwiched in between negatively charged layers. She then hypothesized how such a charge structure could develop. Scientists believe that storms become electrified after small ice crystals collide and transfer charge with small hail-like particles. Updrafts separate the charge by carrying the small crystals skyward, leaving the graupel (ice pellets) at lower elevations. Tessendorf found that unusually strong and large updrafts were common features of Colorado storms with inverted charge structures and could aid in altering the charge transfer process.

Now a postdoctoral researcher at the University of Colorado at Boulder, Tessendorf uses computer models to study precipitation processes in storms. In her spare time, she enjoys storm chasing. "Out in front of the storm I can feel warm humid air being sucked into the clouds. Then it suddenly gets really still, and cool wind flows outward from the storm. That's the key to get moving again," Tessendorf said. "To feel and experience that calm is both eerie and amazing at the same time."

Tessendorf hopes to continue working in meteorology while sharing her love of storms with others. "The weather is something we all experience in common. I'd like to use it to help convey the excitement of science to the public," she said.

— KATHLEEN WONG



< FIGURE 9.2.A Dr. Sarah Tessendorf, Severe Storm Meteorologist
Dr. Tessendorf's smile comes from a successful day of storm observations on the High Plains in eastern Colorado. *(Sarah Tessendorf)*

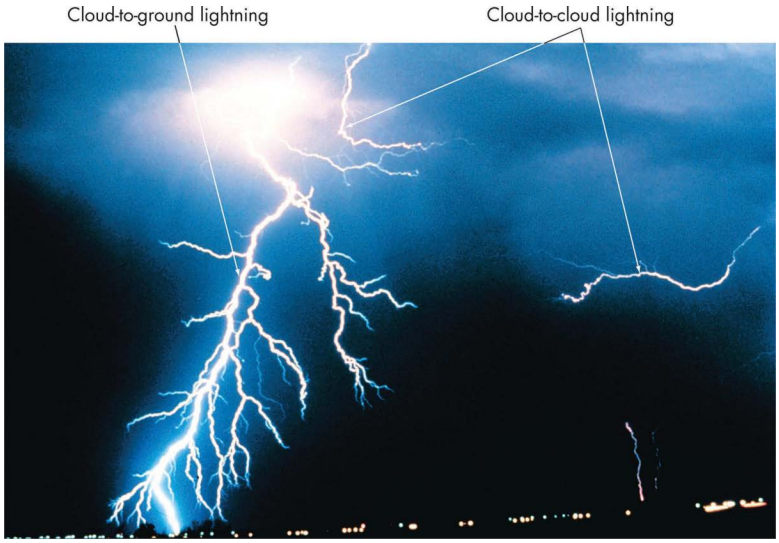
Downbursts of air from severe thunderstorms, especially MCSs, can also generate strong, straight-line windstorms. These windstorms vary in size, with the largest ones, called *derechos*, producing severe, tornado-strength wind gusts along a line that is at least 400 km (~250 mi.) in length.[10] In general, derecho winds exceed 90 km (~55mi.) per hour and can cause numerous trees to fall, widespread power outages, serious injuries, and multiple fatalities. Strong derechos generate winds approaching 210 km (~130 mi.) per hour and produce the same damage as a medium-sized tornado. More than a dozen derechos strike North America each year, with most occurring in the eastern two-thirds of the contiguous United States and southern Canada.[10] Smaller thunderstorm downbursts, called *microbursts*, are more common than derechos and are a serious hazard to aviation.

Lightning A common occurrence during thunderstorms, **lightning** consists of flashes of light produced by the discharge of millions of joules of electricity (Figure 9.20). These discharges can heat the surrounding air to as high as 30,000°C (~54,000°F)—five times hotter than the surface of the sun.[7] This extreme heat causes the air to rapidly expand, producing the familiar accompanying sound of *thunder*.

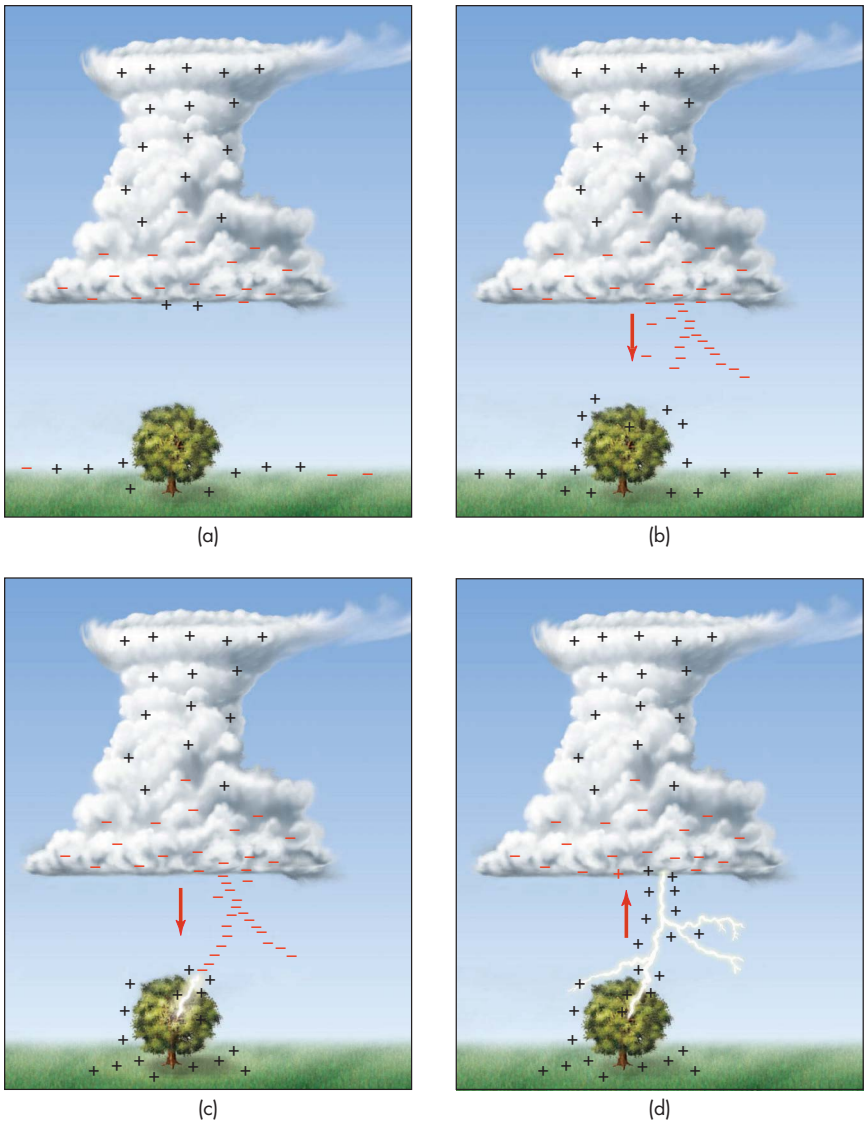
Most lightning bolts are cloud-to-cloud; that is, they start and end within the thunderstorm or end in nearby clouds. Although cloud-to-ground lightning is less common, an estimated 25 million lightning bolts strike in the United States each year.[11] Cloud-to-ground lightning is more complex than it appears to an observer.

Most lightning comes from cumulonimbus clouds that have grown high enough for ice crystals and pellets to form. Similar to how dragging your feet on the carpet can cause you to get an electric shock when you touch something metal, interactions between rising ice crystals and falling ice pellets within the updraft are thought to create an electrical field strong enough to produce lightning.[12] Electrons moving between the two forms of ice build up positive electrical charge in the upper part of the cloud and negative charge in the lower part (Figure 9.21a). Since like electrical charges repel, the increased negative charge in the base of the cloud drives away the negative charge on Earth's surface below. This leaves the ground beneath the thunderstorm with a net positive charge. A strong difference in electrical charge between the cloud and the ground is required for lightning to overcome the natural insulating property of air.

The majority of lightning strikes begin as a narrow column of high-speed electrons moving downward from the base of a cloud toward a pocket of positive charge on Earth. Within milliseconds this column, called a *stepped leader*, branches downward until it is close to the ground while positively charged *streamers* move upward from the ground, emanating from a tall object like a tree or building (Figure 9.21b). As the stepped leader approaches, a spark jumps from the streamer and attaches to the leader (Figure 9.21c). The spark completes a conductive channel of ionized air molecules for an upward surge of positive electrical charge. This surge heats the air to create a brilliant *return stroke* of lightning to the cloud (Figure 9.21d). Within milliseconds, additional leaders and return strokes move along the same path and often cause the lightning flash to appear to flicker to the human eye.



< FIGURE 9.20 Types of Lightning
Nighttime photograph of cloud-to-ground lightning strokes and cloud-to-cloud lightning strokes. Although most lightning that we see goes from cloud-to-ground or cloud-to-cloud, more than half of all lightning occurs within thunderstorm clouds. *(NOAA)*



< FIGURE 9.21 Development of Cloud-to-Ground Lightning
(a) Electrical charge separation occurs in a cumulonimbus cloud. The buildup of a negative electrical charge at the base of the cloud locally induces a positive electrical charge below the thunderstorm. (b) A nearly invisible, stepped leader forms a column of negatively charged air that branches downward from the cloud, while positively charged streamers move upward from the ground. (c) When the stepped leader and the streamer meet, a narrow channel causing a rapid flow of electrons results. (d) Flowing electrons heat the channel to extremely high temperature and create a return stroke back to the cloud.

Lightning strikes constitute a serious natural hazard even though the number of annual lightning deaths in the United States has decreased as more people leave rural areas to live in cities. The chances of being struck by lightning in the United States are estimated to be 1 in 240,000 each year. For an 80-year life span, this becomes 1 in 3,000.[13] Your risk, however, depends on where you live and work. Nevertheless, lightning kills an estimated 100 people and injures more than 300 per year in the United States and kills seven people and injures 60 to 70 each year in Canada.[12,14] Of those who survive a lightning strike, 70 percent suffer serious long-term health effects (see Case Study 9.3: Survivor Story).[6,13]

Hail Although many large thunderstorms can produce hard, rounded, or irregular pieces of ice called *hailstones*, it is large hail from severe thunderstorms that is the greatest hazard (Figure 9.22a). Evidence for the origin of hailstones can be found by cutting a stone in half to reveal a bull's-eye pattern of concentric rings of ice (Figure 9.22b). These rings form as a hailstone is moved up and down in a thunderstorm. Starting with a small ice pellet as a nucleus, a hailstone gets a coating of liquid water in the lower part of the storm, and that coating freezes when a strong updraft carries the stone upward into cold air. This process is repeated many times to form a large piece of hail. The largest authenticated hailstone in North America fell from a severe



(a) (b)

FIGURE 9.22 Hail Damage and Internal Structure
(a) Woman repairs her roof damaged by hail. *(DANIL SEMYONOV/AFP/Getty Images)* (b) Internal structure of hailstone showing concentric rings, which develop due to accretion of successive ice layers around a central core within the thunderstorm. *(deepspacedave/Shutterstock)*

thunderstorm in Aurora, Nebraska, in June 2003. Nearly as large as a volleyball, the hailstone measured 18 cm (~7 in.) in diameter, weighted 0.8 kg (~1.8 lb), and is estimated to have hit the ground at a velocity of more than 160 km (~100 mi.) per hour![15]

Hailstorms generally cause more property damage than casualties. The damage caused by hail in the United States alone averages $1 billion per year. In North America, damaging hailstorms are most common in the Great Plains, particularly in northeastern Colorado and southeastern Wyoming, and in the Calgary area of Alberta, Canada. North-central India, Bangladesh, Kenya, and Australia also frequently experience damaging hailstorms. Although rare in North America, deaths from hailstones are not uncommon in Bangladesh and India in heavily populated areas with poorly constructed dwellings.[15]

TORNADOES

Usually spawned by severe thunderstorms, a tornado is one of nature's most violent natural processes. From 1992 to 2012, tornadoes in the United States killed an average of 62 people per year.[16] These spinning columns of wind can take on a variety of shapes, including a rope, funnel, cylinder, and wedge (Figure 9.23). Other names given to tornadoes include "twisters" and "cyclones," although the term *cyclone* also is used to refer to large spinning columns of wind within clouds, hurricanes, and very large atmospheric low-pressure systems. To be called a tornado, a spinning column of wind or a *vortex* must extend downward from a cloud and touch the ground. In small or newly developed tornadoes, the vortex can be almost invisible until water vapor begins to condense or the tornado picks up dust and debris. In the first stage of tornado development, funnel-shaped vortices called *funnel clouds* that do not reach to the ground form below the thunderstorm (Figure 9.23a). Undoubtedly the number of funnels that develop each year far exceeds the number of tornadoes.

Tornadoes form where there are large differences in atmospheric pressure over short distances, as often results during a major storm such as a supercell thunderstorm. Although meteorologists do not completely understand precisely how tornadoes form, they have recognized that most tornadoes go through similar stages in development. Major updrafts, often in the rear or southwestern part of the storm, lower a portion of the cumulonimbus cloud to form a *wall cloud* (Figure 9.23b). This wall cloud may begin to slowly rotate, and a short funnel cloud may descend. A tornado has formed if dust and debris on the ground begin to swirl below the funnel (Figure 9.23d). Not all wall clouds and mesocyclones produce tornados, and tornados can develop without the formation of a wall cloud or mesocyclone.

In the second, *mature* stage, a visible condensation funnel extends from the thunderstorm cloud to the ground as moist air is drawn upward (Figure 9.23c). In stronger tornadoes, smaller intense whirls, called *suction vortices*, may form within the larger tornado. The suction vortices orbit the center of the large tornado vortex and appear to be responsible for its greatest damage.[17]

When the supply of warm moist air is reduced, the tornado enters the *shrinking stage*. In this stage, the funnel thins and begins to tilt. As the width of the funnel decreases, the winds can increase, making the tornado more dangerous.

In the final decaying stage, or *rope stage* (Figure 9.23d), the upward-spiraling air comes in contact with downdrafts and the tornado begins to move erratically. Although this is the beginning of the end for the tornado, it can still



FIGURE 9.23 Stages in Tornado Development
(a) Airborne funnel clouds, like this one over the state capitol in Austin, Texas, are not considered tornadoes until they touch the ground. *(Dave Chapman/Alamy Stock Photo)* (b) This wall cloud near Miami, Texas, is the lighter gray cloud to the left of the lightning bolt. Wall clouds hang downward from a severe thunderstorm and are often where tornadoes form. *(NOAA)* (c) A tornado in the mature stage of development near Seymour, Texas. *(NOAA)* (d) A tornado in the decaying rope stage of development near Cordell, Oklahoma. A tornado is still dangerous at this stage. *(NOAA)*

be extremely dangerous at this point. Tornadoes may go through all the stages just described, or they may skip stages. Like other types of clouds, new tornadoes can form nearby as older tornadoes disappear.

As tornadoes move along the surface of Earth, they pick up dirt and debris. This debris gives the tornado cloud its characteristic dark color (Figure 9.23d). Tornadoes typically have diameters measured in tens of meters and wind speeds of 65 km (~40 mi.) to more than 450 km (~280 mi.) per hour.[7] Once they touch down, tornadoes usually travel 6 to 8 km (~4 to 5 mi.) and last only a few minutes before weakening and disappearing. However, the largest, most damaging tornadoes may move at speeds of close to 100 km (~60 mi.) per hour along a path several hundreds of kilometers long.

Classification of Tornadoes Tornadoes are classified by the most intense damage that they have produced along their path. Each tornado can be assigned a value on the *Enhanced Fujita* or **EF Scale** (Table 9.1) based on a post-storm damage survey. This survey determines the levels of damage experienced by 26 types of buildings, towers, and poles and by hardwood and softwood trees. Values on the EF Scale estimate the maximum 3-second wind gust in the tornado and range from 105 to 137 km (~65 to 85 mi.) per hour for an EF0 tornado, to more than 322 km (~200 mi.) per hour for an EF5 tornado.[18] The EF Scale replaces the F-scale developed by T. Theodore Fujita in 1971 and is similar to the Modified Mercalli Scale for assessing earthquake intensity.

CASE study

9.3 Survivor Story

Struck by Lightning

Like most of us, Michael Utley didn't worry much about being struck by lightning. The odds, after all, are second to none. So at a charity golf tournament to benefit a local YMCA near his Cape Cod home, he was not overly apprehensive about the looming threat of a thunderstorm. "I didn't pay attention to it," he said.

Four holes into the game, the warning horn blasted, urging golfers to seek shelter. Utley replaced the flag in the hole and was several yards behind his three companions when he was struck by lightning.

Hearing a thunderous crack behind them, Utley's friends turned around. Utley says they reported smoke coming from his body, his shoes torn from his feet, and his zipper blown open.

Luckily, Utley remembers none of this. In fact, he remembers nothing from the next 38 days, which he spent in an intensive care unit. Fortunately for Utley, one of his companions had recently been retrained in CPR, which may very well have saved Utley's life while the EMS vehicles were on their way.

As for the various images we commonly associate with those struck by lightning, Utley said some are accurate and some are not.

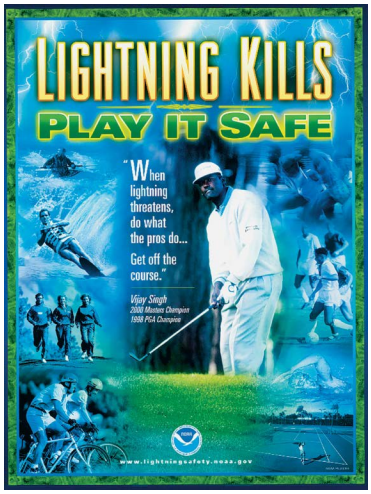


FIGURE 9.3.A Lightning Safety This National Weather Service poster of professional golfer Vijay Singh is a reminder that more people are killed and injured by lightning strikes in outdoor recreation than in any other activity. *(NOAA)*

"The hair standing up, that's real. When that happens, you're pretty close to being dead," he said, "but I didn't see a white light at the end of the tunnel. I don't burn clocks off the wall when I touch them."

Utley's reaction, like that of many victims of lightning, was filled with a variety of ups and downs. His wife, Tamara, recalls that he did not slip into a coma-like state for several days. "It was very, very strange," she said. "When he first got to the ICU, he was able to move and he was very lucid." But within a few days, he began to lose consciousness for extended periods of time. Utley remembers none of this either.

Since the incident, Utley has worked to educate the community about the perils of lightning, including serving as a NOAA spokesman for lightning safety and working with the PGA on the danger electrical storms pose to golfers (Figure 9.3.A). He sums up his message to golfers in one easy slogan: "If you see it, flee it; if you hear it, clear it."

— CHRIS WILSON

Tornadoes that form over water are generally called *waterspouts* rather than tornadoes (Figure 9.24). Most waterspouts develop beneath fair-weather cumulus clouds and appear to be associated with wind shear along the boundary of contrasting air masses.[17] Wind shear means that the winds along a boundary are blowing in different directions and velocities. You can produce a similar kind of shear-induced rotation by holding a pencil vertically between your hands and moving your hands in opposite directions. Small, wind-shear–produced tornadoes can develop on land and, like waterspouts, are typically weak EF1 or EF0 tornadoes.[17] Although not as powerful as most tornadoes in supercell storms, waterspouts and related weak tornadoes on land can cause considerable damage and should be respected.

Occurrence of Tornadoes Although tornadoes are found throughout the world, they are much more common in the United States than in any other location on Earth. The United States has just the right combination of weather, topography, and geographic location to

TABLE 9.1 Enhanced Fujita Scale of Tornado Intensity

Scale	Wind Estimate[a]	Typical Damage[b]
EF0	105–137 km/hr (~65–85 mph)	*Light damage.* Some damage to chimneys; branches broken off trees; shallow-rooted trees pushed over; sign boards damaged.
EF1	138–177 km/hr (~86–110 mph)	*Moderate damage.* Surfaces of roofs peeled off; mobile homes pushed off foundations or over-turned; moving autos blown off roads.
EF2	178–218 km/hr (~111–135 mph)	*Considerable damage.* Roofs torn off frame houses; mobile homes demolished; boxcars over-turned; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.
EF3	219–266 km/hr (~136–165 mph)	*Severe damage.* Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown.
EF4	267–322 km/hr (~166–200 mph)	*Devastating damage.* Well-constructed houses leveled; structures with weak foundations blown away some distance; cars thrown and large missiles generated.
EF5	More than 322 km/hr (More than 200 mph)	*Incredible damage.* Strong frame houses leveled off foundations and swept away; automobile-sized missiles fly through the air in excess of 100 m (~110 yds.); trees debarked; incredible phenomena will occur.

[a] Wind speeds are the maximum estimated for a 3-second gust.
[b] Accurate placement on this scale involves expert assessment of the degree of damage to 28 indicators including homes, buildings, towers, poles, and trees.

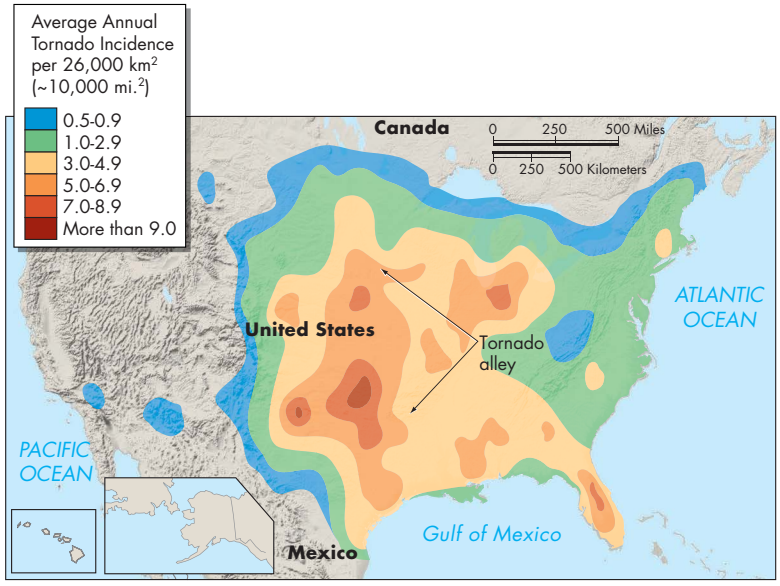
Source: Information from Wind Science Engineering Center, "A Recommendation for an Enhanced Fugita Scale (EF-Scale)." Lubbock, TX: Texas Tech University, 2004. www.spc.noaa.gov/faq/tornado/ef-ttu.pdf. Accessed 6/7/13.



FIGURE 9.24 Waterspouts
Two water spouts can be seen about a mile off shore south of downtown Honolulu Monday, May 2, 2011. Unstable weather conditions over the island of Oahu lead to the formation of of thunderstorms over Oahu. *(Eugene Tanner/AP Images)*

make it the perfect spawning ground for tornadoes.[17] Most U.S. tornadoes occur in the midwestern states, between the Rocky Mountains and the Appalachians. As with severe thunderstorms, spring and summer are the most common time for tornadoes, and most develop in the late afternoon and evening. The highest risk for tornadoes occurs along what is called "Tornado Alley," a belt that stretches from north to south through the Great Plains states (Figure 9.25). This is where all the ingredients for the formation of a tornado collide. Areas of high annual tornado occurrence include a huge region from Florida to Texas and north to the Dakotas, Indiana, and Ohio. Although Canada experiences far fewer tornadoes than the United States, it has several tornado-prone regions, such as Alberta, southern Ontario, and southeastern Quebec, as well as an area running from southern Saskatchewan and Manitoba to Thunder Bay, Ontario.[19]

Possibly with the exception of Bangladesh, violent tornadoes (EF4 or EF5) are rare or nonexistent outside of the United States and Canada.[17] Waterspouts are both less hazardous and more common than tornadoes on land. Most take place in tropical and subtropical waters, but they have been reported off the New England and California coasts as well as on the Great Lakes. They are especially common along the Gulf Coast, Caribbean Sea, Bay of Bengal in the Indian Ocean, and the South Atlantic. A study conducted in the Florida Keys counted 390 waterspouts within 80 km (~50 mi.) of Key West during a five-month period.[17]



< FIGURE 9.25 Tornado Occurrence in the United States

Average occurrence of tornadoes per 26,000 km² (~10,000 mi.²) in the United States and southernmost Canada from 1950 to 2000. *(Based on Christopherson, R. W., Geosystems: An Introduction to Physical Geography, 6th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2006. Data from National Severe Storm Forecast Center, National Weather Service.)*

9.4 CASE study

Tri-State Tornado

In just 3½ hours on March 18, 1925, the Tri-State Tornado killed more people and destroyed more property than any other tornado in historic time. The tornado was unique in several ways. First, it was in contact with the ground for 349 km (~215 mi.), a distance of 183 km (~115 mi.) longer than any other tornado to date. Second, the average width of the tornado was 1.2 km (~0.75 mi.) and at times it reached 1.6 km (~1 mi.) in width. Only 73 of the more than 35,000 reported tornadoes have been as wide as or wider than the Tri-State Tornado.[17] This width produced extreme damage over at least 425 km² (~164 mi.²) (Figure 9.26). Third, the tornado's track was a straight line over much of its path through the states of Missouri, Illinois, and Indiana. This track contrasts with the curved track of most tornadoes. Finally, the tornado's average forward speed of 100 km (~62 mi.) per hour was one of the fastest ever reported. Most tornadoes travel at an average speed of 50 km (30 mi.) per hour.[7] People seeing the storm approach assumed it was a thunderstorm because it was so broad, and in fact, there were associated thunderstorms. The tornado's violent winds inflicted unprecedented damage, killing at least 695 people and injuring more than 2,000. Damages, expressed in year 2000 dollars, totaled about $170 million.

As the Tri-State Tornado moved across the landscape, it traversed hills as high as 425 m (1400 ft.) and crossed valleys and lowlands; the topography essentially had no effect on the tornado. Although much of the death and damage resulted from the collapse of buildings, flying debris was also responsible for significant destruction (Figure 9.27). As the storm moved northeast, the damaging rotational winds had velocities of up to 290 km (~180 mi.) per hour.

The extensive death and damage from the Tri-State Tornado resulted from several factors: (1) There were no tornado forecasts or warnings because the technology for them did not exist in 1925, (2) the storm destroyed telephone lines that could have been used to warn people in the projected path of the tornado, (3) the tornado was exceptionally large and strong, (4) massive amounts of flying debris and dust masked any funnel shape and made it hard to recognize the storm as a tornado, and (5) many of the homes and farms were poorly constructed and unable to withstand the strong winds.[20] Should such a tornado occur in the future, successful forecasting and warning, along with better construction techniques, would likely save countless lives.

BLIZZARDS AND ICE STORMS

Blizzards are severe winter storms in which large amounts of falling or blowing snow are driven by high winds to create low visibilities for an extended period of time. Extremely low visibility, commonly referred to as a *whiteout*, along with cold temperatures and high

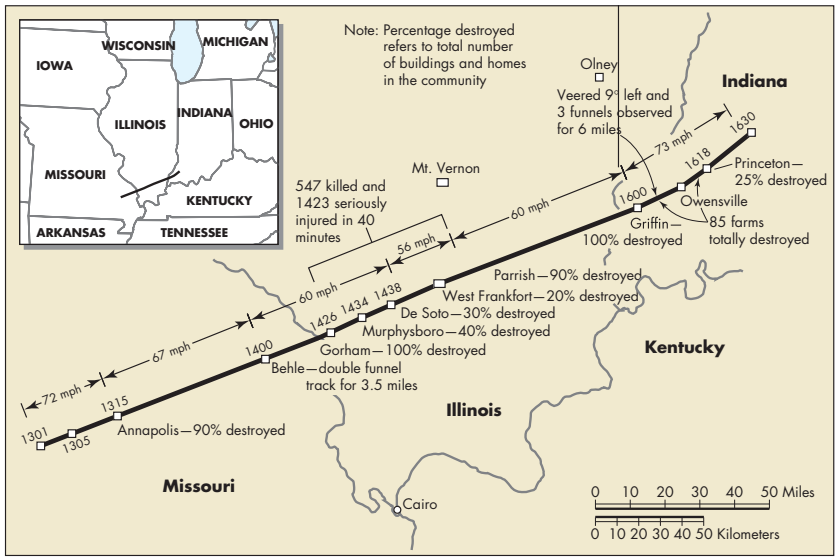


FIGURE 9.26 Tornadoes Traveling Long Distances

In a span of 3½ hours, the Tri-State Tornado of March 18, 1925, traveled 350 km (~217 mi.) from Reynolds County, Missouri, across Illinois to near Princeton, Indiana. Traveling at an average speed of 100 km (~62 mi.) per hour, this tornado varied from 1 to 1.5 km (~0.6 to 0.9 mi. to 1 mi.) in width. The numbers from 1301 to 1630 along the tornado track refer to the time of day. *(Modified after Wilson, J. W., and Changnon Jr., S. A. 1971. Illinois tornadoes. Illinois State Water Survey Circular 103. Urbana, IL.)*

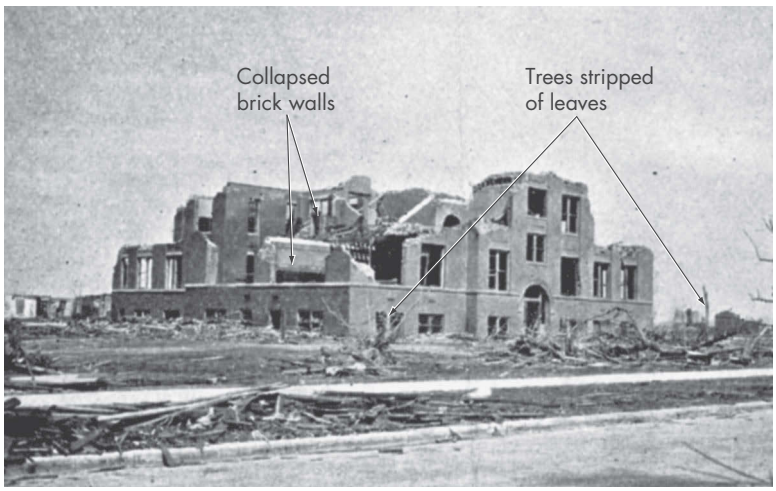


FIGURE 9.27 Most Destructive Tornado in History

Ruins of the Longfellow School in Murphysboro, Illinois, where 17 children were killed by the Tri-State Tornado. The tornado struck the school around 2:34 P.M. on March 18, 1925. Most of the children were killed by the collapse of the unreinforced brick walls. Trees surrounding the school were also destroyed. A total of 234 people were killed in Murphysboro, the largest number of tornado deaths in a single town in U.S. history. *(NOAA)*

winds make a blizzard dangerous. Official thresholds for blizzard conditions differ in the United States and Canada. In the United States, winds must exceed 56 km (~35 mi.) per hour with visibilities of less than 0.4 km (~0.25 mi.) for at least 3 hours, whereas in Canada winds must exceed 40 km (~25 mi.) per hour with visibilities of less than 1 km (~1.6 mi.) for at least 4 hours.[21,22] In either case, a blizzard may involve no additional snowfall. High winds picking up previously fallen snow create a *ground blizzard* in which visibility can drop to a few meters or less for many hours. Ground blizzards develop numerous times each winter in Antarctica, Alaska and parts of Canada, and in the Great Plains states.

In North America, blizzards associated with heavy snowfall are most common in the Great Plains, the Great Lakes area, the U.S. Northeast, the Canadian Atlantic provinces, and the eastern Arctic. Storms producing heavy snowfall and blizzards form from an interaction between upper-level winds associated with a low-pressure trough and a surface low-pressure system.[23] In North America, blizzard-producing storms generally form in eastern Colorado; central Alberta, Canada; or along the coast of North Carolina or the northern Gulf of Mexico (Figure 9.28). Storms in Colorado and along the coast that produce heavy snowfall are derived from moist air originating over the Atlantic Ocean. In contrast, fast-moving storms

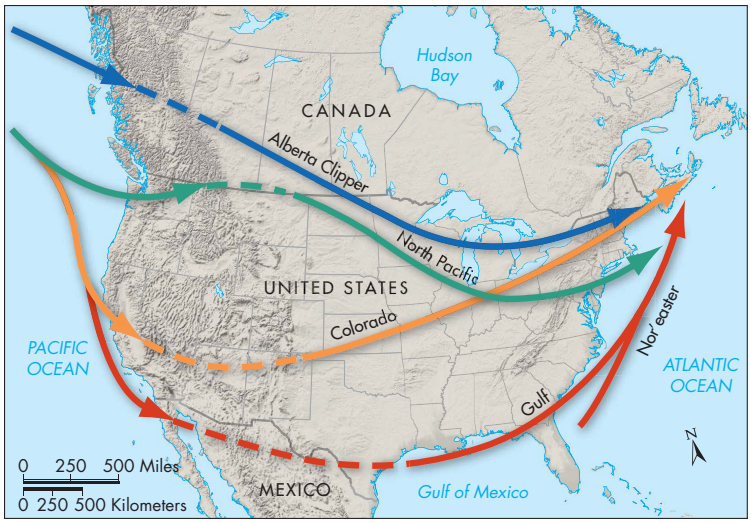


FIGURE 9.28 Winter Storm Track in the United States and Southern Canada
In winter months, low-pressure centers and associated storms develop over the northern Pacific Ocean and come onshore along the west coast of the United States, Canada, and Mexico. The upper-level remnants of these storms (dashed lines) cross the western mountains, and low-pressure centers and associated storms redevelop on the Great Plains. Low-pressure centers and storms also develop along the Gulf and Carolina coasts. Storm tracks are named for geographic origin (e.g., Alberta Clippers, Colorado) or the direction of their prevailing high winds (e.g., nor'easter). *(Adapted from Keen, R. A.,* Skywatch West: The Complete Weather Guide, *revised ed. Golden, CO: Fulcrum Publishing, 2004. Reprinted by permission)*

forming east of the Canadian Rockies, called *Alberta Clippers*, are generally drier with less snow and extremely cold temperatures.

Blizzards can produce lengthy periods of heavy snowfall, wind damage, and large snowdrifts. For example, the Saskatchewan blizzard of 1947 lasted for 10 days and buried an entire train in a 1 km (0.6 mi.) long snowdrift that was 8 m (~26 ft.) high.[24] Another famous storm, the "Blizzard of 1888," killed more than 400 people and paralyzed the northeastern United States for three days with snow drifts that reportedly were as high as the second floor of buildings.

Storms that move along the east coast of the United States and Canada, called *nor'easters*, can produce blizzards (see Chapter 10). Nor'easters wreak havoc with hurricane-force winds, heavy snows, intense precipitation, and high waves that damage coastal areas. These storms are most common between September and April and often create blizzard conditions in large cities such as New York and Boston. In March 1993, a severe nor'easter paralyzed the East Coast, causing snow, tornadoes, and flooding from Alabama to Maine. Damages from this storm, known as the "Blizzard of '93," totaled more than a billion dollars, and more than 240 people were killed.

Less than three years later, in January 1996, a strong winter storm brought another massive blizzard to the East Coast. The storm crippled the eastern United States for several days, produced record-breaking snowfall in Philadelphia and parts of New Jersey, and dropped 51 cm (~20 in.) of snow in New York City's Central Park (Figure 9.29). In all, the blizzard killed at least 100 people and caused an estimated $2 billion in damages.

One reason that blizzards are generally more dangerous than other snowstorms is the **wind chill** effect. Moving air rapidly cools exposed skin by evaporating moisture and removing warm air from next to the body. This chilling reduces the time it takes for *frostbite* to form. Thus, in blizzards the lower wind chill temperature is more important than the air temperature.

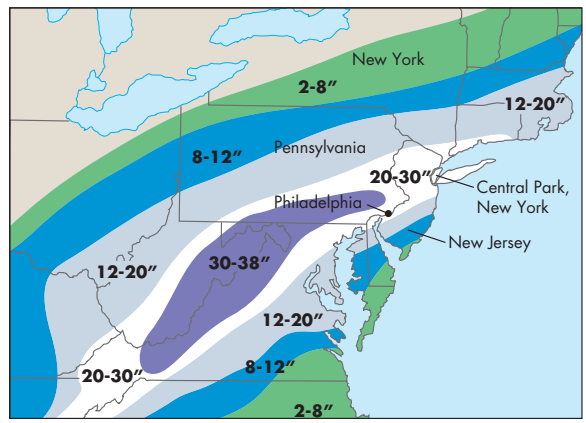


FIGURE 9.29 Snowfall from the Blizzard of 1996
The greatest amount of snow in this storm fell along the Appalachian Mountains. Blizzard-force winds created snowdrifts much deeper than the snow depths indicated on this map.

Ice storms, prolonged periods of freezing rain, can be more damaging than blizzards and just as dangerous. Ice accumulates on all cold surfaces and is especially harmful to utility lines and trees and to surface travel (see Case Study 9.5: The Great Northeastern Ice Storm of 1998). These storms typically develop during the winter in a belt on the north side of a stationary or warm front. In this setting, a combination of three conditions leads to freezing rain: (1) an ample source of moisture in the warm air mass south of the front, (2) warm air uplifted over a shallow layer of cold air,



FIGURE 9.30 Thickness of Cold Air Determines Type of Precipitation
In winter storms, the thickness of cold air at the surface determines the type of precipitation. (a) Most precipitation begins falling as snowflakes and remains as snow if it does not pass through warm air before reaching the ground. (b) Falling snowflakes melt if they encounter warm air aloft, and the resulting rain refreezes to form ice pellets (sleet) if there is sufficient time and cold air before they reach the ground. (c) If there is only a thin layer of cold air at the surface, raindrops become supercooled and then freeze immediately upon contact with a cold surface such as a tree limb, house, or power line. (d) Snowflakes will melt and rain will fall if a thick warm air layer is at the surface. *(Based on Linda Scott and Austin American-Statesman)*

and (3) objects on the land surface at or very close to freezing. Under these conditions, snow begins to fall from the cooled top of the warm air mass. The snow melts as it passes through the warm air, and the resulting raindrops become supercooled when they hit the cold air at the surface (Figure 9.30). Upon contact with cold objects, such as roads, trees, and utility lines, the rain immediately freezes to form a coating of ice. Coatings of 15 to 20 cm (~6 to 8 in.) of ice have been produced by prolonged ice storms in Idaho, Texas, and New York. The regions most prone to ice storms include the Columbia River Valley in the Pacific Northwest, the south-central Great Plains, the Ohio River Valley, the Mid-Atlantic and New England states, and the Atlantic provinces and St. Lawrence River Valley in eastern Canada.[15]

9.5 CASE study
The Great Northeastern Ice Storm of 1998

One of the most destructive and long-lasting ice storms in North American history struck U.S./Canadian border states and provinces in January 1998. In most areas, the storm started late on January 4 and continued for six days. At least 45 people died in the United States and Canada as electric power was cut off to more than 5.2 million people.[25] The power loss contributed to most deaths, primarily from the loss of heat for an extended time. Causes of death ranged from carbon monoxide poisoning produced by improperly vented heat sources to hypothermia from cold temperatures.

Although workers from 14 power companies and military personnel worked long hours to restore power, more than 700,000 people were still without power in the third week after the onset of the storm.[26] The provinces of Quebec, Ontario, and New Brunswick and the states of New York and Maine were the worst hit, although damage was also considerable in Vermont, New Hampshire, and Nova Scotia (Figure 9.31). In addition to substantial damage to the power and telecommunications system, forestry, dairy farming, maple syrup production, and homeowners were severely affected by the storm. Overall losses exceeded $6.2 billion, with more than 80 percent of the losses occurring in Canada.[27] It was Canada's costliest disaster in history.

In many ways, the meteorological conditions that caused the massive storm were typical for ice storms of the Northeastern United States. A persistent flow of warm moist air from the Gulf of Mexico rose up over a thin wedge of cold air to the north of a stationary front (Figure 9.32). Cold air was driven south by northeasterly winds circulating around an Arctic high-pressure center over Hudson Bay, where it settled in river and mountain valleys, including the St. Lawrence and Ottawa River Valleys and the Lake Champlain Valley. Warm air was driven northward by a high-pressure center over Bermuda and a low-pressure trough over the lower Mississippi Valley.[28]

Weather conditions in the region were essentially unchanged for almost a week. The flow of moist air from the Gulf of Mexico acted like a conveyor belt to constantly deliver water vapor for precipitation both north and south of the stationary front. South of the front, heavy rains caused severe flooding in the mountains of North Carolina and Tennessee, killing nine people.[29] North of the front, most of the precipitation took the form of



FIGURE 9.31 Ice Glazes Power Lines and Trees
Freezing rain turns to clear ice once it falls on a surface that is at or below freezing. Many tree limbs and utility lines, like these in the January 1998 ice storm in Watertown, New York, bend and break with the weight of accumulated ice. *(Syracuse Newspapers/Dick Blume/The Image Works)*

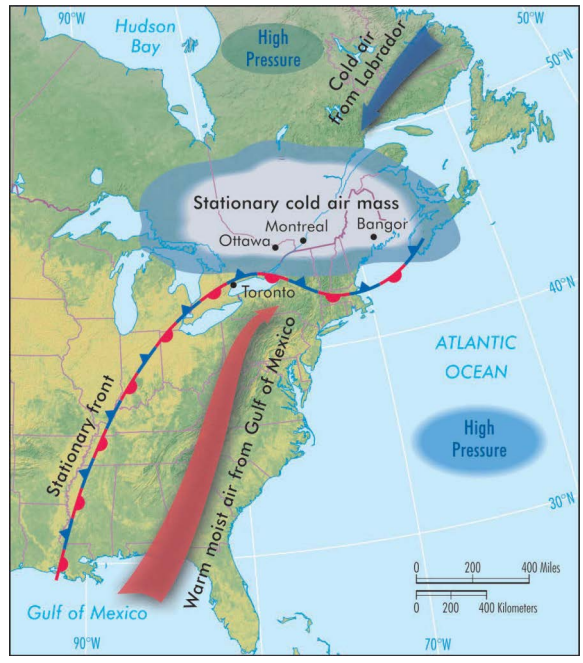


FIGURE 9.32 Weather Conditions That Caused the Ice Storm of 1998
A conveyor-belt–like flow of warm, moist air from the Gulf of Mexico overrode a stationary cold air mass in Quebec, eastern Ontario, Nova Scotia, Prince Edward Island, and the northeastern United States to cause the ice storm of 1998. This system remained in place for nearly a week, causing the worst disaster in Canadian history. *(Based on Environment Canada)*

freezing rain with total liquid-equivalent accumulations of 20 to 100 mm (~0.8 to 4 in.). Ice accumulations of more than 250 mm (~9.8 in.) were reported from the freezing rain at stations in Canada and the United States.[26,30]

Why was this storm so catastrophic? As with most other modern catastrophes, both natural processes and humans contributed to the losses. For many Canadian communities, including Ottawa and Montreal, and some U.S. towns, such as Burlington, Vermont, and Massena, New York, the ice storm of 1998 was the most prolonged period of freezing precipitation on record.[26,28] Historically most episodes of freezing rain last only a few hours at a time; however, the 1998 ice storm brought more than 80 hours of freezing rain and drizzle over a six-day period, twice the annual average.

On the human side, the ice storm demonstrated how dependent our society has become on electricity, especially the electrical grid. The storm destroyed more than 1,000 high-voltage towers, 35,000 telephone poles, and more than 120,000 km (~75,000 mi.) of power lines (Figure 9.33).[25] Montreal lost its water supply after treatment plants and pumping stations experienced a power failure on January 9. In many places emergency backup electrical generators were either absent, failed, or eventually ran out of fuel.

Also apparent was an increasing reliance on "just-in-time" delivery for many items. It was difficult in some cases to repair the electrical grid when needed supplies, such as telephone poles, had to be shipped long distances when transportation systems were shut down. This was repeated more recently in Austin, Texas, when an ice storm depleted deicing fluid for several airlines at the city's airport, resulting in the cancellation of more than 100 flights.[31] The airline's reliance on ground delivery, rather than adequate on-site storage, caused the transportation disruption.

Sometimes the lessons learned from a disaster or catastrophe are not conclusions drawn from scientific observations, technological malfunctions, or policy failures. They are simple observations about human interactions. Responses from Maine schoolchildren to the question "What did you learn from the Ice Storm of '98?" provide valuable lessons:[32]



FIGURE 9.33 Transmission Towers Collapse Under Weight of Ice

A series of Hydro-Quebec high-voltage power transmission towers collapsed under the weight of ice accumulations during the January 1998 ice storm near Bruno, Quebec, south of Montreal. More than 5.2 million people lost power in the ice storm and some power outages lasted more than three weeks. *(AP Photo/ Jacques Boissinot)*

> "I learned that we take things like power, heat, and water for granted." (student at Readfield Elementary School)
>
> "People must have been together as families a lot more before there was electricity." (13-year-old student at South Meadow School)
>
> "I learned that if you are in a big storm it helps if you help others." (12-year-old student at Woodside Elementary School)
>
> "I learned that ice can cripple a whole state." (12-year-old student at Woodside Elementary School)

Source: Federal Emergency Management Agency. 1998. Disaster Connections Kids to Kids, "*Kids from Maine Talk About Surviving the Ice Storm of '98.*" *www.fema.gov/kids/me98_04.htm. Accessed 1/20/07.*

FOG

Like many other natural phenomena, there is nothing innately hazardous about **fog**; it is simply a cloud in contact with the ground. Fog can become hazardous when it obscures visibility for travel and other human activities and when air pollutants are added to form smog or vog (see Chapter 5).

Clouds and, thus, fog form either by air cooling until condensation occurs or by evaporation—adding water vapor to already cool air. Cooling can produce fog as heat radiates from the land at night, as warm moist air blows over cold coastal water, and as humid air rises up a mountainside. Fog can also develop by evaporation when cold air flows over river, lake, or coastal water that is warmer than the air and when warm rain falls through cool air along a frontal boundary.

In North America, the foggiest areas are the Pacific, New England, and Atlantic Canada coasts and the valleys and hills of the Appalachians. Fog contributed to the worst aircraft accident ever when 583 people died in the 1977 collision of two Boeing 747 airliners on a runway in the Canary Islands.[33] Dense fog was also responsible for the worst maritime accident in Canadian history when 1,014 people died in the 1914 collision of two ships on the St. Lawrence River.[34] Although technological advancements make collisions in the fog less likely, dense fog still contributes to numerous accidents, injuries, and deaths each year.

DROUGHT

Drought is defined as an extended period of unusually low precipitation that produces a temporary shortage of water for people, other animals, and plants. More than 1 billion people live in semiarid regions where droughts are common, and more than 100 million people are threatened with malnutrition or death if drought causes their crops to fail. Droughts commonly contribute to regional food shortages, but today the worldwide food distribution system is usually able to prevent drought from causing widespread famine in an area.

In the United States, drought affects more people than any other natural hazard causing serious water and hydroelectric power shortages, as well as agricultural problems. Since the late 1990s, moderate to extreme drought conditions have persisted across a significant area of the United States (Figure 9.34). Particularly hard hit by drought conditions are regions of the western United States where precipitation amounts are relatively low during normal conditions. During the summer of 2016, Lake Mead—the largest reservoir in the United States that provides drinking water and electricity to more than 25 million people in the states of Arizona, California, and Nevada—recorded its lowest water level since Hoover Dam was completed in 1936. The reservoir is currently at about 37 percent capacity,

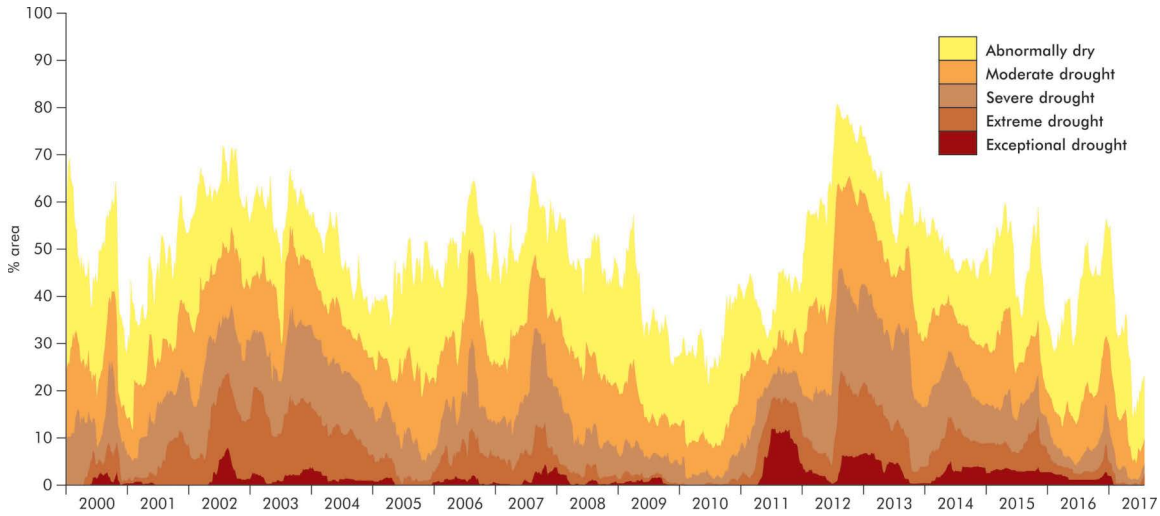


FIGURE 9.34 United States Drought Data
United States time-series drought severity data since the beginning of the twenty-first century. Drought severity catagories are defined by probability of occurence over the next 100 years: Exceptional (1–2 percent), Extreme (2–5 percent), Severe (5–10 percent), Moderate (10–20 percent), Abnormally dry (20–30 percent). *(From the National Drought Mitigation Center)*

and was last full in 1983. Since 1999 the elevation of the water surface has plummeted more than 41 m (135 ft.) which can be clearly seen by the prominent "bathtub ring" preserved along its margins (Figure 9.35). This low water has caused about a about a 30 percent decrease in hydroelectric power output of Hoover Dam, which is the cheapest source of energy in the country. On average drought in the United States has caused an average revenue lose of approximately $7.8 billion per year, since 1980.[35]



FIGURE 9.35 Drought Depletion of Water Reservoirs
Behind Hoover Dam, a small fraction of the Lake Mead Reservoir is visible in the upper part of the photo. Sustained drought conditions have led to a significant reduction in water reserves and hydroelectric power generation over the past two decades. Rising 45 m (~150 ft) above the current lake level, the high-water mark is clearly visible as a white band rimming the reservoir.

MOUNTAIN WINDSTORMS

Mountain windstorms that develop seasonally on the downwind or lee side of mountain ranges and downslope of large glacial ice fields can be extremely destructive. Mountains act as barriers to prevailing winds and can, under specific temperature and pressure conditions, cause winds to roar down their slopes at speeds that can exceed 185 km (~115 mi.) per hour. Referred to as Chinooks east of the Rocky Mountains and Santa Ana winds west of the Transverse Ranges in southern California, these windstorms also occur downwind of the Sierra Nevada, Cascades, and mountain ranges on other continents such as the Alps of Europe. Mountain windstorms sometimes persist for a day or more, cause widespread roof and tree damage, can blow vehicles off highways, and contribute to large wildfires (see Chapter 13).

DUST STORMS AND SANDSTORMS

Dust storms are strong windstorms in which suspended dust that is carried by the wind reduces visibility for a significant period of time. Wind velocities in these storms exceed 48 km (~30 mi.) per hour, and

visibility is reduced to less than 0.8 km (~0.5 mi.).[3] A typical dust storm is several hundred kilometers in diameter and may carry more than 100 million tons of dust. Most natural dust particles are pieces of minerals less than 0.05 mm (~0.002 in.) in diameter. Natural dust also contains minor amounts of biological particles, such as spores and pollen. In addition to being a safety hazard for travel, airborne dust particles can affect climate and human health. Once suspended in the air, fine dust particles of less than 0.01 mm (~0.0004 in.) can travel long distances in the upper atmosphere. Satellite images show dust storms from West Africa crossing the Atlantic Ocean to Florida. It is not uncommon to hear television weather reporters mistakenly call these events "sandstorms."

Unlike dust storms, *sandstorms* are almost exclusively a desert phenomenon in which sand is transported in a cloud of bouncing grains that rarely extends more than 2 m (~6.6 ft.) above the land surface.[36] Blowing sand is abrasive. One of your authors learned this firsthand when his windshield was frosted by blowing sand while driving in Colorado.

Dust storms and sandstorms occur mostly in mid-latitude, semiarid, and arid regions. In the United States, huge dust storms in the southern High Plains during the 1930s produced conditions known as the "Dust Bowl." A combination of drought and poor agricultural practices during the Great Depression caused severe soil erosion in parts of five states centered on the Oklahoma panhandle. Frequent, sometimes daily, dust storms originated in this area and destroyed crops and pastureland (Figure 9.36).

HEAT WAVES

All of North America, and much of the world, is vulnerable to the effects of heat waves. In most areas, **heat waves** are considered to be prolonged periods of extreme heat that are both longer and hotter than normal. Since 2000, heat waves in the United States have killed

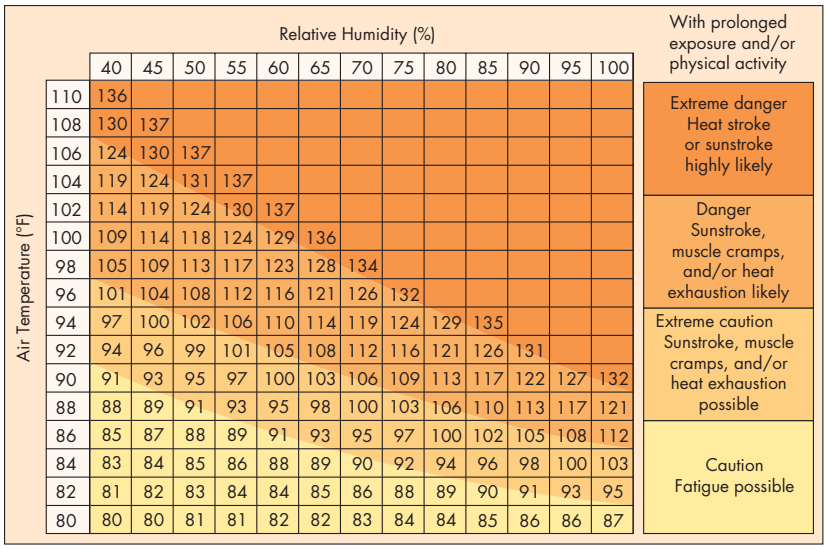


(a)



(b)

< FIGURE 9.36 Dust Storms
(a) Dust storm approaching Elkhart, Kansas, on May 21, 1937. Sometimes called "black blizzards" because of their color, these storms eroded topsoil from cropland in the southern High Plains during the Unites States "Dust Bowl." *(MPI/Getty Images)* (b) Dust storm approaching Phoenix, Arizona in 2011. *(REUTERS/Joshua Lott)*



< FIGURE 9.37 Heat Index Chart
This National Weather Service chart is used to calculate the heat index by combining information about air temperature and relative humidity. A similar chart, the Humidex Chart, is used by the Meteorological Service of Canada. *(From Excessive Heat Awareness and Safety, National Weather Service, NOAA, www. erh.noaa.gov/rah/heat/)*

an average of 200 people per year, which is about equivalent to deaths from flooding, lightning, tornadoes, and hurricanes combined during the same 10-year period. Heat waves can be especially deadly in urban areas in cooler climates where residents are not acclimated to periods of prolonged heat and humidity. This was apparent in a heat wave in 2006, when more than 200 heat-related deaths occurred in the United States and Canada, and in August 2003, when there were an estimated 14,800 heat-related deaths in France (see Case Study 9.6: Europe's Hottest Summer in More Than 500 Years).[37]

Heat waves in the eastern United States and Canada are commonly associated with elongated areas of high pressure, called *ridges*. Wet conditions are generally found to the west of the ridge, whereas sunny, dry conditions prevail to the east. If such a ridge stays in place for several days, air temperatures below the ridge will rise to above-normal levels and cause a heat wave.

Heat waves can accompany either severe humidity or extreme dryness. In either case, it is important to monitor the **heat index** (Figure 9.37). This index measures the body's perception of air temperature, which is greatly influenced by humidity. For example, a temperature of 35°C (~95°F) will feel significantly hotter in parts of Florida when the relative humidity is 75 percent. In this example, the combination of high temperature and high humidity produces a heat index of 128, which is extremely dangerous. In addition to humidity, the length of time that someone is exposed to direct sunlight, the wind speed, and an individual's health will affect heat stress.

9.5 CHECK your understanding

1. What are the conditions necessary for both thunderstorms and severe thunderstorms to form? Describe the three stages of thunderstorm development.
2. What are supercells, mesoscale convective systems? And squall lines? How do they differ? Why are they significant natural hazards?
3. Characterize a tornado in terms of wind speed, size, typical speed of movement, duration, and length of travel.
4. Describe the five stages of tornado development.
5. What is a blizzard? How does a blizzard develop?
6. Describe the weather conditions that cause an ice storm.
7. How are the heat index and wind chill temperature alike? How are they different?

9.6 Human Interaction with Weather

Many natural hazards are clearly and significantly altered by human activities. For example, we have discussed how changes in land use affect flooding and landslides and how deep-well disposal and the filling of large water reservoirs may contribute to earthquakes. Land-use practices may also increase the effects of weather events. For example, the farming practice of

plowing cropland after fall harvest and leaving the topsoil exposed to wind erosion during the winter significantly increased the size of dust storms in the Dust Bowl of the 1930s. Also, locating mobile homes in areas subject to frequent high winds and tornadoes greatly increases damages and loss of life from this type of severe weather. Finally, land-use practices in cities can intensify the effects of heat waves. Large areas of pavement, "big box" one-story buildings, and sparse park land contribute to the **urban heat island effect**, a local climatic condition in which a metropolitan area may become as much as 12°C (~22°F) warmer than the surrounding countryside (see Case Study 9.6: Europe's Hottest Summer).[7]

On a larger scale, human interaction with severe weather is taking place through global warming. On the basis of computer models, atmospheric scientists conclude that global warming is likely to increase the heat index and number of heat waves over land and the intensity of precipitation events in most areas.[38] Computer models also indicate that global warming is likely to increase the risk of drought in midlatitude continental interiors and increase wind and precipitation **intensities** in hurricanes, typhoons, and other tropical cyclones. The effect of global warming on small-scale events such as tornadoes, thunderstorms, hail, and lightning is still being studied. Overall, global warming will likely increase the incidence of severe weather.[39]

9.6 CASE study

Europe's Hottest Summer in More Than 500 Years

Heat waves are one of the deadliest of natural hazards but often get little publicity and are not long remembered. Many Americans have heard of the hurricane that destroyed Galveston, Texas, in 1900 and killed more than 6,000 people, but few people know that a year later, a midwestern July heat wave killed more than 9,500 people.[12] Even today, with rapid global communication, heat waves do not get as much attention as other less deadly natural hazards. This was even true for the 2003 European heat wave that killed more than 30,000 people—more than any other heat wave in recorded history.

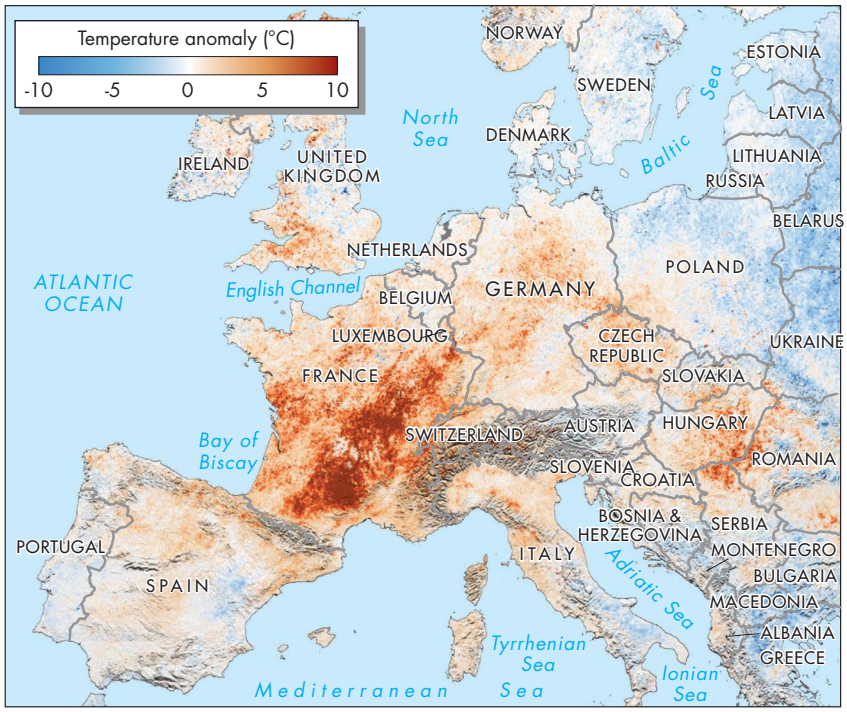
Like most heat waves, the severe 2003 heat wave in Europe started gradually, many weeks before it peaked. Late spring and summer drought conditions set the stage for a long, hot summer. Record-setting temperatures began in Switzerland, breaking a 250-year record for the hottest June ever reported.[40] Extreme daily high temperatures of 35° to 40°C (~95° to 104°F) continued through July in central and southern Europe (Figure 9.38). The heat wave peaked in early August, with August 10 the hottest day ever recorded in the United Kingdom—a high temperature of 38.1°C (~100.6°F) was measured in Gravesend, Kent, breaking records dating back to 1875.[41] That same day, Belgium had a high of 40°C (~104°F). Overall, climatologists have concluded that the summer of 2003 was probably the hottest in Europe in more than 500 years.[42]

In human terms, the 2003 heat wave was a disaster of major proportions. France was hit the hardest with more than 14,800 deaths, followed by 7,000 deaths in Germany, 4,200 in Spain, and 4,000 in Italy. Drought conditions severely affected agriculture, and Europe experienced more than 25,000 fires burning an estimated 647,069 hectares (1,599,000 acres) of forests. The global impact of the European drought and forest fires has been estimated at more than $17 billion.[40] Drought also had a major impact on power production: France, Europe's major energy producer, had to cut its power exports in half because of a lack of cooling water for its power plants.

European ecosystems were also significantly altered by the 2003 heat wave. Alpine glaciers lost up to 10 percent of their volume, the greatest loss of ice in any year on record. Ice also melted in the soil, as Alpine permafrost thawed to depths of up to 2 m (~6 ft.).[40] With permafrost ice no longer present to bind weathered rock, there were numerous rockfalls in the Alps. A rockfall on the Matterhorn, Switzerland's highest peak, forced the evacuation of 90 climbers.

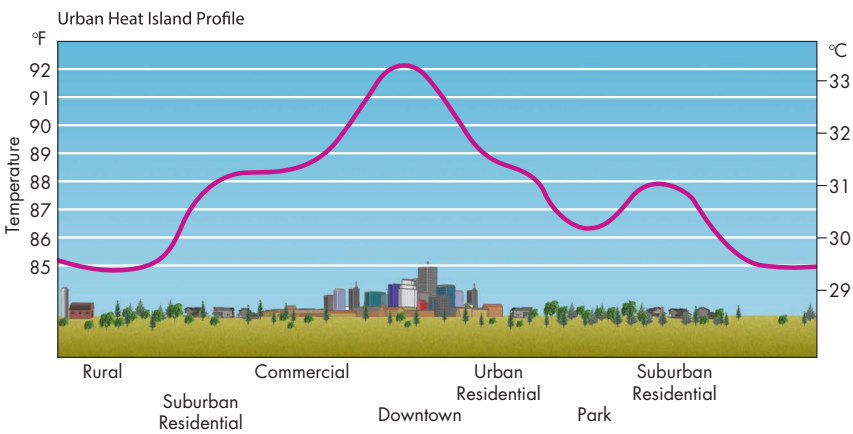
As with many other heat waves, the 2003 event in Europe was enhanced by a stagnant pattern of atmospheric circulation. Stagnant air circulation centered around an anticyclone, a ridge of high atmospheric pressure, that remained nearly stationary over Western Europe for more than 20 days. The anticyclone produced nearly cloudless skies and a downward flow of dry air and also blocked rainfall from storms in the North Atlantic. Exceptionally dry soil moisture and clear atmospheric conditions lasted from May through August and contributed significantly to the heat wave.[43] With clear skies, solar radiation heated the ground day after day and dried out the soil. As soil moisture decreased, there was less water to evaporate and cool the air. Heat built up in the soil and then radiated back into the atmosphere each night to significantly warm nighttime temperatures. Hot days followed by hot nights greatly increased heat stress for many people.

For several reasons, the greatest number of deaths occurred in Paris and surrounding French communities. First, heat waves are generally worse in cities



< FIGURE 9.38 Land Surface Heats Up in 2003 European Heat Wave

Difference between the daytime temperature of the land surface in July 2003 and the cooler, more normal temperatures of July 2001. Temperatures were measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite. The dark red areas were at least 10°C (18°F) hotter in 2003 than in 2001. *(NASA Earth Observing System)*



< FIGURE 9.39 Urban Heat Island Effect

Late afternoon temperature profile across urban, suburban, and rural areas on a summer day. The urban and suburban areas are significantly warmer than nearby rural areas, a phenomenon known as the urban heat island effect. This effect is greatest on calm, clear evenings when a city is often 5.6°C (~10°F) warmer than the surrounding countryside. *(Based on the U.S. Environmental Protection Agency, "Heat Island Effect." www.epa.gov/heatisland/about, 2006)*

because of the *urban heat island* effect. Environmental conditions associated with cities often make them 5.6°C (~10°F) warmer than surrounding natural areas (Figure 9.39).[44] The urban heat island effect is caused primarily by waste heat from vehicles, factories, and air conditioners; reduced airflow between buildings that traps heat; and more heat-absorbing concrete and other materials with less vegetation in urban areas. In contrast, evaporation from plant leaves and the soil in natural areas cools the air and mitigates processes that heat up urban areas. For Paris, the urban heat island effect during the first six days of August contributed to raising the air temperatures 7°C (~13°F) above normal (Figure 9.40).

A second reason that Paris and its suburbs experienced numerous casualties is that air pollution levels generally rise in cities during a heat wave. Stagnant air circulation associated with most heat waves allows air pollutants to accumulate and form photochemical smog. The smog contains ozone and other gases that cause or amplify respiratory problems. Finally, for Paris and other European cities, August is customarily a holiday month.

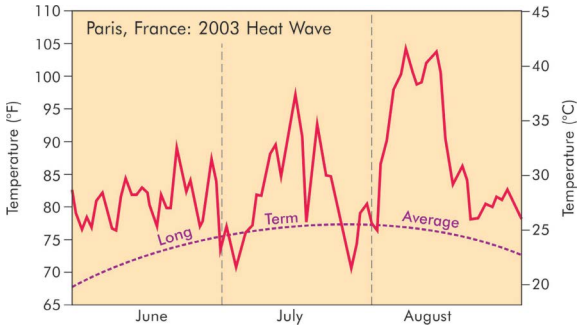


FIGURE 9.40 A Hot Time in Paris
The 2003 (orange line) and long-term average (purple line) daily high temperatures in Paris, France. Although the June and July daily high temperatures are not exceptional for many U.S. cities, they were a tremendous increase above the long-term average for Parisians. *(Based on the U.S. Environmental Protection Agency,* Excessive Heat Events Guidebook. *Publication EPA 430-B-06–005), 2006.)*

With many people on vacation, health services were short staffed and unable to handle the thousands of heat-related illnesses. Even morgues were unable to keep pace with the increased number of deaths.

Many Europeans wanted to know if the heat wave was caused by global warming. Meteorologists cannot tell if a single weather event is the result of changes that humans have caused in the atmosphere. They can, however, estimate the probability that human influence has increased the risk of a heat wave exceeding a given magnitude. For the 2003 European heat wave, computer climate models indicate that the greenhouse gases that humans have added to the troposphere (see Chapter 12) have doubled the probability of an event of this magnitude.[45]

LESSONS LEARNED

Warning and mitigation programs for heat waves have been slow to develop. Philadelphia, Pennsylvania, and Toronto, Ontario, have established model programs, and Lisbon, Portugal, and Rome, Italy, had systems in place before the 2003 European heat wave.

Warning Systems: At the time of the 2003 heat wave, most areas of Europe did not have heat health warning systems.[46] A similar situation existed in North America prior to the deadly 1995 heat wave in Chicago, Illinois. Today, a number of European cities and countries and more than 15 major metropolitan areas in the United States have heat health warning systems. These systems establish different criteria for warnings based on local meteorological conditions and the adaptation of residents to high heat conditions. The conditions required to trigger excessive heat warnings in Phoenix, Arizona, which regularly experiences temperatures higher than 38°C (~100°F), differ from those in normally cooler Toronto.

Vulnerable Populations: The elderly, infants and young children, people with mental illness or mobility impairments, the homeless and poor, people engaged in vigorous outdoor exercise or work, and those who are socially isolated or physically ill are at greatest risk from periods of prolonged heat. Most of those who died in France in the 2003 heat wave were elderly, although an unusually high number of heat-related deaths occurred among younger people.[47] Vulnerable individuals need to be monitored regularly by caregivers or other concerned citizens for signs of heat exhaustion or heat stroke.

Cooling Systems: Heat waves, including the 2003 European event, are often accompanied by power failures. Loss of air conditioning and power for fans and refrigeration is especially problematic for people who live in urban areas, especially in high-rise buildings (Figure 9.41). Spending a few hours every day in air conditioning can lower heat stress. Mobile cooling centers, such as city buses, can be routinely dispatched to publicized locations to provide heat relief to urban residents.

Public Education: Government officials and the mass media must provide the public with timely and consistent information about heat conditions and mitigation



FIGURE 9.41 Parisians Cool Off in Record Heat
Children and adults cool off in the Trocadero Fountains near the Eiffel Tower in Paris on August 12, 2003. Temperatures in Paris reached 40°C (104°F). *(AP Photo/Franck Prevel)*

TABLE 9.2 Personal Adjustments for Heat Waves

Do
• Minimize direct exposure to the sun
• Use air conditioners or spend time in air-conditioned places
• Use portable fans to exhaust hot air from or draw cooler air into rooms
• Take a cool bath or shower
• Stay hydrated by regularly drinking water or other nonalcoholic beverages
• Eat light, cool, and easy-to-digest foods such as fruit or salads
• Wear loose-fitting, light-colored clothes
• Check on older, sick, or frail people who may need help adjusting to the heat
• Know the symptoms of heat exhaustion and heat stroke and the appropriate responses
Don't
• Direct air from fans toward yourself when room temperature is hotter than 32°C (~90°F)
• Leave children and pets alone in cars for any amount of time
• Drink alcoholic beverages to try to stay cool
• Eat heavy, hot, or hard-to-digest foods
• Wear heavy or dark clothing

Source: Based on U.S. Environmental Protection Agency, *Excessive Heat Events Guidebook.* Publication EPA 430-B-06–005, 2006.

actions. Use of a heat index, which combines temperature and humidity (see Figure 9.37), is critical to communicating conditions that could result in heat-related illness. Individuals can take a number of actions (Table 9.2) to reduce their heat stress and prevent medical conditions caused by excessive heat exposure, such as heat cramps, heat exhaustion, and heat stroke (sunstroke).

PROSPECTS FOR THE FUTURE

Climate studies indicate that additional extreme heat events similar to the European heat wave of 2003 are likely to occur in the twenty-first century. Atmospheric scientists have calculated that, because of continued global warming, it is 100 times more likely that an event similar to the 2003 heat wave will take place in the next 40 years.[45] Environmental and public health agencies in the United States, Canada, and elsewhere have established programs to prepare for extreme heat events. In particular, these agencies advocate long-term programs to reduce the urban heat island effect that intensifies heat waves. Methods to reduce the effect include increasing the reflectivity of urban surfaces, such as by installing light-colored rooftops; increasing the amount of pervious pavement to provide the air access to moisture in the soil; and adding vegetation to urban areas, even to the flat roofs of buildings.

9.6 CHECK your understanding

1. How is global warming expected to affect severe weather?
2. Explain how drought, soil moisture, and a heat wave can be interrelated.
3. What causes the urban heat island effect? How can this effect be mitigated?

9.7 Linkages with Other Hazards

Severe weather is directly linked to short-term events such as flooding, mass movements, and wildfires, and to long-term changes in global climate. Linkages related to large tropical and extratropical cyclones are discussed in Chapter 10.

Flooding, often flash flooding, can be produced by one or more intense, slow-moving thunderstorms that produce a large amount of rain in a relatively short time (see Chapter 6). Thunderstorms move slowly if prevailing winds are relatively stagnant. Light prevailing winds can cause essentially the same storm, such as a mesoscale convective system, to remain fixed over a geographic area, or it can cause stagnation of a frontal boundary, such as a stationary front. Since thunderstorms

commonly move parallel to a stationary front, the stagnation of a front can cause storms to track over the same area, dropping large amounts of rainfall. In 2016, for example, a week-long period of sustained thunderstorm activity along a stationary front near the capital city of Lousiana, Baton Rouge, caused local rainfall totals in excess of 61 cm (~24 in.), and about one-third of the state being declared a federal disaster area due to flooding. Stagnation of thunderstorms can also occur over mountain foothills and cause deadly flash floods, like those in Rapid City, South Dakota, in 1972; Big Thompson Canyon west of Longmont, Colorado, in 1976; and Fort Collins and Boulder, Colorado, in 1997 and 2013.

Thunderstorms also produce lightning, the primary, natural ignition source for wildfires (see Chapter 13). However, not all lightning strikes in undeveloped areas cause wildfires. Only an estimated one out of every four cloud-to-ground lightning strikes has the continuous current necessary to start a wildfire, and then the fire may spread only if moisture conditions are low.[48]

Drought, dust/sandstorms, and heat waves are all hazardous weather events that may become more prevalent in some regions with global warming (see Chapter 12). Heat waves in the Arctic have already contributed to the melting of permafrost, which in turn has caused subsidence (see Chapter 7) and the release of additional greenhouse gases (see Chapter 12).

9.8 Natural Service Functions of Severe Weather

For many of us, it may be difficult to envision any benefits from severe weather; this is probably because most of the natural service functions are long term and not obvious. For example, lightning is the primary ignition source for natural wildfires, and wildfires are a vital process in prairie, tundra, and forest ecosystems (see Chapter 13). Windstorms also help maintain the health of forests. These storms topple dead and diseased trees, which then are recycled in the soil. Fallen trees also create clearings that become new habitats for diverse plants and animals. Even ice storms, which appear to be so destructive to trees, are part of a natural ecological cycle that increases plant and animal diversity in the forest.

In the hydrologic cycle, blizzards and other snowstorms, thunderstorms, and tropical storms are important, and in some areas these storms constitute the primary water source for an area. A continual supply of water from snowmelt and seasonal rainfall reduces a region's vulnerability to drought.

Finally, there are some uniquely human benefits to severe weather. Snowfall, cloud formations, and lightning displays have long had an aesthetic value. Severe weather also excites many people. Thanks to movies and television, tornado chasing has become a popular avocation and a new form of tourism. Guided expeditions in specially equipped vehicles regularly drive into "Tornado Alley" to chase and photograph tornadoes. Tornado chasing, however, can be extremely dangerous—serious injury, and even death, can occur if a vehicle actually encounters a tornado.

9.8 CHECK your understanding

1. Describe some of the natural service functions of severe weather.

9.9 Minimizing Severe Weather Hazards

Thunderstorms, tornadoes, mountain windstorms, ice storms, blizzards, and heat waves will continue to threaten human lives and property. As long as people live in the path of such hazards, we must take steps to minimize the damage and loss of life associated with them. We must be able to predict these events accurately in order to reduce their hazard.

FORECASTING AND PREDICTING WEATHER HAZARDS

Timely and accurate prediction of severe weather events is extremely important if human lives are to be spared. Even with improvements in satellite sensors and computer modeling, severe weather events are still difficult to forecast, and their behavior is unpredictable. A network of *Doppler radar* stations across North America has significantly improved our ability to predict the path of severe storms. Doppler radar antennas send out electromagnetic radiation that has a wavelength a little longer than microwaves (see Figure 9.5). Clouds, raindrops, ice particles, and other objects in the sky reflect these electromagnetic waves back to a receiving antenna. The wavelength of the reflected waves changes depending on whether the objects are moving toward or away from the antenna. This change in wavelength, called the *Doppler effect*, is similar to the difference in the pitch of sound waves as an ambulance siren approaches you and then goes away from you. The changes in radar wavelength are analyzed and can be used to make short-term predictions about the weather, on the scale of hours. For example, Doppler radar can detect a mesocyclone within a thunderstorm and allow meteorologists to issue some tornado warnings up to 30 minutes in advance (see Applying the 5 Fundamental Concepts).

Watches and Warnings You may have heard on the news that a tornado **watch** has been issued for a given area. A tornado watch warns the public of the possibility of a tornado, or tornadoes, developing in the near future. A typical tornado watch might include an area of 52,000 to 104,000 km^2 (~20,000 to 40,154 $mi.^2$) and last from 4 to 6 hours.[49] A watch does not guarantee that the event will occur; rather, it alerts residents to the possibility of a severe weather event and suggests that they monitor local weather conditions and listen to radio or television stations for more information.

When a tornado has actually been sighted or detected by weather radar, the watch is upgraded to a **warning**. A warning indicates that the area affected is in danger, and people should take immediate action to protect themselves and others. Watches may be upgraded to warnings, or warnings may be issued for an area not previously under a watch. Both watches and warnings may be issued for any type of severe weather—severe thunderstorms, tornadoes, tropical storms, hurricanes, heat waves, blizzards, and others, with some variation in the area covered and duration of the watch or warning.

People's perception of the risk of severe weather hazards differs according to their experience. Someone who has survived a tornado is more likely to perceive the hazard as real than someone who has lived in a region at risk for tornadoes yet has never experienced one. Incorrect predictions of where or when a hazard will strike may also lower risk perception. For example, if people are repeatedly warned of severe thunderstorms that never arrive, they may become complacent and ignore future warnings. As with any other hazard, accurate risk perception by planners and the public alike is key to reducing the threats associated with severe weather events.

Finally, our current theoretical understanding and monitoring technology do not always allow accurate prediction of the intensity and extent of many severe weather events. For example, even though less than 1 percent of tornadoes, the severe EF4 and EF5 storms, are responsible for half of tornado-caused deaths, meteorologists are not yet able to include predictions of intensity in official tornado watches and warnings.[50] Likewise, predicting the amount of icing and depths of snow accumulation in winter storms is often difficult. However, the National Weather Service and private-sector meteorologists are developing computer-based techniques for making real-time predictions of the intensity of some severe weather events.[51] Referred to as *nowcasting*, these techniques use information from weather radar, satellites, and automated weather stations to predict the path and development of severe storms once they have formed.

ADJUSTMENT TO THE SEVERE WEATHER HAZARD

Although we cannot control Earth's atmospheric system to prevent severe weather, we can take a number of steps to reduce the associated death and damage. These actions include both long-term changes to community infrastructure and plans or procedures to be implemented for severe weather. Long-term actions to prevent or minimize death, injuries, and damage are considered *mitigation*. Mitigation activities include the safety-conscious engineering and building of structures, the installation of warning systems, and the establishment of hazard insurance. Establishing community and individual plans and procedures to deal with an impending natural hazard is considered *preparedness*.[52]

Mitigation Although mitigation techniques differ for each weather hazard, some general statements can be made. Building new structures and modifying existing buildings can save lives and protect property from weather hazards. For example, windproofing buildings may significantly reduce damage from severe storms such as tornadoes, derechos, mountain windstorms, and hurricanes. In the United States, the Federal Emergency Management Agency (FEMA) offers grants and architectural plans to establish community shelters and safe rooms in buildings for tornado protection.[53]

Ensuring that electric, gas, water, wastewater, and communications systems continue to function following storms or severe winter weather is a continuing challenge. For example, electrical transmission lines are generally designed to survive ice storms that have a 50-year recurrence interval in the area that they serve.[30] However, in wooded areas, winds can combine with ice storms to cause power outages for weeks because ice-loaded branches fall on low-voltage power lines. For many water and wastewater systems, the use of pump stations makes them vulnerable to power interruptions caused by lightning, wind, and ice storms. Without backup sources that can provide power for days until a power grid is restored, these systems remain vulnerable to weather-related interruption. Finally, communication systems have the greatest potential to survive severe weather events if they have redundancy. A combination of landline telephone, cell phone, voice-over-Internet, multifrequency radio, and satellite communication links has the best potential for surviving various combinations of wind, water, ice, and lightning damage.

Other mitigation techniques include developing and installing warning systems and ensuring that universal hazard insurance is available. The goal of warning systems is to give the public the earliest possible notification of impending severe weather. Announcements can be made by commercial radio, television, and the

Internet; by U.S. and Canadian government weather radio broadcasts; and by local warning sirens. Some local U.S. and Canadian governments have recently installed community notification systems that call telephone subscribers, including registered mobile/Internet phone users, and warn them of emergencies.

Finally, insurance policies should be available to property holders living in regions at risk for weather disasters. Basic policies cover damage from water and wind but often exclude specific types of hazards such as flooding. Residents of risk areas should determine whether extra coverage is required for a severe storm, tornado, hurricane, blizzard, or other natural hazards.

Preparedness and Personal Adjustments

Individuals can take several steps to prepare for severe weather. Many of these steps can and should be carried out before a watch or warning is issued, whereas others are more appropriate when the danger is imminent. In areas prone to severe weather, people should be aware of the times of year that are most hazardous and make adequate preparations for themselves and their home. Information about how to prepare for various weather-related disasters is available from the U.S. National Oceanic and Atmospheric Administration (NOAA) and its subsidiary, the National Weather Service; from FEMA; and from Environment Canada and its subsidiary, the Meteorological Service of Canada. For example, knowing when and where to take shelter during a storm and what supplies should be kept in emergencies would be useful for more than one severe weather event.

Wearing proper clothing and modifying travel plans are prudent adjustments to many types of severe weather. Protection from direct sunlight in heat waves and the need for insulated clothing in snowstorms and blizzards are intuitive for most adults. Where people often are not prepared is in cool (5° to 15°C [41° to 59°F]), wet, and windy weather during which the human body can lose heat rapidly by evaporation from the skin and lungs and by contact with cold air and water. Rapid loss of core body heat causes intense shivering, loss of muscle coordination, mental sluggishness, and confusion, a medical condition known as *hypothermia*. In cool, wet, and windy weather, an improperly dressed person can show symptoms of hypothermia within several hours. People can become hypothermic immersed in 25°C (~77°F) water, or if improperly dressed and wet, in 20°C (~68°F) air temperature.[54,55] Unless body heat is restored, the continued loss of heat from a hypothermic person will cause unconsciousness and eventually death.

Low-visibility conditions can develop rapidly in dust storms, blizzards, and fog and are especially hazardous for travel on freeways and other roads where vehicles normally travel at high speed. For example, on average in the United States 40,000 highway accidents each year occur in fog conditions, resulting in nearly 640 deaths and more than 16,000 injuries.[56] When traveling by automobile, "onward through the fog" is not the best course of action.

9.9 CHECK your understanding

1. What is the difference between a severe weather watch and warning?
2. How do preparedness planning and mitigation differ?
3. List ways to personally prepare for a severe weather event.

APPLYING the 5 Fundamental Concepts

Moore, Oklahoma, Tornadoes

1. **Science helps us predict hazards.**
2. **Knowing hazard risks can help people make decisions.**
3. **Linkages exist between natural hazards.**
4. **Humans can turn disastrous events into catastrophes.**
5. **Consequences of hazards can be minimized.**

The United States is the tornado capital of the world, experiencing about 1,000 tornadoes per year, with Canada in second place with about 100 per year.[57] About 40 percent of those tornadoes occur in states within "Tornado Alley," such as Oklahoma (see Figure 9.25). That said, the probability of your town being struck by a tornado is only a few percent on any particular day during the spring months, even in Tornado Alley—and the chances of being hit by a powerful

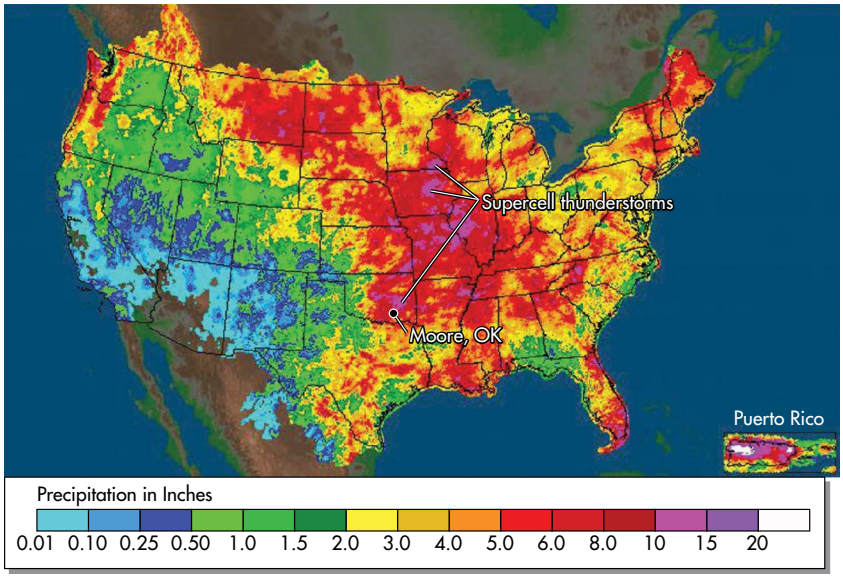
tornado is even less. The webpage of the city of Moore, Oklahoma, discusses the powerful 1999 tornado (see the chapter opener) and states, "May 3 was an extremely unique event weather wise," and "There's an extremely small chance of Moore experiencing another 'May 3' type event."[58] Statistically speaking this is a true statement, but a 1 percent chance per day that parts of your town could be completely leveled still represents a significant risk to life and property. This point was made 14 years later when a another EF5 tornado destroyed about 1,200 homes and killed 23 of Moore's residents.[59]

The tornado that struck Moore on May 20, 2013, was only one of 22 tornadoes that touched down that day but was the most destructive of the bunch. The tornadoes were spun out of a severe thunderstorm system that generated a total of 60 tornadoes and caused flooding in numerous states across the Great Plains (Figure 9.42). The tornado that struck Moore had the destructive power of an EF5. It was on the ground for 39 minutes and cut a 27 km (~17 mi.) long path that was as wide as 2 km (~1.3 mi.) through parts of the city.[60] Fortunately, wind velocities along much of its path were below 322 km (~200 mi.) per hour and only reached EF5 strength for a short distance (Figure 9.43).

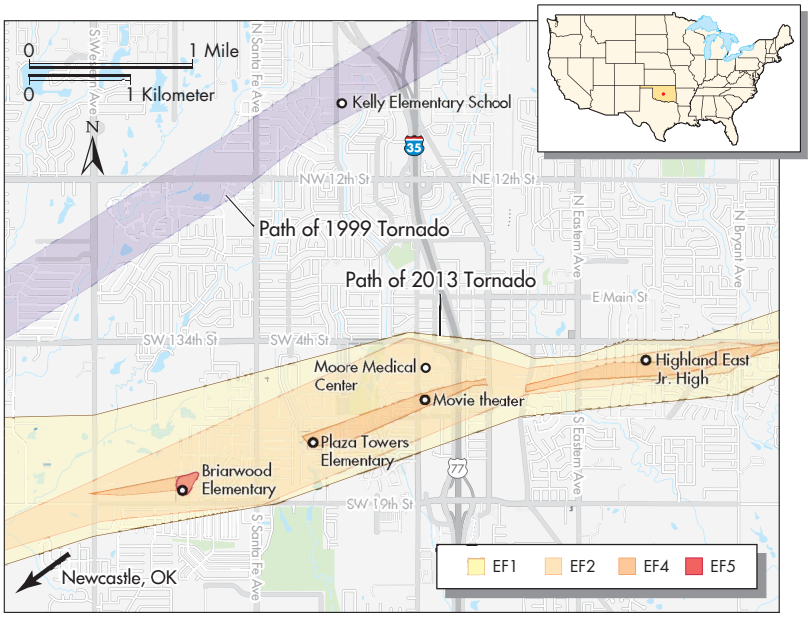
For several days the National Weather Service (NWS) had been forecasting a moderate risk of severe thunderstorms capable of producing baseball-sized hail with damaging winds and the potential for a few tornadoes. On the morning of May 20, the NWS issued a severe thunderstorm warning through 3:00 P.M. and a tornado watch through 10:00 P.M. for 30 counties in central Oklahoma. At 2:40 P.M. a tornado warning was issued for Moore and Newcastle, and by 2:52 P.M. Doppler radar had detected a distinct hook echo—the telltale sign of vertical axis rotation of a supercell with tornadic winds reaching for the ground (Figure 9.44).[61]

Moore is an NWS certified "Storm Ready City," which means the city (1) has a 24-hour warning and emergency operation center with multiple methods for receiving severe weather warnings and forecasts and for alerting the public; (2) has its own local weather monitoring system; (3) promotes public readiness through community seminars; and (4) has developed a formal hazardous weather plan, which includes trained weather spotters and regular emergency exercises. As soon as the tornado warning was issued, Moore's system of 36 sirens went off, automated mass calls to phone numbers, text messages, tweets, and emails went out, in addition to radio and TV public announcements.[62]

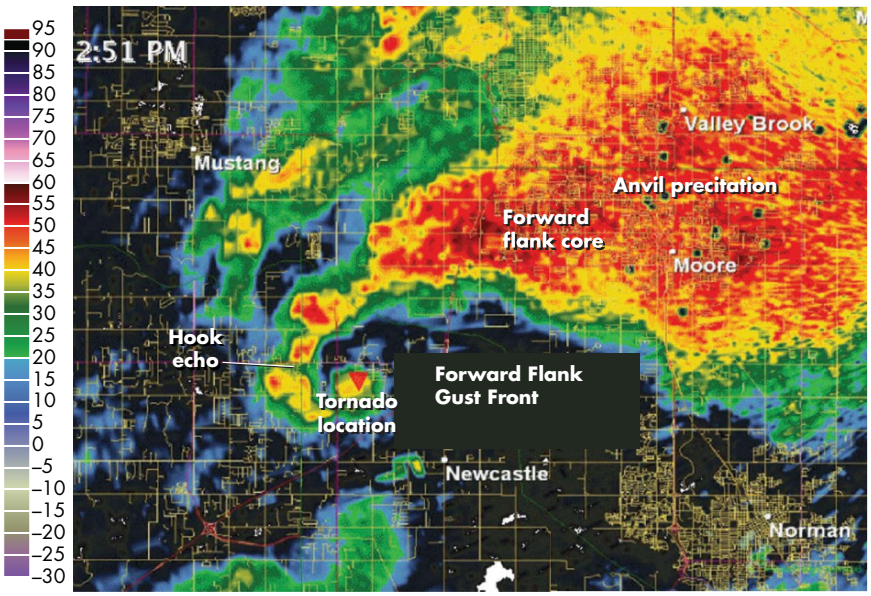
The tornado touched down 12 minutes after the warning went out. Nationally, the average



< FIGURE 9.42 Heavy Rain and Flooding
Doppler radar image showing heavy precipitation across the United States and supercell thunderstorm outbreaks in the mid-continental region on May 20, 2013. *(NOAA)*



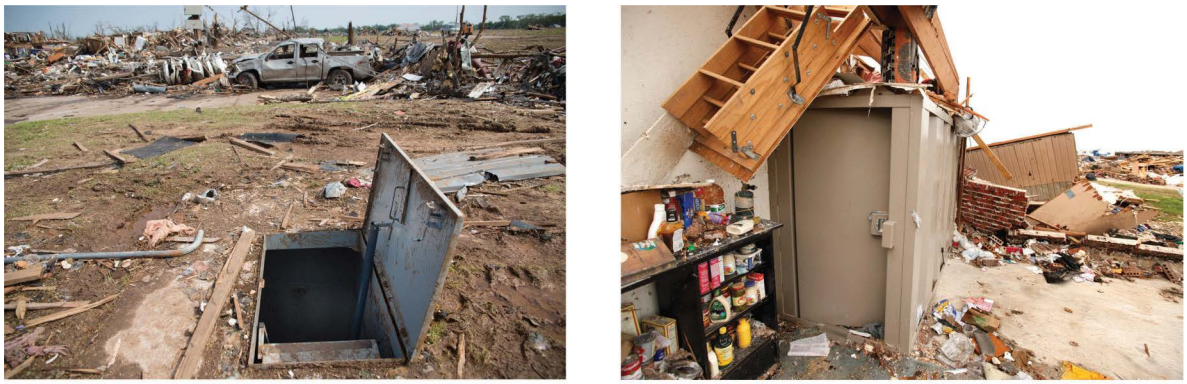
< FIGURE 9.43 Moore Tornado Paths
Map of Moore Oklahoma showing the paths of the 1999 and 2013 EF5 tornadoes and the locations of some of the key landmarks that experienced disastrous consequences due to high wind velocity.



< FIGURE 9.44 Hook Echo Indicates Tornado
Doppler radar image of super cell thunderstorm passing over southeastern Oklahoma, and the city of Moore. Meteorologists have come to recognize that a characteristic hook shape develops in the southwest corner of supercell thunderstorm when tornadic wind conditions ideal for tornado formation are present. *(NOAA)*

early warning lead time is 13 minutes; when Moore was hit in 1999, lead time was about 10 minutes.[63] Many Moore residents had more than 30 minutes of lead time before the tornado struck densely populated regions of the city—in theory, long enough for everyone to get out of the tornado's path, assuming they had some place safe to go.

Although Moore has more experience with EF5 tornadoes than most cities, less than one-tenth of its homes have basements or below-ground shelters.[58] This lack of underground shelters in Oklahoma is largely the result of the underlying geology of the region. Specifically, the soil that underlies much of central Oklahoma is clay rich, which is problematic for building



(a) (b)

FIGURE 9.45 Tornado Shelters

(a) Open hatch to below ground shelter that saved the lives of the family who lived in the home next to the shelter, the remnants of can be seen in the background. *(Photo by Paul Hellstern, The Oklahoman, copyright 2013)* (b) Above-ground safe room constructed in a garage of a house that was paritally destroyed by the 2013 Moore tornado. *(Julie Dermansky/Corbis)*

below-ground structures because of the way clay expands and contracts due to wetting and drying (see Chapter 8). Underground shelters can be built (Figure 9.45a) but may cost $15,000 to $20,000 to be correctly engineered for this type of soil, making them prohibitively expensive for most families. Although below ground is the safest place to be in a tornado, above-ground shelters are the less expensive route ($4,000–5,000), and all 16 above-ground shelters in the tornado's path survived (Figure 9.45b).[64] Unfortunately, these structures are small, usually holding less than six people, and are not appropriate for large groups of people gathered at a school or office building.

There are no community shelters in Moore, and most large buildings are not equipped with shelters big enough to hold all occupants. People at the elementary schools and the medical center (Figure 9.43), which laid along the path of the tornado, had no safe place to go other than into the interior of the buildings, as far away from outside walls and windows as possible. Briarwood Elementary and a few homes nearby took a direct hit from EF5 winds and were completely obliterated (Figure 9.46a), but fortunately the school and most of the homes had been evacuated. Unfortunately, Plaza Towers Elementary (Figure 9.43), hit just a few minutes later, had not been completely evacuated and seven children were killed. The 1999 tornado similarly destroyed Kelley Elementary (Figure 9.43), but it has since been rebuilt with "safe hallways" with overhead doors that can be shut to enclose the halls, making them safe while the tornado passes overhead. The school district superintendent has proposed a similar plan for the schools destroyed in 2013 when they are reconstructed.[65]

Compared to the 1999 tornado, the loss of life due to the 2013 tornado was relatively light, killing one-third less people. This is in part due to a greater warning lead time as well as differences in the location and length of the tornado path. Some might say that Moore got lucky in 2013, while others might say the opposite. What we do know is that since 1999 the population of Oklahoma has grown by about 10 percent and the population of Moore has grown by about 30 percent.[66] Not surprisingly, the Moore school district, which includes Briarwood and Plaza Towers Elementary schools, is the fastest-growing district in Oklahoma.[65] As you will learn in Chapter 12, climate change will likely bring more tornadoes to this region in the future, and it seems inevitable that the citizens of Moore will be confronted with yet another destructive tornado.



(a)



(b)

< FIGURE 9.46 2013 Moore Tornado Devastation
(a) Arial view of the remains of Briarwood elementary after taking a direct hit by EF5 velocity winds. *(Tony Gutierrez/AP Images)* (b) Cars piled up outside the heavily damaged Moore Medical Center. See Figure 9.43 for location of these landmarks. *(Brett Deering/Getty Images)*

APPLYING THE 5 FUNDAMENTAL CONCEPTS

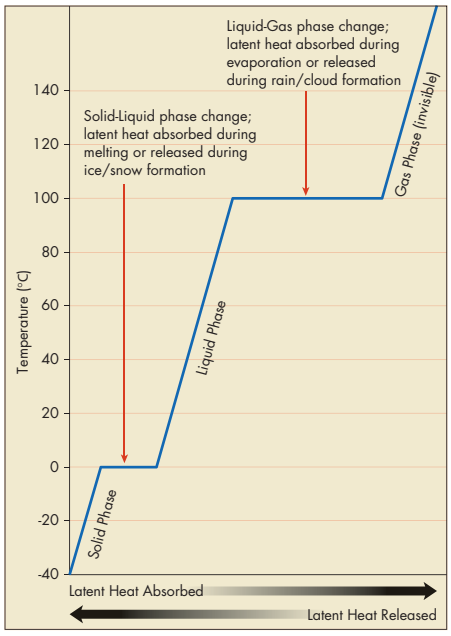
1. What precursor events and scientific tools were used to forecast the 2013 tornado? Discuss how successful or unsuccessful the forecasting and warnings were for Moore in 2013.
2. Explain the tornado risk you would face if you bought a home and moved your family, including young children, to Moore. How might you limit your personal tornado risk?
3. What other natural hazards are linked to tornadoes in Moore, Oklahoma?
4. Discuss the impact of population growth in Oklahoma and Moore with regard to tornado hazard. List ways that Moore could limit future loss of life due to tornadoes even with continued population growth.
5. Describe Moore's warning system and the city's preparedness to minimize the tornado hazard. How successful were these techniques and tools for saving lives and preventing property damage? If money was not an obstacle, what actions would you recommend to prevent future loss of life?

CONCEPTS in review

9.1 Energy

LO:1 Differentiate the three ways in which heat is transferred in the atmosphere.

- Energy can simply be thought of as the ability to do work. To move heavy boxes from one place to another, you must expend energy in order to do the work—energy is the force you must apply to the boxes to pick them up and move them.
- Three primary forms of energy are potential, kinetic, and heat energy. Potential energy is stored energy; kinetic energy is energy of motion; and heat energy is the energy produced by the random motion of molecules.
- In the atmosphere, heat energy occurs as sensible heat that can be measured and latent heat that is stored. Latent heat is either absorbed or released in phase changes. Evaporation absorbs latent heat and cools the air, whereas condensation, which forms clouds, releases latent heat and warms the air. Energy transfer occurs by convection, conduction, and radiation. Of these, convection is the most significant in producing clouds and severe weather.



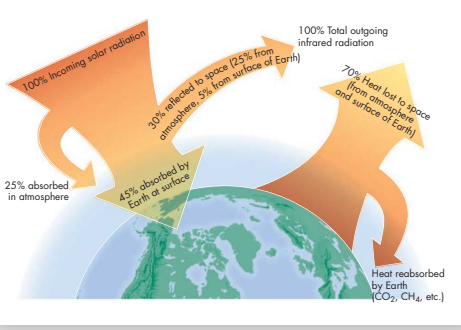
KEY WORDS

conduction (p. 347), **convection** (p. 348), **latent heat** (p. 347), **radiation** (p. 348)

9.2 Earth's Energy Balance

LO:2 Discuss how Earth's energy balance and energy exchanges produce climate and weather.

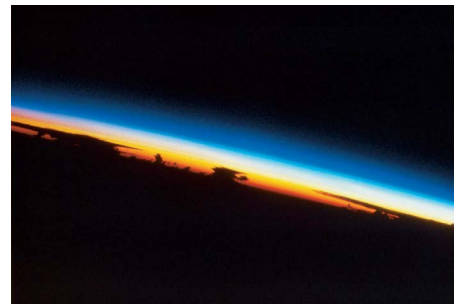
- Earth receives energy from the sun, and this energy affects the atmosphere, oceans, land, and all living things before being radiated back into space.
- Earth receives primarily short-wavelength, electromagnetic energy from the sun. This energy is reflected, scattered, transmitted, or absorbed on Earth. Dark-colored surfaces reflect less and absorb more solar energy and thus generally heat up. Most absorbed solar energy is radiated back into the atmosphere as long-wavelength, infrared radiation.



9.3 The Atmosphere

LO:3 Compare and contrast the different layers of Earth's atmosphere.

- Most weather occurs in the troposphere, the lowest of the five major layers of the atmosphere.
- Clouds are formed primarily in the troposphere and are composed of water droplets and ice crystals.



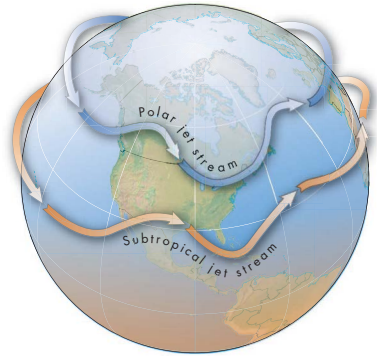
KEY WORDS

atmosphere (p. 350), **relative humidity** (p. 351), **troposphere** (p. 351)

9.4 Weather Processess

LO:4 Explain the different types of severe weather events and discuss the local weather conditions that cause these events.

- Changes in atmospheric pressure and temperature are responsible for air movement. Air flows from areas of high pressure to low pressure. Convergence of air produces low atmospheric pressure and divergence produces high pressure.
- Atmospheric stability is the tendency of a parcel of air to remain in place or change its vertical postion. The atmosphere is unstable if air parcels rise until they reach air of similar temperature and density. Severe weather is associated with unstable air.
- Winds blowing over long distances curve because Earth rotates beneath the atmosphere. Called the Coriolis effect, this curvature is to the right in the Northern Hemisphere. Low-level wind patterns and the jet streams are controlled by horizontal changes in atmospheric pressure; the Coriolis effect; and, for surface winds, friction.
- Boundaries between cooler and warmer air masses, called fronts, are described as cold, warm, stationary, or occluded. Many thunderstorms, tornadoes, snowstorms, ice storms, and dust storms are associated with fronts.



KEY WORDS

Coriolis effect (p. 357), **fronts** (p. 358), **jet streams** (p. 355)

9.5 Hazardous Weather and Geographic Regions at Risk

LO:5 Explain how movement of air masses control the distribution of different severe weather hazards.

- Rainstorms with lightning and thunder, called thunderstorms, form where there is moist air in the lower troposphere, rapid cooling of rising air, and updrafts to create cumulonimbus clouds. Thunderstorm development proceeds through cumulus, mature, and dissipative stages. Most thunderstorms form during maximum daytime heating, either as individual air-mass storms or as lines or clusters of storms associated with fronts.



KEY WORDS

blizzards (p. 370), **drought** (p. 375), **dust storm** (p. 376), **EF Scale** (p. 367), **fog** (p. 375), **hail** (p. 365), **heat index** (p. 378), **heat waves** (p. 377), **ice storms** (p. 372), **lightning** (p. 364), **supercell storm** (p. 361), **vertical wind shear** (p. 361), **wind chill** (p. 372)

- Severe thunderstorms have winds exceeding 93 km (~58 mi.) per hour, hail diameters greater than 1.9 cm (~0.75 in.), or a tornado. Severe thunderstorms form where there is strong vertical wind shear, uplift of air, and dry air above moist air. The three major types of severe thunderstorms are mesoscale convective systems (MCS), linear squall lines, and large individual storms called supercells.
- Lightning is an underestimated safety hazard associated primarily with thunderstorms. Large differences in electrical charge develop within a thunderstorm cloud or between the cloud and the ground. Flow of electrical charges within the cloud or between the ground and the cloud produces lightning.
- Tornadoes are generally funnel-like columns of rotating winds of 65 to more than 450 km (~40 to more than 280 mi.) per hour that extend downward from a cloud to the ground. With diameters in tens of meters, these storms usually travel at 50 km (31 mi.) per hour from southwest to northeast. Damage by tornadoes is rated on the Enhanced Fujita (EF) Scale, with EF5 as the most severe.
- Blizzards are severe winter storms in which large amounts of falling or blowing snow reduce visibilities for extended periods of time. Safety during cool and cold weather is based on the wind chill temperature, a combination of air temperature and wind speed.
- Ice storms occur with prolonged freezing rain along a stationary or warm front, below-freezing surface temperature, and a shallow layer of cold air at the surface. Sleet and snow occur where there is a progressively greater thickness of cold air at the surface.
- Weather conditions such as a dust storm or fog can greatly reduce visibility, resulting in deadly accidents. Fog is simply a cloud in contact with the ground. Other hazardous weather conditions include sandstorms, mountain windstorms, droughts, and heat waves.
- Drought and heat waves are often linked to high-pressure centers that stagnate over regions for extended periods of time. Heat waves are intensified in cities because of the urban heat island effect. Safety in hot weather requires knowing the heat index, which is based on a combination of air temperature and relative humidity.

9.6 Human Interaction with Weather

LO:6 Discuss how humans interact with severe weather.

- Potential human interactions with weather and its hazards are varied. At the local level, land use such as type of housing, landscaping, and agricultural practices may increase the effect of severe weather. On the global scale, atmospheric warming in response to burning of fossil fuels is changing our planet's weather systems. This warming of both the atmosphere and the oceans may feed more energy into storms, potentially increasing the incidence of severe weather events.



KEY WORDS

intensities (p. 379), **urban heat island effect** (p. 379)

9.7 and 9.8 Linkages with Other Hazards Natural Service Functions of Severe Weather

LO:7 Summarize the effects of severe weather events, as well as their linkages to other natural hazards.

LO:8 Recognize some natural service functions of severe weather.

- Severe weather is directly linked to short-term events such as tropical and extratropical cyclones, flooding, mass movements, and wildfires, as well as to long-term changes in global climate.
- Benefits of severe weather for the natural environment are primarily related to the transfer of water in the form of rain or snow. Fires from lightning strikes benefit landscapes in the long term.

9.9 Minimizing Severe Weather Hazards

LO:9 Identify how we can minimize the effects of severe weather hazards.

KEY WORDS
warning (p. 384), **watch** (p. 384)

- Minimizing hazards associated with severe weather such as thunderstorms, tornadoes, heat waves, droughts, blizzards, and ice storms requires a multifaceted approach. This approach should include (1) more accurate prediction that leads to better forecasting and warnings; (2) mitigation techniques designed to prevent or minimize death and loss of property, such as constructing buildings to better withstand severe weather; (3) hazard preparedness, such as short-term activities that individuals and communities can take once they have been warned of severe weather; and (4) education and insurance programs to reduce risk.

CRITICAL thinking questions

1. What severe weather events are potential hazards in the area where you live? What are some steps you might take to protect yourself from such hazards? Which of these hazards is your community the least prepared for?
2. Tornadoes can often be spotted on weather radar, whereas many other clouds cannot. What makes tornadoes visible?
3. Study the diagrams of cold fronts and warm fronts, and read the description about the development of ice storms. Explain why sleet (small pellets of ice) is more likely to accompany cold fronts than is freezing rain.
4. Why does hail form in thunderstorms and not in other rainstorms or snowstorms?
5. Has your community ever experienced a heat wave? If so, when did it occur and how were people affected? Does your community have a heat health warning system? If so, what actions do local officials and emergency personnel take when the system is activated? If not, what type of system would you recommend? What actions could you take to mitigate the effects of a heat wave on your living conditions?

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