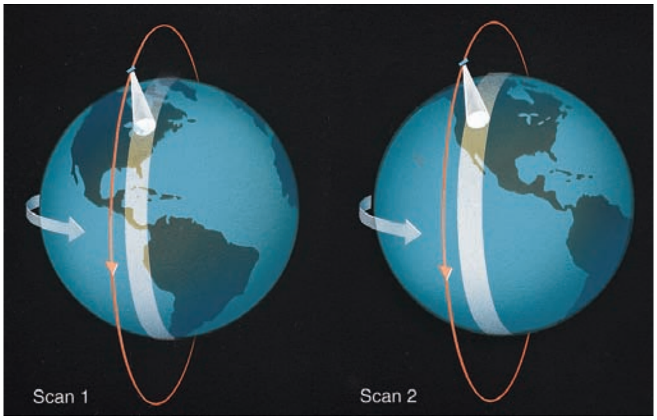


FIGURE 9.6 Polar-orbiting satellites scan from north to south, and on each successive orbit the satellite scans an area farther to the west.

rotates to the east beneath the satellite, each pass monitors an area to the west of the previous pass (see Fig. 9.6). Eventually, the satellite covers the entire earth.

Polar-orbiting satellites have the advantage of photographing clouds directly beneath them. Thus, they provide sharp images in polar regions, where images from a geostationary satellite are distorted because of the low angle at which the satellite "sees" this region. Polar orbiters also circle the earth at a much lower altitude (about 850 km, or 530 mi) than geostationary satellites and provide detailed photographic information about objects, such as violent storms and cloud systems.

Continuously improved detection devices make weather observation by satellites more versatile than ever. Early satellites, such as *TIROS I,* launched on April 1, 1960, used television cameras to photograph clouds. Contemporary satellites use radiometers, which can observe clouds during both day and night by detecting radiation that emanates from the top of the clouds. Additionally, the new generation *Geostationary Operational Environmental Satellite (GOES)* series has the capacity to obtain cloud images and, at the same time, provide vertical profiles of atmospheric temperature and moisture by detecting emitted radiation from atmospheric gases, such as water vapor. In modern satellites, a special type of advanced radiometer (called an *imager*) provides satellite pictures with much better resolution than did previous imagers. Moreover, another type of special radiometer (called a *sounder*) gives a more accurate profile of temperature and moisture at different levels in the atmosphere than did earlier instruments. In the latest *GOES* series, the imager and sounder are able to operate independently of each other.

The forecaster can obtain information on cloud thickness and height from satellite images. Visible images show the sunlight reflected from a cloud's upper surface. Because thick clouds have a higher reflectivity than thin clouds, they appear brighter on a visible satellite photograph. However, high, middle, and low clouds have just about the same reflectivity, so it is difficult to distinguish among them simply by using visible light photographs. To make this distinction, *infrared cloud images* are used. Such pictures produce a better image of the actual radiating surface because they do not show the strong visible reflected light. Since warm objects radiate more energy than cold objects, high temperature regions can be artificially made to appear darker on an infrared image. Because the tops of low clouds are warmer than those of high clouds, cloud observations made in the infrared can distinguish between warm low clouds (dark) and cold high clouds (light)—see Fig. 9.7. Moreover, cloud temperatures can be converted by a computer into a three-dimensional image of the cloud. These are the 3-D cloud photos presented on television by many weathercasters (see Fig. 9.8).

Figure 9.9a shows a visible satellite image (from a geostationary satellite) of an occluded storm system in the eastern Pacific. Notice that all of the clouds in the

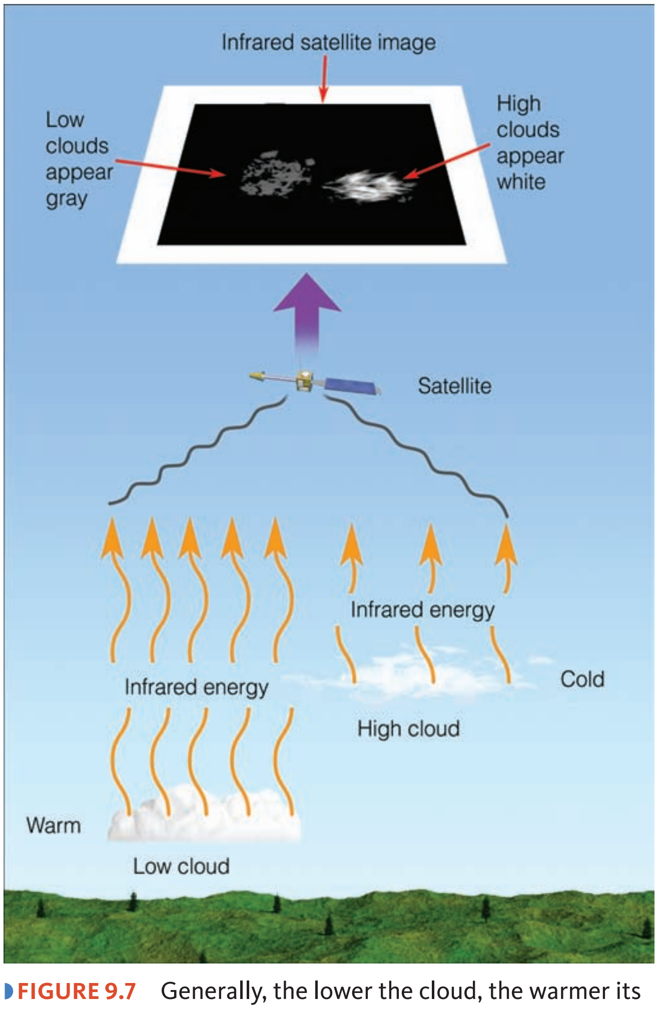


FIGURE 9.7 Generally, the lower the cloud, the warmer its top. Warm objects emit more infrared energy than do cold objects. Thus, an infrared satellite picture can distinguish warm, low (gray) clouds from cold, high (white) clouds.

NOAA

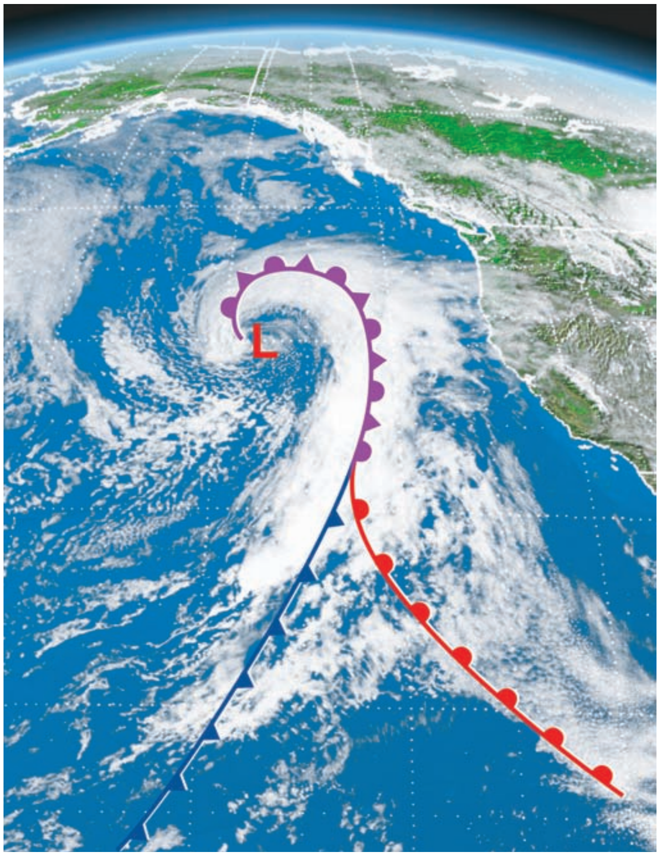
FIGURE 9.8 A 3-D image of Hurricane Rita over the Gulf of Mexico on September 21, 2005.

image appear white. However, in the infrared image (Fig. 9.9b), taken on the same day (and just about the same time), the clouds appear to have many shades of gray. In the visible image, the clouds covering part of Oregon and northern California appear relatively thin compared to the thicker, bright clouds to the west. Furthermore, these thin clouds must be high because they also appear bright in the infrared image.

Along the elongated band of clouds associated with the occluded front, the clouds appear white and bright in both images, indicating a zone of thick, heavy clouds. Behind the front, the forecaster knows that the lumpy clouds are probably cumulus because they appear gray in the infrared image, suggesting that their tops are low and relatively warm.

When temperature differences are small, it is difficult to directly identify significant cloud and surface features on an infrared image. Some way must be found to increase the contrast between features and their backgrounds. This can be done by a process called *computer enhancement.* Certain temperature ranges in the infrared image are assigned specific shades of gray—grading from black to white. Often, clouds with cold tops, and those with tops near freezing, are assigned the darkest gray color. Figure 9.10 is an infrared-enhanced image for the same day and area as shown in Fig. 9.9.

To make these types of features more obvious, often dark blue, red, or purple is assigned to clouds with the coldest (highest) tops. Hence, the dark red areas embedded along the front represent the region where the cold-



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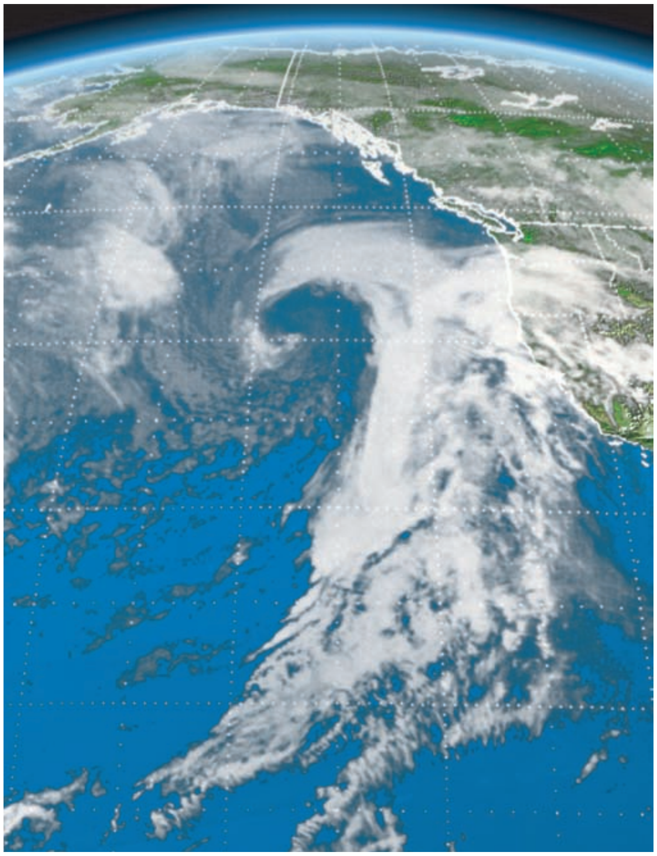
Active **FIGURE 9.9a** A visible image of the eastern Pacific Ocean taken at just about the same time on the same day as the image in Fig. 9.9b. Notice that the clouds in the visible image appear white. Superimposed on the image are the cold, warm, and occluded fronts.



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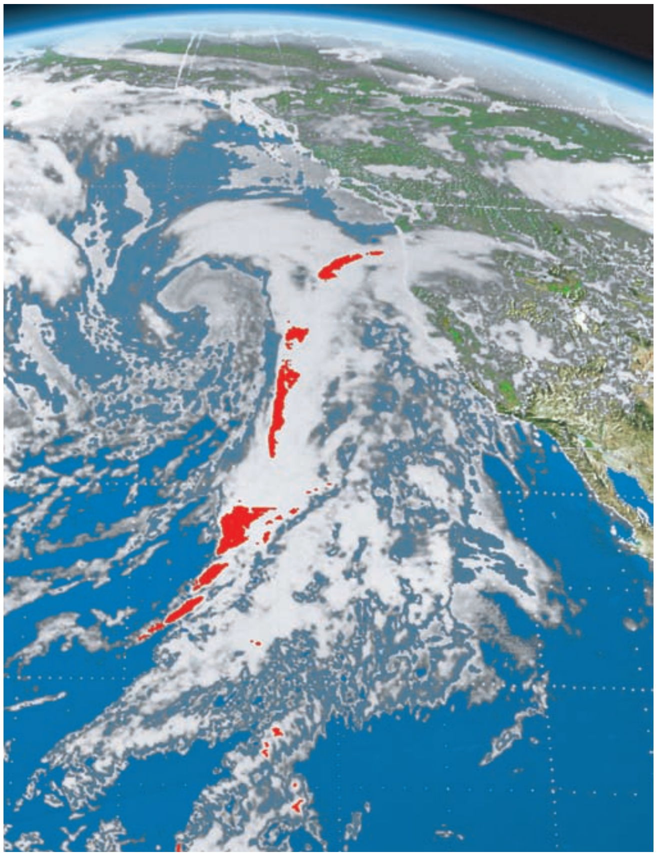
Active **FIGURE 9.9b** Infrared satellite image of the eastern Pacific Ocean taken at just about the same time on the same day as the image in Fig. 9.9a. Notice that the low clouds in the infrared image appear in various shades of gray.

est and, therefore, highest and thickest clouds are found. It is here where the stormiest weather is probably occurring. Also notice that, near the southern tip of the picture, the dark red blotches surrounded by areas of white are thunderstorms that have developed over warm tropical waters. They show up clearly as white, thick clouds in both the visible and infrared images. By examining the movement of these clouds on successive satellite images, the forecaster can predict the arrival of clouds and storms, and the passage of weather fronts.

In regions where there are no clouds, it is difficult to observe the movement of the air. To help with this situation, geostationary satellites are equipped with water-vapor sensors that can profile the distribution of atmospheric water vapor in the middle and upper troposphere (see ◗Fig. 9.11). In time-lapse films, the swirling patterns of moisture clearly show wet regions and dry regions, as well as middle tropospheric swirling wind patterns and jet streams.

The *TRMM* (*T*ropical *R*ainfall *M*easuring *M*ission) satellite provides the forecaster with the information on clouds and precipitation from about 35°N to 35°S. A



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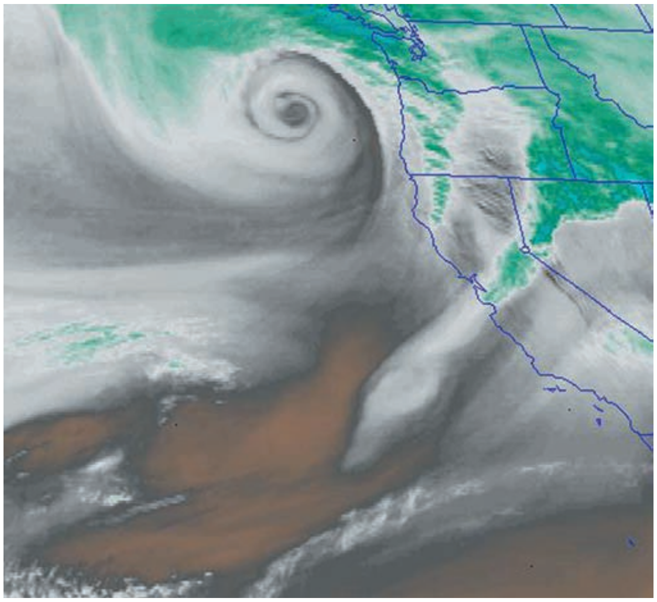
◗**FIGURE 9.10** An enhanced infrared image of the eastern Pacific Ocean taken on the same day as the images shown in Figs. 9.9a and 9.9b.



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◗**FIGURE 9.11** Infrared water-vapor image. The darker areas represent dry air aloft; the brighter the gray, the more moist the air in the middle or upper troposphere. Bright white areas represent dense cirrus clouds or the tops of thunderstorms. The area in color represents the coldest cloud tops. The swirl of moisture off the West Coast represents a well-developed mid-latitude cyclonic storm.

joint venture of NASA and the National Space Agency of Japan, this satellite orbits the earth at an altitude of about 400 km (250 mi). From this vantage point the satellite, when looking straight down, can pick out individual cloud features as small as about 1.5 miles in diameter. Some of the instruments onboard the *TRMM* satellite include a visible and infrared scanner, a microwave imager, and precipitation radar. These instruments help provide three-dimensional images of clouds and storms, along with the intensity and distribution of precipitation (see ◗Fig. 9.12). Additional onboard instruments send back information concerning the earth's energy budget and lightning discharges in storms.

Up to this point, we have examined some of the weather data and tools a forecaster might use in making a weather prediction. With all of this information available to the forecaster, including hundreds of charts and maps, just *how* does a meteorologist make a weather forecast?

DID YOU KNOW?

On April 1, 1960, *TIROS*-1 (*T*elevision *I*nfrared *O*bservation *S*atellite) became the first successful weather satellite put into orbit. Although it only operated for 78 days, it sent the first televised images of earth from space and proved that satellites would be able to effectively observe global weather patterns and greatly enhance the science of weather forecasting.

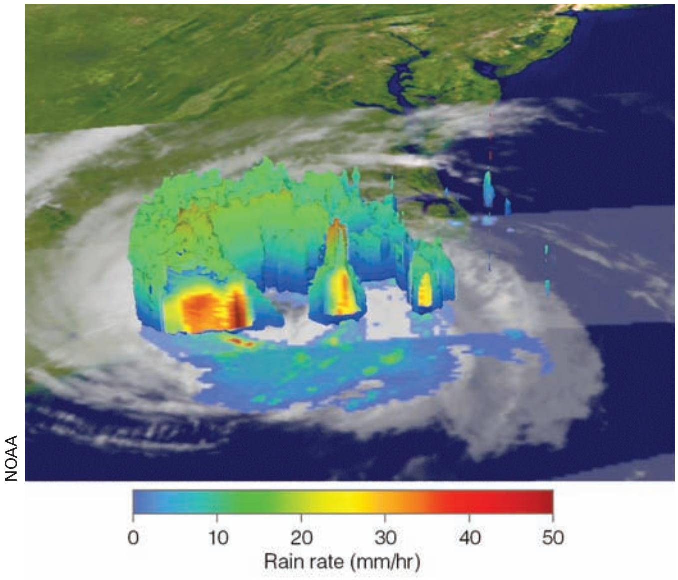


FIGURE 9.12 A three-dimensional *TRMM* satellite image of Hurricane Ophelia along the North Carolina coast on September 14, 2005. The light green areas in the cutaway view represent the region of lightest rainfall, whereas dark red and orange indicate regions of heavy rainfall.

Weather Forecasting Methods

As late as the mid-1950s, all weather maps and charts were plotted by hand and analyzed by individuals. Meteorologists predicted the weather using certain rules that related to the particular weather system in question. For short-range forecasts of six hours or less, surface weather systems were moved along at a steady rate. Upper-air charts were used to predict where surface storms would develop and where pressure systems aloft would intensify or weaken. The predicted positions of these systems were extrapolated into the future using linear graphical techniques and current maps. Experience played a major role in making the forecast. In many cases, these forecasts turned out to be amazingly accurate. They were good but, with the advent of modern computers, along with our present observing techniques, today's forecasts are even better.

THE COMPUTER AND WEATHER FORECASTING: NUMERICAL WEATHER PREDICTION Modern electronic computers can analyze large quantities of data extremely fast. Each day the many thousands of observations transmitted to NCEP are fed into a high-speed computer, which plots and draws lines on surface and upper-air charts. Meteorologists interpret the weather patterns and then correct any errors that may be present. The final chart is referred to as an **analysis**.

The computer not only plots and analyzes data, it also predicts the weather. The routine daily forecasting of weather by the computer using mathematical equations has come to be known as **numerical weather prediction.**

Because the many weather variables are constantly changing, meteorologists have devised **atmospheric models** that describe the present state of the atmosphere. These are not physical models that paint a picture of a developing storm; they are, rather, mathematical models consisting of many mathematical equations that describe how atmospheric temperature, pressure, winds, and moisture will change with time. Actually, the models do not fully represent the real atmosphere but are approximations formulated to retain the most important aspects of the atmosphere's behavior.

The models are programmed into the computer, and surface and upper-air observations of temperature, pressure, moisture, winds, and air density are fed into the equations. To determine how each of these variables will change, each equation is solved for a small increment of future time—say, five minutes—for a large number of locations called *grid points,* each situated a given distance apart.* In addition, each equation is solved for as many as 50 levels in the atmosphere. The results of these computations are then fed back into the original equations. The computer again solves the equations with the new "data," thus predicting weather over the following five minutes. This procedure is done repeatedly until it reaches some desired time in the future, usually 6, 12, 24, 36, and out to 84 hours. The computer then analyzes the data and draws the projected positions of pressure systems with their isobars or contour lines. The final forecast chart representing the atmosphere at a specified future time is called a **prognostic chart,** or, simply, a **prog.** Computer-drawn progs have come to be known as "machine-made" forecasts.

The computer solves the equations more quickly and efficiently than could be done by hand. For example, just to produce a 24-hour forecast chart for the Northern Hemisphere requires many hundreds of millions of mathematical calculations. It would, therefore, take a group of meteorologists working full time with hand calculators years to produce a single chart; by the time the forecast was available, the weather for that day would already be ancient history.

The forecaster uses the progs as a guide to predicting the weather. At present, there are a variety of models (and, hence, progs) from which to choose, each producing a slightly different interpretation of the weather for the same projected time and atmospheric level (see Fig. 9.13). The differences between progs may result

*Some models have a grid spacing smaller than 0.5 km, whereas the spacing in others exceeds 100 km. There are models that actually describe the atmosphere using a set of mathematical equations with wavelike characteristics rather than a set of discrete numbers associated with grid points.

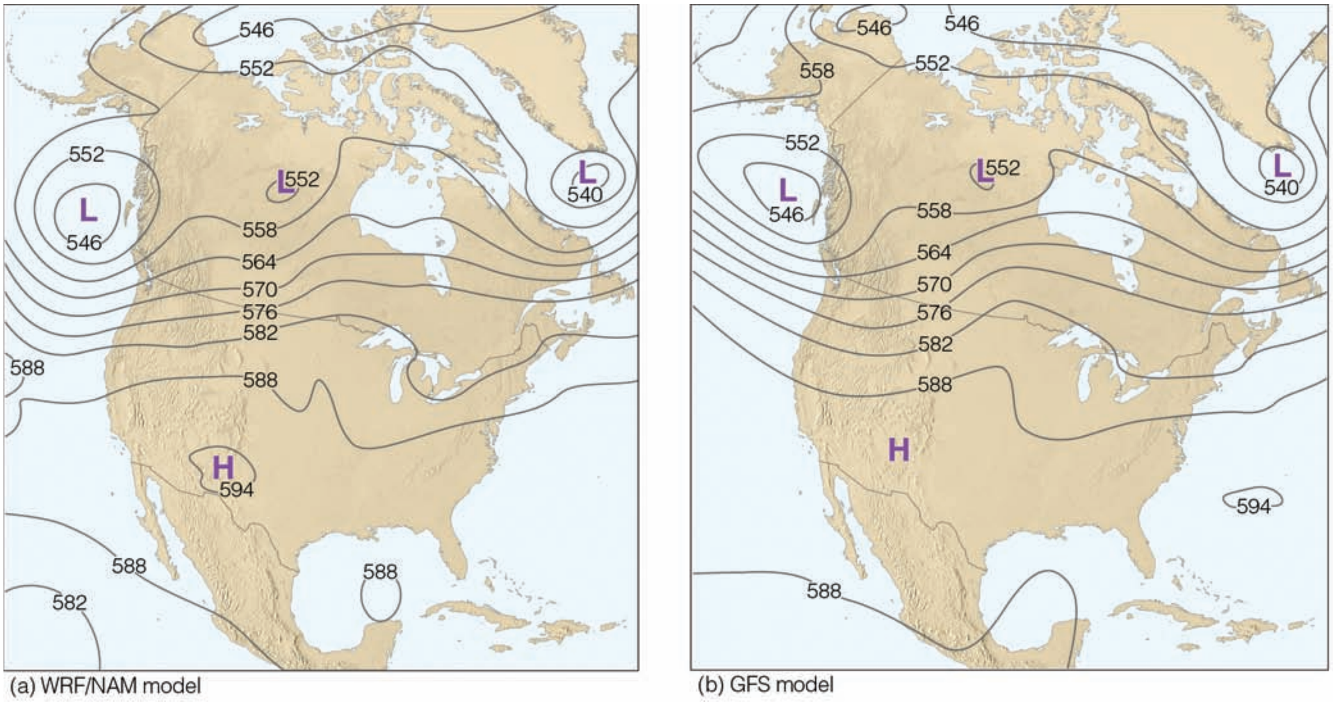


FIGURE 9.13 Two 500-mb progs for 7 P.M. EST, July 12, 2006 — 48 hours into the future. Prog (a) is the WRF/NAM model, with a resolution (grid spacing) of 12 km, whereas prog (b) is the GFS model with a resolution of 60 km. Solid lines on each map are height contours, where 570 equals 5700 meters. Notice how the two progs (models) agree on the atmosphere's large scale circulation. The main difference between the progs is in the way the models handle the low off the west coast of North America. Model (a) predicts that the low will dig deeper along the coast, while model (b) predicts a more elongated west-to-east (zonal) low. (The abbreviation WRF/NAM stands for Weather Research Forecast/North American Mesoscale Model, and GFS stands for Global Forecast Systems.)

from the way the models use the equations, or the distance between grid points, called *resolution.* Some models predict some features better than others: One model may work best in predicting the position of troughs on upper-level charts, whereas another forecasts the position of surface lows quite well. Some models even forecast the state of the atmosphere 384 hours (16 days) into the future. Look at Fig. 9.14 and notice that model (b) in Fig. 9.13, with a resolution of 60 km, actually did a better job of forecasting the structure of the low off the west coast of North America than did model (a) with a resolution of only 12 km.

A good forecaster knows the idiosyncrasies of each model (such as model (a) and model (b) in Fig. 9.13) and carefully scrutinizes all the progs. The forecaster then makes a prediction based on the *guidance* from the computer, a personalized practical interpretation of the weather situation and any local geographic features that influence the weather within the specific forecast area.

Currently, forecast models predict the weather reasonably well 4 to 6 days into the future. These models tend to do a better job of predicting temperature and jet-stream patterns than predicting precipitation. However, even with all of the modern advances in weather forecasting provided by ever more powerful computers, National Weather Service forecasts are sometimes wrong.

WHY NWS FORECASTS GO AWRY AND STEPS TO IMPROVE THEM Why do forecasts sometimes go wrong? There are a number of reasons for this unfortunate situation. For one, computer models have inher-

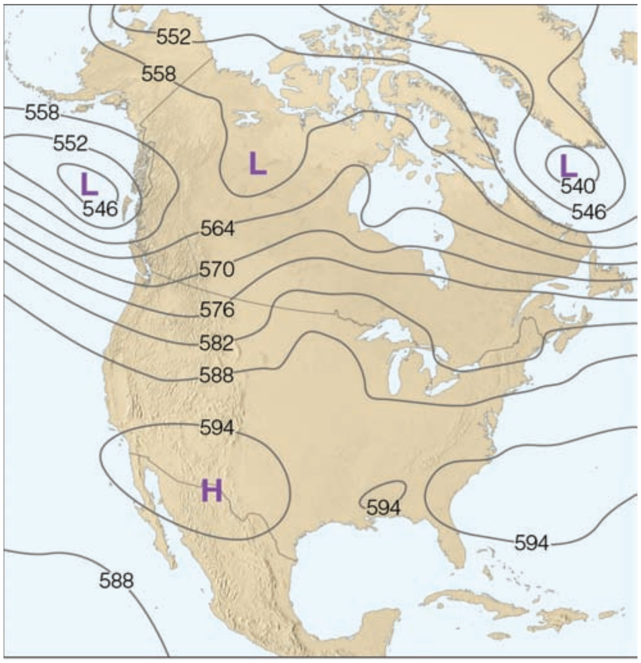


FIGURE 9.14 The 500-mb analysis for 7 P.M. EST, July 12, 2006.

ent flaws that limit the accuracy of weather forecasts. For example, computer-forecast models idealize the real atmosphere, meaning that each model makes certain assumptions about the atmosphere. These assumptions may be on target for some weather situations and be way off for others. Consequently, the computer may produce a prog that on one day comes quite close to describing the actual state of the atmosphere, and not so close on another. A forecaster who bases a prediction on an "off day" computer prog may find a forecast of "rain and windy" turning out to be a day of "clear and colder."

Another forecasting problem arises because the majority of models are not global in their coverage, and errors are able to creep in along the model's boundaries. For example, a model that predicts the weather for North America may not accurately treat weather systems that move in along its boundary from the western Pacific. This kind of inaccuracy is probably why model (b) in Fig. 9.13—a global model with a lower resolution—actually did a better job in predicting the low off the west coast than did model (a), which is a non-global model with a higher resolution. Obviously, a global model would always be preferred. But a global model of similar sophistication with a high resolution requires an incredible number of computations.

Even though many thousands of weather observations are taken worldwide each day, there are still regions where observations are sparse, particularly over the oceans and at higher latitudes. As we saw in the previous section, to help alleviate this problem, the newest *GOES* satellite, with advanced atmospheric sounders, is providing a more accurate profile of temperature and humidity for the computer models. Wind information now comes from a variety of sources, such as Doppler radar, commercial aircraft, buoys, and satellites that translate ocean surface roughness into surface wind speed. (See Chapter 6, p. 172.)

Earlier, we saw that the computer solves the equations that represent the atmosphere at many locations called grid points, each spaced from 100 km to as low as 0.5 km apart. As a consequence, on computer models with large spacing between grid points (say 60 km), weather systems, such as extensive mid-latitude cyclones and anticyclones, show up on computer progs, whereas much smaller systems, such as thunderstorms, do not. The computer models that forecast for a large area such as North America are, therefore, better at predicting the widespread precipitation associated with a large cyclonic storm than local showers and thunderstorms. In summer, when much of the precipitation falls as local showers, a computer prog may have indicated fair weather, while outside it is pouring rain.

To capture the smaller-scale weather features as well as the terrain of the region, the distance between grid points on some models is being reduced. For example, the forecast model known as MM5 has a grid spacing as low as 0.5 km. This model predicts mesoscale atmospheric conditions over a limited region, such as a coastal area where terrain might greatly impact the local weather. The problem with models that have a small grid spacing (high resolution) is that, as the horizontal spacing between grid points decreases, the number of computations increases. When the distance is halved, there are 8 times as many computations to perform, and the time required to run the model goes up by a factor of 16.

Another forecasting problem is that many computer models cannot adequately interpret many of the factors that influence surface weather, such as the interactions of water, ice, surface friction, and local terrain on weather systems. Many large-scale models now take mountain regions and oceans into account. Some models (such as the MM5) take even smaller factors into account—features that large-scale computers miss due to their longer grid spacing. Given the effect of local terrain, as well as the impact of some of the other problems previously mentioned, computer models that forecast the weather over a vast area do an inadequate job of predicting local weather conditions, such as surface temperatures, winds, and precipitation.

Even with better observing techniques and near perfect computer models, there are countless small, unpredictable atmospheric fluctuations that fall under the heading of **chaos.** For example, tiny eddies are much smaller than the grid spacing on the computer model and, therefore, go unmeasured. These small disturbances, as well as small errors (uncertainties) in the data, generally amplify with time as the computer tries to project the weather farther and farther into the future. After a number of days, these initial imperfections tend to dominate, and the forecast shows little or no accuracy in predicting the behavior of the real atmosphere. In essence, what happens is that the small uncertainty in the initial atmospheric conditions eventually leads to a huge uncertainty in the model's forecast.

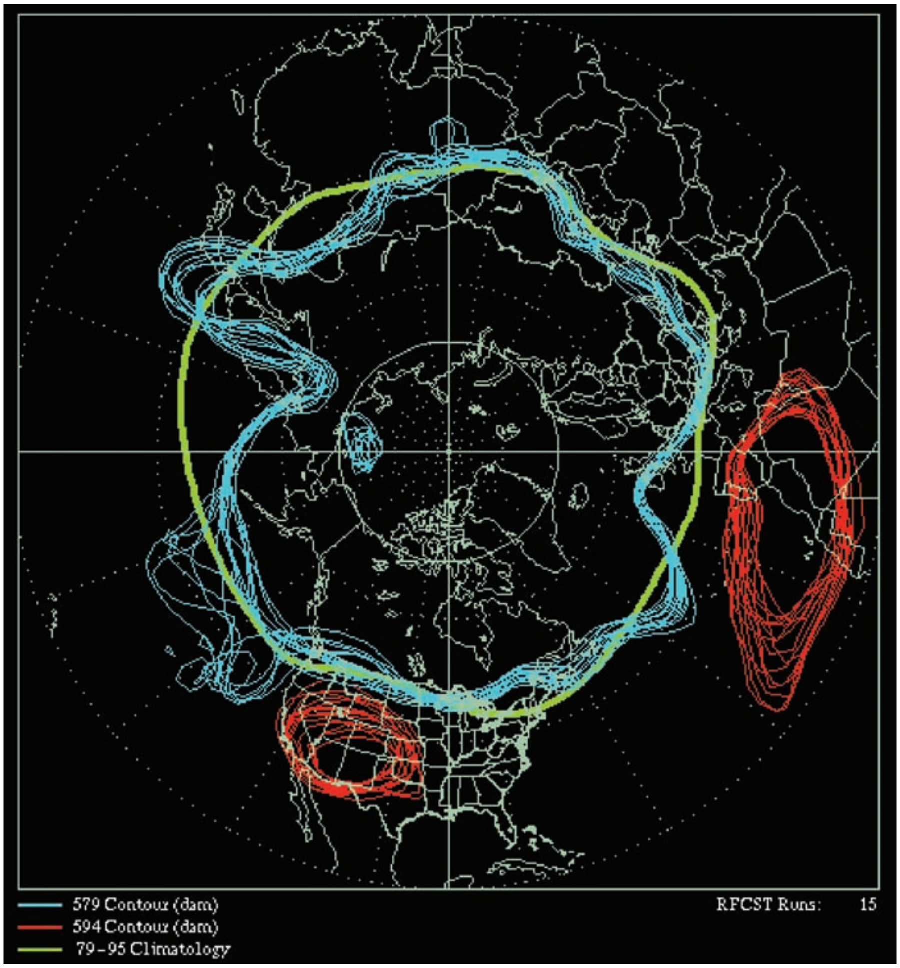
Because of the atmosphere's chaotic nature, meteorologists are turning to a technique called **ensemble forecasting** to improve short- and medium-range forecasts. The ensemble approach is based on running several forecast models—or different versions (simulations) of a single model—each beginning with slightly different weather information to reflect the errors inherent in the measurements. Suppose, for example, a forecast model predicts the state of the atmosphere 24 hours into the future. For the ensemble forecast, the entire model simulation is repeated, but only after the initial conditions are "tweaked" just a little. The "tweaking," of course, represents the degree of uncertainty in the observations. Repeating this process several times creates an ensemble of forecasts for a range of small initial changes.

▶Figure 9.15 shows an ensemble 500-mb forecast chart for July 21, 2005 (48 hours into the future) using the global atmospheric circulation model. The chart is constructed by running the model 15 different times, each time starting with slightly different initial conditions. Notice that the red contour line (which represents a height of 5940 meters) circles the southwestern United States, indicating a high degree of confidence in the model for that region. Here, a large upper-level high pressure area covers the region, and so a forecast for the southwestern United States would be "very hot and dry." The blue scrambled contour lines (representing a height of 5790 meters) off the west coast of North America indicates a great deal of uncertainty in the forecast model. As the forecast goes further and further into the future, the lines look more and more like scrambled spaghetti, which is why an ensemble forecast chart such as this one is often referred to as a *spaghetti plot*.

If, at the end of a specific time, the progs, or model runs, match each other fairly well, as they do over the southwestern United States in Fig. 9.15, the forecast is considered *robust*. This situation allows the forecaster to issue a prediction with a high degree of confidence. If the progs disagree, as they do off the west coast of North America in Fig. 9.15, the forecaster with little faith in the computer model prediction issues a forecast with limited confidence. In essence, *the less agreement among the progs, or model runs, the less predictable the weather.* Consequently, it would not be wise to make outdoor plans for Saturday when on Monday the weekend forecast calls for "sunny and warm" with a low degree of confidence.

In summary, imperfect numerical weather predictions may result from flaws in the computer models, from errors that creep in along the models' boundaries, from the sparseness of data, and/or from inadequate representation of many pertinent processes, interactions, and inherently chaotic behavior that occurs within the atmosphere.

Up to this point, we have looked primarily at weather forecasts made by high-speed computers using atmospheric models. There are, however, other forecasting



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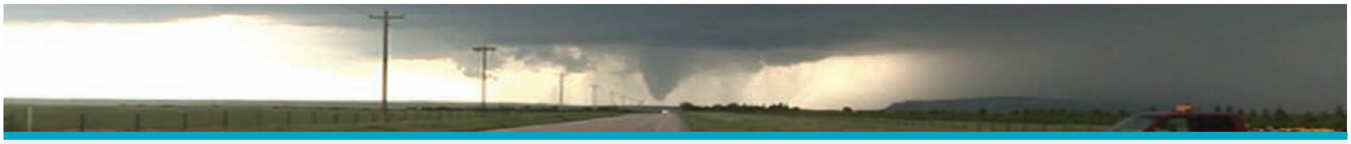
▶**FIGURE 9.15** Ensemble 500-mb forecast chart for July 21, 2005 (48 hours into the future). The chart is constructed by running the model 15 different times, each time beginning with a slightly different initial condition. The blue lines represent the 5790-meter contour line; the red lines, the 5940-meter contour line; and the green line, the 500-mb 25-year average, called *climatology*.



FOCUS ON AN OBSERVATION

TV Weathercasters—How Do They Do It?

As you watch the TV weathercaster, you typically see a person describing and pointing to specific weather information, such as satellite and radar images, and weather maps, as illustrated in Fig. 2. What you may not know is that in many instances the weathercaster is actually pointing to a blank board (usually green or blue) on which there is nothing (Fig. 3).* This process of electronically superimposing weather information in the TV camera against a blank wall is called color-separation overlay, or *chroma key*.

The chroma key process works because the studio camera is constructed to pick up all colors except (in this case) blue. The various maps, charts, satellite photos, and other graphics are electronically inserted from a computer into this blue area of the color spectrum. The person in the TV studio should not wear blue clothes because such clothing would not be picked up by the camera—what you would see on your home screen would be a head and hands moving about the weather graphics!

How, then, does a TV weathercaster know where to point on the blank wall? Positioned on each side of the blue wall are TV monitors (look carefully at Fig. 3) that weathercasters watch so that they know where to point.

*On The Weather Channel, forecasters point to weather information that appears on a very large TV screen.

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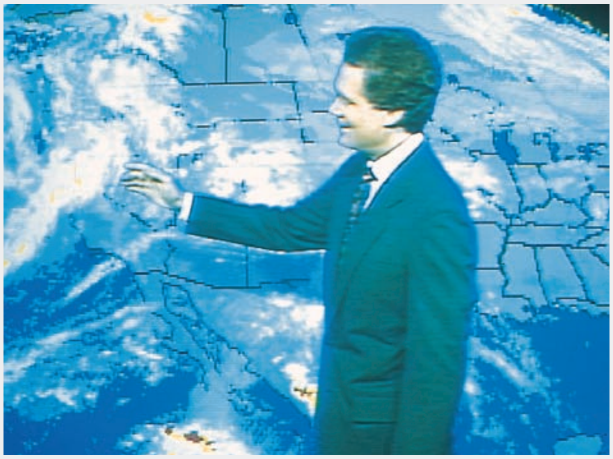


FIGURE 2 On your home television, the weather forecaster Tom Loffman appears to be pointing to weather information directly behind him.

© C. Donald Ahrens

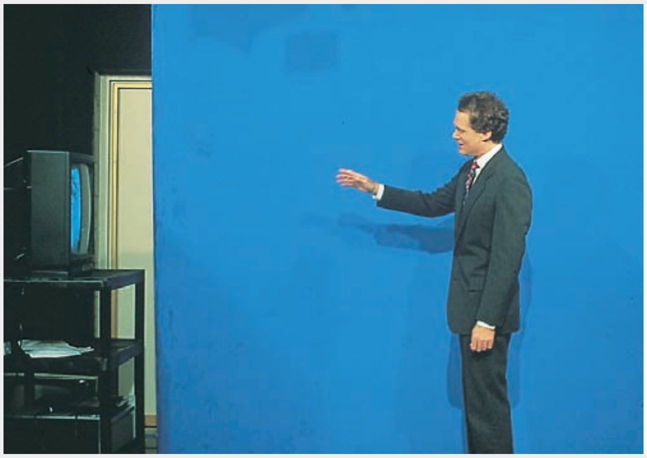


FIGURE 3 In the studio, however, he is actually standing in front of a blank board.

methods, many of which have stood the test of time and are based mainly on the experience of the forecaster. Many of these techniques are of value, but often they give more of a general overview of what the weather should be like, rather than a specific forecast. (Before going on, you may wish to read the Focus section above that describes how TV weather forecasters present weather visuals.)

OTHER FORECASTING METHODS Probably the easiest weather forecast to make is a **persistence forecast**, which is simply a prediction that future weather will be the same as present weather. If it is snowing today, a persistence forecast would call for snow through tomorrow. Such forecasts are most accurate for time periods of several hours and become less and less accurate after that.

Another method of forecasting is the **steady-state,** or **trend forecast.** The principle involved here is that surface weather systems tend to move in the same direction and at approximately the same speed as they have been moving, providing no evidence exists to indicate otherwise. Suppose, for example, that a cold front is moving eastward at an average speed of 30 mi/hr and it is 90 mi west of your home. Using the steady-state method, we might extrapolate and predict that the front should pass through your area in three hours.

The **analogue method** is yet another form of weather forecasting. Basically, this method relies on the fact that existing features on a weather chart (or a series of charts) may strongly resemble features that produced certain weather conditions sometime in the past. To the forecaster, the weather map "looks familiar," and for this reason the analogue method is often referred to as *pattern recognition.* A forecaster might look at a prog and say "I've seen this weather situation before, and this happened." Prior weather events can then be utilized as a guide to the future. The problem here is that, even though weather situations may appear similar, they are never *exactly* the same. There are always sufficient differences in the variables to make applying this method a challenge.

The analogue method can be used to predict a number of weather elements, such as maximum temperature. Suppose that in New York City the average maximum temperature on a particular date for the past 30 years is 10°C (50°F). By statistically relating the maximum temperatures on this date to other weather elements—such as the wind, cloud cover, and humidity—a relationship between these variables and maximum temperature can be drawn. By comparing these relationships with current weather information, the forecaster can predict the maximum temperature for the day.

Presently, **statistical forecasts** are made routinely of weather elements based on the past performance of computer models. Known as *Model Output Statistics,* or MOS, these predictions, in effect, are statistically weighted analogue forecast corrections incorporated into the computer model output. For example, a forecast of tomorrow's maximum temperature for a city might be derived from a statistical equation that uses a numerical model's forecast of relative humidity, cloud cover, wind direction, and air temperature.

When the Weather Service issues a forecast calling for rain, it is usually followed by a probability. For example: "The chance of rain is 60 percent." Does this mean (a) that it will rain on 60 percent of the forecast area or (b) that there is a 60 percent chance that it will rain within the forecast area? Neither one! The expression means that there is a 60 percent chance that any random place in the forecast area, such as your home, will receive measurable rainfall. Looking at the forecast in another way, if the forecast for 10 days calls for a 60 percent chance of rain, it should rain where you live on 6 of those days. The verification of the forecast (as to whether it actually rained or not) is usually made at the Weather Service office, but remember that the computer models forecast for a given region, not for an individual location. When the National Weather Service issues a forecast calling for a "slight chance of rain," what is the probability (percentage) that it will rain? ■ Table 9.1 provides this information.

An example of a **probability forecast** using climatological data is given in ◗ Fig. 9.16. The map shows the probability of a "White Christmas"—1 inch or more of snow on the ground—across the United States. The map is based on the average of 30 years of data and gives the likelihood of snow in terms of a probability. For instance, the chances are greater than 90 percent (9 Christmases out of 10) that portions of northern Minnesota, Michigan, and Maine will experience a White Christmas. In Chicago, it is close to 50 percent; and in Washington, D.C., about 20 percent. Many places in the far west and south have probabilities less than 5 percent, but nowhere is the probability exactly 0, for there is always some chance (no matter how small) that a mantle of white will cover the ground on Christmas day. As an example, on Christmas day, 2004, Corpus Christi, Texas, reported over 4 inches of snow on the ground, and Brownsville, Texas, at the very southern part of the state, had 1.5 inches of snow, making it the first snowfall in Brownsville in 109 years!

DID YOU KNOW?

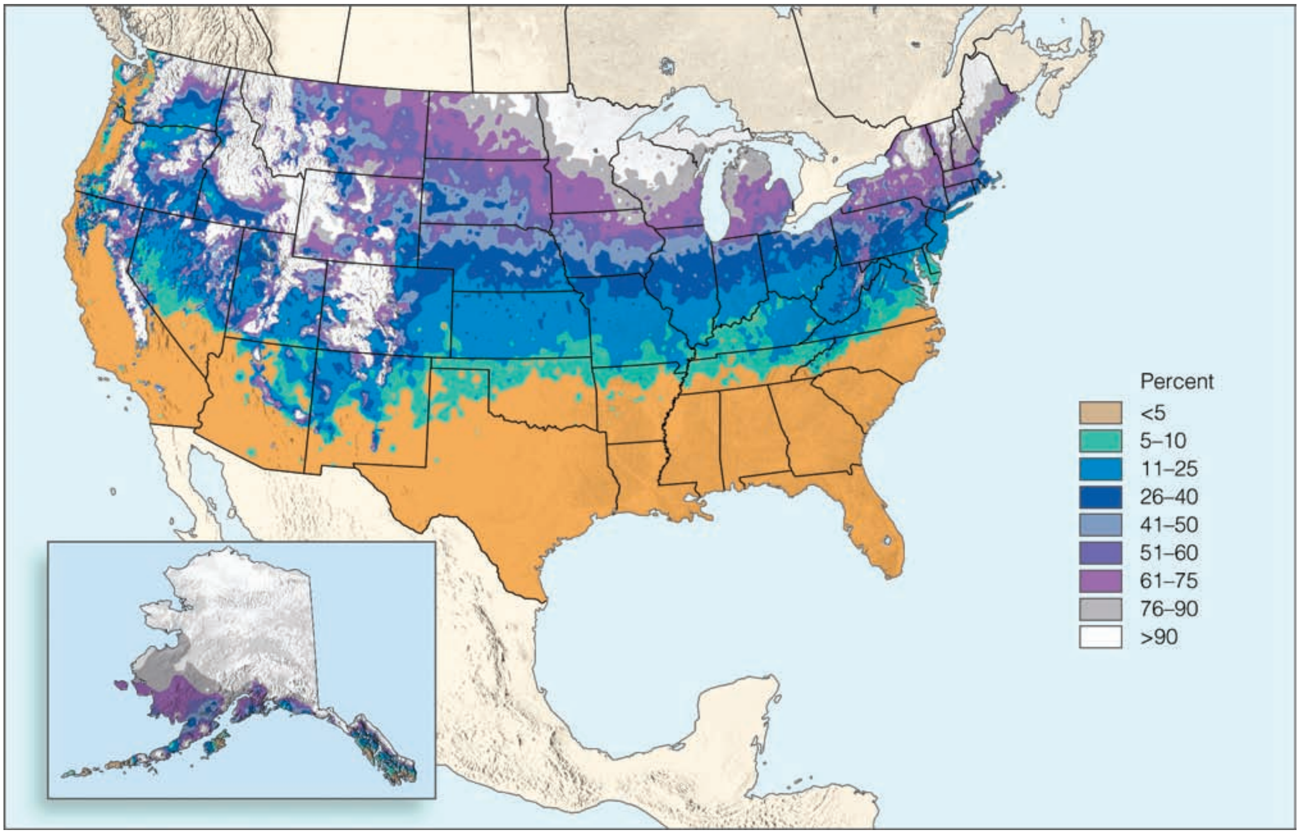
Nightly news weather presentations have come a long way since the early days of television. The "weather girl," a fad that became popular during the 1960s, employed crazy gimmicks to attract viewers. Women gave weather forecasts in various attire (from bathing suits to bunny outfits), sometimes with the aid of hand puppets that resembled odd-looking turtles. One West Coast television station actually hired a woman to do the nightly news weather segment with the requirement that she be able to write backwards on a clear, Plexiglas screen.

■ **TABLE 9.1 Forecast wording used by the National Weather Service to describe the percentage probability of measurable precipitation (0.01 inch or greater) for steady precipitation and for convective, showery precipitation.**

PERCENT PROBABILITY OF PRECIPITATION	FORECAST WORDING FOR STEADY PRECIPITATION	FORECAST WORDING FOR SHOWERY PRECIPITATION
20 percent	*Slight chance* of precipitation	*Widely scattered* showers
30 to 50 percent	*Chance* of precipitation	*Scattered* showers
60 to 70 percent	Precipitation *likely*	*Numerous* showers
≥80 percent	Precipitation,* *rain, snow*	*Showers***

*A forecast that calls for an 80 percent chance of rain in the afternoon might read like this: ". . . cloudy today with rain this afternoon. . . ." For an 80 percent chance of rain showers, the forecast might read ". . . cloudy today with rain showers this afternoon. . . ."

**The 60 percent chance of rain does not apply to a situation that involves rain showers. In the case of showers, the percentage refers to the expected area over which the showers will fall.



◗ **FIGURE 9.16** Probability of a "White Christmas"—one inch or more of snow on the ground—based on a 30-year average. The probabilities do not include all of the mountainous areas in the western United States. (NOAA)

Predicting the weather by **weather types** employs the analogue method. In general, weather patterns are categorized into similar groups or "types," using such criteria as the position of the subtropical highs, the upper-level flow, and the prevailing storm track. As an example, when the Pacific high is weak or depressed southward and the flow aloft is zonal (west-to-east), surface storms tend to travel rapidly eastward across the Pacific Ocean and into the United States without developing into deep systems. But when the Pacific high is to the north of its normal position and the upper airflow is meridional (north-south), looping waves form in the flow with surface lows usually developing into huge storms. Since upper-level longwaves move slowly, usually remaining almost stationary for perhaps a few days to a week or more, the particular surface weather at different positions around the wave is likely to persist for some time. ◗ Figure 9.17 presents an example of weather conditions most likely to prevail with a winter meridional weather type.

A forecast based on the climate* of a particular region is known as a **climatological forecast.** Anyone who has lived in Los Angeles for a while knows that July and August are practically rain-free. In fact, rainfall data for the summer months taken over many years reveal that rainfall amounts of more than a trace occur in Los Angeles about 1 day in every 90, or only about 1 percent of the time. Therefore, if we predict that it will not rain on some day next year during July or August in Los Angeles, our chances are nearly 99 percent that the forecast will be correct based on past records. Since it is unlikely that this pattern will significantly change in the near future, we can confidently make the same forecast for the year 2020.

*The climate of a region represents the total accumulation of daily and seasonal weather events for a specific interval of time, most often 30 years.

TYPES OF FORECASTS Weather forecasts are normally grouped according to how far into the future the forecast extends. For example, a weather forecast for up to a few hours (usually not more than 6 hours) is called a **very short-range forecast**, or *nowcast*. The techniques used in making such a forecast normally involve subjective interpretations of surface observations, satellite imagery, and Doppler radar information. Often weather systems are moved along by the steady state or trend method of forecasting, with human experience and pattern recognition coming into play.

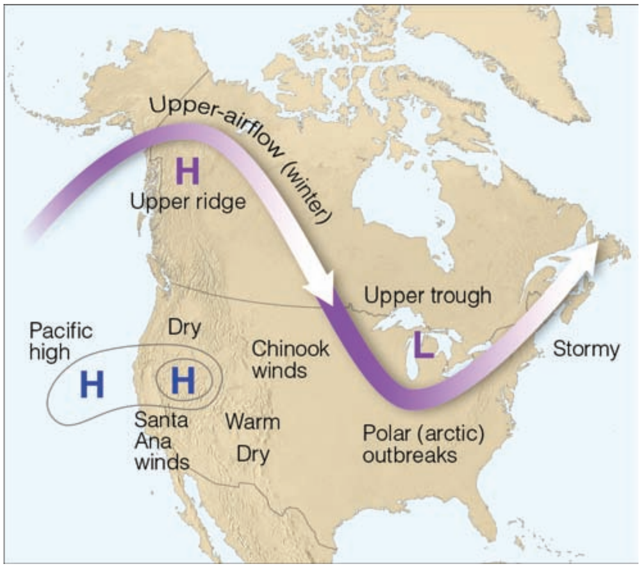
Weather forecasts that range from about 6 hours to a few days (generally 2.5 days or 60 hours) are called **short-range forecasts.** The forecaster may incorporate a variety of techniques in making a short-range forecast, such as satellite imagery, Doppler radar, surface weather maps, upper-air winds, and pattern recognition. As the forecast period extends beyond about 12 hours, the forecaster tends to weight the forecast heavily on computer-drawn progs and statistical information, such as Model Output Statistics (MOS).

A **medium-range forecast** is one that extends from about 3 to 8.5 days (200 hours) into the future. Medium-range forecasts are almost entirely based on computer-derived products, such as forecast progs and statistical forecasts (MOS). A forecast that extends beyond 3 days is often called an *extended forecast.*

A forecast that extends beyond about 8.5 days (200 hours) is called a **long-range forecast.** Although computer progs are available for up to 16 days into the future, they are not accurate in predicting temperature and precipitation, and at best only show the broad-scale weather features. Presently, the Climate Prediction Center issues forecasts, called *outlooks,* of average weather conditions for a particular month or a season. These are not forecasts in the strict sense, but rather an overview of how average precipitation and temperature patterns may compare with normal conditions. ◗Figure 9.18 gives a typical 90-day outlook.

Initially, outlooks were based mainly on the relationship between the projected average upper-air flow and the surface weather conditions that the type of flow will create. Today, many of the outlooks are based on persistence statistics that carry over the general weather pattern from immediately preceding months, seasons, and years. In addition, long-range forecasts are made from models that link the atmosphere with the ocean surface temperature.

In Chapter 7, we saw how a vast warming (El Niño) or cooling (La Niña) of the equatorial tropical Pacific can affect the weather in different regions of the world. These interactions, where a warmer or cooler tropical Pacific can influence rainfall in California, are called *teleconnections.** These types of interactions between widely separated regions are identified through statistical correlations. For example, over regions of North America, where temperature and precipitation patterns tend to depart from normal during El Niño and La Niña events, the Climate Prediction Center can issue a *seasonal outlook* of an impending wetter or drier winter, months in advance. Forecasts using teleconnections have shown promise. For example, as the tropical equatorial Pacific became much warmer than normal during the spring and early summer of 1997, forecasters predicted a wet rainfall season over central and southern



◗**FIGURE 9.17** Winter weather type showing upper-airflow (heavy arrow), surface position of Pacific high, and general weather conditions that should prevail.

California. Although the heavy rains didn't begin until late November, the weather during the winter of 1997–1998 was wet and wild: Storm after storm pounded the region, producing heavy rains, mud slides, road closures, and millions of dollars in damages.

In most locations throughout North America, the weather is fair more often than rainy. Consequently, there is a forecasting bias toward fair weather, which means that, if you made a forecast of "no rain" where you live for each day of the year, your forecast would be correct more than 50 percent of the time. But did you show any *skill* in making your correct forecast? What constitutes skill, anyway? And how accurate are the forecasts issued by the National Weather Service?

ACCURACY AND SKILL IN FORECASTING In spite of the complexity and ever-changing nature of the atmosphere, forecasts made for between 12 and 24 hours are usually quite accurate. Those made for between 2 and 5 days are fairly good. Beyond about 7 days, due to the chaotic nature of the atmosphere, computer prog forecast accuracy falls off rapidly. Although weather predictions made for up to 3 days are by no means

DID YOU KNOW?

When a weather forecast calls for "fair weather," does the "fair" mean that the weather is better than "poor" but not up to being "good"? According to the National Weather Service, the subjective term "fair" implies a rather pleasant weather situation where there is no precipitation, no extremes in temperature, good visibility, and less than 40 percent of the sky is covered by opaque clouds, such as stratus.

*Teleconnections include not only El Niño and La Niña but other indices, such as the Pacific Decadal Oscillation, the North Atlantic Oscillation, and the Arctic Oscillation. For more information on these indices, see Chapter 7, pp. 207–209.

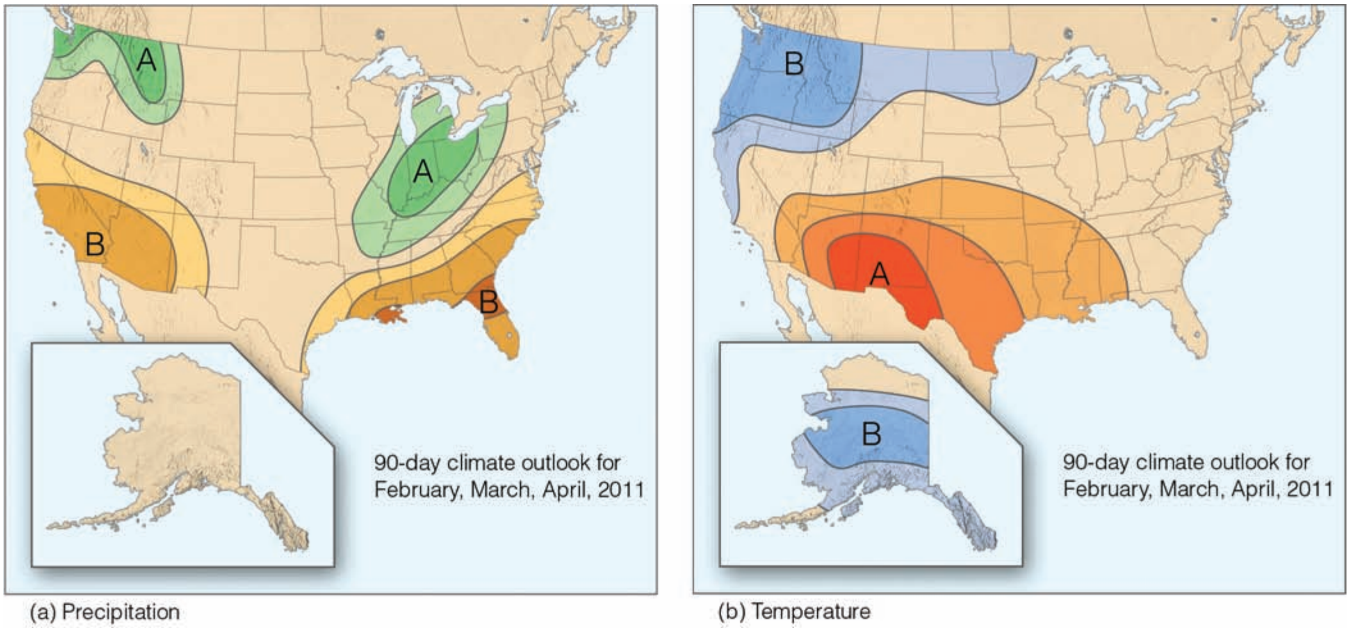


FIGURE 9.18 The 90-day outlook for (a) precipitation and (b) temperature for February, March, and April, 2011. For precipitation (a), the darker the green color the greater the probability of precipitation being above normal, whereas the deeper the brown color the greater the probability of precipitation being below normal. For temperature (b), the darker the orange/red colors the greater the probability of temperatures being above normal, whereas the darker the blue color, the greater the probability of temperatures being below normal. On both maps, the letter A stands for above normal and the letter B for below normal. (National Weather Service/NOAA)

perfect, they are far better than simply flipping a coin. But how accurate are they?

One problem with determining forecast accuracy is deciding what constitutes a right or wrong forecast. Suppose tomorrow's forecast calls for a minimum temperature of 35°F. If the official minimum turns out to be 37°F, is the forecast incorrect? Is it as incorrect as one 10 degrees off? By the same token, what about a forecast for snow over a large city, and the snow line cuts the city in half with the southern portion receiving heavy amounts and the northern portion none? Is the forecast right or wrong? At present, there is no clear-cut answer to the question of determining forecast accuracy.

How does forecast accuracy compare with forecast skill? Suppose you are forecasting the daily summertime weather in Los Angeles. It is not raining today and your forecast for tomorrow calls for "no rain." Suppose that tomorrow it doesn't rain. You made an accurate forecast, but did you show any skill in so doing? Earlier, we saw that the chance of measurable rain in Los Angeles on any summer day is very small indeed; chances are good that day after day it will not rain. For a forecast to show skill, it should be better than one based solely on the current weather (*persistence*) or on the "normal" weather (*climatology*) for a given region. Therefore, during the summer in Los Angeles, a forecaster will have many accurate forecasts calling for "no measurable rain," but will need skill to predict correctly on which summer days it will rain. So, if on a sunny July day in Los Angeles you forecast rain for tomorrow and it rains, you not only made an accurate forecast, you also showed skill in making your forecast because your forecast was better than both persistence and climatology.

Meteorological forecasts, then, show skill when they are more accurate than a forecast utilizing only persistence or climatology. Persistence forecasts are usually difficult to improve upon for a period of time of several hours or less. Weather forecasts ranging from 12 hours to a few days generally show much more skill than those of persistence. However, as the range of the forecast period increases, because of chaos the skill drops quickly. The 6- to 14-day mean outlooks both show some skill (which has been increasing over the last several decades) in predicting temperature and precipitation, although the accuracy of precipitation forecasts is less than that for temperature. Presently, 7-day forecasts now show about as much skill as 3-day forecasts did a decade ago. Beyond 15 days, specific forecasts are only slightly better than climatology. However, the level of skill in making forecasts of average monthly temperature and precipitation has approximately doubled from 1995 to 2006.

Forecasting large-scale weather events several days in advance (such as the blizzard of 1996 along the eastern seaboard of the United States) is far more accurate than forecasting the precise evolution and movement of small-scale, short-lived weather systems, such as tornadoes and severe thunderstorms. In fact, 3-day forecasts of the development and movement of a major low-pressure system show more skill today than 36-hour forecasts did 15 years ago.

Even though the *precise* location where a tornado will form is presently beyond modern forecasting techniques, the general area where the storm is *likely* to form can often be predicted up to 3 days in advance. With improved observing systems, such as Doppler radar and advanced satellite imagery, the lead time of watches and warnings for severe storms has increased. In fact, the lead time* for tornado warnings has more than doubled over the last decade, with the average lead time being close to 15 minutes.

Although scientists may never be able to skillfully predict the weather beyond about 15 days using available observations, the prediction of *climatic trends* appears to be more promising. Whereas individual weather systems vary greatly and are difficult to forecast very far in advance, global-scale patterns of winds and pressure frequently show a high degree of persistence and predictable change over periods of a few weeks to a month or more. With the latest generation of high-speed supercomputers, general circulation models (GCMs) are doing a far better job at predicting large-scale atmospheric behavior than did the earlier models.

As new knowledge and methods of modeling are fed into the GCMs, it is hoped that they will become a reliable tool in the forecasting of weather and climate. (In Chapter 13, we will examine in more detail the climatic predictions based on numerical models.)

BRIEF REVIEW

Up to this point, we have looked at the various methods of weather forecasting. Before going on, here is a review of some of the important ideas presented so far:

- Available to the forecaster are a number of tools that can be used when making a forecast, including surface and upper-air maps, computer progs, meteograms, soundings, Doppler radar, and satellite information.
- Geostationary satellites remain fixed nearly 37,000 kilometers above a spot on the equator and orbit the earth at the same rate the earth spins. Polar-orbiting satellites, at about 850 kilometers above the earth, closely parallel meridian lines and scan the earth from north to south.
- The forecasting of weather by high-speed computers is known as *numerical weather prediction*. Mathematical models that describe how atmospheric temperature, pressure, winds, and moisture will change with time are programmed into the computer. The computer then draws surface and upper-air charts, and produces a variety of forecast charts called *progs*.
- After a number of days, flaws in the computer models—atmospheric chaos and small errors in the data—greatly limit the accuracy of weather forecasts.
- Ensemble forecasting is a technique based on running several forecast models (or different versions of a single model), each beginning with slightly different weather information to reflect errors in the measurements.
- A *persistence forecast* is a prediction that future weather will be the same as the present weather, whereas a *climatological forecast* is based on the climatology of a particular region.
- For a forecast to show skill, it must be better than a persistence forecast or a climatological forecast.
- Weather forecasts for up to a few hours are called *very short-range forecasts;* those that range from about 6 hours to a few days are called *short-range forecasts; medium-range forecasts* extend from about 3 to 5 days into the future, whereas *long-range forecasts* extend beyond, to about 8.5 days.
- Seasonal outlooks provide an overview of how temperature and precipitation patterns may compare with normal conditions.

**Lead time* is the interval of time between the issue of the warning and actual observance of the event, in this case, the tornado.

PREDICTING THE WEATHER FROM LOCAL SIGNS

Because the weather affects every aspect of our daily lives, attempts to predict it accurately have been made for centuries. One of the earliest attempts was undertaken by Theophrastus, a pupil of Aristotle, who in 300 B.C. compiled all sorts of weather indicators in his *Book of Signs.* A dominant influence in the field of weather forecasting for 2000 years, this work consists of ways to foretell the weather by examining natural signs, such as the color and shape of clouds, and the intensity at which a fly bites. Some of these signs have validity and are a part of our own weather folklore—"a halo around the moon portends rain" is one of these. Today, we realize that the halo is caused by the bending of light as it passes through ice crystals and that ice crystal-type clouds (cirrostratus) are often the forerunners of an approaching storm (see Fig. 9.19).

Weather predictions can be made by observing the sky and using a little weather wisdom. If you keep your eyes

DID YOU KNOW?

Groundhog Day (February 2) is the day that is supposed to represent the midpoint of winter—halfway between the winter solstice and the vernal equinox. Years ago, in an attempt to forecast what the remaining half of winter would be like, people placed the burden of weather prognostication on various animals, such as the groundhog, which is actually a woodchuck. Folklore says that if the groundhog emerges from his burrow and sees (or casts) his shadow on the ground and then returns to his burrow, there will be six more weeks of winter weather. One can only wonder whether it is really the groundhog's shadow that drives him back into his burrow or the people standing around gawking at him.

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FIGURE 9.19 A halo around the sun (or moon) means that rain is on the way, a weather forecast made by simply observing the sky.

open and your senses keenly tuned to your environment, you should, with a little practice, be able to make fairly good short-range local weather forecasts by interpreting the messages written in the weather elements. Table 9.2 is designed to help you with this endeavor.

Weather Forecasting Using Surface Charts

We are now in a position to forecast the weather, utilizing more sophisticated techniques. Suppose, for example, that we wish to make a short-range weather forecast and the only information available is a surface weather map. Can we make a forecast from such a chart? Most definitely. And our chances of that forecast being correct improve markedly if we have maps available from several days back. We can use these past maps to locate the previous position of surface features and predict their movement.

A simplified surface weather map is shown in Fig. 9.20 (p. 266). The map portrays early winter weather conditions on Tuesday morning at 6:00 A.M. A single isobar is drawn around the pressure centers to show their positions without cluttering the map. Note that an open wave cyclone is developing over the Central Plains with showers forming along a cold front and light rain, snow, and sleet ahead of a warm front. The dashed lines on the map represent the position of the weather systems six hours ago. Our first question is: How will these systems move?

DETERMINING THE MOVEMENT OF WEATHER SYSTEMS There are several methods we can use in forecasting the movement of surface pressure systems and fronts. The following are a few of these forecasting rules of thumb:

1. For short time intervals, mid-latitude cyclonic storms and fronts tend to move in the same direction and at approximately the same speed as they did during the previous six hours (providing, of course, there is no evidence to indicate otherwise).
2. Low-pressure areas tend to move in a direction that parallels the isobars in the warm air (the warm sector) ahead of the cold front.
3. Lows tend to move toward the region of greatest surface pressure drop, whereas highs tend to move toward the region of greatest surface pressure rise.
4. Surface pressure systems tend to move in the same direction as the wind at 5500 m (18,000 ft)—the 500-mb level. The speed at which surface systems move is about half the speed of the winds at this level.

When the surface map (Fig. 9.20) is examined carefully and when rules of thumb 1 and 2 are applied, it appears that—based on present trends—the low-pressure area over the Central Plains should move northeast. When we observe the 500-mb upper-air chart (Fig. 9.21, p. 267), it too suggests that the surface low should move northeast at a speed of about 25 knots.

A FORECAST FOR SIX CITIES We are now in a position to make a weather forecast for six cities. To do so, we will project the surface pressure systems, fronts, and current weather into the future by assuming steady-state conditions. Fig. 9.22 (p. 267) gives the 12- and 24-hour projected positions of these features.

A word of caution before we make our forecasts. We are assuming that the pressure systems and fronts are moving at a constant rate, which may or may not occur. Low-pressure areas, for example, tend to accelerate until they occlude, after which their rate of movement slows. Furthermore, the direction of moving systems may change due to "blocking" highs and lows that exist in their path or because of shifting upper-level wind patterns. We will assume a constant rate of movement and forecast accordingly, always keeping in mind that the longer our forecasts extend into the future, the more susceptible they are to error.

If we move the low- and high-pressure areas eastward, as illustrated in Fig. 9.22, we can make a basic weather forecast for various cities. For example, the cold front moving into north Texas on Tuesday morning is projected to pass Dallas by that evening, so a forecast for the Dallas area would be "warm with showers, then turning colder." But we can do much better than this. Knowing the weather conditions that accompany advancing pressure areas and fronts, we can make more detailed weather forecasts that will take into account changes in

TABLE 9.2 Forecast at a Glance–Forecasting the Weather from Local Weather Signs. Listed below are a few forecasting rules that may be applied when making a short-range local weather forecast.

OBSERVATION	INDICATION	LOCAL WEATHER FORECAST
Surface winds from the S or from the SW; clouds building to the west; warm (hot) and humid (pressure falling)	Possible cool front and thunderstorms approaching from the west	Possible showers; possibly turning cooler; windy
Surface winds from the E or from the SE, cool or cold; high clouds thickening and lowering; halo (ring of light) around the sun or moon (pressure falling)	Possible approach of a warm front	Possibility of precipitation within 12–24 hours; windy (rain with possible thunderstorms during the summer; snow changing to sleet or rain in winter)
Strong surface winds from the NW or W; cumulus clouds moving overhead (pressure rising)	A low-pressure area may be moving to the east, away from you; and an area of high pressure is moving toward you from the west	Continued clear to partly cloudy, cold nights in winter; cool nights with low humidity in summer
Winter night		
(a) If clear, relatively calm with low humidity (low dew-point temperature)	(a) Rapid radiational cooling will occur	(a) A very cold night
(b) If clear, relatively calm with low humidity and snow covering the ground	(b) Rapid radiational cooling will occur	(b) A very cold night with minimum temperatures lower than in (a)
(c) If cloudy, relatively calm with low humidity	(c) Clouds will absorb and radiate infrared (IR) energy to surface	(c) Minimum temperature will not be as low as in (a) or (b)
Summer night		
(a) Clear, hot, humid (high dew points)	(a) Strong absorption and emission of IR energy to surface by water vapor	(a) High minimum temperatures
(b) Clear and relatively dry	(b) More rapid radiational cooling	(b) Lower minimum temperatures
Summer afternoon		
Scattered cumulus clouds that show extensive vertical growth by mid-morning	Atmosphere is relatively unstable	Possible showers or thunderstorms by afternoon with gusty winds
Afternoon cumulus clouds with limited vertical growth and with tops at just about the same level	Stable layer above clouds (region dominated by high pressure)	Continued partly cloudly with no precipitation; probably clearing by nightfall

temperature, pressure, humidity, cloud cover, precipitation, and winds. Our forecast will include the 24-hour period from Tuesday morning to Wednesday morning for the cities of Augusta, Georgia; Washington, D.C.; Chicago, Illinois; Memphis, Tennessee; Dallas, Texas; and Denver, Colorado. We will begin with Augusta.

Weather Forecast for Augusta, Georgia On Tuesday morning, continental polar air associated with a high-pressure area brought freezing temperatures and fair weather to the Augusta area (see Fig. 9.20). Clear skies, light winds, and low humidities allowed rapid nighttime cooling so that, by morning, temperatures were in the low thirties. Now look closely at Fig. 9.22 and observe that the high-pressure area is moving slowly eastward, away from Augusta. Southerly winds on the western side of this system will bring warmer and more humid air to the region. Therefore, afternoon temperatures will be warmer than those of the day before. As the warm front approaches from the west, clouds will increase, appearing first as cirrus, then thickening and lowering into the normal sequence of warm-front clouds. Barometric pressure should fall. Clouds and high humidity should keep minimum temperatures well above freezing on Tuesday night. Note in Fig. 9.22 that the projected area of precipitation (green-shaded

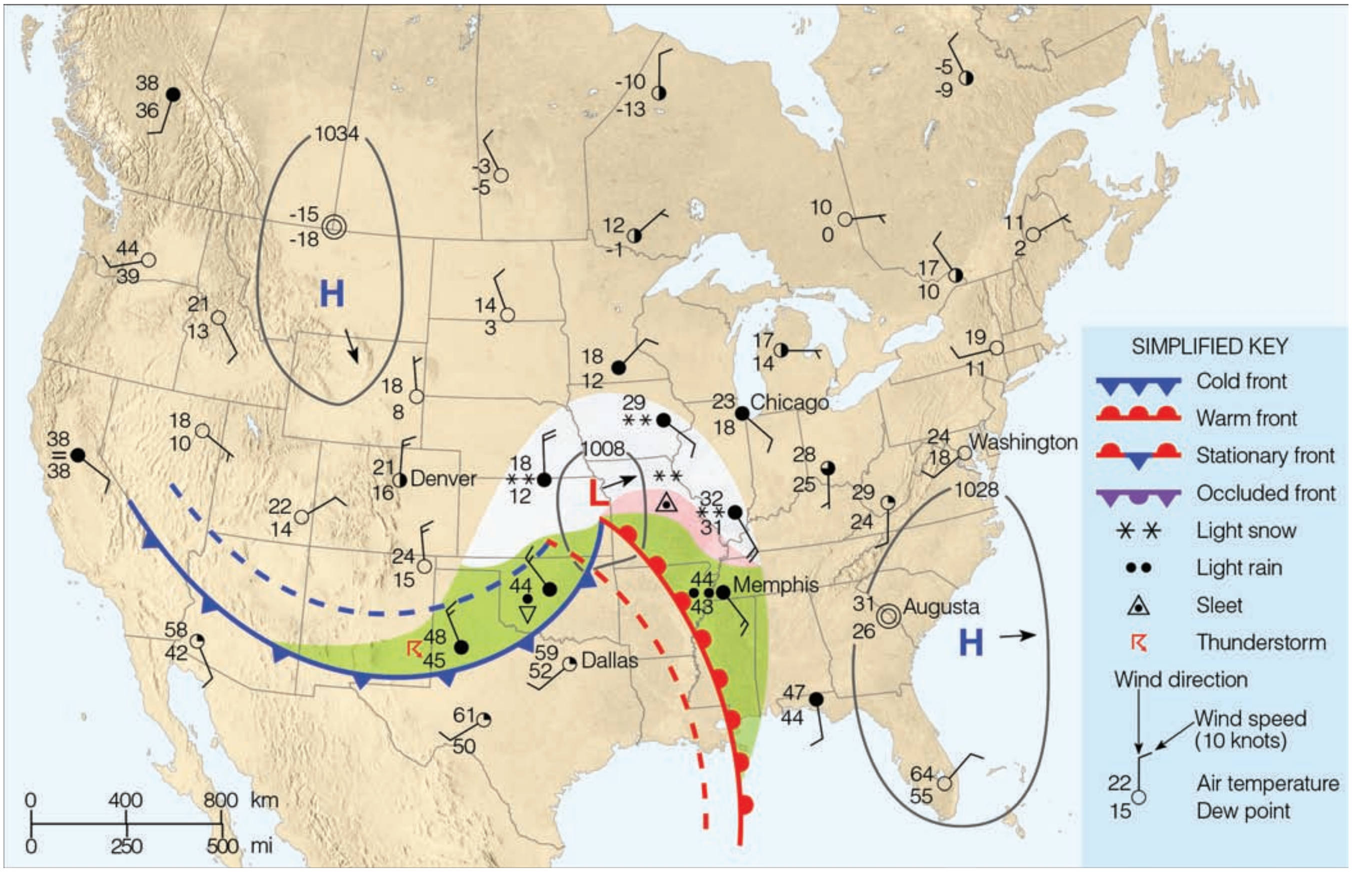


FIGURE 9.20 Surface weather map for 6:00 A.M. Tuesday. Dashed lines indicate positions of weather features six hours ago. Areas shaded green are receiving rain, while areas shaded white are receiving snow, and those shaded pink, freezing rain or sleet.

region) does not quite reach Augusta. With all of this in mind, our forecast might sound something like this:

> Clear and cold this morning with moderating temperatures by afternoon. Increasing high clouds with skies becoming overcast by evening. Cloudy and not nearly as cold tonight and tomorrow morning. Winds will be light and out of the south or southeast. Barometric pressure will fall slowly.

Wednesday morning we discover that the weather in Augusta is foggy with temperatures in the upper 40s (°F). But fog was not in the forecast. What went wrong? We forgot to consider that the ground was still cold from the recent cold snap. The warm, moist air moving over the cold surface was chilled below its dew point, resulting in fog. Above the fog were the low clouds we predicted. The minimum temperatures remained higher than anticipated because of the release of latent heat during fog formation and the absorption of infrared energy by the fog droplets. Not bad for a start. Now we will forecast the weather for Washington, D.C.

Rain or Snow for Washington, D.C.? Look at Fig. 9.22 and observe that the low-pressure area over the Central Plains is slowly approaching Washington, D.C., from the west. Hence, the clear weather, light southwesterly winds, and low temperatures on Tuesday morning (Fig. 9.20) will gradually give way to increasing cloudiness, winds becoming southeasterly, and slightly higher temperatures. By Wednesday morning, the projected band of precipitation will be over the city. Will it be in the form of rain or snow? Without a vertical profile of temperature (a sounding), this question is difficult to answer. We can see in Fig. 9.22, however, that on Tuesday morning cities south of Washington, D.C.'s latitude are receiving snow. So a reasonable forecast would call for snow, possibly changing to rain as warm air moves in aloft in advance of the approaching fronts. A 24-hour forecast for Washington, D.C., might sound like this:

> Increasing clouds today and continued cold. Snow beginning by early Wednesday morning, possibly changing to rain. Winds will be out of the southeast. Pressures will fall.

Wednesday morning a friend in Washington, D.C., calls to tell us that the sleet began to fall but has since changed to rain. Sleet? Another fractured forecast! Well, almost. What we forgot to account for this time was the intensification of the storm. As the low-pressure area moved eastward, it deepened; central pressure lowered, pressure gradients tightened, and southeasterly winds blew stronger than anticipated. As air moved inland off the warmer Atlantic, it rode up and over the colder surface air. Snow

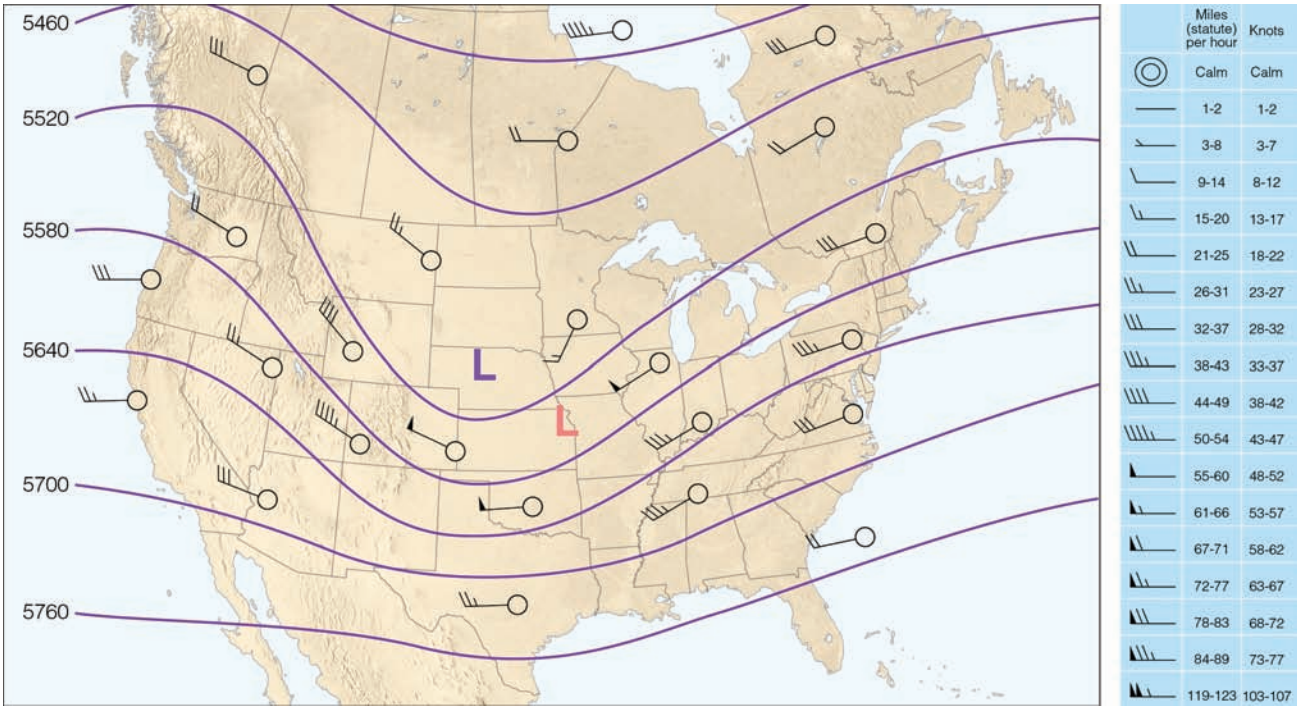


FIGURE 9.21 A 500-mb chart for 6:00 A.M. Tuesday, showing wind flow. The light orange L represents the position of the surface low. The winds aloft tend to steer surface pressure systems along and, therefore, indicate that the surface low should move northeastward at about half the speed of the winds at this level, or 25 knots. Solid lines are contours in meters above sea level.

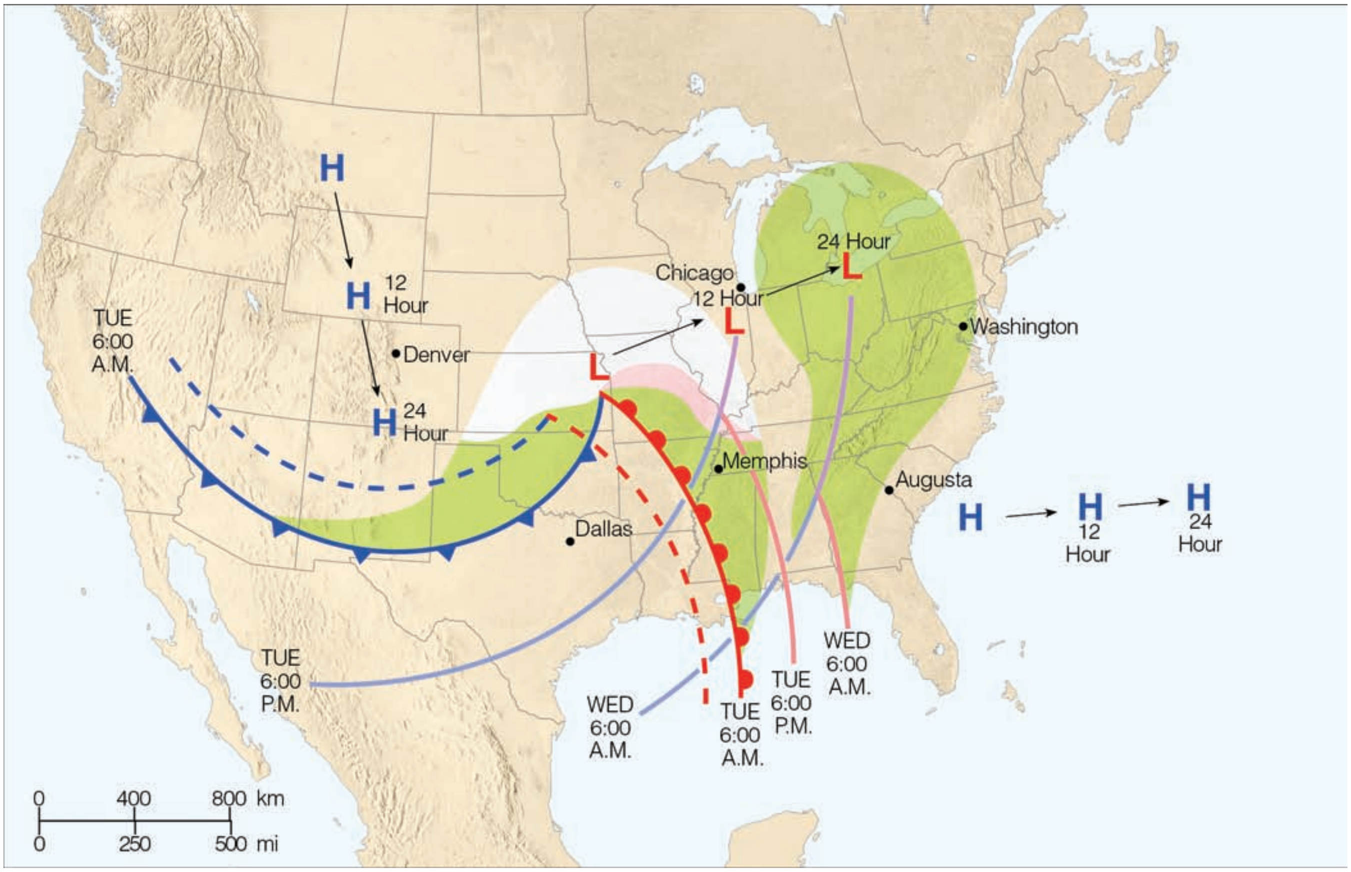


FIGURE 9.22 Projected 12- and 24-hour movement of fronts, pressure systems, and precipitation from 6:00 A.M. Tuesday until 6:00 A.M. Wednesday. (The dashed lines represent frontal positions 6 hours ago.)

falling into this warm layer at least partially melted; it then refroze as it entered the colder air near ground level. The influx of warmer air from the ocean slowly raised the surface temperatures, and the sleet soon became rain. Although we did not see this possibility when we made our forecast, a forecaster more familiar with local surroundings would have. Let's move on to Chicago.

Big Snowstorm for Chicago From Figs. 9.20 and 9.22, it appears that Chicago is in for a major snowstorm. Overrunning of warm air has produced a wide area of snow which, from all indications, is heading directly for the Chicago area. Since cold air north of the low's center will be over Chicago, precipitation reaching the ground should be frozen. On Tuesday morning (Fig. 9.22) the leading edge of precipitation is less than six hours away from Chicago. Based on the projected path of the low-pressure area (Fig. 9.22) light snow should begin to fall around noon on Tuesday.

By evening, as the storm intensifies, snowfall should become heavy. It should taper off and finally end around midnight as the center of the low moves on east. If it snows for a total of twelve hours—six hours as light snow (around one inch every three hours) and six hours as heavy snow (around one inch per hour)—then the total expected accumulation will be between six and ten inches. As the low moves eastward, passing south of Chicago, winds on Tuesday will gradually shift from southeasterly to easterly, then northeasterly by evening. Since the storm system is intensifying, it should produce strong winds that will swirl the snow into huge drifts, which may bring traffic to a crawl.

The winds will continue to shift to the north and finally become northwesterly by Wednesday morning. By then the storm center will probably be far enough east so that skies should begin to clear. Cold air moving in from the northwest behind the storm will cause temperatures to drop further. Barometer readings during the storm will fall as the low's center approaches and reach a low value sometime Tuesday night, after which they will begin to rise. A weather forecast for Chicago might be:

> Cloudy and cold with light snow beginning by noon, becoming heavy by evening and ending by Wednesday morning. Total accumulations will range between six and ten inches. Winds will be strong and gusty out of the east or northeast today, becoming northerly tonight and northwesterly by Wednesday morning. Barometric pressure will fall sharply today and rise tomorrow.

A call Wednesday morning to a friend in Chicago reveals that our forecast was correct except that the total snow accumulation so far is 13 inches. We were off in our forecast because the storm system slowed as it became occluded. We did not consider this because we moved the system by the steady-state forecast method. At this time of year (early winter), Lake Michigan is not quite frozen over, and the added moisture picked up from the lake by the strong easterly and northeasterly winds also helped to enhance the snowfall. Again, a knowledge of the local surroundings would have helped make a more accurate forecast. The weather about 500 miles south of Chicago should be much different from this.

Mixed Bag of Weather for Memphis Observe in Fig. 9.22 that, within twenty-four hours, both a warm and a cold front should move past Memphis, Tennessee. The light rain that began Tuesday morning should saturate the cool air, creating a blanket of low clouds and fog by midday. The warm front, as it moves through sometime Tuesday afternoon, should cause temperatures to rise slightly as winds shift to the south or southwest. At night, clear to partly cloudy skies should allow the ground and air above to cool, offsetting any tendency for a rapid rise in temperature. Falling pressures should level off in the warm air, then fall once again as the cold front approaches. According to the projection in Fig. 9.22, the cold front should arrive sometime before midnight on Tuesday, bringing with it gusty northwesterly winds, showers, the possibility of thunderstorms, rising pressures, and colder air. Taking all of this into account, our weather forecast for Memphis will be:

> Cloudy and cool with light rain, low clouds, and fog early today, becoming partly cloudy and warmer by late this afternoon. Clouds increasing with possible showers and thunderstorms later tonight and turning colder. Winds southeasterly this morning, becoming southerly or southwesterly this evening and shifting to northwesterly tonight. Pressures falling this morning, leveling off this afternoon, then falling again, but rising after midnight.

A friend who lives near Memphis calls Wednesday to inform us that our forecast was correct except that the thunderstorms did not materialize and that Tuesday night dense fog formed in low-lying valleys, but by Wednesday morning it had dissipated. Apparently, in the warm air, winds were not strong enough to mix the cold, moist air that had settled in the valleys with the warm air above. It's on to Dallas.

Cold Wave for Dallas From Fig. 9.22, it appears that our weather forecast for Dallas should be straightforward, since a cold front is expected to pass the area around noon on Tuesday. Weather along the front (Fig. 9.20) is showery with a few thunderstorms developing; behind the front the air is clear but cold. By Wednesday morning it looks as if the cold front will be far to the east and south of Dallas and an area of high pressure will be centered over southern Colorado. North or northwesterly winds on the east side of the high will bring cold arctic air into Texas, dropping temperatures as much as 40°F within a 24-hour period. With minimum temperatures well below freezing, Dallas will be in the grip of a cold wave. Our weather forecast should therefore sound something like this:

> Increasing cloudiness and mild this morning with the possibility of showers and thunderstorms this afternoon. Clearing and turning much colder tonight and tomorrow. Winds will be southwesterly today, becoming gusty north or northwesterly this afternoon and tonight. Pressures falling this morning, then rising later today.

How did our forecast turn out? A quick call to Dallas on Wednesday morning reveals that the weather there is cold but not as cold as expected, and the sky is overcast. Cloudy weather? How can this be?

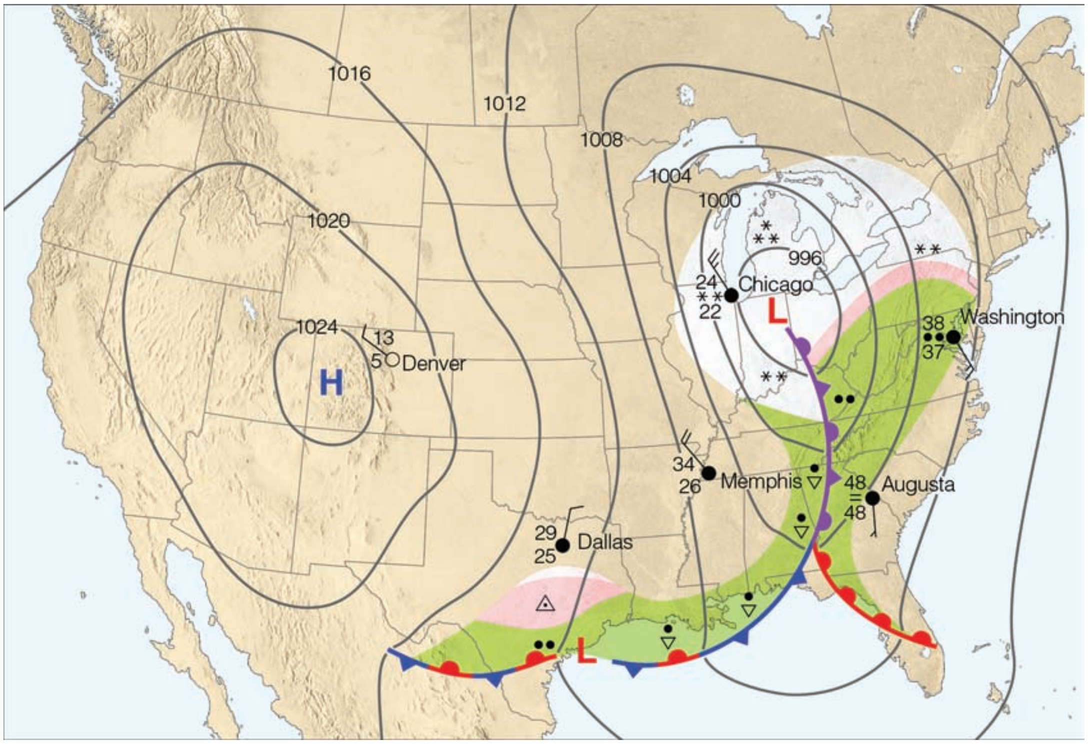
The cold front moved through on schedule Tuesday afternoon, bringing showers, gusty winds, and cold weather with it. Moving southward, the front gradually slowed and became stationary along a line stretching from the Gulf of Mexico westward through southern Texas and northern Mexico. (From the surface map alone, we had no way of knowing this would happen.) Along the stationary front a wave of low pressure formed. This wave caused warm, moist Gulf air to slide northward up and over the cold surface air. Clouds formed, minimum temperatures did not go as low as expected, and we are left with a fractured forecast. Let's try Denver.

Clear but Cold for Denver In Fig. 9.20, we can see that, based on our projections, the cold high-pressure area will be centered slightly to the south of Denver by Wednesday morning. Sinking air aloft associated with this high-pressure area should keep the sky relatively free of clouds. Weak pressure gradients will produce only weak winds and this, coupled with dry air, will allow for intense radiational cooling. Minimum temperatures will probably drop to well below 0°F. Our forecast should therefore read:

> Clear and cold through tomorrow. Northerly winds today becoming light and variable by tonight. Temperatures tomorrow morning will be below zero. Barometric pressure will continue to rise.

Almost reluctantly Wednesday morning, we inquire about the weather conditions at Denver. "Clear and very cold" is the reply. A successful forecast at last! We are told, however, that the minimum temperature did not go below zero; in fact, 13°F was as cold as it got. A downslope wind coming off the mountains to the west of Denver kept the air mixed and the minimum temperature higher than expected. Again, a forecaster familiar with the local topography of the Denver area would have foreseen the conditions that lead to such downslope winds and would have taken this into account when making the forecast.

A complete picture of the surface weather systems for 6:00 A.M. Wednesday morning is given in ▶Fig. 9.23. By comparing this chart with Fig. 9.21, we can summarize why our forecasts did not turn out exactly as we had predicted. For one thing, the center of the low-pressure area over the Central Plains moved slower than expected.



▶**FIGURE 9.23**
Surface weather map for 6:00 A.M. Wednesday.

This slow movement allowed a southeasterly flow of mild Atlantic air to overrun cooler surface air ahead of the storm while, behind the low, cities remained in the snow area for a longer time. The weak wave that developed along the trailing cold front over South Texas brought cloudiness and precipitation to Texas and prevented the really cold air from penetrating deep into the south. Further west, the high-pressure area originally over Montana moved more southerly than southeasterly, which set up a pressure gradient that brought westerly downslope winds to eastern Colorado.

In summary, the forecasting techniques discussed in this section are those you can use when making a short-range weather forecast. Keep in mind, however, that this chapter was not intended to make you an expert weather forecaster, nor was it designed to show you all the methods of weather prediction. It is hoped that you now have a better understanding of some of the problems confronting anyone who attempts to predict the behavior of this churning mass of air we call our atmosphere.

SUMMARY

Forecasting tomorrow's weather entails a variety of techniques and methods. Persistence, surface maps, satellite imagery, and Doppler radar are all useful when making a very short range (0–6 hour) prediction. For short- and medium-range forecasts, the current analysis, satellite data, pattern recognition, meteorologist intuition, and experience, along with statistical information and guidance from the many computer progs supplied by the National Weather Service, all go into making a prediction. For monthly and seasonal long-range forecasts, meteorologists incorporate changes in sea-surface temperature in the Pacific and Atlantic Oceans into seasonal outlooks of temperature and precipitation in North America.

Different computer progs are based upon different atmospheric models that describe the state of the atmosphere and how it will change with time. The atmosphere's chaotic behavior, along with flaws in the models and tiny errors (uncertainties) in the data, generally amplify as the computer tries to project weather farther and farther into the future. At present, computer progs that predict the weather over a vast region are better at forecasting the position of mid-latitude highs and lows and their development than at forecasting local showers and thunderstorms. To skillfully forecast smaller features, the grid spacing on some models is being reduced.

Satellites aid the forecaster by providing a bird's-eye view of clouds and storms. Polar-orbiting satellites obtain data covering the earth from pole to pole, whereas geostationary satellites situated above the equator supply the forecaster with dynamic images of cloud and storm development and movement. To show where the highest and thickest clouds are located in a particular storm, infrared images are often enhanced by computer.

In the latter part of this chapter, we learned how people, by observing the weather around them, and by watching the weather systems on surface weather maps, can make fairly good short-range weather predictions.

Most of the forecasting methods in this chapter apply mainly to skill in predicting events associated with large-scale weather systems, such as fronts and mid-latitude cyclones. The next chapter on severe weather deals with the formation and forecasting of smaller-scale (mesoscale) systems, such as thunderstorms, squall lines, and tornadoes.

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.

watch (weather), 247
warning (weather), 247
AWIPS, 247
meteogram, 249
sounding, 249
geostationary satellites, 250
polar-orbiting satellites, 250
analysis, 254
numerical weather prediction, 254
atmospheric models, 254
prognostic chart (prog), 254
chaos, 256
ensemble forecasting, 256
persistence forecast, 258
steady-state (trend) forecast, 258
analogue method, 258
statistical forecast, 259
probability forecast, 259
weather types, 260
climatological forecast, 260
very short-range forecast (nowcast), 260
short-range forecast, 260
medium-range forecast, 261
long-range forecast, 261

QUESTIONS FOR REVIEW

1. What is the function of the National Center for Environmental Prediction?
2. How does a *weather watch* differ from a *weather warning*?
3. How does a prog differ from an analysis?
4. In what ways have high-speed computers assisted the meteorologist in making weather forecasts?
5. How are computer-generated weather forecasts prepared?
6. What are some of the problems associated with computer-model forecasts?
7. List some of the tools a weather forecaster might use when making a short-range forecast.
8. How do geostationary satellites differ from polar-orbiting satellites?
9. (a) Explain how satellites aid in forecasting the weather.
   (b) Using infrared satellite information, how can a forecaster distinguish high clouds from low clouds?
   (c) Why is it often necessary to enhance infrared satellite images?
10. Describe four methods of forecasting the weather and give an example for each one.
11. How does pattern recognition aid a forecaster in making a prediction?
12. Suppose that where you live, the middle of January is typically several degrees warmer than the rest of the month. If you forecast this "January thaw" for the middle of next January, what type of weather forecast will you have made?
13. (a) Look out the window and make a persistence forecast for tomorrow at this time.
    (b) Did you use any skill in making this prediction?
14. How can ensemble forecasts improve medium-range forecasts?
15. Explain how teleconnections are used in making a long-range seasonal outlook.
16. If today's weather forecast calls for a "*chance of snow*," what is the percentage probability that it will snow today? (Hint: See Table 9.1, p. 259).
17. Do all accurate forecasts show skill on the part of the forecaster? Explain.
18. List three methods that you would use to predict the movement of a surface mid-latitude cyclonic storm.
19. Do monthly and seasonal forecasts make specific predictions of rain or snow? Explain.

QUESTIONS FOR THOUGHT AND EXPLORATION

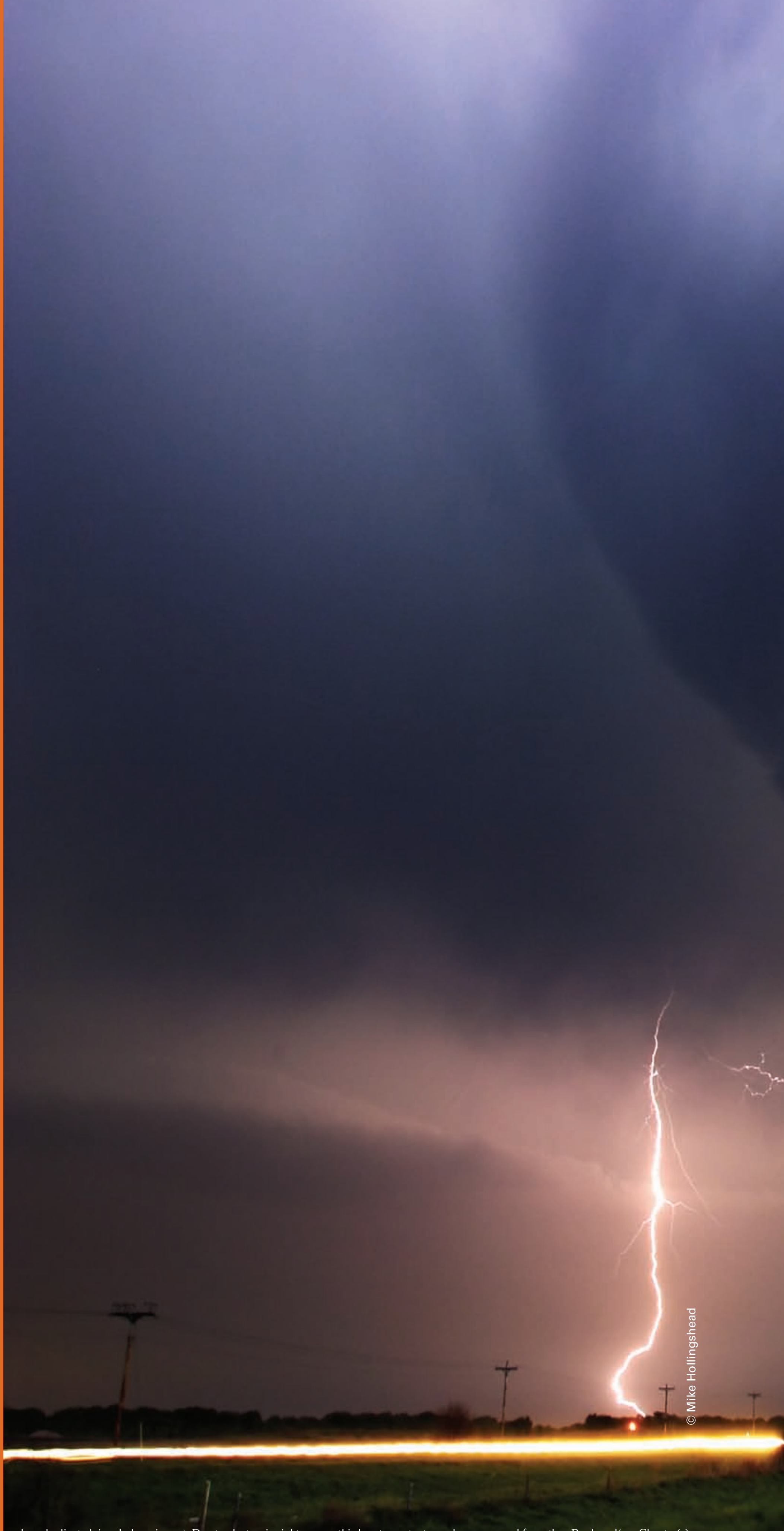
1. What types of watches and warnings are most commonly issued for your area?
2. Since computer models have difficulty in adequately considering the effects of small-scale geographic features on a weather map, why don't numerical weather forecasters simply reduce the grid spacing to, say, 1 kilometer on all models?
3. Suppose it's warm and raining outside. A cold front will pass your area in 3 hours. Behind the front, it is cold and snowing. Make a persistence forecast for your area 6 hours from now. Would you expect this forecast to be correct? Explain. Now, make a forecast for your area using the steady-state or trend forecasting method.
4. Why isn't the steady-state method very accurate when forecasting the weather more than a few hours into the future? What considerations can be taken into account to improve a steady-state forecast?
5. Go outside and observe the weather. Make a weather forecast using the weather signs you observe. Explain the rationale for your forecast.
6. Explain how the phrase "sensitive dependence on initial conditions" relates to the final outcome of a computer-based weather forecast.
7. Suppose the chance for a "White Christmas" at your home is 10 percent. Last Christmas was a white one. If for next year you forecast a "nonwhite" Christmas, will you have shown any skill if your forecast turns out to be correct? Explain.
8. Compare the visible satellite picture (Fig. 9.9a, p. 252) with the infrared image (Fig. 9.9b). With the aid of the infrared image, label on the visible image the regions of middle, high, and low clouds. On the enhanced infrared image (Fig. 9.10, p. 253), label where the highest and thickest clouds appear to be located.

ONLINE RESOURCES

Log in to the CourseMate website at: www.cengagebrain.com to view the active figures and concept animations as noted in the text, as well as additional resources, including video exercises, practice quizzes, an interactive eBook, and more.

10

Contents



An intense thunderstorm near Grand Rapids, Nebraska, during May, 2005, produces heavy rain and many cloud-to-ground lightning flashes.

Thunderstorms and Tornadoes

Wednesday, March 18, 1925, was a day that began uneventfully, but within hours 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 (which was most likely a series of tornadoes) 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 a rising air parcel 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 the air surrounding it, the greater the buoyant force and the stronger the convection. The trigger (or "forcing mechanism") needed to start air moving upward may be:

1. unequal heating at the surface
2. the effect of terrain, or the lifting of air along shallow boundaries of converging surface winds
3. diverging upper-level winds, coupled with converging surface winds and rising air
4. warm air rising along a frontal zone

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

*A conditionally unstable atmosphere exists when cold, dry air aloft overlies warm, moist surface air. However, thunderstorms may form when a cold "pool" of air moves over a region where the surface air temperature is no more than 10°C (50°F). This situation often occurs during the winter along the west coast of North America. Additionally, thunderstorms occasionally form in wintertime snowstorms. In both of these cases, the air aloft is considerably colder than the surface air, which generates instability. More information on atmospheric instability is given in Chapter 5.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▸FIGURE 10.1 An ordinary thunderstorm in its mature stage. Note the distinctive anvil top.

Most thunderstorms that form over North America are short-lived, produce 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 having at least one of the following: large hail with a diameter of at least three-quarters of an inch and/or surface wind gusts of 50 knots (58 mi/hr) or greater, or can produce a tornado.

Scattered thunderstorms (sometimes called "pop-up" storms) that typically form on warm, humid days are 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. Ordinary cell (air mass) thunderstorms 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*—a huge 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.

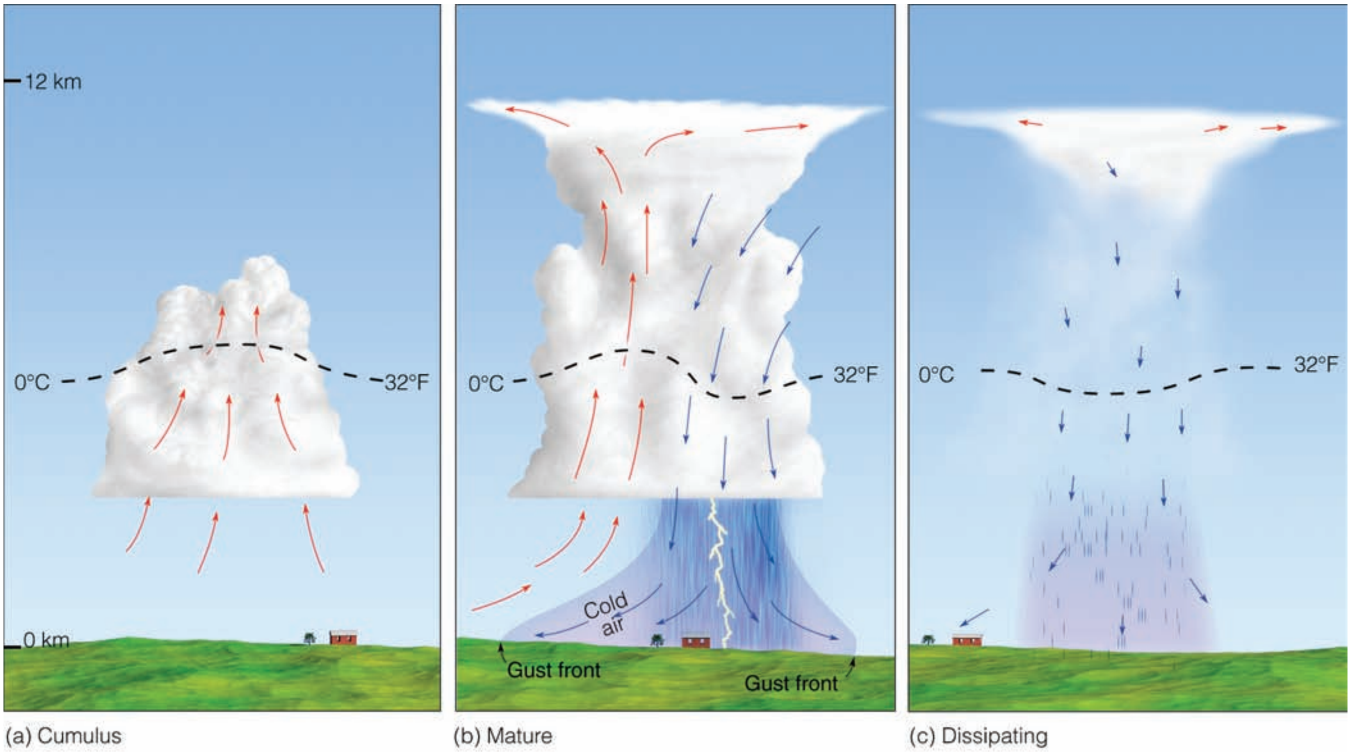
ORDINARY CELL THUNDERSTORMS

Ordinary cell (air mass) thunderstorms or, simply, *ordinary thunderstorms*, tend to form in a region where there is limited wind shear—that is, where the wind speed and 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, then it dissipates. The top of the cloud dissipates 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

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



Active ▸ **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.)

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. 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.* The downdraft may be 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.

DID YOU KNOW?

The folks of Elgin, Manitoba, literally had their "goose cooked" during April, 1932, when a lightning bolt from an intense thunderstorm killed 52 geese that were flying overhead in formation. As the birds fell to the ground, they were reportedly gathered up and distributed to the townspeople for dinner.

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 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 of over 12 km (40,000 ft) and be several kilometers in diameter near its base. Updrafts and downdrafts reach their greatest strength 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 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 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 lower as much as 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

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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.

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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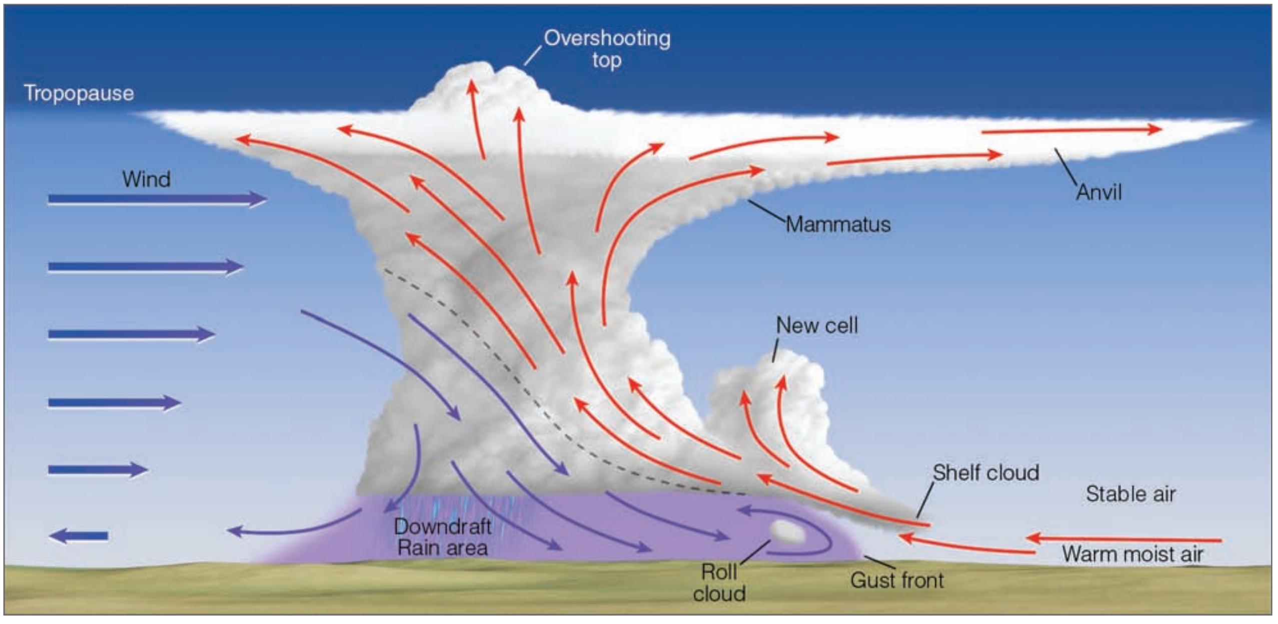
the storm complex can survive for a long time. Because the likelihood that a thunderstorm will become severe increases with the length of time the storm exists, long-lasting multicell storms can become intense and produce severe weather.

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 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



Active **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 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.

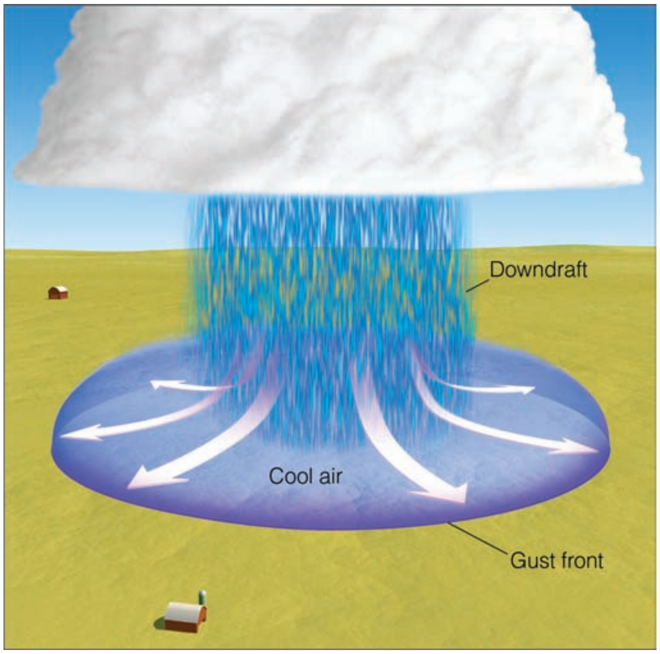
Along the leading edge of the gust front, the air is quite turbulent. Here, strong winds can pick up loose dust and soil and lift them into a huge tumbling cloud.* The cold surface air behind the gust front may even linger close to the ground for hours, well after thunderstorm activity has ceased.

As warm, moist air rises along the forward edge of the gust front, a **shelf cloud** (also called an *arcus cloud*) 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 shown above.) 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 146 knots. (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 of Denver, Colorado. Since a microburst

*In dry, dusty areas or desert regions, the leading edge of the gust front is the haboob described in Chapter 7, p. 191.



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

◗**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.

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. Moreover, microbursts and their accompanying *wind shear* (that is, rapid changes in wind speed or wind direction) appear to be responsible for several airline crashes. 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.

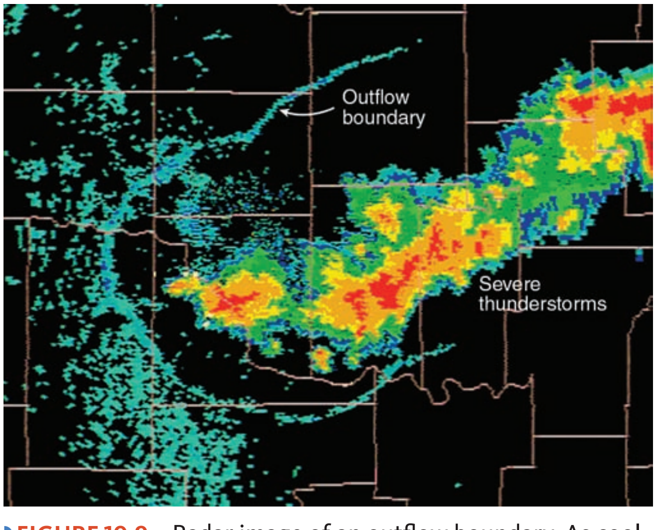


FIGURE 10.9 Radar image of an outflow boundary. As cool (more-dense) air from inside the severe thunderstorms (red and orange colors) spreads outward, away from the storms, it comes in contact with the surrounding warm, humid (less-dense) air, forming a density boundary (blue line) called an *outflow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

One accident attributed to a microburst 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 over 100 passengers. To detect the hazardous wind shear associated with microbursts, many major airports use a high resolution Doppler radar. The radar uses algorithms that are computer programmed to detect microbursts and low-level wind shear.

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.

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, during the evening of May 22, 1996, in the town of Chickasha, Oklahoma, a blast of hot, dry air from a dissipating thunderstorm raised the surface air temperature from 88°F to 102°F in just 25 minutes. Such sudden warm downbursts are called **heat bursts**.

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

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 Chickasha 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.

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 (see Fig. 10.13). 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, 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. 10.14. 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.

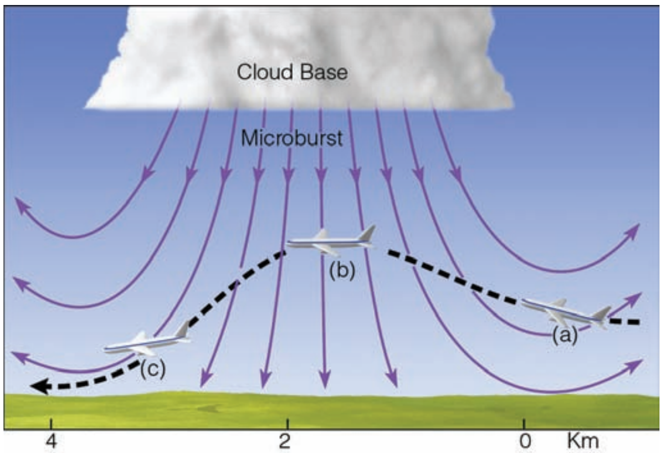
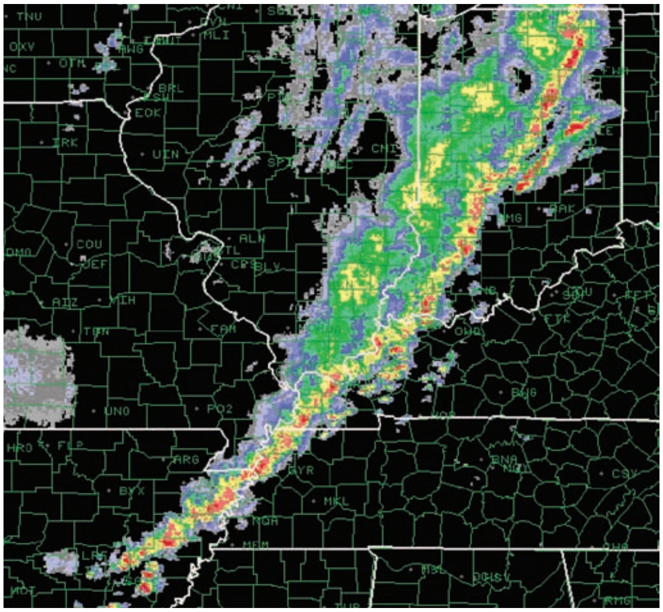


FIGURE 10.11 Flying into a microburst. At position (a), the pilot encounters a headwind; at position (b), a strong downdraft; and at position (c), a tailwind that reduces lift and causes the aircraft to lose altitude.

*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.



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.

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. 10.15). When the damage associated with the straight-line winds extends for a considerable distance along the squall line's path, the windstorm is called a **derecho** (day-ray-sho), after the Spanish word for "straight ahead."

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. In an average year about 20 derechoes occur in the United States. During July, 2005, two derechoes within three days moved through the St. Louis, Missouri, metro area. With winds gusting to over 75 knots, they downed trees and power lines all across the region, leaving half a million residents without power.

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 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. 10.16).

Within the MCCs, the individual thunderstorms apparently work together to generate a long-lasting

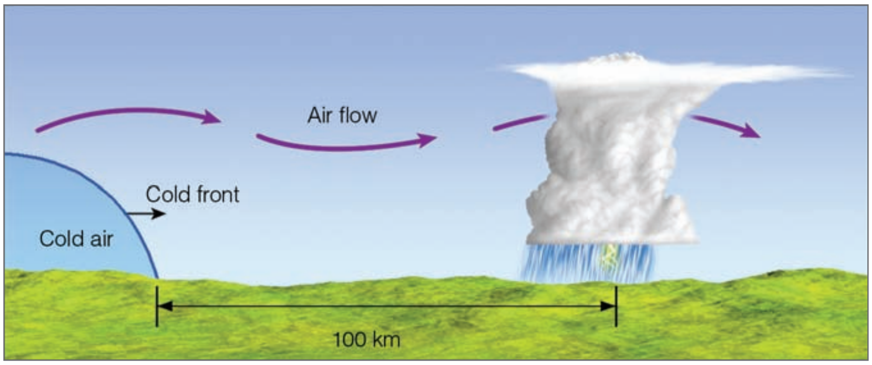


FIGURE 10.13 Pre-frontal squall-line thunderstorms may form ahead of an advancing cold front as the upper-air flow develops waves downwind from the cold front.

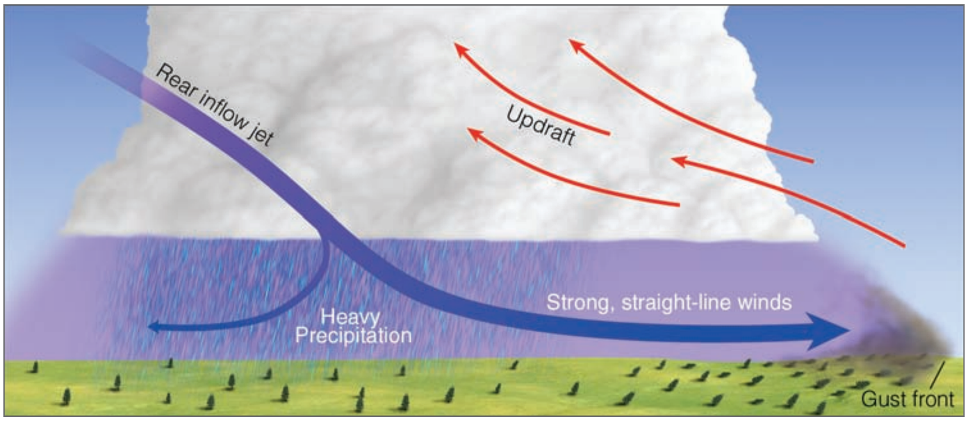


FIGURE 10.14 A side view of the lower half of a squall-line thunderstorm with the rear-inflow jet carrying strong winds from high altitudes down to the surface. These strong winds push forward along the surface, causing damaging straight-line winds that may reach 100 knots. If the high winds extend horizontally for a considerable distance, the wind storm is called a *derecho*.

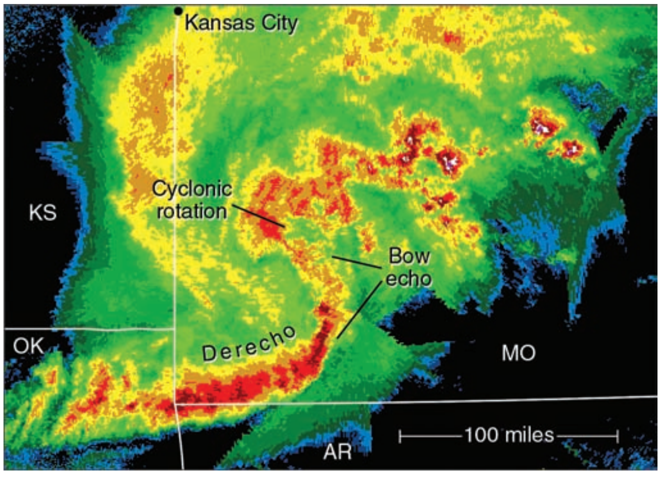


FIGURE 10.15 A Doppler radar image showing an intense squall line in the shape of a bow—called a *bow echo*—moving eastward across Missouri on the morning of May 8, 2009. The strong thunderstorms (red and orange in the image) are producing damaging straight-line winds over a wide area. Damaging straight-line wind that extends for a good distance along a squall line is called a *derecho*.

(more than 6 hours) weather system that moves slowly (normally less than 20 knots) and 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, as 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. With only weak upper-level winds, most MCCs move southeast very slowly.

SUPERCELL THUNDERSTORMS In a region where there is strong vertical wind shear (both speed and direction 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. A large, 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 10.17 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 for hours. Storms of this type are capable of producing an updraft that may exceed 90 knots, damaging surface winds, and large tornadoes. Violent updrafts keep hailstones suspended in the cloud long enough for them to grow to considerable size—sometimes to the size of grapefruits. Once they 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. In some cases, the top of the storm may extend to as high as 18 km (60,000 ft) above the surface, and the width of the storm may exceed 40 km (25 mi).

A model of a classic supercell with many of its features is given in Fig. 10.18. 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").

*Smaller thunderstorms that occur with rotating updrafts are referred to as *mini supercells*.

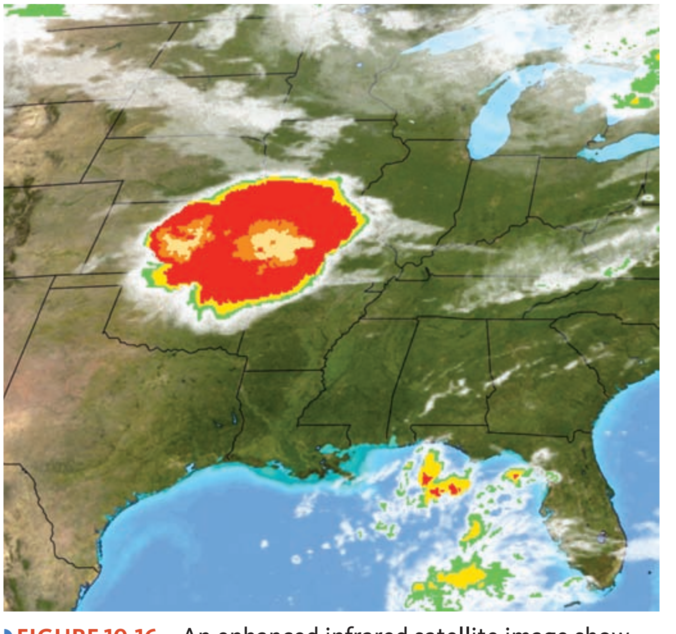


FIGURE 10.16 An enhanced infrared satellite image showing the cold cloud tops (dark red and orange colors) of a Mesoscale Convective Complex extending from central Kansas across western Missouri. This organized mass of multicell thunderstorms brought hail, heavy rain, and flooding to this area.

FIGURE 10.17 A supercell thunderstorm with a tornado sweeps over Texas.

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 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, and the heaviest rain occurs just north of the falling hail, with the lighter rain falling in the northeast quadrant of the storm. If low-level humid air is drawn into the updraft, a rotating

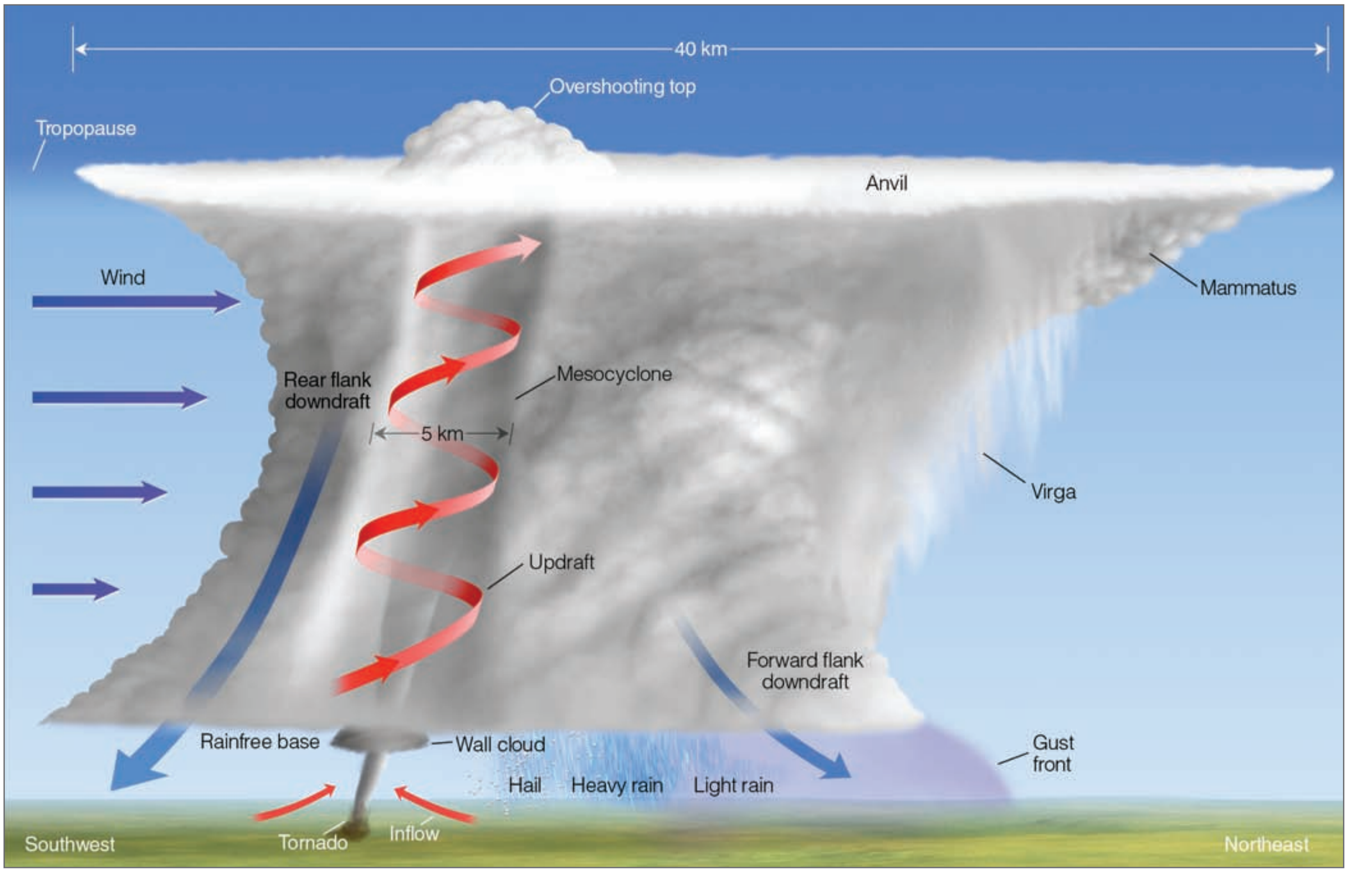


FIGURE 10.18 Some of the features associated with a classic tornado-breeding supercell thunderstorm as viewed from the southeast. The storm is moving to the northeast.

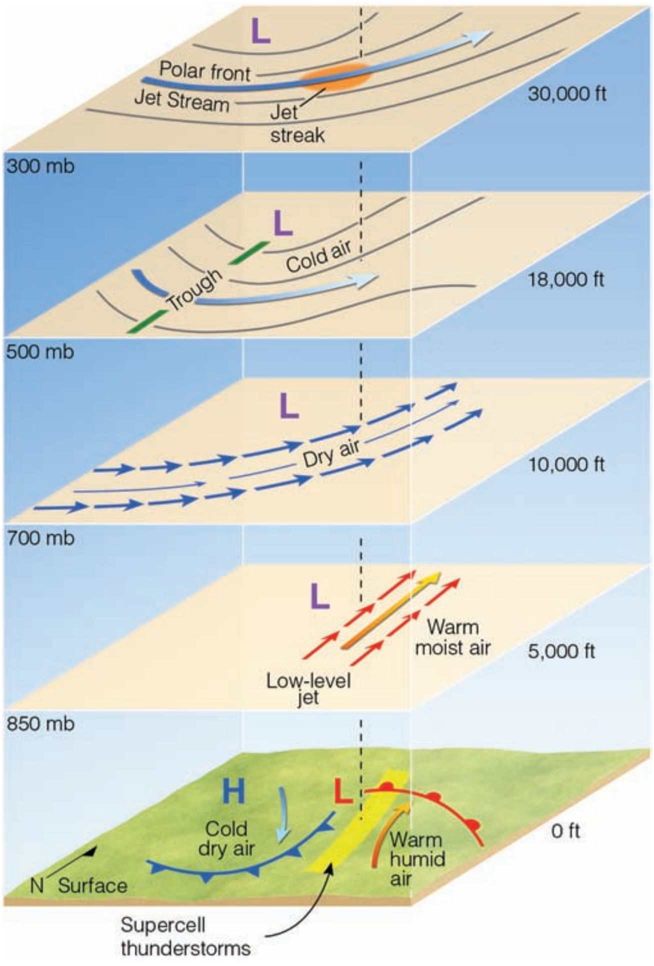
▶ **FIGURE 10.19** A wall cloud photographed southwest of Norman, Oklahoma.

cloud, called a **wall cloud**, may descend from the base of the storm (see ▶ Fig. 10.19).

We can obtain a better picture of how wind shear plays a role in the development of supercell thunderstorms by observing ▶ Fig 10.20. The illustration represents atmospheric conditions 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. 10.20) shows where supercells are likely to form. They tend to form in 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



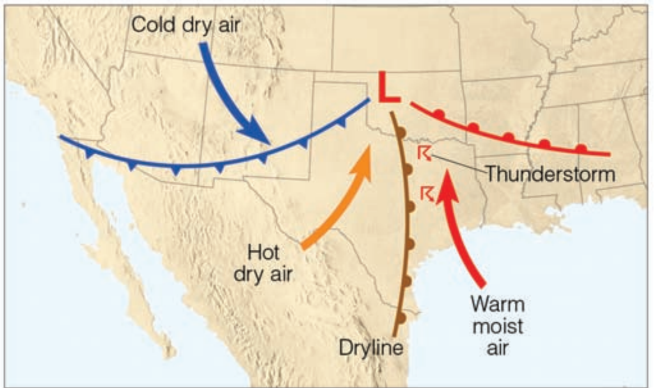
▶ **FIGURE 10.20** Conditions leading to the formation of severe thunderstorms, and especially supercells. The area in yellow shows where supercell thunderstorms are likely to form.

hand, parallel to the table. 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, 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 lid on the humid air below. 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. (The stable layer is important because it prevents many small thunderstorms from forming.) Divergence at the jet-stream level then draws this humid air upward into the cold, conditionally unstable air aloft, and a large supercell quickly develops to great heights.

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 10.21 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, warm dry continental tropical air moves in from the southwest. Further east, warm but very humid maritime tropical air sweeps northward from the Gulf of Mexico. The dryline is the north–south oriented boundary that separates the warm, dry air and the warm, humid air.



◗**FIGURE 10.21** 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.

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.

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

- 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).
- The stronger the convection and the longer a multistorm system exists, the greater the chances of the thunderstorm becoming severe.
- Supercell thunderstorms are large, 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 wind shear — rapid changes in wind speed and wind direction.
- A derecho is a strong straight-line wind produced by strong downbursts from intense thunderstorms that often appear as a bow (bow echo) on a radar screen.
- Intense thunderstorms often form along a dryline, a narrow zone that separates warm, dry air from warm, humid air.

THUNDERSTORMS AND FLOODING Intense thunderstorms can be associated with **flash floods**—floods that rise 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 tropical moist 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*. (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 the Focus section on p. 288.)

During the summer of 1993, thunderstorm after thunderstorm rumbled across the upper Midwest, causing the worst flood ever in that part of the United States (see Fig. 10.22). Estimates are that $6.5 billion in crops were lost as millions of acres of valuable farmland were inundated by flood waters. The worst flooding this area had ever seen took 45 human lives, damaged or destroyed 45,000 homes, and forced the evacuation of 74,000 people.

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

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FIGURE 10.22 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.

FOCUS ON A SPECIAL TOPIC

The Terrifying Flash Flood in the Big Thompson Canyon

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 an incredible 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. 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 1 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.

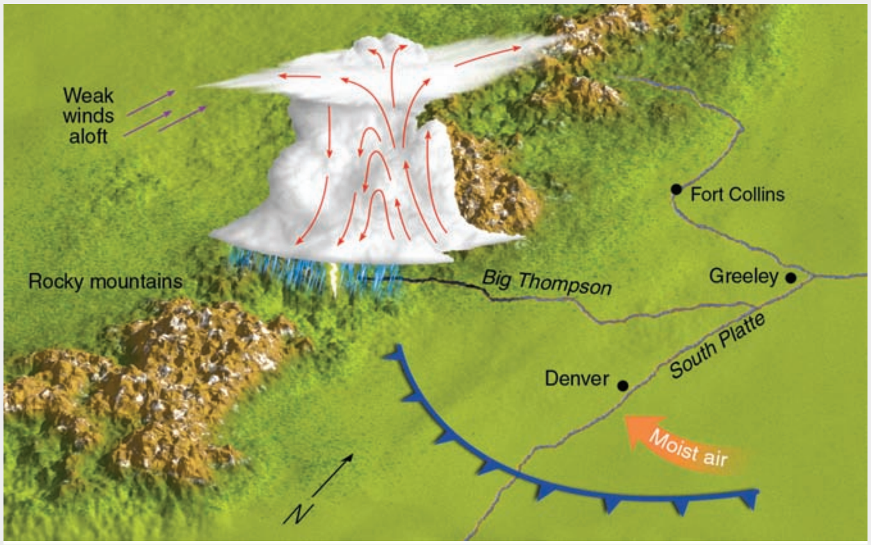


FIGURE 1 Weather conditions that led to the development of intensive multicell thunderstorms, which remained nearly stationary over the Big Thompson Canyon in the Colorado Rockies. The arrows within the thunderstorm represent air motions.

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 10.23 shows the average annual number of days having thunderstorms in various parts of the United States. Notice that they occur most frequently in the southeastern states along the Gulf Coast with a maximum in Florida. A secondary maximum exists over the central Rockies. The region with the fewest thunderstorms is the Pacific coastal and interior valleys.

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. Over the Central Plains, thunderstorms tend to form more frequently at night. These storms may be caused by a low-level southerly jet stream that forms at night, and not only carries humid air northward but also initiates areas of converging surface air, which helps to trigger uplift. As the thunderstorms build, their tops cool by radiating infrared energy to space. This cooling process tends to destabilize the atmosphere, making it more suitable for nighttime thunderstorm development.

At this point, it is interesting to compare Fig. 10.23 and Fig. 10.24. 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

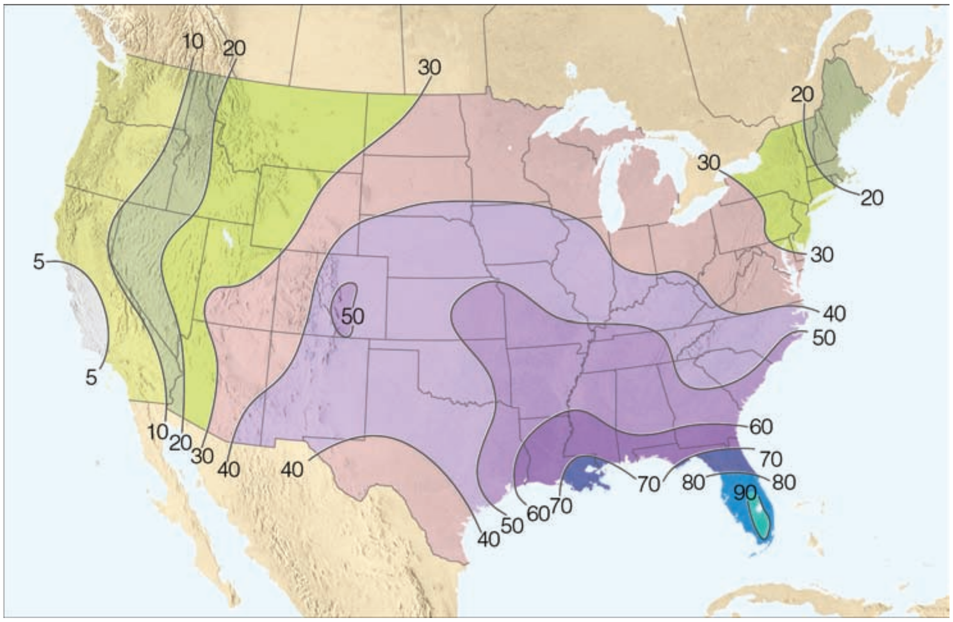


FIGURE 10.23 The average number of days each year on which thunderstorms are observed throughout the United States. (Due to the scarcity of data, the number of thunderstorms is underestimated in the mountainous far west.) (NOAA)

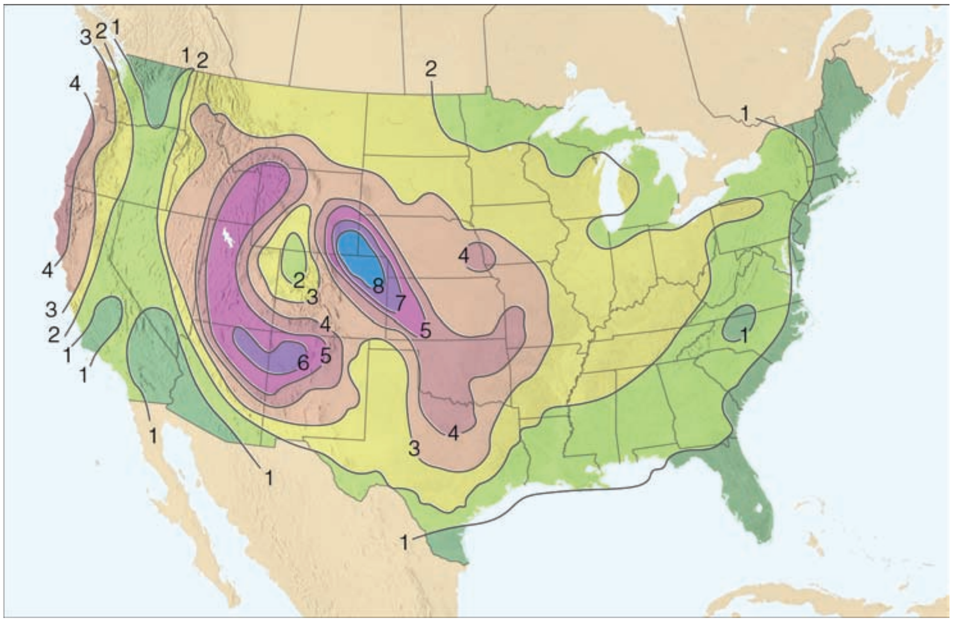


FIGURE 10.24 The average number of days each year on which hail is observed throughout the United States. (NOAA)

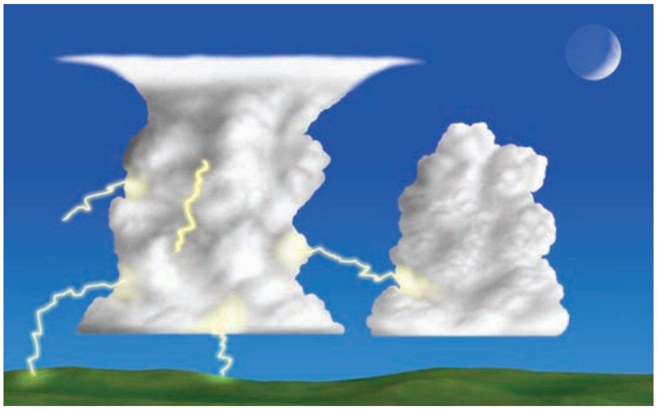


FIGURE 10.25 The lightning stroke can travel in a number of directions. It can occur within a cloud, from one cloud to another cloud, from a cloud to the air, or from a cloud to the ground. Notice that the cloud-to-ground lightning can travel out away from the cloud, then turn downward, striking the ground many miles from the thunderstorm. When lightning behaves in this manner, it is often described as a "*bolt from the blue*."

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.*

Now that we have looked at the development and distribution of thunderstorms, we are ready to examine an interesting, though yet not fully understood, aspect of all thunderstorms—lightning.

LIGHTNING AND THUNDER

Lightning is simply a discharge of electricity, a giant spark, which usually occurs in mature thunderstorms.** Lightning may take place within a cloud, from one cloud to another, from a cloud to the surrounding air, or from a cloud to the ground (see Fig. 10.25). (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.

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 we see the lightning until we hear the thunder, we can determine how far away the stroke is. Because it takes sound about 5 seconds to travel 1 mile, if we see lightning and hear the thunder 5 seconds later, the lightning stroke occurred about 1 mile 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. Moreover, the rumbling is accentuated when the sound wave reaches an observer after having bounced off obstructions, such as hills and buildings.

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 will not.

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.)

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

*The formation of hail is described in Chapter 5 on p. 140.

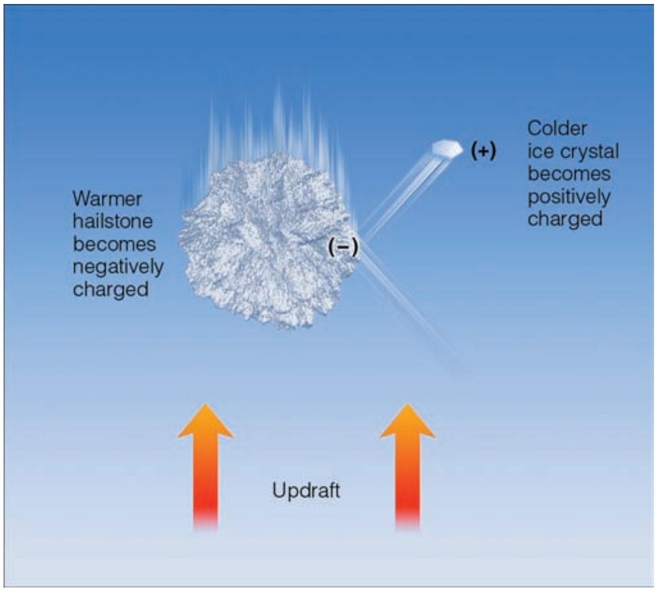
**Lightning may also occur in snowstorms, in duststorms, on rare occasions in nimbostratus clouds, and in the gas cloud of an erupting volcano.

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, 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.

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, and when it becomes sufficiently large (on



◗**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.

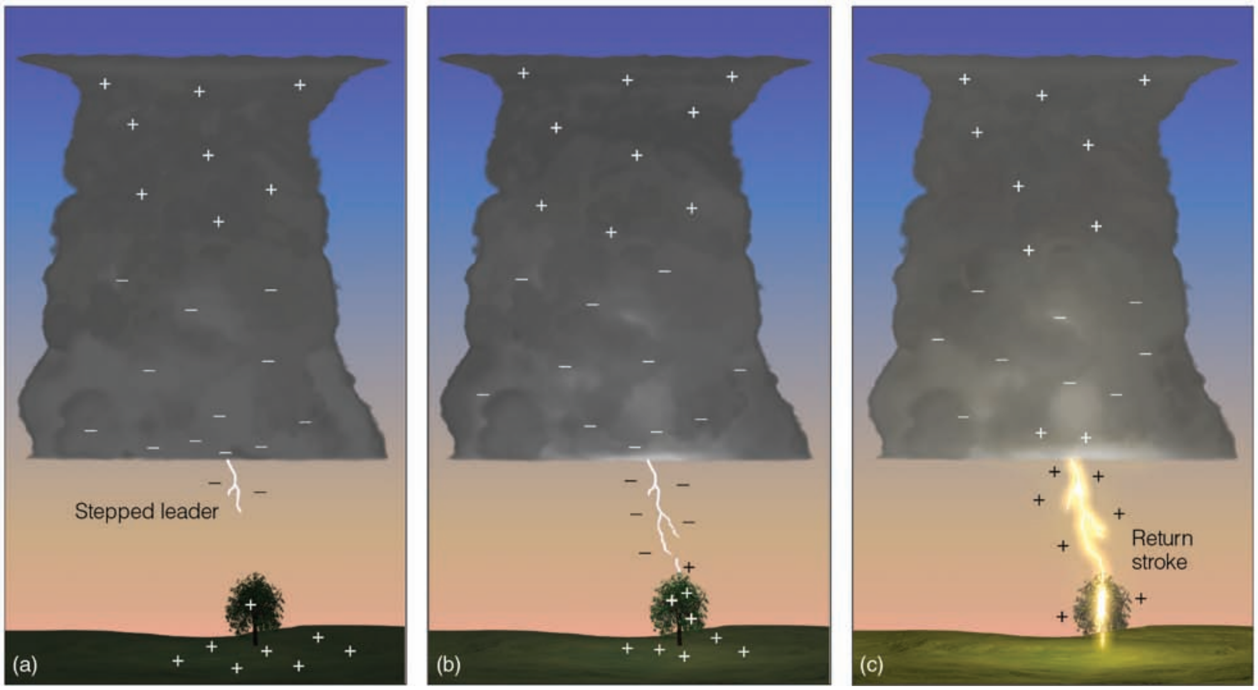
◗**FIGURE 10.27** The generalized charge distribution in a mature thunderstorm.

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 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



Active **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.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▸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.

the cloud is positively charged and the ground negatively charged, a *positive cloud-to-ground lightning* 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 for a longer duration 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, and it 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. 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. *Ball lightning* looks like a luminous sphere that appears to float in the air or slowly dart about for several seconds. 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. 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.

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. 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.*

As the electric potential near the ground increases, 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 **Saint Elmo's Fire,** named after the patron saint of sailors (see ▸Fig. 10.30). Saint Elmo's Fire is also

DID YOU KNOW?

Florida is "the Lightning Capital of the United States," as it is hit by lightning more than any other state. The most lightning-prone area of Florida is located in Pasco County, just north of Tampa Bay, where about 40 lightning strikes per square mile occur each year.

FIGURE 10.30 Saint Elmo's Fire tends to form above objects, such as aircraft wings, ships' masts, and flag poles.

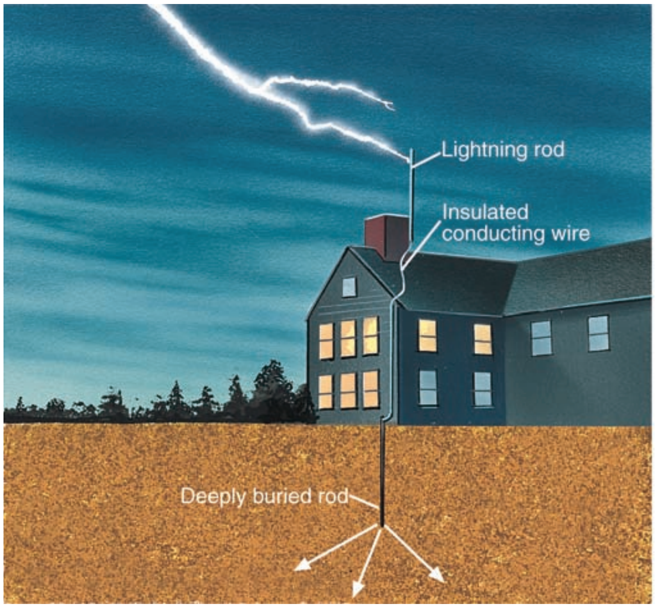

FIGURE 10.31 The lightning rod extends above the building, increasing the likelihood that lightning will strike the rod rather than some other part of the structure. After lightning strikes the metal rod, it follows an insulated conducting wire harmlessly into the ground.

seen around power lines and the wings of aircraft. When Saint 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.

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 (see Fig. 10.31). 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, lightning normally 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 (see Fig. 10.32). 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. 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 the Focus section on p. 296.

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. A web of these magnetic devices is a valuable tool in pinpointing lightning strokes throughout the United States, Canada, and Alaska. 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.*

Moreover, satellites now have the capability of providing more lightning information than ground-based sensors, because satellites can continuously detect all forms of lightning over land and over water (see Fig. 10.33). 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

*In fact, with the aid of these instruments and computer models of the atmosphere, the National Weather Service currently issues lightning probability forecasts for the western United States.

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FIGURE 10.32 The four marks on the road surface represent areas where lightning, after striking a car traveling along south Florida's Sunshine State Parkway, entered the roadway through the tires. Lightning flattened three of the car's tires and slightly damaged the radio antenna. The driver and a six-year-old passenger were taken to a nearby hospital, treated for shock, and released.

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 that blows around a small area of intense low pressure with a circulation that reaches the ground. A tornado's circulation

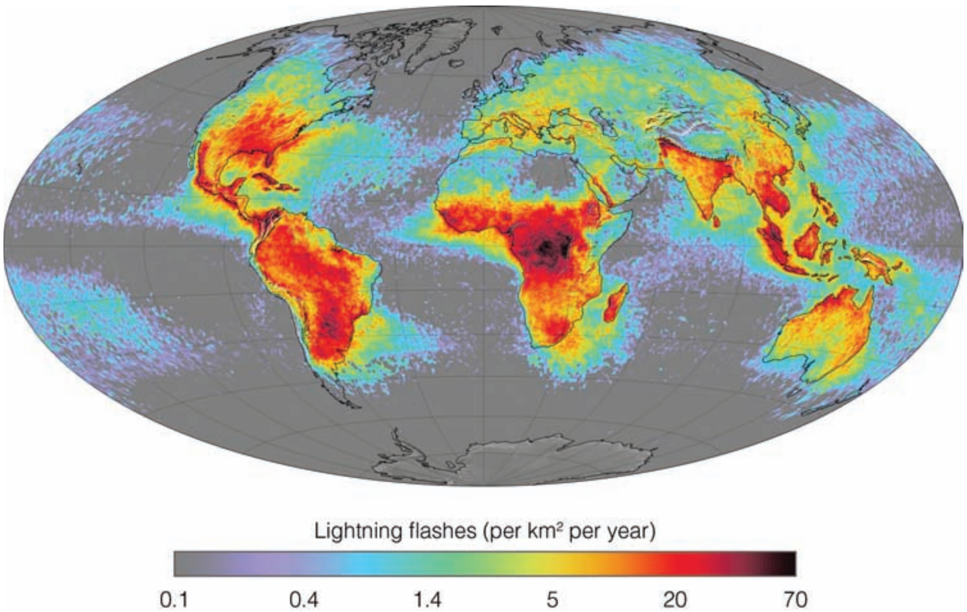
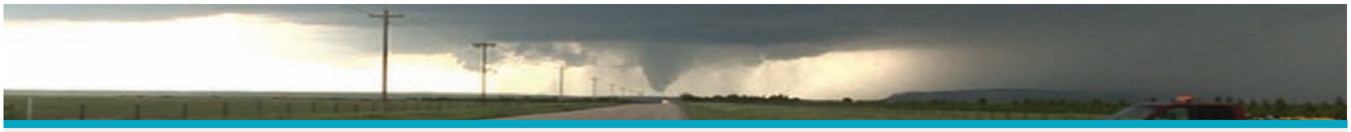


FIGURE 10.33 The average yearly number of lightning flashes per square kilometer based on data collected by NASA satellites between 1995 and 2002. (NASA)



FOCUS ON AN OBSERVATION

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. The average yearly death toll in the United States attributed to lightning is nearly 100, 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. 2). As a tragic example, during June, 2004, three people were killed near Atlanta, Georgia, 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.

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.

© Johnny Autery

FIGURE 2 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.

is present on the ground either as a funnel-shaped cloud or as a swirling cloud of dust and debris. 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. A **funnel cloud** is a tornado whose circulation has not reached the ground. When viewed from above, the majority of North American tornadoes rotate counterclockwise about their central core of low pressure. A few have been seen rotating clockwise, but those are rare.

The majority of tornadoes have wind speeds of less than 100 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, one of the largest tornadoes on record touched down near Hallam, Nebraska, with a diameter of about 4000 m (2.5 mi). Tornadoes that form ahead of an advancing cold front are often steered by southwesterly winds and, therefore, tend to move from the southwest toward the northeast at speeds usually between 20 and 40 knots. However, some 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). There are cases where they have reportedly traveled for hundreds of kilometers and have existed for many 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.

TORNADO LIFE CYCLE 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). As the tornado moves out of its mature stage, the width of the funnel shrinks and becomes more tilted. At the surface, the width of the damage swath narrows, although the tornado may still be capable of inflicting intense and sometimes violent damage. 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 actually 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 and experienced a record 1819 tornadoes during 2004. 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. 10.35).

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. 10.20 on p. 285, 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. 10.36, 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 6 per day) while the most violent tornadoes seem to occur in April when vertical 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

*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)—the most in any month ever.

© D. Lloyd/Weatherstock

◗**FIGURE 10.34** A tornado in its mature stage over the Great Plains.

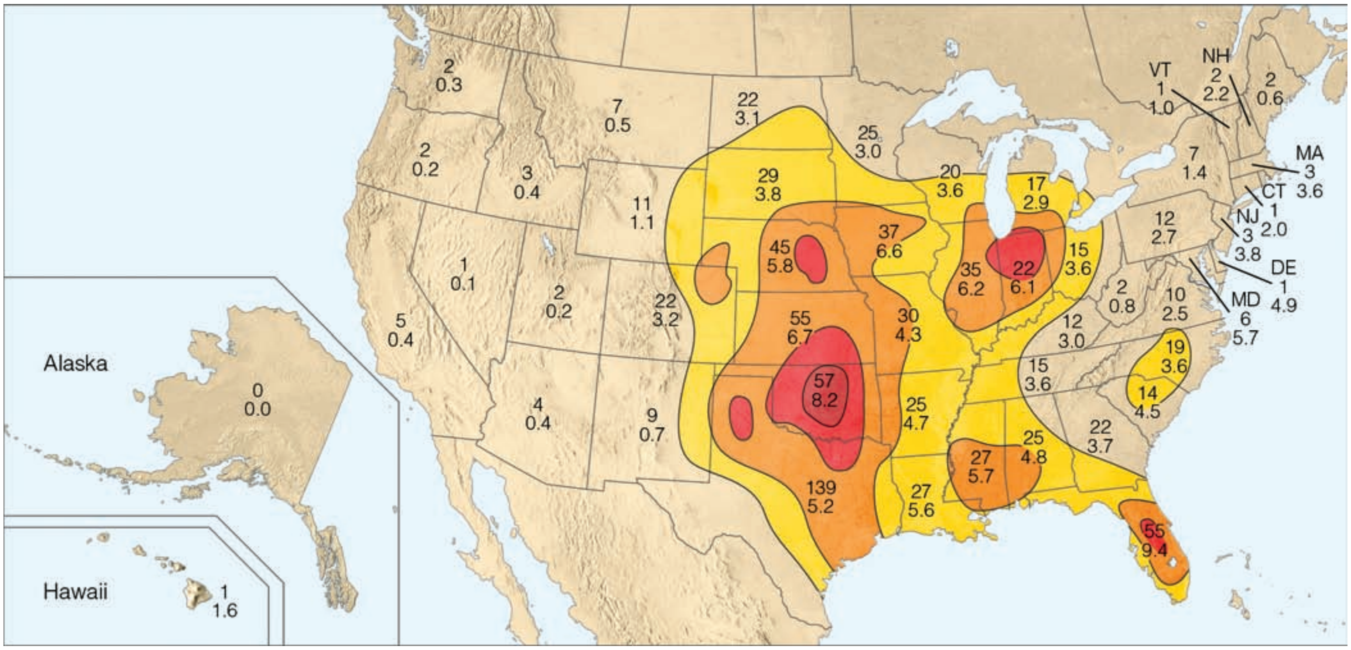


FIGURE 10.35 Tornado incidence by state. The upper figure shows the average annual number of tornadoes observed in each state from 1953–2004. The lower figure is the average annual number of tornadoes per 10,000 square miles in each state during the same period. The darker the shading, the greater the frequency of tornadoes. (NOAA)

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.

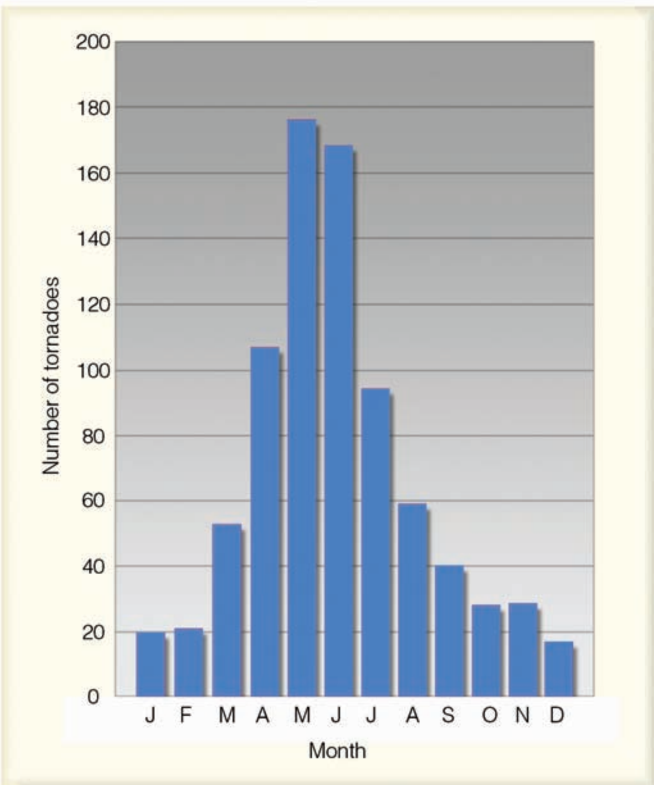


FIGURE 10.36 Average number of tornadoes during each month in the United States.

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 of almost 4000 m (2.5 mi) 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 a small tornado touched down in New York City on July 25, 2010, causing minimal damage and injuring 7 people.

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 likely 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 25 meters 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 over 100 yards without one 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 after 1973 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.

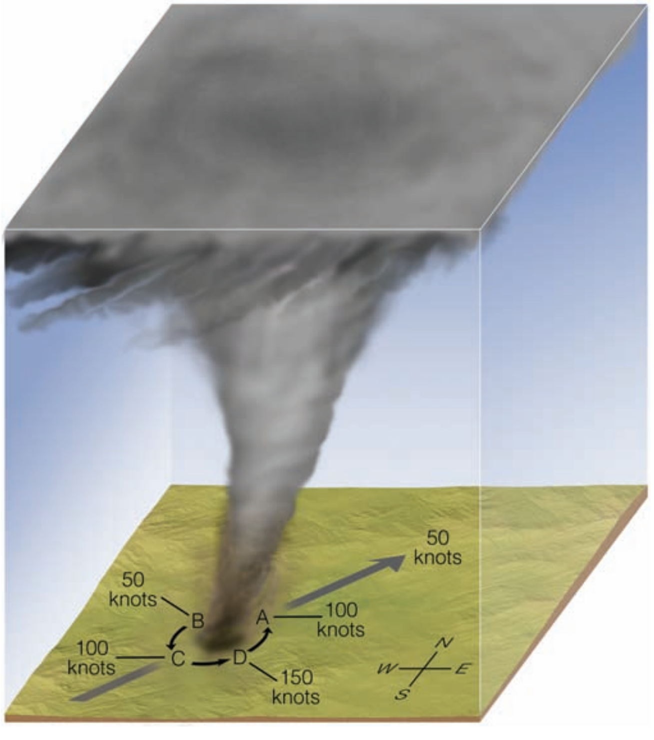
DID YOU KNOW?

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.

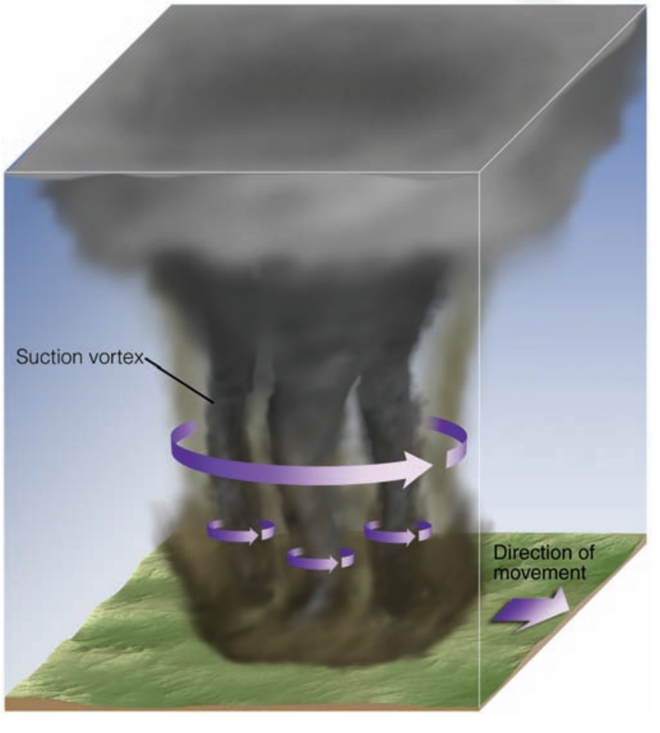
When a tornado is approaching from the southwest, its strongest winds are on its southeast side. We can see why in ▶Fig. 10.37. The tornado is heading northeast at 50 knots. If its rotational speed is 100 knots, then its forward speed will add 50 knots to its southwestern side (position D) and subtract 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. 10.38). 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



▶**FIGURE 10.37** 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.



▶**FIGURE 10.38** A powerful multi-vortex tornado with three suction vortices.

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.) So stay away from windows. 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. 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 to protect your head from flying debris. 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.

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. If a tornado is spotted in the watch area, keep abreast of its movement by listening to NOAA Weather Radio. Once a tornado is spotted—either visually or on a radar screen—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, tornado-related deaths have actually shown a decrease (see ■Table 10.1).

■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
2000–2009	1277*	56

*More tornadoes are being reported as populations increase and tornado-spotting technology improves.

The 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. However, classifying a tornado based solely on the damage it causes is rather subjective. But the scale became widely used and is presented in ■Table 10.2.

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. These indicators include items such as small barns, mobile homes, schools, and trees. Each item 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 EF scale are given in ■Table 10.3.

*In October, 2007, the National Weather Service launched a new, more specific tornado warning system called *Storm Based Warnings*. The new system provides more precise information on where a tornado is located and where it is heading.

TABLE 10.2 Fujita Scale for Damaging Wind

SCALE	CATEGORY	MI/HR	KNOTS	EXPECTED DAMAGE
F0	Weak	40–72	35–62	Light: tree branches broken, sign boards damaged
F1		73–112	63–97	Moderate: trees snapped, windows broken
F2	Strong	113–157	98–136	Considerable: large trees uprooted, weak structures destroyed
F3		158–206	137–179	Severe: trees leveled, cars overturned, walls removed from buildings
F4	Violent	207–260	180–226	Devastating: frame houses destroyed
F5*		261–318	227–276	Incredible: structures the size of autos moved over 100 meters, steel-reinforced structures highly damaged

*The scale continues up to a theoretical F12. Very few (if any) tornadoes have wind speeds in excess of 318 mi/hr.

TABLE 10.3 Modified (EF) Fujita Scale for Damaging Winds

EF SCALE	MI/HR*	KNOTS
EF0	65–85	56–74
EF1	86–110	75–95
EF2	111–135	96–117
EF3	136–165	118–143
EF4	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.

Statistics reveal that the majority of tornadoes are relatively weak, with wind speeds less than about 110 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, a powerful 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. A powerful F5 tornado moving through Hesston, Kansas, is shown in Fig. 10.39.

TORNADO OUTBREAKS Each year, tornadoes take the lives of many people. The yearly average is less than 100, although over 100 may die in a single day. In recent years, an alarming statistic is that 45 percent of all fatalities occurred in mobile homes. The deadliest tornadoes are those that occur in *families,* that is, different tornadoes spawned by the same thunderstorm. (Some

© Wade Balzer/Weatherstock

FIGURE 10.39 A devastating tornado about 200 meters wide plows through Hesston, Kansas, on March 13, 1990, leaving almost 300 people homeless and 13 injured.

DID YOU KNOW?

In Kansas, during 1991, a tornado swept a mother, her son, and their dog from their house in a bathtub. The tub with its occupants hit the ground hard, rose into the air, then hit the ground again, tossing its passengers into the neighbor's backyard. Battered and bruised with scratches and lumps, the mother and son survived. The bathtub and dog, which disappeared in the tornado, were never found.

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) forms over a particular region, this constitutes what is termed a **tornado outbreak.**

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 (see ◗Fig. 10.40).

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 747 people died as at least 7 tornadoes traveled a total of 703 km (437 mi) across portions of Missouri, Illinois, and Indiana.

© 1999 C. Doswell

◗**FIGURE 10.40** Total destruction caused by an F5 tornado that devastated parts of Oklahoma on May 3, 1999.

Tornado Formation

Although not everything is known about the formation of a tornado, we do know that many tornadoes tend to form with intense thunderstorms and that a conditionally unstable atmosphere is essential for their development. Most often they 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 a supercell is a thunderstorm that has a single rotating updraft that can exist for hours. ◗Figure 10.41 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 produces a strong downdraft. The separation of the updraft from the downdraft helps the storm maintain itself as a single entity, capable of existing for hours.

Tornadoes are rapidly rotating columns of air, so what is it that starts the air rotating? We can obtain an idea as to how rotation can develop by looking at ◗Fig. 10.42a. Notice that there is wind direction shear, as the surface winds are southerly and several thousand feet above the surface they are northerly. There is also wind speed shear as the wind speed increases rapidly with height. This 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 spirally 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. 10.41b, 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

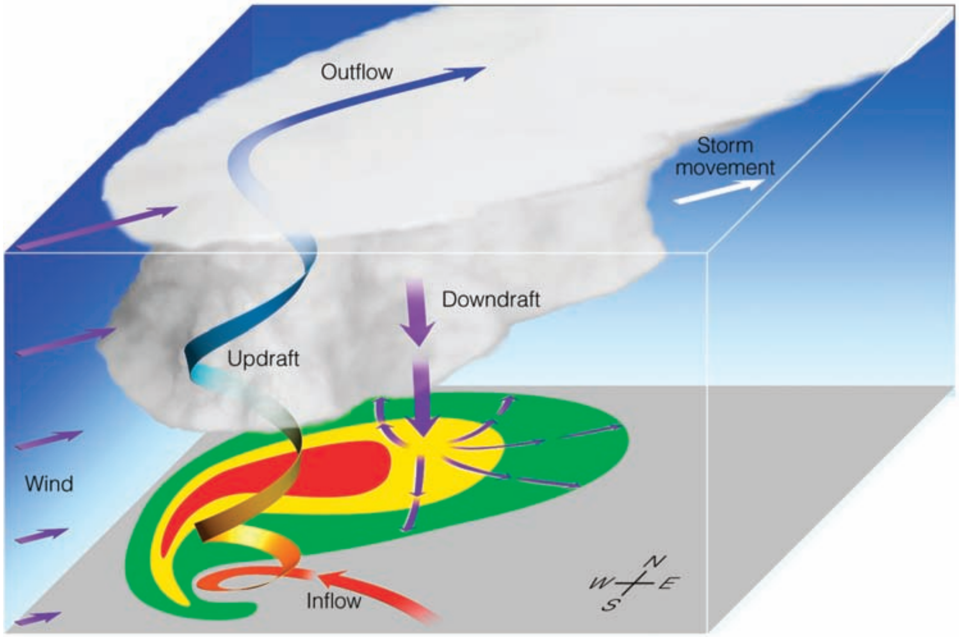


FIGURE 10.41 A simplified view of a supercell thunderstorm with a strong updraft and downdraft, forming in a region of strong wind speed shear. Regions beneath the supercell receiving precipitation are shown in color: green for light rain, yellow for heavier rain, and red for very heavy rain and hail.

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.*

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. 10.43.

At this point in the storm's development, the updraft, the counterclockwise swirling precipitation, and

*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.

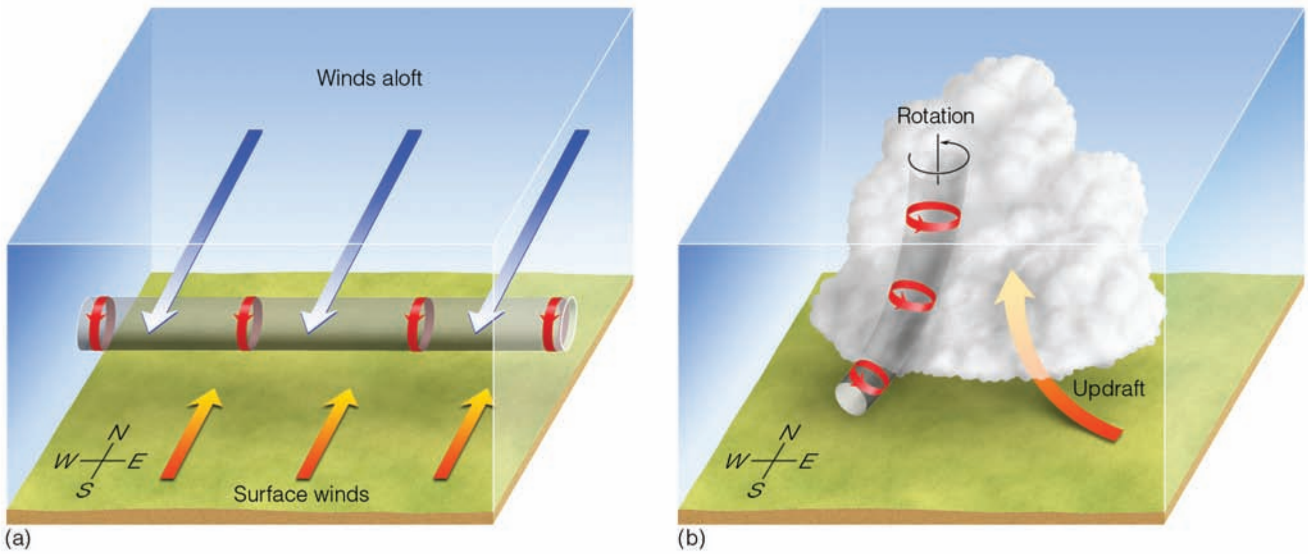
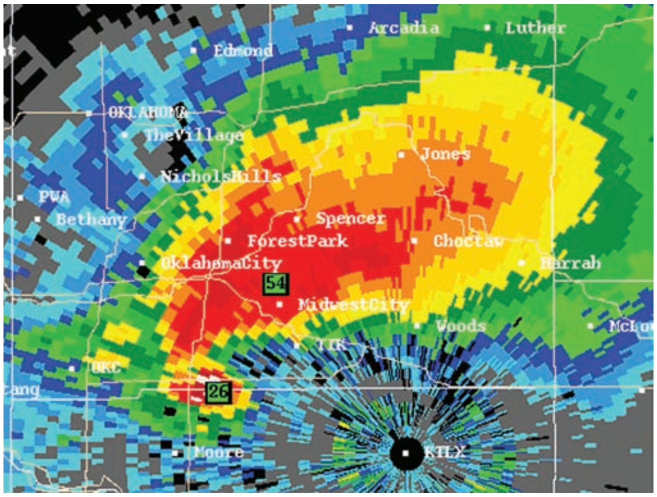


FIGURE 10.42 (a) A spinning vortex tube created by wind shear. (b) The strong updraft in the developing thunderstorm carries the vortex tube into the thunderstorm, producing a rotating air column that is oriented in the vertical plane.



NOAA/National Weather Service

FIGURE 10.43 A tornado-spawning supercell thunderstorm over Oklahoma City on May 3, 1999, shows a hook echo in its rainfall 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. 10.41.

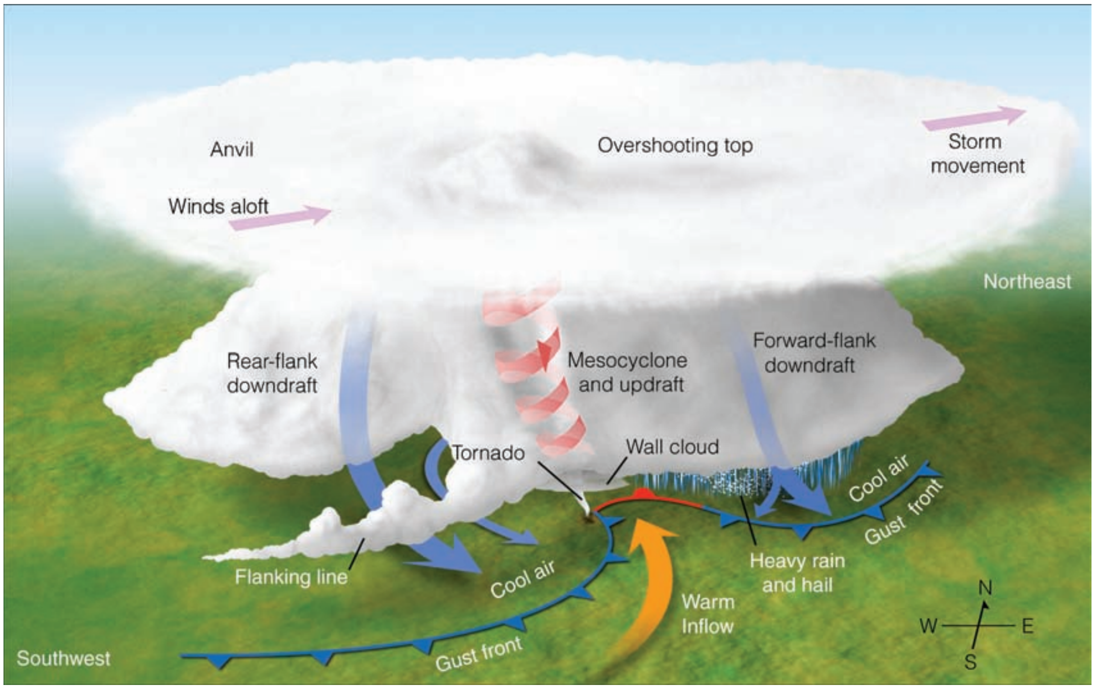
the surrounding air may all interact to produce the *rear-flank downdraft* (to the south of the updraft), as shown in Fig. 10.44. The strength of the downdraft is driven by the amount of precipitation-induced cooling in the upper levels of the storm. The rear-flank downdraft appears to play an important role in producing tornadoes in classic supercells.

When the rear-flank downdraft strikes the ground, as illustrated in Fig. 10.44, it may (under favorable shear conditions) interact with the forward-flank downdraft beneath the mesocyclone to initiate the formation of a tornado. At the surface, the cool rain-chilled air of the rear-flank downdraft (and the forward-flank downdraft) sweeps around the center of the mesocyclone, effectively cutting off the rising air from the warmer surrounding air. The lower half of the updraft now rises more slowly. 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 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 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 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

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

FIGURE 10.44 A classic 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.



rear sector of the storm, on the southwestern side of a northeastward-moving storm, as shown in Fig. 10.44.

Not all supercells produce tornadoes; in fact, perhaps less than 15 percent do. However, recent 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. 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.

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. 10.44 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 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 tornado is touching the surface. However, not all tornadoes make this sound and, when these storms strike, they become silent killers.

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 (supercells).

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**. See ◗Fig. 10.45. These relatively weak tornadoes normally are short-lived and rarely inflict significant damage. Gustnadoes are often seen as a rotating cloud of dust or debris rising above the surface.

Occasionally, rather weak, short-lived tornadoes will occur with rapidly building cumulus congestus clouds. Tornadoes such as these commonly form over east-central Colorado. Because they look similar to waterspouts that form over water, they are sometimes called **landspouts*** (see ◗Fig. 10.46).

◗Figure 10.47 illustrates how a landspout can form. Suppose, for example, that the winds at the surface converge along a boundary, as illustrated in Fig. 10.47a. (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

*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.

*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.

© Perry Samson

◗**FIGURE 10.45** A gustnado that formed along a gust front swirls across the plains of eastern Nebraska.

FIGURE 10.46 A well-developed landspout moves over eastern Colorado.

region of rotating air (Fig. 10.47b), the spinning air may be drawn up into the cloud by the storm's updraft. As the spinning, rising air shrinks in diameter, it produces a tornado-like structure, a *landspout,* similar to the one shown in Fig. 10.46. 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 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 short-lived tornadoes are sometimes called *cold-air funnels*.

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. 10.43, p. 304, represents 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. 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

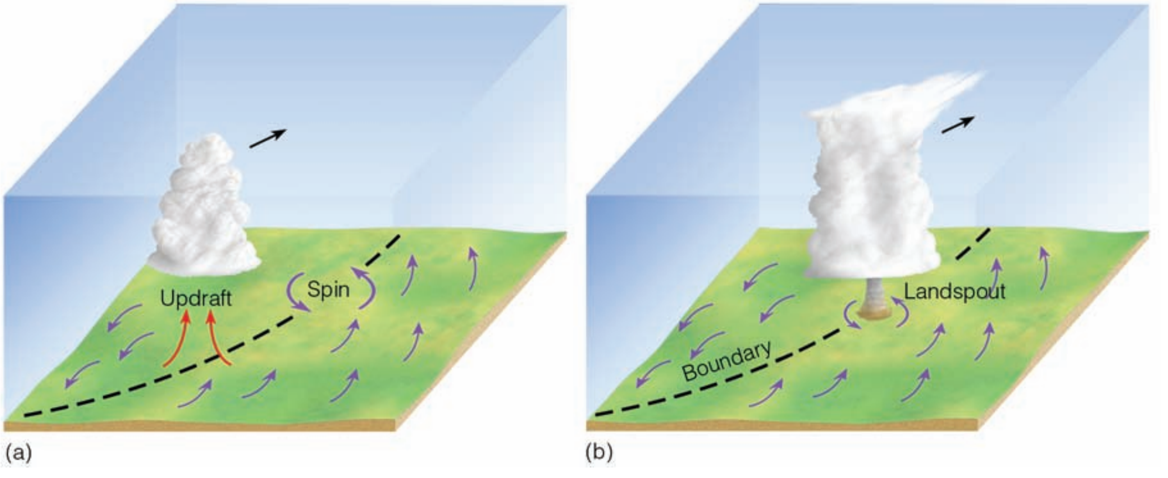


FIGURE 10.47 (a) Along the boundary of converging winds, the air rises and condenses into a cumulus congestus cloud. At the surface the converging winds along the boundary create a region of counterclockwise spin. (b) As the cloud moves over the area of rotation, the updraft draws the spinning air up into the cloud producing a nonsupercell tornado, or landspout. (Modified after Wakimoto and Wilson)

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.

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 blue or green; 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. 10.48).

Even a single 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. 10.48.

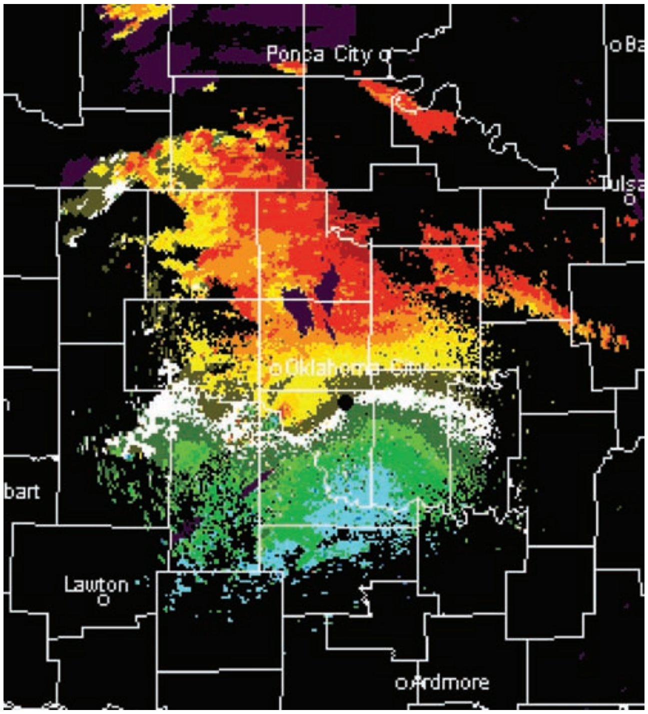
Unfortunately, the resolution of the Doppler radar is not high enough to measure actual wind speeds of most small tornadoes. However, a new and experimental Doppler system — called *Doppler lidar* — uses a light beam (instead of microwaves) to measure the change in frequency of falling precipitation, 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, will 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,

*The name WSR-88D stands for *W*eather *S*urveillance *R*adar, 19*88* *D*oppler.



NOAA/National Severe Storms Lab

◗**FIGURE 10.48** Doppler radar display of winds associated with the supercell storm that moved through parts of Oklahoma City during the afternoon of May 3, 1999. The close packing of the horizontal winds blowing toward the radar (green and blue shades), and those blowing away from the radar (yellow and red shades), indicate strong cyclonic rotation and the presence of a tornado.

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

The next advance in Doppler radar technology is the *polarimetric radar* (or *dual-polarization radar*) that transmits both a horizontal and a vertical radar pulse that will, among other things, allow forecasters to better distinguish between very heavy rain and hail. This information, in turn, should improve flash flood watches and warnings.

In an attempt to unravel some of the mysteries of the tornado, several studies are underway. In one study, called *VORTEX 2* (*V*erification of the *O*rigin of *R*otational *T*ornadoes *Ex*periment *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. 10.49), 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,

© Pat Skinner

FIGURE 10.49 Researchers from Texas Tech University set up a mobile Doppler radar unit near a supercell thunderstorm.

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.

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 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.

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. 10.50.

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

© G. Kaufman

FIGURE 10.50 A powerful waterspout moves across Lake Tahoe, California. Compare this photo of a waterspout with the photo of a landspout in Fig. 10.46 on p. 306.

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—a storm with cells in various stages of development. Some multicell storms form as a complex of thunderstorms, such as the squall line (which forms as a line of thunderstorms either along or out ahead of an advancing cold front), 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 large, 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. The rotating air of the tornado may begin within the thunderstorm or it may begin at the surface and extend upwards. Tornadoes can form with supercells, as well as with less intense thunderstorms. Tornadoes that do not form with supercells are the landspout and the gustnado. 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. 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.

A normally small and less destructive cousin of the tornado is the "fair weather" waterspout that commonly forms above the warm waters of the Florida Keys and the Great Lakes in summer.

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, 275
cumulus stage, 275
mature stage, 276
dissipating stage, 277
multicell thunderstorm, 277
overshooting top, 278
gust front, 278
straight-line winds, 278
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nonsupercell tornadoes, 305
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landspout, 305
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QUESTIONS FOR REVIEW

1. What is a thunderstorm?
2. What atmospheric conditions are necessary for the development of ordinary cell (air mass) thunderstorms?
3. Describe the stages of development of an ordinary cell (air mass) thunderstorm.
4. How do downdrafts form in ordinary cell thunderstorms?
5. Why do ordinary cell thunderstorms most frequently form in the afternoon?
6. Explain why ordinary cell thunderstorms tend to dissipate much sooner than multicell storms.
7. How does the National Weather Service define a severe thunderstorm?
8. What atmospheric conditions are necessary for a multicell thunderstorm to form?
9. (a) How do gust fronts form?
   (b) What type of weather does a gust front bring when it passes?
10. (a) Describe how a microburst forms.
    (b) Why is the term *wind shear* often used in conjunction with a microburst?
11. How do derechoes form?
12. How does a squall line differ from a Mesoscale Convective Complex (MCC)?
13. Give a possible explanation for the generation of a pre-frontal squall-line thunderstorm.
14. How do supercell thunderstorms differ from ordinary cell (air mass) thunderstorms?
15. Describe the atmospheric conditions at the surface and aloft that are necessary for the development of most supercell thunderstorms. (Include in your answer the role that the low-level jet plays in the rotating updraft.)
16. When thunderstorms are *training*, what are they doing?
17. In what region in the United States do dryline thunderstorms most frequently form? Why there?
18. Where does the highest frequency of thunderstorms occur in the United States? Why there?
19. Why is large hail more common in Kansas than in Florida?
20. Describe one process by which thunderstorms become electrified.
21. How is thunder produced?
22. Explain how a cloud-to-ground lightning stroke develops.
23. Why is it unwise to seek shelter under an isolated tree during a thunderstorm? If caught out in the open, what should you do?
24. What is a tornado? Give some statistics about size, wind speed, and movement.
25. What is the primary difference between a tornado and a funnel cloud?
26. Why do tornadoes frequently move from southwest to northeast?
27. Why should you *not* open windows when a tornado is approaching?
28. Why is the central part of the United States more susceptible to tornadoes than any other region of the world?
29. How does a tornado *watch* differ from a tornado *warning*?
30. If you are in a single-story home (without a basement) during a tornado warning, what should you do?
31. Supercell thunderstorms that produce tornadoes form in a region of strong wind shear. Explain how the wind changes in speed and direction to produce this shear.
32. Explain how a nonsupercell tornado, such as a landspout, might form.
33. Describe how Doppler radar measures the winds inside a severe thunderstorm.
34. How has Doppler radar helped in the prediction of severe weather?
35. What atmospheric conditions lead to the formation of "fair weather" waterspouts?

QUESTIONS FOR THOUGHT AND EXPLORATION

1. Why does the bottom half of a dissipating thunderstorm usually "disappear" before the top?
2. Sinking air warms, yet thunderstorm downdrafts are usually cold. Why?
3. If you are confronted by a large tornado in an open field and there is no way that you can outrun it, your only recourse might be to run and lie down in a depression. If given the choice, when facing the tornado, would you run toward your left or toward your right as the tornado approaches? Explain your reasoning.

4. Suppose while you are standing on a high mountain ridge a thundercloud passes overhead. What would be the wisest thing to do—stand upright? lie down? or crouch? Explain.
5. Tornadoes apparently form in the region of a strong updraft, yet they descend from the base of a cloud. Why?
6. On a map of the United States, place the surface weather conditions (air masses, fronts, and so on) as well as weather conditions aloft (jet stream, and so on) that are necessary for the formation of most supercell thunderstorms.
7. Suppose several of your friends went on a storm-chasing adventure in the central United States. To help guide their chase, you stay behind, with an Internet-connected computer and a cellular phone. Which current weather and forecast maps would you use to guide their storm chase? Explain why you choose those maps.
8. A multi-vortex tornado with a rotational wind speed of 125 knots is moving from southwest to northeast at 30 knots. Assume the suction vortices within this tornado have rotational winds of 100 knots:
   (a) What is the maximum wind speed of this multi-vortex tornado?
   (b) If you are facing the approaching tornado, on which side (northeast, northwest, southwest, or southeast) would the strongest winds be found? the weakest winds? Explain both of your answers.
   (c) According to Table 10.2 and Table 10.3, p. 301 how would this tornado be classified on the old Fujita scale and on the new EF scale?

ONLINE RESOURCES

Log in to the CourseMate website at: www.cengagebrain.com to view the active figures and concept animations as noted in the text, as well as additional resources, including video exercises, practice quizzes, an interactive eBook, and more.