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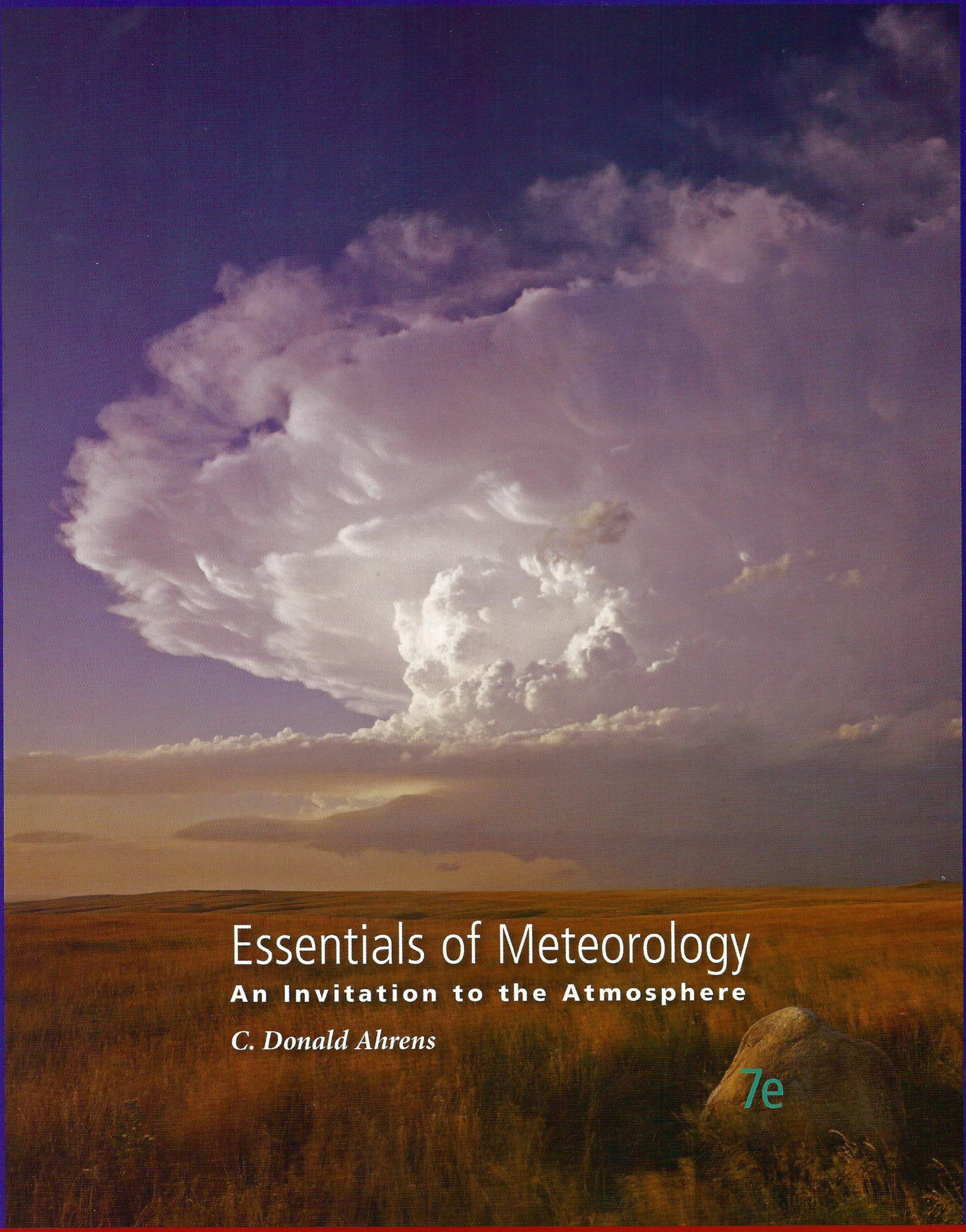

Essentials of Meteorology

An Invitation to the Atmosphere

C. Donald Ahrens

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SEVENTH EDITION

Essentials of Meteorology

AN INVITATION TO THE ATMOSPHERE

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Seventh Edition
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Cover Image: © Dykinga Photography/National Geographic
Compositor: Graphic World, Inc.

Library of Congress Control Number: 2013947768

ISBN-13: 978-1-285-46236-3
ISBN-10: 1-285-46236-X

Cengage Learning
200 First Stamford Place, 4th Floor
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Printed in the United States of America
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BRIEF REVIEW

Before moving on to the next section here is a brief review of some of the main points so far:

- The size of atmospheric circulations range from the smallest *microscale* to the larger *mesoscale*, to the largest *macroscale*.
- Thermal pressure systems are shallow pressure systems that are driven by the unequal heating and cooling of the earth's surface.
- The sea breeze and the land breeze are types of thermal circulations that are due to uneven heating and cooling rates of land and water.
- At the surface, a sea breeze blows from water to land; whereas a land breeze blows from land to water.
- A valley breeze blows uphill during the day and a mountain breeze blows downhill at night.
- Chinook (foehn) winds are warm, dry winds that blow downhill along the eastern side of the Rocky Mountains.
- The main source of warmth for the chinook is compressional heating.
- Santa Ana winds are warm, dry downslope winds that warm by compressional heating and blow from the east or northeast into Southern California.
- Dust devils tend to form over dry terrain on clear, hot days. They are not tornadoes, although the winds of a large dust devil may cause minor damage to structures.
- Monsoon winds are winds that change direction seasonally. In southern Asia, the winter monsoon, which blows from land to water, is dry; the summer monsoon, which blows from water to land, is wet.

Global Winds

Up to now, we have seen that local winds vary considerably from day to day and from season to season. As you may suspect, these winds are part of a much larger circulation—the little whirls within larger whirls that we spoke of earlier in this chapter. Indeed, if the rotating high- and low-pressure areas in our atmosphere are like spinning eddies in a huge river, then the flow of air around the globe is like the meandering river itself. When winds throughout the world are averaged over a long period of time, the local wind patterns vanish, and what we see is a picture of the winds on a global scale—what is commonly called the **general circulation of the atmosphere.**

General Circulation of the Atmosphere

Before we study the general circulation, we must remember that it only represents the *average* air flow around the world. Actual winds at any one place and at any given time may vary considerably from this average. Nevertheless, the average can answer why and how the winds blow around the world the way they do—why, for example, prevailing surface winds are northeasterly in Honolulu, Hawaii, and westerly in New York City. The average can also give a picture of the driving mechanism behind these winds, as well as a model of how heat is transported from equatorial regions poleward, keeping the climate in middle latitudes tolerable.

The underlying cause of the general circulation is the unequal heating of the earth's surface. We learned in Chapter 2 that, averaged over the entire earth, incoming solar radiation is roughly equal to outgoing earth radiation. However, we also know that this energy balance is not maintained for each latitude, since the tropics experience a net gain in energy, while polar regions suffer a net loss. To balance these inequities, the atmosphere transports warm air poleward and cool air equatorward. Although seemingly simple, the actual flow of air is complex; certainly not everything is known about it. In order to better understand it, we will first look at some models (that is, artificially constructed analogies) that eliminate some of the complexities of the general circulation.

Single-Cell Model The first model is the single-cell model, in which we assume that:

1. The earth's surface is uniformly covered with water (so that differential heating between land and water does not come into play).
2. The sun is always directly over the equator (so that the winds will not shift seasonally).
3. The earth does not rotate (so that the only force we need deal with is the pressure gradient force).

With these assumptions, the general circulation of the atmosphere on the side of the earth facing the sun would look much like the representation in ● Fig. 7.24a—a huge thermally driven convection cell in each hemisphere. (For reference, the names of the different regions of the world and their approximate latitudes are given in Figure 7.24b.)

The circulation of air described in Fig. 7.24a is the **Hadley cell** (named after the eighteenth-century English meteorologist George Hadley, who first proposed the idea). It is driven by energy from the sun. Excessive heating of the equatorial area produces a broad region of surface low pressure, while at the poles excessive cooling creates a region of surface high pressure. In response to the horizontal pressure gradient, cold surface polar air flows equatorward, while at higher levels air flows toward the poles. The entire circulation consists of a closed loop with rising air near the equator, sinking air over the poles,

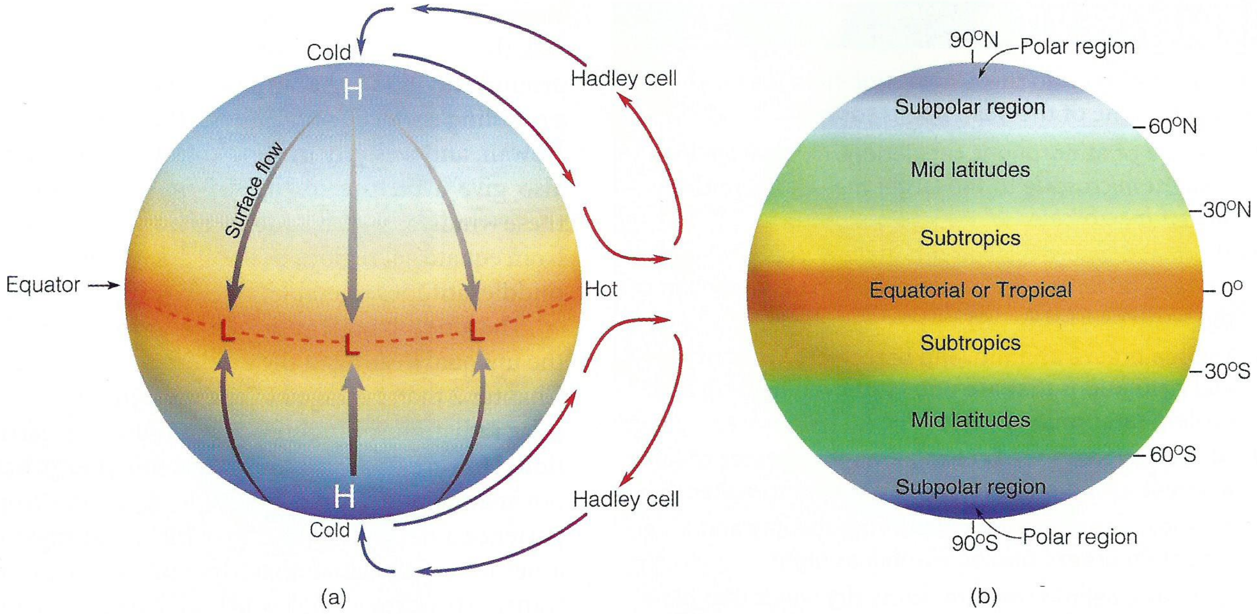

Figure 7.24 Diagram (a) shows the general circulation of air on the side of the earth facing the sun on a non-rotating earth uniformly covered with water and with the sun directly above the equator. (Vertical air motions are highly exaggerated in the vertical.) Diagram (b) shows the names that apply to the different regions of the world and their approximate latitudes.

an equatorward flow of air near the surface, and a return flow aloft. In this manner, some of the excess energy of the tropics is transported as sensible and latent heat to the regions of energy deficit at the poles.

Such a simple cellular circulation as this does not actually exist on the earth. For one thing, the earth rotates, so the Coriolis force would deflect the southward-moving surface air in the Northern Hemisphere to the right, producing easterly surface winds at practically all latitudes north of the equator. We know that this does not happen and that prevailing winds in middle latitudes actually blow from the west. Therefore, observations alone tell us that a closed circulation of air between the equator and the poles is not the proper model for a rotating earth. But this model does show us how a non-rotating planet would balance an excess of energy at the equator and a deficit at the poles. How, then, does the wind blow on a rotating planet? To answer, we will keep our model simple by retaining our first two assumptions—that is, that the earth is covered with water and that the sun is always directly above the equator.

Three-Cell Model If we allow the earth to spin, the simple convection system breaks into a series of cells as shown in Fig. 7.25. Although this model is considerably more complex than the single-cell model, there are some similarities. The tropical regions still receive an excess of heat and the poles a deficit. In each hemisphere, three cells instead of one have the task of energy redistribution. A surface high-pressure area is located at the poles, and a broad trough of surface low pressure still exists at the equator. From the equator to latitude 30°, the circulation is the Hadley cell. Let's look at this model more closely by examining what happens to the air above the equator. (Refer to Fig. 7.25 as you read the following section.)

Over equatorial waters, the air is warm, horizontal pressure gradients are weak, and winds are light. This region is referred to as the **doldrums.** (The monotony of the weather in this area has given rise to the expression "down in the doldrums.") Here, warm, humid air rises, often condensing into huge cumulus clouds and thunderstorms that liberate an enormous amount of latent heat. This heat makes the air more buoyant and provides energy to drive the Hadley cell. The rising air reaches the tropopause, which acts like a barrier, causing the air to move laterally toward the poles. The Coriolis force deflects this poleward flow toward the right in the Northern Hemisphere and to the left in the Southern Hemisphere, providing westerly winds aloft in both hemispheres. (We will see later that these westerly winds reach maximum velocity and produce jet streams near 30° latitude and 60° latitude.)

Air aloft moving poleward from the tropics constantly cools by giving up infrared radiation, and at the same time it also begins to converge, especially as it approaches the middle latitudes.* This convergence (piling up) of air aloft increases the mass of air above the surface, which in turn

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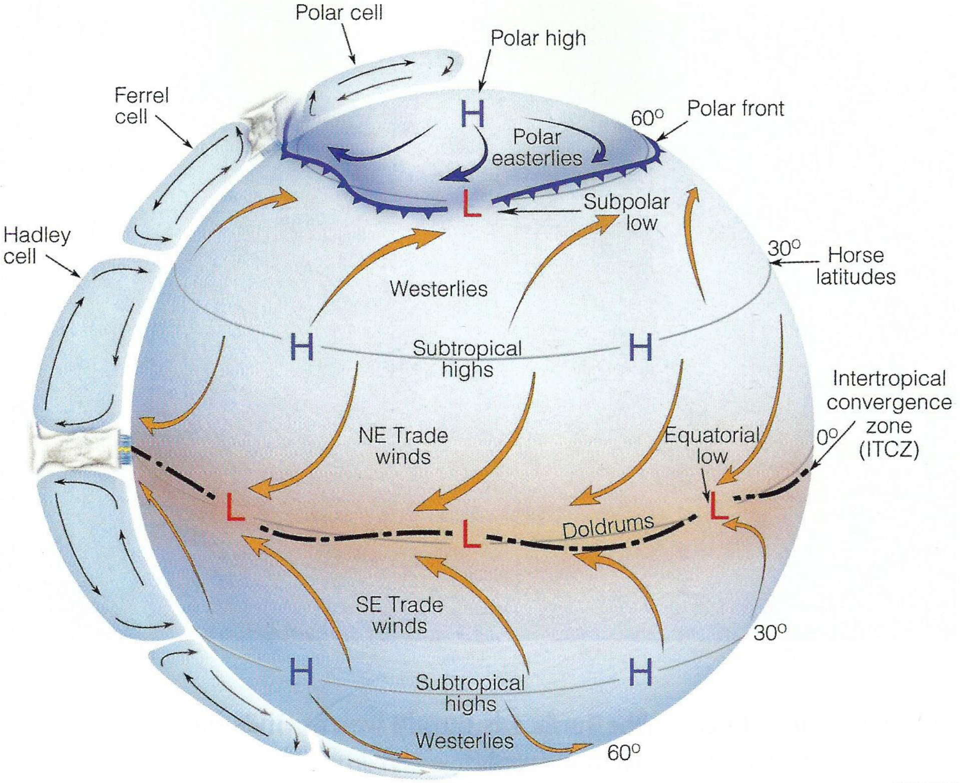
*You can see why the air converges if you have a globe of the world. Put your fingers on meridian lines at the equator and then follow the meridians poleward. Notice how the lines and your fingers bunch together in the middle latitudes.



•Figure 7.25 The idealized wind and surface-pressure distribution over a uniformly water-covered rotating earth.

causes the air pressure at the surface to increase. Hence, at latitudes near 30°, the convergence of air aloft produces belts of high pressure called **subtropical highs** (or anticyclones). As the converging, relatively dry air above the highs slowly descends, it warms by compression. This subsiding air produces generally clear skies and warm surface temperatures; hence, on earth it is here that we find the major deserts of the world, such as the Sahara of Africa and the Sonoran of North America (see • Fig. 7.26).

Over the ocean, the weak pressure gradients in the center of the high produce only weak winds. According to legend, sailing ships traveling to the New World were frequently becalmed in this region; and, as food and supplies dwindled, horses were either thrown overboard or eaten. As a consequence, this region is sometimes called the *horse latitudes.*

From the horse latitudes near latitude 30°, some of the surface air moves back toward the equator. It does not

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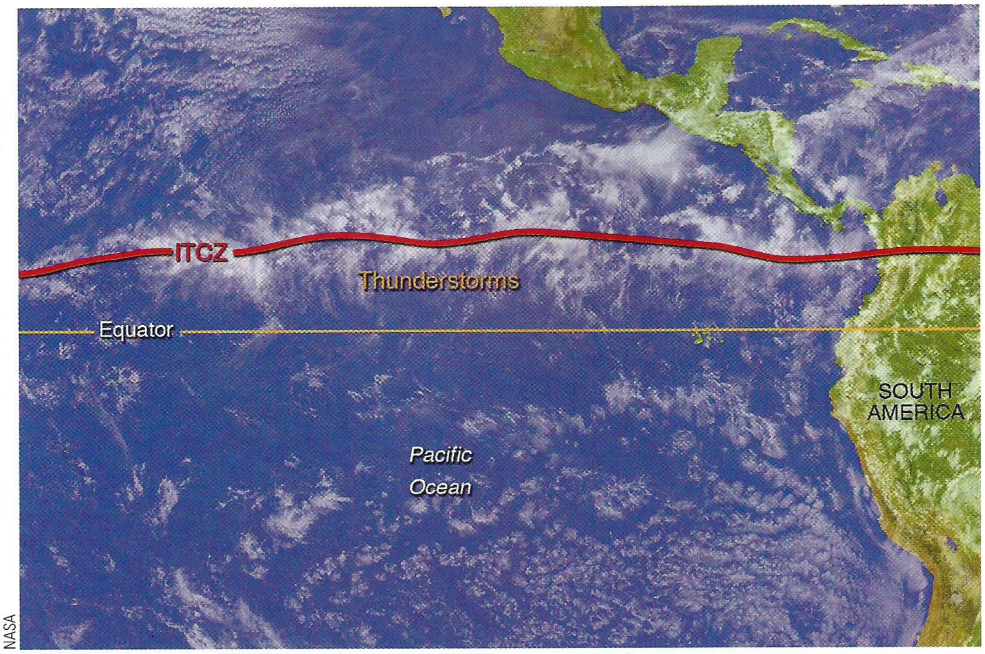
•Figure 7.26 Subtropical deserts, such as the Sonoran desert shown here, are mainly the result of sinking air associated with subtropical high-pressure areas.

•Figure 7.27 The solid red line in this visible satellite image marks the position of the ITCZ in the eastern Pacific. The bright white clouds are huge thunderstorms forming along the ITCZ.



flow straight back, however, because the Coriolis force deflects the air, causing it to blow from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. These steady winds provided sailing ships with an ocean route to the New World; hence, these winds are called the **trade winds.** Near the equator, the *northeast trades* converge with the *southeast trades* along a boundary called the **intertropical convergence zone (ITCZ).** In this region of surface convergence, air rises and continues its cellular journey. Along the ITCZ, it is usually very wet as the rising air develops into huge thunderstorms that drop copious amounts of rain in the form of heavy showers (see • Fig. 7.27).

Meanwhile, at latitude 30°, not all of the surface air moves equatorward. Some air moves toward the poles and deflects toward the east, resulting in a more or less westerly air flow—called the *prevailing westerlies,* or, simply, **westerlies**—in both hemispheres. Consequently, from Texas northward into Canada, it is much more common to experience winds blowing out of the west than from the east. The westerly flow in the real world is not constant as migrating areas of high and low pressure break up the surface flow pattern from time to time. In the middle latitudes of the Southern Hemisphere, where the surface is mostly water, winds blow more steadily from the west.

As this mild surface air travels poleward from latitude 30°, it encounters cold air moving down from the poles. These two air masses of contrasting temperature do not readily mix. They are separated by a boundary called the **polar front,** a zone of low pressure—the **subpolar low**—where surface air converges and rises, and storms and clouds develop. In our model in Fig. 7.25, some of the rising air returns at high levels to the horse latitudes, where it sinks back to the surface in the vicinity of the subtropical high. This middle cell (called the *Ferrel cell,* after the American meteorologist William Ferrel) is completed when surface air from the horse latitudes flows poleward toward the polar front.

Notice in Fig. 7.25, p. 203 that, in the Northern Hemisphere, behind the polar front the cold air from the poles is deflected by the Coriolis force, so that the general flow of air is from the northeast. Hence, this is the region of the **polar easterlies.** In winter, the polar front, with its cold air, can move into middle and subtropical latitudes, producing a cold polar outbreak. Along the front, a portion of the rising air moves poleward, and the Coriolis force deflects the air into a westerly wind at high levels. Air aloft eventually reaches the poles, slowly sinks to the surface, and flows back toward the polar front, completing the weak *polar cell.*

We can summarize all of this by referring back to Fig. 7.25 on p. 203 and noting that, at the surface, there are two major areas of high pressure and two major areas of low pressure. Areas of high pressure exist near

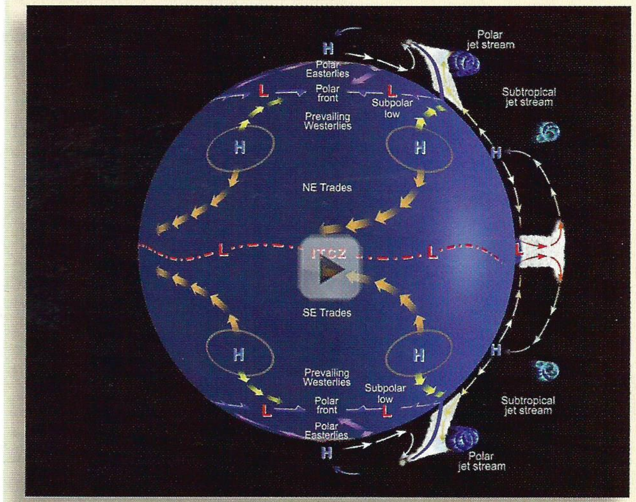
DID YOU KNOW?

Christopher Columbus was a lucky man. The year he set sail for the New World, the trade winds had edged unusually far north, and a steady northeast wind eased his ships along. Only for about ten days did he encounter the light and variable wind more typical of this notorious region (30°N)—the horse latitudes.

latitude 30° and the poles; areas of low pressure exist over the equator and near 60° latitude in the vicinity of the polar front. Knowing the way the surface winds blow around these pressure systems on the three-cell model, gives us a generalized picture of how surface winds blow throughout the world. The trade winds extend from the subtropical high to the equator, the westerlies from the subtropical high to the polar front, and the polar easterlies from the poles to the polar front.

How does this three-cell model compare with actual observations of winds and pressure in the real world? We know, for example, that upper-level winds at middle latitudes generally blow from the west. The middle cell in our model, however, suggests an east wind aloft as air flows equatorward. Hence, discrepancies exist between this model and atmospheric observations. This model does, however, agree closely with the winds and pressure distribution at the *surface,* and so we will examine this next.

CONCEPT ANIMATION



For a quick review of the concepts presented in the previous section, go to the Meteorological CourseMate website at www.cengagebrain.com and view the animation entitled *General Circulation of the Atmosphere.*

Average Surface Winds and Pressure: The Real World

When we examine the real world with its continents and oceans, mountains and ice fields, we obtain an average distribution of sea-level pressure and winds for January and July, as shown in ● Figs. 7.28a and 7.28b. Look closely at both maps and observe that there are regions where pressure systems appear to persist throughout the year. These systems are referred to as *semipermanent highs and lows* because they move only slightly during the course of a year.

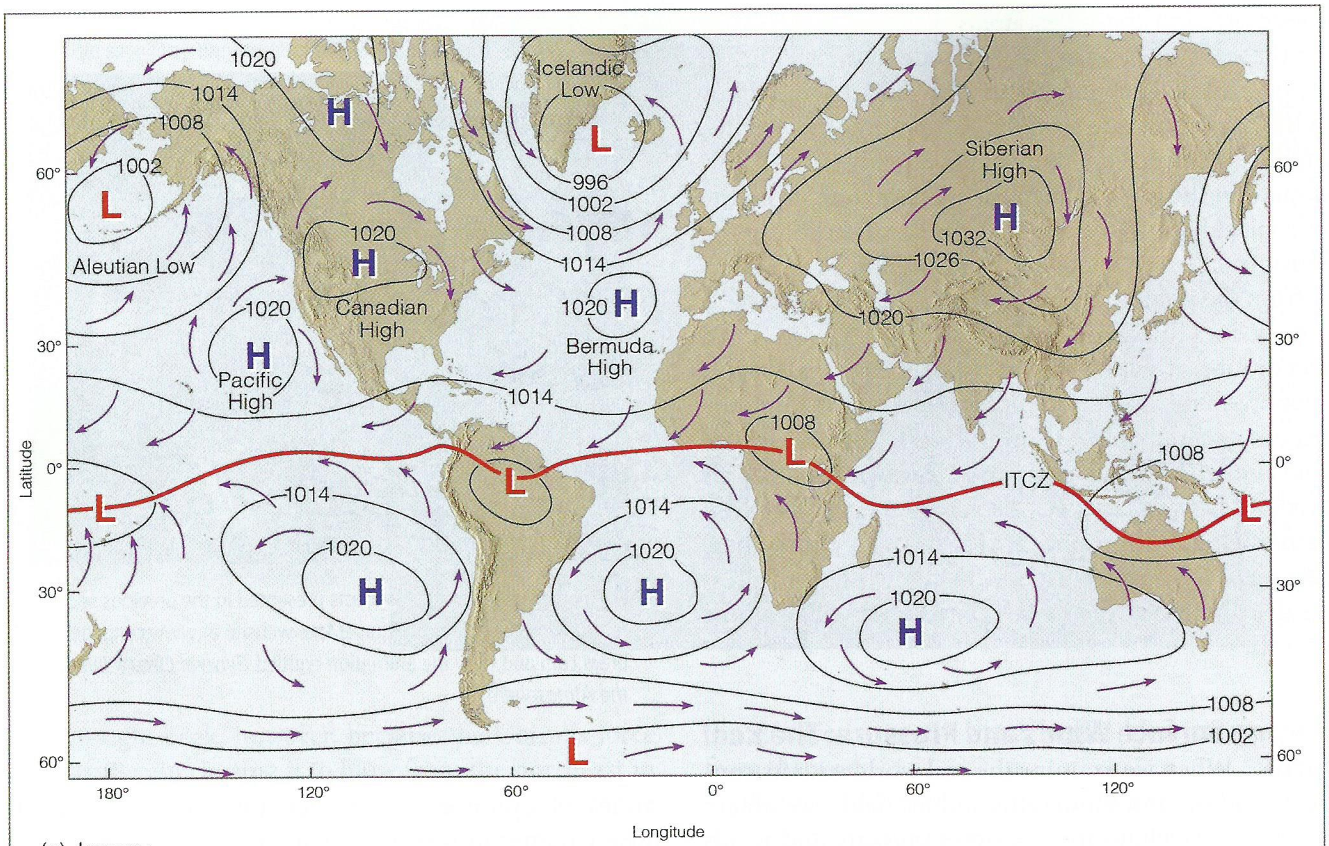
In Fig. 7.28a, we can see that there are four semipermanent pressure systems in the Northern Hemisphere during January. In the eastern Atlantic, between latitudes 25° and 35°N is the *Bermuda-Azores high,* often called the **Bermuda high,** and, in the Pacific Ocean, its counterpart, the **Pacific high.** These are the subtropical anticyclones that develop in response to the convergence of air aloft. Since surface winds blow clockwise around these systems, we find the trade winds to the south and the prevailing westerlies to the north. In the Southern Hemisphere, where there is relatively less land area, there is less contrast between land and water, and the subtropical highs show up as well-developed systems with a clearly defined circulation.

Where we would expect to observe the polar front (between latitudes 40° and 65°), there are two semipermanent subpolar lows. In the North Atlantic, there is the *Greenland-Icelandic low,* or simply **Icelandic low,** which covers Iceland and southern Greenland, while the **Aleutian low** sits over the Gulf of Alaska and the Bering Sea near the Aleutian Islands in the North Pacific. These zones of cyclonic activity actually represent regions where numerous storms, having traveled eastward, tend to converge, especially in winter. In the Southern Hemisphere, where there is very little land to disrupt the flow, the subpolar low forms a continuous trough that completely encircles the globe.

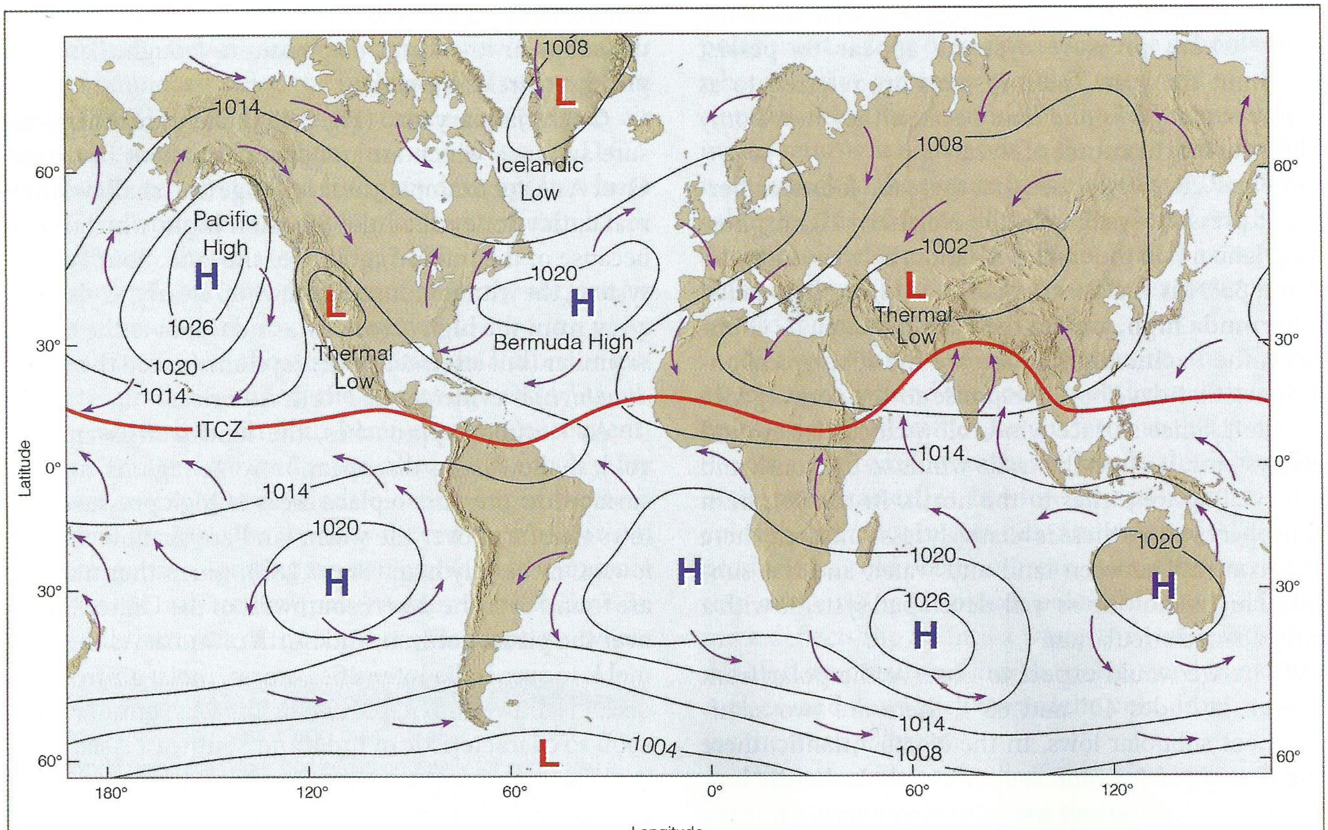
On the January map (Fig. 7.28a), there are other pressure systems, which are not semipermanent in nature. Over Asia, for example, there is a huge (but shallow) thermal anticyclone called the **Siberian high,** which forms because of the intense cooling of the land. South of this system, the winter monsoon shows up clearly, as air flows away from the high across Asia and out over the ocean. A similar (but less intense) anticyclone (called the *Canadian high*) is evident over North America.

As summer approaches, the land warms and the cold, shallow highs disappear. In some regions, areas of surface low pressure replace areas of high pressure. The lows that form over the warm land are shallow *thermal lows.* On the July map (Fig. 7.28b), warm thermal lows are found over the desert southwest of the United States, over the plateau of Iran, and north of India. As the thermal low over India intensifies, warm, moist air from the ocean is drawn into it, producing the wet summer monsoon so characteristic of India and Southeast Asia.

When we compare the January and July maps, we can see several changes in the semipermanent pressure systems. The strong subpolar lows so well developed in January over the Northern Hemisphere are hardly

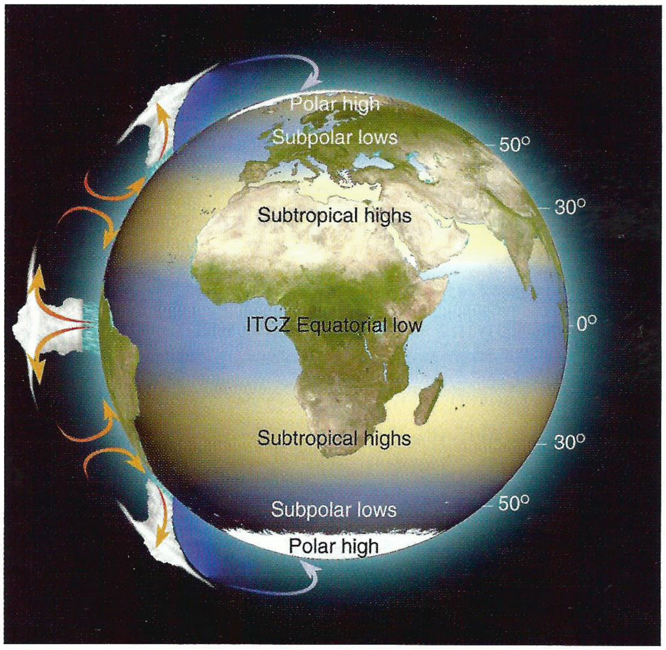


(a) January



(b) July

•Figure 7.28 Average sea-level pressure distribution and surface wind-flow patterns for January (a) and for July (b). The solid red line represents the position of the ITCZ.



●**Figure 7.29** Rising and sinking air associated with the major pressure systems of the earth's general circulation. Where the air rises, precipitation tends to be abundant (blue shade); where the air sinks, drier regions prevail (tan shade). Note that the sinking air of the subtropical highs produces the major desert regions of the world.

discernible on the July map. The subtropical highs, however, remain dominant in both seasons. Because the sun is overhead in the Northern Hemisphere in July and overhead in the Southern Hemisphere in January, the zone of maximum surface heating shifts seasonally. In response to this shift, the major pressure systems, wind belts, and ITCZ (heavy red line in Fig. 7.28) *shift toward the north in July and toward the south in January.**

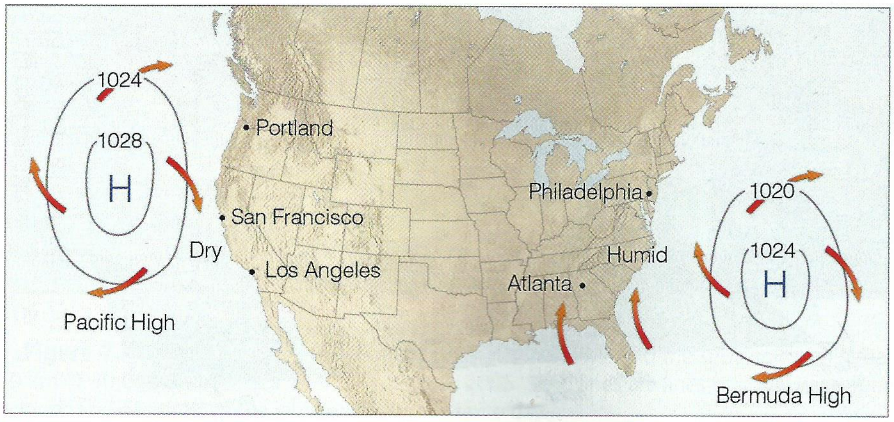
The General Circulation and Precipitation Patterns

The position of the major features of the general circulation and their latitudinal displacement (which annually averages about 10° to 15°) strongly influence the climate of many areas. For example, on the global scale, we would expect abundant rainfall where the air rises and very little where the air sinks. Consequently, areas of high rainfall exist in the tropics, where humid air rises in conjunction with the ITCZ, and between 40° and 55° latitude, where middle-latitude cyclonic storms and the polar front force air upward. Areas of low precipitation are found near 30° latitude in the vicinity of the subtropical highs and in polar regions where the air is cold and dry (see ● Fig. 7.29).

During the summer, the Pacific high drifts northward to a position off the California coast (see ● Fig. 7.30). Sinking air on its eastern side produces a strong upper-level subsidence inversion, which tends to keep summer weather along the West Coast relatively dry. The rainy season typically occurs in winter when the high moves south and storms are able to penetrate the region. Observe in Fig. 7.30 that along the East Coast, the clockwise circulation of winds around the Bermuda high brings warm, tropical air northward into the United States and southern Canada from the Gulf of Mexico and the Atlantic Ocean. Because sinking air is not as well developed on this side of the high, the humid air can rise and condense into towering cumulus clouds and thunderstorms. So, in part, it is the air motions associated with the subtropical highs that keep summer weather dry in California and moist in Georgia. (Compare the precipitation patterns for Los Angeles, California, and Atlanta, Georgia, in ● Fig. 7.31.)

Westerly Winds and the Jet Stream

In Chapter 6, we learned that the winds above the middle latitudes in both hemispheres blow in a wavy west-to-east direction. The reason for these westerly winds is that, aloft, we generally find higher pressure over equatorial regions and lower pressures over polar regions. Where these upper-level winds tend to concentrate into narrow bands, we find rivers of fast-flowing air—what we call **jet streams.**



●**Figure 7.30** During the summer, the Pacific high moves northward. Sinking air along its eastern margin (over California) produces a strong subsidence inversion, which causes relatively dry weather to prevail. Along the western margin of the Bermuda high, southerly winds bring in humid air, which rises, condenses, and produces abundant rainfall.

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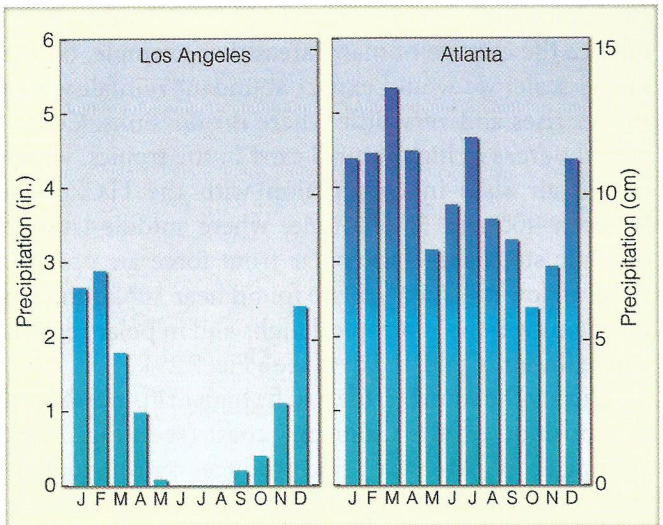
*An easy way to remember the seasonal shift of surface pressure systems is to think of birds—in the Northern Hemisphere, they migrate south in the winter and north in the summer.



•Figure 7.31 Average annual precipitation for Los Angeles, California, and Atlanta, Georgia.

Characteristics of Jet Streams Atmospheric jet streams are swiftly flowing air currents hundreds of miles long, normally less than several hundred miles wide, and typically less than a mile thick. Wind speeds in the central core of a jet stream often exceed 100 knots and occasionally 200 knots. Jet streams are usually found at the tropopause at elevations between 10 and 14 km (33,000 and 46,000 ft) although they may occur at both higher and lower altitudes.

Jet streams were first encountered by high-flying military aircraft during World War II, but their existence was suspected before that time. Ground-based observations of fast-moving cirrus clouds had revealed that westerly winds aloft must be moving rapidly indeed.

• Figure 7.32 illustrates the average position of two jet streams, the tropopause, and the general circulation of air for the Northern Hemisphere in winter. Both jet streams are located at tropopause gaps, where mixing between tropospheric and stratospheric air takes place. The jet stream situated near 30° latitude at about 13 km (43,000 ft) above the subtropical high is the **subtropical jet stream.*** To the north, the jet stream situated at a lower altitude at about 10 km (33,000 ft) near the polar front is known as the **polar front jet stream** or, simply, the *polar jet stream.*

In Fig. 7.32, the wind in the center of the jet stream would be flowing as a westerly wind away from the viewer. This direction, of course, is only an average, as jet streams often flow in a wavy west-to-east pattern. When the polar jet stream flows in broad loops that sweep north and south, it may even merge with the subtropical jet. Occasionally, the polar jet splits into two jet streams. The jet stream to the north is often called the *northern branch* of the polar jet, whereas the one to the south is called the *southern branch.* • Figure 7.33 illustrates how the polar jet stream and the subtropical jet stream might appear as they sweep around the earth in winter.

We can better see the looping pattern of the jet by studying • Fig. 7.34a, which shows the position of the polar jet stream and the subtropical jet stream at the 300-mb level (near 9 km or 30,000 ft) on March 9, 2005. The fastest flowing air, or *jet core,* is represented by the heavy dark arrows. The map shows a strong polar jet stream sweeping south over the Great Plains with an equally strong subtropical jet over the Gulf states. Notice that the polar jet has a number of loops, with one off the west coast of North America and another over eastern Canada. Observe in the satellite image (Fig. 7.34b) that the polar jet stream (blue arrow) is directing cold, polar air into the Plains States, while

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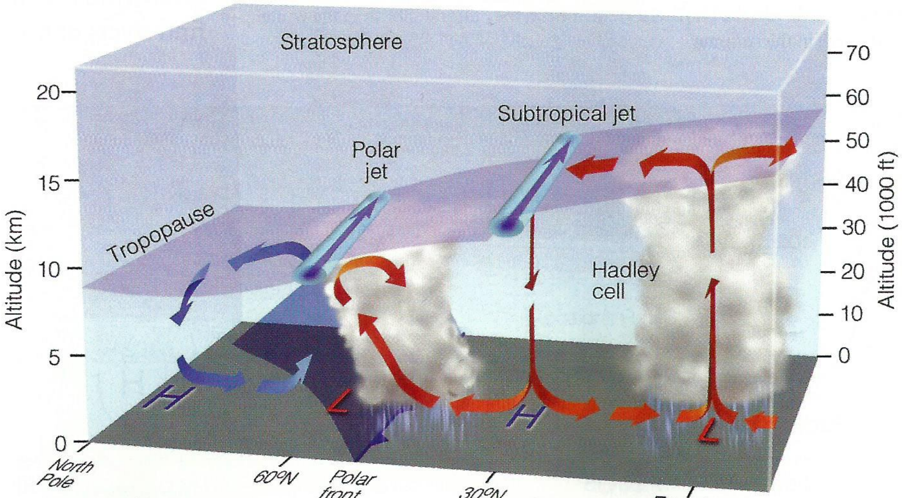
*The subtropical jet stream is normally found between 20° and 30° latitude.

•Figure 7.32 Average position of the polar jet stream and the subtropical jet stream, with respect to a model of the general circulation in winter. Both jet streams are flowing from west to east.



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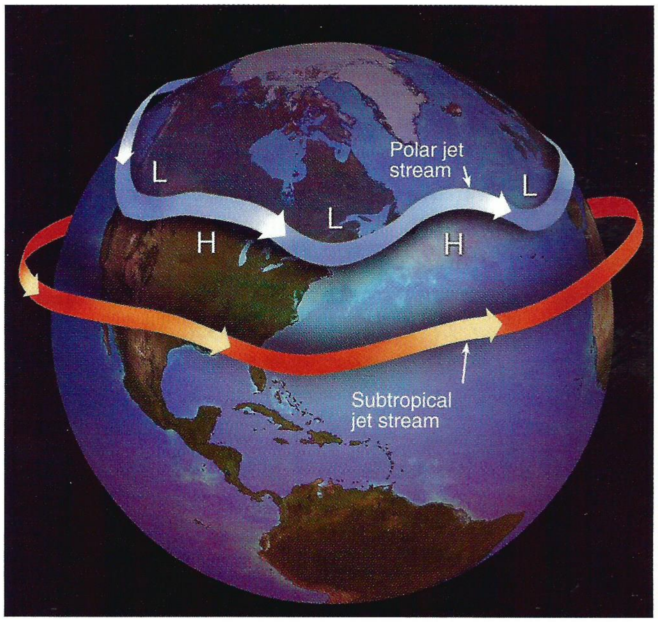


•Figure 7.33 Jet streams are swiftly flowing currents of air that move in a wavy west-to-east direction. The figure shows the position of the polar jet stream and subtropical jet stream in winter. Although jet streams are shown as one continuous river of air, in reality they are discontinuous, with their position varying from one day to the next.

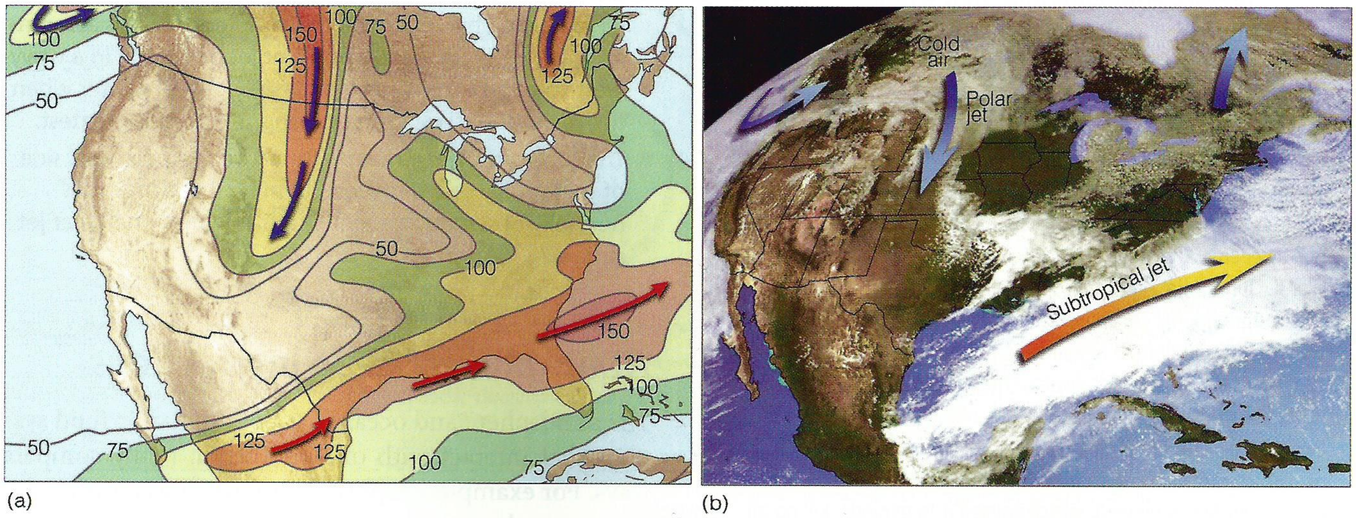
the subtropical jet stream (orange arrow) is sweeping subtropical moisture, in the form of a dense cloud cover, over the southeastern states.

The looping pattern of the polar jet stream has an important function. In the Northern Hemisphere, where the air flows southward, swiftly moving air directs cold air equatorward; where the air flows northward, warm air is carried toward the poles. Jet streams, therefore, play a major role in the global transfer of heat. Moreover, since jet streams tend to meander around the world, we can easily understand how pollutants or volcanic ash injected into the atmosphere in one part of the globe could eventually settle to the ground many thousands of kilometers downwind. And, as we will see in Chapter 8, the looping nature of the polar jet stream has an important role in the development of mid-latitude cyclonic storms.

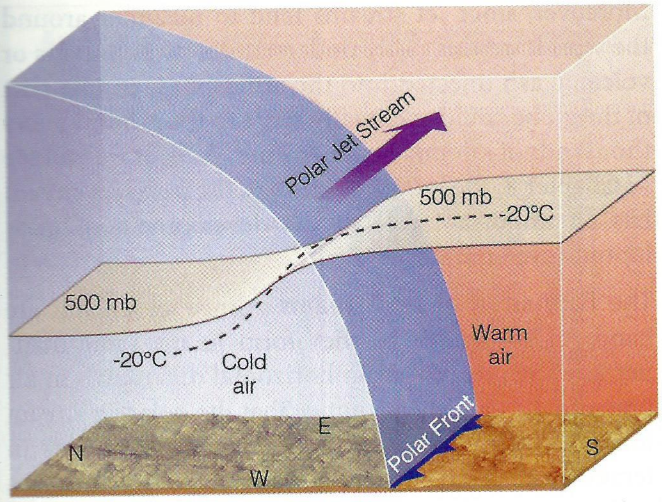
The Formation of Jet Streams Since jet streams are bands of strong winds, they form in the same manner as all winds do—from horizontal differences in air pressure. In • Fig. 7.35a, notice that the polar jet stream forms along the polar front where sharp contrasts in temperature produce rapid horizontal pressure changes and strong winds. Notice in Fig. 7.35a that as the 20°C isotherm crosses the frontal boundary, it dips sharply. This rapid change in temperature causes the constant pressure (isobaric) 500-mb surface to bend sharply as it passes through the front.

The bending of 500-mb surface in Fig. 7.35a shows up as tightly packed contour lines and strong winds along the front on the 500-mb chart (Fig. 7.35b). Due to the fact that the north-to-south temperature contrasts along the front are greater in winter than they are in summer, the polar jet stream shows seasonal variations. In winter, the polar jet stream winds are stronger and the jet moves farther south, sometimes as far south as Florida and Mexico. In summer, the polar jet stream is weaker and forms over higher latitudes.

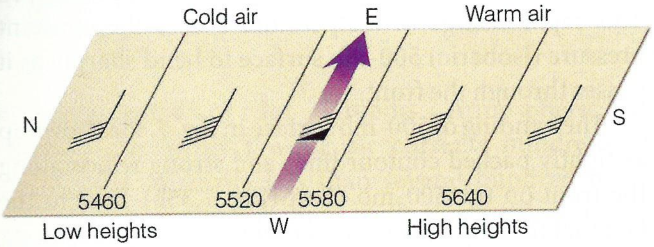
Look back at Fig. 7.32 on p. 208 and see that the subtropical jet stream forms on the poleward (north) side of the Hadley cell, at a higher altitude than the polar jet stream. Here, warm air aloft carried poleward by the



•Figure 7.34 (a) Position of the polar jet stream (blue arrows) and the subtropical jet stream (orange arrows) at the 300-mb level (about 9 km or 30,000 ft above sea level) on March 9, 2005. Solid lines are lines of equal wind speed (isotachs) in knots. (b) Satellite image showing clouds and positions of the jet streams for the same day.



(a) 3-D view



(b) 500-mb chart

•Figure 7.35 Diagram (a) is a model that shows a vertical 3-D view of the polar front in association with a sharply dipping 500-mb pressure surface, an isotherm (dashed line), and the position of the polar front jet stream in winter. The diagram is highly exaggerated in the vertical. Diagram (b) represents a 500-mb chart that cuts through the polar front as illustrated by the dipping 500-mb surface in (a). Sharp temperature contrasts along the front produce tightly packed contour lines and strong winds (contour lines are in meters above sea level).

Hadley cell produces sharp temperature differences, strong pressure gradients, and high winds.

Although the polar and subtropical jets are the two most frequently in the news, there are other jet streams that deserve mentioning. For example, there is a *low-level jet stream* that forms just above the Central Plains of the United States. During the summer, this jet (which usually has peak winds of less than 60 knots) often contributes to the formation of nighttime thunderstorms by transporting moisture and warm air northward. Higher up in the atmosphere, over the subtropics, a summertime easterly jet called the *tropical easterly jet* forms at the base of the tropopause. And during the dark polar winter, a *stratospheric polar jet* forms near the top of the stratosphere.

DID YOU KNOW?

The jet stream is in part responsible for the only American casualties by enemy attack on the continental United States in World War II. During the war, when the existence of the jet stream was first confirmed, the Japanese attempted to drop bombs on the United States mainland by launching balloons that carried explosives and incendiary devices. The hydrogen-filled balloons drifted east from Japan for thousands of miles across the Pacific Ocean at an altitude above 30,000 feet. Unfortunately, a group of six picnickers in Oregon found a balloon bomb in the woods and attempted to move it, which caused it to explode, killing all six people. Estimates are that as many as 300 balloon bombs may still be scattered throughout regions of the western United States.

BRIEF REVIEW

Before going on to the next section, which describes the many interactions between the atmosphere and the ocean, here is a review of some of the important concepts presented so far:

- The two major semipermanent subtropical highs that influence the weather of North America are the Pacific high situated off the west coast and the Bermuda high situated off the southeast coast.
- The polar front is a zone of low pressure where cyclonic storms often form. It separates the mild westerlies of the middle latitudes from the cold, polar easterlies of the high latitudes.
- In equatorial regions, the intertropical convergence zone (ITCZ) is a boundary where air rises in response to the convergence of the northeast trades and the southeast trades. Along the ITCZ huge thunderstorms produce heavy rain showers.
- In the Northern Hemisphere, the major global pressure systems and wind belts shift northward in summer and southward in winter.
- The northward movement of the Pacific high in summer tends to keep summer weather along the west coast of North America relatively dry.
- Jet streams exist where strong winds become concentrated in narrow bands. The polar-front jet stream is associated with the polar front. The polar jet meanders in a wavy west-to-east pattern, becoming strongest in winter when the contrast in temperature along the front is greatest.
- The subtropical jet stream is found on the poleward side of the Hadley cell, between 20° and 30° latitude. It is normally observed at a higher altitude than the polar jet stream.

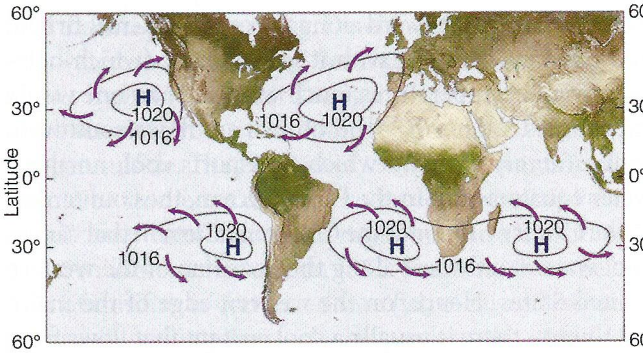
Atmosphere-Ocean Interactions

The atmosphere and oceans are both dynamic fluid systems that interact with one another in many complex ways. For example, evaporation of ocean water provides the atmosphere with surplus water that falls as precipitation. The latent heat that is taken up by the water vapor during evaporation goes into the atmosphere during condensation to fuel storms. The storms, in turn, produce winds that blow over the ocean, which causes waves and currents. The currents, in turn, may modify the weather and climate of a region by bringing in vast quantities of warm or cold water.

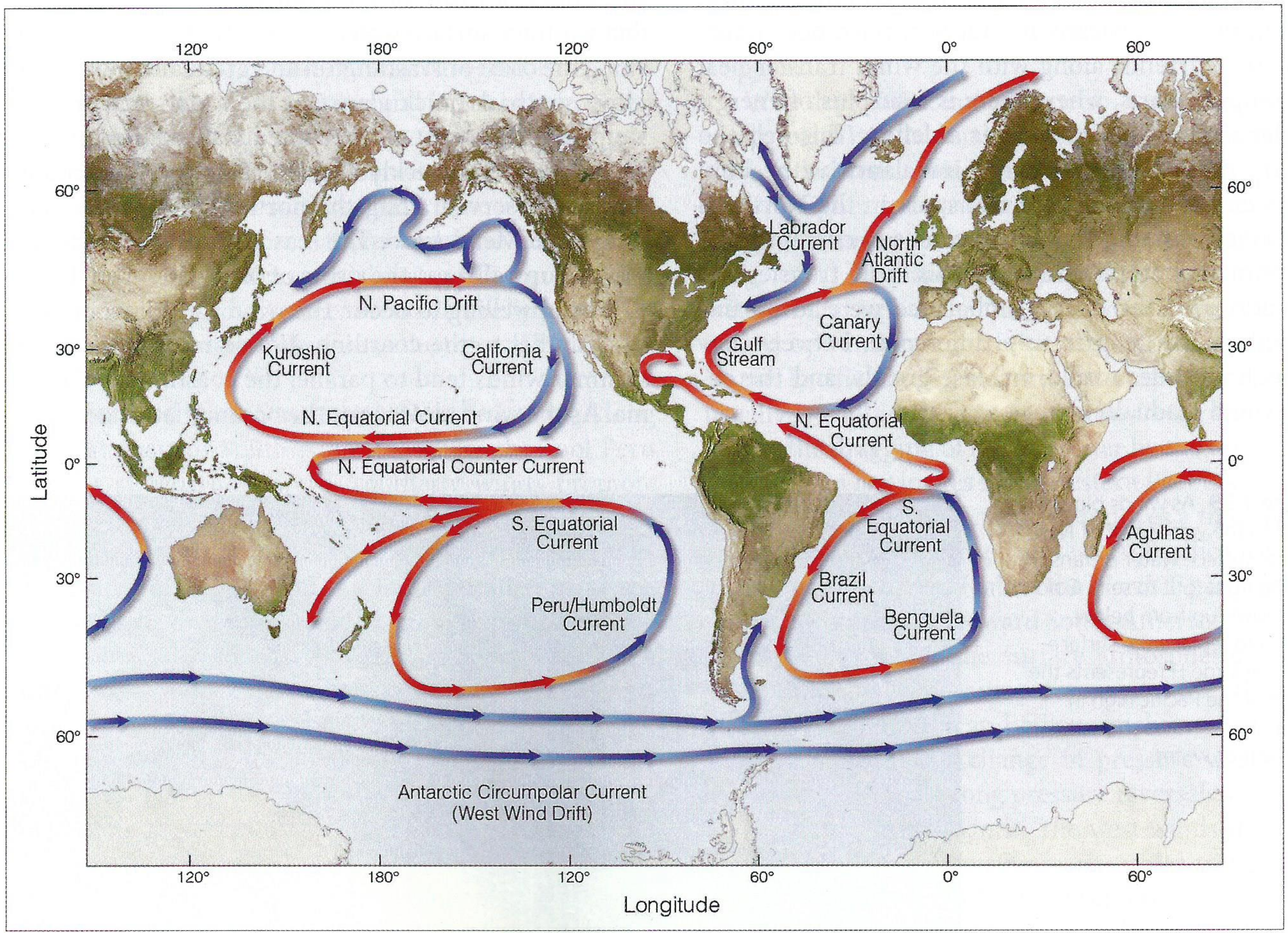
The complexity between the atmosphere and ocean makes our scientific understanding of how one influences the other on a global scale far from complete. What we will focus on in the remainder of this chapter is what we do know, beginning with ocean currents. Later, we will concentrate on some of the most important weather and climate oscillations that result from atmosphere-ocean interactions.

Global Wind Patterns and Surface Ocean Currents As the wind blows over the oceans, it causes the surface water to drift along with it. The moving water gradually piles up, creating pressure differences within the water itself. This leads to further motion several hundreds of meters down into the water. In this manner, the general wind flow around the globe starts the major surface ocean currents moving. The relationship between the general wind flow and ocean currents can be seen by comparing ● Fig. 7.36 with ● Fig. 7.37.

Because of the larger frictional drag in water, ocean currents move more slowly than the prevailing winds above. Typically, they range in speed from several kilometers per day to several kilometers per hour. However, comparing Fig. 7.36 with Fig. 7.37, we can see that ocean currents do not follow the wind pattern exactly; rather, they spiral in semi-closed circular whirls. On the eastern edge of continents there is usually a warm current that flows from the equator to the pole. For example, in the



● **Figure 7.36** Annual average global wind patterns and surface high-pressure areas over the oceans.

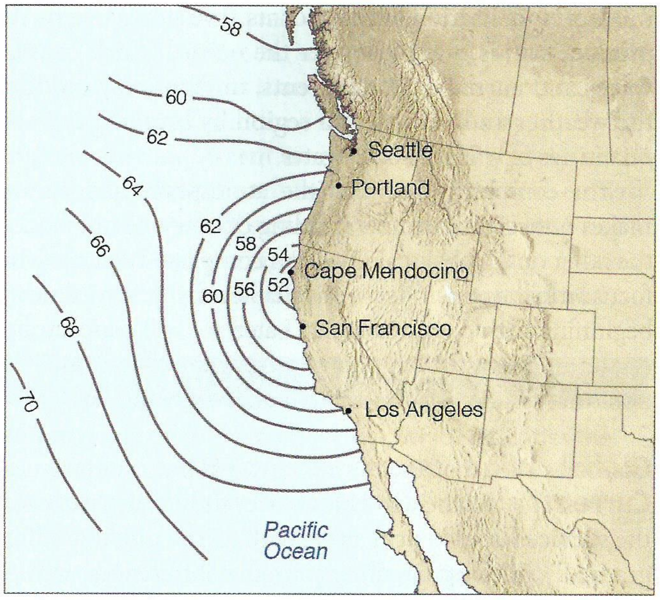


● **Figure 7.37** Average position and extent of the major surface ocean currents. Cold currents are shown in blue; warm currents are shown in red.

North Atlantic, flowing northward along the east coast of the United States, is a tremendous warm water current called the **Gulf Stream**, which carries vast quantities of tropical water into higher latitudes. Off the coast of North Carolina, the Gulf Stream provides warmth and moisture for developing mid-latitude cyclonic storms.

Notice in Fig. 7.37 that as the Gulf Stream moves northward, the prevailing westerlies steer it away from the coast of North America and eastward toward Europe. Generally, it widens and slows as it merges into the broader *North Atlantic Drift*. As this current approaches Europe, part of it flows northward along the coasts of Great Britain and Norway, bringing with it warm water (which helps keep winter temperatures much warmer than one would expect this far north). The other part flows southward as the *Canary Current*, which transports cool, northern water equatorward. In the Pacific Ocean, the counterpart to the *Canary Current* is the *California Current* that carries cool water southward along the coastline of the western United States. Hence, on the western edge of the major continents, there is usually a cool current that flows from the pole toward the equator.

Up to now, we have seen that atmospheric circulations and ocean circulations are closely linked; wind blowing over the oceans produces surface ocean currents. The currents, along with the wind, transfer heat from tropical areas, where there is a surplus of energy, to polar regions, where there is a deficit. This helps to equalize the latitudinal energy imbalance with about 40 percent of the total heat transport in the Northern Hemisphere coming from surface ocean currents. The environmental implications of this heat transfer are tremendous. If the energy imbalance were to go unchecked, yearly temperature differences between low and high latitudes would increase greatly, and the climate would gradually change.

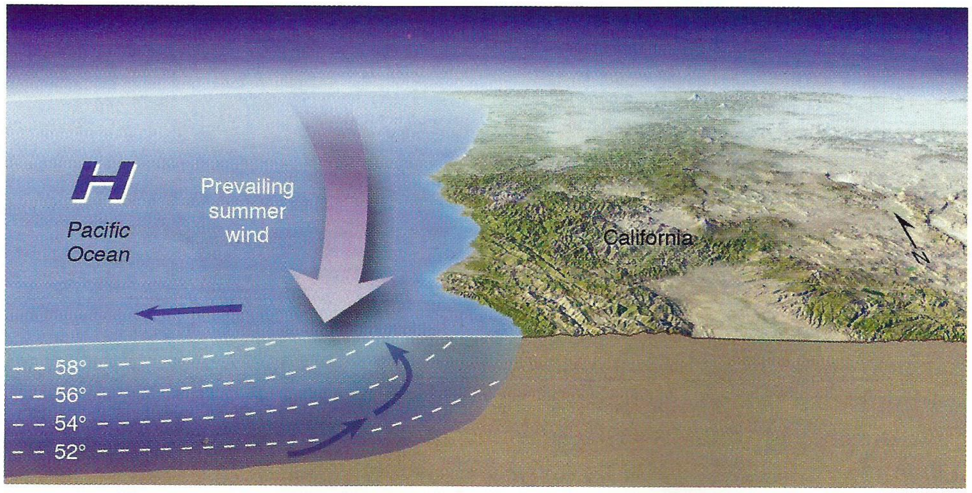


●Figure 7.38 Average sea surface temperatures (°F) along the west coast of North America during August.

Winds and Upwelling Earlier, we saw that the cool California Current flows roughly parallel to the west coast of North America. From this, we might conclude that summer surface water temperatures would be cool along the coast of Washington and gradually warm as we move south. A quick glance at the water temperatures along the west coast of the United States during August (see ● Fig. 7.38) quickly alters that notion. The coldest water is observed along the northern California coast near Cape Mendocino. The reason for the cold, coastal water is **upwelling**—the rising of cold water from below.

For upwelling to occur, the wind must flow more or less parallel to the coastline. Notice in ● Fig. 7.39 that summer winds tend to parallel the coastline of California. As the wind blows over the ocean, the surface water

●Figure 7.39 As winds blow parallel to the west coast of North America, surface water is transported to the right (out to sea). Cold water moves up from below (upwells) to replace the surface water. The large H represents the position of the Pacific high in summer. Blue arrows show the movement of water.



beneath it is set in motion. As the surface water moves, it bends slightly to its right due to the Coriolis effect. (Remember, it would bend to the left in the Southern Hemisphere.) The water beneath the surface also moves, and it too bends slightly to its right. The net effect of this phenomenon is that a rather shallow layer of surface water moves at right angles to the surface wind and heads seaward. As the surface water drifts away from the coast, cold, nutrient-rich water from below rises (upwells) to replace it. Upwelling is strongest and surface water is coolest where the wind parallels the coast, such as it does in summer along the coast of northern California.

Because of the cold coastal water, summertime weather along the West Coast often consists of low clouds and fog, as the air over the water is chilled to its saturation point. On the brighter side, upwelling produces good fishing, as higher concentrations of nutrients are brought to the surface. But swimming is only for the hardiest of souls, as the average surface water temperature along the coast of northern California in summer is nearly 10°C (18°F) colder than the average coastal water temperature found at the same latitude along the Atlantic coast.

Between the ocean surface and the atmosphere, there is an exchange of heat and moisture that depends, in part, on temperature differences between water and air. In winter, when air-water temperature contrasts are greatest, there is a substantial transfer of sensible and latent heat from the ocean surface into the atmosphere. This energy helps to maintain the global air flow. Consequently, even a relatively small change in surface ocean temperatures could modify atmospheric circulations and have far-reaching effects on global weather and climate patterns. The next section describes how weather events can be linked to surface ocean temperature changes in the tropical Pacific.

El Niño and the Southern Oscillation

Along the west coast of South America, where the cool Peru Current sweeps northward, southerly winds promote upwelling of cold, nutrient-rich water that gives rise to large fish populations, especially anchovies. The abundance of fish supports a large population of sea birds whose droppings (called *guano*) produce huge phosphate-rich deposits, a valuable source of fertilizer. Every two to five years or so, a warm current of nutrient-poor tropical water moves southward, replacing the cold, nutrient-rich surface water. Because this condition frequently occurs around Christmas, local fishermen (more than a century ago) called this warm current *Corrieste del Niño,* which translated means current of the Christ Child. Hence, the warm current's name—*El Niño.*

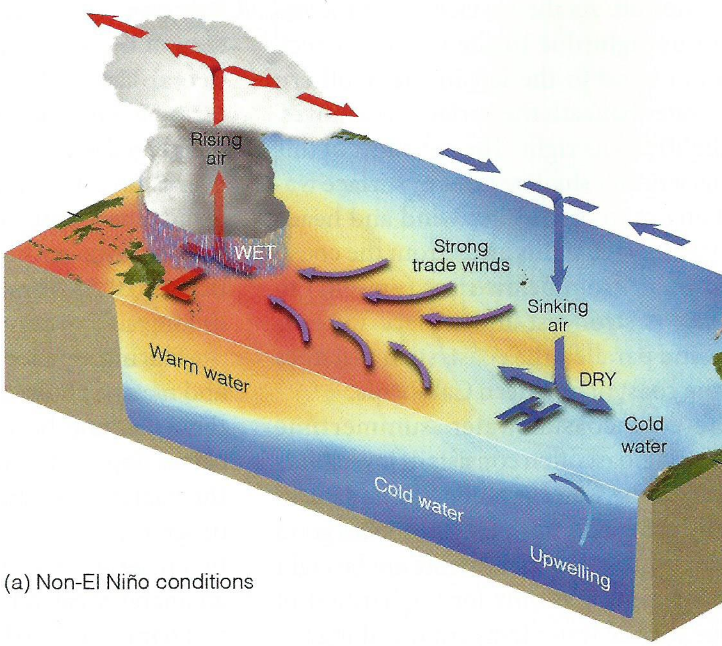
It was once thought that El Niño was a local event that occurred only along the west coast of Peru and Ecuador. It is now known that the ocean-warming can cover an area of the tropical Pacific much larger than the continental United States. Although in recent decades the term **El Niño** has gained global prominence, the large, prolonged warming that develops at irregular intervals every three to seven years is often referred to as a *major El Niño event.* During these events, the surface water temperature across much of the tropical Pacific rises by 0.5°C (0.9°F) or more for periods lasting a few months or longer.

During a major El Niño event, large numbers of fish and marine plants may die. Dead fish and birds may litter the water and beaches of Peru; their decomposing carcasses deplete the water's oxygen supply, which leads to the bacterial production of huge amounts of smelly hydrogen sulfide. The El Niño of 1972–1973 was one of the first to be studied in depth. It reduced the annual Peruvian anchovy catch from 10.3 million metric tons in 1971 to 4.6 million metric tons in 1972. Since much of the harvest of this fish is converted into fish meal and exported for use in feeding livestock and poultry, the world's fish meal production in 1972 was greatly reduced. Countries such as the United States that rely on fish meal for animal feed had to use soybeans as an alternative. This raised poultry prices in the United States by more than 40 percent.

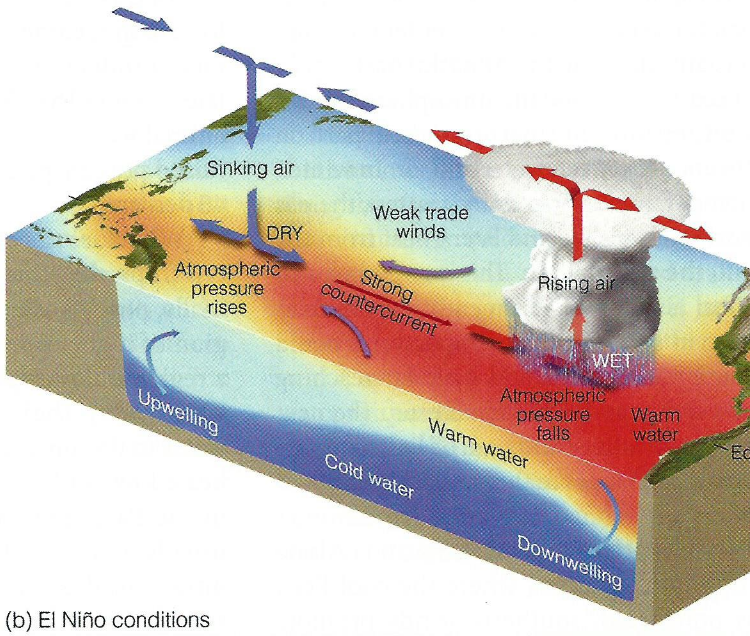
Why does the ocean become so warm over the eastern tropical Pacific during a major El Niño event? Normally, persistent trade winds blow westward from a region of higher pressure over the eastern Pacific toward a region of lower pressure centered near Indonesia (see ● Fig. 7.40a). The trades create upwelling that brings cold water to the surface. As this water moves westward, it is heated by sunlight and the atmosphere. Consequently, in the Pacific Ocean, surface water along the equator usually is cool in the east and warm in the west. In addition, the dragging of surface water by the trades raises sea level by a few inches in the western Pacific and lowers it in the eastern Pacific, which produces a thick layer of warm water over the tropical western Pacific Ocean and a weak ocean current (called the *North Equatorial*) that flows slowly eastward toward South America.

Every few years, the surface atmospheric pressure patterns break down, as air pressure rises over the region of the western Pacific and falls over the eastern Pacific (see Fig. 7.40b). This change in pressure weakens the trades, and, during strong pressure reversals, east winds are replaced by west winds. The west winds strengthen the countercurrent, causing warm water to head eastward toward South America over broad areas of the tropical Pacific. Toward the end of the warming period, which may last between one and two years, atmospheric

Figure 7.40 In diagram (a), under non-El Niño conditions higher pressure over the southeastern Pacific and lower pressure near Indonesia produce easterly trade winds along the equator. These winds promote upwelling and cooler ocean water in the eastern Pacific, while warmer water prevails in the western Pacific. The trades are part of a circulation that typically finds rising air and heavy rain over the western Pacific and sinking air and generally dry weather over the eastern Pacific. When the trades are exceptionally strong, water along the equator in the eastern Pacific becomes quite cool. This cool event is called La Niña. During El Niño conditions—diagram (b)—atmospheric pressure decreases over the eastern Pacific and rises over the western Pacific. This change in pressure causes the trades to weaken or reverse direction. This situation enhances the countercurrent that carries warm water from the west over a vast region of the eastern tropical Pacific.



(a) Non-El Niño conditions



(b) El Niño conditions

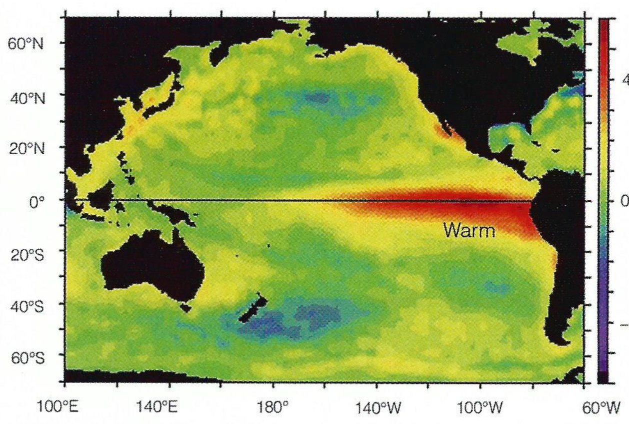
pressure over the eastern Pacific reverses and begins to rise, whereas, over the western Pacific, it falls. This seesaw pattern of reversing surface air pressure at opposite ends of the Pacific Ocean is called the **Southern Oscillation.** Because the pressure reversals and ocean warming are more or less simultaneous, scientists call this phenomenon the *El Niño/Southern Oscillation* or **ENSO** for short. Although most ENSO episodes follow a similar evolution, each event has its own personality, differing in both strength and behavior.

During especially strong ENSO events (such as in 1982–1983 and 1997–1998) the easterly trades may actually become westerly winds, as illustrated in Fig. 7.40b. As these winds push eastward, they drag surface water with them. This dragging raises sea level in the eastern Pacific and lowers sea level in the western Pacific. The eastward-moving water gradually warms under the tropical sun, becoming as much as 6°C (11°F) warmer than normal in the eastern equatorial Pacific. Gradually, a thick layer of warm water pushes into coastal areas of Ecuador and Peru, choking off the upwelling that supplies cold, nutrient-rich water to South America's coastal region. The unusually warm water may extend from South America's coastal region for many thousands of kilometers westward along the equator (see ● Fig. 7.41).

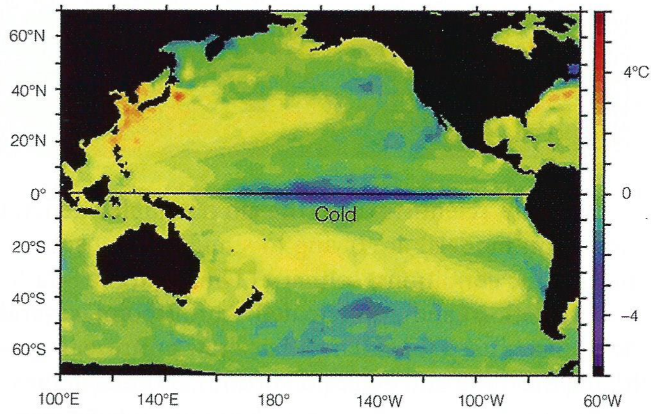
Such a large area of abnormally warm water can have a substantial effect on global wind patterns. The warm tropical water fuels the atmosphere with additional warmth and moisture, which the atmosphere turns into additional storminess and rainfall. The presence of so much warm, rising air above the eastern tropical Pacific appears to help lead to drying, sinking air in other regions. The resulting chain of events can leave some parts of the world experiencing too much rainfall, whereas others have too little. Over the warm tropical central Pacific, the frequency of typhoons usually increases. However, over the tropical Atlantic, between Africa and Central America, the winds aloft tend to disrupt the organization of thunderstorms that is necessary for hurricane development; hence, there are fewer hurricanes in this region during strong El Niño events. And, as we saw earlier in this chapter, during a strong El Niño, summer monsoon conditions tend to weaken over India, although this weakening did not happen during the strong El Niño of 1997.

Although the actual mechanism by which changes in surface ocean temperatures influence global wind patterns is not fully understood, the by-products are plain to see. For example, during exceptionally warm El Niños, drought is normally felt in Indonesia, southern Africa, and Australia, while heavy rains and flooding often occur in Ecuador and Peru. In the Northern Hemisphere, a strong subtropical westerly jet stream normally directs mid-latitude cyclonic storms into California and heavy rain into the Gulf Coast states. The total damage worldwide due to flooding, winds, and drought may exceed many billions of dollars. A major El Niño event can also pump so much heat into the atmosphere that global temperatures rise by several tenths of a degree Fahrenheit for a few months.

Following an ENSO event, the trade winds usually return to normal. However, if the trades are exceptionally strong, unusually cold surface water moves over the central and eastern Pacific, as shown in Fig. 7.41b. Warm water and rainy weather is confined mainly to the western tropical Pacific. This cold-water episode has been termed **La Niña** (the girl child). La Niña, however, is not the exact opposite of El Niño, but in some parts of the world, the two phenomena produce highly contrasting effects. In the Pacific Northwest, for example, La Niña winters tend to be wetter than usual, while drought is more likely during El Niño. The storm track across the central and eastern United States is often intensified during La Niña, which can lead to especially strong outbreaks of severe thunderstorms and tornadoes.



(a) El Niño Conditions, December 1997

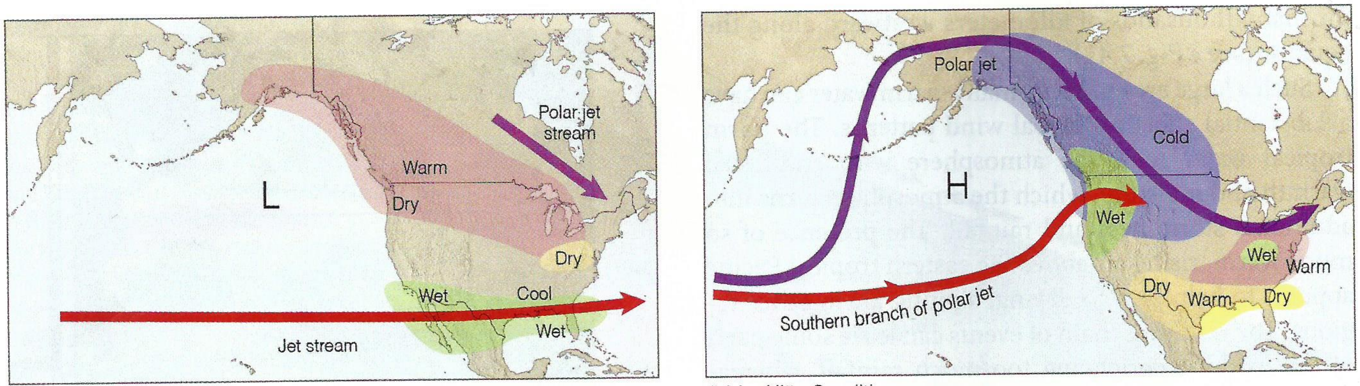


(b) La Niña Conditions, December 1998

●Figure 7.41 (a) Average sea surface temperature departures from normal as measured by satellite. During El Niño conditions, upwelling is greatly diminished and warmer than normal water (deep red color) extends from the coast of South America westward, across the Pacific. (b) During La Niña conditions, strong trade winds promote upwelling, and cooler than normal water (dark blue color) extends over the eastern and central Pacific. (NOAA/PHEL/TAO)

As we have seen, El Niño and the Southern Oscillation are part of a large-scale ocean-atmosphere interaction that can take several years to run its course. During this time, there are certain regions in the world where significant climatic responses to an ENSO event are likely. ● Figure 7.42 shows how typical winter weather patterns over North America will change between El Niño conditions and La Niña conditions. Such ocean-atmosphere interactions, where a warmer or colder ocean surface can influence weather patterns in distant parts of the world, are called **teleconnections.**

Some scientists feel that the trigger necessary to start an ENSO event lies within the changing of the seasons, especially the transition periods of spring and fall. Others feel that the winter monsoon plays a major role in triggering a major El Niño event. As noted earlier, it appears that an ENSO episode and the monsoon system are intricately linked, so that a change in one brings about a change in the other.



(a) El Niño Conditions

(b) La Niña Conditions

●Figure 7.42 Typical winter weather patterns across North America during an El Niño warm event (a) and during a La Niña cold event (b). During El Niño conditions, a persistent trough of low pressure forms over the north Pacific and, to the south of the low, the jet stream (from off the Pacific) steers wet weather and cyclonic storms into California and the southern part of the United States. During La Niña conditions, a persistent high-pressure area forms south of Alaska forcing the polar jet stream and accompanying cold air over much of western North America. The southern branch of the polar jet stream directs moist air from the ocean into the Pacific Northwest, producing a wet winter for that region.

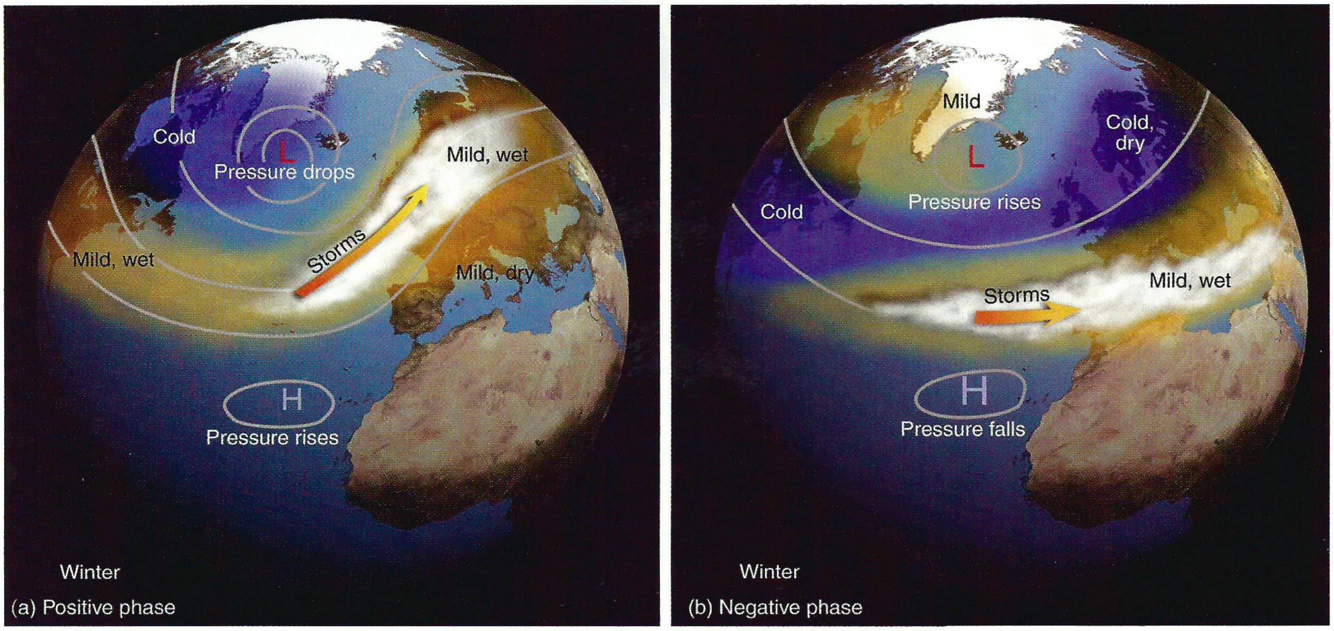
Presently, scientists (with the aid of coupled general circulation models) are trying to simulate atmospheric and oceanic conditions, so that El Niño and the Southern Oscillation can be anticipated. At this point, several models have been formulated that show promise in predicting the onset and evolution of an ENSO event a season or more in advance. If an El Niño or La Niña event is developing in the Northern Hemisphere's autumn, forecasters can now provide several months notice of the type of conditions that are more likely to occur in the winter, when the events usually reach their full strength. In addition, in-depth studies of the tropical Pacific Ocean are providing scientists with valuable information about the interactions that occur between the ocean and the atmosphere. The primary aim of these ocean studies is to provide enough scientific information so that researchers can better predict climatic fluctuations (such as ENSO) that occur over periods of months and years. The hope is that a better understanding of El Niño and the Southern Oscillation will provide improved long-range forecasts of weather and climate.

Up to this point, we have looked at El Niño and the Southern Oscillation, as well as how the reversal of surface ocean temperatures and atmospheric pressure combine to influence regional and global weather and climate patterns. There are other atmosphere-ocean interactions that can have an effect on large-scale weather patterns. Some of these are described in the following section.

Other Atmosphere-Ocean Interactions Is there a similar pattern in the Atlantic that compares to the Southern Oscillation in the Pacific? Over the Atlantic there is a reversal of pressure (called the **North Atlantic Oscillation,** or **NAO**) that has an effect on the weather in Europe and along the east coast of North America. For example, in winter if the atmospheric pressure in the vicinity of the Icelandic low drops, and the pressure in the region of the Bermuda-Azores high rises, there is a corresponding large difference in atmospheric pressure between these two regions that strengthens the westerlies. The strong westerlies in turn direct strong cyclonic storms on a more northerly track into northern Europe, where winters tend to be wet and mild. During this *positive (warm) phase* of the NAO, winters in the eastern United States tend to be wet and relatively mild, while northern Canada and Greenland are usually cold and dry (see ● Fig. 7.43a).

The *negative (cool) phase* of the NAO occurs when the atmospheric pressure in the vicinity of the Icelandic low rises, while the pressure drops in the region of the Bermuda high (see Fig. 7.43b). This pressure change results in a reduced pressure gradient and weaker westerlies that steer fewer and weaker winter storms across the Atlantic in a more westerly path. Because of the reduced pressure gradient and weaker westerlies, the jet stream may evolve in an erratic fashion, which can allow major winter cyclonic storms and outbreaks of bitterly cold air to reach eastern North America and northern Europe. Meanwhile, storms bring wet weather to southern Europe and to the region around the Mediterranean Sea. Winters in northern Europe are usually cold and dry, as are the winters along the east coast of North America. Greenland and northern Canada usually experience mild winters.

Closely related to the North Atlantic Oscillation is the **Arctic Oscillation (AO),** where changes in



●**Figure 7.43** Change in surface atmospheric pressure and typical winter weather patterns associated with the (a) positive phase and (b) negative phase of the North Atlantic Oscillation.

atmospheric pressure between the Arctic and regions to the south cause changes in the upper-level westerly winds. During the *positive (warm) phase* of the *AO,* strong pressure differences produce strong westerly winds aloft that prevent cold arctic air from invading the United States, and so winters in this region tend to be warmer than normal. With cold arctic air in place to the north, winters over Newfoundland and Greenland tend to be very cold. Meanwhile, strong winds over the Atlantic direct storms into northern Europe, bringing with them wet, mild weather.

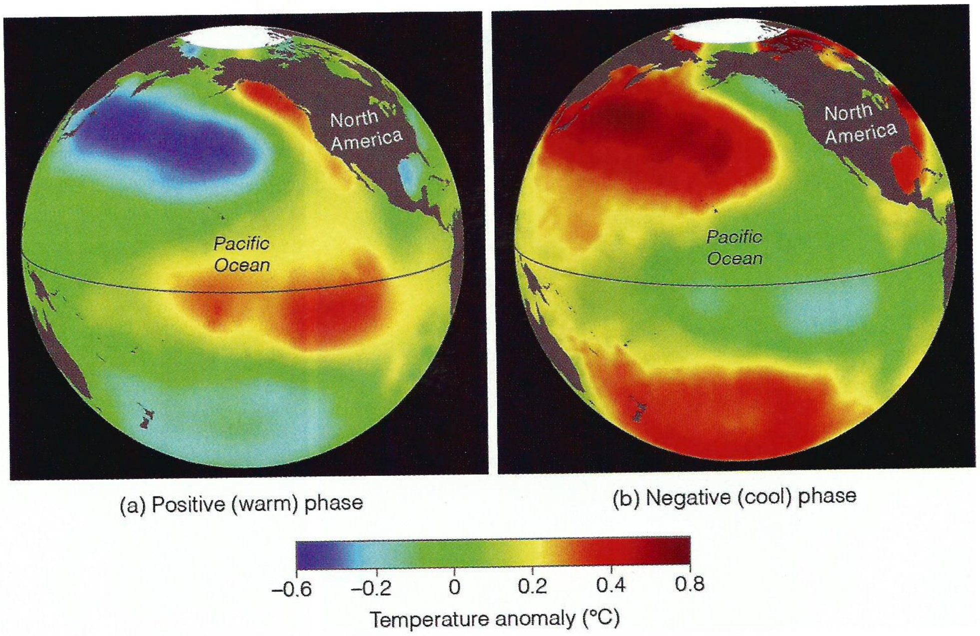
During the *negative (cold) phase* of the *AO,* small pressure differences between the Arctic and regions to the south produce weaker westerly winds aloft. Cold arctic air is now able to penetrate farther south, producing colder than normal winters over much of the United States. Cold air also invades northern Europe and Asia, while Newfoundland and Greenland normally experience warmer than normal winters.

So, when Greenland has mild winters, northern Europe has cold winters and vice versa. This seesaw in winter temperatures between Greenland and northern Europe has been known for many years. What was not known until recently is that, during the warm Arctic Oscillation phase, relatively warm, salty water from the Atlantic is able to move into the Arctic Ocean, where it melts sea ice, sometimes causing it to thin by more than 40 centimeters. During the cold phase, surface winds tend to keep warmer Atlantic water to the south, which promotes thicker sea ice. Although the Arctic Oscillation switches from one phase to another on an irregular basis, one phase may predominate for several years in a row, bringing with it a succession of either cold or mild winters.

Over the Pacific Ocean, changes in surface ocean temperatures appear to influence winter weather along the west coast of North America. In the mid 1990s, scientists at the University of Washington, while researching connections between Alaskan salmon production and Pacific climate, identified a long-term Pacific Ocean temperature fluctuation, which they called the **Pacific Decadal Oscillation (PDO)** because the ocean surface temperature reverses every 20 to 30 years. The Pacific Decadal Oscillation is like ENSO in that it has a warm phase and a cool phase, but its temperature behavior is much different from that of El Niño in the tropical Pacific.

During the *positive (warm) phase,* unusually warm surface water exists along the west coast of North America, while over the central North Pacific, cooler than normal surface water prevails (see ● Fig. 7.44a). At the same time, the Aleutian low in the Gulf of Alaska strengthens, which causes more Pacific storms to move into Alaska and California. This situation causes winters, as a whole, to be warmer and drier over northwestern North America. Elsewhere, winters tend to be drier over the Great Lakes, and cooler and wetter in the southern United States.

The present *negative (cool) phase* of the PDO has cooler-than-average surface water along the west coast



(a) Positive (warm) phase

(b) Negative (cool) phase

Figure 7.44 Typical winter sea surface temperature departure from normal in °C during the Pacific Decadal Oscillation's warm phase (a) and cool phase (b). (Source: JISAO, University of Washington, http://jisao.washington.edu/pdo.)

of North America and an area of warmer-than-normal surface water extending from Japan into the central North Pacific (see Fig. 7.44b). Winters in the cool phase tend to be cooler and wetter than average over northwestern North America, wetter over the Great Lakes, and warmer and drier in the southern United States.

The climate patterns described so far only represent average conditions, as individual years within either phase may vary considerably. Hopefully, as our understanding of the interactions between the ocean and atmosphere improves, climate forecasts across North America and elsewhere will improve as well.

SUMMARY

In this chapter, we examined a variety of atmospheric circulations. We looked at small-scale winds and found that eddies can form in a region of strong wind shear, especially in the vicinity of a jet stream. On a slightly larger scale, land and sea breezes blow in response to local pressure differences created by the uneven heating and cooling rates of land and water. Monsoon winds change direction seasonally, while mountain and valley winds change direction daily.

A warm, dry wind that descends the eastern side of the Rocky Mountains is the chinook. The same type of wind in the Alps is the foehn. A warm, dry downslope wind that blows into southern California is the Santa Ana wind. Local intense heating of the surface can produce small rotating winds, such as the dust devil, while downdrafts in a thunderstorm are responsible for the desert haboob.

The largest pattern of winds that persists around the globe is called the general circulation. At the surface in both hemispheres, winds tend to blow from the east in the tropics, from the west in the middle latitudes, and from the east in polar regions. Where upper-level westerly winds tend to concentrate into narrow bands, we find jet streams. The annual shifting of the major pressure systems and wind belts—northward in July and southward in January—strongly influences the annual precipitation of many regions.

Toward the end of the chapter we examined the interaction between the atmosphere and oceans. Here we found the interaction to be an ongoing process where everything, in one way or another, seems to influence everything else. On a large scale, winds blowing over the surface of the water drive the major ocean currents; the oceans, in turn, release energy to the atmosphere, which helps to maintain the general circulation of winds.

When atmospheric circulation patterns change over the tropical Pacific, and the trade winds weaken or reverse direction, warm tropical water is able to flow eastward toward South America where it chokes off upwelling. When the warm water extends over a vast area of the tropical Pacific, and persists for several months to a year or more, the warming is called a major El Niño event, and the associated reversal of pressure over the Pacific Ocean is called the Southern Oscillation. The large-scale interaction between the atmosphere and the ocean during El Niño and the Southern Oscillation (ENSO) affects global atmospheric circulation patterns resulting in too much rain in some areas and not enough in others.

Over the Atlantic Ocean there is a periodic reversal of air pressure called the North Atlantic Oscillation that influences weather in various regions of the world. Atmospheric pressure changes over the Arctic produce a related phenomenon, the Arctic Oscillation which causes winter weather patterns to change across the United States, Greenland, and Europe. Over the northern central Pacific and along the west coast of North America the surface water temperature reverses every 20 to 30 years, a phenomenon called the Pacific Decadal Oscillation (PDO). Studies now in progress are designed to determine how the interchange between atmosphere and ocean can produce such events.

KEY TERMS

The following terms are listed (with page numbers) in the order they appear in the text. Define each. Doing so will aid you in reviewing the material covered in this chapter.

scales of motion, 186
microscale, 186
mesoscale, 186
macroscale, 186
rotor, 187
wind shear, 188
clear air turbulence (CAT), 188
thermal circulation, 188
sea breeze, 190
land breeze, 190
valley breeze, 192
mountain breeze, 192
katabatic wind, 192
chinook wind, 193
Santa Ana wind, 195
haboob, 197
dust devils (whirlwinds), 197
monsoon, 199
monsoon wind system, 199
general circulation of the atmosphere, 201
Hadley cell, 201
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teleconnections, 215
North Atlantic Oscillation (NAO), 216
Arctic Oscillation (AO), 216
Pacific Decadal Oscillation (PDO), 217

QUESTIONS FOR REVIEW

1. Describe the various scales of motion and give an example of each.
2. What is wind shear and how does it relate to clear air turbulence?
3. Using a diagram, explain how a thermal circulation develops.
4. Why does a sea breeze at the surface blow from sea to land and a land breeze from land to sea?
5. Which wind will produce clouds: a valley breeze or a mountain breeze? Why?
6. What are katabatic winds? How do they form?
7. Explain why chinook winds are warm and dry.
8. (a) What is the primary source of warmth for a Santa Ana wind?
   (b) What atmospheric conditions contribute to the development of a strong Santa Ana wind?
9. Describe how dust devils usually form.
10. (a) Briefly explain how the monsoon wind system develops over eastern and southern Asia.
    (b) Why in India is the summer monsoon wet and the winter monsoon dry?
11. Draw a large circle. Now, place the major surface semipermanent pressure systems and the wind belts of the world at their appropriate latitudes.
12. According to Fig. 7.25 (p. 203), most of the United States is located in what wind belt?
13. Explain how and why the average surface pressure features shift from summer to winter.
14. Explain why summers along the West Coast of the United States tend to be dry, whereas along the East Coast summers tend to be wet.
15. How does the polar front influence the development of the polar front jet stream?
16. Why is the polar jet stream more strongly developed in winter?
17. Explain the relationship between the general circulation of air and the circulation of surface ocean currents.
18. Describe how the winds along the west coast of North America produce upwelling.
19. (a) What is a major El Niño event?
    (b) What happens to the surface pressure at opposite ends of the Pacific Ocean during the Southern Oscillation?
    (c) Describe how an ENSO event may influence the weather in different parts of the world.
20. What are the conditions over the tropical eastern and central Pacific Ocean during the phenomenon known as La Niña?
21. How does the positive (warm) phase of the Northern Atlantic Oscillation differ from the negative (cold) phase?
22. During the negative (cold) phase of the Arctic Oscillation when Greenland is experiencing mild winters, what type of winters (cold or mild) is Northern Europe usually experiencing?
23. Describe the ocean surface temperatures associated with the Pacific Decadal Oscillation.

QUESTIONS FOR THOUGHT AND EXPLORATION

1. Suppose you are fishing in a mountain stream during the early morning. Is the wind more likely to be blowing upstream or downstream? Explain why.
2. Why, in Antarctica, are winds on the high plateaus usually lighter than winds in steep, coastal valleys?
3. What atmospheric conditions must change so that the westerly flowing polar front jet stream reverses direction and becomes an easterly flowing jet stream?
4. After a winter snowstorm, Cheyenne, Wyoming, reports a total snow accumulation of 48 cm (19 in.), while the maximum depth in the surrounding countryside is only 28 cm (11 in.). If the storm's intensity and duration were practically the same for

CHAPTER 10

Thunderstorms and Tornadoes

Contents

Wednesday, March 18, 1925, was a day that began uneventfully, but within hours it had turned into a day that changed the lives of thousands of people and made meteorological history. Shortly after 1:00 P.M., the sky turned a dark greenish-black and the wind began whipping around the small town of Murphysboro, Illinois. Arthur and Ella Flatt lived on the outskirts of town with their only son, Art, who would be four years old in two weeks. Arthur was working in the garage when he heard the roar of the wind and saw the threatening dark clouds whirling overhead.

Instantly concerned for the safety of his family, he ran toward the house as the tornado began its deadly pass over the area. With debris from the house flying in his path and the deafening sound of destruction all around him, Arthur reached the front door. As he struggled in vain to get to his family, whose screams he could hear inside, the porch and its massive support pillars caved in on him. Inside the house, Ella had scooped up young Art in her arms and was making a panicked dash down the front hallway towards the door when the walls collapsed, knocking her to the floor, with Art cradled beneath her. Within seconds, the rest of the house fell down upon them. Both Arthur and Ella were killed instantly, but Art was spared, nestled safely under his mother's body.

As the dead and survivors were pulled from the devastation that remained, the death toll mounted. Few families escaped the grief of lost loved ones. The infamous Tri-State Tornado killed 234 people in Murphysboro and leveled 40 percent of the town.

The devastating tornado described in our opening cut a mile-wide path for a distance of more than 200 miles through the states of Missouri, Illinois, and Indiana. The tornado totally obliterated 4 towns, killed an estimated 695 persons, and left over 2000 injured. Tornadoes such as these, as well as much smaller ones, are associated with severe thunderstorms. Consequently, we will first examine the different types of thunderstorms. Later, we will focus on tornadoes, examining how and where they form, and why they are so destructive.

Thunderstorms

It probably comes as no surprise that a *thunderstorm* is merely a storm containing lightning and thunder. Sometimes a thunderstorm produces gusty surface winds with heavy rain and hail. The storm itself may be a single cumulonimbus cloud, or several thunderstorms may form into a cluster. In some cases, a line of thunderstorms will form that may extend for hundreds of miles.

Thunderstorms are *convective storms* that form with rising air. So the birth of a thunderstorm often begins when warm, moist air rises in a conditionally unstable environment.* The rising air may be a parcel of air ranging in size from a large balloon to a city block, or an entire layer, or slab of air, may be lifted. As long as the rising air is warmer (less dense) than the air surrounding it, there is an upward-directed *buoyant force* acting on it. The warmer the parcel compared to its surroundings, the greater the buoyant force and the stronger the convection. The trigger (or "forcing mechanism") needed to start air moving upward may be:

1. random, turbulent eddies that lift small bubbles of air
2. unequal heating at the surface
3. the effect of terrain (such as small hills) or the lifting of air along shallow boundaries of converging surface winds
4. diverging upper-level winds, coupled with converging surface winds and rising air
5. large-scale uplift along mountain barriers or gently rising terrain
6. warm air rising along a frontal zone

Usually, several of these mechanisms work together with vertical wind shear to generate severe thunderstorms.

Although we often see thunderstorms forming where the surface air is quite warm and humid, they may also form when the surface air temperature is no more than 10°C (50°F). This latter situation often occurs in winter along the west coast of North America, when cold air aloft moves over the region. The cold air aloft destabilizes the atmosphere to the point where air parcels, given an initial push upwards, are able to continue their upward journey because they remain warmer (less dense) than the colder air surrounding them. The cold air aloft may even cause sufficient instability to generate thunderstorms in wintertime snowstorms, producing *thundersnow*.

Most thunderstorms that form over North America are short-lived, producing rain showers, gusty surface winds, thunder and lightning, and sometimes small hail. Many have an appearance similar to the mature thunderstorm shown in ●Fig. 10.1. The majority of these storms do not reach severe status. *Severe thunderstorms* are defined by the National Weather Service as storms that produce at least one of the following: large hail with a diameter of at least one inch, surface wind gusts of at least 50 knots (58 mi/hr), or a tornado.

Scattered thunderstorms (sometimes called "pop-up" storms) that typically form on warm, humid days are


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●Figure 10.1 An ordinary thunderstorm in its mature stage. Note the distinctive anvil top.

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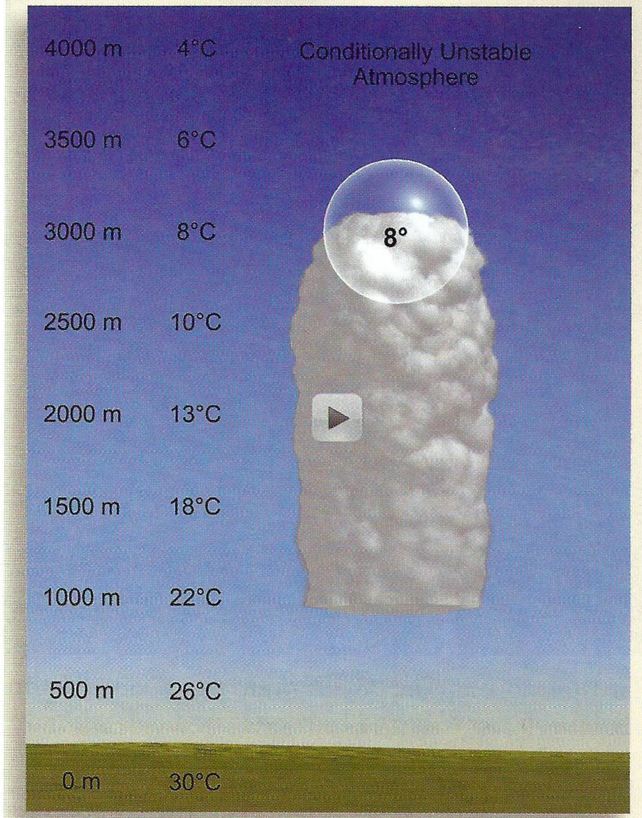
*As described in Chapter 5, a conditionally unstable atmosphere exists when cold, dry air aloft overlies warm, moist surface air. Additional information on atmospheric instability is given in Chapter 5, beginning on p. 128.

CONCEPT ANIMATION



To refresh your memory about instability and cumulus cloud development go to Meteorological CourseMate website at www.cengagebrain.com and view the animations entitled *Unstable Atmosphere* and *Conditionally Unstable Atmosphere.*

often referred to as *ordinary cell thunderstorms** or *air-mass thunderstorms* because they tend to form in warm, humid air masses away from significant weather fronts. These can be considered "simple storms" because they rarely become severe, typically are less than a kilometer wide, and they go through a rather predictable life cycle from birth to maturity to decay that usually takes less than an hour to complete. However, under the right atmospheric conditions (described later in this chapter), more intense "complex thunderstorms" may form, such as the *multicell thunderstorm* and the *supercell thunderstorm*—an intense rotating storm that can last for hours and produce severe weather such as strong surface winds, large damaging hail, flash floods, and violent tornadoes.

We will examine the development of ordinary cell (air mass) thunderstorms first, before we turn our attention to the more complex multicell and supercell storms.

Ordinary Cell Thunderstorms **Ordinary cell (air mass) thunderstorms** or, simply, *ordinary thunderstorms,* tend to form in a region where there is limited vertical wind shear—that is, where the wind speed and/or wind direction do not abruptly change with increasing height above the surface.* Many ordinary thunderstorms appear to form as parcels of air are lifted from the surface by turbulent overturning in the presence of wind. Moreover, ordinary storms often form along shallow zones where surface winds converge. Such zones may be due to any number of things, such as topographic irregularities, sea-breeze fronts, or the cold outflow of air from inside a thunderstorm that reaches the ground and spreads horizontally. These converging wind boundaries are normally zones of contrasting air temperature and humidity and, hence, air density.

Extensive studies indicate that ordinary thunderstorms go through a cycle of development from birth to maturity to decay. The first stage is known as the **cumulus stage,** or *growth stage.* As a parcel of warm, humid air rises, it cools and condenses into a single cumulus cloud or a cluster of clouds (see ● Fig. 10.2a). If you have ever watched a thunderstorm develop, you may have noticed that at first the cumulus cloud grows upward only a short distance before the top of the cloud dissipates. This phenomenon occurs because the cloud droplets evaporate as the drier air surrounding the cloud mixes with it. However, after the water drops evaporate, the air is more moist than before. So, the rising air is now able to condense at successively higher levels, and the cumulus cloud grows taller, often appearing as a rising dome or tower.

As the cloud builds, the transformation of water vapor into liquid or solid cloud particles releases large quantities of latent heat, a process that keeps the rising air inside the cloud warmer (less dense) than the air surrounding it. The cloud continues to grow in the unstable atmosphere as long as it is constantly fed by rising air from below. In this manner, a cumulus cloud may show extensive vertical development and grow into a towering cumulus cloud (cumulus congestus) in just a few minutes. During the cumulus stage, there normally is insufficient time for precipitation to form, and the updrafts keep water droplets and ice crystals suspended within the cloud. Also, there is no lightning or thunder during this stage.

As the cloud builds well above the freezing level, the cloud particles grow larger and heavier as they collide and join with one another. Eventually, the rising air is no longer able to keep them suspended, and they begin to fall.

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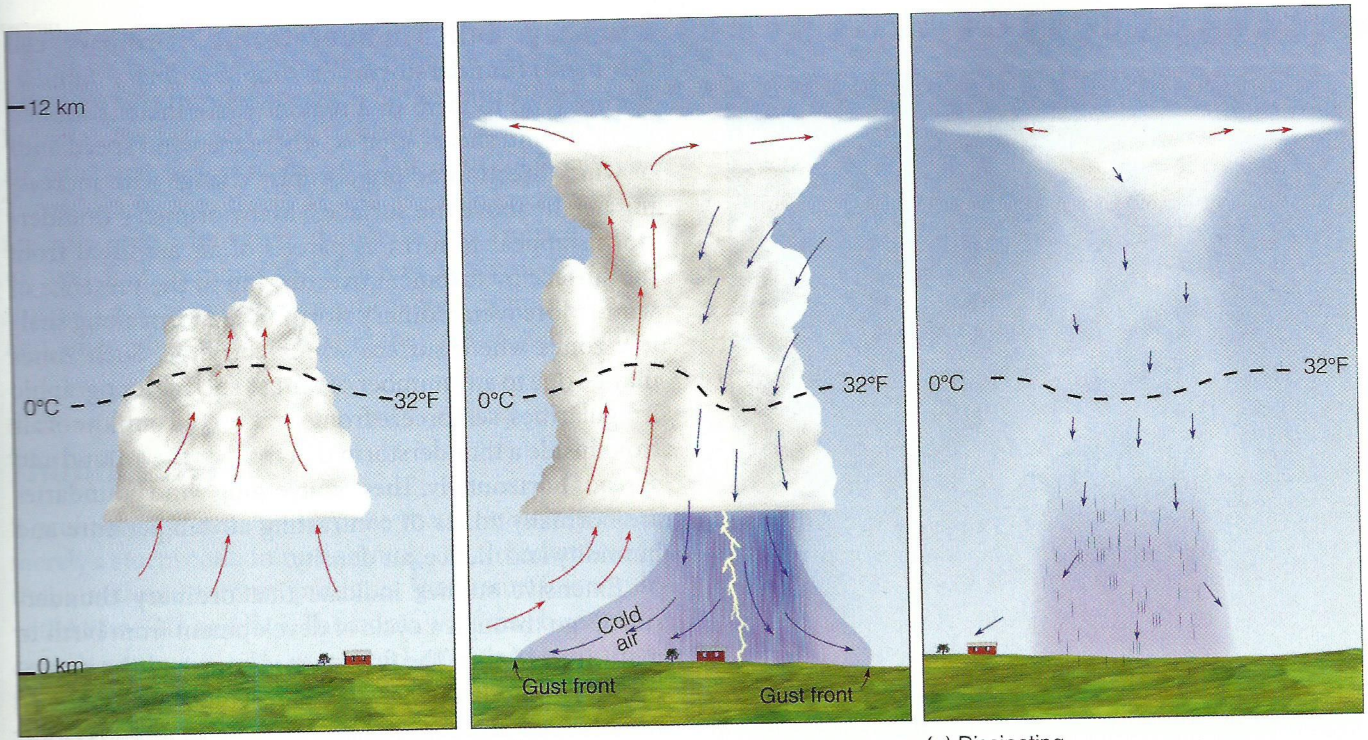
*In convection, the cell may be a single updraft or a single downdraft, or a combination of the two.

*As we will see later in this chapter, vertical wind shear is different from the horizontal wind shear (the changing of wind direction and/or speed in the horizontal) that pilots are concerned about.



(a) Cumulus (b) Mature (c) Dissipating

Figure 10.2 Simplified model depicting the life cycle of an ordinary thunderstorm that is nearly stationary. (Arrows show vertical air currents. Dashed line represents freezing level, 0°C isotherm.)

While this phenomenon is taking place, drier air from around the cloud is being drawn into it in a process called *entrainment.* The entrainment of drier air causes some of the raindrops to evaporate, which chills the air. The air, now colder and heavier than the air around it, begins to descend as a *downdraft.* As the air descends, the ice crystals begin to melt, which chills the air and enhances the downdraft. The downdraft may be further enhanced as falling precipitation drags some of the air along with it.

The appearance of the downdraft marks the beginning of the **mature stage.** The downdraft and updraft within the mature thunderstorm now constitute the cell. In some storms, there are several cells, each of which may last for less than 30 minutes.

During its mature stage, the thunderstorm is most intense. The top of the cloud, having reached a stable region of the atmosphere (which may be as high as the stratosphere), begins to take on the familiar anvil shape, as upper-level winds spread the cloud's ice crystals horizontally (see Fig. 10.2b). The cloud itself may extend upward to an altitude more than 12 km (40,000 ft) and be several kilometers in diameter near its base. Updrafts and downdrafts are strongest in the middle of the cloud, creating severe turbulence. Lightning and thunder are also present in the mature stage. Heavy rain (and occasionally small hail) falls from the cloud. And, at the surface, there is often a downrush of cold air with the onset of precipitation.

Where the cold downdraft reaches the surface, the air spreads out horizontally in all directions. The surface boundary that separates the advancing cooler air from the surrounding warmer air is called a *gust front.* Along the gust front, winds rapidly change both direction and speed. Look at Fig. 10.2b and notice that the gust front forces warm, humid air up into the storm, which enhances the cloud's updraft. In the region of the downdraft, rainfall may or may not reach the surface, depending on the relative humidity beneath the storm. In the dry air of the desert Southwest, for example, a mature thunderstorm may look ominous and contain all of the ingredients of any other storm, except that the raindrops evaporate before reaching the ground. However, intense downdrafts from the storm may reach the surface, producing strong, gusty winds and a gust front.

After the storm enters the mature stage, it begins to dissipate in about 15 to 30 minutes. The **dissipating stage** occurs when the updrafts weaken as the gust front moves away from the storm and no longer enhances the updrafts. At this stage, as illustrated in Fig. 10.2c, downdrafts tend to dominate throughout much of the cloud. The reason the storm does not normally last very long is that the downdrafts inside the cloud tend to cut off the storm's fuel supply by destroying the humid updrafts. Deprived of the rich supply of warm, humid air, cloud

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•Figure 10.3 A dissipating thunderstorm near Naples, Florida. Most of the cloud particles in the lower half of the storm have evaporated.

droplets no longer form. Light precipitation now falls from the cloud, accompanied by only weak downdrafts. As the storm dies, the lower-level cloud particles evaporate rapidly, sometimes leaving only the cirrus anvil as the reminder of the once mighty presence (see •Fig. 10.3). A single ordinary thunderstorm may go through its three stages in one hour or less.

Not only do thunderstorms produce summer rainfall for a large portion of the United States but they can also bring with them momentary cooling after an oppressively hot day. The cooling comes during the mature stage, as the downdraft reaches the surface in the form of a blast of welcome relief. Sometimes, the air temperature may drop by more than 10°C (18°F) in just a few minutes. Unfortunately, the cooling effect often is short-lived, as the downdraft diminishes or the thunderstorm moves on. In fact, after the storm has ended, the air temperature usually rises; and as the moisture from the rainfall evaporates into the air, the humidity increases, sometimes to a level where it actually feels more oppressive after the storm than it did before.

Up to this point, we've looked at ordinary cell thunderstorms that are short-lived, rarely become severe, and form in a region with weak vertical wind shear. As these storms develop, the updraft eventually gives way to the downdraft, and the storm ultimately collapses on itself. However, in a region where strong vertical wind shear exists, thunderstorms often take on a more complex structure. Strong, vertical wind shear can cause the storm to tilt in such a way that it becomes a *multicell thunderstorm*—a thunderstorm with more than one cell.

Multicell Thunderstorms

Thunderstorms that contain a number of cells, each in a different stage of development, are called **multicell thunderstorms** (see •Fig. 10.4). Such storms tend to form in a region of moderate-to-strong vertical wind speed shear. Look at •Fig. 10.5 and notice that on the left side of the illustration the wind speed increases rapidly with height, producing strong wind speed shear. This type of shearing causes the cell inside the storm to tilt in such a way that the updraft actually rides up and over the downdraft. Note that the rising updraft is capable of generating new cells that go on to become mature thunderstorms. Notice also that precipitation inside the storm does not fall into the updraft (as it does in the ordinary cell thunderstorm), so the storm's fuel supply is not cut off and the storm complex can survive for a long time. Long-lasting multicell storms can become intense and produce severe weather for brief periods.

When convection is strong and the updraft intense (as it is in Fig. 10.5), the rising air may actually intrude well into the stable stratosphere, producing an **overshooting top**. As the air spreads laterally into the anvil, sinking air in this region of the storm can produce beautiful mammatus clouds. At the surface, below the thunderstorm's cold downdraft, the cold, dense air may cause the surface air pressure to rise—sometimes several millibars. The relatively small, shallow area of high pressure is called a *mesohigh* (meaning "mesoscale high"). The mesohigh increases the pressure gradient between the storm-cooled air and the warmer, unstable air that lies beyond the storm, a situation that raises the risk of high winds.

Figure 10.4 This multicell storm complex is composed of a series of cells in successive stages of growth. The thunderstorm in the middle is in its mature stage, with a well-defined anvil. Heavy rain is falling from its base. To the right of this cell, a thunderstorm is in its cumulus stage. To the left, a well-developed cumulus congestus cloud is about ready to become a mature thunderstorm. With new cells constantly forming, the multicell storm complex can exist for hours.

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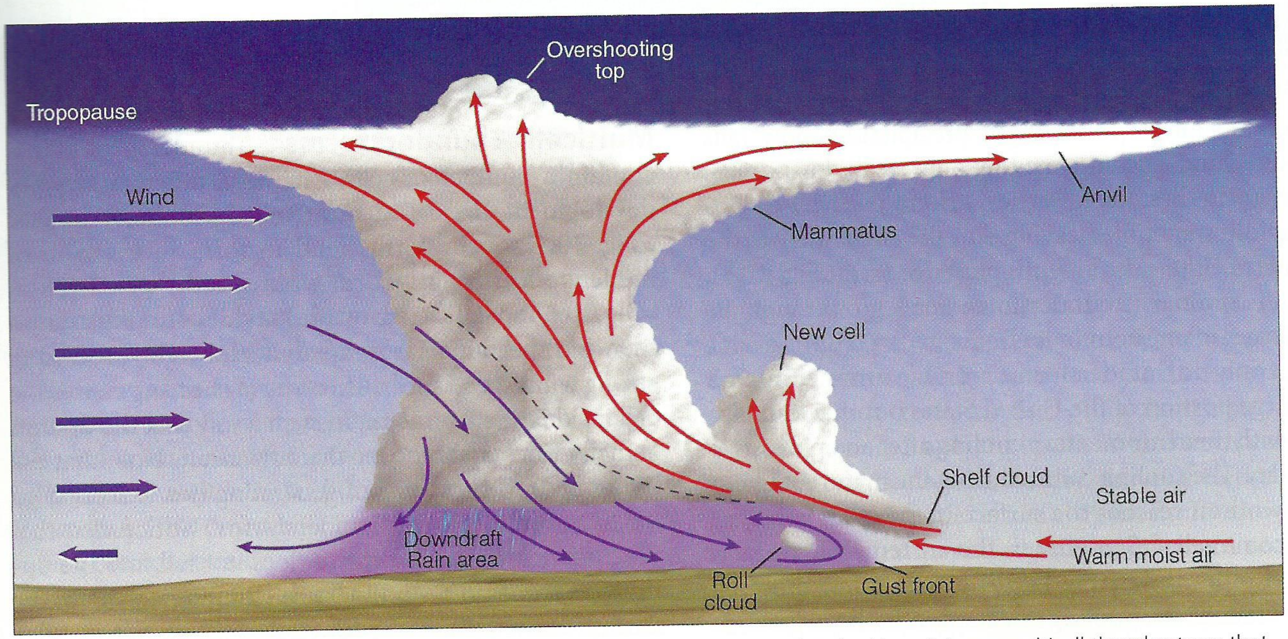

Figure 10.5 A simplified model describing air motions and other features associated with an intense multicell thunderstorm that has a tilted updraft. The severity depends on the intensity of the storm's circulation pattern.

The Gust Front When the cold downdraft reaches the earth's surface, it pushes outward in all directions, producing a strong **gust front** that represents the leading edge of the cold outflowing air (see ●Fig. 10.6). To an observer on the ground, the passage of the gust front resembles that of a cold front. During its passage, the temperature drops sharply and the wind shifts and becomes strong and gusty, with speeds occasionally exceeding 60 mi/hr. These high winds behind a strong gust front are called **straight-line winds** to distinguish them from the rotating winds of a tornado. As we will see later in this chapter, straight-line winds are capable of inflicting a great deal of damage, such as blowing down trees and overturning mobile homes.

Along the leading edge of the gust front, the air is quite turbulent. Here, strong winds can pick up loose dust and soil and lift them into a huge tumbling cloud.* The cold surface air behind the gust front may even linger close to the ground for hours, well after thunderstorm activity has ceased.

As warm, moist air rises along the forward edge of the gust front, a **shelf cloud** (also called an *arcus cloud*)

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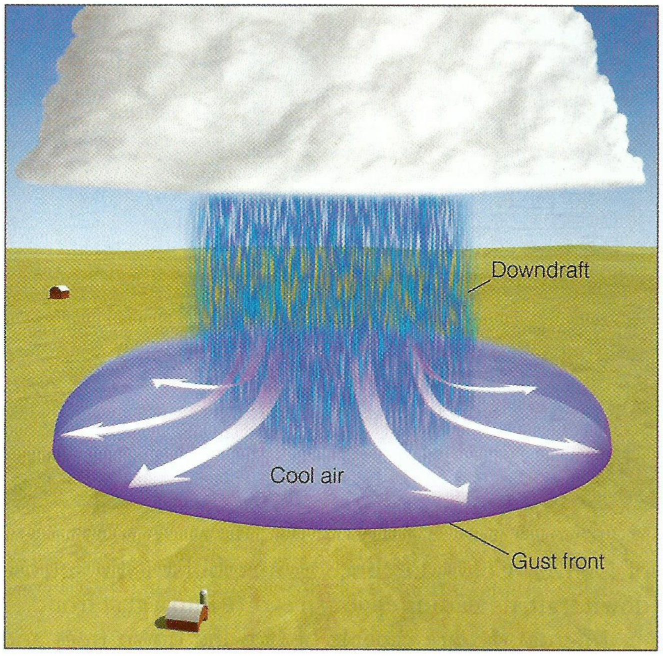
*In dry, dusty areas or desert regions, the leading edge of the gust front is the haboob described in Chapter 7, p. 197.



●**Figure 10.6** When a thunderstorm's downdraft reaches the ground, the air spreads out, forming a gust front.

DID YOU KNOW?

On August 13, 2011, as hundreds of fans waited for the country band *Sugarland* to perform at the Indiana State Fair in Indianapolis, strong gust front winds exceeding 60 miles per hour blew over the fairgrounds. The winds were so strong they toppled the stage, sending metal scaffolding, lights, and stage equipment into the crowd, where five people died and dozens were seriously injured.

may form, such as the one shown in ●Fig. 10.7. These clouds are especially prevalent when the atmosphere is very stable near the base of the thunderstorm. Look again at Figs. 10.5 and 10.7 and notice that the shelf cloud is attached to the base of the thunderstorm. Occasionally, an elongated ominous-looking cloud forms just behind the gust front. These clouds, which appear to slowly spin about a horizontal axis, are called **roll clouds** (see ●Fig. 10.8).

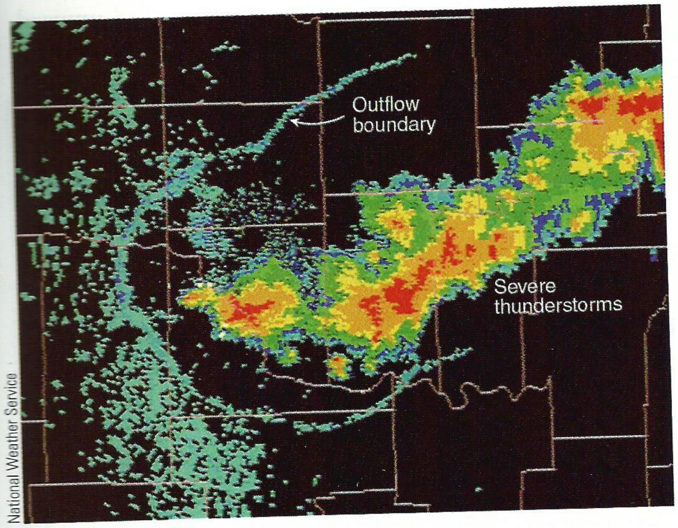
When the atmosphere is conditionally unstable, the leading edge of the gust front may force the warm, moist air upward, producing a complex of multicell storms, each with new gust fronts. These gust fronts may then merge into a huge gust front called an **outflow boundary**. Along the outflow boundary, air is forced upward, often generating new thunderstorms (see ●Fig. 10.9).

Microbursts Beneath an intense thunderstorm, the downdraft may become localized so that it hits the ground and spreads horizontally in a radial burst of wind, much like water pouring from a tap and striking the sink below. (Look at the downdraft in Fig. 10.6.) Such downdrafts are called **downbursts.** A downburst with winds extending only 4 km or less is termed a **microburst.** In spite of its small size, an intense microburst can induce damaging straight-line winds as high as 140 knots (161 mi/hr) or more. (A larger downburst with winds extending more than 4 kilometers is termed a *macroburst.*) ●Figure 10.10 shows the dust clouds generated from a microburst north


© Richard F. Picanso

●**Figure 10.7** A dramatic example of a shelf cloud (or arcus cloud) associated with an intense thunderstorm. The photograph was taken in the Philippines as the thunderstorm approached from the northwest.

•Figure 10.8 A roll cloud forming behind a gust front.

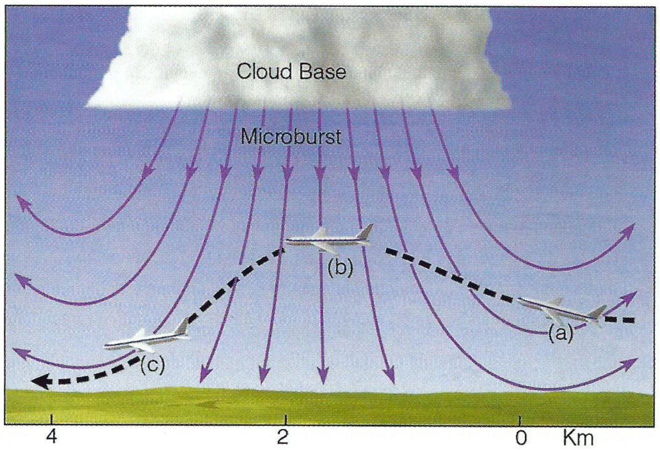


•Figure 10.9 Radar image of an outflow boundary. As cool (more-dense) air from inside the severe thunderstorms (red and orange colors) spreads outward, away from the storms, it comes in contact with the surrounding warm, humid (less-dense) air, forming a density boundary (blue line) called an *outflow boundary* between cool air and warm air. Along the outflow boundary, new thunderstorms often form.

of Denver, Colorado. Since a microburst is an intense downdraft, its leading edge can evolve into a gust front.

Microbursts are capable of blowing down trees and inflicting heavy damage upon poorly built structures as well as upon sailing vessels that encounter microbursts over open water. In fact, microbursts may be responsible for some damage once attributed to tornadoes. They pose an especially serious hazard to aircraft, largely due to the accompanying horizontal wind shear (that is, rapid changes in wind speed and/or wind direction). When an aircraft flies through a microburst at a relatively low altitude, say 300 m (1000 ft) above the ground, it first encounters a headwind that generates extra lift. This is position (a) in •Fig. 10.11. At this point, the aircraft tends to climb (it gains lift), and if the pilot noses the aircraft downward there could be grave consequences, for in a matter of seconds the aircraft encounters the powerful downdraft (position b), and the headwind is replaced by a tailwind (position c). This situation causes a sudden loss of lift and a subsequent decrease in the performance of the aircraft, which is now accelerating toward the ground.

•Figure 10.10 Dust clouds rising in response to the outburst winds of a microburst north of Denver, Colorado.



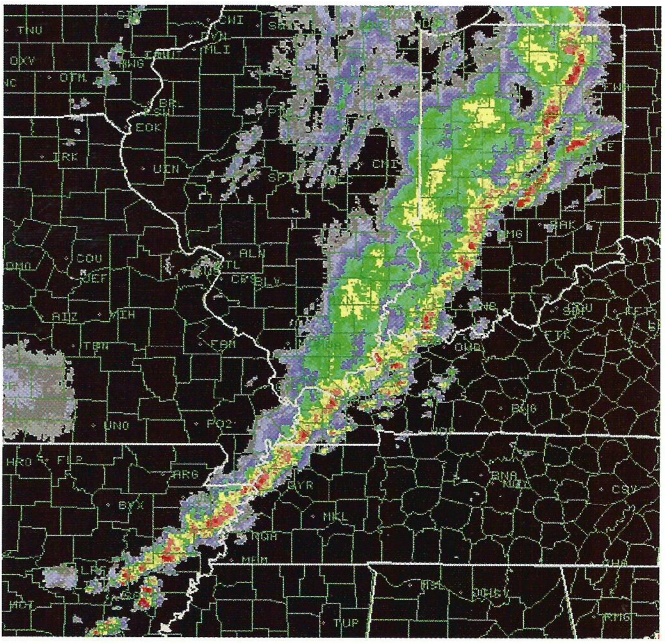
•Figure 10.11 Flying into a microburst. At position (a), the pilot encounters a headwind; at position (b), a strong downdraft; and at position (c), a tailwind that reduces lift and causes the aircraft to lose altitude. (This horizontal wind shear is different from the vertical wind shear that acts to increase storm severity.)

A number of major aviation disasters were attributed to microbursts through the 1980s. One of those occurred north of Dallas–Fort Worth Regional Airport during August 1985. Just as an aircraft was making its final approach, it encountered severe wind shear beneath a small but intense thunderstorm. The aircraft then dropped to the ground and crashed, killing more than 100 passengers. Recognizing the danger that microbursts posed to aviation, scientists carried out intensive research that led to a warning system installed at airports in the 1990s throughout the United States. This system includes automated weather stations, Doppler radars, and computer algorithms designed to detect microbursts and low-level wind shear. The system has virtually eliminated microburst-related accidents in United States commercial flights.

Microbursts can be associated with severe thunderstorms, producing strong, damaging winds. But studies show that they can also occur with ordinary cell thunderstorms and with clouds that produce only isolated showers—clouds that may or may not contain thunder and lightning. Microbursts can also be classified as *wet microbursts* or *dry microbursts*, based on whether they are accompanied by heavy rain or by little or no rain.

Up to this point, you might think that thunderstorm downdrafts are always cool. Most are cool, but occasionally they can be extremely hot. For example, just after midnight on June 9, 2011, a blast of hot, dry air from a dissipating thunderstorm raised the surface air temperature in Wichita, Kansas, from 85°F to 102°F in just 20 minutes. Such sudden warm downbursts are called **heat bursts**.

Apparently, the heat burst originates high up in the thunderstorm and warms by compressional heating as it plunges toward the surface. The heat burst that hit Wichita was exceptionally strong. Along with the hot air, it was accompanied by high winds that toppled trees, ripped down power lines, and lifted roofs off homes.



National Weather Service/NOAA

•Figure 10.12 A Doppler radar composite showing a pre-frontal squall line extending from Indiana southwestward into Arkansas. Severe thunderstorms (red and orange colors) associated with the squall line produced large hail and high winds during October 2001.

Squall-Line Thunderstorms Multicell thunderstorms may form as a line of thunderstorms, called a **squall line**. The line of storms may form directly along a cold front and extend for hundreds of kilometers, or the storms may form in the warm air 100 to 300 km out ahead of the cold front. These *pre-frontal squall-line thunderstorms* of the middle latitudes represent the largest and most severe type of squall line, with huge thunderstorms causing severe weather over much of its length (see • Fig. 10.12).*

There is still debate as to exactly how pre-frontal squall lines form. Models that simulate their formation suggest that, initially, convection begins along the cold front, then re-forms farther away. Moreover, the surging nature of the main cold front itself, or developing cumulus clouds along the front, may cause the air aloft to develop into waves (called *gravity waves*), much like the waves that form downwind of a mountain chain. Out ahead of the cold front, the rising motion of the wave may be the trigger that initiates the development of cumulus clouds and a pre-frontal squall line.

Rising air along the frontal boundary (and along the gust front), coupled with the tilted nature of the updraft,

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*Within a squall line there may be multicell thunderstorms, as well as supercell storms—violent thunderstorms that contain a single rapidly rotating updraft. We will look more closely at supercells in the next section.

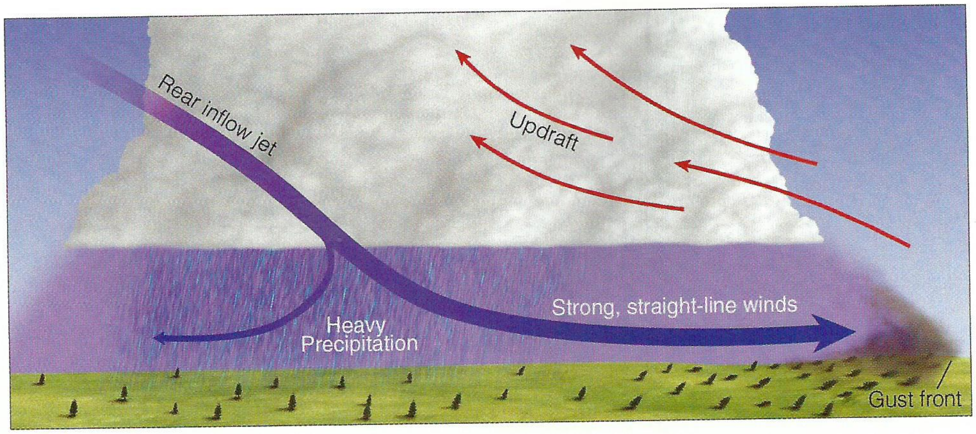
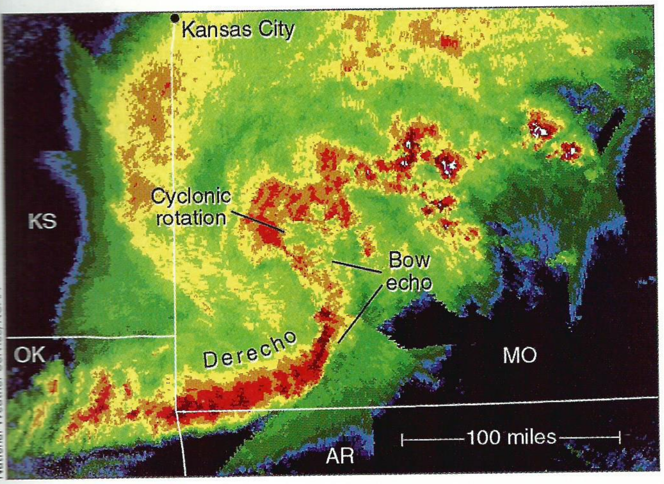


Figure 10.13 A side view of the lower half of a squall-line thunderstorm with the rear-inflow jet carrying strong winds from high altitudes down to the surface. These strong winds push forward along the surface, causing damaging straight-line winds that may reach 100 knots.

promotes the development of new cells as the storm moves along. Hence, as old cells decay and die out, new ones constantly form, and the squall line can maintain itself for hours on end. Occasionally, a new squall line will actually form out ahead of the front as the gust front pushes forward, beyond the main line of storms.

Strong downdrafts often form to the rear of the squall line, as some of the falling precipitation evaporates and chills the air. The heavy, cooler air then descends, dragging some of the surrounding air with it. If the cool air rapidly descends, it may concentrate into a rather narrow band of fast-flowing air called the *rear-flank inflow jet*, because it enters the storm from the west, as shown in Fig. 10.13. Sometimes the rear-inflow jet will bring with it the strong upper-level winds from aloft. Should these winds reach the surface, they rush outward producing damaging *straight-line winds* that may exceed 90 knots.

As the strong winds rush forward along the ground, they sometimes push the squall line outward so that it appears as a *bow* (or a series of bows) on a radar screen. Such a bow-shaped squall line is called a **bow echo** (see Fig. 10.14). The strongest winds tend to form near the center of the bow, where the sharpest bending occurs. Tornadoes can form, especially near the left (northern) end of the bow, but they are usually small and short-lived.



National Weather Service/NOAA

Figure 10.14 A Doppler radar image showing an intense squall line in the shape of a bow—called a *bow echo*—moving eastward across Missouri on the morning of May 8, 2009. The strong thunderstorms (red and orange in the image) are producing damaging straight-line winds over a wide area. Damaging straight-line wind that extends for a good distance along a squall line is called a *derecho*.

If straight-line winds, gusting to more than 50 knots (58 mi/hr) persist along a path at least 400 km (250 mi) long, the windstorm is called a **derecho** (day-ray-sho), after the Spanish word for "straight ahead." In an average year about 20 derechos occur in the United States. Typically, derechoes form in the early evening and last throughout the night. An especially powerful derecho roared through New York State during the early morning of July 15, 1995, where it blew down millions of trees in Adirondack State Park. Another extremely strong derecho swept through the midwest in the Washington, D.C., area on June 29, 2012. With winds gusting to more than 70 knots (80 mi/hr), the derecho killed 22 people and left more than 4 million without power in some places for days.

Squall lines are one type of convective phenomenon called a *mesoscale convective system* (MCS). Squall lines come under this heading because they are driven by convective processes and because they are mesoscale (middle scale) in size. Mesoscale convective systems are organized thunderstorms that can take on a variety of configurations, from the elongated squall line, to the more circular *mesoscale convective complex* described in the next section.

Mesoscale Convective Complexes

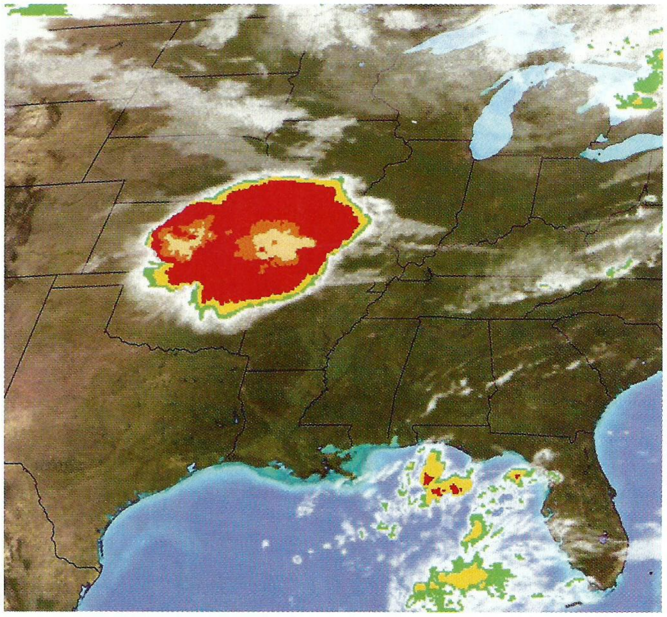
Where conditions are favorable for convection, a number of individual multicell thunderstorms may occasionally grow in size and organize into a large circular convective weather system. These convectively driven systems, called **mesoscale convective complexes (MCCs)**, are quite large—they can be as much as 1000 times larger in area than an individual ordinary cell thunderstorm. In fact, they are often large enough to cover an entire state, an area in excess of 100,000 square kilometers (see ● Fig. 10.15).

Within the MCCs, the individual thunderstorms apparently work together to generate a long-lasting (more than 6 hours) weather system that often exists for periods exceeding 12 hours. Thunderstorms that comprise MCCs support the growth of new thunderstorms as well as a region of widespread precipitation. These systems are beneficial in that they provide a significant portion of the growing season rainfall over much of the corn and wheat belts of the United States. However, MCCs can also produce a wide variety of severe weather, including hail, high winds, destructive flash floods, and tornadoes.

Mesoscale convective complexes tend to form during the summer in regions where the upper-level winds are weak, which is often beneath a ridge of high pressure. If a weak cold front should stall beneath the ridge, surface heating and moisture may be sufficient to generate thunderstorms on the cool side of the front. Often moisture from the south is brought into the system by a low-level jet stream often found within 5000 ft of the surface. Within the multicell storm complex new thunderstorms form as older ones dissipate. When upper-level winds are especially weak, MCCs can move very slowly toward the east or southeast and dump torrential rain.

Supercell Thunderstorms In a region where there is strong vertical wind shear (speed and/or directional shear), the thunderstorm may form in such a way that the outflow of cold air from the downdraft never undercuts the updraft. In such a storm, the wind shear may be so strong as to create horizontal spin, which, when tilted into the updraft, causes it to rotate. An intense long-lasting thunderstorm with a single violently rotating updraft is called a **supercell.*** As we will see later in this chapter, it is the rotating aspect of the supercell that can lead to the formation of tornadoes.

● Figure 10.16 shows a supercell with a tornado. The internal structure of a supercell is organized in such a way that the storm may maintain itself as a single entity


NOAA

● Figure 10.15 An enhanced infrared satellite image showing the cold cloud tops (dark red and orange colors) of a mesoscale convective complex extending from central Kansas across western Missouri. This organized mass of multicell thunderstorms brought hail, heavy rain, and flooding to this area.

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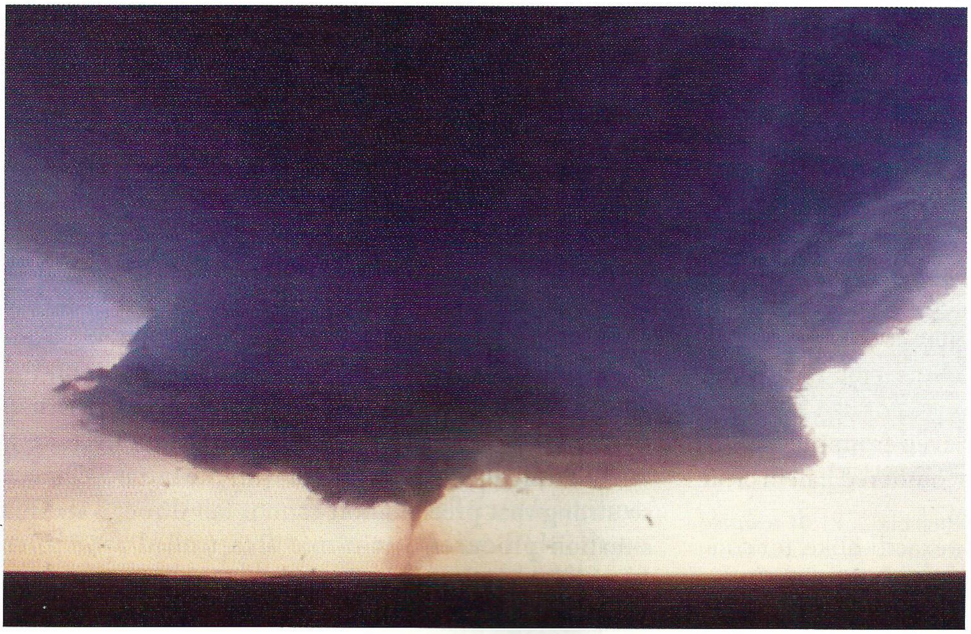
*Smaller thunderstorms that occur with rotating updrafts are referred to as *mini supercells.*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● Figure 10.16 A supercell thunderstorm with a tornado sweeps over Texas.

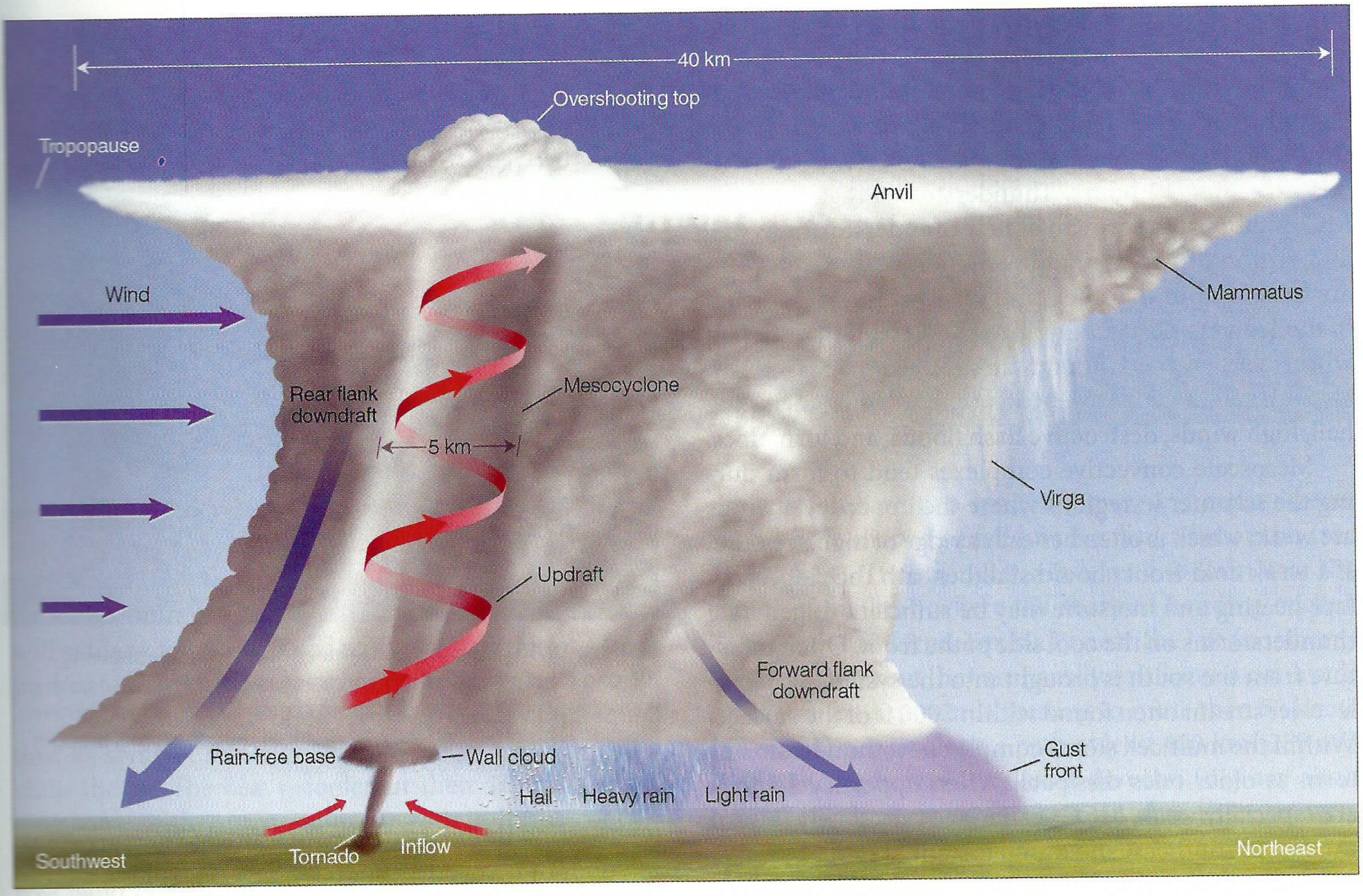


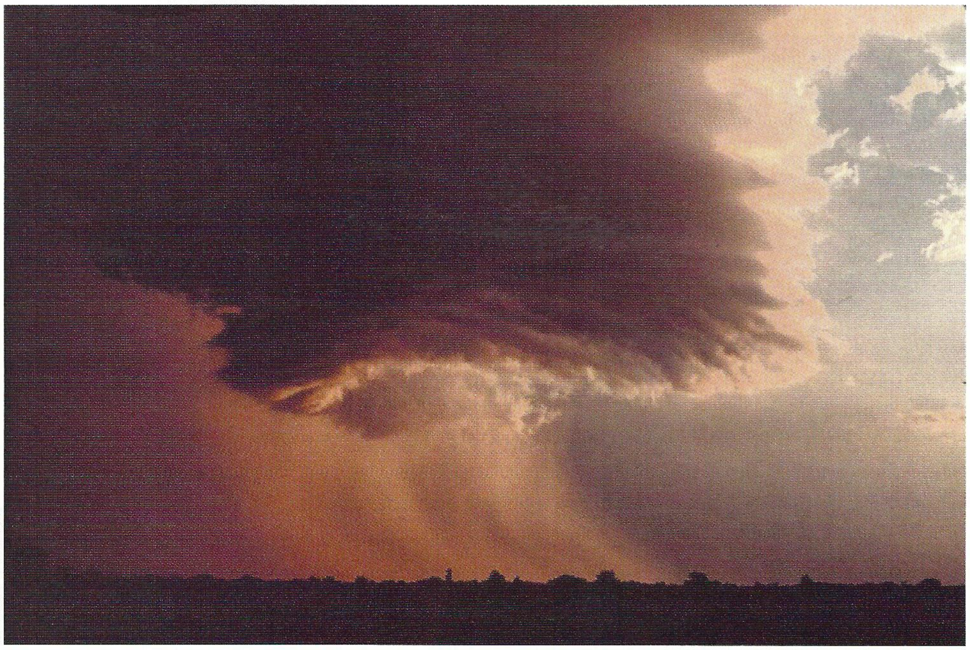
Figure 10.17 Some of the features associated with a classic tornado-breeding supercell thunderstorm as viewed from the southeast. The storm is moving to the northeast.

for hours. Storms of this type are capable of producing an updraft that may exceed 90 knots, damaging surface winds, and large tornadoes. In some cases, the top of the storm may extend to as high as 18 km (60,000 ft) above the surface, and its width may exceed 40 km (25 mi).

The largest hail observed on earth forms within supercells because of updrafts that are both wide and intense. In rare cases, such hailstones can grow to the size of grapefruits or even larger. One hailstone that fell in Vivian, South Dakota, on July 23, 2010, weighed nearly 2 pounds and measured 8 inches across, which made it the heaviest and widest hailstone on record. The broad and powerful updrafts within supercells can keep hailstones airborne for relatively long periods, which allows many water droplets to accumulate and freeze on them. Once the hailstones are large enough, they may fall out the bottom of the cloud with the downdraft, or the violent spinning updraft may whirl them out the side of the cloud or even from the base of the anvil. Aircraft have actually encountered hail in clear air several kilometers from a storm.

Although no two supercells are exactly alike, for convenience they are often divided into three types. *Classic supercells* produce heavy rain, large hail, high surface winds, and the majority of tornadoes. When a supercell becomes dominated by heavy precipitation, strong downdrafts (downbursts), and large hail, it is referred to as an *HP (high precipitation) supercell.* Tornadoes in an HP supercell may be wrapped in heavy rain and difficult to see. On the other hand, tornadoes and cloud features are often quite visible in an *LP (low precipitation) supercell* (see Fig. 10.16). Although LP supercells tend to produce little rain, they are still capable of producing large hail as well as tornadoes. The rotation of an LP supercell is often visible as a bell-shaped tower, with a corkscrew-like pattern along its sides.

A model of a classic supercell with many of its features is given in ● Fig. 10.17. In the diagram, we are viewing the storm from the southeast, and the storm is moving from southwest to northeast. The rotating air column on the south side of the storm, usually 5 to 10 kilometers across, is called a **mesocyclone** (meaning "mesoscale cyclone"). The rotating updraft associated with the mesocyclone is so strong that precipitation cannot fall through it. This situation produces a rain-free area (called a *rain-free base*) beneath the updraft. Strong southwesterly winds



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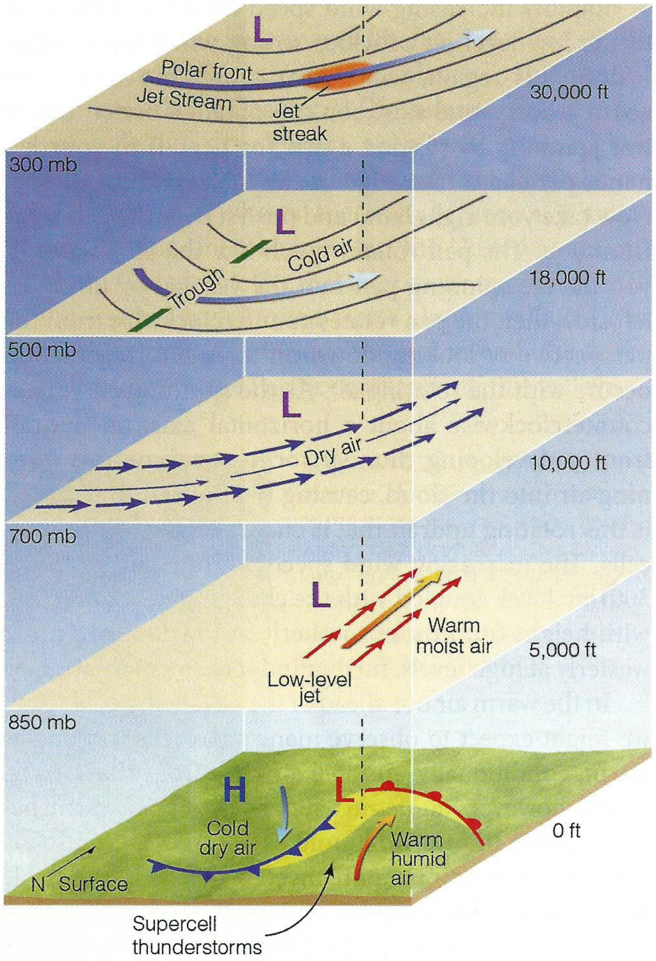
●**Figure 10.18** A wall cloud photographed southwest of Norman, Oklahoma.

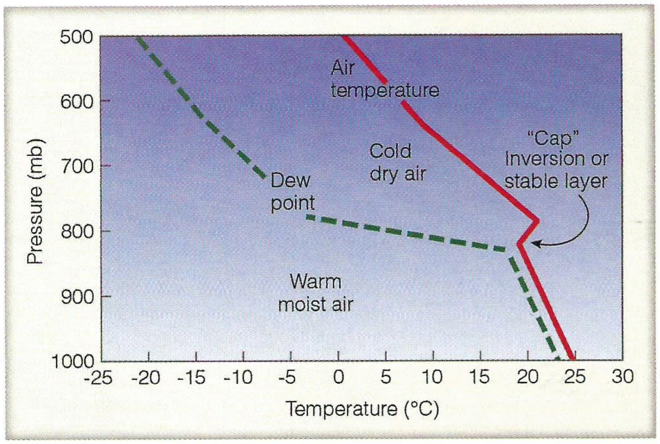


●**Figure 10.19** Conditions leading to the formation of severe thunderstorms, and especially supercells. The area in yellow shows where supercell thunderstorms are likely to form.

aloft usually blow the precipitation northeastward. Notice that large hail, having remained in the cloud for some time, usually falls just north of the updraft. The heaviest rain occurs just north of the falling hail, with the lighter rain falling in the northeast quadrant of the storm. If humid low-level air is drawn into the updraft, a rotating cloud, called a **wall cloud**, may descend from the base of the storm (see ● Fig. 10.18).

We can obtain a better picture of how vertical wind shear plays a role in the development of supercell thunderstorms by observing ● Fig 10.19. The illustration represents atmospheric conditions often observed during the spring over the Central Plains. At the surface, we find an open-wave middle-latitude cyclone with cold, dry air moving in behind a cold front, and warm humid air pushing northward from the Gulf of Mexico behind a warm front. Above the warm surface air, a wedge or "tongue" of warm, moist air is streaming northward. It is in this region we find a relatively narrow band of strong winds, sometimes exceeding 50 knots, called the *low-level jet.* Directly above the moist layer is a wedge of cooler, drier air moving in from the southwest. Higher up, at the 500-mb level, a trough of low pressure exists to the west of the surface low. At the 300-mb level, the polar-front jet stream swings over the region, often with an area of maximum wind (a jet streak) above the surface low. At this level, the jet stream provides an area of divergence that enhances surface convergence and rising air. The stage is now set for the development of supercell thunderstorms.

The yellow area on the surface map (Fig. 10.19) shows where supercells are likely to form. They tend to form in



•Figure 10.20 A typical sounding of air temperature and dew point that frequently precedes the development of supercell thunderstorms. The thickness of the warm, moist air from the surface up to the cap at 800 mb is usually on the order of about 2000 m or 6000 ft.

this region because (1) the position of cold air above warm air produces a conditionally unstable atmosphere and because (2) strong vertical wind shear induces rotation.

Rapidly increasing wind speed from the surface up to the low-level jet provides strong wind speed shear. Within this region, wind shear causes the air to spin about a horizontal axis. You can obtain a better idea of this spinning by placing a pen (or pencil) in your left hand, parallel to the edge of the table in front of you. Now take your right hand and push it over the pen away from you. The pen rotates much like the air rotates. If you tilt the spinning pen into the vertical by lifting its left side, then the pen rotates counterclockwise from the perspective of looking down on it. A similar situation occurs with the rotating air. As the spinning air rotates counterclockwise about a horizontal axis, an updraft from a developing thunderstorm can draw the spinning air into the cloud, causing the updraft to rotate. It is this rotating updraft that is characteristic of all supercells. The increasing wind speed with height up to the 300-mb level, coupled with the changing wind direction with height from more southerly at low levels to more westerly at high levels, further induces storm rotation.*

In the warm air out ahead of the advancing cold front, we might expect to observe many supercells forming as warm, conditionally unstable air rises from the surface. Often, however, numerous supercells do not form because above the warm, humid surface air there usually exists a shallow temperature inversion (or at least a stable layer) that acts like a cap (or a lid) on the humid air below as illustrated in •Fig. 10.20. (The stable layer is important because it prevents many small thunderstorms from forming.) During the morning the stable air caps the humid air, and only small cumulus clouds form. As the day progresses, and the surface becomes warmer, rising blobs of air are able to break through the stable layer at isolated places, and clouds build rapidly, sometimes explosively, as the humid air is vented upward through the opening. Divergence at the jet-stream level then draws this humid air upward into the cold, conditionally unstable air aloft, and supercells may quickly develop to great heights.

BRIEF REVIEW

In the last several sections, we examined different types of thunderstorms. Listed below for your review are important concepts we considered:

- All thunderstorms need three basic ingredients: (1) moist surface air; (2) a conditionally unstable atmosphere; and (3) a mechanism "trigger" that forces the air to rise.
- Ordinary cell (air-mass) thunderstorms tend to form where warm, humid air rises in a conditionally unstable atmosphere and where vertical wind shear is weak. They are usually short-lived and go through their life cycle of growth (cumulus stage), maturity (mature stage), and decay (dissipating stage) in less than an hour. They rarely produce severe weather.
- As wind shear increases (and the winds aloft become stronger), multicell thunderstorms are more likely to form as the storm's updraft rides up and over the downdraft. The tilted nature of the storm allows new cells to form as old ones die out.
- Multicell storms often form as a complex of storms, such as the squall line (a long line of thunderstorms that form along or out ahead of a frontal boundary) and the mesoscale convective complex (a large circular cluster of thunderstorms).
- Supercell thunderstorms are long-lasting violent thunderstorms, with a single rotating updraft that forms in a region of strong vertical wind shear. A rotating supercell is more likely to develop when (a) the winds aloft are strong and change direction from southerly at the surface to more westerly aloft and (b) a low-level jet exists just above the earth's surface.
- A gust front, or outflow boundary, represents the leading edge of cool air that originates inside a thunderstorm, reaches the surface as a downdraft, and moves outward away from the thunderstorm.
- Strong downdrafts of a thunderstorm, called downbursts (or microbursts if the downdrafts are smaller than 4 km), have been responsible for several airline crashes, because upon striking the surface, these winds produce extreme horizontal wind shear.
- A derecho is a long-lived straight-line wind produced by strong downbursts from intense thunderstorms that often appear as a bow (bow echo) on a radar screen.

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*As we will see later in this chapter, it is this rotation that sets the stage for tornado development.

Thunderstorms and Flooding

Intense thunderstorms can be associated with **flash floods**—floods that develop rapidly with little or no advance warning. Such flooding often results when thunderstorms stall or move very slowly, causing heavy rainfall over a relatively small area. Such flooding occurred over parts of New England and the mid-Atlantic states during June 2006, when a stationary front stalled over the region, and moist tropical air, lifted by the front, produced thunderstorms and heavy rainfall that caused extensive flooding and damage to thousands of homes. Flooding may also occur when thunderstorms move quickly, but keep passing over the same area, a phenomenon called *training* much like railroad cars, one after another, passing over the same tracks. In recent years, floods and flash floods in the United States have claimed an average of more than 100 lives a year and have accounted for untold property and crop damage. (An example of a terrible flash flood that took the lives of more than 135 people is given in Focus section 10.1.)

If thunderstorms bring repeated heavy rain to a region for days or weeks, the result can be one or more *river floods.* A river flood occurs when a major river system rises slowly but floods a large area, whereas a flash flood may devastate a smaller area in minutes to hours. During the summer of 1993, dozens of mesoscale convective complexes rumbled across the upper Midwest, causing the worst flood ever recorded in that part of the United States (see ● Fig. 10.21). Estimates are that $6.5 billion in crops were lost as millions of acres of valuable farmland were inundated by flood waters. The flooding, much of it along the Mississippi River, took 45 lives, damaged or destroyed 45,000 homes, and forced the evacuation of 74,000 people.

DID YOU KNOW?

The Great Flood of 1993 in the Mississippi and Missouri river basins had an impact on the living and the dead as the Hardin Cemetery in Missouri had more than 700 graves opened. Some caskets were swept away by raging flood waters and deposited many miles downstream, and some were never found.

Distribution of Thunderstorms

It is estimated that more than 50,000 thunderstorms occur each day throughout the world. Hence, over 18 million occur annually. The combination of warmth and moisture make equatorial landmasses especially conducive to thunderstorm formation. Here, thunderstorms occur on about one out of every three days. Thunderstorms are also prevalent over water along the intertropical convergence zone, where the low-level convergence of air helps to initiate uplift. The heat energy liberated in these storms helps the earth maintain its heat balance by distributing heat poleward (see Chapter 7). Thunderstorms are much less prevalent in dry climates, such as the polar regions and the desert areas dominated by subtropical highs.

● Figure 10.22 shows the average annual number of days having thunderstorms in the United States and southern Canada. Notice that they occur most frequently in the southeastern United States along the Gulf Coast with a maximum in Florida. The region with the fewest thunderstorms is the Pacific coast and interior valleys.

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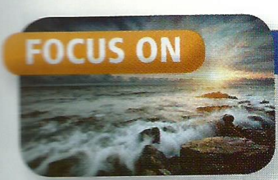
●Figure 10.21 Flooding during the summer of 1993 covered a vast area of the upper Midwest. Here, floodwaters near downtown Des Moines, Iowa, during July 1993, inundate buildings of the Des Moines waterworks facility. Flood-contaminated water left 250,000 people without drinking water.



A SPECIAL TOPIC 10.1

The Terrifying Flash Flood in the Big Thompson Canyon

Robert J. Janett Photo/USGS

Figure 1 This car is one of more than 400 destroyed by floodwaters in the Big Thompson Canyon on July 31, 1976.

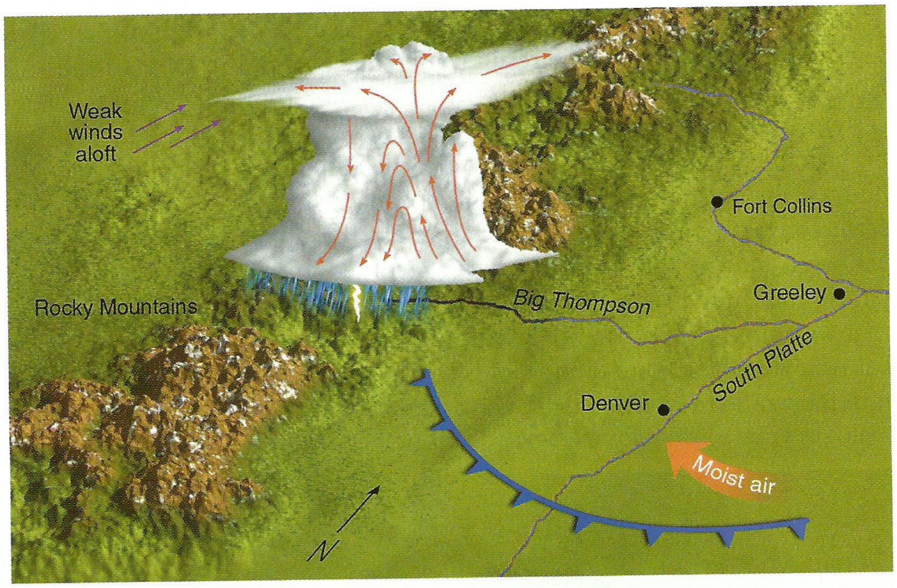


Figure 2 Weather conditions that led to the development of intense multicell thunderstorms that remained nearly stationary over the Big Thompson Canyon in the Colorado Rockies. The arrows within the thunderstorm represent air motions.

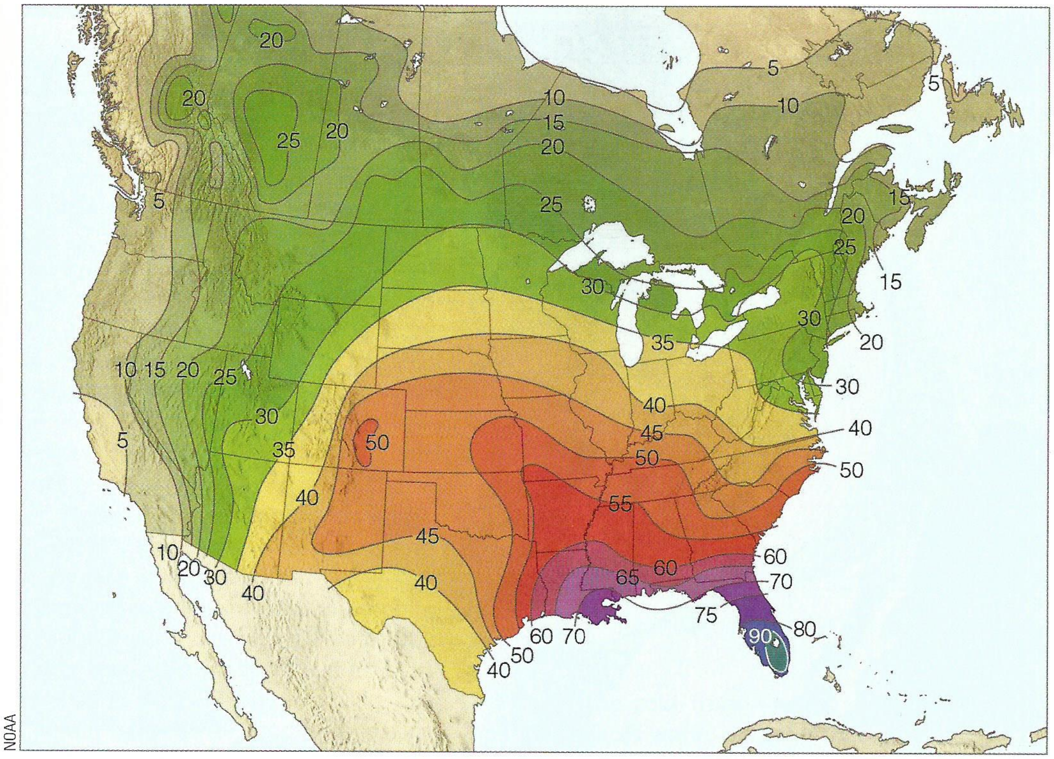
July 31, 1976, was like any other summer day in the Colorado Rockies, as small cumulus clouds with flat bases and dome-shaped tops began to develop over the eastern slopes near the Big Thompson and Cache La Poudre rivers. At first glance, there was nothing unusual about these clouds, as almost every summer afternoon they form along the warm mountain slopes. Normally, strong upper-level winds push them over the plains, causing rainshowers of short duration. But the cumulus clouds on this day were different. For one thing, they were much lower than usual, indicating that the southeasterly surface winds were bringing in a great deal of moisture. Also, their tops were somewhat flattened, suggesting that an inversion aloft was stunting their growth. But these harmless-looking clouds gave no clue that later that evening in the Big Thompson Canyon more than 135 people would lose their lives in a terrible flash flood.

By late afternoon, a few of the cumulus clouds were able to puncture the inversion. Fed by moist southeasterly winds, these clouds soon developed into gigantic multicell thunderstorms with tops exceeding 18 km (60,000 ft). By early evening, these same clouds were producing incredible downpours in the mountains.

In the narrow canyon of the Big Thompson River, some places received as much as 30.5 cm (12 in.) of rain in the four hours between 6:30 P.M. and 10:30 P.M. local time. This is truly an impressive amount of precipitation, considering that the area normally receives about 40.5 cm (16 in.) for an entire year. The heavy downpours turned small creeks into raging torrents, and the Big Thompson River was quickly filled to capacity. Where the canyon narrowed, the river overflowed its banks and water covered the road. The relentless pounding of water caused the road to give way.

Soon cars, tents, mobile homes, resort homes, and campgrounds were being claimed by the river (see Fig 1). Where the debris entered a narrow constriction, it became a dam. Water backed up behind it, then broke through, causing a wall of water to rush downstream.

Figure 2 shows the weather conditions during the evening of July 31, 1976. A cool front moved through earlier in the day and is now south of Denver. The weak inversion layer associated with the front kept the cumulus clouds from building to great heights earlier in the afternoon. However, the strong southeasterly flow behind the cool front pushed unusually moist air upslope along the mountain range. Heated from below, the conditionally unstable air eventually punctured the inversion and developed into a huge multicell thunderstorm complex that remained nearly stationary for several hours due to the weak southerly winds aloft. The deluge may have deposited 19 cm (7.5 in.) of rain on the main fork of the Big Thompson River in about one hour. Of the approximately 2000 people in the canyon that evening, over 135 lost their lives and property damage exceeded $35.5 million.



●Figure 10.22 The average number of days each year on which thunderstorms are observed throughout the United States and southern Canada. (Due to the scarcity of data, the number of thunderstorms is underestimated in the mountainous far west.)

In many areas, thunderstorms form primarily in summer during the warmest part of the day when the surface air is most unstable. There are some exceptions, however. During the summer in the valleys of central and southern California, dry, sinking air produces an inversion that inhibits the development of towering cumulus clouds. In these regions, thunderstorms are most frequent in winter and spring, particularly when cold, moist, conditionally unstable air aloft moves over moist, mild surface air. The surface air remains relatively warm because of its proximity to the ocean.

On many summer days, thunderstorms develop near the Rocky Mountains in the afternoon, then intensify in the evening as they move eastward across the Central Plains. In fact, one of the most common times to experience a thunderstorm in parts of Iowa and Missouri is between midnight and dawn. Such storms can be fueled by a southerly low-level jet that often strengthens after sunset, bringing humid air northward and helping trigger convergence and uplift of surface air. As the thunderstorms build, their tops cool by radiating infrared energy to space. This cooling process tends to destabilize the atmosphere, making it even more suitable for nighttime thunderstorms.

At this point, it is interesting to compare Fig. 10.22 and ● Fig. 10.23. Notice that, even though the greatest frequency of thunderstorms is near the Gulf Coast, the greatest frequency of hailstorms is over the western Great Plains. One reason for this situation is that conditions over the Great Plains are more favorable for the development of severe thunderstorms and especially supercells that have strong updrafts capable of keeping hailstones suspended within the cloud for a long time so that they can grow to an appreciable size before plunging to the ground. We also find that, in summer along the Gulf Coast, a thick layer of warm, moist air extends upward from the surface. Most hailstones falling into this warm layer will melt before reaching the ground.* In contrast, when a thunderstorm is located on the high plains east of the Rocky Mountains, a much larger portion of the storm will typically be located above the freezing level, so hail has a much better chance of occurring.

Now that we have looked at the development and distribution of thunderstorms, we are ready to examine an interesting, though not yet fully understood, aspect of all thunderstorms—lightning. (However, before reading about lightning and thunder, you may want to read Focus section 10.2, which discusses thunderstorm development along the dryline.)

Lightning and Thunder

Lightning is simply a discharge of electricity, a giant spark, which usually occurs in mature thunderstorms.** Lightning may travel within a cloud, from one cloud to another, from a cloud

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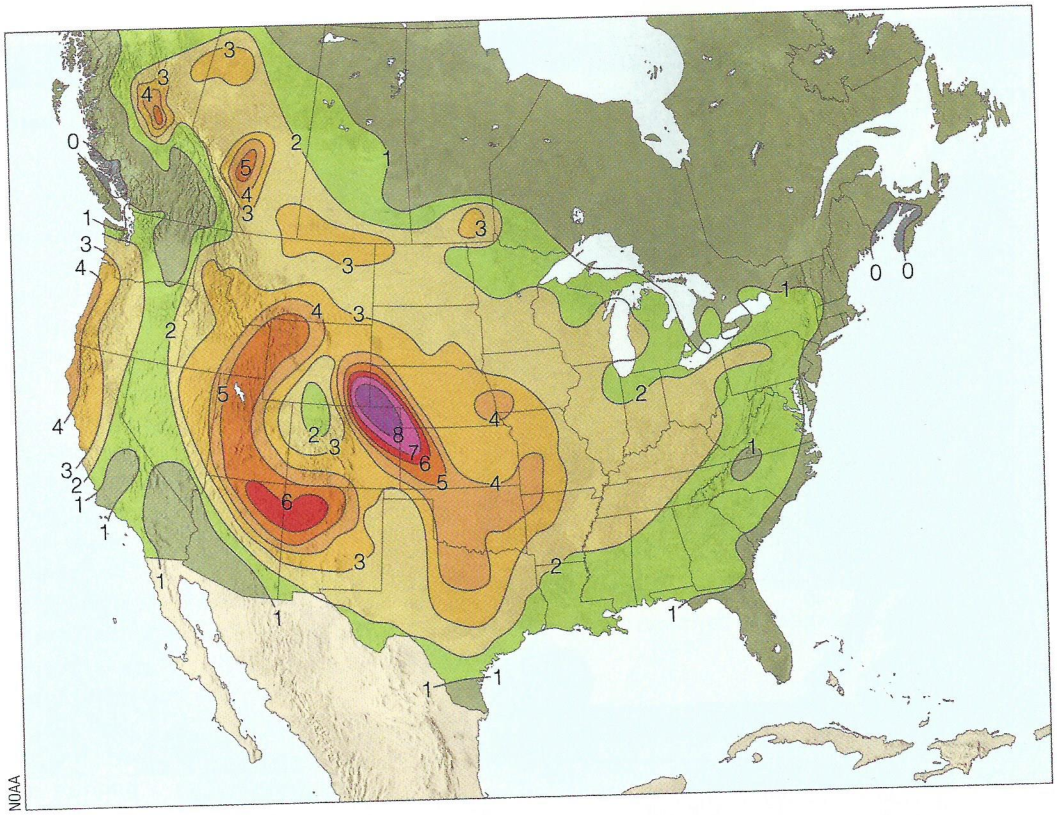
*The formation of hail is described in Chapter 5 on p. 148.

**Lightning may also occur in snowstorms, in duststorms, on rare occasions in nimbostratus clouds, and in the gas cloud of an erupting volcano.

Figure 10.23 The average number of days each year on which hail is observed throughout the United States and southern Canada.



NOAA

to the surrounding air, or from a cloud to the ground (see • Fig. 10.24). (The majority of lightning strikes occur within the cloud, while only about 20 percent or so occur between cloud and ground.) The lightning stroke can heat the air through which it travels to an incredible 30,000°C (54,000°F), which is 5 times hotter than the surface of the sun. This extreme heating causes the air to expand explosively, thus initiating a shock wave that becomes a booming sound wave—called **thunder**—that travels outward in all directions from the flash.

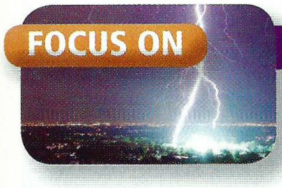
Figure 10.24 The lightning stroke can travel in a number of directions. It can occur within a cloud, from one cloud to another cloud, from a cloud to the air, or from a cloud to the ground. Notice that the cloud-to-ground lightning can travel out away from the cloud, then turn downward, striking the ground many miles from the thunderstorm. When lightning behaves in this manner, it is often described as a *"bolt from the blue."*

A sound occasionally mistaken for thunder is the **sonic boom.** Sonic booms are produced when an aircraft exceeds the speed of sound at the altitude at which it is flying. The aircraft compresses the air, forming a shock wave that trails out as a cone behind the aircraft. Along the shock wave, the air pressure changes rapidly over a short distance. The rapid pressure change causes the distinct boom. (Exploding fireworks generate a similar shock wave and a loud bang.)

How Far Away Is the Lightning?—Start Counting

When you see a flash of lightning, how can you tell how far away (or how close) it is? Light travels so fast that we see light instantly after a lightning flash. But the sound of thunder, traveling at only about 1100 ft/sec, takes much longer to reach the ear. If we start counting seconds from the moment you see the lightning until you hear the thunder, you can determine how far away the stroke is. Because it takes sound about 5 seconds to travel one mile, if you see lightning and hear the thunder 15 seconds later, the lightning stroke (and the thunderstorm) is about 3 miles away.

When the lightning stroke is very close (several hundred feet or less) thunder sounds like a clap or a crack followed immediately by a loud bang. When it is farther away, it often rumbles. The rumbling can be due to the sound emanating from different areas of the stroke (see • Fig. 10.25). Moreover, the rumbling is accentuated when the sound wave reaches an observer after having bounced off obstructions, such as hills and buildings.



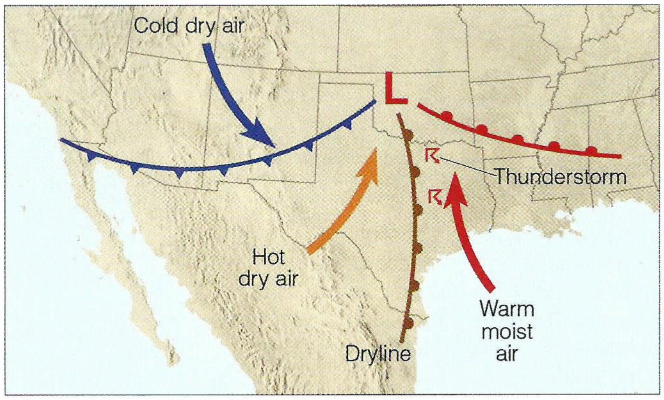
AN OBSERVATION

10.2

Thunderstorms and the Dryline

Thunderstorms may form along or just east of a boundary called a *dryline.* Recall from Chapter 8 that the dryline represents a narrow zone where there is a sharp horizontal change in moisture. In the United States, drylines are most frequently observed in the western half of Texas, Oklahoma, and Kansas. In this region, drylines occur most frequently during spring and early summer.

● Figure 3 shows springtime weather conditions that can lead to the development of a dryline and intense thunderstorms. The map shows a developing mid-latitude cyclone with a cold front, a warm front, and three distinct air masses. Behind the cold front, cold dry continental polar air or modified cool dry Pacific air pushes in from the northwest. In the warm air, ahead of the cold front, hot, dry continental tropical air moves in from the southwest. Farther east, warm but very humid air sweeps northward from the Gulf of Mexico. The dryline is the north–south oriented boundary that separates the hot, dry air and the warm, humid air.



●Figure 3 Surface conditions that can produce a dryline with intense thunderstorms.

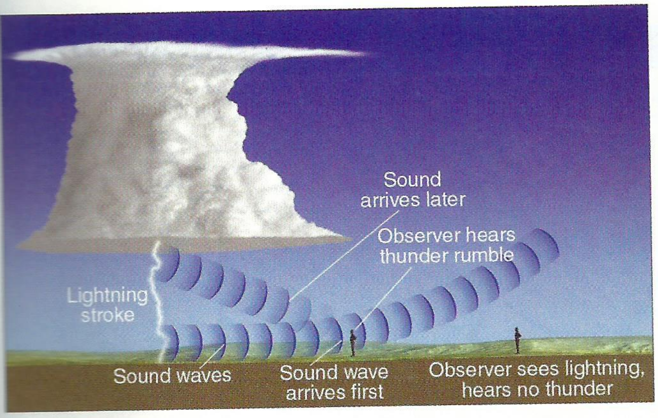
Along the cold front—where cold, dry air replaces warm, dry air—there is insufficient moisture for thunderstorm development. The moisture boundary lies along the dryline. Because the Central Plains of North America are elevated to the west, some of the hot, dry air from the southwest is able to ride over the slightly cooler, more humid air from the Gulf. This condition sets up a potentially unstable atmosphere just east of the dryline. Converging surface winds in the vicinity of the dryline, coupled with upper-level outflow, may result in rising air and the development of thunderstorms. As thunderstorms form, the cold downdraft from inside the storm may produce a blast of cool air that moves along the ground as a gust front and initiates the uplift necessary for generating new (possibly more severe) thunderstorms.

In some instances, lightning is seen but no thunder is heard. Does this mean that thunder was not produced by the lightning? Actually, there is thunder, but the atmosphere refracts (bends) and attenuates the sound waves, making the thunder inaudible. Sound travels faster in warm air than in cold air. Because thunderstorms form in a conditionally unstable atmosphere, where the temperature normally drops rapidly with height, a sound wave moving outward away from a lightning stroke will often bend upward, away from an observer at the surface. Consequently, an observer closer than about 5 km (3 mi) to a lightning stroke will usually hear thunder, while an observer 15 km (about 9 mi) away usually will not.

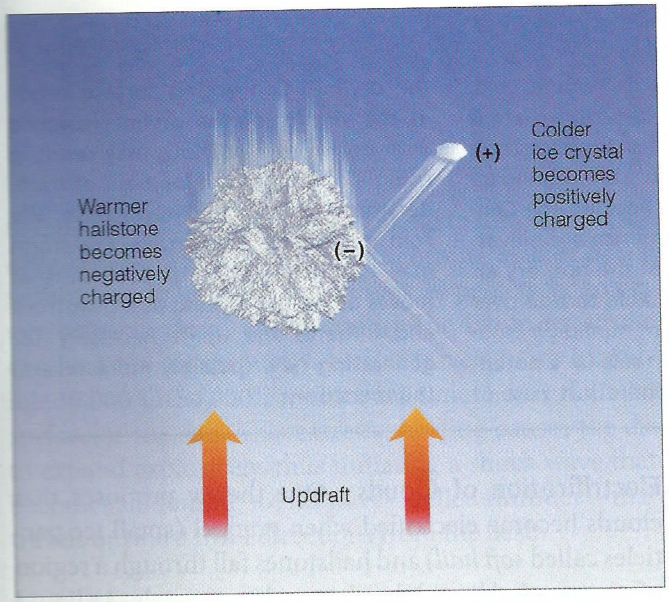
As for lightning, what causes it? The normal fair weather electric field of the atmosphere is characterized by a negatively charged surface and a positively charged upper atmosphere. For lightning to occur, separate regions containing opposite electrical charges must exist within a cumulonimbus cloud. Exactly how this charge separation comes about is not totally comprehended; however, there are many theories to account for it.

Electrification of Clouds One theory proposes that clouds become electrified when graupel (small ice particles called *soft hail*) and hailstones fall through a region of supercooled liquid droplets and ice crystals. As liquid droplets collide with a hailstone, they freeze on contact and release latent heat. This process keeps the surface of the hailstone warmer than that of the surrounding ice crystals. When the warmer hailstone comes in contact with a colder ice crystal, an important phenomenon occurs: *There is a net transfer of positive ions (charged molecules) from the warmer object to the colder object.* Hence, the hailstone (larger, warmer particle) becomes negatively charged and the ice crystal (smaller, cooler particle) positively charged, as the positive ions are incorporated into the ice crystal (see ● Fig. 10.26).

The same effect occurs when colder, supercooled liquid droplets freeze on contact with a warmer hailstone and tiny splinters of positively charged ice break off. These lighter, positively charged particles are then carried to the upper part of the cloud by updrafts. The larger hailstones (or graupel), left with a negative charge,



•Figure 10.25 Thunder travels outward from the lightning stroke in the form of waves. If the sound waves from the lower part of the stroke reach an observer before the waves from the upper part of the stroke, the thunder appears to rumble. If the sound waves bend upward away from an observer, the lightning stroke may be seen, but the thunder will not be heard.



•Figure 10.26 When the tiny colder ice crystals come in contact with the much larger and warmer hailstone (or graupel), the ice crystal becomes positively charged and the hailstone negatively charged. Updrafts carry the tiny positively charged ice crystal into the upper reaches of the cloud, while the heavier hailstone falls through the updraft toward the lower region of the cloud.

either remain suspended in an updraft or fall toward the bottom of the cloud. By this mechanism, the cold upper part of the cloud becomes positively charged, while the middle of the cloud becomes negatively charged. The lower part of the cloud is generally of negative and mixed charge except for an occasional positive region located in the falling precipitation near the melting level (see •Fig. 10.27).

Another school of thought proposes that during the formation of precipitation, regions of separate charge exist within tiny cloud droplets and larger precipitation particles. In the upper part of these particles we find negative charge, while in the lower part we find positive charge. When falling precipitation collides with smaller particles, the larger precipitation particles become negatively charged and the smaller particles, positively charged. Updrafts within the cloud then sweep the smaller positively charged particles into the upper reaches of the cloud, while the larger negatively charged particles either settle toward the lower part of the cloud or updrafts keep them suspended near the middle of the cloud. These two theories of cloud electrification do not rule each other out. It is possible that both processes are at work during the evolution of a thunderstorm.

•Figure 10.27 The generalized charge distribution in a mature thunderstorm.

The Lightning Stroke Because unlike charges attract one another, the negative charge at the bottom of the cloud causes a region of the ground beneath it to become positively charged. As the thunderstorm moves along, this region of positive charge follows the cloud like a shadow. The positive charge is most dense on protruding objects, such as trees, poles, and buildings. The difference in charges causes an electric potential between the cloud and ground. In dry air, however, a flow of current does not occur because the air is a good electrical insulator. Gradually, the electrical potential gradient builds,

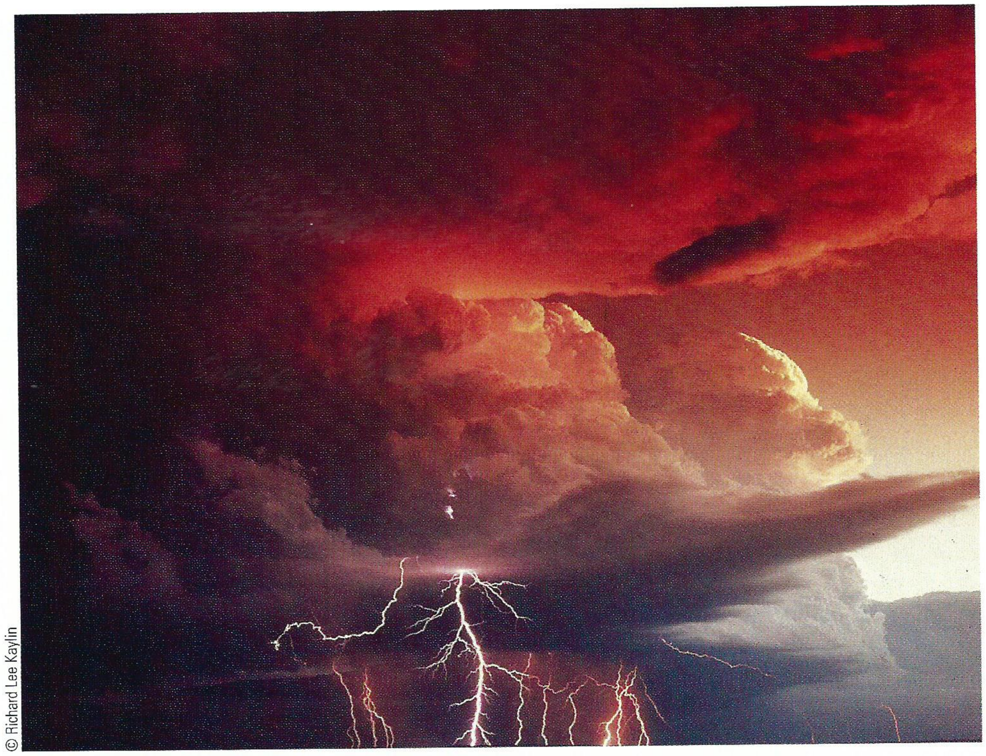
●Figure 10.28 The development of a lightning stroke. (a) When the negative charge near the bottom of the cloud becomes large enough to overcome the air's resistance, a flow of electrons—the stepped leader — rushes toward the earth. (b) As the electrons approach the ground, a region of positive charge moves up into the air through any conducting object, such as trees, buildings, and even humans. (c) When the downward flow of electrons meets the upward surge of positive charge, a strong electric current — a bright return stroke—carries positive charge upward into the cloud.

and when it becomes sufficiently large (on the order of one million volts per meter), the insulating properties of the air break down, a current flows, and lightning occurs.

Cloud-to-ground lightning begins within the cloud when the localized electric potential gradient exceeds roughly 3 million volts per meter along a path perhaps 50 meters long. This situation causes a discharge of electrons to rush toward the cloud base and then toward the ground in a series of steps (see ● Fig. 10.28a). Each discharge covers about 50 to 100 meters, then stops for about 50-millionths of a second, then occurs again over another 50 meters or so. This **stepped leader** is very faint and is usually invisible to the human eye. As the tip of the stepped leader approaches the ground, the potential gradient (the voltage per meter) increases, and a current of positive charge starts upward from the ground (usually along elevated objects) to meet it (see Fig. 10.28b). After they meet, large numbers of electrons flow to the ground and a much larger, more luminous **return stroke** several centimeters in diameter surges upward to the cloud along the path followed by the stepped leader (Fig. 10.28c). Hence, the downward flow of electrons establishes the bright channel of upward propagating current. Even though the bright return stroke travels from the ground up to the cloud, it happens so quickly—in one ten-thousandth of a second—that our eyes cannot resolve the motion, and we see what appears to be a continuous bright flash of light (see ● Fig. 10.29).

Sometimes there is only one lightning stroke, but more often the leader-and-stroke process is repeated in the same ionized channel at intervals of about four-hundredths of a second. The subsequent leader, called a **dart leader,** proceeds from the cloud along the same channel as the original stepped leader; however, it proceeds downward more quickly because the electrical resistance of the path is now lower. As the leader approaches the ground, normally a less energetic return stroke than the first one travels from the ground to the cloud. Typically, a lightning flash will have three or four leaders, each followed by a return stroke. A lightning flash consisting of many strokes (one photographed flash had 26 strokes) usually lasts less than a second. During this short period of time, our eyes may barely be able to perceive the individual strokes, and the flash appears to flicker.

The lightning described so far (where the base of the cloud is negatively charged and the ground positively charged) is called *negative cloud-to-ground-lightning,* because the stroke carries negative charges from the cloud to the ground. About 90 percent of all cloud-to-ground lightning is negative. However, when the base of the cloud is positively charged and the ground negatively charged, a *positive cloud-to-ground lightning*



© Richard Lee Kaylin

Figure 10.29 Time exposure of an evening thunderstorm with an intense lightning display near Denver, Colorado. The bright flashes are return strokes. The lighter forked flashes are probably stepped leaders that did not make it to the ground.

flash may result. Positive lightning, most common with supercell thunderstorms, has the potential to cause more damage because it generates a much higher current level and its flash lasts longer than negative lightning.

Types of Lightning Notice in Fig. 10.29 that lightning may take on a variety of shapes and forms. When a dart leader moving toward the ground deviates from the original path taken by the stepped leader, the lightning appears crooked or forked as shown in ● Fig. 10.30a. Lightning that takes on this shape is called *forked lightning*. An interesting type of lightning is *ribbon lightning* that forms when the wind moves the ionized channel between each return stroke, causing the lightning to appear as a ribbon hanging from the cloud (see Fig. 10.30b). If the lightning channel breaks up, or appears to break up, the lightning (called *bead lightning*) looks like a series of beads tied to a string (see Fig. 10.30c). *Ball lightning* looks like a luminous sphere that appears to float in the air or slowly dart about for several seconds as illustrated in 10.30d). Although many theories have been proposed, the actual cause of ball lightning remains an enigma. *Sheet lightning* forms when either the lightning flash occurs inside a cloud or intervening clouds obscure the flash, such that a portion of the cloud (or clouds) appears as a luminous white sheet (see Fig. 10.30e).

Distant lightning from thunderstorms that is seen but not heard is commonly called **heat lightning** because it frequently occurs on hot summer nights when the overhead sky is clear. As the light from distant electrical storms is refracted through the atmosphere, air molecules and fine dust scatter the shorter wavelengths of visible light, often causing heat lightning to appear orange to a distant observer (see Fig. 10.30f). When cloud-to-ground lightning occurs with thunderstorms that do not produce rain, the lightning is often called **dry lightning**. Such lightning often starts forest fires in regions of dry timber.

Lightning may also shoot upward from the tops of thunderstorms into the upper atmosphere as a dim red flash called a *red sprite,* or as a narrow blue cone called a *blue jet.* These phenomena were seen for years by pilots, but they were not widely studied until they were photographed by sensitive low-light cameras, beginning in 1989.

As the electric potential near the ground increases during a thunderstorm, a current of positive charge moves up pointed objects, such as antennas and masts of ships. However, instead of a lightning stroke, a luminous greenish or bluish halo may appear above them, as a continuous supply of sparks—a *corona discharge*—is sent into the air. This electric discharge, which can cause the top of a ship's mast to glow, is known as **St. Elmo's Fire,** named after the patron saint of sailors (see ● Fig. 10.31). St. Elmo's Fire is also seen around power lines and the wings of aircraft. When St. Elmo's Fire is visible and a thunderstorm is nearby, a lightning flash may occur in the near future, especially if the electric field of the atmosphere is increasing.

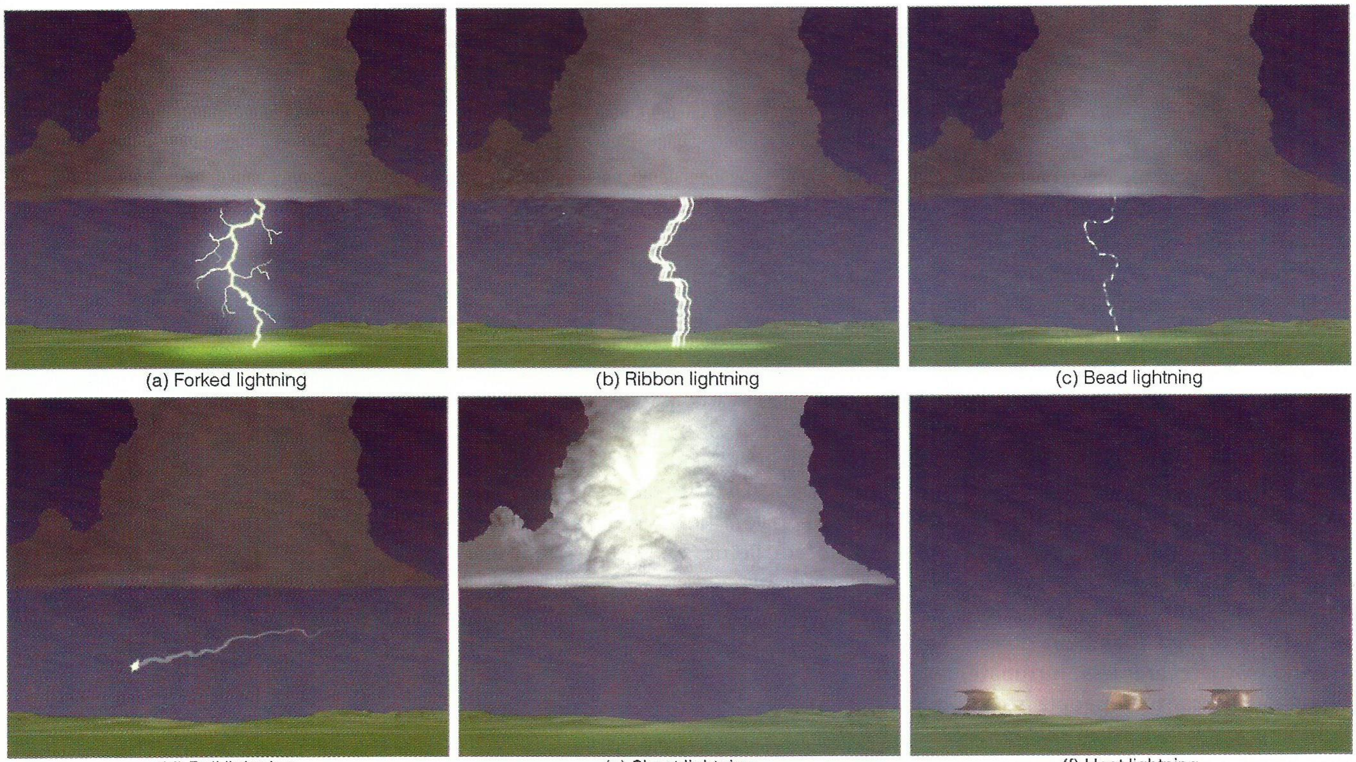


Figure 10.30 Different forms of lightning.

Lightning rods are placed on buildings to protect them from lightning damage. The rod is made of metal and has a pointed tip, which extends well above the structure. The positive charge concentration will be maximum on the tip of the rod, thus increasing the probability that the lightning will strike the tip and follow the metal rod harmlessly down into the ground, where the other end is deeply buried.

When lightning strikes an object such as a car, the bolt typically leaves the passengers unharmed because it usually takes the quickest path to the ground along the outside metal casing of the vehicle. The lightning then jumps to the road through the air, or it enters the roadway through the tires. The same type of protection is provided by the metal skin of a jet airliner, as hundreds of aircraft are struck by lightning each year without harming passengers.

If you should be caught in the open in a thunderstorm, what should you do? Of course, seek shelter immediately, but under a tree? If you are not sure, please read Focus section 10.3.

Lightning Detection and Suppression For many years, lightning strokes were detected primarily by visual observation. Today, cloud-to-ground lightning is located by means of an instrument called a *lightning direction-finder,* which works by detecting the radio waves produced by lightning. Webs of these

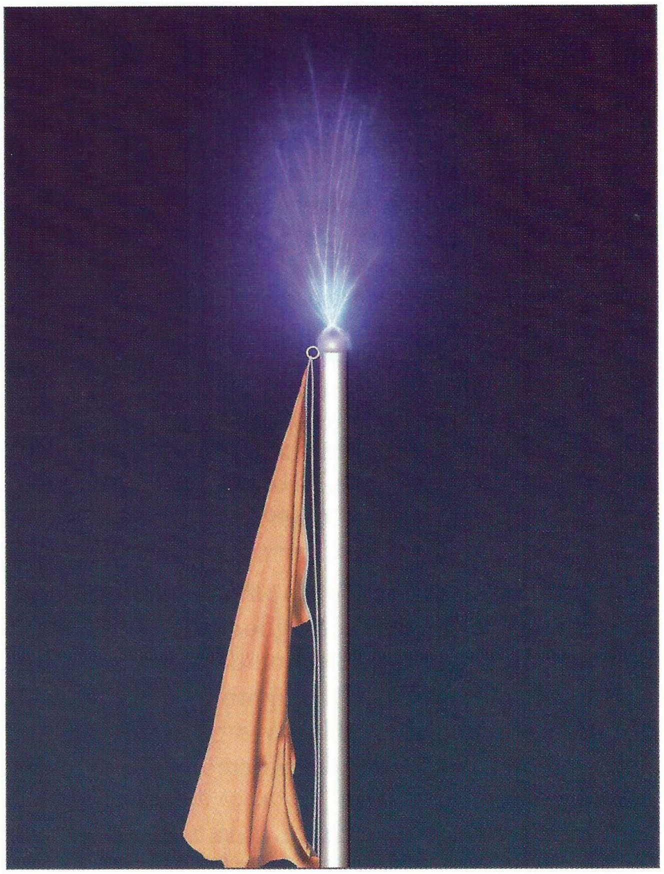
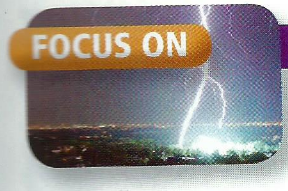


Figure 10.31 St. Elmo's Fire tends to form above objects, such as aircraft wings, ships' masts, and flagpoles.



AN OBSERVATION

10.3

Don't Sit Under the Apple Tree

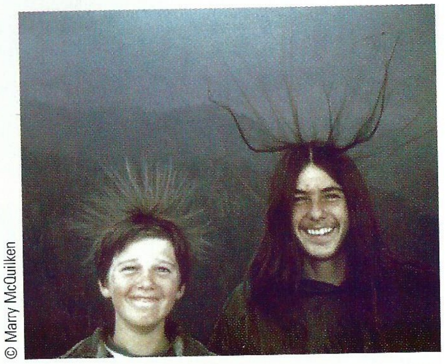
Because a single lightning stroke may involve a current as great as 100,000 amperes, animals and humans can be electrocuted when struck by lightning. Although the per-capita rate of lightning deaths in the United States has decreased by more than 90 percent in the last century, several dozen Americans are killed by lightning each year, with Florida accounting for the most fatalities. Many victims are struck in open places, riding on farm equipment, playing golf, attending sports events, or sailing in a small boat. Some live to tell about it, as did the retired champion golfer Lee Trevino. Others are less fortunate, as about 10 percent of people struck by lightning are killed. Most die from cardiac arrest. Consequently, when you see someone struck by lightning, immediately give CPR (cardiopulmonary resuscitation), as lightning normally leaves its victims unconscious without heartbeat and without respiration. Those who do survive often suffer from long-term psychological disorders, such as personality changes, depression, and chronic fatigue.

Many lightning fatalities occur in the vicinity of relatively isolated trees (see ●Fig. 4). As a tragic example, during June 2004, three people were killed near Atlanta, Georgia, while seeking shelter under a tree. Because a positive charge tends to concentrate in upward projecting objects, the upward return stroke that meets the stepped leader is most likely to originate from such objects. Clearly, sitting under a tree during an electrical storm is not wise. What *should* you do?

When caught outside in a thunderstorm, the best protection, of course, is to get inside a building. But stay away from electrical appliances and corded phones, and avoid taking a shower. Automobiles with metal frames and trucks (but not golf carts) may also provide protection. If no such shelter exists, be sure to avoid elevated places and isolated trees. If you are on level ground, try to keep your head as low as possible, but do not lie down. Because lightning channels usually emanate outward through the ground at the point of a lightning strike, a surface current may travel through your body and injure or kill you. Therefore, crouch down as low as possible and minimize the contact area you have with the ground by touching it with only your toes or your heels.


© Johnny Autery

●Figure 4 A cloud-to-ground lightning flash hitting a 65-foot sycamore tree. It should be apparent why one should *not* seek shelter under a tree during a thunderstorm.


© Marry McQuilken

●Figure 5 Lightning can be both hair-raising and deadly. This photograph, taken by Mary McQuilken, shows her younger brother, Sean (on the left), and older brother, Michael (on the right), standing beneath a thunderstorm atop Moro Rock in California's Sequoia National Park. Shortly after this photo was taken, Sean was struck by lightning and seriously injured, and a nearby hiker was killed by the same lightning strike.

There are some warning signs to alert you to a strike. If your hair begins to stand on end or your skin begins to tingle and you hear clicking sounds, beware—lightning may be about to strike. And if you are standing upright, you may be acting as a lightning rod (see ●Fig. 5).

magnetic devices can be used to pinpoint the location of cloud-to-ground flashes throughout the United States and Canada. Lightning detection devices allow scientists to examine in detail the lightning activity inside a storm as it intensifies and moves. Such investigation gives forecasters a better idea where intense lightning strokes might be expected.*

Satellites now have the capability of providing even more lightning information than ground-based sensors, because satellites can continuously detect all forms of lightning over land and over water (see ●Fig. 10.32). Lightning information correlated with satellite images provides a more complete and precise structure of a thunderstorm.

Each year, approximately 10,000 fires are started by lightning in the United States alone and around $50 million worth of timber is destroyed. For this reason, tests have been conducted to see whether the number of cloud-to-ground lightning discharges can be

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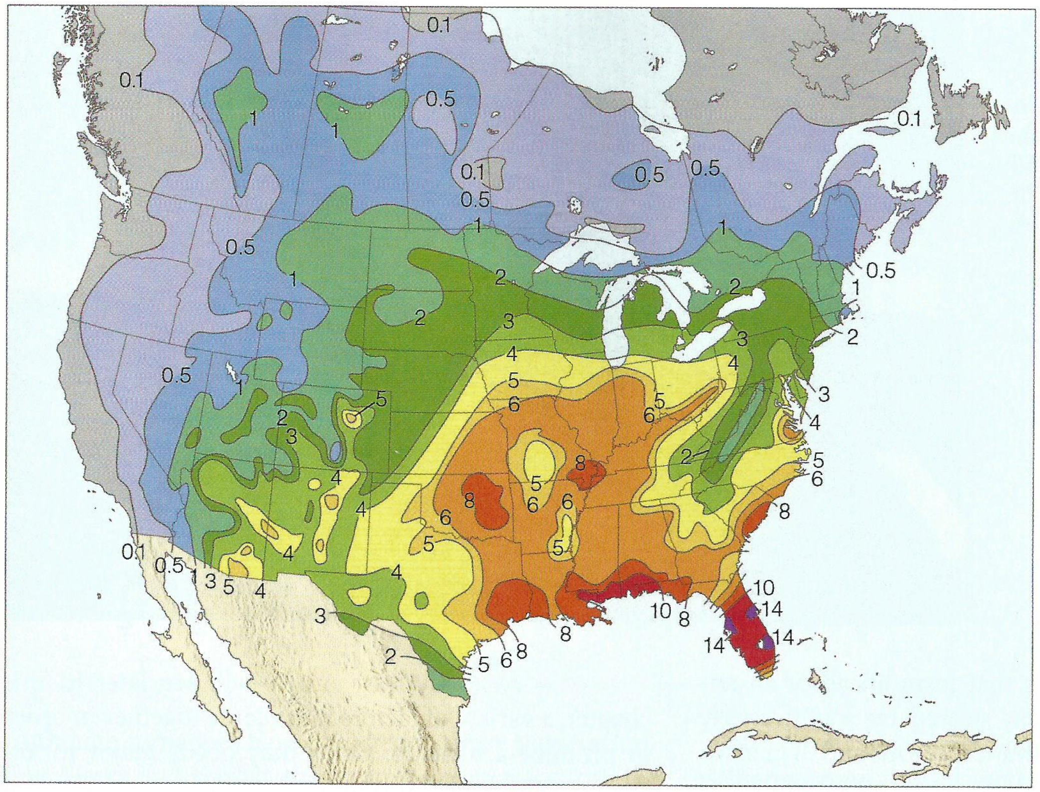
*In fact, with the aid of these instruments, together with satellite images, radar displays, and computer models of the atmosphere, the National Weather Service currently issues experimental lightning probability forecasts for the contiguous United States.



●**Figure 10.32** Average lightning flash density per square kilometer per year from 1997 to 2010. Notice that in the United States, Florida is the most lightning-prone state. (Data from the North American Lightning Detection Network. Courtesy of Vaisala.)

reduced. One technique that has shown some success in suppressing lightning involves seeding a cumulonimbus cloud with hair-thin pieces of aluminum about 10 cm long. The idea is that these pieces of metal will produce many tiny sparks, or corona discharges, and prevent the electrical potential in the cloud from building to a point where lightning occurs. While the results of this experiment are inconclusive, many forestry specialists point out that nature itself may use a similar mechanism to prevent excessive lightning damage. The long, pointed needles of pine trees may act as tiny lightning rods, diffusing the concentration of electric charges and preventing massive lightning strokes.

Now that we have looked at thunderstorms, we are ready to explore a product of a thunderstorm that is one of nature's most awesome phenomena: the tornado, a rapidly spiraling column of air that usually extends down from the base of a cumulonimbus cloud and can strike sporadically and violently.

Tornadoes

A **tornado** is a rapidly rotating column of air extending down from a cumuliform cloud that blows around a small area of intense low pressure with a circulation that reaches the ground. A tornado's circulation may be visible as a funnel-shaped cloud extending from a cumulonimbus cloud to the surface, or as a swirling cloud of dust and debris on the ground. Sometimes called *twisters* or *cyclones,* tornadoes can assume a variety of shapes and forms that range from twisting rope-like funnels, to cylindrical-shaped funnels, to massive black wedge-shaped funnels, to funnels that resemble an elephant's trunk hanging from a large cumulonimbus cloud (see ●Fig. 10.33).

Sometimes the term **funnel cloud** is used to refer to a visible funnel that does not touch the ground. However, a tornado may still be present even if the visible cloud does not extend to the surface. Perhaps only about 30 percent of funnel clouds become active tornadoes. When viewed from above, the vast majority of North American tornadoes rotate counterclockwise about their central core of low pressure. Some have been seen rotating clockwise, but those are infrequent, accounting for as few as two percent of all tornadoes.

Tornadoes can vary greatly in their size, strength, speed, and duration. About 75 percent of all reported tornadoes in the United States have wind speeds of less than 110 knots, although violent tornadoes may have winds exceeding 220 knots. The diameter of most tornadoes is between 100 and 600 m (about 300 to 2000 ft), although some are just a few meters wide and others have diameters exceeding 1600 m (1 mi). In fact, on May 22, 2004, one of the largest tornadoes on record struck near Hallam, Nebraska, with a diameter of about 4 km (2.5 mi).

© Tony Hake/Denver Weather Examiner

Figure 10.33 A large wedge-shaped violent tornado moves northwestward directly for Windsor, Colorado, on May 22, 2008. The photo (taken by a webcam) shows hail the size of golf balls falling from the thunderstorm and covering the ground. It also illustrates how an approaching tornado can appear as a massive dark cloud.

Tornadic thunderstorms that form ahead of an advancing cold front are often steered by southwesterly winds and, therefore, these thunderstorms and their associated tornadoes tend to move from the southwest toward the northeast at speeds usually between 20 and 40 knots. However, some tornadoes have been clocked at speeds greater than 70 knots. Most tornadoes last only a few minutes and have an average path length of about 7 km (4 mi), yet there are cases where they have reportedly traveled for hundreds of kilometers over several hours, such as the one that cut a path 352 km (219 mi) long through portions of Missouri, Illinois, and Indiana on March 18, 1925.

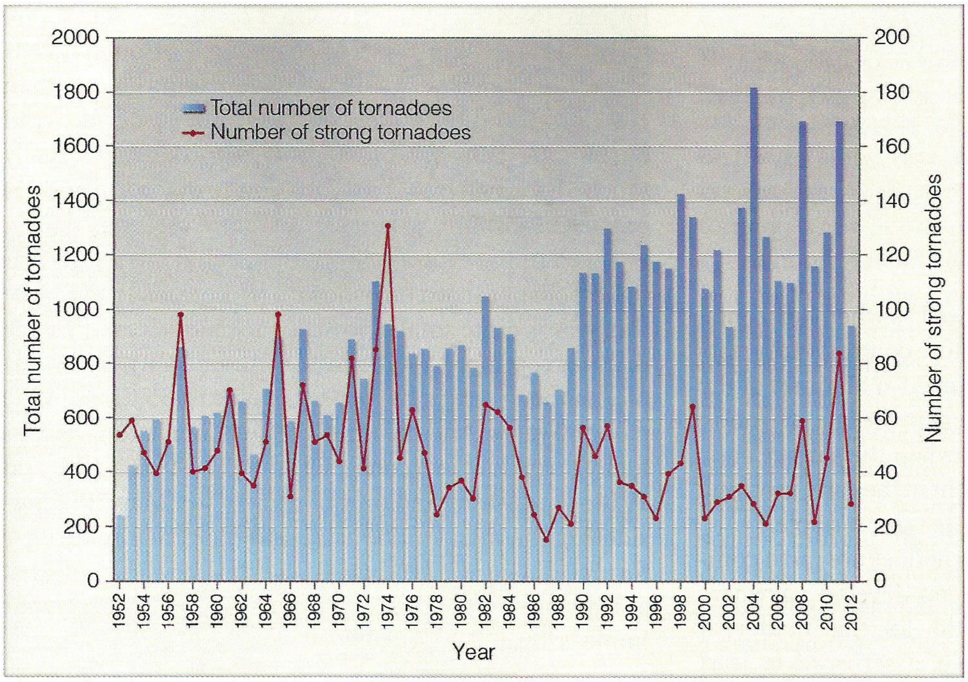
© D. Lloyd/WeatherStock

Figure 10.34 A tornado in its mature stage roars over the Great Plains.

Tornado Life Cycle As we will see later in this chapter, a variety of factors must come together in order to produce a tornado. Once they occur major tornadoes usually evolve through a series of stages. The first stage is the *dust-whirl stage,* where dust swirling upward from the surface marks the tornado's circulation on the ground and a short funnel often extends downward from the thunderstorm's base. Damage during this stage is normally light. As the tornado increases in strength, it enters its *mature stage.* During this stage, damage normally is most severe as the funnel reaches its greatest width and is almost vertical (see ● Fig. 10.34). The final stage, called the *decay stage,* usually finds the tornado stretched into the shape of a rope. Normally, the tornado becomes greatly contorted before it finally dissipates.

Although these are the typical stages of a major tornado, minor tornadoes may skip the mature stage and go directly into the decay stage. However, when a tornado reaches its mature stage, its circulation usually stays in contact with the ground until it dissipates.

Tornado Occurrence and Distribution Tornadoes occur in many parts of the world, but no country experiences more tornadoes than the United States, which, in recent years, has averaged more than 1000 annually. In 2004, a record was set with 1819 tornadoes observed. The number of total tornadoes reported each year has more than doubled since the 1950s (see ● Fig. 10.35), even though the number of strong tornadoes (those with winds exceeding 117 knots or 135 mi/hr) has shown no significant trend. This difference is most likely due to the fact that many weaker, short-lived tornadoes are being reported (and photographed) than was the case decades ago.



●Figure 10.35 Total number of tornadoes reported in the United States for each year from 1952 to 2012 (blue bar); and the total number of strong tornadoes with winds exceeding 117 knots or 135 mi/hr reported during the same period (red line). (Note: Tornadoes that occurred before the introduction of the Enhanced Fujita (EF) Scale in 2007 have been converted to the new scale.) (Storm Prediction Center/NOAA)

Although tornadoes have occurred in every state, including Alaska and Hawaii, the greatest number occur in the tornado belt or **Tornado Alley** of the Central Plains, which stretches from central Texas to Nebraska* (see ● Fig. 10.36). The belt of tornadoes that occur over Mississippi and Alabama is sometimes called **Dixie Alley**.

The Central Plains region is most susceptible to tornadoes because it often provides the proper atmospheric setting for the development of the severe thunderstorms that spawn tornadoes. You may recall from Fig. 10.19 on p. 299, that over the Central Plains (especially in spring) warm, humid surface air is overlain by cooler, drier air aloft, producing a conditionally unstable atmosphere. When a strong vertical wind shear exists (usually provided by a low-level jet and the polar jet stream) and the surface air is forced upward, large supercell thunderstorms capable of spawning tornadoes may form. Therefore, tornado frequency is highest during the spring and lowest during the winter when the warm surface air is normally absent.

In ● Fig. 10.37, we can see that about 70 percent of all tornadoes in the United States develop from March to July. The month of May normally has the greatest number of tornadoes* (the average is about 9 per day) while the most violent tornadoes seem to occur in April when vertical

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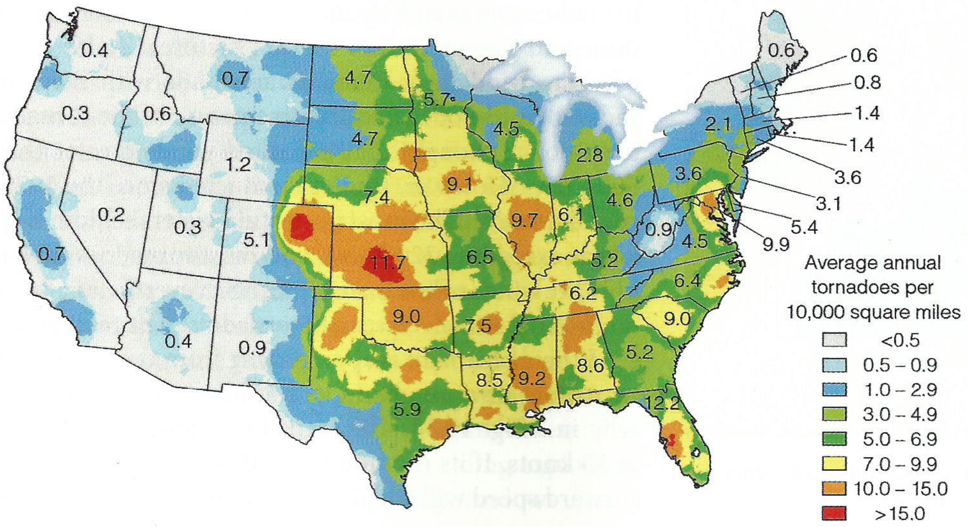
*Many of the tornadoes that form along the Gulf Coast are generated by thunderstorms embedded within the circulation of hurricanes.

*During May 2003, a record 516 tornadoes touched down in the United States, an average of over 16 per day. However, during April 2011, a record 748 tornadoes were reported, the most in any month ever.



●Figure 10.36 The average annual number of observed tornadoes per 10,000 square miles in each state from 1991 to 2012. (NOAA)

DID YOU KNOW?

Although the United States and Canada rank one and two in the world in annual number of tornadoes, Bangladesh has experienced the deadliest tornadoes. About 1300 people died when a violent tornado struck north of Dacca on April 26, 1989, and on May 13, 1996, over 700 lives were lost when a violent tornado touched down in Tangail.

wind shear tends to be present as well as when horizontal and vertical temperature and moisture contrasts are greatest. Although tornadoes have occurred at all times of the day and night, they are most frequent in the late afternoon (between 4:00 P.M. and 6:00 P.M.), when the surface air is most unstable; they are least frequent in the early morning before sunrise, when the atmosphere is most stable.

Although large, destructive tornadoes are most common in the Central Plains, they can develop anywhere in the United States (or the world, for that matter) if conditions are right. For example, a series of at least 36 tornadoes, more typical of those that form over the plains, marched through North and South Carolina on March 28, 1984, claiming 59 lives and causing hundreds of millions of dollars in damage. One tornado was enormous, with a diameter over 2 miles wide and winds that exceeded 200 knots. No place is totally immune to a tornado's destructive force. On March 1, 1983, a rare tornado cut a 5-km swath of destruction through downtown Los Angeles, California, damaging more than 100 homes and businesses and injuring 33 people. And during the summer of 2010, two tornadoes actually touched down in New York City. One tornado (on July 25) caused only minimal damage but injured seven people.

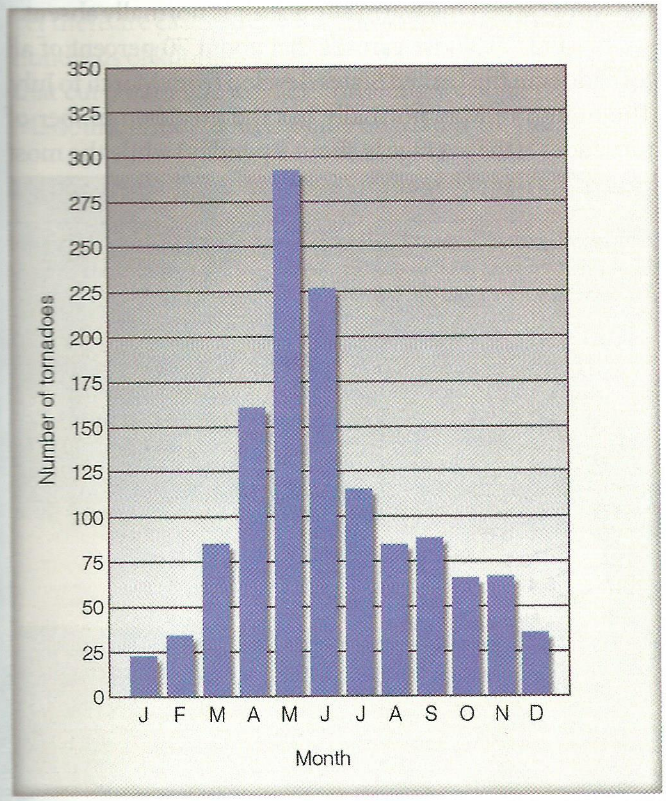


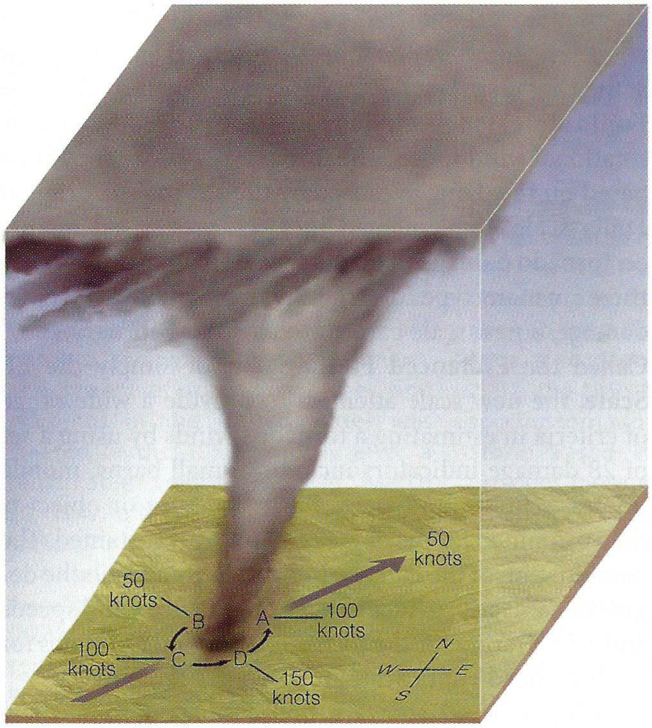
Figure 10.37 Average number of tornadoes during each month in the United States from 2000 to 2010. (NOAA)

Even in the central part of the United States, the statistical chance that a tornado will strike a particular place this year is quite small. However, tornadoes can provide many exceptions to statistics. Oklahoma City, for example, has been struck by tornadoes at least 35 times in the past 100 years. And the little town of Codell, Kansas, was hit by tornadoes in 3 consecutive years—1916, 1917, and 1918—and each time on the same date: May 20! Considering the many millions of tornadoes that must have formed during the geological past, it is very probable that at least one actually moved across the land where your home is located, especially if it is in the Central Plains.

Tornado Winds The strong winds of a tornado can destroy buildings, uproot trees, and hurl all sorts of lethal missiles into the air. People, animals, and home appliances all have been picked up, carried several kilometers, then deposited. Tornadoes have accomplished some astonishing feats, such as lifting a railroad coach with its 117 passengers and dumping it in a ditch about 25 m (82 ft) away. Showers of toads and frogs have poured out of a cloud after tornadic winds sucked them up from a nearby pond. Other oddities include chickens losing all of their feathers, pieces of straw being driven into metal pipes, and frozen hot dogs being driven into concrete walls. Miraculous events have occurred, too. In one instance, a schoolhouse was demolished, and the 85 students inside were carried more than 90 m (295 ft) without any of them being killed.

Our earlier knowledge of the furious winds of a tornado came mainly from observations of the damage done and the analysis of motion pictures. Today more accurate wind measurements are made with Doppler radar. Because of the destructive nature of the tornado, it was once thought that it packed winds greater than 500 knots. However, studies conducted since the 1970s reveal that even the most powerful twisters seldom have winds exceeding 220 knots, and most tornadoes probably have winds of less than 125 knots. Nevertheless, being confronted with even a small tornado can be terrifying.

When a tornado is approaching from the southwest, its strongest winds are on its southeast side. We can see why in Fig. 10.38. The tornado is heading northeast at 50 knots. If its rotational speed is 100 knots, then its forward speed will add 50 knots to its southwestern side



•**Figure 10.38** The total wind speed of a tornado is greater on one side than on the other. When facing an on-rushing tornado, the strongest winds will be on your left side.

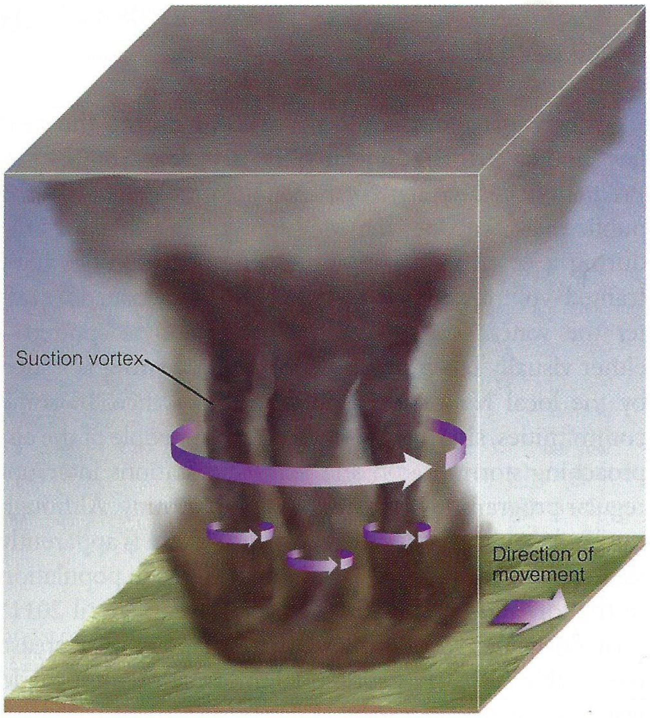
(position D) and subtract 50 knots from its northwestern side (position A). Hence, the most destructive and extreme winds will be on the tornado's southeastern side.

Many violent tornadoes (with winds exceeding 180 knots) contain smaller whirls that rotate within them. Such tornadoes are called *multi-vortex tornadoes* and the smaller whirls are called **suction vortices** (see •Fig. 10.39). Suction vortices are only about 10 m (30 ft) in diameter, but they rotate very fast and apparently do a great deal of damage.

Seeking Shelter The high winds of the tornado cause the most damage as walls of buildings buckle and collapse when blasted by the extreme wind force and by debris carried by the wind. Also, as high winds blow over a roof, lower air pressure forms above the roof. The greater air pressure inside the building then lifts the roof just high enough for the strong winds to carry it away. A similar effect occurs when the tornado's intense low-pressure center passes overhead. Because the pressure in the center of a tornado may be more than 100 mb (3 in.) lower than that of its surroundings, there is a momentary drop in outside pressure when the tornado is above the structure. It was once thought that opening windows and allowing inside and outside pressures to equalize would minimize the chances of the building exploding. However, it is now known that opening windows during a tornado actually increases the pressure on the opposite wall and *increases* the chances that the building will collapse. (The windows are usually shattered by flying debris anyway.) Damage from tornadoes may also be inflicted on people and structures by flying debris. Hence, the wisest course to take when confronted with an approaching tornado is to *seek shelter immediately.*

At home, take shelter in a basement or storm shelter. In a large building without a basement, the safest place is usually in a small room, such as a bathroom, closet, or interior hallway, preferably on the lowest floor and near the middle of the edifice. Pull a mattress around you as the handles on the side make it easy to hang onto. Wear a bike or football helmet, if one is available, to protect your head from flying debris, and stay away from windows. At school, move to the hallway and lie flat with your head covered. In a mobile home, leave immediately and seek substantial shelter. If none exists, lie flat on the ground in a depression or ravine.

Don't try to outrun an oncoming tornado in a car or truck, as tornadoes often cover erratic paths with speeds sometimes exceeding 70 knots (80 mi/hr). Stop your car and let the tornado go by, or turn around on the road's shoulder and drive in the opposite direction. And do not take shelter under a freeway overpass, as the tornado's winds are actually funneled (strengthened) by the overpass structure. If caught outdoors in an open field, look for a ditch, streambed, or ravine, and lie flat with your head covered.



•**Figure 10.39** A powerful multi-vortex tornado with three suction vortices.

▮TABLE 10.1 Average Annual Number of Tornadoes and Tornado Deaths by Decade

DECADE	TORNADOES/ YEAR	DEATHS/YEAR
1950–59	480	148
1960–69	681	94
1970–79	858	100
1980–89	819	52
1990–99	1220	56
2000–09	1277*	56
2010–12	1304†	226†

†More tornadoes are being reported as populations increase and tornado-spotting technology improves.
*A three year average.

▮TABLE 10.2 Enhanced Fujita (EF) Scale for Damaging Tornado Winds

EF SCALE	CATEGORY	MI/HR*	KNOTS*
EF0	Weak	65–85	56–74
EF1		86–110	75–95
EF2	Strong	111–135	96–117
EF3		136–165	118–143
EF4	Violent	166–200	144–174
EF5		>200	>174

*The wind speed is a 3-second gust estimated at the point of damage, based on a judgment of damage indicators.

When tornadoes are likely to form during the next few hours, a **tornado watch** is issued by the Storm Prediction Center in Norman, Oklahoma, to alert the public that tornadoes may develop within a specific area during a certain time period. Many communities have trained volunteer spotters, who look for tornadoes after the watch is issued. Once a tornado is spotted—either visually or on radar—a **tornado warning** is issued by the local National Weather Service Office. In some communities, sirens are sounded to alert people of the approaching storm. Radio and television stations interrupt regular programming to broadcast the warning. Although not completely effective, this warning system is apparently saving many lives. Despite the large increase in population in the tornado belt during the past 30 years, until 2011* tornado-related deaths had actually shown a decrease (see ▮Table 10.1). (For additional information on tornado watches and warnings, read Focus section 10.4.)

The Enhanced Fujita Scale In the 1960s, the late Dr. T. Theodore Fujita, a noted authority on tornadoes at the University of Chicago, proposed a scale (called the **Fujita scale**) for classifying tornadoes according to their rotational wind speed. The tornado winds are estimated based on the damage caused by the storm. The original Fujita scale, implemented in 1971, was based mainly on tornado damage incurred by a frame house. Because there are many types of structures susceptible to tornado damage, a new scale came into effect in February 2007. Called the **Enhanced Fujita Scale**, or simply the **EF Scale**, the new scale attempts to provide a wide range of criteria in estimating a tornado's winds by using a set of 28 damage indicators including small barns, mobile homes, schools, and trees. Each structure or object is then examined for the degree of damage it sustained. The combination of the damage indicators along with the degree of damage provides a range of probable wind speeds and an EF rating for the tornado. The wind estimates for the Enhanced Fujita Scale are given in ▮Table 10.2.

●Figure 10.40 shows a house situated somewhere on the Great Plains of the United States or Canada, and ●Fig. 10.41 shows the damaging effect that tornadoes ranging in intensity from EF0 to EF5 can have on this structure and its surroundings. Notice that an EF0 tornado causes only minimal damage, whereas an EF5 completely demolishes the house and sweeps it off its foundation. Determining the EF intensity of a tornado is often not an easy task, as one part of the tornado's path may exhibit EF3 damage, while another area may show EF4 damage.

Statistics reveal that the majority of tornadoes are relatively weak, with wind speeds less than about 110 knots (115 mi/hr). Only a few percent each year are classified as violent, with perhaps one or two EF5 tornadoes reported annually (although several years may pass without the United States experiencing an EF5). However, it is the violent tornadoes that account for the majority of tornado-related deaths.

As an example, an EF5 tornado roared through the town of Greensburg, Kansas, on the evening of May 4, 2007. The tornado, with winds estimated at 180 knots (205 mi/hr) and a width approaching 2 miles, completely destroyed over 95 percent of the town. The tornado took 11 lives, and probably more would have perished had it not been for the tornado warning issued by the National Weather Service and the sirens in the town signaling "take cover" about 20 minutes before the tornado struck.

ONLINE APPENDICES

To view the original Fujita scale and other information on winds, go to the Online Appendix at the Meteorological CourseMate website at www.cengagebrain.com.

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*The year 2011 was an exceptionally deadly year for tornadoes, as 553 people perished in these storms.

FOCUS ON A SPECIAL TOPIC 10.4

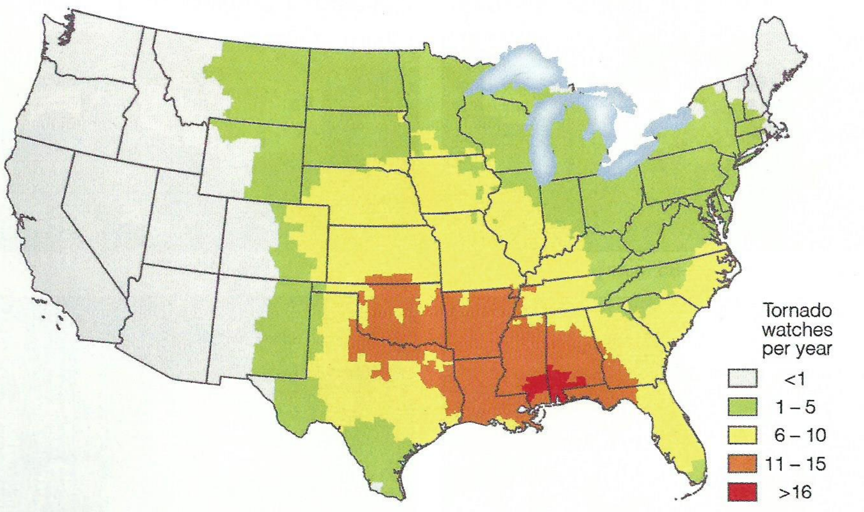
The Evolution of Tornado Watches and Warnings

Few weather situations are as terrifying as the approach of a churning tornado. Fortunately, the United States has a well-established system for letting people know when twisters are possible and when one is imminent. The system of tornado watches and warnings in the United States was created in the 1950s, shortly after a remarkable coincidence. On March 20, 1947, a destructive tornado struck Tinker Air Force Base, just southeast of Oklahoma City. A total of 50 aircraft were destroyed, at a cost of $10 million (likely more than $100 million in today's dollars). The next day, two Air Force meteorologists, E.J. Fawbush and Robert Miller, were asked to develop a technique for predicting when tornadoes were likely. Fawbush and Miller quickly created a scheme based on such factors as instability, wind shear, and the approach of a front. Incredibly, another tornado struck the base only five days after the first one. This time the brand-new Fawbush-Miller technique provided notice that tornadoes were very likely, so aircraft were safely sheltered and the damage toll was far less.

As we previously learned, a tornado watch is issued when conditions favor the formation of severe thunderstorms and tornadoes. The average tornado watch covers a period of 6 to 8 hours and an area of roughly 65,000 square km, about the size of South Carolina. Tornado watches are issued by the National Weather Service's Storm Prediction Center in Norman, Oklahoma, in coordination with local NWS offices. When conditions are most threatening, a watch will receive the "PDS" tag—*particularly dangerous situation*. The center also issues more general outlooks that highlight where severe weather is possible up to eight days in advance. If you are in a region under a tornado watch, stay aware of changing weather conditions and watch or listen for possible warnings.

When a tornado is actually sighted, or when a tornadic circulation is evident on radar, the local NWS office will issue a *tornado warning*. In October 2007, the NWS launched a new, more specific tornado warning system called *Storm Based Warnings*. This system provides more precise information on where a tornado is located and where it is heading. Warning's typically cover parts of one to several counties and are in effect for 30 to 60 minutes. If your smartphone is equipped to receive Wireless Emergency Alerts (WEA), you will normally receive a text message if a tornado warning is issued in your area. Should you find yourself in a tornado warning, you need to take cover immediately—ideally in an interior room on the lowest floor of a well-built structure, but not in a vehicle or a mobile home.

The tornado warning system is not perfect. As many as 30 percent of all tornadoes come and go before a warning can be issued, and more than half of all warnings are "false alarms," typically because a tornadic signature on radar has failed to produce a twister. Even when a tornado is accurately warned, it will usually strike only part of a warned area. Still, the risk of injury or death is very real in these situations, and many lives are saved by quick response to a tornado warning. The advent of the United States Next Generation Doppler Radar network helped improve the warning system substantially. The average lead time for a tornado warning rose from 3 minutes in the late 1970s to 13 minutes by the late 1990s, and the lead time is now often 20 minutes or more for the longest-lived and most violent tornadoes. A new NWS initiative is exploring whether high-resolution computer models that incorporate radar data could help increase the lead time of tornado warnings to as much as 1 to 2 hours.



•Figure 6 Average annual number of tornado watches per county issued by the Storm Prediction Center from 1999-2008. (NOAA)

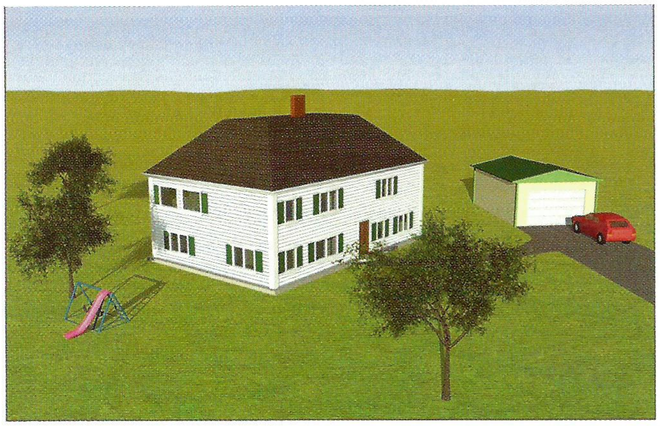


Figure 10.40 A house situated on the Great Plains. Observe in Fig. 10.41 how tornadoes of varying EF intensity can damage this house and its surroundings.

And on May 22, 2011, a violent EF5 multi-vortex tornado struck Joplin, Missouri, completely demolishing part of the city.* The tornado injured almost 1000 people and took 159 lives—the greatest death toll from a single tornado in the United States since the Woodward, Oklahoma, tornado in April 1947.

Tornado Outbreaks As we have seen in the previous situations, tornadoes each year take the lives of many people. The yearly average is less than 100, although over 100 may die in a single day, as tragically occurred in Joplin, Missouri. In recent years, an alarming statistic is that (except for 2011) roughly half of all fatalities occurred in mobile homes. The deadliest tornadoes are those that occur in *families,* that is, a group or series of tornadoes spawned by the same thunderstorm. (Some thunderstorms produce a sequence of several tornadoes over 2 or more hours and over distances of 100 km or more.) Tornado families often are the result of a single, long-lived supercell thunderstorm. When a large number of tornadoes (typically 6 or more) form over a particular region, this constitutes what is termed a **tornado outbreak.** The most severe tornado outbreaks are typically very well predicted because they involve large areas of conditionally unstable air and extremely strong, vertical wind shear, along with an upper-level trough that helps trigger widespread supercell formation. These features can often be spotted by computer forecast models several days in advance.

A particularly devastating outbreak occurred on May 3, 1999, when 78 tornadoes marched across parts of Texas, Kansas, and Oklahoma. One tornado, whose width at times reached one mile and whose wind speed was measured by Doppler radar at 276 knots (318 mi/ hr), moved through the southwestern section of Oklahoma City. Within its 40-mile path, it damaged or destroyed thousands of homes, injured nearly 600 people, claimed 38 lives, and caused over $1 billion in property damage. Ironically, on May 20, 2013, an EF5 tornado with maximum winds estimated at 183 knots (210 mi/hr), took roughly the same path as the deadly May 3, 1999, tornado. The tornado was on the ground for 27 km (17 mi) and cut

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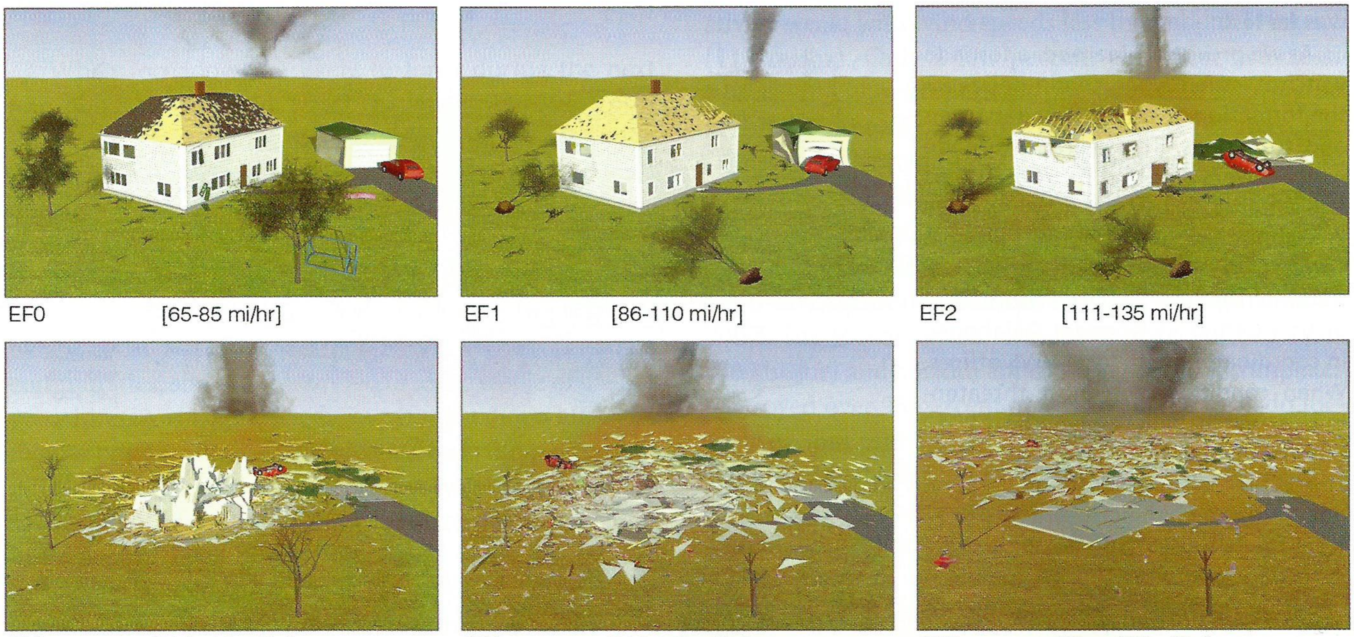
*A photo of the Joplin tornado is shown in Fig. 1.20, on p. 23 The destruction caused by this tornado are shown in Figure 1.21.



EF0 [65-85 mi/hr]
EF1 [86-110 mi/hr]
EF2 [111-135 mi/hr]
EF3 [136-165 mi/hr]
EF4 [166-200 mi/hr]
EF5 [Over 200 mi/hr]

Figure 10.41 Damage to the house in Fig. 10.40 and its surroundings caused by tornadoes of varying EF intensity.


AP Photo/The Tuscaloosa News, Dusty Compton, File

•**Figure 10.42** This huge EF4 multi-vortex tornado devastated sections of Tuscaloosa, Alabama, on April 27, 2011. (See also Fig. 10.43.)

a devastating path through a highly populated section of Moore, Oklahoma, killing 24 people, including 10 children, and causing over $1 billion in damage.

One of the most violent outbreaks ever recorded occurred on April 3 and 4, 1974. During a 16-hour period, 148 tornadoes cut through parts of 13 states, killing 307 people, injuring more than 6000, and causing an estimated $600 million in damage. Some of these tornadoes were among the most powerful ever witnessed, as at least 6 tornadoes reached F5 intensity. The combined path of all the tornadoes during this *super outbreak* amounted to 4181 km (2598 mi), well over half of the total path for an average year. The greatest loss of life attributed to tornadoes occurred during the tri-state outbreak of March 18, 1925, when an estimated 695 people died as at least 7 tornadoes traveled a total of 703 km (437 mi) across portions of Missouri, Illinois, and Indiana.

A more recent super outbreak occurred in 2011 on April 25 through April 28, when 336 tornadoes (4 of which reached EF5 intensity) moved across portions of the southern United States. The tornadoes claimed 322 lives, injured thousands of people, and caused more than $10 billion in damages. One particularly strong EF4 tornado, with winds estimated at 190 mi/hr, moved through the City of Tuscaloosa, Alabama, on April 27 (see • Fig. 10.42). The tornadoes which had a damage path width of about 1.5 miles, left 43 dead in Tuscaloosa and injured more than 1000 (see • Fig. 10.43).

At this point it is important to note that it may be almost impossible to survive the powerful winds of a


NOAA

•**Figure 10.43** Damage in Tuscaloosa, Alabama, after a massive EF4 tornado (shown in Fig. 10.42) plowed through the city on April 27, 2011.

violent tornado if you are inside the wrong type of structure, such as a mobile home. During the May 3, 1999, tornado outbreaks many people who abandoned their unprotected homes in favor of muddy ditches survived largely because the ditches were below ground level and out of the path of wind-blown objects. Many who stayed in the confines of their inadequate homes perished when tornado winds blew their homes away, leaving only the foundations.

Tornado Formation

Although not everything is known about the formation of a tornado, we do know that tornadic thunderstorms require a conditionally unstable atmosphere. Most often, tornadoes form with supercell thunderstorms in an environment with strong vertical wind shear.* The rotating air of the tornado may begin within a thunderstorm and work its way downward, or it may begin at the surface and work its way upward. First, we will examine tornadoes that form with supercells; then we will examine nonsupercell tornadoes.

Supercell Tornadoes Tornadoes that form with supercell thunderstorms are called **supercell tornadoes**. Earlier, we learned that supercell is a thunderstorm that has a single rotating updraft that can exist for hours. ●Figure 10.44 illustrates this updraft and the pattern of precipitation associated with the storm. Notice that as warm, humid air is drawn into the supercell, it spins counterclockwise as it rises. Near the top of the storm, strong winds push the rising air to the northeast. Heavy precipitation falling northeast of the updraft mixes with drier air. Evaporative cooling chills the air. The heavy rain-chilled air then descends as a strong downdraft called the *forward-flank downdraft*. The separation of the updraft from the downdraft means that the downdraft is unable to fall into the updraft and suppress it. This is why the storm is able to maintain itself as a single entity for hours.

Tornadoes are rapidly rotating columns of air, so what is it that starts the air rotating? We can see how rotation can develop by looking at ●Fig. 10.45a. Notice that there is vertical directional wind shear, as the surface winds are southerly and a kilometer or so above the surface they are northerly. There is also vertical wind speed shear as the wind speed increases rapidly with height. This vertical wind shear causes the air near the surface to rotate about a horizontal axis much like a pencil rotates around its long axis. Such horizontal tubes of spinning air are called *vortex tubes*. (These spinning vortex tubes also form when a southerly low-level jet exists just above southerly surface winds.) If the strong updraft of a developing thunderstorm should *tilt* the rotating tube upward and draw it into the storm, as illustrated in Fig. 10.45b, the tilted rotating tube then becomes a rotating air column inside the storm. The rising, spinning air is now part of the storm's structure called the *mesocyclone*—an area of lower pressure (a small cyclone) perhaps 5 to 10 kilometers across. The rotation of the updraft lowers the pressure in the mid-levels of the thunderstorm, which acts to increase the strength of the updraft.*

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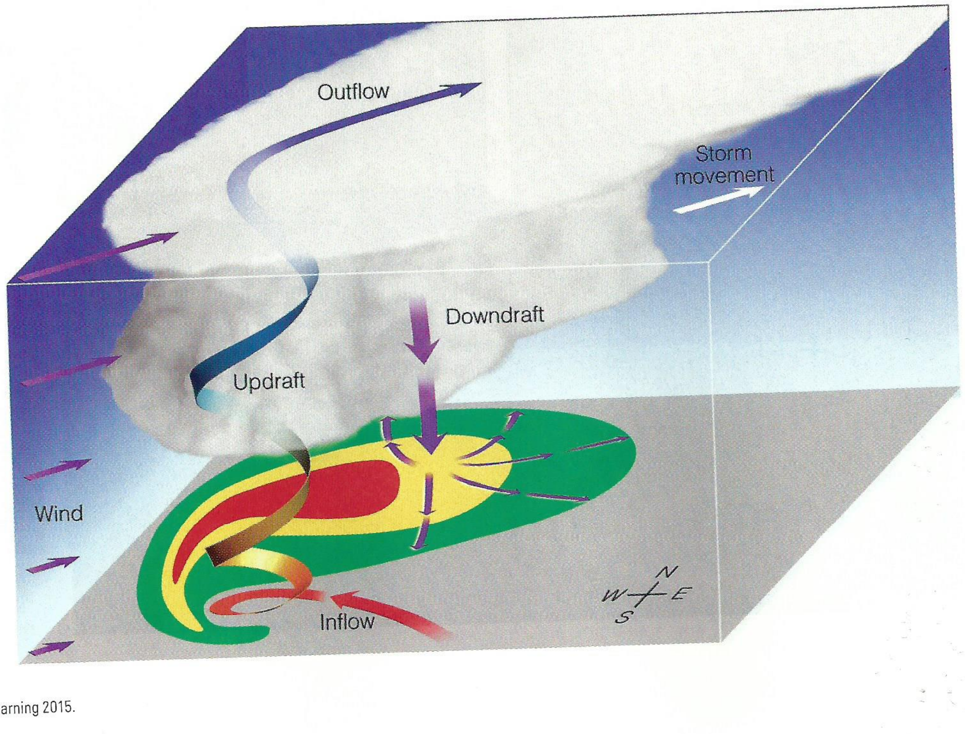
*Atmospheric conditions favorable for the formation of supercell thunderstorms is presented beginning on p. 297.

*You can obtain an idea of what might be taking place in the supercell by stirring a cup of coffee or tea with a spoon and watching the low pressure form in the middle of the beverage.



●Figure 10.44 A simplified view of a supercell thunderstorm with a strong updraft and downdraft, forming in a region of strong vertical wind speed shear. Regions beneath the supercell receiving precipitation are shown in color: green for light rain, yellow for heavier rain, and red for very heavy rain and hail.

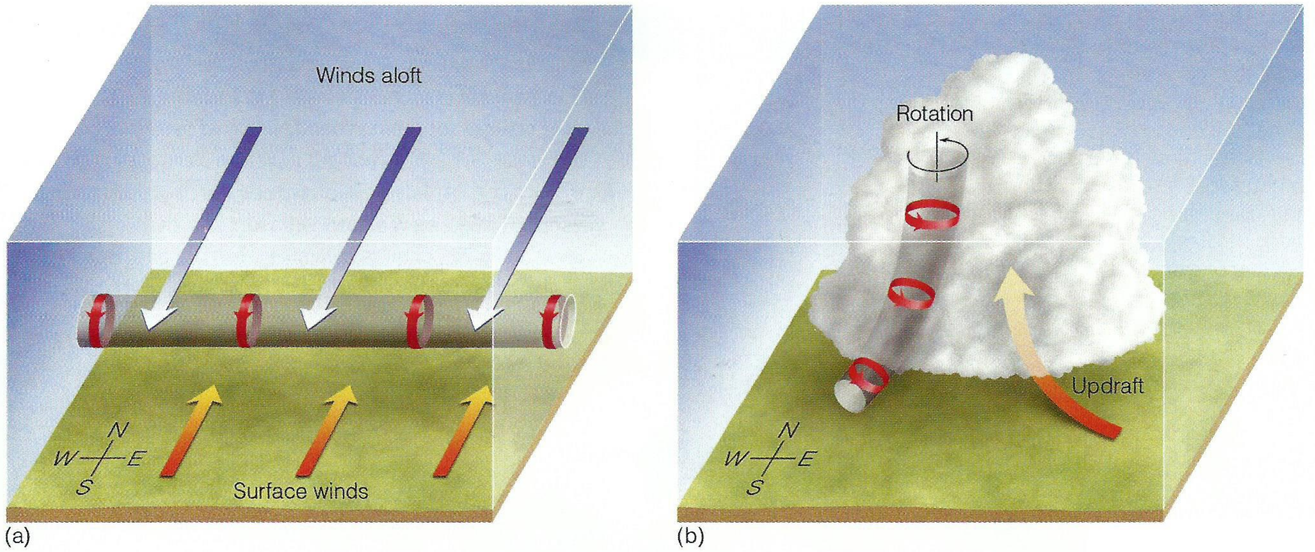
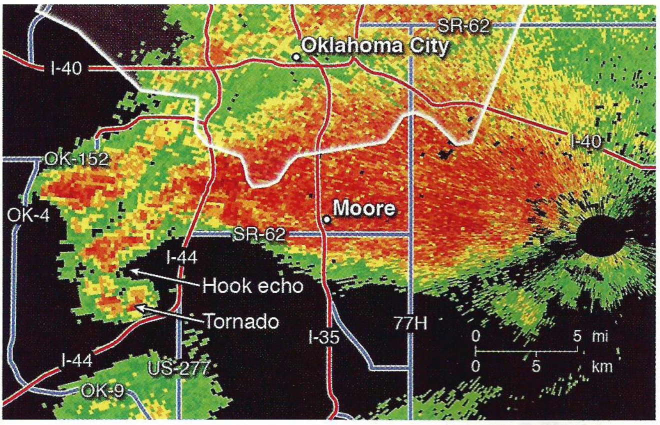


Figure 10.45 (a) A spinning vortex tube created by vertical wind shear. (b) The strong updraft in the developing thunderstorm carries the vortex tube into the thunderstorm producing a rotating air column that is oriented in the vertical plane.

As we learned earlier in the chapter, the updraft is so strong in a supercell, sometimes 90 knots (104 mi/hr), that precipitation cannot fall through it. Southwesterly winds aloft usually blow the precipitation northeastward. If the mesocyclone persists, it can circulate some of the precipitation counterclockwise around the updraft. This swirling precipitation shows up on the radar screen, whereas the area inside the mesocyclone (nearly void of precipitation at lower levels) does not. The region inside the supercell where radar is unable to detect precipitation is known as the *bounded weak echo region (BWER)*. Meanwhile, as the precipitation is drawn into a cyclonic spiral around the mesocyclone, the rotating precipitation may, on the Doppler radar screen, unveil itself in the shape of a hook, called a **hook echo**, as shown in Fig. 10.46.



NOAA/National Weather Service

Figure 10.46 A tornado-spawning supercell thunderstorm over Oklahoma City during the afternoon of May 20, 2013, shows a hook echo west of Moore, Oklahoma, in its rainfall reflectivity pattern on a Doppler radar screen. The colors red and orange represent the heaviest precipitation. Compare this precipitation pattern with the precipitation pattern illustrated in Fig. 10.44. (A photo of this tornado can be found in Chapter 9, Fig. 9.12, on p. 272.)

At this point in the storm's development, the updraft, the counterclockwise swirling precipitation, and the surrounding air may all interact to produce the *rear-flank downdraft* (to the south of the updraft), as shown in Fig. 10.47. The strength of the downdraft is driven in part by the amount of precipitation-induced cooling in the upper levels of the storm. The rear-flank downdraft (often simply called *RFD*) appears to play an important role in producing tornadoes in classic supercells. However, researchers are still looking into many questions about how the rear-flank downdraft develops.

When the rear-flank downdraft strikes the ground as illustrated in Fig. 10.47, it may (under favorable shear conditions) interact with the forward-flank downdraft beneath the mesocyclone to initiate **tornadogenesis**–the formation of a tornado. At the surface of the mature supercell the relatively cool air of the rear-flank downdraft now wraps around the updraft at the center of the mesocyclone. This situation may initiate additional spin which can be lifted into the mesocyclone. At this point, the lower half of the updraft begins to rise more slowly than the updraft aloft.

The rising updraft, which we can imagine as a column of air, now shrinks horizontally and stretches vertically. This *vertical stretching* of the spinning column of air causes the rising, spinning air to spin faster.* If this stretching process continues, the rapidly rotating

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*As the rotating air column stretches vertically into a narrow column, its rotational speed increases, a situation called the *conservation of angular momentum.*

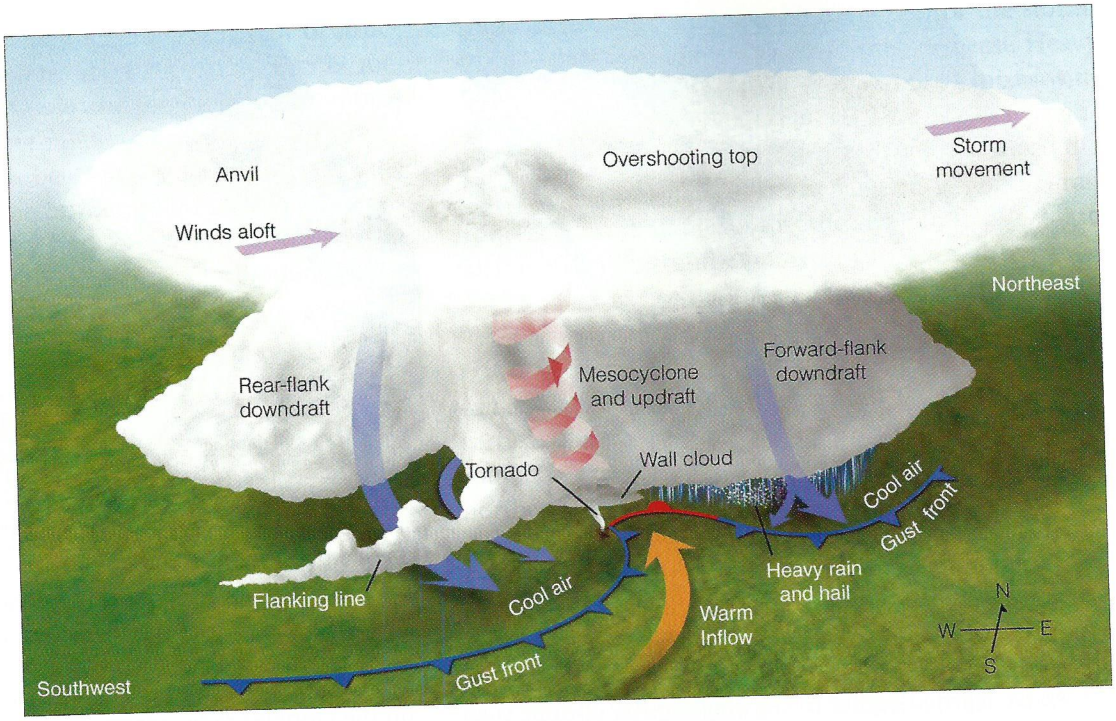

Figure 10.47 A classic mature tornadic supercell thunderstorm showing updrafts and downdrafts, along with surface air flowing counterclockwise and in toward the tornado. The flanking line is a line of cumulus clouds that form as surface air is lifted into the storm along the gust front.

air column may shrink into a narrow column of rapidly rotating air—a *tornado vortex.*

As air rushes upward and spins around the low-pressure core of the vortex, the air expands, cools, and, if sufficiently moist, condenses into a visible cloud—the *funnel cloud.* As the air beneath the funnel cloud is drawn into its core, the air cools rapidly and its moisture condenses, and the funnel cloud descends toward the surface. Upon reaching the ground, the tornado's circulation usually picks up dirt and debris, making it appear both dark and ominous. While the air along the outside of the funnel is spiraling upward, Doppler radar reveals that, within the core of large violent tornadoes, the air is descending toward the extreme low pressure at the ground (which may be 100 mb lower than that of the surrounding air). As the air descends, it warms, causing the cloud droplets to evaporate. This process leaves the core free of clouds. Tornadoes usually develop in supercells near the right rear sector of the storm, on the southwestern side of a northeastward-moving storm, as shown in Fig. 10.47.

Not all supercells produce tornadoes; in fact, perhaps less than 15 percent do. However, studies reveal that supercells are more likely to produce tornadoes when they interact with a pre-existing boundary, such as an old gust front (outflow boundary) that supplies the surface air with horizontal spin that can be tilted and lifted into the storm by its updraft. Another favorable factor for tornado development is a relatively low cloud base, which allows the rapidly rising air near the base of the thunderstorm to coincide with strong low-level wind shear. Latest observations show that a tornado is more likely to form if the shear near the surface is strong and the rear-flank downdraft is nearly as warm as the inflowing air.

Many atmospheric situations may suppress tornado formation. For example, if the precipitation in the cloud is swept too far away from the updraft, or if too much precipitation wraps around the mesocyclone, the necessary interactions that produce the rear-flank downdraft are disrupted, and a tornado is not likely to form. Moreover, tornadoes are not likely to form if the supercell is fed warm, moist air that is elevated above a deep layer of cooler surface air. And tornadoes usually will not form when the cool air of the rear-flank downdraft is too cold.

The first sign that a supercell is about to give birth to a tornado is the sight of *rotating clouds* at the base of the storm.* If the area of rotating clouds lowers, it becomes the *wall cloud.* Notice in Fig. 10.47 that the tornado extends from within the wall cloud to the earth's surface. Sometimes the air is so dry that the swirling, rotating wind remains invisible until it reaches the ground and begins to pick up dust. Unfortunately, people have mistaken these "invisible tornadoes" for dust devils, only to find out (often too late) that they were not. Occasionally, the funnel cannot be seen due to falling rain, clouds of dust, or darkness. When the tornado is not visible because it is surrounded by falling rain, it is referred to as being "*rain wrapped.*" Even when not clearly visible, many tornadoes

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*Occasionally, people will call a sky dotted with mammatus clouds "a tornado sky." Mammatus clouds may appear with both severe and nonsevere thunderstorms as well as with a variety of other cloud types (see Chapter 4). Mammatus clouds are not funnel clouds, do not rotate, and their appearance has no relationship to tornadoes.

DID YOU KNOW?

A massive multivortex tornado formed during the afternoon of May 31, 2013, just west of Oklahoma City, near the town of El Reno. As measured by mobile Doppler radar, the tornado spanned 2.6 miles at its peak, making it the widest ever measured. This huge rain-wrapped tornado overtook several storm chasers; tragically, four chasers and four other people were killed. Fortunately, the tornado and its winds, estimated at up to 295 mi/hr, never reached Oklahoma City. However, the parent storm did bring the metropolitan area its deadliest flash flood on record, as 13 people lost their lives.

have a distinctive roar that can be heard as the tornado approaches. This sound, which has been described as "a roar like a thousand freight trains," appears to be loudest when the tornadic circulation is touching the surface. However, not all tornadoes make this sound and, when these storms strike, they can become silent killers.

Forecasters use a variety of indexes to help calculate the odds that a supercell might form on a given day, or that a supercell might produce a tornado. The amount of instability in the atmosphere is represented by *Convective Available Potential Energy* (CAPE), which is a measure of how much energy is available to produce strong updrafts. The amount of wind shear can be calculated by comparing the wind speed and direction at various heights. And the amount of potential circulation within a storm can be estimated by calculating *storm-relative helicity*, which is a function of low-level wind shear. It measures how helical (corkscrew-like) the updraft will be in a growing thunderstorm.

Certainly, the likelihood of a thunderstorm producing a tornado increases when the storm becomes a supercell, but not all supercells produce tornadoes. And not all tornadoes come from rotating thunderstorms.

Nonsupercell Tornadoes Tornadoes that do not occur in association with a pre-existing wall cloud (or a mid-level mesocyclone) of a supercell are called **nonsupercell tornadoes**. These tornadoes may occur with intense multicell storms as well as with ordinary cell thunderstorms, even relatively weak ones. Some nonsupercell tornadoes extend from the base of a thunderstorm whereas others may begin on the ground and build upwards in the absence of a condensation funnel.

Nonsupercell tornadoes may form along a gust front where the cool downdraft of the thunderstorm forces warm, humid air upwards. Tornadoes that form along a gust front are commonly called **gustnadoes**. These relatively weak tornadoes normally are short-lived and rarely inflict significant damage. Gustnadoes typically form as a result of strongly converging winds along the edge of a rear-flank or forward downdraft. They are often seen as a rotating cloud of dust or debris rising above the surface (see • Fig. 10.48).


© Perry Samson

•**Figure 10.48** A gustnado that formed along a gust front swirls across the plains of eastern Nebraska.

Occasionally, rather weak, short-lived tornadoes will occur with rapidly building cumulus congestus clouds. Tornadoes such as these commonly form over eastern Colorado. Because they look similar to waterspouts that form over water, and form in similar ways, they are sometimes called **landspouts*** (see • Fig. 10.49).

• Figure 10.50 illustrates how a landspout can form. Suppose, for example, that the winds at the surface converge along a boundary, as illustrated in Fig. 10.50a. (The wind may converge due to topographic irregularities or any number of other factors, including temperature and moisture variations.) Notice that along the boundary, the air is rising, condensing, and forming into a cumulus congestus cloud. Notice also that along the surface at the boundary there is horizontal rotation (spin) created by the wind blowing in opposite directions along the boundary. If the developing cloud should move over the region of rotating air (Fig. 10.50b), the spinning air column may be drawn up into the cloud by the storm's updraft. In this case, the column of rising air typically narrows and its rotation intensifies as it is stretches upward. As the spinning, rising air shrinks in diameter, it produces a tornado-like structure, a *landspout*, similar to the one shown in Fig. 10.49. Landspouts usually dissipate when rain falls through the cloud and destroys the updraft. Tornadoes may form in this manner along many types of converging wind boundaries, including

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*Landspouts occasionally form on the backside of a squall line where southerly winds ahead of a cold front and northwesterly winds behind it create swirling eddies that can be drawn into thunderstorms by their strong updrafts.


NCAR/UCAR/NSF

Figure 10.49 A well-developed landspout moves over eastern Colorado.

sea breezes and gust fronts. Nonsupercell tornadoes and funnel clouds may also form with thunderstorms when cold air aloft (associated with an upper-level trough) moves over a region. Common along the west coast of North America, these often short-lived tornadoes are sometimes called *cold-air funnels* (see Fig. 10.51).

Waterspouts A **waterspout** is a rotating column of air that is connected to a cumuliform cloud over a large body of water. The waterspout may be a tornado that formed over land and then traveled over water. In such a case, the waterspout is sometimes referred to as a *tornadic waterspout*. Such tornadoes can inflict major damage to ocean-going vessels, especially when the tornadoes are of the supercell variety. Strong waterspouts that form over water and then move over land can cause considerable damage. For example, on August 30, 2009, an intense waterspout formed over the warm Gulf of Mexico, then moved onshore into Galveston, Texas, where it caused EF1 damage over several blocks and injured three people.

Waterspouts not associated with supercells that form over water, especially above warm, tropical coastal waters (such as in the vicinity of the Florida Keys, where almost 100 occur each month during the summer), are often referred to as *"fair weather" waterspouts.** These waterspouts are generally much smaller than an average tornado, as they have diameters usually between 3 and 100 meters. Fair weather waterspouts are also less intense, as their rotating winds are typically less than 45 knots. In addition, they tend to move more slowly than tornadoes and they only last for about 10 to 15 minutes, although some have existed for up to one hour.

Fair weather waterspouts tend to form in much the same way that landspouts do — when the air is conditionally unstable and cumulus clouds are developing. Some form with small thunderstorms, but most form with developing cumulus congestus clouds whose tops are frequently no higher than 3600 m (12,000 ft) and do not

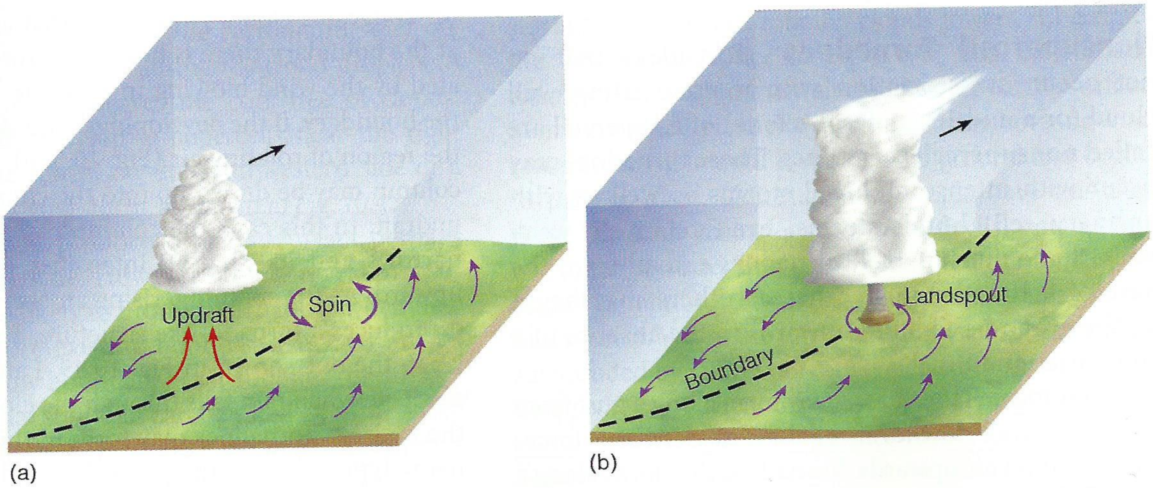

Figure 10.50 (a) Along the boundary of converging winds, the air rises and condenses into a cumulus congestus cloud. At the surface the converging winds along the boundary create a region of counterclockwise spin. (b) As the cloud moves over the area of rotation, the updraft draws the spinning air up into the cloud producing a nonsupercell tornado, or landspout. (Modified after Wakimoto and Wilson)

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*"Fair weather" waterspouts may form over any large body of warm water. Hence, they occur frequently over the Great Lakes in summer.

extend to the freezing level. Apparently, the warm, humid air near the water helps to create atmospheric instability, and the updraft beneath the resulting cloud helps initiate uplift of the surface air. Studies even suggest that gust fronts and converging sea breezes may play a role in the formation of some of the waterspouts that form over the Florida Keys. As with a landspout, a waterspout may become more likely when a pre-existing boundary of converging air moves beneath a thunderstorm's updraft.

The waterspout funnel is similar to the tornado funnel in that both are clouds of condensed water vapor with converging winds that rise about a central core. Contrary to popular belief, the waterspout does not draw water up into its core; however, swirling spray may be lifted several meters when the waterspout funnel touches the water. A photograph of a particularly well-developed and intense waterspout is shown in ● Fig. 10.52.


© Chris Whittier

●**Figure 10.51** A funnel cloud—called a *cold-air funnel*—descends from a thunderstorm in California's Central Valley near Lodi.

Observing Tornadoes and Severe Weather

Most of our knowledge about what goes on inside a tornado-generating thunderstorm has been gathered through the use of *Doppler radar*. Remember from Chapter 5 that a radar transmitter sends out microwave pulses and that, when this energy strikes an object, a small fraction is scattered back to the antenna. Precipitation particles are large enough to bounce microwaves back to the antenna. Consequently, as we saw earlier, the colorful area on the radar screen in Fig. 10.46, p. 321, represents the amount of reflected microwave energy translated into precipitation intensity inside a supercell thunderstorm.

Doppler radar can do more than measure rainfall intensity; it can actually measure the speed at which precipitation is moving horizontally toward or away from the radar antenna. Because precipitation particles are carried by the wind, Doppler radar can peer into a severe storm and reveal its winds.

Doppler radar works on the principle that, as precipitation moves toward or away from the antenna, the returning radar pulse will change in frequency when compared to the transmitted frequency. A similar change occurs when the high-pitched sound (high frequency) of an approaching noise source, such as a siren or train whistle, becomes lower in pitch (lower frequency) after it passes by the person hearing it. This change in frequency in sound waves or microwaves is called the *Doppler shift* and this, of course, is where the Doppler radar gets its name.


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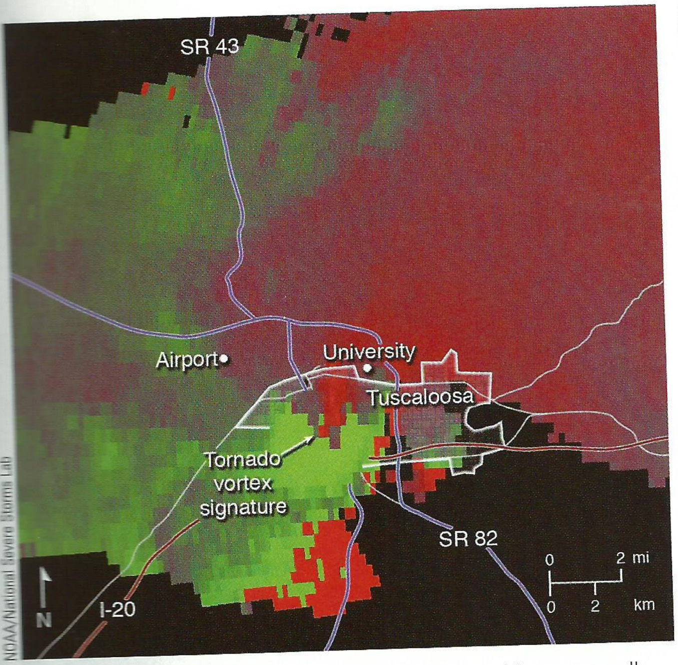
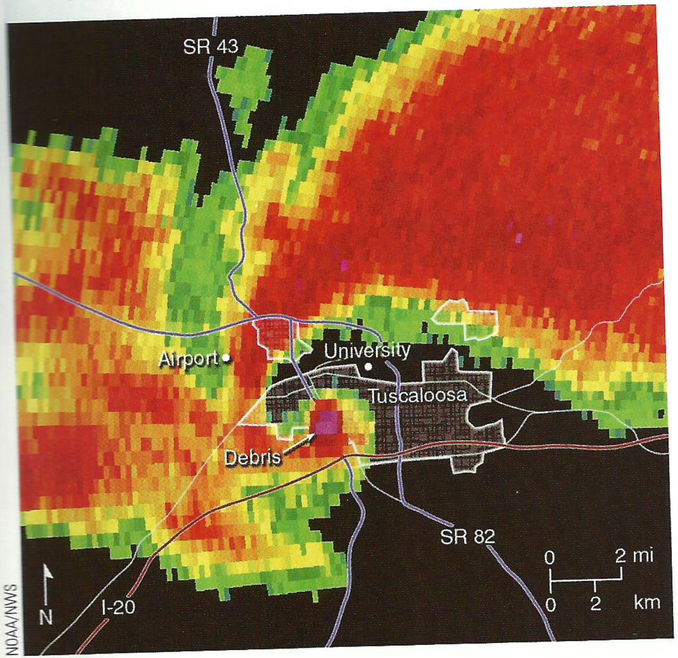
●**Figure 10.52** A powerful waterspout moves across Lake Tahoe, California. Compare this photo of a waterspout with the photo of a landspout in Fig. 10.49.



NOAA/National Severe Storms Lab

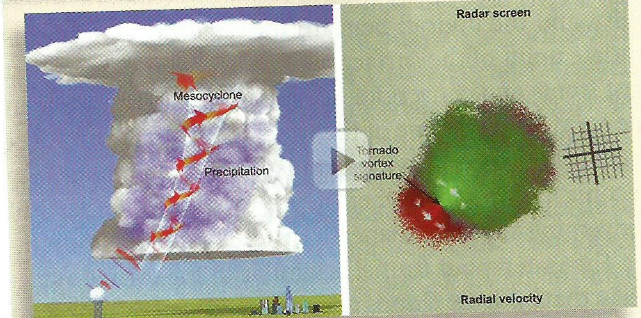
Figure 10.53 Doppler radar display of winds within a supercell thunderstorm that moved through Tuscaloosa, Alabama, on April 27, 2011. The close packing of the horizontal winds blowing toward the radar (green shades) and those blowing away from the radar (red shades) indicate strong cyclonic rotation. A tornadic circulation (*tornado vortex signature*) exists where a small packet of red is adjacent to a small packet of green. (Doppler radar reflectivity for this tornado is shown below in Figure 10.54.)



NOAA/NWS

Figure 10.54 Doppler radar display showing precipitation inside a large supercell that takes on the shape of a hook. This *hook echo* is associated with a violent multi-vortex tornado that is moving through Tuscaloosa, Alabama, just south of the University of Alabama, on April 27, 2011. (Damage caused by this tornado is shown in Fig. 10.43 on p. **319**.)

CONCEPT ANIMATION



To see how Doppler radar identifies winds moving toward and away from its antenna, go to the Meteorological CourseMate website at www.cengagebrain.com and view the last section of the animation entitled *Doppler Radar.*

To help distinguish the storm's air motions, wind velocities can be displayed in color. Winds blowing toward the radar antenna are usually displayed in green (or blue) those winds blowing away from the antenna are usually shown in shades of red. Color contouring the wind field gives a good picture of how winds are changing within a storm and the possibility of a tornado (see ● Fig. 10.53).

Doppler radar can uncover many of the features of a severe thunderstorm. For example, studies conducted in the 1970s revealed, for the first time, the existence of the swirling winds of the mesocyclone inside a supercell storm. Mesocyclones have a distinct image (signature) on the radar display. Tornadoes also have a distinct signature on the radar screen, known as the *tornado vortex signature (TVS)*, which shows up as a region of rapidly (or abruptly) changing wind directions within the mesocyclone, as shown in Fig. 10.53.

When Doppler radar displays precipitation intensity (reflectivity) inside a supercell thunderstorm, a signature of a mesocyclone (or tornado) may appear on the radar screen as a hook-shaped appendage, or *hook echo*, as shown in ● Fig 10.54.* The hook becomes visible as precipitation (and sometimes debris) swirls counterclockwise around the mesocyclone (or tornado). The doughnut-shaped dark red area at the end of the hook in Fig. 10.54 represents a massive multi-vortex tornado that is moving through Tuscaloosa, Alabama, on April 27, 2011, at about 5:10 P.M. CST. The purple area in the center of the hook represents debris that, having been picked up by the tornado, is now swirling counterclockwise around it. Debris on a radar screen such as this is referred to as a *debris ball.* With the addition of dual-polarization technology to Doppler radar, debris can be observed even more clearly (see ● Fig. 10.55). Although

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*See Fig. 10.42 on p. 319 for photo of this massive tornado.

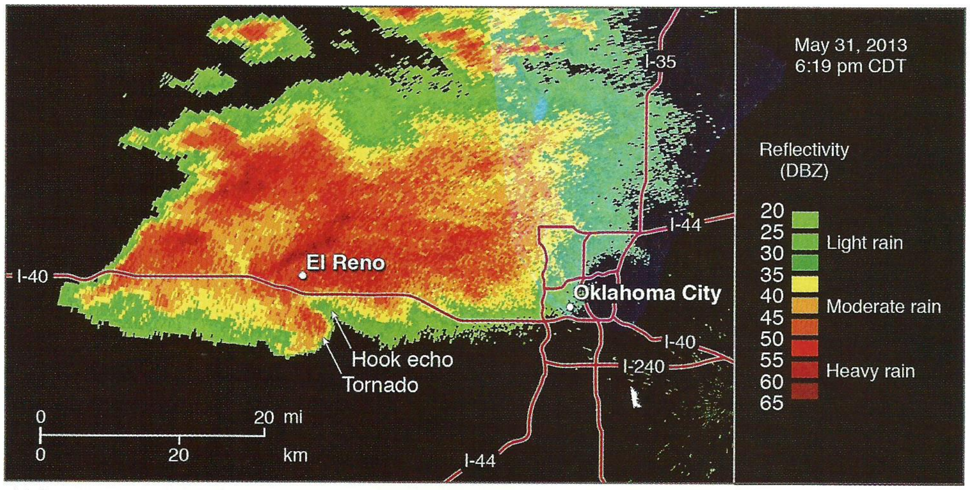
the hook echo in Fig. 10.54 has a tornado embedded in it, it should be noted that not all hook echoes are associated with tornadoes and not all tornadoes show a distinctive hook echo on the radar screen.

Unfortunately, the resolution of the Doppler radar is not high enough to measure actual wind speeds of most small tornadoes. However, a new and experimental Doppler system — called *Doppler lidar* — uses a light beam (instead of microwaves) to measure the change in frequency of falling precipitation, cloud particles, and dust. Because it uses a shorter wavelength of radiation, it has a narrower beam and a higher resolution than does Doppler radar.

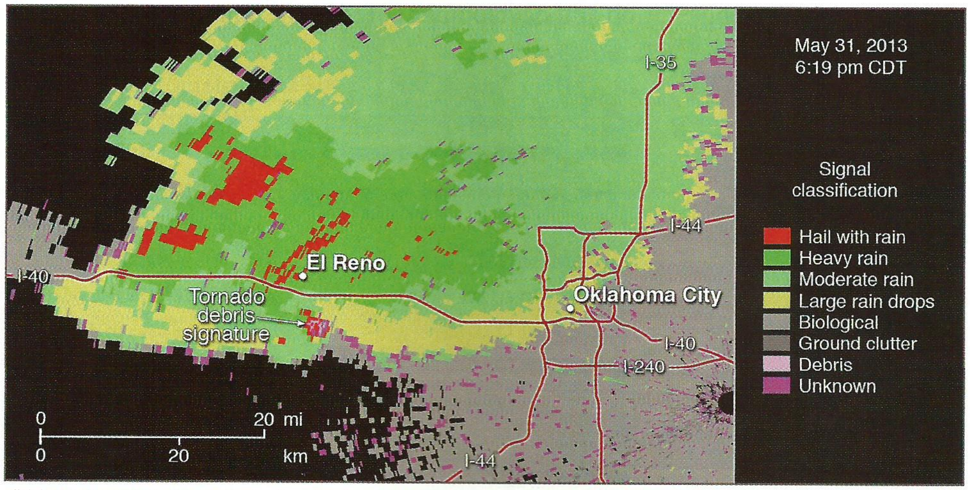
The network of more than 150 Doppler radar units deployed at selected weather stations within the continental United States is referred to as **NEXRAD** (an acronym for *NEX*t Generation Weather *RAD*ar). The NEXRAD system consists of the WSR-88D* Doppler radar and a set of computers that perform a variety of functions.

The computers take in data, display them on a monitor, and run computer programs called *algorithms*, which, in conjunction with other meteorological data, detect severe weather phenomena, such as storm cells, hail, mesocyclones, and tornadoes. Algorithms provide a great deal of information to the forecasters that allows them to make better decisions as to which thunderstorms are most likely to produce severe weather and possible flash flooding. In addition, the algorithms give advanced and improved warning of an approaching tornado. More reliable warnings, of course, cut down on the number of false alarms.

Because the Doppler radar shows horizontal air motion within a storm, it can help to identify the magnitude of other severe weather phenomena, such as gust fronts, derechoes, microbursts, and wind shears that are dangerous to aircraft. Certainly, as more and more information from Doppler radar becomes available, our understanding of the processes that generate severe thunderstorms and tornadoes will be enhanced, and hopefully there will



(a) Doppler radar (reflectivity)



(b) Doppler radar, dual-polarization (hydrometeor classification)

●Figure 10.55 (a) Doppler radar (reflectivity) shows precipitation intensity inside a large supercell thunderstorm on May 31, 2013, with heavy rain (red and yellow shades) falling west of Oklahoma City. A hook echo with a tornado exists to the south of El Reno, Oklahoma. (b) Doppler radar with dual-polarization technology more clearly depicts the different types of precipitation, as well as the tornado's debris which show up as a *tornado debris signature*.

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*The name WSR-88D stands for *W*eather *S*urveillance *R*adar, *1988* *D*oppler.

Pat Skinner

Figure 10.56 Researchers from Texas Tech University set up a mobile Doppler radar unit near a supercell thunderstorm.

be an even better tornado and severe storm warning system, resulting in fewer deaths and injuries.

As noted earlier, one recent advance in Doppler radar technology is the *polarimetric radar* (or *dual-polarization radar*) that transmits both a horizontal and a vertical radar pulse that, among other things, allows forecasters to better distinguish between very heavy rain and hail. This information, in turn, should improve flash flood watches and warnings. In 2012 and 2013, the national NEXRAD network was upgraded to provide dual-polarization capabilities. Researchers are also exploring the use of *phased array* radars, which allow a single radar unit to gather much more information by including many small transmitters and receivers on a flat plate.

In an attempt to unravel some of the mysteries of the tornado, several studies have been conducted in recent years with the help of new mobile observing systems. In one study, called *VORTEX 2* (Verification of the Origin of Rotational Tornadoes Experiment 2), scientists using an armada of observational vehicles and state-of-the-art equipment, including instruments attached to the tops of cars, lasers, unmanned small aircraft, and mobile Doppler radar units mounted on trucks (see Fig. 10.56), pursued tornado-generating thunderstorms over portions of the Plains during the spring and summer of 2009 and 2010. To obtain as much information as possible, some instruments were placed directly in the path of an approaching storm, while others surrounded the storm. The data obtained from the study are providing valuable information about the inner workings of supercells and tornadoes. At the same time, laboratory models of tornadoes in chambers (called *vortex chambers*), along with mathematical computer models, are offering new insights into the formation and development of these fascinating storms.

SUMMARY

In this chapter, we examined thunderstorms and the atmospheric conditions that produce them. Thunderstorms are convective storms that produce lightning and thunder. Lightning is a discharge of electricity that occurs in mature thunderstorms. The lightning stroke momentarily heats the air to an incredibly high temperature. The rapidly expanding air produces a sound called thunder.

The ingredients for the isolated ordinary cell thunderstorm are humid surface air, plenty of sunlight to heat the ground, a conditionally unstable atmosphere, a "trigger" to start the air rising, and weak vertical wind shear. When these conditions prevail, and the air begins to rise, small cumulus clouds may grow into towering clouds and thunderstorms within 30 minutes.

When conditions are ripe for thunderstorm development, and moderate or strong vertical wind shear exists, the updraft in the thunderstorm may tilt and ride up and over the downdraft. As the forward edge of the downdraft (the gust front) pushes outward along the ground, the air is lifted and new cells form, producing a multicell thunderstorm. Some multicell storms form as a complex of thunderstorms, such as the squall line (which forms as a line of thunderstorms), and the Mesoscale Convective Complex (which forms as a cluster of storms). When convection in the multicell storm is strong, it may produce severe weather, such as strong damaging surface winds, hail, and flooding.

Supercell thunderstorms are intense thunderstorms with a single rotating updraft. The updraft and the downdraft in a supercell are nearly in balance, so that the storm may exist for many hours. Supercells are capable of producing severe weather, including strong damaging tornadoes.

Tornadoes are rapidly rotating columns of air with a circulation that reaches the ground. Tornadoes can form with supercells, as well as with less intense thunderstorms. Most tornadoes are less than a few hundred meters wide with wind speeds less than 100 knots, although violent tornadoes may have wind speeds that exceed 250 knots. A violent tornado may actually have smaller whirls (suction vortices) rotating within it. A normally small and less destructive cousin of the tornado is the "fair weather" waterspout that commonly forms above warm bodies of water. With the aid of Doppler radar, scientists are probing tornado-spawning thunderstorms, hoping to better predict tornadoes and to better understand where, when, and how they form.

KEY TERMS

The following terms are listed (with page numbers) in the order they appear in the text. Define each. Doing so will aid you in reviewing the material covered in this chapter.

ordinary cell (air mass) thunderstorms, 289
cumulus stage, 289
mature stage, 290
dissipating stage, 290
multicell thunderstorm, 291
overshooting top, 291
gust front, 292
straight-line winds, 292
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