

# 19

## Weather Patterns and Severe Storms

### FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

- 19.1** Discuss air masses, their classification, and associated weather.
- 19.2** Compare and contrast typical weather associated with a warm front and a cold front. Describe an occluded front and a stationary front.
- 19.3** Summarize the weather associated with the passage of a mature midlatitude cyclone. Describe how airflow aloft is related to cyclones and anticyclones at the surface.
- 19.4** List the basic requirements for thunderstorm formation and locate places on a map that exhibit frequent thunderstorm activity. Describe the stages in the development of a thunderstorm.
- 19.5** Summarize the atmospheric conditions and locations that are favorable to the formation of tornadoes. Discuss tornado destruction and tornado forecasting.
- 19.6** Identify areas of hurricane formation on a world map and discuss the conditions that promote hurricane formation. List the three broad categories of hurricane destruction.

This satellite image shows Hurricane Sandy, called Superstorm Sandy in the media, battering the East coast on October 30, 2012. This view of the storm is looking south from Canada. Florida is near the top of the image. (NASA)

**T**ornadoes and hurricanes rank among nature's most destructive forces. Each spring, newspapers report the death and destruction left in the wake of a band of tornadoes. During late summer and fall, we hear occasional news reports about hurricanes. Storms with names such as Katrina, Rita, Sandy, and Ike make front-page headlines. Thunderstorms, although less intense and far more

common than tornadoes and hurricanes, are also part of our discussion on severe weather in this chapter. Before looking at violent weather, however, we will study the atmospheric phenomena that most often affect our day-to-day weather: air masses, fronts, and traveling midlatitude cyclones. We will see the interplay of the elements of weather discussed in Chapters 16, 17, and 18.

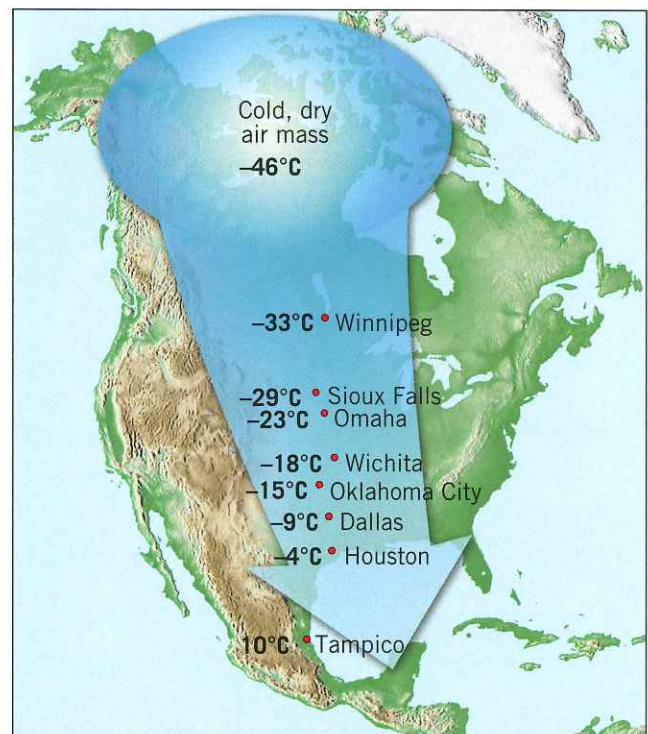
## 19.1 AIR MASSES

Discuss air masses, their classification, and associated weather.

For many people who live in the middle latitudes, which include much of the United States, summer heat waves and winter cold spells are familiar experiences. In the first instance, several days of high temperatures and oppressive humidity may finally end when a series of thunderstorms pass through the area, followed by a few days of relatively cool relief. By contrast, the clear skies that often accompany a span of frigid subzero days may be replaced by thick gray clouds and a period of snow as temperatures rise to levels that seem mild compared to those that existed just a day earlier. In both examples, what was experienced was a period of generally constant weather conditions followed by a relatively short period of change and then the reestablishment of a new set of weather conditions that remained for perhaps several days before changing again.

### What Is an Air Mass?

The weather patterns just described result from movements of large bodies of air, called air masses. An **air mass**, as the term implies, is an immense body of air, usually 1,600 kilometers (1,000 miles) or more across and perhaps



**FIGURE 19.2 An Invasion of Frigid Air** As this very cold air mass moved southward from Canada, it brought some of the coldest weather of the winter to the areas in its path. As it advanced into the United States, the air mass slowly got warmer. Thus, the air mass was gradually modified at the same time that it modified the weather in the areas over which it moved. (From *Physical Geography: A Landscape Appreciation*, 9th edition, by Tom L. McKnight and Darrell Hess, ©2008. Reprinted and electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, NJ.)



**FIGURE 19.1 Lake-Effect Snow Storm** This satellite image shows a cold, dry air mass moving from its source region in Canada across Lake Superior. It illustrates the process that leads to lake-effect snow storms. (NASA)

several kilometers thick, that is characterized by a similarity of temperature and moisture at any given altitude. When this air moves out of its region of origin, it will carry these temperatures and moisture conditions with it, eventually affecting a large portion of a continent (**FIGURE 19.1**).

An excellent example of the influence of an air mass is illustrated in **FIGURE 19.2**, which shows a cold, dry mass from northern Canada moving southward. With a beginning temperature of  $-46^{\circ}\text{C}$  ( $-51^{\circ}\text{F}$ ), the air mass warms to  $-33^{\circ}\text{C}$  ( $-27^{\circ}\text{F}$ ) by the time it reaches Winnipeg. It continues to warm as it moves

southward through the Great Plains and into Mexico. Throughout its southward journey, the air mass becomes warmer. But it also brings some of the coldest weather of the winter to the places in its path. Thus, the air mass is modified, but it also modifies the weather in the areas over which it moves.

The horizontal uniformity of an air mass is not perfect, of course. Because air masses extend over large areas, small differences occur in temperature and humidity from place to place. Still, the differences observed within an air mass are small compared to the rapid changes experienced across air-mass boundaries.

Since it may take several days for an air mass to move across an area, the region under its influence will probably experience fairly constant weather, a situation called **air-mass weather**. Certainly, there are usually some day-to-day variations, but the events will be very unlike those in an adjacent air mass.

The air-mass concept is an important one because it is closely related to the study of atmospheric disturbances. Most disturbances in the middle latitudes originate along the boundary zones that separate different air masses.

## Source Regions

When a portion of the lower atmosphere moves slowly or stagnates over a relatively uniform surface, the air will assume the distinguishing features of that area, particularly with regard to temperature and moisture conditions.

The area where an air mass acquires its characteristic properties of temperature and moisture is called its **source region**. The source regions that produce air masses influencing North America are shown in **FIGURE 19.3**.

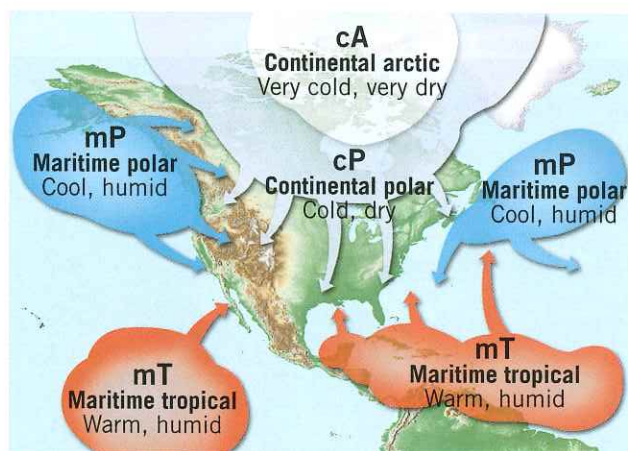
Air masses are classified according to their source region. **Polar (P)** and **arctic (A)** air masses originate in high latitudes toward Earth's poles, whereas those that form in low latitudes are called **tropical (T)** air masses. The designation *polar*, *arctic*, or *tropical* gives an indication of the temperature characteristics of an air mass. *Polar* and *arctic* indicate cold, and *tropical* indicates warm.

In addition, air masses are classified according to the nature of the surface in the source region. **Continental (c)** air masses form over land, and **maritime (m)** air masses originate over water. The designation *continental* or *maritime* thus suggests the moisture characteristics of the air mass. Continental air is likely to be dry, and maritime air is likely to be humid.

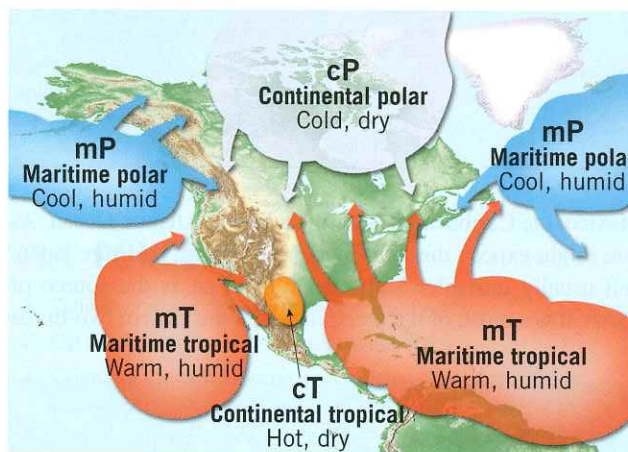
The basic types of air masses according to this scheme of classification are continental polar (cP), continental arctic (cA), continental tropical (cT), maritime polar (mP), and maritime tropical (mT).

## Weather Associated with Air Masses

Continental polar and maritime tropical air masses influence the weather of North America most, especially east of the Rocky Mountains. Continental polar air masses originate in northern Canada, interior Alaska, and the Arctic—areas that are uniformly cold and dry in winter and cool and dry in summer. In winter, an invasion of continental polar air brings the clear skies and cold temperatures we associate with a cold wave as it moves southward from Canada into



A. Winter pattern



B. Summer pattern

**FIGURE 19.3 Air-Mass Source Regions for North America** Source regions are largely confined to subtropical and subpolar locations. The fact that the middle latitudes are where cold and warm air masses clash, often because the converging winds of a traveling cyclone draw them together, means that this zone lacks the conditions necessary to be a source region. The differences between polar and arctic are relatively small and serve to indicate the degree of coldness of the respective air masses. By comparing the winter (A) and summer (B) maps, it is clear that the extent and temperature characteristics fluctuate.

the United States. In summer, this air mass may bring a few days of cooling relief.

Although cP air masses are not, as a rule, associated with heavy precipitation, those that cross the Great Lakes during late autumn and winter sometimes bring snow to the leeward shores. These localized storms often form when the surface weather map indicates no apparent cause for a snowstorm. These are known as **lake-effect snows**, and they make Buffalo and Rochester, New York, among the snowiest cities in the United States (**FIGURE 19.4**).

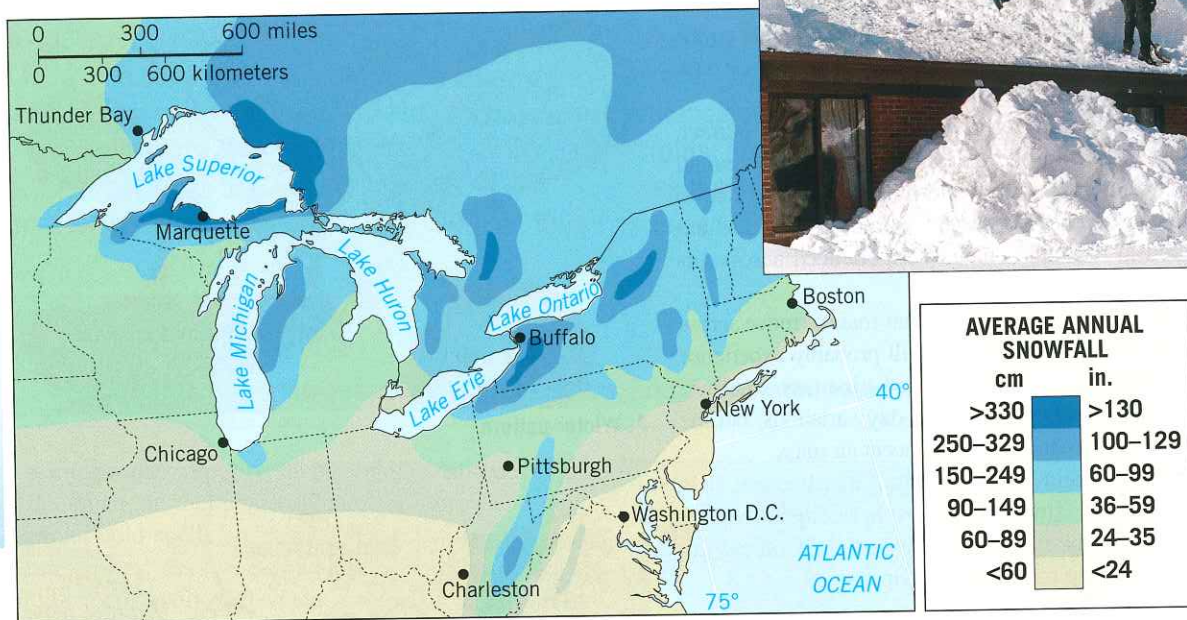
What causes lake-effect snow? During late autumn and early winter, the temperature contrast between the lakes and adjacent land areas can be large.<sup>1</sup> The temperature contrast can be especially great when a very cold cP air mass pushes southward across the lakes. The satellite image in Figure 19.1 illustrates the process. Notice that as the cloud-free air moves across Lake Superior, clouds develop because the air acquires large quantities of heat and moisture from the relatively warm lake surface. By the time the cP air reaches the opposite shore, the air mass is humid and unstable, and heavy snow showers are occurring.

Maritime tropical air masses affecting North America most often originate over the warm waters of the Gulf of

<sup>1</sup>Recall that land cools more rapidly and to lower temperatures than water. See the discussion of land and water in the section "Why Temperatures Vary: The Controls of Temperature" in Chapter 16.

### SmartFigure 19.4 Snowfall Map

The snowbelts of the Great Lakes are easy to pick out on this snowfall map. (Data from NOAA) The photo was taken following a 6-day lake-effect snowstorm in November 1996 that dropped 175 centimeters (nearly 69 inches) of snow on Chardon, Ohio, setting a new state record. (Photo by Tony Dejak/AP Photo)



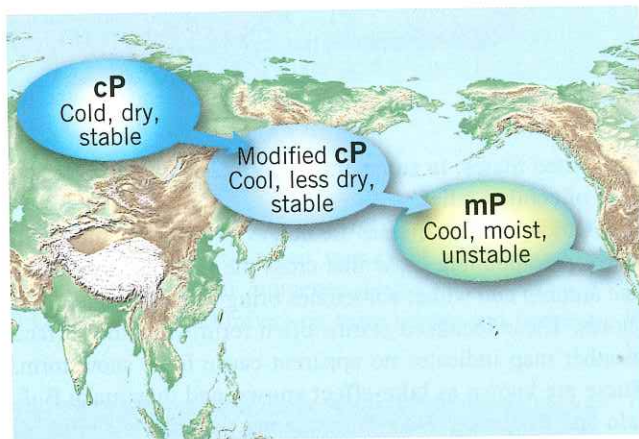
Mexico, the Caribbean Sea, or the adjacent Atlantic Ocean. As you might expect, these air masses are warm, moisture laden, and usually unstable. Maritime tropical air is the source of much, if not most, of the precipitation in the eastern two-thirds

of the United States. In summer, when an mT air mass invades the central and eastern United States, and occasionally southern Canada, it brings the high temperatures and oppressive humidity typically associated with its source region.

Of the two remaining air masses, maritime polar and continental tropical, the latter has the least influence on the weather of North America. Hot, dry continental tropical air, originating in the Southwest and Mexico during the summer, only occasionally affects the weather outside its source region.

During the winter, maritime polar air masses coming from the North Pacific often originate as continental polar air masses in Siberia. The cold, dry cP air is transformed into relatively mild, humid, unstable mP air during its long journey across the North Pacific (FIGURE 19.5). As this mP air arrives at the western shore of North America, it is often accompanied by low clouds and shower activity. When this air advances inland against the western mountains, orographic uplift produces heavy rain or snow on the windward slopes of the mountains. Maritime polar air also

**FIGURE 19.5 Air-Mass Modification** During winter, maritime polar (mP) air masses in the North Pacific usually begin as continental polar (cP) air masses in Siberia. The cP air is modified to mP as it slowly crosses the ocean.



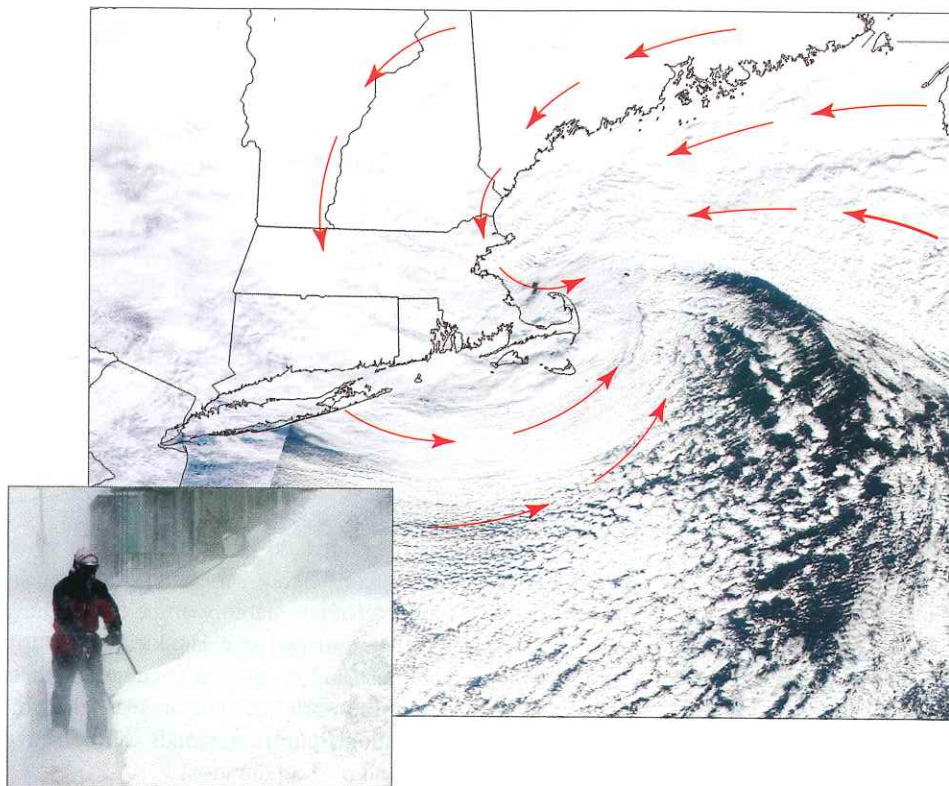
## EYE ON EARTH



This satellite image from December 27, 2010, shows a strong winter storm off the East Coast of the United States. (NASA)

- QUESTION 1** Can you identify the very center of the storm?
- QUESTION 2** What air mass is being drawn into the storm to produce the dense clouds in the upper right?
- QUESTION 3** What term is applied to a storm such as this?
- QUESTION 4** Farther south, a cold air mass over the southeastern states is cloud free. What is its likely classification? Explain how it is being modified as it moves over the Atlantic.





**FIGURE 19.6 Classic Nor'easter** The satellite image shows a strong winter storm called a *nor'easter* along the coast of New England on January 12, 2011. In winter, a *nor'easter* exhibits a weather pattern in which strong northeast winds carry cold, humid mP air from the North Atlantic into New England and the middle Atlantic states. The ground-level view of the storm in Boston shows that the combination of ample moisture and strong convergence can result in heavy snow. (Satellite image by NASA; photo by Michael Dwyer/Alamy Images)

originates in the North Atlantic off the coast of eastern Canada and occasionally influences the weather of the northeastern United States. In winter, when New England is on the northern or northwestern side of a passing low-pressure center, the counterclockwise cyclonic winds draw in maritime polar air. The result is a storm characterized by snow and cold temperatures, known locally as a **nor'easter** (FIGURE 19.6).

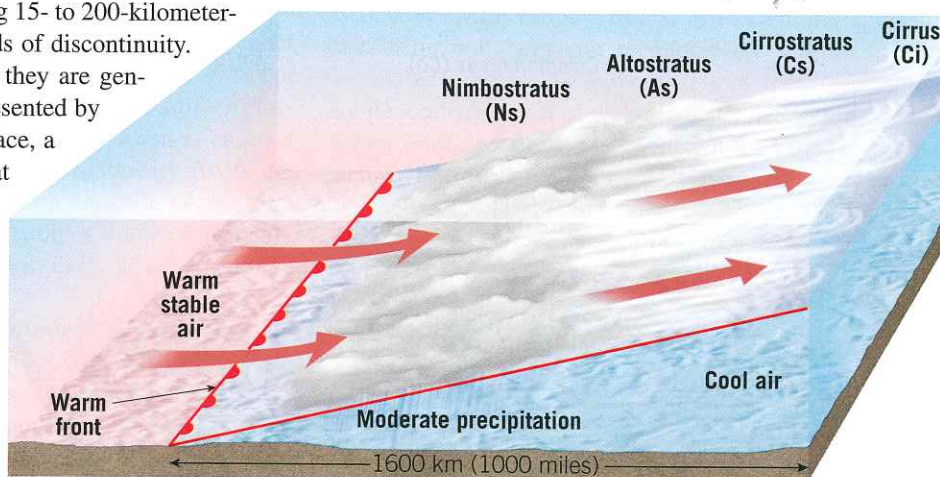
## 19.1 CONCEPT CHECKS

- 1 Define *air mass*. What is air-mass weather?
- 2 On what basis are air masses classified?
- 3 Compare the temperature and moisture characteristics of the following air masses: cP, mP, mT, and cT.
- 4 Which air mass is associated with lake-effect snow? What causes lake-effect snow?

## 19.2 FRONTS Compare and contrast typical weather associated with a warm front and a cold front. Describe an occluded front and a stationary front.

**Fronts** are boundaries that separate different air masses, one warmer than the other and often having a higher moisture content. A front can form between any two contrasting air masses. Considering the vast size of the air masses involved, fronts are relatively narrow, being 15- to 200-kilometer-wide (9- to 120-mile-wide) bands of discontinuity. On the scale of a weather map, they are generally narrow enough to be represented by a broad line. Above Earth's surface, a front slopes at a low angle so that warmer air overlies cooler air (FIGURE 19.7). In the ideal case, the air masses on both sides of the front move in the same direction and at the same speed. Under this condition, the front acts simply as a barrier, moving along between the two contrasting air masses.

Generally, however, an air mass on one side of a front moves faster relative to the frontal boundary than the air mass on the other side. Thus, one air mass actively advances into another and “clashes” with it. In fact, during World War I,



**FIGURE 19.7 Warm Front** This diagram shows the idealized clouds and weather associated with a warm front. During most of the year, warm fronts produce light to moderate precipitation over a wide area.

Norwegian meteorologists called these boundaries *fronts*, analogous to battle lines between two armies. Along these “battlegrounds,” centers of low pressure develop and generate much of the precipitation and severe weather in the middle latitudes. As one air mass advances into another, limited mixing occurs along the frontal surface, but for the most part, the air masses retain their distinct identities as one is displaced upward over the other. No matter which air mass is advancing, *it is always the warmer (less dense) air that is forced aloft*, whereas *the cooler (denser) air acts as the wedge on which lifting takes place*. The term **overrunning** is generally applied to warmer air gliding up along a colder air mass. We will now take a look at different types of fronts.

## Warm Fronts

When the surface position of a front moves so that warm air occupies territory formerly covered by cooler air, it is called a **warm front** (see Figure 19.7). On a weather map, the surface position of a warm front is shown by a red line with red semicircles protruding into the cooler air.

East of the Rockies, warm tropical air often enters the United States from the Gulf of Mexico and overruns receding cool air. As the cold air retreats, friction with the ground slows the advance of the surface position of the front more so than its position aloft. Stated another way, less dense, warm air has a hard time displacing denser, cold air. For this reason, the boundary separating these air masses acquires a very gradual slope. The average slope of a warm front is about 1:200, which means that if you are 200 kilometers (120 miles) ahead of the surface location of a warm front, you will find the frontal surface at a height of 1 kilometer (0.6 mile).

As warm air ascends the retreating wedge of cold air, it expands and cools adiabatically to produce clouds and, frequently, precipitation. The sequence of clouds shown in Figure 19.7 typically precedes a warm front. The first sign of the approach of a warm front is the appearance of cirrus clouds overhead. These high clouds form 1000 kilometers (600 miles) or more ahead of the surface front, where the overrunning warm air has ascended high up the wedge of cold air.

As the front nears, cirrus clouds grade into cirrostratus, which blend into denser sheets of altostratus. About 300 kilometers (180 miles) ahead of the front, thicker stratus and nimbostratus clouds appear, and rain or snow begins. Because of their slow rate of advance and very low slope, warm fronts usually produce light to moderate precipitation over a large area for an extended period. Warm fronts, however, are occasionally associated with cumulonimbus clouds and thunderstorms. This occurs when the overrunning air is unstable and the temperatures on opposite sides of the front contrast sharply. At the other extreme, a warm front associated with a dry air mass could pass unnoticed at the surface.

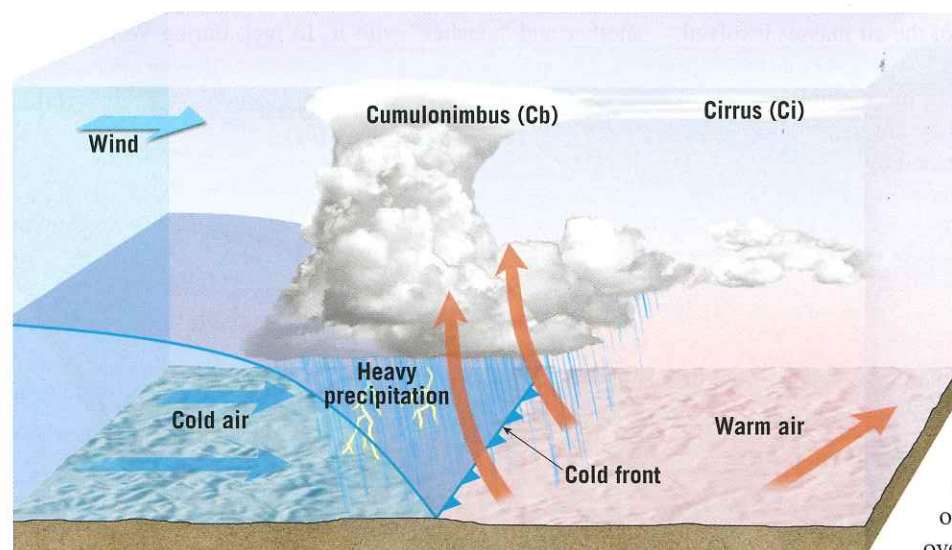
A gradual increase in temperature occurs with the passage of a warm front. The increase is most noticeable when there is a large temperature difference between the adjacent air masses. The moisture content and stability of the encroaching warm air mass largely determine when clear skies will return. During summer, cumulus, and occasionally cumulonimbus, clouds are embedded in the warm unstable air mass that follows the front. Precipitation from these clouds can be heavy but is usually scattered and of short duration.

## Cold Fronts

When dense cold air is actively advancing into a region occupied by warmer air, the boundary is called a **cold front** (FIGURE 19.8). As with warm fronts, friction tends to slow the surface position of a cold front more so than its position aloft. However, because of the relative positions of the adjacent air masses, the cold front steepens as it moves. On average, cold fronts are about twice as steep as warm fronts, having a slope of perhaps 1:100. In addition, cold fronts advance at speeds around 35 to 50 kilometers (20 to 35 miles) per hour compared to 25 to 35 kilometers (15 to 20 miles) per hour for warm fronts. These two differences—rate of movement and steepness of slope—largely account for the more violent nature of cold-front weather compared to the weather generally accompanying a warm front (FIGURE 19.9).

As a cold front approaches, commonly from the west

or northwest, towering clouds can often be seen in the distance. Near the front, a dark band of ominous clouds foretells the coming weather. The forceful lifting of air along a cold front is often so rapid that the latent heat released when water vapor condenses increases the air's buoyancy appreciably. The heavy downpours and vigorous wind gusts associated with mature cumulonimbus clouds frequently result. A cold front produces roughly the same amount of lifting as a warm front, but over a shorter distance. As a result,



### SmartFigure 19.8

**Cold Front** Fast-moving cold front and cumulonimbus clouds. Thunderstorms may occur where the warm air is unstable.





**FIGURE 19.9 Splashing Hailstones** Cumulonimbus clouds along a cold front produced hail and heavy rain at this ballpark in Wichita, Kansas. Dozens of cars in the parking lot were damaged. (Photo by Fernando Salazar/AP Photo)

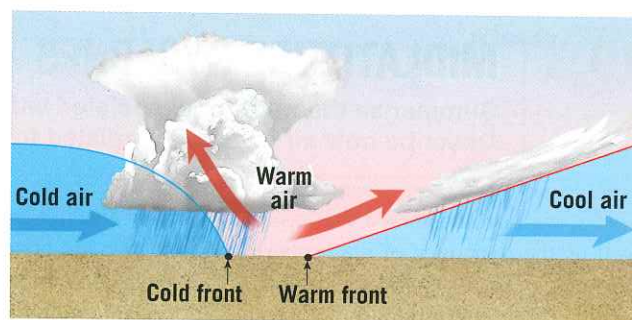
the intensity of precipitation is greater, but the duration is shorter. In addition, a marked temperature drop and a wind shift from the south to west or northwest accompany the passage of the front. The sometimes violent weather and sharp temperature contrast along the cold front are symbolized on a weather map by a blue line with blue triangle-shaped points that extend into the warmer air mass (see Figure 19.8).

The weather behind a cold front is dominated by a subsiding and relatively cold air mass. Thus, clearing usually begins soon after the front passes. Although the compression of air due to subsidence causes some adiabatic heating, the effect on surface temperatures is minor. In winter, the long, cloudless nights that often follow the passage of a cold front allow for abundant radiation cooling that reduces surface temperatures. When a cold front moves over a relatively warm area, surface heating can produce shallow convection. This, in turn, may generate low cumulus or stratocumulus clouds behind the front.

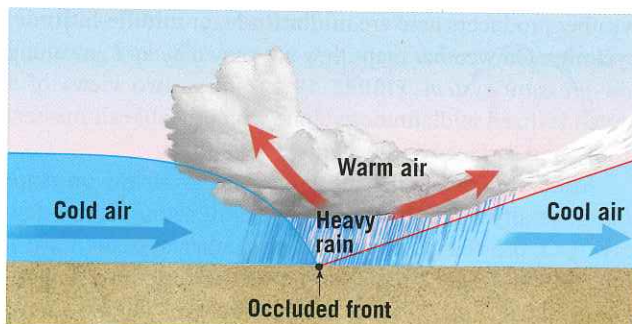
## Stationary Fronts and Occluded Fronts

Occasionally, the flow on both sides of a front is neither toward the cold air mass nor toward the warm air mass but almost parallel to the line of the front. Thus, the surface position of the front does not move. This condition is called a **stationary front**. On a weather map, stationary fronts are shown with blue triangular points on one side of the front and red semicircles on the other. At times, some overrunning occurs along a stationary front, most likely causing gentle to moderate precipitation.

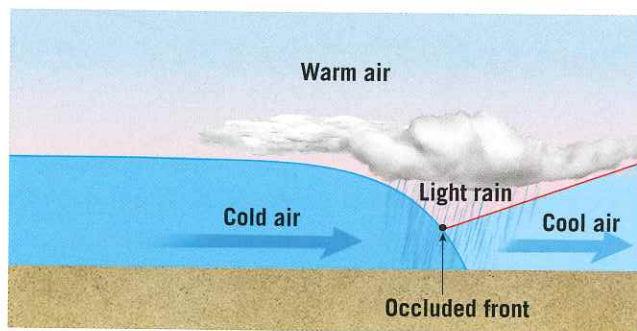
The fourth type of front is an **occluded front**, an active cold front that overtakes a warm front, as shown in **FIGURE 19.10**. As the advancing cold air wedges the warm front upward, a new front emerges between the advancing cold air and the air over which the warm front is gliding. The weather of an occluded front is generally complex. Most precipitation is



In this example, the air behind the cold front is colder and denser than the air ahead of the warm front.



The surface cold front moves faster than the surface warm front and overtakes it to form an occluded front.



The denser cold air lifts the warm air and advances into and displaces the cool air.

associated with the warm air being forced aloft. When conditions are suitable, however, the newly formed front is capable of initiating precipitation of its own.

A word of caution is in order concerning the weather associated with various fronts. Although the preceding discussion will help you recognize the weather patterns associated with fronts, remember that these descriptions are generalizations. The weather generated along any individual front may or may not conform fully to this idealized picture. Fronts, like all other aspects of nature, do not lend themselves to classification as easily as we would like.

## 19.2 CONCEPT CHECKS

- 1 Compare the weather of a typical warm front with that of a typical cold front.
- 2 Why is cold-front weather usually more severe than warm-front weather?
- 3 Describe a stationary front and an occluded front.

## 19.3 MIDLATITUDE CYCLONES

Summarize the weather associated with the passage of a mature midlatitude cyclone. Describe how airflow aloft is related to cyclones and anticyclones at the surface.

So far, we have examined the basic elements of weather as well as the dynamics of atmospheric motions. We are now ready to apply our knowledge of these diverse phenomena to an understanding of day-to-day weather patterns in the middle latitudes. For our purposes, *middle latitudes* refers to the region between southern Florida and Alaska. The primary weather producers here are **midlatitude**, or **middle-latitude, cyclones**. On weather maps they are shown by an *L*, meaning *low-pressure system*. **FIGURE 19.11** shows two views of a large idealized midlatitude cyclone with probable air masses, fronts, and surface wind patterns.

Midlatitude cyclones are large centers of low pressure that generally travel from west to east. Lasting from a few days to more than a week, these weather systems have a counterclockwise circulation, with an airflow inward toward their centers. Most midlatitude cyclones also have

a cold front extending from the central area of low pressure, and frequently a warm front as well. Convergence and forceful lifting initiate cloud development and frequently cause abundant precipitation.

As early as the 1800s, it was known that middle-latitude cyclones were the bearers of precipitation and severe weather. But it was not until the early part of the 1900s that a model was developed to explain how cyclones form. A group of Norwegian scientists formulated and published this model in 1918. The model was created primarily from near-surface observations.

Years later, as data from the middle and upper troposphere and from satellite images became available, modifications were necessary. However, this model is still a useful working tool for interpreting the weather. If you keep this model in mind when you observe changes in the weather,

the changes will no longer come as a surprise. You should begin to see some order in what once appeared to be disorder, and you might even occasionally “predict” the impending weather.

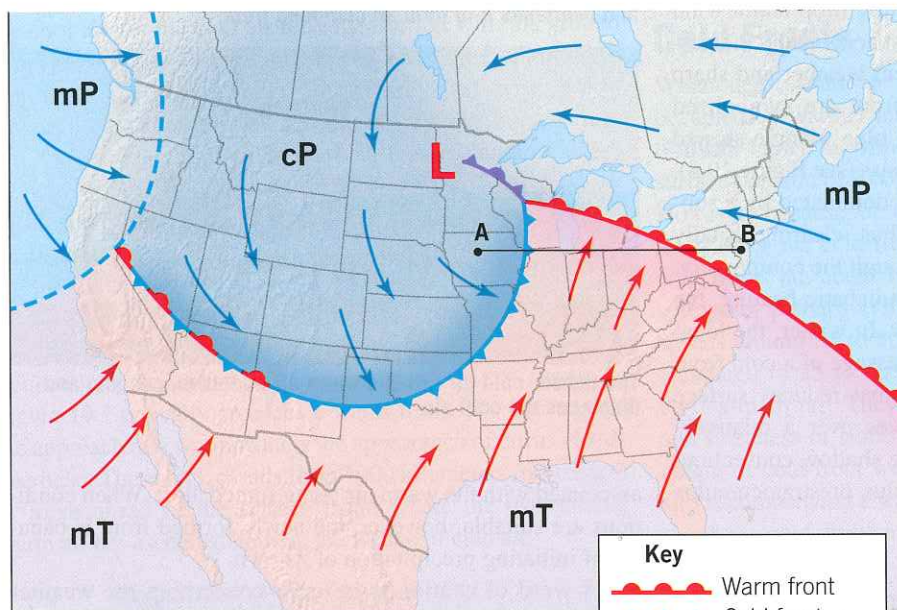
### Idealized Weather of a Midlatitude Cyclone

The midlatitude cyclone model provides a useful tool for examining the weather patterns of the middle latitudes. **FIGURE 19.12** illustrates the distribution of clouds and thus the regions of possible precipitation associated with a mature system. Compare this drawing to the satellite image shown in **FIGURE 19.13**. It is easy to see why we often refer to the cloud pattern of a midlatitude cyclone as having a “comma” shape.

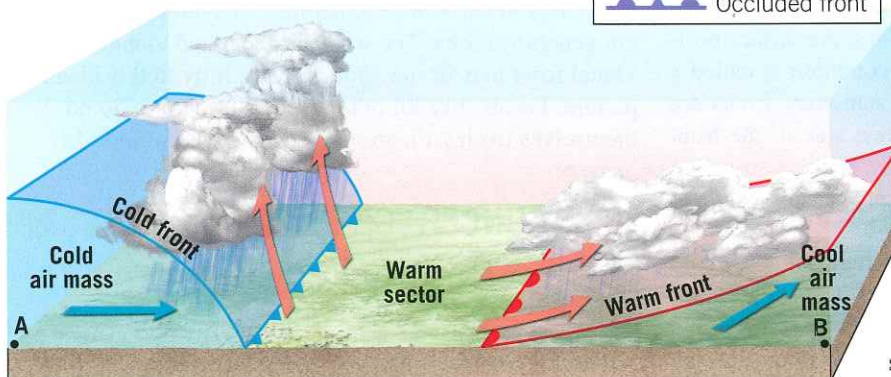
Guided by the westerlies aloft, cyclones generally move eastward across the United States, so we can expect the first signs of their arrival in the west. However, often in the region of the Mississippi River Valley, cyclones begin a more northeasterly path and occasionally move directly northward. A midlatitude cyclone typically requires 2

#### SmartFigure 19.11 Idealized Structure of a Large, Mature Midlatitude Cyclone

**A.** This map view shows fronts, air masses, and surface winds. **B.** The three-dimensional view is a cross section through warm and cold fronts along a line from point A to point B.



**A.** Map view



**B.** Three-dimensional view from point A to point B

Key	
	Warm front
	Cold front
	Stationary front
	Occluded front

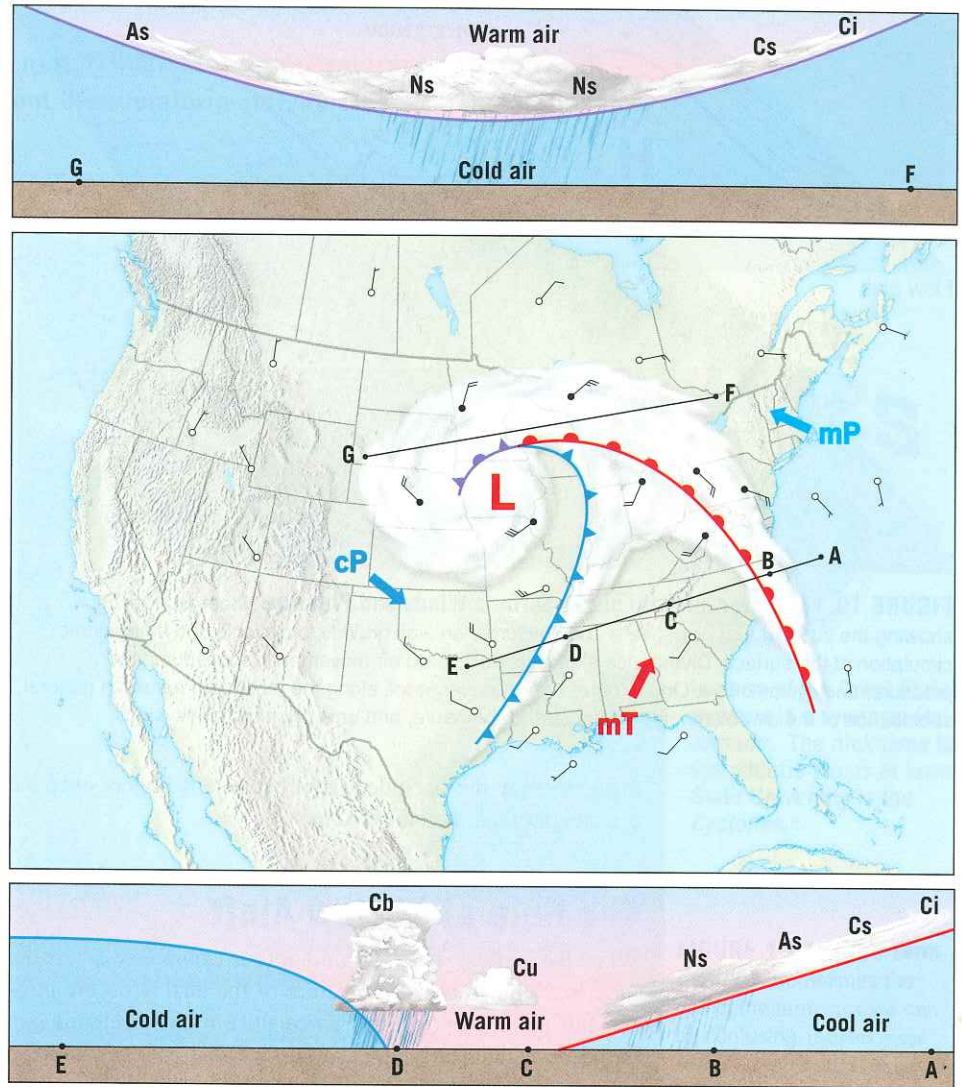
to 4 days to move completely across a region. During that brief period, abrupt changes in atmospheric conditions may be experienced. This is particularly true in the winter and spring, when the largest temperature contrasts occur across the middle latitudes.

Using Figure 19.12 as a guide, we will now consider these weather producers and what we should expect from them as they move over an area. To facilitate our discussion, Figure 19.12 includes two profiles along lines A–E and F–G:

- Imagine the change in weather as you move along profile A–E. At point A, the sighting of high cirrus clouds would be the first sign of the approaching cyclone. These high clouds can precede the surface front by 1000 kilometers (600 miles) or more, and they generally are accompanied by falling pressure. As the warm front advances, a lowering and thickening of the cloud deck is noticed.
- Usually within 12 to 24 hours after the first sighting of cirrus clouds, light precipitation begins (point B). As the front nears, the rate of precipitation increases, a rise in temperature is noticed, and winds begin to change from east or southeast to south or southwest.
- With the passage of the warm front, an area is under the influence of a maritime tropical air mass (point C). Generally, the region affected by this sector of the cyclone experiences warm to hot temperatures, southwesterly winds, fairly high humidity, and clear to partly cloudy skies containing cumulus clouds.
- The relatively warm, humid weather of the warm sector passes quickly and is replaced by gusty winds and precipitation generated along the cold front. The approach of a rapidly advancing cold front is marked by a wall of dark clouds (point D). Severe weather accompanied by heavy precipitation, hail, and an occasional tornado is a definite possibility, especially during spring and summer. The passage of the cold front is easily detected by a wind shift: The southwest winds are replaced by winds from the west to northwest and by a pronounced drop in temperature. Also, the rising pressure hints of the subsiding cool, dry air behind the front.
- Once the front passes, skies clear as cooler air invades the region (point E). Often a day or two of almost cloudless deep blue skies occurs, unless another cyclone is edging into the region.

A very different set of weather conditions prevails in the regions north of the storm's center along profile F–G of Figure 19.12. In this part of the storm, temperatures remain cool. The first hints of the approaching low-pressure center are a continual drop in air pressure and increasingly overcast conditions that bring varying amounts of precipitation. This section of the cyclone most often generates snow during the winter months.

Once the formation of an occluded front begins, the character of the storm changes. Because occluded

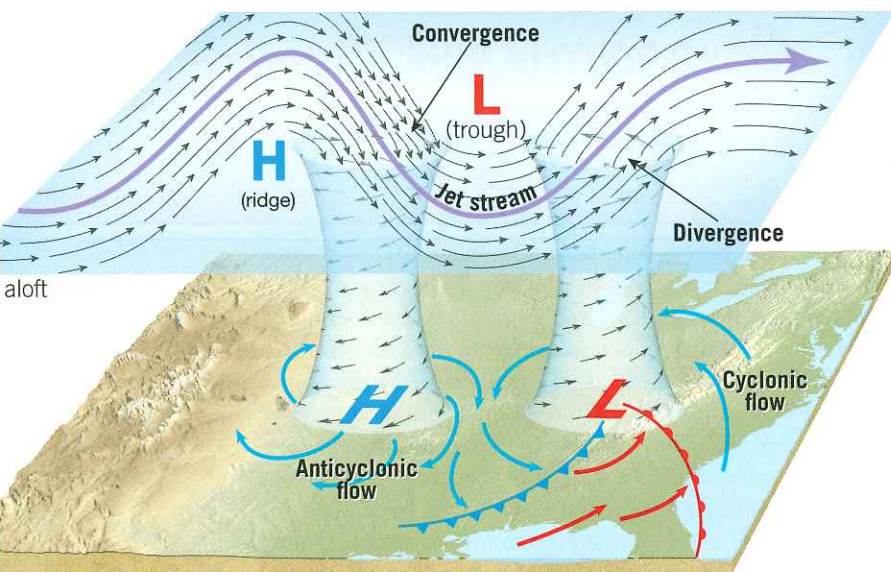


**FIGURE 19.12 Cloud Patterns Typically Associated with a Mature Midlatitude Cyclone** The middle section is a map view. Note the cross-sectional lines (F–G, A–E). Above the map is a vertical cross section along line F–G. Below the map is a section along A–E. For cloud abbreviations, refer to Figures 19.7 and 19.8.

fronts tend to move more slowly than other fronts, the entire wishbone-shaped frontal structure of the storm rotates counterclockwise. As a result, the occluded front appears to “bend over backward.” This effect adds to the misery of the region



**FIGURE 19.13 Satellite View of a Mature Midlatitude Cyclone** This storm swept across the central United States and produced strong wind gusts (up to 125 kilometers [78 miles] per hour), rain, hail, and snow. It also spawned 61 tornadoes on October 26, 2010. This cyclone set a record for the lowest pressure not associated with a hurricane ever recorded over land in the continental United States: 28.21 inches of mercury. It is easy to see why we often refer to the cloud pattern of a cyclone as having a “comma” shape. (NASA)



**FIGURE 19.14 Flow Aloft Influences Surface Winds and Pressure** Idealized depiction showing the support that divergence and convergence aloft provide to cyclonic and anticyclonic circulation at the surface. Divergence aloft initiates upward air movement, reduced surface pressure, and cyclonic flow. On the other hand, convergence along the jet stream results in general subsidence of the air column, increased surface pressure, and anticyclonic surface winds.

influenced by the occluded front because it lingers over the area longer than the other fronts.

## The Role of Airflow Aloft

When the earliest studies of midlatitude cyclones were made, little was known about the nature of the airflow in the middle and upper troposphere. Since then, a close relationship has been established between surface disturbances and the flow aloft. Airflow aloft plays an important role in maintaining cyclonic and anticyclonic circulation. In fact, more often than not, these rotating surface wind systems are actually generated by upper-level flow.

Recall that the airflow around a cyclone (low-pressure system) is inward, a fact that leads to mass convergence,

or coming together (**FIGURE 19.14**). The resulting accumulation of air must be accompanied by a corresponding increase in surface pressure. Consequently, we might expect a low-pressure system to “fill” rapidly and be eliminated. However, this does not occur. On the contrary, cyclones often exist for a week or longer. For this to happen, surface convergence must be offset by a mass outflow at some level aloft (see Figure 19.14). As long as divergence (spreading out) aloft is equal to or greater than surface inflow, the low pressure and its accompanying convergence can be sustained.

Because cyclones are bearers of stormy weather, they have received far more attention than anticyclones. Nevertheless, a close relationship exists, which makes it difficult to separate any discussion of these two types of pressure systems. The surface air that feeds a cyclone, for example, generally originates as air flowing out of an anticyclone. Consequently, cyclones and anticyclones typically are found adjacent to each other. Like a cyclone, an anticyclone depends on the flow far above to maintain its circulation. Divergence at the surface is balanced by convergence aloft and general subsidence of the air column (see Figure 19.14).

## 19.3 CONCEPT CHECKS

- Briefly describe the weather associated with the passage of a mature midlatitude cyclone when the center of low pressure is about 200 to 300 kilometers (125 to 200 miles) north of your location.
- If the midlatitude cyclone described in Question 1 took 3 days to pass your location, on which day would temperatures likely be warmest? On which day would they likely be coldest?
- What winter weather might be expected with the passage of a mature midlatitude cyclone when the center of low pressure is located about 100 to 200 kilometers (60 to 125 miles) south of your location?
- Briefly explain how flow aloft aids the formation of cyclones at the surface.

## EYE ON EARTH



This image of a line of clouds was taken by astronauts aboard the International Space Station. The dashed line on the image shows the approximate surface position of the front responsible for the cloud development. Assume that this front is located over the central United States as you answer the following questions. (NASA)

- QUESTION 1** What is the cloud type of the tallest clouds in the image?
- QUESTION 2** Are these clouds more typical of a cold front or a warm front?
- QUESTION 3** Is the front most likely moving toward the southeast or toward the northwest?
- QUESTION 4** Is the air mass located to the southeast of the front more likely continental polar (cP) or maritime tropical (mT)?



## 19.4 THUNDERSTORMS

List the basic requirements for thunderstorm formation and locate places on a map that exhibit frequent thunderstorm activity. Describe the stages in the development of a thunderstorm.

Thunderstorms are the first of three severe weather types we will examine in this chapter. Sections on tornadoes and hurricanes follow. All these phenomena can be related to low-pressure systems (cyclones).

Severe weather is more fascinating than everyday weather phenomena. The lightning display and booming thunder generated by a severe thunderstorm can be a spectacular event that elicits both awe and fear (FIGURE 19.15). Of course, hurricanes and tornadoes also attract a great deal of much-deserved attention. A single tornado outbreak or hurricane can cause many deaths as well as billions of dollars in property damage. In a typical year, the United States experiences thousands of violent thunderstorms, hundreds of tornadoes, and several hurricanes.

### What's in a Name?

Up to now we have examined midlatitude cyclones, which play an important role in causing day-to-day weather changes. Yet the use of the term *cyclone* is often confusing. To many people, the term implies only an intense storm, such as a tornado or a hurricane. When a hurricane unleashes its fury on India or Bangladesh, for example, it is usually



**FIGURE 19.15 Summertime Lightning Display** A storm is classified as a thunderstorm only after thunder is heard. Because thunder is produced by lightning, lightning must also occur. (Photo by agefotostock/SuperStock)



In southern Asia and Australia, the term *cyclone* is applied to storms that are called *hurricanes* in the United States. This image shows Cyclone Yasi, which struck eastern Australia in February 2011.

In parts of the Great Plains *cyclone* is a synonym for *tornado*. The nickname for the athletic teams at Iowa State University is the *Cyclones*.\*

**FIGURE 19.16 The Term Cyclone** Sometimes the use of the term *cyclone* can be confusing. (Satellite image courtesy of NASA; logo courtesy of Iowa State University)

reported in the media as a *cyclone* (the term denoting a hurricane in that part of the world).

Similarly, tornadoes are referred to as *cyclones* in some places. This custom is particularly common in portions of the Great Plains of the United States. Recall that in *The Wizard of Oz*, Dorothy's house was carried from her Kansas farm to the land of Oz by a cyclone. Indeed, the nickname for the athletic teams at Iowa State University is the *Cyclones* (FIGURE 19.16). Although hurricanes and tornadoes are, in fact, cyclones, the vast majority of cyclones are *not* hurricanes or tornadoes. The term *cyclone* simply refers to the circulation around any low-pressure center, no matter how large or intense it is.

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

\* Iowa State University is the only Division I school to use Cyclones as its team name. The pictured logo was created to better communicate the school's image by combining the mascot, a cardinal bird named Cy, and the Cyclone team name.

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

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

## Thunderstorm Occurrence

Almost everyone has observed various small-scale phenomena that result from the vertical movements of relatively warm, unstable air. Perhaps you have seen a dust devil over an open field on a hot day, whirling its dusty load to great heights. Or maybe you have noticed a bird glide effortlessly skyward on an invisible thermal of hot air. These examples illustrate the dynamic thermal instability that occurs during the development of a thunderstorm.

A **thunderstorm** is a storm that generates lightning and thunder. Thunderstorms frequently produce gusty winds, heavy rain, and hail. A thunderstorm may be produced by a single cumulonimbus cloud and influence only a small area, or it may be associated with clusters of cumulonimbus clouds covering a large area.

Thunderstorms form when warm, humid air rises in an unstable environment. Various mechanisms can trigger the upward air movement needed to create thunderstorm-producing cumulonimbus clouds. One mechanism, the unequal heating of Earth’s surface, significantly contributes to the formation of *air-mass thunderstorms*. These storms are associated with the scattered puffy cumulonimbus clouds that commonly form

within maritime tropical air masses and produce scattered thunderstorms on summer days. Such storms are usually short-lived and seldom produce strong winds or hail.

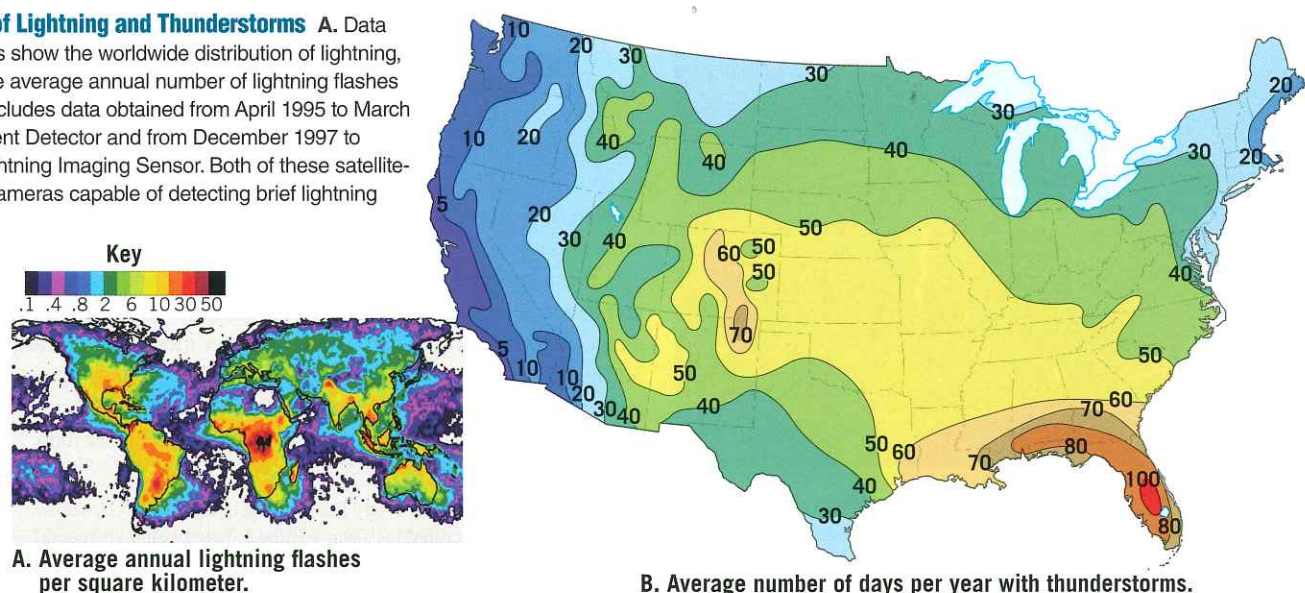
Another type of thunderstorm not only benefits from uneven surface heating but is associated with the lifting of warm air, as occurs along a front or a mountain slope. Moreover, diverging winds aloft frequently contribute to the formation of these storms because they tend to draw air from lower levels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

At any given time, an estimated 2000 thunderstorms are in progress on Earth. As we would expect, the greatest number occur in the tropics, where warmth, plentiful moisture and instability are always present. About 45,000 thunderstorms take place each day, and more than 16 million occur annually around the world. The lightning from these storms strikes Earth 100 times each second (FIGURE 19.17A). Annually, the United States experiences about 100,000 thunderstorms and millions of lightning strikes. A glance at FIGURE 19.17B shows that thunderstorms are most frequent in Florida and the eastern Gulf coast region, where such activity is recorded between 70 and 100 days each year. The region on the eastern side of the Rockies in Colorado and New Mexico is next, with thunderstorms occurring on 60 to 70 days each year. Most of the rest of the nation experiences thunderstorms on 30 to 50 days annually. The western margin of the United States has little thunderstorm activity. The same is true for the northern tier of states and for Canada, where warm, moist, unstable mT air seldom penetrates.

## Stages of Thunderstorm Development

All thunderstorms require warm, moist air, which, when lifted, releases sufficient latent heat to provide the buoyancy necessary to maintain its upward flight. This instability and associated buoyancy are triggered by a number of different processes, yet most thunderstorms have a similar life history.

**FIGURE 19.17 Occurrence of Lightning and Thunderstorms** A. Data from space-based optical sensors show the worldwide distribution of lightning, with color variations indicating the average annual number of lightning flashes per square kilometer. The map includes data obtained from April 1995 to March 1997 from NASA’s Optical Transient Detector and from December 1997 to March 2000 from NASA’s Lightning Imaging Sensor. Both of these satellite-based sensors use high-speed cameras capable of detecting brief lightning strikes even under daytime conditions. (NASA) B. Average number of days each year with thunderstorms. The subtropical climate that prevails in the southeastern United States receives much more precipitation in the form of thunderstorms. Most of the Southeast averages 50 or more days each year with thunderstorms. (Environmental Science Service, NOAA)





A.



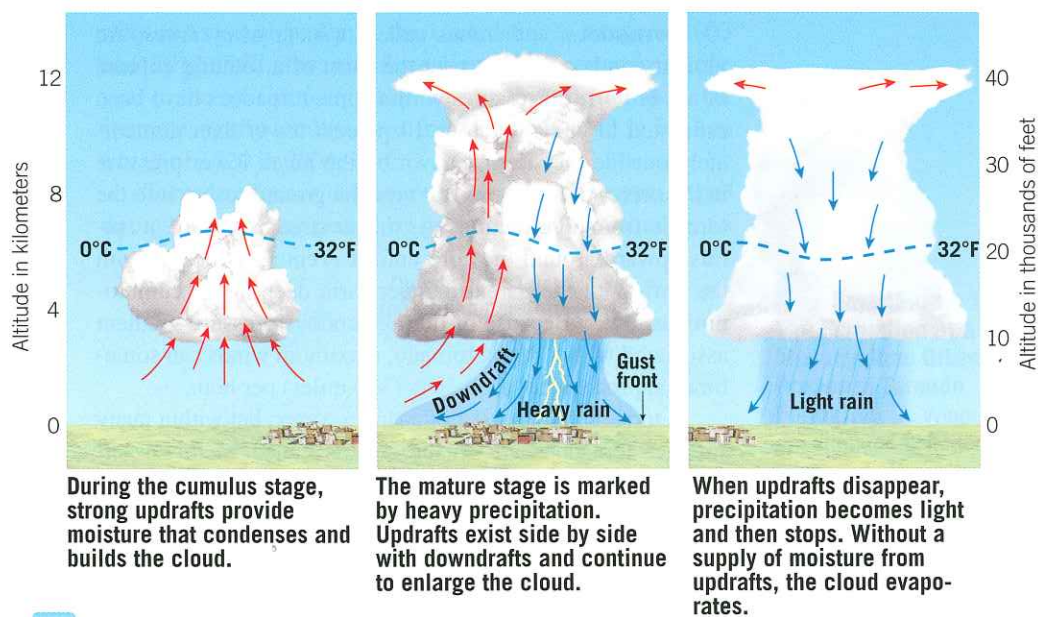
B.

**FIGURE 19.18 Cumulus Development** A. Buoyant thermals often produce fair-weather cumulus clouds that soon evaporate into the surrounding air, making it more humid. As this process of cumulus development and evaporation continues, the air eventually becomes sufficiently humid so that newly forming clouds do not evaporate but continue to grow. (Photo by Henry Lansford/ Science Source) B. This developing cumulonimbus cloud became a towering August thunderstorm over central Illinois. (Photo by E. J. Tarbuck)

Because instability and buoyancy are enhanced by high surface temperatures, thunderstorms are most common in the afternoon and early evening (FIGURE 19.18A). However, surface heating alone is not sufficient for the growth of towering cumulonimbus clouds. A solitary cell of rising hot air produced by surface heating could, at best, produce a small cumulus cloud, which would evaporate within 10 to 15 minutes.

The development of 12,000-meter (40,000-foot) (or, on rare occasions, 18,000-meter [60,000-foot]) cumulonimbus towers requires a continual supply of moist air (FIGURE 19.18B). Each new surge of warm air rises higher than the last, adding to the height of the cloud (FIGURE 19.19). These updrafts occasionally reach speeds greater than 100 kilometers (60 miles) per hour, based on the size of hailstones they are capable of carrying upward. Usually within an hour, the amount and size of precipitation that has accumulated is too much for the updrafts to support, and consequently downdrafts develop in one part of the cloud, releasing heavy precipitation. This is the most active stage of the thunderstorm. Gusty winds, lightning, heavy precipitation, and sometimes hail are experienced.

Eventually the warm, moist air supplied by updrafts ceases as downdrafts dominate throughout the cloud. The cooling effect of falling precipitation, coupled with the influx of colder air aloft, marks the end of the thunderstorm activity. The life span of a typical cumulonimbus cell within a thunderstorm complex is only about an hour, but as the storm moves, fresh supplies of warm, water-laden air generate new cells to replace those that are dissipating.



During the cumulus stage, strong updrafts provide moisture that condenses and builds the cloud.

The mature stage is marked by heavy precipitation. Updrafts exist side by side with downdrafts and continue to enlarge the cloud.

When updrafts disappear, precipitation becomes light and then stops. Without a supply of moisture from updrafts, the cloud evaporates.



**SmartFigure 19.19 Thunderstorm Development** Once a cloud passes beyond the freezing level, the Bergeron process begins producing precipitation. Eventually, the accumulation of precipitation in the cloud is too great for the updraft to support. The falling precipitation causes drag on the air and initiates a downdraft. Once downdrafts dominate, rainfall diminishes, and the cloud starts to dissipate.



## 19.4 CONCEPT CHECKS

- 1 Briefly compare and contrast midlatitude cyclones, hurricanes, and tornadoes. How are thunderstorms related to each?
- 2 What are the basic requirements for the formation of a thunderstorm?
- 3 Where are thunderstorms most common on Earth? In the United States?
- 4 Summarize the stages in the development of a thunderstorm.

## 19.5 | TORNADOES

Summarize the atmospheric conditions and locations that are favorable to the formation of tornadoes. Discuss tornado destruction and tornado forecasting.

Tornadoes are local storms of short duration that rank high among nature's most destructive forces (FIGURE 19.20). Their sporadic occurrence and violent winds cause many deaths each year. The nearly total destruction in some stricken areas has led many to liken their passage to bombing raids during war (FIGURE 19.21).

During the very stormy spring of 2011, there were 753 confirmed tornadoes during April, setting a record for the number of tornadoes in a single month. The deadliest and most destructive outbreak occurred between April 25 and 28, when 326 confirmed tornadoes struck, mostly in the South. The loss of life and property were extraordinary. Estimated fatalities numbered between 350 and 400, and damages were in the billions of dollars. The tornado that struck Tuscaloosa, Alabama, was especially notable for the death and destruction it caused. A few weeks later, on May 22, another outbreak struck the Midwest. Joplin, Missouri, was in the direct path of a storm that took more than 150 lives.

**Tornadoes**, sometimes called *twisters* or *cyclones*, are violent windstorms that take the form of a rotating column of air, or *vortex*. Pressures within some tornadoes have been estimated to be as much as 10 percent lower than immediately outside the storm. Drawn by the much lower pressure in the center of the vortex, air near the ground rushes into the tornado from all directions. As the air streams inward, it spirals upward around the core until it eventually merges with the airflow of the parent thunderstorm deep in the cumulonimbus tower. Because of the tremendous pressure gradient associated with a strong tornado, maximum winds can sometimes approach 480 kilometers (300 miles) per hour.

A tornado may consist of a single vortex, but within many stronger tornadoes are smaller whirls called *suction vortices* that rotate within the main vortex (FIGURE 19.22). Suction vortices have diameters of only about 10 meters (33 feet)



**FIGURE 19.21 Tornado Destruction at Moore, Oklahoma** On May 20, 2013, central Oklahoma was devastated by an EF-5 tornado, the most severe category. It took 24 lives, injured 377, and caused damages in excess of \$2 billion. At least 13,000 structures were destroyed or damaged. The tornado was on the ground for 39 minutes and had a path that extended for 27 kilometers (17 miles). At its peak, the tornado was 2.1 kilometers (1.3 miles) wide and had winds of 340 kilometers (210 miles) per hour. (Photo by Jewel Samad/Getty Images)

and rotate very rapidly. This structure accounts for occasional observations of virtually total destruction of one building while another one, just 10 meters (33 feet) away, suffers little damage.

### Tornado Occurrence and Development

Tornadoes form in association with severe thunderstorms that produce high winds, heavy (sometimes torrential) rainfall, and often damaging hail. Fortunately, fewer than 1 percent of all thunderstorms produce tornadoes. Nevertheless, a much higher number of thunderstorms must be monitored as potential tornado producers. A tornado is the product of the interaction between strong updrafts in a thunderstorm and the winds in the troposphere.

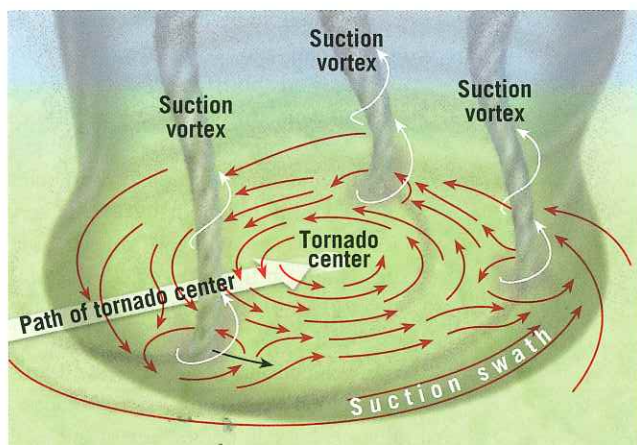
Tornadoes can form in any situation that produces severe weather, including cold fronts and tropical cyclones (hurricanes). The most intense tornadoes are usually those that form in association with huge

### FIGURE 19.20 A Violent Tornado Near Manchester, North Dakota

A tornado is a violently rotating column of air in contact with the ground. The air column is visible when it contains condensation or when it contains dust and debris. When the appearance is the result of both. When the column of air is aloft and does not produce damage, the visible portion is properly called a *funnel cloud*.

(Photo by Carsten Peter/National Geographic Stock)





**FIGURE 19.22 Multiple-Vortex Tornado** Some tornadoes have multiple suction vortices. These small and very intense vortices are roughly 10 meters (30 feet) across and move in a counterclockwise path around the tornado center. Because of this multiple-vortex structure, one building might be heavily damaged and another one, just 10 meters away, might suffer little damage.

thunderstorms called *supercells*. An important precondition linked to tornado formation in severe thunderstorms is the development of a **mesocyclone**—a vertical cylinder of rotating air, typically about 3 to 10 kilometers (2 to 6 miles) across, that develops in the updraft of a severe thunderstorm (FIGURE 19.23). The formation of this large vortex often precedes tornado formation by 30 minutes or so.

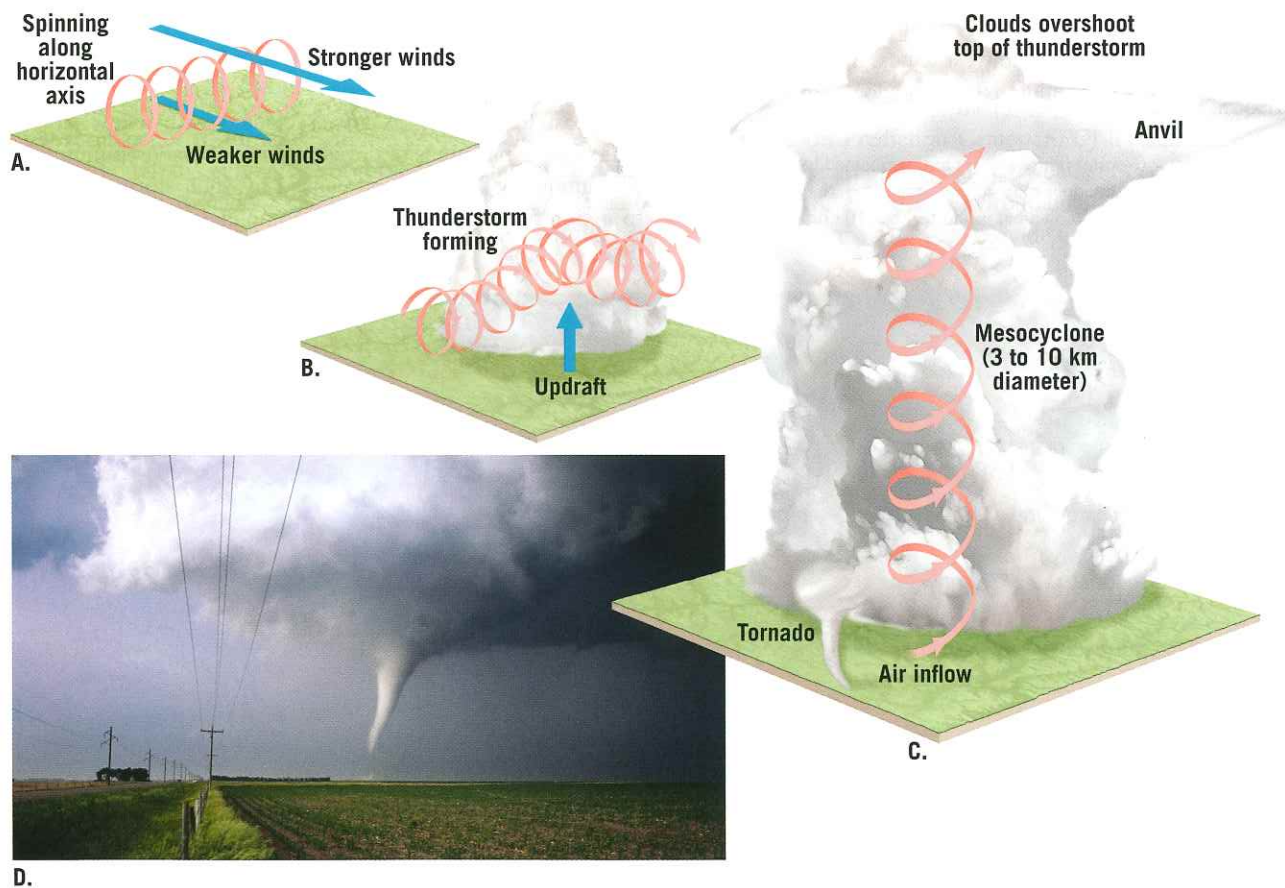
The formation of a mesocyclone does not necessarily mean that tornado formation will follow. Only about half of

all mesocyclones produce tornadoes. Forecasters cannot determine in advance which mesocyclones will spawn tornadoes.

**General Atmospheric Conditions** Severe thunderstorms—and, hence, tornadoes—are most often spawned along the cold front of a midlatitude cyclone or in association with a supercell thunderstorm such as the one pictured in Figure 19.23D. Throughout spring, air masses associated with midlatitude cyclones are most likely to have greatly contrasting conditions. Continental polar air from Canada may still be very cold and dry, whereas maritime tropical air from the Gulf of Mexico is warm, humid, and unstable. The greater the contrast when these air masses meet, the more intense the storm. The two contrasting air masses are most likely to meet in the central United States because there is no significant natural barrier separating the center of the country from the Arctic or the Gulf of Mexico. Consequently, this region generates more tornadoes than any other area of the country or, in fact, the world. The map in FIGURE 19.24, which depicts tornado incidence in the United States for a 27-year period, readily substantiates this fact.

**Tornado Climatology** An average of 1352 tornadoes were reported annually in the United States between 2003 and 2012. Still, the actual number that occurs from one year to the next varies greatly. During this 10-year span, for example, yearly totals ranged from a low of 1043 in 2012 to a high of 1820 in 2004.

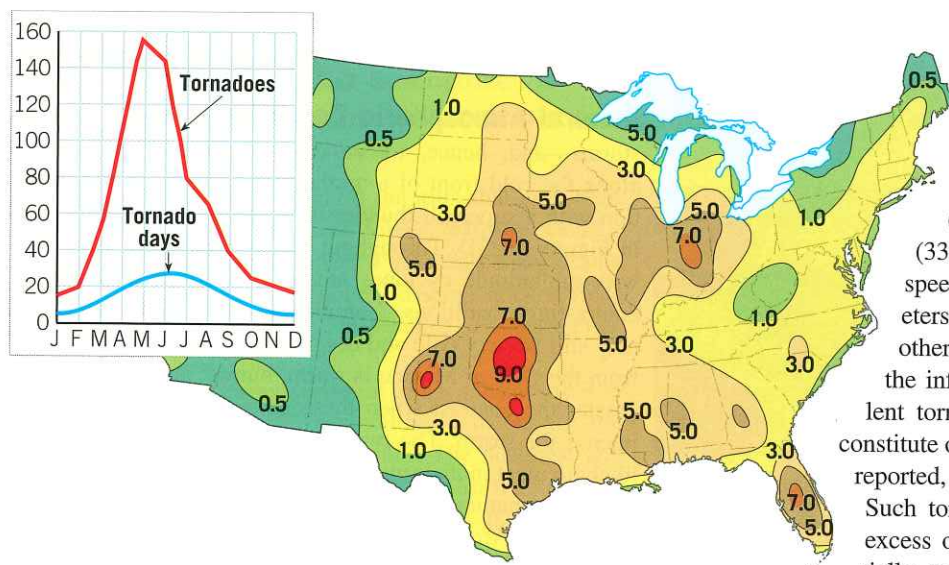
Tornadoes occur during every month of the year. April through June is the period of greatest tornado frequency in



**SmartFigure 19.23**  
**The Formation of a Mesocyclone Often Precedes Tornado Formation**  
**A.** Winds are stronger aloft than at the surface (called speed wind shear), producing a rolling motion about a horizontal axis. **B.** Strong thunderstorm updrafts tilt the horizontally rotating air to a nearly vertical alignment. **C.** The mesocyclone, a vertical cylinder of rotating air, is established. **D.** If a tornado develops, it will descend from a slowly rotating wall cloud in the lower portion of the mesocyclone. (Photo by Gene Rhoden/Weatherpix/Getty Images)



**FIGURE 19.24 Tornado Occurrence** The map shows average annual tornado incidence per 26,000 square kilometers (10,000 square miles) for a 27-year period. The graph shows the average number of tornadoes and tornado days each month in the United States for the same period.



the United States; the number is lowest during December and January (see Figure 19.24, graph inset). Of the 40,522 confirmed tornadoes reported over the contiguous 48 states during the 50-year period from 1950 through 1999, an average of almost 6 per day occurred during May. At the other extreme, a tornado was reported only about every other day in December and January.

**Profile of a Tornado** An average tornado has a diameter of between 150 and 600 meters (500 and 2000 feet), travels across the landscape at approximately 45 kilometers (30 miles) per hour, and cuts a path about 10 kilometers (6 miles) long.<sup>2</sup> Because tornadoes usually occur slightly ahead of a cold front, in the zone of southwest winds, most move toward the northeast. Of the hundreds of tornadoes reported in the

<sup>2</sup>The 10-kilometer (6-mile) figure applies to documented tornadoes. Because many small tornadoes may go undocumented, the real average path of all tornadoes is unknown but is shorter than 10 kilometers.

United States annually, more than half are comparatively weak and short-lived. Most of these small tornadoes have lifetimes of 3 minutes or less and paths that seldom exceed 1 kilometer (0.6 mile) in length and 100 meters (330 feet) in width. Typical wind speeds are on the order of 150 kilometers (90 miles) per hour or less. On the other end of the tornado spectrum are the infrequent and often long-lived violent tornadoes. Although large tornadoes constitute only a small percentage of the total reported, their effects are often devastating. Such tornadoes may exist for periods in excess of 3 hours and produce an essentially continuous damage path more than 150 kilometers (90 miles) long and perhaps 1 kilometer (0.6 mile) or more wide. Maximum winds range beyond 500 kilometers (310 miles) per hour.

## Tornado Destruction and Loss of Life

The potential for tornado destruction depends largely on the strength of the winds generated by the storm. Because tornadoes generate the strongest winds in nature, they have accomplished many seemingly impossible tasks, such as driving a piece of straw through a thick wooden plank and uprooting huge trees. Although it may seem impossible for winds to cause some of the extensive damage attributed to tornadoes, tests in engineering facilities have repeatedly demonstrated that winds in excess of 320 kilometers (200 miles) per hour are capable of incredible feats (FIGURE 19.25).

Most tornado losses are associated with a few storms that strike urban areas or devastate entire small communities. The amount of destruction caused by such storms depends to a significant degree (but not completely) on the strength

## EYE ON EARTH



This satellite image shows a portion of the diagonal path left by a tornado as it moved across northern Wisconsin in 2007. (NASA)

**QUESTION 1** Toward what direction did the storm advance: the northeast or the southwest?

**QUESTION 2** Did the tornado more likely occur ahead of or behind a cold front? Explain.

**QUESTION 3** Is it more probable that the storm took place in March or June? Why is the date you selected more likely?





A.



B.

**FIGURE 19.25 Tornado Winds: The Strongest in Nature** **A.** The force of the wind during a tornado near Wichita, Kansas, in April 1991 was enough to drive this piece of metal into a utility pole. (Photo by John Sokich/NOAA) **B.** The remains of a truck wrapped around a tree in Bridge Creek, Oklahoma, on May 4, 1999, following a major tornado outbreak. (LM Otero/AP Photo)

of the winds. A wide spectrum of tornado strengths, sizes, and lifetimes are observed. The commonly used guide to tornado intensity is the **Enhanced Fujita intensity scale**, or **EF-scale** for short (**TABLE 19.1**). Because tornado winds cannot be measured directly, a rating on the EF-scale is determined by assessing the worst damage produced by a storm. Although widely used, the EF-scale is not perfect. Estimating tornado intensity based on damage alone does not take into account the structural integrity of the objects hit by a tornado. A well-constructed building can withstand very high winds, whereas a poorly built structure can suffer devastating damage from the same or weaker winds.

Although the greatest part of tornado damage is caused by violent winds, most tornado injuries and deaths result from flying debris. The proportion of tornadoes that result in loss of life is small. In most years, slightly fewer than 2 percent of all reported tornadoes in the United States are “killers.” Although the percentage of tornadoes resulting in death is small, each tornado is potentially lethal. When tornado fatalities and storm intensities are compared, the results are

quite interesting: The majority (63 percent) of tornadoes are weak (EF-0 and EF-1), and the number of storms decreases as tornado intensity increases. The distribution of tornado fatalities, however, is just the opposite. Although only 2 percent of tornadoes are classified as violent (EF-4 and EF-5), they account for nearly 70 percent of tornado deaths.

## Tornado Forecasting

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

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

*Severe thunderstorm outlooks* are issued several times daily. *Day 1* outlooks identify the areas that are likely to be affected by severe thunderstorms during the next 6 to 30 hours, and *day 2* outlooks extend the forecast through the following day. Both outlooks describe the type, coverage, and intensity of the severe weather expected. Many local NWS field offices also issue severe weather outlooks that provide more local descriptions of the severe weather potential for the next 12 to 24 hours.

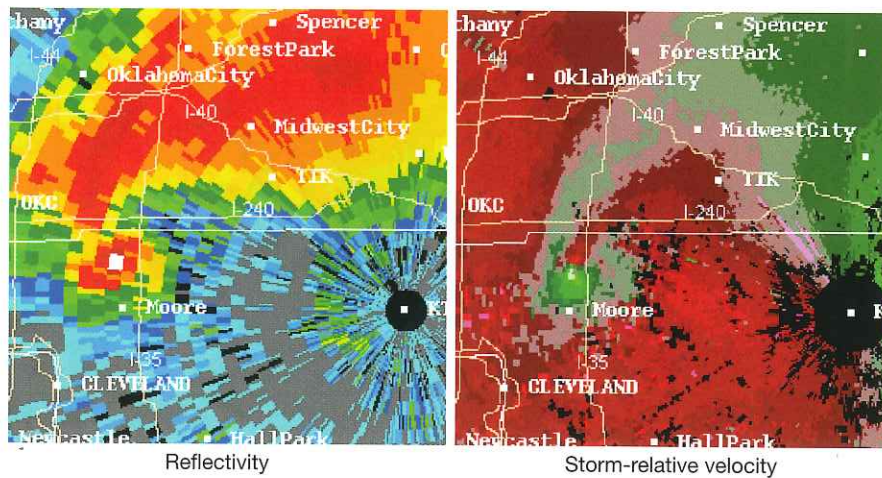
**TABLE 19.1 Enhanced Fujita Intensity Scale\***

Scale	Wind Speed		Damage
	Km/Hr	Mi/Hr	
EF-0	105–137	65–85	<i>Light.</i> Some damage to siding and shingles.
EF-1	138–177	86–110	<i>Moderate.</i> Considerable roof damage. Winds can uproot trees and overturn single-wide mobile homes. Flagpoles bend.
EF-2	178–217	111–135	<i>Considerable.</i> Most single-wide homes destroyed. Permanent homes can shift off foundations. Flagpoles collapse. Softwood trees debarked.
EF-3	218–265	136–165	<i>Severe.</i> Hardwood trees debarked. All but small portions of houses destroyed.
EF-4	266–322	166–200	<i>Devastating.</i> Complete destruction of well-built residences, large sections of school buildings.
EF-5	>322	>200	<i>Incredible.</i> Significant structural deformation of mid- and high-rise buildings.

\*The original Fujita scale was developed by T. Theodore Fujita in 1971 and put into use in 1973. The Enhanced Fujita intensity scale is a revision that was put into use in February 2007. Winds speeds are estimates (not measurements) based on damage, and represent 3-second gusts at the point of damage.

**FIGURE 19.26 Doppler**

This is a dual Doppler image of a violent tornado near Moore, Oklahoma, on May 3, 1999. The left image (reflectivity) shows precipitation in the cell thunderstorm. The right image shows motion of precipitation along the radar beam—that is, how rain or hail is moving toward or away from the radar. In this example, the radar shows unusually close to the radar—close enough to show the signature of the tornado itself. Most of the time the weaker and larger mesocyclone is detected.



**Tornado Watches and Warnings** Tornado watches alert the public to the possibility of tornadoes over a specified area for a particular time interval. Watches serve to fine-tune forecast areas already identified in severe weather outlooks. A typical watch covers an area of about 65,000 square kilometers (25,000 square miles) for a 4- to 6-hour period. A tornado watch is an important part of the tornado alert system because it sets in motion the procedures necessary to deal adequately with detection, tracking, warning, and response. Watches are generally reserved for organized severe weather events where the tornado threat will affect at least 26,000 square kilometers (10,000 square miles) and/or persist for at least 3 hours. Watches typically are not issued when the threat is thought to be isolated and/or short-lived.

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

If the direction and the approximate speed of the storm are known, an estimate of its most probable path can be made. Because tornadoes often move erratically, the warning area is fan-shaped downwind from the point where the tornado has been spotted. Improved forecasts and advances

in technology have contributed to a significant decline in tornado deaths over the past 50 years.

**Doppler Radar** Many of the difficulties that once limited the accuracy of tornado warnings have been reduced or eliminated by an advancement in radar technology called **Doppler radar**. Doppler radar not only performs the same tasks as conventional radar but also has the ability to detect motion directly (FIGURE 19.26). Doppler radar can detect the initial formation and subsequent development

of a mesocyclone, the intense rotating wind system in the lower part of a thunderstorm that frequently precedes tornado development. Almost all mesocyclones produce damaging hail, severe winds, or tornadoes. Those that produce tornadoes (about 50 percent) can sometimes be distinguished by their stronger wind speeds and their sharper gradients of wind speeds.

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

The benefits of Doppler radar are many. As a research tool, it is not only providing data on the formation of tornadoes but also helping meteorologists gain new insights into thunderstorm development, the structure and dynamics of hurricanes, and air-turbulence hazards that plague aircraft. As a practical tool for tornado detection, Doppler radar has significantly improved our ability to track thunderstorms and issue warnings.

## 19.5 CONCEPT CHECKS

- 1 Why do tornadoes have such high wind speeds?
- 2 What general atmospheric conditions are most conducive to the formation of tornadoes?
- 3 During what months is tornado activity most pronounced in the United States?
- 4 Name the scale commonly used to rate tornado intensity. How is a rating on this scale determined?
- 5 Distinguish between a tornado watch and a tornado warning.

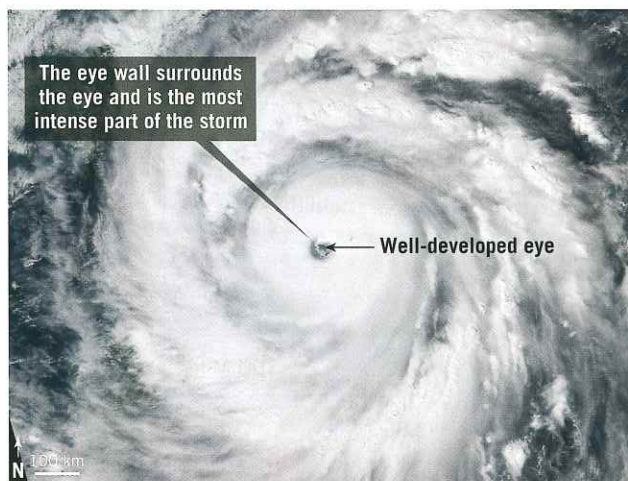
## 19.6 HURRICANES

Identify areas of hurricane formation on a world map and discuss the conditions that promote hurricane formation. List the three broad categories of hurricane destruction.

Most of us view the weather in the tropics with favor. Places such as the islands of the Caribbean are known for their lack of significant day-to-day variations. Warm breezes, steady temperatures, and rains that come as heavy but brief tropical showers are often the rule. It is ironic that these relatively tranquil regions produce some of the most violent storms on Earth.

**Hurricanes** are intense centers of low pressure that form over tropical oceans and are characterized by intense convective (thunderstorm) activity and strong cyclonic circulation (FIGURE 19.27). Sustained winds must equal or exceed 119 kilometers (74 miles) per hour. Unlike midlatitude cyclones, hurricanes lack contrasting air masses and fronts. Rather, the source of energy that produces and maintains hurricane-force winds is the huge quantity of latent heat liberated during the formation of the storm's cumulonimbus towers.

The vast majority of hurricane-related deaths and damage are caused by relatively infrequent, yet powerful, storms. Hurricane Sandy, shown in the chapter-opening photo, devastated coastal areas of New Jersey, New York, and Connecticut and caused billions of dollars in damages in late October 2012. The storm that pounded an unsuspecting Galveston, Texas, in 1900 was not just the deadliest U.S. hurricane ever but the deadliest natural disaster of *any kind* to affect the United States. The deadliest and most costly storm in recent memory occurred in August 2005, when Hurricane Katrina devastated the Gulf Coast of Louisiana, Mississippi, and Alabama and took an estimated 1800 lives. Although hundreds of thousands fled before the storm made landfall, thousands of others were caught by the storm. In addition to the human suffering and tragic loss of life that were left in the wake of Hurricane Katrina, the financial losses caused by the storm are practically incalculable.



**FIGURE 19.27 Super Typhoon Jangmi** In the western Pacific, hurricanes are called typhoons. This storm struck portions of Taiwan, China, and Japan in late September 2008. It was the strongest storm worldwide that year, with sustained winds that reached 270 kilometers (165 miles) per hour. The counterclockwise spiral of the clouds indicates that it is a Northern Hemisphere storm. (NASA)

### Profile of a Hurricane

Most hurricanes form between the latitudes of  $5^{\circ}$  and  $20^{\circ}$  over all the tropical oceans except the South Atlantic and the eastern South Pacific (FIGURE 19.28). The North Pacific has the greatest number of storms, averaging 20 each year. Fortunately for those living in the coastal regions of the southern and eastern United States, fewer than 5 hurricanes, on the average, develop annually in the warm sector of the North Atlantic.

These intense tropical storms are known in various parts of the world by different names. In the western Pacific, they are called *typhoons*, and in the Indian Ocean, including the Bay of Bengal and Arabian Sea, they are simply called *cyclones*. In the following discussion, these storms will be referred to as hurricanes. The term *hurricane* is derived from Huracan, a Carib god of evil.

Although many tropical disturbances develop each year, only a few reach hurricane status. By international

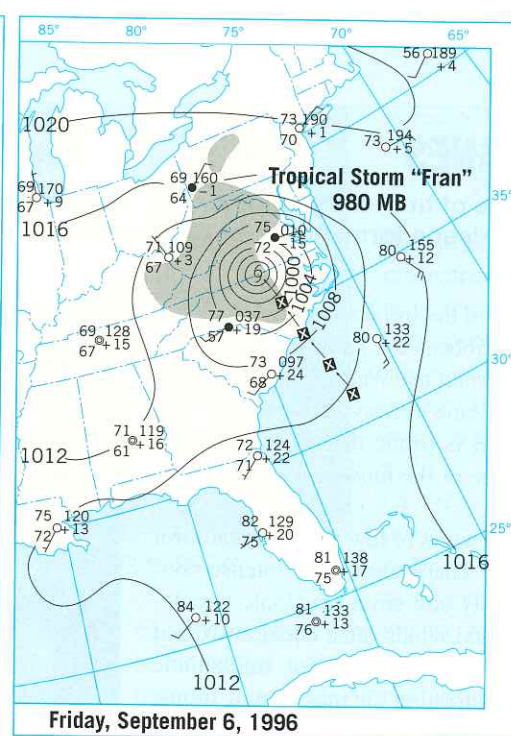
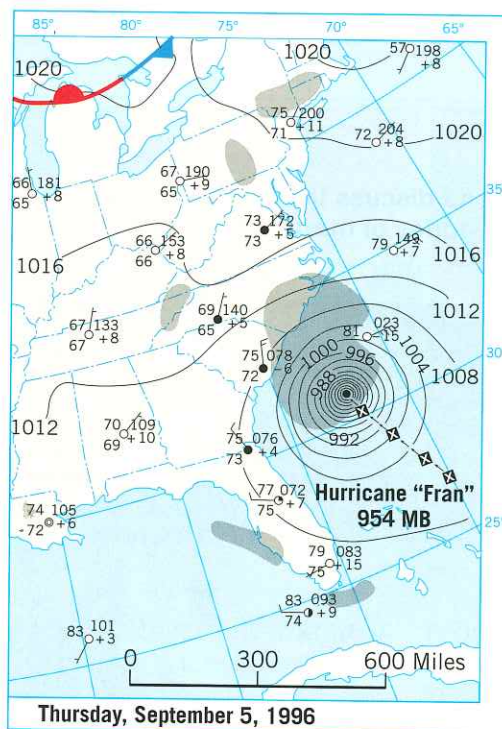


**FIGURE 19.28 Regions Where Hurricanes Form** This world map shows the regions where most hurricanes form as well as their principal months of occurrence and the most common tracks they follow. Hurricanes do not develop within about  $5^{\circ}$  of the equator because the Coriolis effect is too weak. Because warm surface ocean temperatures are necessary for hurricane formation, they seldom form poleward of  $20^{\circ}$  latitude nor over the cool waters of the South Atlantic and the eastern South Pacific.

### FIGURE 19.29 Hurricane

These weather maps show Hurricane Fran at 7:00 AM EST on two successive days, September 5 and 6, 1996.

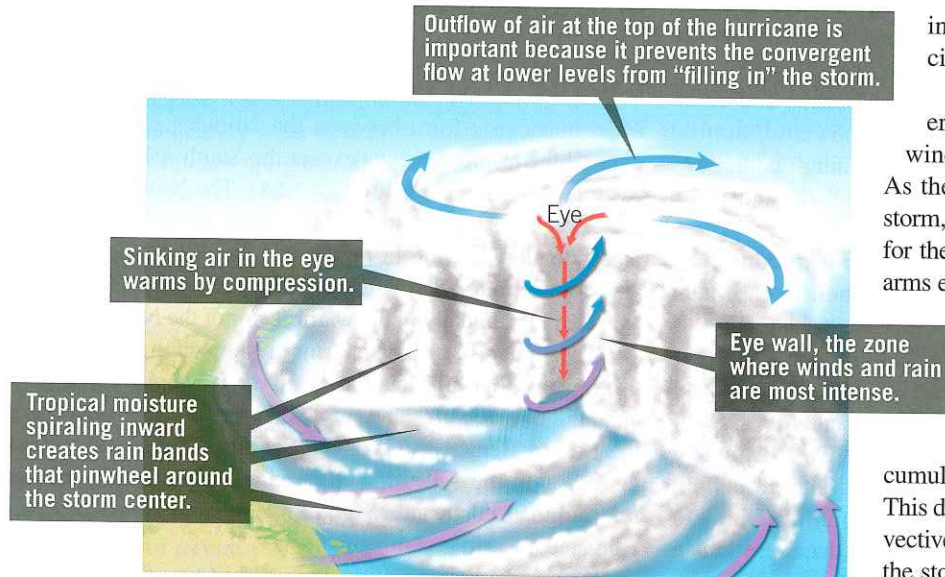
On September 5, winds reached 190 kilometers (118 miles) per hour. As the storm moved inland, heavy rains caused flash floods, killed people, and caused more than \$3 billion in damages. Station information and wind speed off the Gulf and Atlantic coasts is from data buoys, which are remote sensing instrument packages. Small boxes extending east from the storm's center show the position of the storm at 6-hour intervals.



agreement, a hurricane has wind speeds in excess of 119 kilometers (74 miles) per hour and a rotary circulation. Mature hurricanes average 600 kilometers (375 miles) across, although they can range in diameter from 100 kilometers (60 miles) up to about 1500 kilometers (930 miles). From the outer edge to the center, the barometric pressure has on occasion dropped 60 millibars, from 1010 millibars to 950 millibars. The lowest pressures ever recorded

### FIGURE 19.30 Cross-section of a hurricane

Note that the vertical dimension is greatly exaggerated. (After NOAA)



Outflow of air at the top of the hurricane is important because it prevents the convergent flow at lower levels from "filling in" the storm.

Sinking air in the eye warms by compression.

Tropical moisture spiraling inward creates rain bands that pinwheel around the storm center.

Eye wall, the zone where winds and rain are most intense.

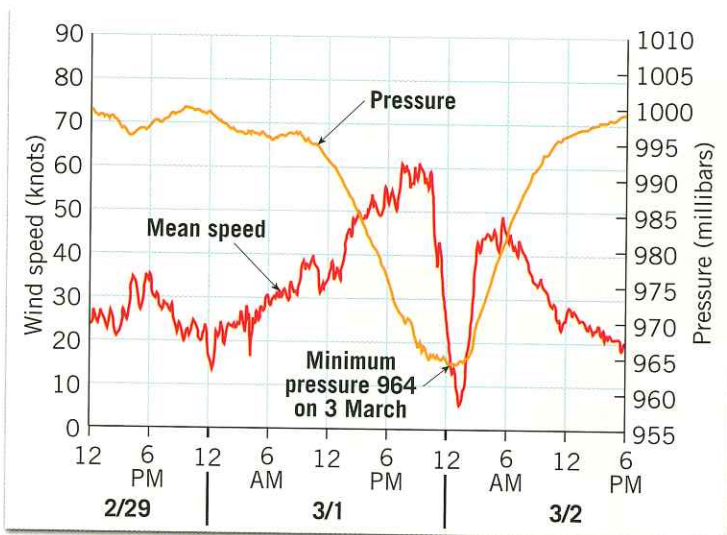
in the Western Hemisphere are associated with these storms.

A steep pressure gradient generates the rapid, inward-spiraling winds of a hurricane (FIGURE 19.29). As the air rushes toward the center of the storm, its velocity increases. This occurs for the same reason that skaters with their arms extended spin faster as they pull their arms in close to their bodies.

As the inward rush of warm, moist surface air approaches the core of the storm, it turns upward and ascends in a ring of cumulonimbus towers (FIGURE 19.30). This doughnut-shaped wall of intense convective activity surrounding the center of the storm is called the **eye wall**. It is here that the greatest wind speeds and heaviest rainfall occur. Surrounding the eye wall are curved bands of clouds that trail away in a spiral fashion. Near the top of the hurricane, the airflow is outward, carrying the rising air away from the storm center, thereby providing room for more inward flow at the surface.

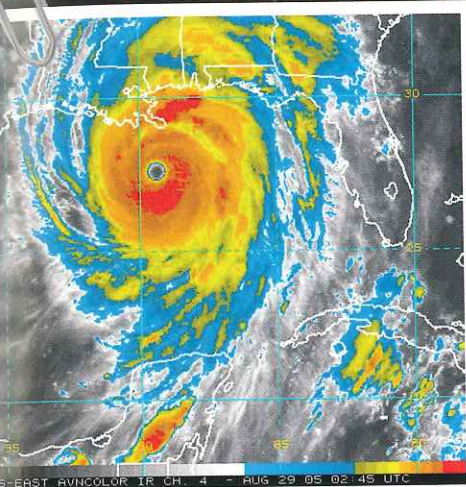
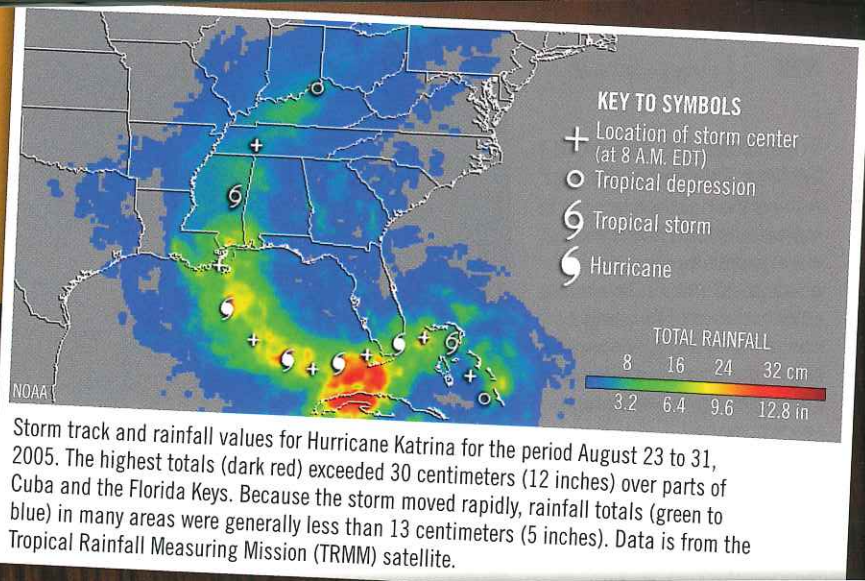
At the very center of the storm is the **eye** of the hurricane. This well-known feature is a zone about 20 kilometers (12.5 miles) in diameter where precipitation ceases and winds subside. It offers a brief but deceptive break from the extreme weather in the enormous curving wall clouds that surround it. The air within the eye gradually descends and heats by compression, making it the warmest part of the storm. Although many people believe that the eye is characterized by clear blue skies, this is usually not the case because the subsidence in the eye is seldom strong enough to produce cloudless conditions. Although the sky appears much brighter in this region, scattered clouds at various levels are common.

Measurements of the pressure and wind speed during the passage of the Monty die Station, in Australia, on February 2, 1996 (Hurricanes led to "names" in this the world.)



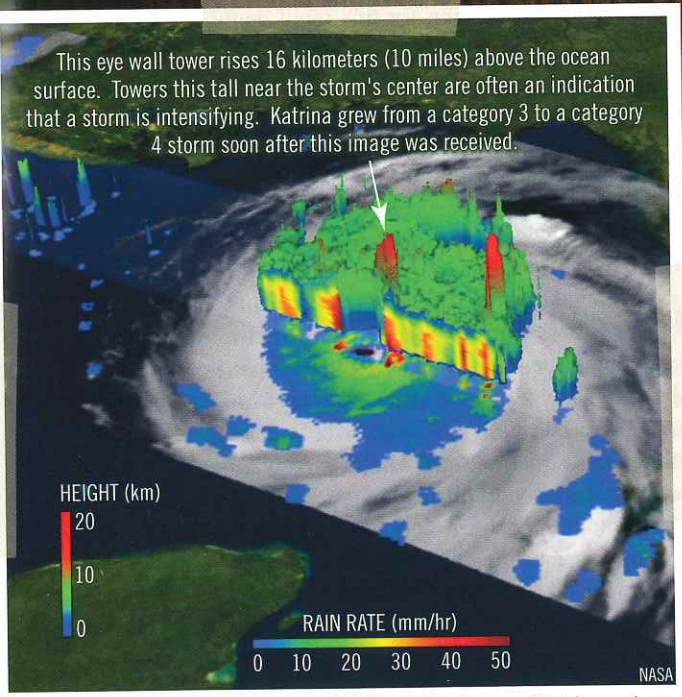
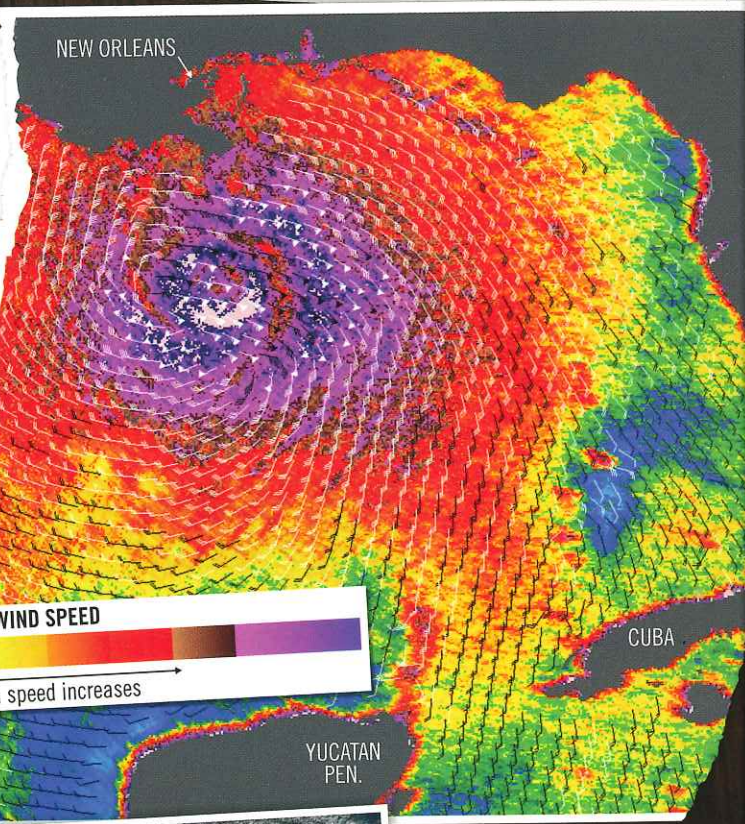
# Hurricane Katrina from Space

Satellites allow us to track the formation, movement, and growth of hurricanes. In addition, their specialized instruments provide data that can be transformed into images that allow scientists to analyze the internal structure and workings of these huge destructive storms.

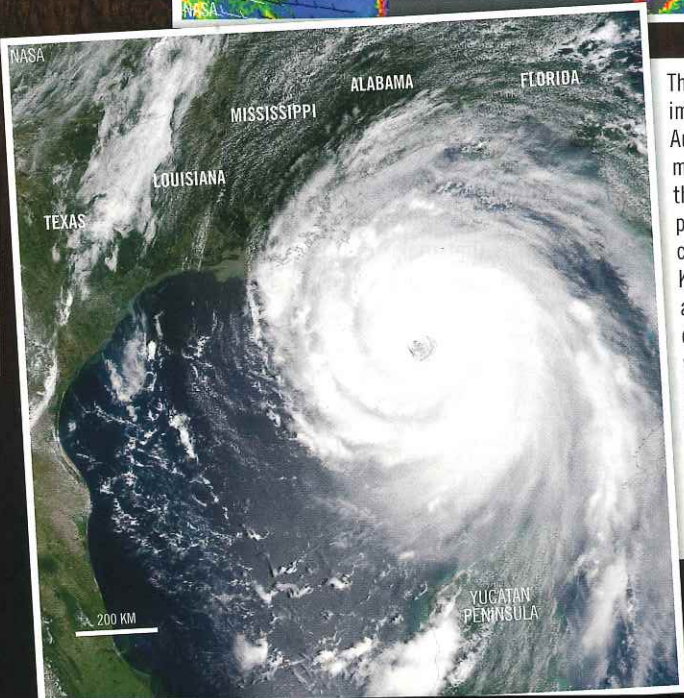


A color-enhanced infrared image from the GOES-East satellite. Infrared wavelengths are invisible but can be detected as heat. Wavelengths of radiation emitted by an object depend on temperature. Longer infrared wavelengths indicate colder temperatures and shorter wavelengths are associated with warmer temperatures. The high tops of towering storm clouds are colder than the tops of clouds that produce less intense weather. The highest (coldest) cloud tops and the most intense storms are easily seen.

This image from NASA's QuikSCAT satellite provides a detailed look at Katrina's surface winds shortly before the storm made landfall. The image depicts relative wind speeds. The strongest winds, shown in shades of purple, circle a well-defined eye. The barbs fly with the wind and show the strong counterclockwise flow of the storm.



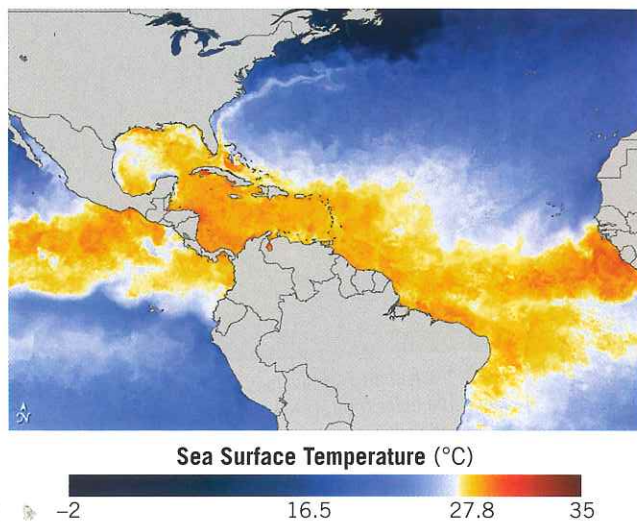
Tropical Rainfall Measuring Mission (TRMM) satellite image of Katrina early on August 28, 2005. The cutaway view of the inner portion of the storm shows cloud height (vertical scale) and rainfall rates (horizontal scale). Two isolated towers (in red) are visible: one in an outer rain band and the other in the eye wall.



This relatively "traditional" image shows Katrina on August 28, 2005 as the massive storm approached the Gulf Coast. After passing over Florida as a category 1 hurricane, Katrina entered the Gulf and intensified to a category 5 storm with winds of 257 kilometers (160 miles) per hour, and even stronger gusts. When Katrina came ashore the next day it was a slightly less vigorous category 4 storm.

### FIGURE 19.31 Sea Surface Temperatures

g the necessary  
dients for a hurricane is  
ocean temperatures  
e 27°C (80°F). This  
oded satellite image  
June 1, 2010, shows  
urface temperatures at  
eginning of hurricane  
on. (NASA)



## Hurricane Formation and Decay

A hurricane is a heat engine that is fueled by the latent heat liberated when huge quantities of water vapor condense. The amount of energy produced by a typical hurricane in just a single day is truly immense. The release of latent heat warms the air and provides buoyancy for its upward flight. The result is to reduce the pressure near the surface, which encourages a more rapid inward flow of air. To get this engine started, a large quantity of warm, moisture-laden air is required, and a continual supply is needed to keep it going.

**Hurricane Formation** Hurricanes develop most often in the late summer, when ocean waters have reached temperatures of 27°C (80°F) or higher and thus are able to provide the necessary heat and moisture to the air (FIGURE 19.31). This ocean-water temperature requirement accounts for the fact that hurricanes do not form over the relatively cool waters of the South Atlantic and the eastern South Pacific. For the same reason, few hurricanes form poleward of 20° latitude. Although water temperatures are sufficiently high, hurricanes do not form within 5° of the equator because the Coriolis effect is too weak to initiate the necessary rotary motion.

Many tropical storms begin as disorganized arrays of clouds and thunderstorms that develop weak pressure gradients but exhibit little or no rotation. Such areas of low-level convergence and lifting are called *tropical disturbances*. Most of the time, these zones of convective activity die out. However, tropical disturbances occasionally grow larger and develop a strong cyclonic rotation.

What happens on occasions when conditions favor hurricane development? As latent heat is released from the clusters of thunderstorms that make up the tropical disturbance, areas within the disturbance get warmer. As a result, air density

lowers and surface pressure drops, creating a region of weak low pressure and cyclonic circulation. As pressure drops at the storm center, the pressure gradient steepens. If you were watching an animated weather map of the storm, you would see the isobars get closer together. In response, surface wind speeds increase and bring additional supplies of moisture to nurture storm growth. The water vapor condenses, releasing latent heat, and the heated air rises. Adiabatic cooling of rising air triggers more condensation and the release of more latent heat, which causes a further increase in buoyancy. And so it goes.

Meanwhile, at the top of the storm, air is diverging. Without this outward flow up top, the inflow at lower levels would soon raise surface pressures (that is, fill in the low) and thwart storm development.

**Other Tropical Storms** Many tropical disturbances occur each year, but only a few develop into full-fledged hurricanes. By international agreement, lesser tropical cyclones are placed in different categories, based on wind strength. When a cyclone's strongest winds do not exceed 61 kilometers (38 miles) per hour, it is called a **tropical depression**. When winds are between 61 and 119 kilometers (38 and 74 miles) per hour, the cyclone is termed a **tropical storm**. It is during this phase that a name is given (Andrew, Katrina, Sandy, etc.). If the tropical storm becomes a hurricane, the name remains the same. Each year, between 80 and 100 tropical storms develop around the world. Of these, usually half or more eventually become hurricanes.

**Hurricane Decay** Hurricanes diminish in intensity whenever they (1) move over ocean waters that cannot supply warm, moist tropical air; (2) move onto land; or (3) reach a location where the large-scale flow aloft is unfavorable. When a hurricane moves onto land, it loses its punch rapidly. The most important reason for this rapid demise is the fact that the storm's source of warm, moist air is cut off. When an adequate supply of water vapor does not exist, condensation and the release of latent heat must diminish. In addition, friction from the increased roughness of the land surface rapidly slows surface wind speeds. This factor causes the winds to move more directly into the center of the low, thus helping to eliminate the large pressure differences.

## Hurricane Destruction

A location only a few hundred kilometers from a hurricane—just 1 day's striking distance away—may experience clear skies and virtually no wind. Prior to the age of weather satellites, this situation made the task of warning people of impending storms very difficult.

The amount of damage caused by a hurricane depends on several factors, including the size and population density of the area affected and the shape of the ocean bottom near the shore. The most significant factor, of course, is the strength of the storm itself. By studying past storms, a scale has been established to rank the relative intensities of hurricanes. As TABLE 19.2 indicates, a *category 5* storm is the worst possible, whereas a *category 1* hurricane is least severe.

TABLE 19.2 Saffir–Simpson Hurricane Scale

Category	Central Pressure (millibars)	Winds (km/hr)	Storm Surge (meters)	Damage
1	980	119–153	1.2–1.5	Minimal
2	965–979	154–177	1.6–2.4	Moderate
3	945–964	178–209	2.5–3.6	Extensive
4	920–944	210–250	3.7–5.4	Extreme
5	<920	>250	>5.4	Catastrophic



**FIGURE 19.32 Storm Surge Destruction** This is Crystal Beach, Texas, on September 16, 2008, 3 days after Hurricane Ike came ashore. At landfall the storm had sustained winds of 165 kilometers (105 miles) per hour. The extraordinary storm surge caused most of the damage shown here. (Photo by Texas Parks & Wildlife Dept., Earl Nottingham/AP Photo)

During hurricane season, it is common to hear scientists and reporters use the numbers from the **Saffir–Simpson hurricane scale**. When Hurricane Katrina made landfall, sustained winds were 225 kilometers (140 miles) per hour, making it a strong category 4 storm. Storms that fall into category 5 are rare. Damage caused by hurricanes can be divided into three categories: (1) storm surge, (2) wind damage, and (3) heavy rains and inland flooding.

**Storm Surge** The most devastating damage in the coastal zone is usually caused by storm surge (**FIGURE 19.32**). It not only accounts for a large share of coastal property losses but also is responsible for a high percentage of all hurricane-caused deaths. A **storm surge** is a dome of water 65 to 80 kilometers (40 to 50 miles) wide that sweeps across the coast near the point where the eye makes landfall. If all wave activity were smoothed out, the storm surge would be the height of the water above normal tide level. In addition, tremendous wave activity is superimposed on the surge. The worst surges occur in places like the Gulf of Mexico, where the continental shelf is very shallow and gently sloping. In addition, local features such as bays and rivers can cause the surge height to double and increase in speed.

As a hurricane advances toward the coast in the Northern Hemisphere, storm surge is always most intense on the right side of the eye (viewed from the ocean), where winds are blowing *toward* the shore. In addition, on this side of the storm, the forward movement of the hurricane contributes to the storm surge. In **FIGURE 19.33**, assume that a hurricane



**FIGURE 19.33 An Approaching Hurricane** Winds associated with a Northern Hemisphere hurricane that is advancing toward the coast. This hypothetical storm, with peak winds of 175 kilometers (109 miles) per hour, is moving toward the coast at 50 kilometers (31 miles) per hour. On the right side of the advancing storm (as viewed from the ocean), the 175-kilometer-per-hour winds are in the same direction as the movement of the storm (50 kilometers per hour). Therefore, the *net* wind speed on the right side of the storm is 225 kilometers (140 miles) per hour. On the left side of the storm, the hurricane's winds are blowing opposite the direction of storm movement, so the *net* winds of 125 kilometers (78 miles) per hour are away from the coast. Storm surge will be greatest along the part of the coast hit by the right side of the advancing hurricane.

with peak winds of 175 kilometers (109 miles) per hour is moving toward the shore at 50 kilometers (31 miles) per hour. In this case, the net wind speed on the right side of the advancing storm is 225 kilometers (140 miles) per hour. On the left side, the hurricane's winds are blowing opposite the direction of storm movement, so the net winds are *away* from the coast at 125 kilometers (78 miles) per hour. Along the shore facing the left side of the oncoming hurricane, the water level may actually decrease as the storm makes landfall.

**Wind Damage** Destruction caused by wind is perhaps the most obvious of the classes of hurricane damage. Debris such as signs, roofing materials, and small items left outside become dangerous flying missiles in hurricanes. For some structures, the force of the wind is sufficient to cause total ruin. Mobile homes are particularly vulnerable. High-rise buildings are also susceptible to hurricane-force winds. Upper floors are most vulnerable because wind speeds usually increase with height. Recent research suggests that people should stay below the 10th floor but remain above any floors at risk for flooding. In regions with good building codes, wind damage is usually not as catastrophic as storm-surge damage. However, hurricane-force winds affect a much larger area than storm surge and can cause huge economic losses. For example, in 1992 it was largely the winds associated with Hurricane Andrew that produced more than \$25 billion of damage in southern Florida and Louisiana.

A hurricane may produce tornadoes that contribute to the storm's destructive power. Studies have shown that more than half of the hurricanes that make landfall produce at least one tornado. In 2004 the number of tornadoes associated with tropical storms and hurricanes was extraordinary. Tropical Storm Bonnie and five landfalling hurricanes—Charley, Frances, Gaston, Ivan, and Jeanne—produced nearly 300 tornadoes that affected the southeastern and mid-Atlantic states.

**Heavy Rains and Inland Flooding** The torrential rains that accompany most hurricanes contribute to a third significant threat: flooding. Whereas the effects of storm surge and strong winds are concentrated in coastal areas, heavy rains may affect places hundreds of kilometers from the coast for up to several days after the storm has lost its hurricane-force winds.

In September 1999, Hurricane Floyd brought flooding rains, high winds, and rough seas to a large portion of the Atlantic seaboard. More than 2.5 million people evacuated their homes from Florida north to the Carolinas and beyond. It was the largest peacetime evacuation in U.S. history up to that time. Torrential rains falling on already saturated ground created devastating inland flooding. Altogether Floyd dumped more than 48 centimeters (19 inches) of rain on Wilmington, North Carolina, 33.98 centimeters (13.38 inches) in a single 24-hour span.

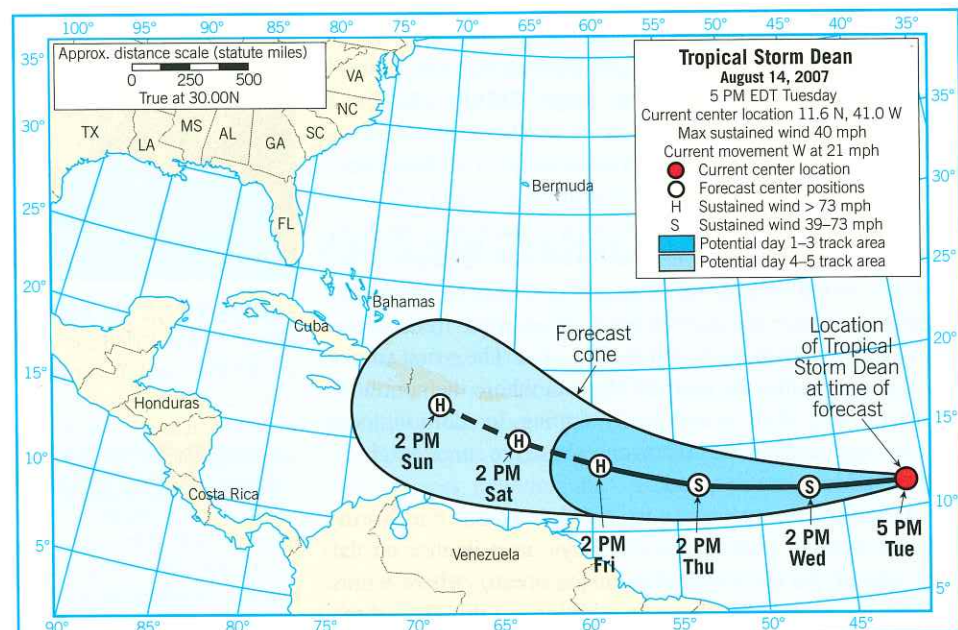
## Tracking Hurricanes

Today we have the benefit of numerous observational tools for tracking tropical storms and hurricanes. Using input from satellites, aircraft reconnaissance, coastal radar, and remote data buoys in conjunction with sophisticated computer models, meteorologists monitor and forecast storm movements and intensity. The goal is to issue timely watches and warnings.

An important part of this process is the *track forecast*—the predicted path of the storm. The track forecast is probably the most basic information because accurate prediction of other storm characteristics (winds and rainfall) is of little value if there is significant uncertainty about where the storm is going. Accurate track forecasts are important because they can lead to timely evacuations from the surge zone, where the greatest number of deaths usually occur. Fortunately, track forecasts have been steadily improving. During the span

### FIGURE 19.34 Five-Day Track Forecast for Tropical Storm Dean, Issued at 5 P.M. EDT, Tuesday, August 14,

When a hurricane track forecast is issued by the National Hurricane Center, it is termed a *forecast cone*. The cone represents the probable track of the center of the storm and is defined by enclosing the area swept out by a set of circles along the forecast track (at 12 hours, 24 hours, 36 hours, etc.). The diameter of each circle gets larger with time. Based on statistics from 1950 to 2007, the entire track of an Atlantic tropical cyclone can be expected to remain entirely within the cone roughly 60 to 70 percent of the time. (National Weather Service/National Hurricane Center)



2001 to 2005, forecast errors were roughly half of what they were in 1990. During the very active 2004 and 2005 Atlantic hurricane seasons, 12- to 72-hour track forecast accuracy was at or near record levels. Consequently, the length of official track forecasts issued by the National Hurricane Center was extended from 3 days to 5 days (FIGURE 19.34). Current 5-day track forecasts are now as accurate as 3-day forecasts were 15 years ago.

Despite improvements in accuracy, forecast uncertainty still requires that hurricane warnings be issued for relatively large coastal areas. During the span 2000 to 2005, the average length of coastline under a hurricane warning in the United States was 510 kilometers (316 miles). This represents a significant improvement over the preceding decade, when the average was 730 kilometers (452 miles). Nevertheless, only about one-quarter of an average warning area experiences hurricane conditions.

## 19.6 CONCEPT CHECKS

- 1 Define *hurricane*. What other names are used for this storm?
- 2 In what latitude zone do hurricanes develop?
- 3 Distinguish between the eye and the eye wall of a hurricane. How do conditions differ in these zones?
- 4 What is the source of energy that drives a hurricane?
- 5 Why do hurricanes *not* form near the equator? Explain the lack of hurricanes in the South Atlantic and eastern South Pacific.
- 6 When do most hurricanes in the North Atlantic and Caribbean occur? Why are these months favored?
- 7 Why does the intensity of a hurricane diminish rapidly when it moves over land?
- 8 What are the three broad categories of hurricane damage?

# 19 CONCEPTS IN REVIEW

## Weather Patterns and Severe Storms

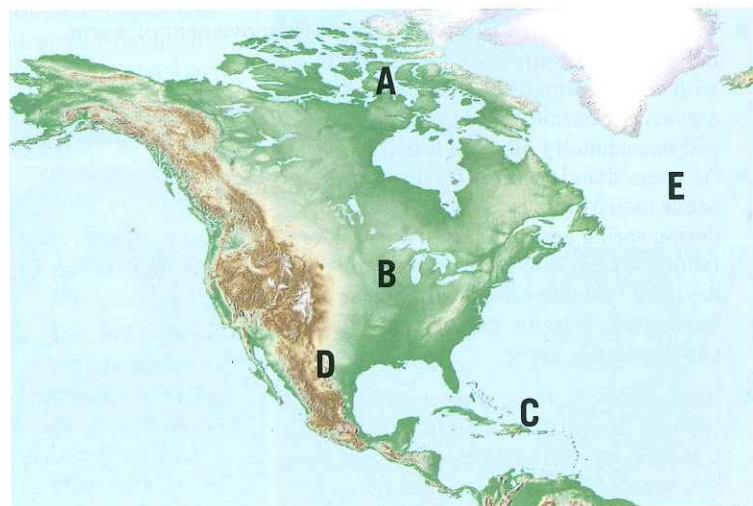
### 19.1 AIR MASSES

Discuss air masses, their classification, and associated weather.

**KEY TERMS:** air mass, air-mass weather, source region, polar (P) air mass, arctic (A) air mass, tropical (T) air mass, continental (c) air mass, maritime (m) air mass, lake-effect snow, nor'easter

- An *air mass* is a large body of air, usually 1600 kilometers (1000 miles) or more across, that is characterized by a sameness of temperature and moisture at any given altitude. When this air moves out of its region of origin, called the source region, it carries these temperatures and moisture conditions elsewhere, perhaps eventually affecting a large portion of a continent.
- Air masses are classified according to the nature of the surface in the source region and the latitude of the source region. Continental (c) designates an air mass of land origin, with the air likely to be dry; a maritime (m) air mass originates over water and, therefore, will be relatively humid. Polar (P) and arctic (A) air masses originate in high latitudes and are cold. Tropical (T) air masses form in low latitudes and are warm. According to this classification scheme, the four basic types of air masses are continental polar (cP), continental tropical (cT), maritime polar (mP), and maritime tropical (mT).
- Continental polar (cP) and maritime tropical (mT) air masses influence the weather of North America most, especially east of the Rocky Mountains. Maritime tropical air is the source of much, if not most, of the precipitation received in the eastern two-thirds of the United States.

**Q** Identify the source region associated with each letter on this map. One letter is *not* associated with a source region. Which one is it?



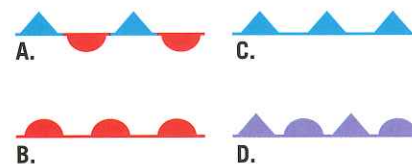
## 19.2 FRONTS

Compare and contrast typical weather associated with a warm front and a cold front. Describe an occluded front and a stationary front.

**KEY TERMS:** front, overrunning, warm front, cold front, stationary front, occluded front

- Fronts are boundary surfaces that separate air masses of different densities, one usually warmer and more humid than the other. As one air mass moves into another, the warmer, less dense air mass is forced aloft in a process called overrunning.
- Along a warm front, a warm air mass overrides a retreating mass of cooler air. As the warm air ascends, it cools adiabatically to produce clouds and, frequently, light to moderate precipitation over a large area.
- A cold front forms where cold air is actively advancing into a region occupied by warmer air. Cold fronts are about twice as steep as and move more rapidly than warm fronts. Because of these two differences, precipitation along a cold front is generally more intense and of shorter duration than precipitation associated with a warm front.

**Q** Identify each of these symbols used to designate fronts. On which side of each symbol are the warm air and the cool air?



## 19.3 MIDLATITUDE CYCLONES

Summarize the weather associated with the passage of a mature midlatitude cyclone. Describe how airflow aloft is related to cyclones and anticyclones at the surface.

**KEY TERMS:** midlatitude (middle-latitude) cyclone

- The primary weather producers in the middle latitudes are large centers of low pressure that generally travel from west to east, called midlatitude cyclones. These bearers of stormy weather, which last from a few days to a week, have a counterclockwise circulation

pattern in the Northern Hemisphere, with an inward flow of air toward their centers.

- Most midlatitude cyclones have a cold front and frequently a warm front extending from the central area of low pressure. Convergence and forceful lifting along the fronts initiate cloud development and frequently cause precipitation. The particular weather experienced by an area depends on the path of the cyclone.
- Guided by west-to-east-moving jet streams, cyclones generally move eastward across the United States. Airflow aloft (divergence and convergence) plays an important role in maintaining cyclonic and anticyclonic circulation. In cyclones, divergence aloft supports the inward flow at the surface.

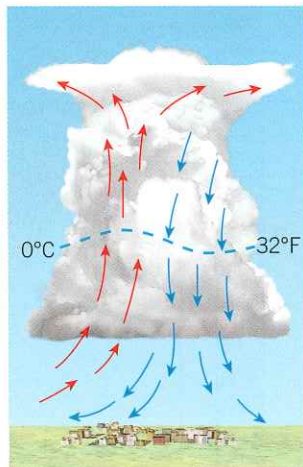
## 19.4 THUNDERSTORMS

List the basic requirements for thunderstorm formation and locate places on a map that exhibit frequent thunderstorm activity. Describe the stages in the development of a thunderstorm.

**KEY TERM:** thunderstorm

- Thunderstorms are caused by the upward movement of warm, moist, unstable air. They are associated with cumulonimbus clouds that generate heavy rainfall, lightning, thunder, and occasionally hail and tornadoes.
- Air mass thunderstorms frequently occur in maritime tropical (mT) air during spring and summer in the middle latitudes. Generally, three stages are involved in the development of these storms: the cumulus stage, mature stage, and dissipating stage.

**Q** Which stage in the development of a thunderstorm is shown in this sketch? Describe what is occurring. Is there a stage that follows this one? If so, describe what occurs during that stage.



## 19.5 TORNADOES

Summarize the atmospheric conditions and locations that are favorable to the formation of tornadoes. Discuss tornado destruction and tornado forecasting.

**KEY TERMS:** tornado, mesocyclone, Enhanced Fujita intensity scale (EF-scale), tornado watch, tornado warning, Doppler radar

- A tornado is a violent windstorm that takes the form of a rotating column of air called a vortex that extends downward from a cumulonimbus cloud. Many strong tornadoes are multiple-vortex storms. Because of the tremendous pressure gradient associated with a strong tornado, maximum winds can approach 480 kilometers (300 miles) per hour.
- Tornadoes are most often spawned along the cold front of a midlatitude cyclone or in association with a supercell thunderstorm. Tornadoes also form in association with tropical cyclones (hurricanes). In the United States, April through June is the period of greatest tornado activity, but tornadoes can occur during any month of the year.
- Most tornado damage is caused by the tremendously strong winds. One commonly used guide to tornado intensity is the Enhanced Fujita intensity scale (EF-scale). A rating on the EF-scale is determined by assessing damage produced by the storm.
- Because severe thunderstorms and tornadoes are small and short-lived phenomena, they are among the most difficult weather features to forecast precisely. When weather conditions favor the formation of tornadoes, a tornado watch is issued. The National Weather Service issues a tornado warning when a tornado has been sighted in an area or is indicated by Doppler radar.

## 19.6 HURRICANES

Identify areas of hurricane formation on a world map and discuss the conditions that promote hurricane formation. List the three broad categories of hurricane destruction.

**KEY TERMS:** hurricane, eye wall, eye, tropical depression, tropical storm, Saffir–Simpson hurricane scale, storm surge

- Hurricanes, the greatest storms on Earth, are tropical cyclones with wind speeds in excess of 119 kilometers (74 miles) per hour. These complex tropical disturbances develop over tropical ocean waters and are fueled by the latent heat that is liberated when huge quantities of water vapor condense.
- Hurricanes form most often in late summer, when ocean-surface temperatures reach 27°C (80°F) or higher and thus are able to provide the necessary heat and moisture to the air. Hurricanes diminish in intensity when they move over cool ocean water that cannot supply adequate heat and moisture, move onto land, or reach a location where large-scale flow aloft is unfavorable.
- The Saffir–Simpson scale ranks the relative intensities of hurricanes. A 5 on the scale represents the strongest storm possible, and a 1 indicates the lowest severity. Damage caused by hurricanes is divided into three

categories: (1) storm surge, (2) wind damage, and (3) heavy rains and inland flooding.

- Q** This image taken from the International Space Station shows the inner portion of Hurricane Igor in September 2010. Identify the eye and the eye wall. In which of these zones are winds and rainfall most intense?



NASA

## GIVE IT SOME THOUGHT

1. Refer to Figure 19.4 to answer these questions:
  - a. Thunder Bay and Marquette are both on the shore of Lake Superior, yet Marquette gets much more snow than Thunder Bay. Why is this the case?
  - b. Notice the narrow, north–south zone of relatively heavy snow east of Pittsburgh and Charleston. This region is too far from the Great Lakes to receive lake-effect snowfall. Speculate on a likely reason for the higher snowfalls here. Does your answer explain the shape of this snowy zone?
2. Refer to the accompanying weather map to answer the following questions:
  - a. What is a likely wind direction at each city?
  - b. Identify the likely air mass that is influencing each city.
  - c. Identify the cold front, warm front, and occluded front.
  - d. What is the barometric tendency at city A and city C?
  - e. Which one of the three cities is probably coldest? Which one is probably warmest?

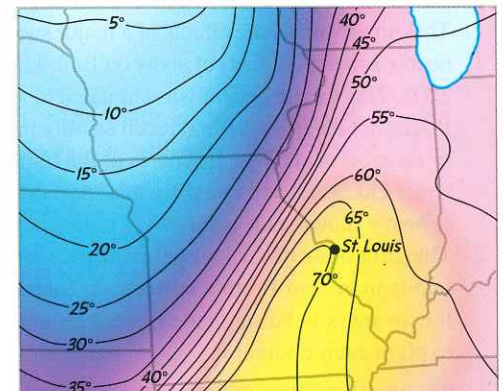


3. Apply your knowledge of fronts to explain the following weather proverb:
 

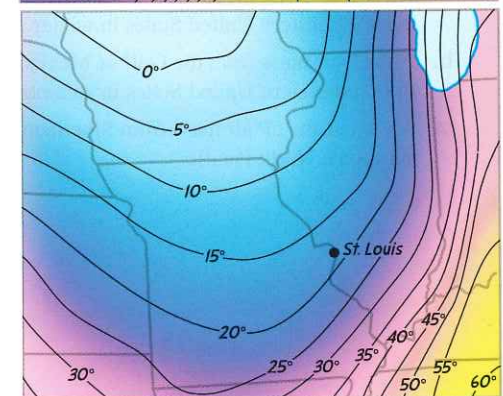
Rain long foretold, long last;  
Short notice, soon past.

4. If you hear that a cyclone is approaching, should you immediately seek shelter? Why or why not?

5. The accompanying diagrams show surface temperatures with isotherms labeled in degrees Fahrenheit for noon and 6 P.M. on January 29, 2008. On this day, a powerful front moved through Missouri and Illinois.



- a. What type of front passed through the Midwest?
- b. Describe how the temperature changed in St. Louis, Missouri, over the 6-hour period.
- c. Describe the likely shift in wind direction in St. Louis during this time span.



- If you were located 400 kilometers ahead of the surface position of a typical warm front that had a slope of 1:200, how high would the frontal surface be above you?
- Assume that after seeing a lightning bolt you heard thunder 10 seconds later. About how far away did the lightning occur?
- The accompanying table lists the number of tornadoes reported in the United States by decade. Propose a reason to explain why the totals for the 1990s and 2000s are so much higher than for the 1950s and 1960s.

Decade	Number of Tornadoes Reported
1950-1959	4796
1960-1969	6613
1970-1979	8579
1980-1989	8196
1990-1999	12,138
2000-2009	12,914

- The number of tornado deaths in the United States in the 2000s was less than 40 percent the number that occurred in the 1950s, even though there was a significant increase in population. Suggest a likely reason for the decline in the death toll.
- A television meteorologist is able to inform viewers about the intensity of an approaching hurricane. However, the meteorologist can report the intensity of a tornado only after it has occurred. Why is this the case?

- Refer to the graph in Figure 19.30. Explain why wind speeds are greatest when the slope of the pressure curve is steepest.
- Assume that it is late September 2016, and that the eye of Hurricane Gaston, a category 5 storm, is projected to follow the path shown on the accompanying map of Texas. Answer the following questions:
  - Name the stages of development that Gaston must have gone through to become a hurricane. At what stage did the storm receive its name?
  - If the storm follows the projected path, will the city of Houston experience Gaston's fastest winds and greatest storm surge? Explain why or why not.
  - What is the greatest threat to life and property if this storm approaches the Dallas-Fort Worth area?



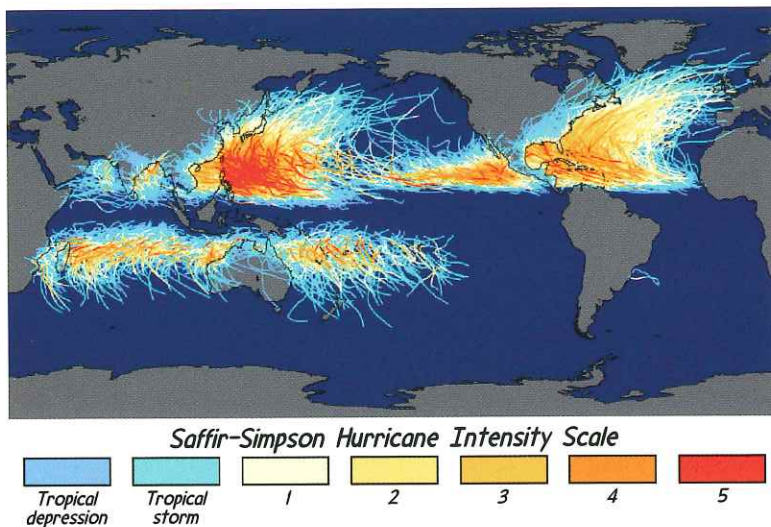
## EXAMINING THE EARTH SYSTEM

- This image shows the effects of a major snowstorm that dropped nearly 2 meters (7 feet) of snow on Buffalo, New York, in December 2001. This weather event was unrelated to a midlatitude cyclone. Places not far from Buffalo received only modest amounts of snow or no snow at all. Which spheres of the Earth system interacted in the Great Lakes region to produce this snowstorm? What term is applied to heavy snows such as this?
- The situations described below involve interactions between the atmosphere and Earth's surface. In each case indicate whether the air mass is being made more stable or more unstable. Briefly explain each choice.
  - An mT air mass moving northward from the Gulf of Mexico over the southeastern United States in winter.
  - An mT air mass from the Gulf of Mexico moving northward over the southeastern United States in summer.
  - A wintertime cP air mass from Siberia moving eastward from Asia across the North Pacific.

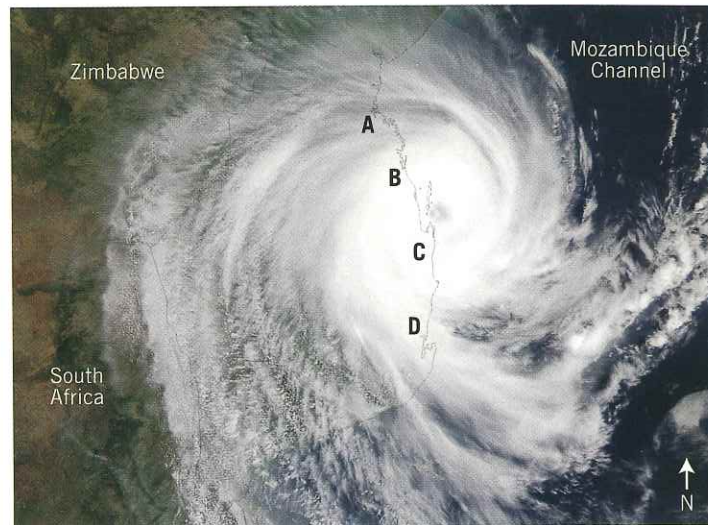


AP Photo/David Duprey

3. This world map shows the tracks and intensities of thousands of hurricanes and other tropical cyclones. It was put together by the National Hurricane Center and the Joint Typhoon Warning Center.
- What area has experienced the greatest number of category 4 and 5 storms?
  - Why do hurricanes not form in the very heart of the tropics, astride the equator?
  - Explain the absence of storms in the South Atlantic and the eastern South Pacific.



4. This satellite image shows Tropical Cyclone Favia as it came ashore along the coast of Mozambique, Africa, on February 22, 2007. This powerful storm was moving from east to west. Portions of the storm had sustained winds of 203 kilometers (126 miles) per hour as it made land-fall. Letters A–D relate to Question c.
- Identify the eye and the eye wall of the cyclone.
  - Based on wind speed, classify the storm using the Saffir–Simpson hurricane scale.
  - Which one of the lettered sites should experience the strongest storm surge? Explain.
  - Describe the possible effects of the storm on coastal lands (geosphere), drainage networks (hydrosphere), and plant and animal life (biosphere).



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