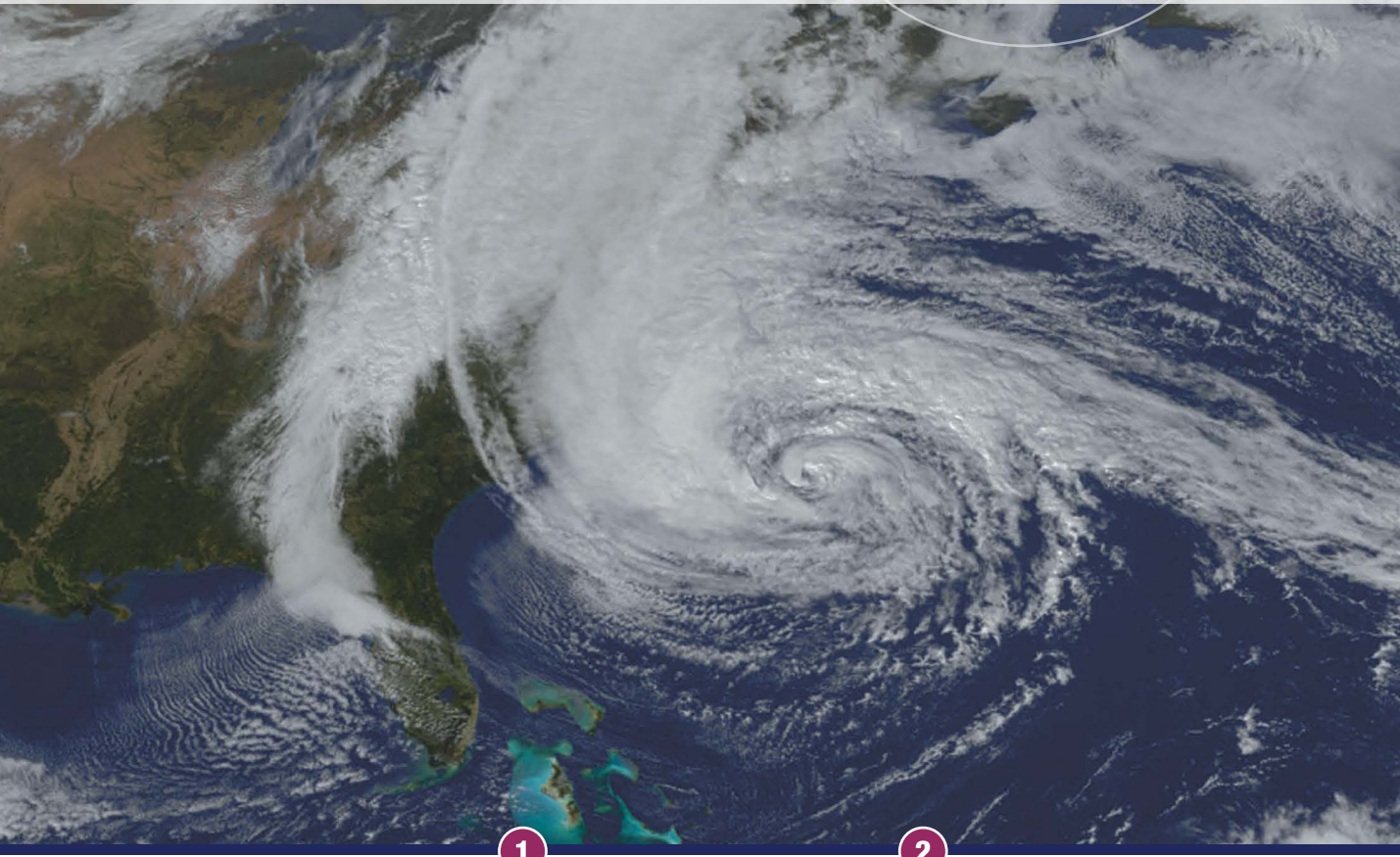
The storm had swelled to a diameter of 1800 km, making Hurricane Sandy the largest Atlantic hurricane on record

10



APPLYING the 5 fundamental concepts Hurricane Sandy

1

Science helps us predict hazards.

Hurricanes are among the most costly natural hazards. Fortunately, our ability to predict the path of these storms and their effects is getting better as hurricane scientists tracking Sandy showed in 2012.

2

Knowing hazard risks can help people make decisions.

Evaluation of the effects of rising sea level, with regards to the hurricane hazard, is just one example of how those living near to sea level along the U.S. eastern seaboard must assess their risk from the negative effects of hurricanes going forward.

Hurricanes and Extratropical Cyclones

Hurricane Sandy

It would take seven days from Sandy's formation in the Caribbean Sea for the hurricane to work its way up the U.S. Eastern Seaboard before finally making landfall just south of New York City, the center of the country's most densely populated metropolitan region. By that time, the storm had swelled to a diameter of 1800 km (~1100 mi.), making Hurricane Sandy the largest Atlantic hurricane on record.[1,2] Due to Sandy's great size, atypical path, and the fact that the storm merged with an arctic cold front before coming onshore, the unofficial name "Superstorm Sandy" was applied by the media.[1] Although the storm no longer had hurricane-force winds upon landfall, at an estimated cost of $71 billion Sandy was the second most expensive storm to ever strike the United States—second only to Hurricane Katrina in 2005.

In just one week, Hurricane Sandy damaged or destroyed more than 200,000 buildings across four countries.[3] In the United States, Sandy triggered intense snowstorms in North Carolina, Maryland,

< Hurricane Sandy Landsat image of Hurricane Sandy on October 28, 2012, headed toward landfall near New York City. By this time Sandy had merged with an arctic cold front causing the storm to swell in size, making Sandy the largest Atlantic hurricane on record. *(NASA)*

LEARNING Objectives

Hurricanes, the most intense form of tropical cyclones, and their midlatitude relative, extra-tropical cyclones, are powerful storm systems that are among the most deadly and costly of natural hazards. Understanding the science behind these storms helps us predict when and where they are likely to occur and allows us to issue warnings to residents. But as our coasts become more densely populated and climate change causes the sea level to rise, these storms will pose a greater threat to shoreline communities.

After reading this chapter, you should be able to:

LO:1 Describe the weather conditions that create, maintain, and dissipate cyclones.

LO:2 Explain why it can be difficult to forecast cyclone behavior.

LO:3 Locate several geographic regions at risk for hurricanes and extratropical cyclones.

LO:4 Give examples of the effects of cyclones in coastal and inland areas.

LO:5 Recognize linkages between cyclones and other natural hazards.

LO:6 List the benefits derived from cyclones.

LO:7 Describe adjustments that can minimize damage and personal injury from coastal cyclones.

LO:8 Propose prudent actions to take for hurricane or extratropical cyclone watches and warnings.

3

Linkages exist between natural hazards.

Flooding and coastal erosion along the eastern seaboard represent just a couple of the natural hazards linked to Hurricane Sandy.

4

Humans can turn disastrous events into catastrophes.

Making landfall just south of New York City along the New Jersey coastline, the most densely populated metropolitan region in the United States, clearly led to Hurricane Sandy's great financial impact.

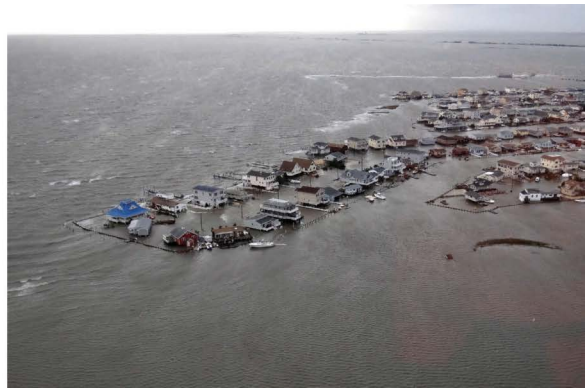
5

Consequences of hazards can be minimized.

When we return to Hurricane Sandy at the end of this chapter it will become clear how both state and federal agencies are involved in minimizing the effects of future hurricane events such as Sandy, through reevaluation of flooding and evacuation maps and other more extreme measures.



(a)



(b)

FIGURE 10.1 The Effects of Sandy on New York City and New Jersey
(a) FDR Drive in Manhattan's Lower East Side, flooded by Hurricane Sandy. *(Beth Carey, Wiki Commons)*
(b) Eroded New Jersey coastline and flooded neighborhood in the town of Tuckerton. *(2012 U.S. Coast Guard/ Getty Images)*

and the Virginias, which caused extensive power outages along the eastern seaboard. New York City and the New Jersey coast were hit particularly hard by the large waves and heavy wind and rain, which caused extensive flooding and coastal erosion (Figure 10.1). By the time the storm dissipated over Pennsylvania on October 31, 2012, Hurricane Sandy had killed more than 130 people in the United States, half of whom lived in New York.[3] For nearly a decade, scientists had warned that New York City was particularly susceptible to rising sea levels, changing tides, extreme weather patterns, and more frequent flooding due to climate change.[4] A warning came in 2011 when Hurricane Irene passed by New York City, flooding low-lying areas and inundating several sewage treatment plants that resulted in raw sewage spills into local waters. Hurricanes Irene and Sandy are responsible for two of the top three worst flooding events to hit New York City since 1900.[4] Rising sea level is likely to cause more extensive and frequent flooding later in the twenty-first century, raising the risk and insurance costs for those who live in low-lying areas adjacent to the coast or along river valleys.

10.1 Introduction to Cyclones

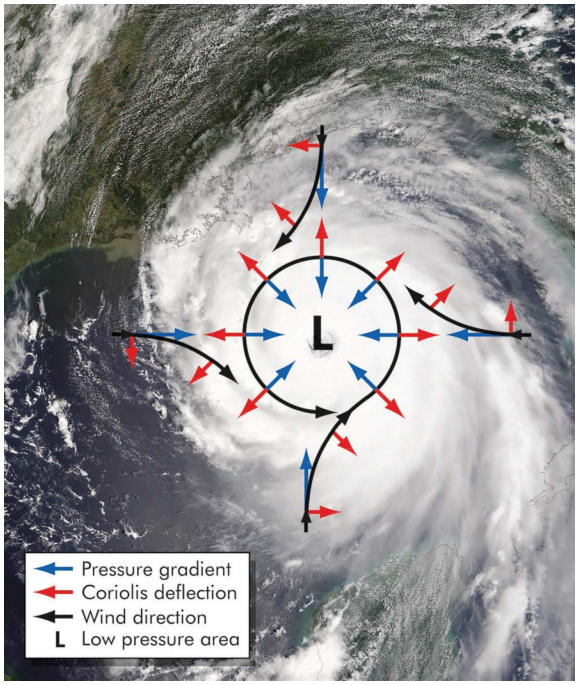
In meteorological terms, Hurricane Sandy was a **cyclone**, an area or center of low atmospheric pressure characterized by rotating winds. Because of the Coriolis effect (see Case Study 9.1: A Closer Look), winds in the Northern Hemisphere are deflected to the right and blow in a counterclockwise rotation around the low-pressure center (Figure 10.2), whereas in the Southern Hemisphere, the Coriolis effect causes winds to rotate clockwise. Cyclones rarely develop within 5° of the equator, where the Coriolis effect is weakest. Cyclones are classified as tropical or extratropical based on their place of origin and the temperature of their center or core region. The modifier *extratropical* means "outside of the tropics." **Tropical cyclones** form over warm tropical or subtropical ocean water, typically between 5° and 20° latitude. Unlike extratropical cyclones, they are not associated with fronts (boundaries between warm and cold air masses) and have warm central cores. In contrast, **extratropical cyclones** develop over land or water in temperate regions, typically between 30° and 70° latitude. These midlatitude cyclones are generally associated with fronts and have cool central cores. Both types of storms are characterized by their **cyclone intensity**, which is indicated by their sustained wind speeds and lowest atmospheric pressure.

Cyclones are associated with the most severe weather in North America. Tropical cyclones include tropical depressions, tropical storms, and hurricanes that can produce high winds, heavy rain, and surges of rising seawater along the U.S. Eastern and Gulf Coasts. Extratropical cyclones can cause strong windstorms, heavy rains, and surges of rising seawater on both the West and East Coasts during warmer months and snowstorms and blizzards during cooler months. Extratropical cyclones are typically less severe than tropical cylones, however, they can produce outbreaks of tornadoes and severe thunderstorms, especially east of the Rocky Mountains in the United States and Canada.

Although the destructive effects of tropical and extratropical cyclones can be similar, the two types of storms differ in their source of energy and their structure. Tropical cyclones derive energy from warm ocean water and the latent heat that is released as rising air condenses to form clouds (latent heat of condensation).

Extratropical cyclones obtain their energy from the horizontal temperature contrast between the air masses on either side of a front (see Chapter 9). In hurricanes, the most intense of the tropical cyclones, warm air rises to form a spiraling pattern of clouds (Figure 10.2). The rising and warming air surrounding the center of a hurricane heats the entire core of the storm. In contrast, most extratropical cyclones are fed by cold air at the surface and another flow of cool, dry air aloft. The resulting storm has a cool core from bottom to top. Tropical cyclones that move over land or cooler water lose their original source of heat—warm ocean water. These storms either dissipate or become extratropical cyclones moving along a front.

The system of classification and naming of cyclones is often debated because it is based on a combination of science, custom, and politics. Scientific classification and description of cyclones have their roots in regional names given to these storms. Naming of individual cyclones is generally limited to the more intense tropical cyclones and is a practice that began in the 1940s.[5]



▲ FIGURE 10.2 Hurricane Rotation
High-pressure air masses outside the storm flow along the pressure gradient (blue arrows) from high pressure toward the central low-pressure zone (L) within the storm. The wind created by the moving air is deflected to the right (black arrows) in the Northern Hemisphere by the Coriolis effect (red arrows). These effects set up a counter counterclockwise rotation around the low pressure region. Because the Coriolis effect acts at right angles to the wind direction, Coriolis deflects winds circling the eye of the storm away from the central low-pressure zone, thereby opposing the pressure gradient and sustaining the storm. *(NASA)*

CLASSIFYING CYCLONES

Although *cyclone* is the general meteorological term applied to a large mass of air circulating around an area of low-pressure, various terms are used to describe these systems in different parts of the world. For example, both forecasters and residents use the term *nor'easter* to describe an extratropical cyclone that tracks northward along the eastern coast of the United States and Canada. Onshore winds from these storms blow from the northeast and can sometimes reach hurricane strength.

The terminology for strong tropical cyclones is especially varied. In the Atlantic and eastern Pacific Oceans, these storms are called **hurricanes** after a Caribbean word for an evil god of winds and destruction.[6] In the Pacific Ocean west of the International Dateline (180° longitude) and north of the equator, the storms are called **typhoons** after a Chinese word for "scary wind" or "wind from four directions." Hurricanes in the Pacific Ocean south of the equator and Indian Ocean are referred to using some variation of *cyclone*, a term coined from the Greek word meaning "coil of a snake."[6] For simplicity, in this book we refer to all of these strong tropical cyclones as hurricanes.

Hurricanes are classified by their wind speed on a damage-potential scale developed by Herbert Saffir, a consulting engineer, and Robert Simpson, a National Weather Service (NWS) meteorologist, in the 1970s. The Saffir–Simpson Hurricane Scale is divided into five categories based on the highest 1-minute average wind speed in the storm and was first used for NWS public advisories in 1975 (Table 10.1).[5] A hurricane's category typically changes as it intensifies or weakens, and all but the weakest hurricanes will have more than one category assigned to them during their lifetime. Meteorologists describe Category 3 through 5 hurricanes as major hurricanes. As a hurricane's wind speed and, thus, its category increase, the atmospheric pressure in the storm's center drops. Category 5 hurricanes generally have a central atmospheric pressure of less than 920 millibars (~27.17 in. of mercury measured in a barometer). The record low pressure for an Atlantic hurricane, 882 millibars (~26.05 in.), was set by Hurricane Wilma in 2005.[7]

NAMING CYCLONES

Only a small percentage of all cyclones are given names, either to identify where they form or to track their movement. Extratropical cyclones, especially those that become

TABLE 10.1 The Saffir–Simpson Hurricane Scale

The Saffir–Simpson Hurricane Scale is a rating of 1 to 5 based on the hurricane's present intensity. This rating is used to give an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. The highest current 1-minute average wind speed is the determining factor in the scale because storm surge values are highly dependent on the slope of the continental shelf where the hurricane makes landfall.

Category	Sustained Winds	Types of Damage Due Hurricane Winds
1	119 to 153 km (~74 to 95 mi.) per hour; storm surge generally 1.2 to 1.5 m (~4 to 5 ft.) above normal	No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs. Also some coastal road flooding and minor pier damage. Hurricanes Irene of 1999 and Katrina of 2005 were Category 1 hurricanes when they made landfall in southern Florida.
2	154 to 177 km (~96 to 110 mi.) per hour; storm surge generally 1.8 to 2.4 m (~6 to 8 ft.) above normal	Some roofing material, door, and window damage of buildings. Considerable damage to shrubbery and trees, with some trees blown down. Considerable damage to mobile homes, poorly constructed signs, and piers. Coastal and low-lying escape routes flood 2 to 4 hours before arrival of the hurricane center. Small craft in unprotected anchorages break moorings. Hurricanes Isabel of 2003 and Frances of 2004 were Category 2 hurricanes when they made landfall in North Carolina and Florida, respectively.
3	178 to 209 km (~111 to 129 mi.) per hour; storm surge generally 2.7 to 3.7 m (~9 to 12 ft.) above normal	Some structural damage to small residences and utility buildings with a minor amount of wall failures. Damage to shrubbery and trees with foliage blown off trees and large trees blown down. Mobile homes and poorly constructed signs are destroyed. Low-lying escape routes are cut off by rising water 3 to 5 hours before arrival of the hurricane center. Flooding near the coast destroys smaller structures, with larger structures damaged by battering of floating debris. Terrain continuously lower than 1.5 m (~5 ft.) above mean sea level may be flooded inland 13 km (~8 mi.) or more. Evacuation of low-lying residences within several blocks of the shoreline may be required. In 2004, Hurricanes Ivan and Jeanne were Category 3 hurricanes when they made landfall along the Alabama and Florida coasts, respectively.
4	210 to 249 km (~130 to 156 mi.) per hour; storm surge generally 4 to 5.5 m (~13 to 18 ft.) above normal	More extensive wall failures with some complete roof structure failures on small residences. Shrubs, trees, and all signs are blown down. Complete destruction of mobile homes. Extensive damage to doors and windows. Low-lying escape routes may be cut off by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of structures near the shore. Terrain lower than 3.1 m (~10 ft.) above sea level may be flooded, requiring massive evacuation of residential areas as far inland as 10 km (~6 mi.). Hurricanes Charley of 2004 and Dennis of 2005 were Category 4 hurricanes when they struck the coasts of Florida and Cuba, respectively.
5	greater than 249 km (~157 mi.) per hour; storm surge generally greater than 5.5 m (~18 ft.) above normal	Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. All shrubs, trees, and signs blown down. Complete destruction of mobile homes. Severe and extensive window and door damage. Low-lying escape routes are cut off by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of all structures located less than 4.6 m (~15 ft.) above sea level and within 458 m (~500 yd.) of the shoreline. Massive evacuation of residential areas on low ground within 8 to 16 km (~5 to 10 mi.) of the shoreline may be required. Three Category 5 hurricanes have made landfall in the United States since records began: the Labor Day Hurricane of 1935, Hurricane Camille of 1969, and Hurricane Andrew of 1992. In 2005, Hurricane Wilma was a Category 5 hurricane at peak intensity in the Gulf of Mexico and is the strongest Atlantic tropical cyclone of record.

Source: Based on Spindler, T., and Beven, J., *Saffir-Simpson Hurricane Scale,* NOAA, 1999. www.nhc.noaa.gov/aboutsshs.shtml. Accessed 12/12/18.

snowstorms, are sometimes named for the geographic area where they form (e.g., Alberta Clipper) (see Figure 9.28). In contrast, all tropical depressions that develop into tropical storms and hurricanes are given individual names by government forecasting centers. These names are established by international agreement through the World Meteorological Organization (WMO). The standardized naming system adopted by the WMO replaced a patchwork of national practices that once included naming hurricanes in honor of the saint on whose holy day the storm came ashore, the military phonetic alphabet, and the names of weather forecasters' girlfriends.

Today, an official name is assigned once the maximum sustained winds of a tropical depression exceed 63 km (~39 mi.) per hour and it becomes a tropical storm. Names are assigned sequentially each year from a previously agreed-upon list for the region in which the storm forms. For example, in the Atlantic Ocean the first three names for 2017 are Arlene, Bret, and Cindy; for 2018 they are Alberto, Beryl, and Chris, and for 2019 Andrea, Barry, and Chantal. Naming tropical storms and hurricanes helps forecasters keep track of multiple storms moving across the ocean at the same time.

In the Atlantic Ocean, the names come from one of six alphabetical lists of alternating men's and women's names. Each list has 21 names derived from English, Spanish, or French. The six lists are used in rotation; therefore, the 2017 list will be used again in 2023 and 2029. Names of especially deadly or damaging hurricanes, such as Sandy, Katrina, Rita, Ivan, and Charley, are retired from the rotating lists, similar to the retirement of the jersey number of a star baseball player.

In 2005, the number of tropical storms and hurricanes in the Atlantic Ocean exceeded the list for that year. This was the first time since lists were established by the NWS National Hurricane Center in 1953 that more than 21 tropical storms and hurricanes formed in the Atlantic Ocean in a single year. Having run through the entire list of names for 2005, NWS forecasters went to their backup plan of assigning letters of the Greek alphabet to the additional storms (Tropical Storm Alpha, Hurricane Beta, etc.).

10.1 CHECK your understanding

1. Describe the basic characteristics of a cyclone. What distinguishes a tropical cyclone from an extratropical cyclone?
2. What is the primary way that hurricanes are classified? Give an example.
3. What is the basic requirement that a storm must meet to be given a name?
4. How many named tropical storms preceded Hurricane Sandy in 2012?

10.2 Cyclone Development and Movement

Tropical and extratropical cyclones differ not only in their development, movement, and characteristics but also in their evolution. Most tropical and extratropical cyclones form, mature, and dissipate independently. Some tropical cyclones, however, transform into extratropical cyclones if they encounter an upper-level low-pressure trough as they weaken over land or over cooler seawater at higher latitudes.

TROPICAL CYCLONES

A *tropical cyclone* is a general term for large thunderstorm complex with winds that circulate inward toward an area of atmospheric low pressure that has formed over warm tropical ocean water. These complexes go by a variety of names depending on their intensity and location. Low-intensity tropical cyclones are called tropical depressions and tropical storms. High-intensity tropical cyclones are known as hurricanes. To be classified as a hurricane, a tropical cyclone must have sustained winds of at least 119 km (~74 mi.) per hour somewhere in the storm (see Table 10.1). Hurricanes require tremendous amounts of heat to develop and generally form only where the sea surface temperature is at least 26°C (~80°F) (Figure 10.3).

Most hurricanes start out as a **tropical disturbance**, a large area of unsettled weather that is typically 200 to 600 km (~120 to 370 mi.) in diameter and has an organized mass of thunderstorms that persists for more than 24 hours. Tropical disturbances form in a variety of ways, including lines of convection similar to squall lines, remnants of cold fronts, or troughs—elongated regions of low pressure (see Chapter 9). Air masses within a tropical disturbance exhibit weak partial rotation caused by the Coriolis effect. Most tropical disturbances in the Atlantic Ocean are related to **easterly waves**. Easterly waves are north–south elongatated troughs that form over west Africa and migrate westward across the Atlantic Ocean with the trade winds at a rate of 15–30 km (~10–20 mi.) per hour. Deflection of air masses around the troughs causes "kinks" in the trade winds and local convergence of air east of the trough axis, which encourages air to rise and clouds to form (Figure 10.4a). West of the trough axis, clear skies dominate as air masses diverge. Consequently, these tropical disturbances can be seen in satellite images as a series of sequential cloud patches moving from east to west across the Atlantic Ocean from Africa (Figure 10.4b).

A tropical disturbance may become a **tropical depression** if winds increase and spiral around the area of disturbed weather to form a low-pressure center. Warm moist air that is drawn into the depression behaves like spinning ice skaters who draw their arms in toward the body, thereby increasing their rate of spin. Once maximum sustained wind speeds increase to 63 km (~39 mi.) per hour, the depression is upgraded to a **tropical storm** and receives a name. Although the winds are not as strong in tropical storms as in hurricanes, their

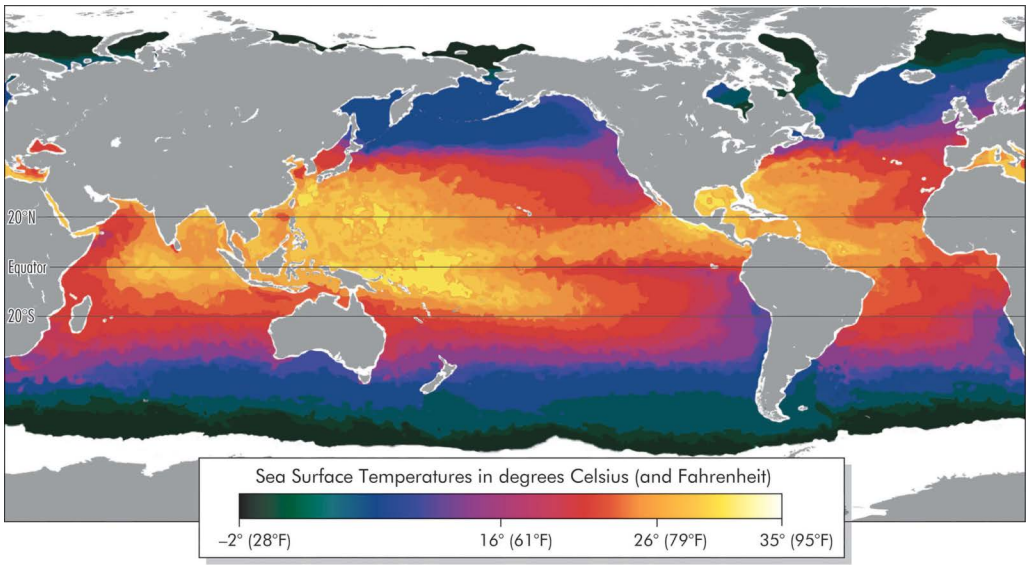
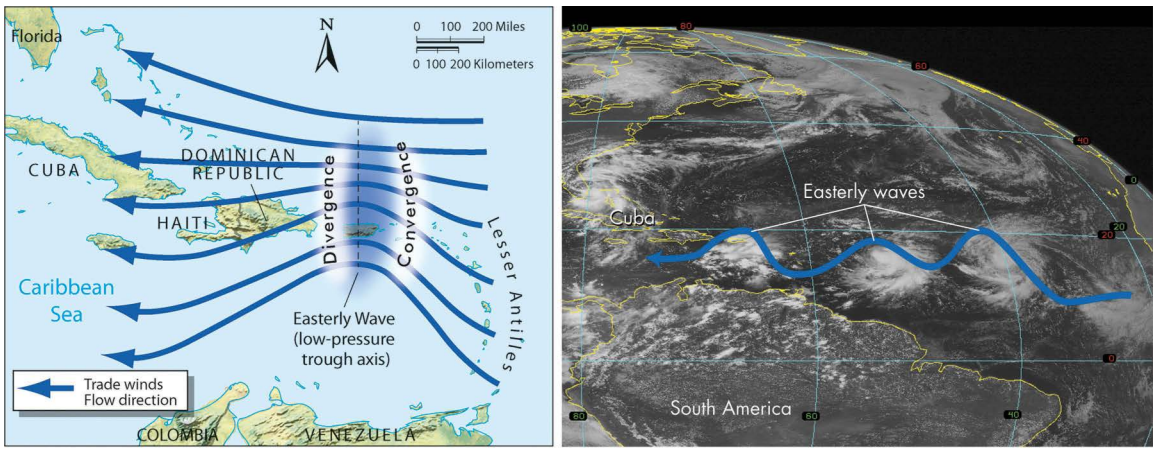


FIGURE 10.3 Ocean Sea Surface Temperatures

Tropical cyclones typically form above oceanic region where sea surface temperatures are at least 26°C (~80°F). These temperature conditions are mostly found within the area of the tropics or about 20° north and south latitude. *(From J. Allen, "Global Sea Surface Temperature," NASA, http://earthobservatory.nasa.gov/IOTD/view.php?id=3513)*



(a) (b)

FIGURE 10.4 Easterly Waves and Formation of Tropical Disturbances

(a) Convergence of trade wind flow paths east of the low pressure trough axis causes air masses to "pile-up" and rise leading to cloud formation and persistent thunderstorms, whereas divergence west of the axis leads to clear skies. *(From NASA)* (b) Doppler radar image of the equatorial Atlantic Ocean showing several tropical disturbances developed within a series of easterly waves between west Africa and the Caribbean Sea. *(NOAA)*

rainfall amounts can be as intense. If the winds continue to increase in speed, a tropical storm may become a hurricane.

Just as not all tropical depressions develop into tropical storms, even fewer tropical storms develop into hurricanes. Several favorable environmental conditions must be present to allow a hurricane to form. First, warm ocean waters of at least 26°C (~79°F) must extend to a depth of 46 m (~150 ft.) or more.[8] Warm surface temperatures alone are not enough for hurricane formation; there has to be an ample depth of warm water to provide energy for the storm. It is the latent heat

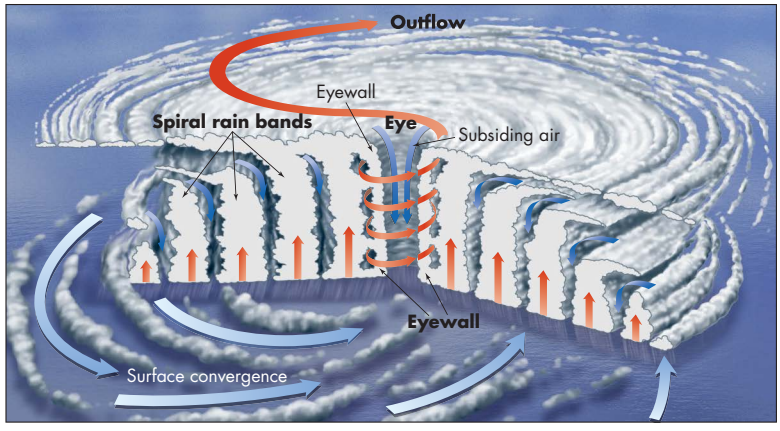
stored within the evaporated water, which will be released as it condenses, that will fuel the storm. Second, the atmosphere must cool fast enough from the surface of the ocean upward to allow moist air to continue to be unstable and convect (uplift), causing condensation. Layers of warm air aloft stop or "cap" hurricane development. Third, there must be little vertical wind shear, that is, a change in wind speed between the ocean surface and the top of the troposphere (see Figure 9.18). Strong winds aloft will prevent hurricane development. Finally, the disturbance must be far enough away from the equator so that the Coriolis effect is strong enough to cause rotation around the region of low pressure.

Once developed, a mature hurricane averages around 500 km (~310 mi.) in diameter and consists of counterclockwise spiraling clouds that swirl toward the storm's center in the northern hemisphere and clockwise in the southern hemisphere.[9] This rotation gives hurricanes their characteristic circular appearance when viewed from satellites (see Figure 10.2). Hurricane-strength winds of 119 km (~74 mi.) per hour or greater are limited to the interior 160 km (~100 mi.) of an average hurricane. The outer area of the storm has gale-force winds, which are greater than 50 km (~30 mi.) per hour. Thus, much of a hurricane actually has winds that are less than hurricane strength.

The clouds that spiral around a hurricane are referred to as **rain bands** and contain numerous thunderstorms (Figure 10.5). Both these thunderstorms and the surface winds generally increase in intensity toward the center of the hurricane. The most intense rainfall and winds occur in the innermost band of clouds, known as the **eyewall**. It is not uncommon for rainfall rates directly beneath the eyewall to reach 250 mm (~10 in.) per hour.[9] A hurricane's eyewall is constantly changing as the storm progresses, and some intense hurricanes develop double eyewalls. In these storms the inner eyewall may gradually dissipate and be replaced with a strengthening outer eyewall. This replacement of one eyewall with another often precedes intensification of the hurricane. Trying to predict changes in hurricane intensity is of great interest to meteorologists responsible for issuing hurricane warnings. Recently, NASA scientists discovered that tall clouds up to 12 km (~7 mi.) high, called *hot towers*, can develop within an eyewall 6 hours before a storm intensifies (Figure 10.6).[10]

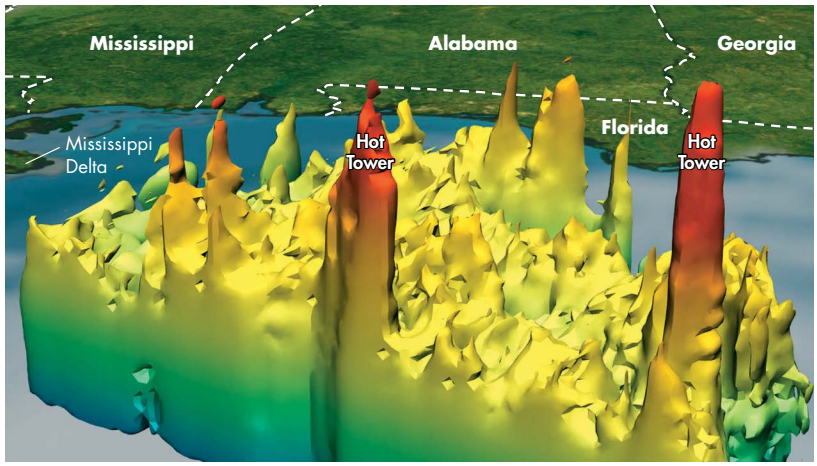
A hurricane's eyewall surrounds a circular area of nearly calm winds and broken clouds known as the **eye**. Eye diameters range from 5 to more than 60 km (3 to more than 37 mi.).[11] Most hurricane eyes are smaller at the surface and widen upward to form a large, amphitheater-like area of nearly cloud-free blue sky surrounded by the white clouds of the eyewall (Figure 10.7). When a hurricane's eye passes directly overhead, there is a "calm before the storm," because the fierce winds of the other side of the eyewall will soon blow from the opposite direction. Birds may become trapped in the eye of a hurricane, and thousands of exhausted birds are sometimes reported roosting as an eye passes overhead.

In a typical hurricane, rising warm and moist air spirals upward around the eyewall. As the air rises, it condenses as clouds and releases large amounts of latent heat. The latent heat of condensation warms the surrounding area, which strengthens convective updrafts and encourages additional warm moist air to rise. This upward spiraling rotation draws air from the eye and causes some of the now dry air aloft to sink back downward in the center of the storm (see Figure 10.5). The upward moving air also flows out of the top of the storm and builds a large cloud platform. Outward flowing air at the top of the storm is concentrated in one or more "exhaust jets."[6] This exhaust system is critical for the continued survival of the



< FIGURE 10.5 Cross-section of a Hurricane

A vertically exaggerated cross-section of clouds and wind patterns in a hurricane. Warm, moist air at the surface spirals toward the center of the storm and rises to form rain bands. Sinking dry air creates spaces between the bands that have fewer clouds. The innermost rain band is the eyewall cloud that surrounds the eye of the storm. Rising warm air from the eyewall either leaves the storm in one of several outflow jets aloft or loses moisture and sinks back into the eye of the storm. Subsiding dry air in the eye warms by compression, giving the storm its characteristic "warm core," with clearer skies and calmer winds in the eye. *(Based on NOAA)*



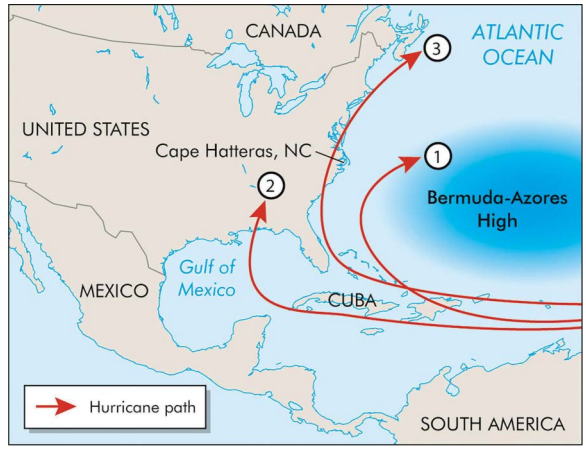
< FIGURE 10.6 "Hot Towers" in Hurricane Katrina

NASA's Tropical Rainfall Measuring Mission (TRMM) satellite spotted a pair of extremely tall thunderstorms in the eyewall and outer rain band of Hurricane Katrina shortly before it intensified to Category 5. Referred to as "hot towers," these clouds were more than 15,000 m (~50,000 ft.) high. Like cylinders in an engine, these towers release huge amounts of heat and contribute to the rising winds in the storm. Detection of hot towers may help predict changes in hurricane intensity. *(NASA/JAXA)*



^ FIGURE 10.7 Stadium-Like Clouds Form a Hurricane's Eyewall

Looking into the eye of Hurricane Katrina, the area of broken clouds in the lower part of the photo mark the eye of the storm where dry air is descending from the top of the troposphere. High winds and rotating clouds in the upper part of the photo compose the eyewall hurricane. Photo taken from a National Oceanic and Atmospheric Administration (NOAA) hurricane hunter aircraft flying through the eye the day before the storm struck the Gulf Coast. Aircraft measurements of a hurricane's wind speed and atmospheric pressure help predict its behavior. *(NOAA)*



^ FIGURE 10.8 Hurricane Paths

Three common hurricanes paths, or tracks. Hurricane tracks in the North Atlantic are controlled by the Coriolis effect, direction and strength of steering atmospheric currents, and the location and strength of the Bermuda-Azores High. While south of the Bermuda-Azores High, hurricanes track westward with the trade winds across the Atlantic before being deflected northward by Coriolis west of the high pressure region. All three paths threaten Caribbean islands; then path 1 can affect Bermuda, path 2 the United States Gulf coast, and path 3 the East Coast of the United States and Atlantic Canada.

hurricane because it allows additional warm, moist air to converge inward in the lower levels of the storm, providing more energy. Outflow of warm air at the top of hurricanes is also a mechanism for the transfer of heat from Earth's tropics to the polar regions.

Movement of a hurricane is controlled by the Coriolis effect, which deflects the storm to the right in the Northern Hemisphere, and by providing steering winds that flow 8 to 11 km (~5 to 7 mi.) above the surface. In the Northern Hemisphere, this means that hurricanes commonly track westward in the trade winds that cross the Atlantic Ocean, before curving northward due to the Coriolis effect (Figure 10.8). Where this northward deflection occurs is strongly influenced by the location and strength of the *Bermuda-Azores High*, a persistent high-pressure anticyclone that remains anchored in the North Atlantic during the summer and early fall (see Case Study 10.1: A Closer Look). Many

North Atlantic Oscillation

10.1 A Closer Look

CASE study

As you have learned from this chapter and Chapter 9, the westerly winds and polar jet stream play a significant role in the development and movement of severe weather including extratropical cyclones (see Applying the Fundamental Concepts). Recall that winds flow from regions of high pressure to regions of low pressure, and due to the Coriolis effect, these winds blow from west to east across the United States and southern Canada toward Europe (Figure 10.1.A). Variations in the location and magnitude of high and low atmospheric pressure regions, therefore, play a significant role in the distribution and severity of weather around the globe. The **North Atlantic Oscillation** (NAO) is a fluctuating atmospheric pressure phenomenon in the North Atlantic Ocean that affects the flow of westerly winds in the midlatitudes primarily during winter months. The NAO index describes atmospheric pressure anomalies between the subtropical Bermuda-Azores High and the subarctic low-pressure center near Iceland (Figure 10.1.A). The NAO index can be either positive (+) or negative (–) depending on deviations from long-term averages.[1]

During positive NAO conditions, higher than average atmospheric pressure in the subtropics and lower than average pressure in the subarctic low persist (Figure 10.1.Aa). The enhanced pressure gradient strengthens the midlatitude westerly winds, including the polar jet stream, which carry winter storms from the North Atlantic Ocean over northern Europe. This leads to a dry and mild winter in southern Europe and a wet and mild winter in northern Europe (Figure 10.1.Aa).

In contrast, negative NAO conditions are characterized by a relatively weak subtropical high-pressure center and a weak subpolar low-pressure center. This

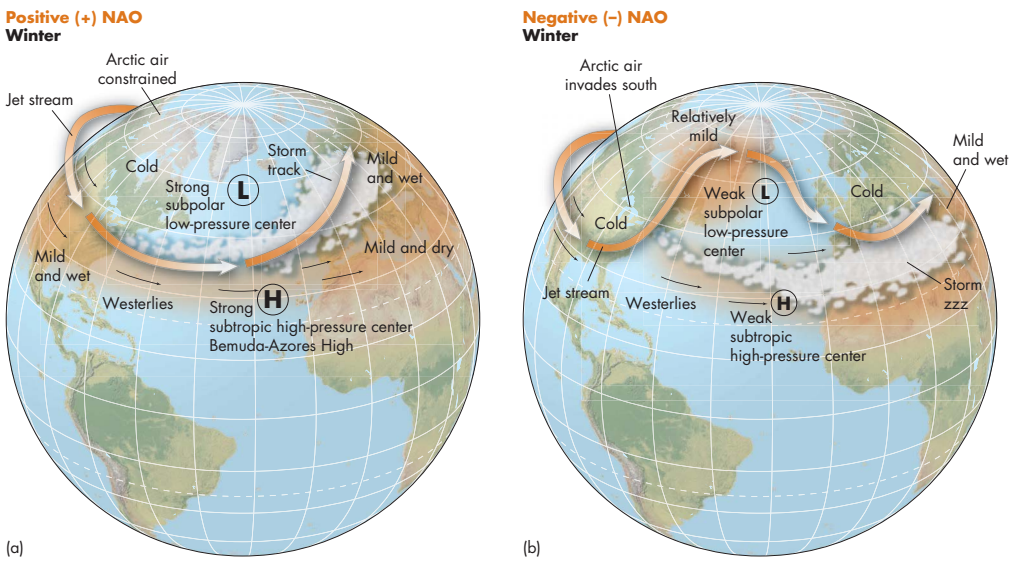


FIGURE 10.1.A North Atlantic Oscillation (NAO)
Generalized (a) positive NAO and (b) negative NAO winter weather patterns. *(Based on "Linking Climate and Weather,"* Scientific America *307(6): 54–55, December 2002)*

atmospheric situation weakens the flow of winds toward the east, causing the paths of the jet stream and the westerly winds to diverge (Figure 10.1.Ab). After leaving eastern North America, the jet stream turns sharply northward flowing over Greenland before heading toward southern Europe, while the westerlies carry the winter storm track directly from the North Atlantic toward the Mediterranean (Figure 10.1.Ab). This brings a wet and mild winter to southern Europe and leads to cold dry conditions to the north. Although the effects of fluctuation in the NAO are less pronounced in North America than in Europe, during negative NAO conditions the northeast and eastern seaboard of North America often experience more frequent snowstorms and cold outbreaks including subfreezing temperatures as far south as Florida (Figure 10.1Ab).

The period of oscillation of the NAO is not constant, but positive conditions appear to be broadly decadal. Although somewhat controversial, some scientists have suggested that long periods of stability of either positive or negative NAO could have a significant effect on global climate and may explain past climate phenomena such as the Medieval Warm Period (A.D. 800–1300) and the Little Ice Age (A.D. 1350–1850) (see Chapter 12).[2]

hurricane paths tend to curve around the west side of the Bermuda-Azores High before turning northeastward upon encountering Northern Hemisphere westerly winds. However, deviations from these paths are common when steering atmospheric currents are weak (see Applying Fundamental Concepts: Hurricane Sandy). Hurricanes have even been known to reverse course and make an entire loop in their path.

A mature hurricane will typically have a forward speed of 19 to 27 km (~12 to 17 mi.) per hour.[12] In most cases, this slow forward speed will mean that a hurricane is a two-day event for communities directly in the path of the storm. Toward the end of a hurricane's life, its forward speed may suddenly increase to 74 to 93 km (~46 to 58 mi.) per hour.[12] This increase in speed happens to many hurricanes that move up the East Coast past Cape Hatteras, toward coastal Canada (see Figure 10.8). A rapid increase in forward speed can be especially dangerous if it results in an early landfall for the hurricane. Once over land or having moved into the cooler waters of the North Atlantic, hurricanes rapidly lose strength and usually dissipate within a few days.

EXTRATROPICAL CYCLONES

Two key ingredients contribute to the formation and movement of an extratropical cyclone—a strong temperature gradient in the air near the surface and wind patterns within the jet stream. Surface temperature gradients are generally strongest along a cold, warm, or stationary front (see Chapter 9). Therefore, most extratropical cyclones develop along fronts.

Large high-pressure ridges and low-pressure troughs in the upper troposphere cause jet streams to bend north or south of their normal path, producing long meanders or waves in their flow. A jet stream may also split in two around isolated high-pressure centers and reunite down flow (Figure 10.9). Extratropical cyclones often develop in an area where jet stream winds curve cyclonically or diverge, such as on the east side of a trough.

Bending or splitting can cause the polar jet stream to dip southward and the subtropical jet stream to flow northeastward into the conterminous United States. The southern branch of a split polar jet stream in the Pacific Ocean brings warm moist air out of the tropics and can be

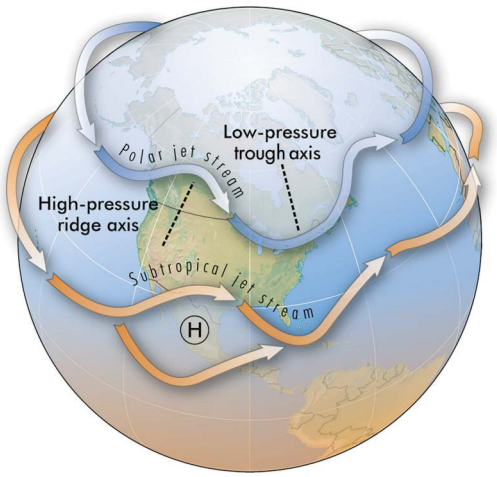
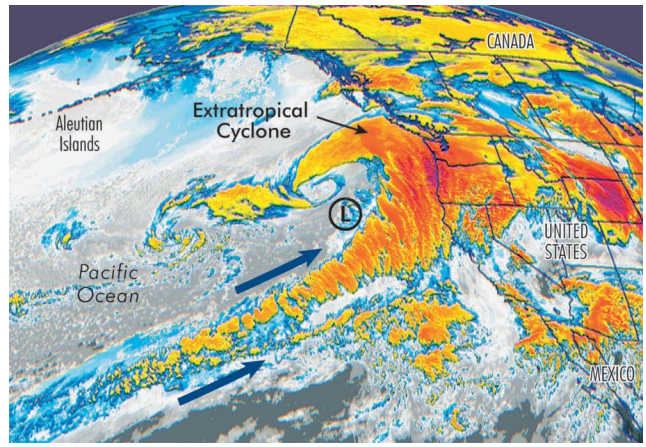
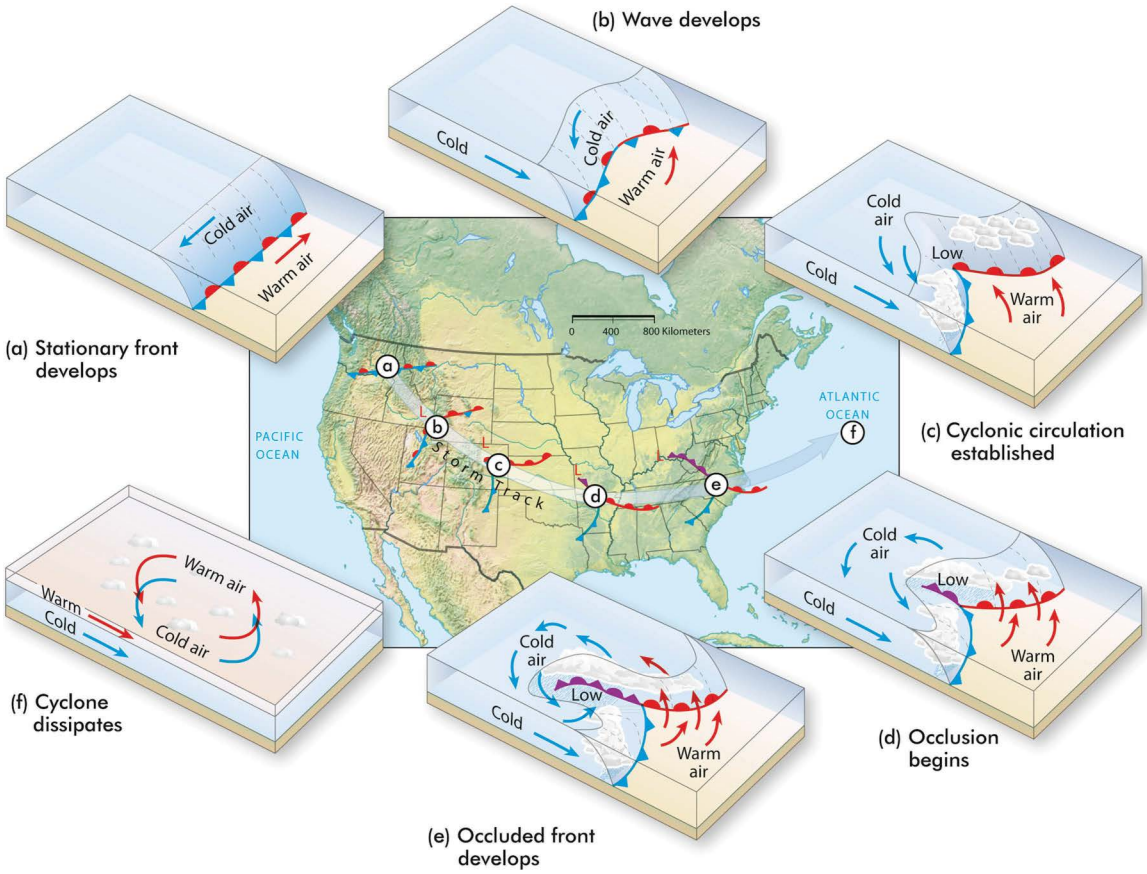


FIGURE 10.9 Bending and Splitting Jet Streams
When jetstreams encounter localized or elongate areas of high or low atmospheric pressure the eastward flow of air tends to bend, dip, and/or split. Such changes in jetsream flow play a fundamental role in the formation of extratropical cylones and the location and path the storm follows. *(Based on E. J. Tarbuck and F. K. Lutgens,* The Atmosphere: An Introduction to Meteorology*, 10th ed. © 2007 Upper Saddle River, NJ: Pearson Prentice Hall)*

➤ FIGURE 10.10 The Pineapple Express Feeding Moisture to West Coast Extratropical Cyclone

In this image, the Pineapple Express, a stream of warm moist air carried along by a southern branch of the polar jet stream, feeds an extratropical cyclone in the Pacific Ocean. Storms following this stream of tropical air hit the West Coast, causing coastal erosion, flooding, and landslides. This color-enhanced infrared image was taken by the NOAA GOES-9 satellite. *(From the National Oceanic and Atmospheric Administration/National Climatic Data Center)*





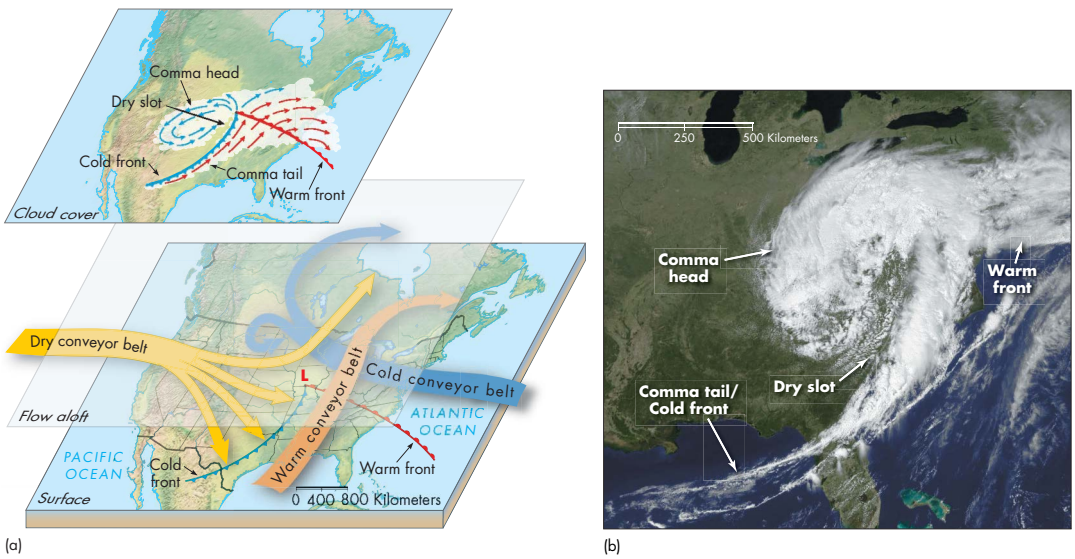
∧ FIGURE 10.11 Development of an Extratropical Cyclone

Stages in the development of an extratropical cyclone: (a) Air masses, moving in opposite directions along a stationary front providing the temperature contrast for cyclone development; (b) a wave forms along the front at a place where upper-level winds diverge, such as a bend in the jet stream; (c) a surface low-pressure center develops as cold air pushes south on the west side and warm air pushes north on the east side of the cyclone; (d) the cold front advances faster than the warm front, catches up with the warm front, and displaces the warm air upward; (e) an occluded front develops with warm air held aloft by cold and cool air masses at the surface; (f) the temperature contrast at the surface disappears, friction slows winds, and atmospheric pressure rises as the cyclone dissipates. *(Based on E. J. Tarbuck and F. K. Lutgens,* The Atmosphere: An Introduction to Meteorology*, 10th ed. © 2007 Upper Saddle River, NJ: Pearson Prentice Hall)*

recognized on infrared satellite images as a band of clouds extending northeastward from the equatorial Pacific Ocean (Figure 10.10). These narrow bands of moist air sometimes contain more water than Earth's largest rivers, which is why meteorologists refer to them as *atmospheric rivers*, or as the "*Pineapple Express*" by West Coast forecasters because of the origin water being near Hawaii. On average, 10 to 15 extratropical cyclones may develop in the eastern Pacific Ocean and are responsible for 20–50 percent of the precipitation delivered to western North American. Between October 2016 and February 2017, "Pineapple Express" fueled storms delivered to California of more than 76 cm (~30 in.) average precipitation (more than twice the annual average) making it the wettest six month period in 122 years of record keeping. Although the higher than average precipitation ended a five-year drought, heavy storm runoff threatened to undermine the tallest dam in the United States, leading to the evacuation of almost 200,000 people living downstream, and damage to California infrastructure estimated to be greater than $1 billion. On the Atlantic Seaboard, extratropical cyclones called nor'easters often form when bends of the polar and subtropical jet streams begin to merge off the southeastern coast of the United States.

Extratropical cyclones can intensify when they cross areas with strong low-level temperature gradients. For example, extratropical cyclones that hit the West Coast often weaken as they cross the Rocky Mountains and then deepen and strengthen as they leave the mountains and enter the Great Plains.

Because extratropical cyclones develop in the midlatitudes within the band of westerly winds, unlike tropical cyclones that form within the equatorial easterly winds, these storms can be seen developing in the west and tracking eastward across the United States. Most extratropical cyclones start as a low-pressure center along a frontal boundary, with a cold front developing on the southwest side of the cyclone and a warm front on the east (Figure 10.11). In the case of a polar front, cold polar easterly winds are to the north of the front and warm moist westerly winds are to the south. A conveyor belt-like flow of cold air circulates counterclockwise around the cyclone, wedging beneath the warm air to the southeast. Lighter, warm moist air rises in another conveyor belt-like flow on the southeast side of the cyclone, overriding cold air at the surface and creating a comma-like pattern of clouds (Figure 10.12a). A third conveyor belt moving dry air



▲ FIGURE 10.12 Structure of an Extratropical Cyclone

(a) Once an extratropical cyclone develops, it is fed by three "conveyor belts" of air: Warm, generally moist air feeds the storm from the south and rises up over a stream of cold air coming from the east, and dry air aloft feeds the storm from the west, sinking behind the advancing cold front at the surface. *(Based on E. J. Tarbuck and F. K. Lutgens,* The Atmosphere: An Introduction to Meteorology, *10th ed. © 2007 Upper Saddle River, NJ: Pearson Prentice Hall)* (b) This NASA Geostationary Observational Environmental Satellite (GOES) image shows the comma-shaped cloud pattern of a mature extratropical cyclone moving across the eastern United States. Clouds in the comma head are formed by counterclockwise circulation of cold air around the cyclone. Sinking dry air behind a cold front forms the dry slot. The comma tail is created by thunderstorms and other clouds ahead of the cold front. *(NOAA)*

aloft often feeds the cyclone and the dry air sinks behind the cold front, forming a *dry slot* that is sometimes visible on satellite images (Figure 10.12b). As the cyclone matures, the cold front wraps around the cyclone and merges with the warm front to become an *occluded front* with warm air trapped aloft (see Chapter 9 and Figure 10.11d). At first, the storm intensifies; then, as the cold air completely displaces the warm air on all sides of the cyclone, the pressure gradient weakens and the storm dissipates within a day or two.

Predicting the birth, development, direction of movement, and death of extratropical cyclones is a challenge for forecasters. If conditions are right, the development and strengthening of an extratropical cyclone can be rapid, occurring within 12 to 24 hours. Once formed, an extratropical cyclone's movement is typically steered by winds in the middle of the troposphere at around the 5600 m (~3.5 mi.) level.[9] The forward movement of an extratropical cyclone is generally at half the speed of the steering winds.[11]

10.2 CHECK your understanding

1. What are easterly waves, and how are they related to tropical cyclones?
2. What are the four requirements for a tropical disturbance to become a hurricane?
3. What factors control the path a hurricane takes in the Atlantic Ocean?
4. Explain the atmospheric factors needed for the formation of an extratropical cyclone.

10.2 CASE study

Hurricane Katrina: "The most anticipated natural disaster in American history"

Unlike the massive earthquake that struck Japan in 2011, which took many scientists and the world by surprise, the flooding of New Orleans by a major hurricane was widely predicted for decades in scientific publications, including the first edition of this book, and in magazine and newspaper articles. A Pulitzer Prize-winning series about the future catastrophe was published in New Orleans's major newspaper, the *Times-Picayune*, in 2002. Overall, as David Brooks of the *New York Times* later wrote, "Katrina was the most anticipated natural disaster in American history."[13]

Why was this disaster so widely anticipated? First, the southeastern U.S. coast has a high incidence of hurricanes; in the past 50 years, hurricanes have flooded New Orleans and devastated coastal Mississippi, Alabama, and Louisiana on more than one occasion. Second, 95 percent of New Orleans has subsided an average of 1.5 m (~5 ft.) below sea level and the city relies on a patchwork of levees, flood walls, and pumps for protection.[14] Parts of the flood protection and drainage system are more than 100 years old. Finally, in the past century, coastal Louisiana has lost wetlands and barrier islands that help mitigate the effects of hurricane storm surges.

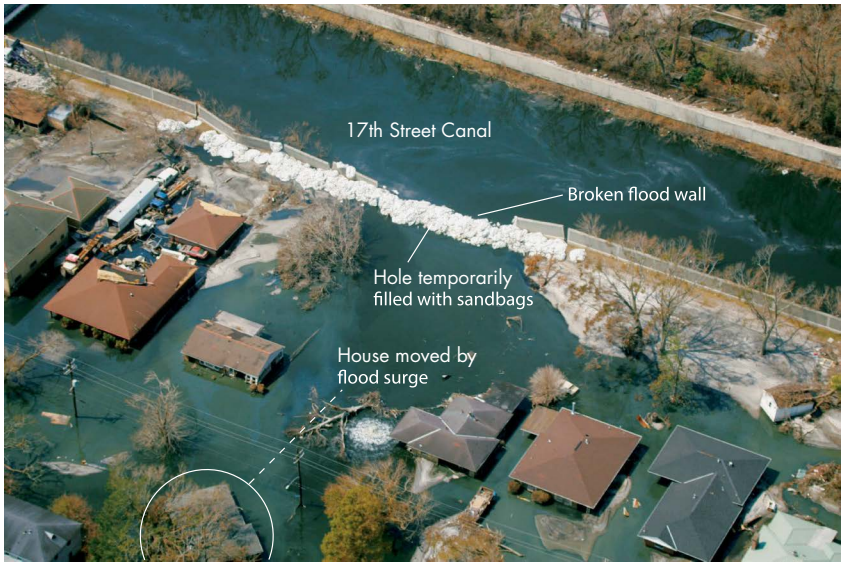
Contrary to initial reports indicating that Katrina was a Category 4 storm when it hit New Orleans, it was actually a Category 3 hurricane when it made its first landfall on the Mississippi Delta about 80 km (~50 mi.) southeast of New Orleans.[15] The storm's intensity then dropped, and most of the city experienced the effects of a Category 1 or weak Category 2 hurricane. Both Katrina's drop in intensity and its path were fortunate for New Orleans. Less than 24 hours before landfall, Hurricane Katrina had been a Category 5 storm, one of the most powerful ever observed in the Gulf of Mexico.[15]

From a hazard-warning standpoint, the National Weather Service did an excellent job of forecasting Katrina's landfall and alerting government officials and the public. NWS forecasters monitored Katrina from its inception almost a week before it came ashore in Louisiana. Air Force and National Oceanic and Atmospheric Administration (NOAA) reconnaissance aircraft, satellites, and radar tracked the progress of the storm as it intensified and then doubled in size over the Gulf of Mexico. A day and a half before Katrina made landfall, Dr. Max Mayfield, then director of the NWS National Hurricane Center, called the governors of Louisiana and Mississippi and the mayor of New Orleans urging evacuation of particularly vulnerable areas.[14] This was only the second time in Mayfield's 36-year career that he believed it necessary to call a governor to warn of a hurricane.[16] The next day he briefed the president and other top federal officials indicating "very, very grave concern" that the New Orleans levees would be overtopped.[17] Special NWS advisories for Katrina accurately warned of storm surge heights of up to 8.5 m (~28 ft.) and floodwaters overtopping levees, resulting in a presidential emergency declaration before the storm hit land and the first-ever mandatory evacuation of New Orleans. Katrina's final landfall was within 35 km (~22 mi.) of the forecast location.[15]

Hurricane Katrina breached the New Orleans flood protection system, the single most costly catastrophic failure of an engineered system in history.[18] Flood walls and levees were breached in at least eight locations by water levels lower than design specifications (Figure 10.13).[17,18] On the east side of New Orleans,

levees and flood walls were overtopped and breached by the storm surge because navigation canals acted like funnels to focus the storm surge.[14] Levee and flood wall failures caused 85 percent of the greater New Orleans metropolitan area to be inundated with 0.3 to 6.1 m (~1 to 20 ft.) of water (Figure 10.14).[18] Much of the city remained flooded for two to three weeks before levees could be temporarily repaired and floodwaters pumped out. Other engineering failures included collapse of the I-10 causeway east of New Orleans due to the storm surge; wind damage to the Super-dome roof; loss of cell phone communications and power for residences, businesses, and hospitals; and collapse of several offshore oil and gas production platforms and refineries responsible for 17 percent of U.S. capacity.

If Katrina was not particularly strong or unexpected, and there was ample advance warning, why did more than 1,800 people die and damage exceed $125 billion, making it the most costly natural disaster in U.S. history? Answers to this question are complex and multifaceted, including failure in the design, construction, and maintenance of levees and flood walls; overreliance on technology to protect life and property; social and psychological denial of the hazard; the poverty and limited education of many residents in the affected area; diversion of military and government resources overseas; and



< FIGURE 10.13 Aerial View of Temporary Repair of Breached Flood Wall and Levee on New Orleans's 17th Street Canal
Army helicopters lowered white sand bags to temporarily fill this breach in the flood wall and levee along the 17th Street drainage canal. The failure, caused by the Hurricane Katrina storm surge, occurred at a water level lower than the design limit for the structure. Both faulty design and incomplete geotechnical information may have been responsible for the failure. *(Bob McMillan/UPI/Newscom)*



< FIGURE 10.14 New Orleans Inundated after Flood Protection System Fails
Levees and flood walls designed to protect New Orleans from a Category 3 storm were breached in at least six places by Hurricane Katrina. As a result, 85 percent of New Orleans was flooded. This photo, taken the day after landfall, shows cars abandoned on freeway overpasses. *(AP Photo/David J. Phillip)*

failures in political leadership, communication, and public policy at all levels. The policy failures include a system of flood insurance and postdisaster aid that encourages people to live in coastal hazard areas and rewards politicians, developers, businesses, and individuals for rebuilding in previously flooded areas.[19]

From a social standpoint, Hurricane Katrina was especially devastating to the Gulf Coast. An estimated 1.2 million people were evacuated, and more than 400,000 people ended up in public shelters in 18 states.[16] Although evacuation is a difficult, costly, and uncertain process, especially for the poor and elderly, it is the most powerful tool emergency managers have to prevent loss of life in a hurricane.[19,20] For those who had no way to evacuate, or chose not to, there were few places to go. In the first 10 days of the disaster, Coast Guard boats, ships, and aircraft rescued more than 23,000 people stranded along the Gulf Coast, and other rescuers saved tens of thousands of lives (see Case Study 10.3: Survivor Story).[21] Katrina also damaged or destroyed more than 800,000 homes in four states.[16]

More than a decade after Katrina struck the New Orleans, the social and economic impact of the storm can still be seen, particularly in poor communities. With about 70 percent of New Orleans occupied housing (~135,000 units) damaged or destroyed, more than half of the city's population (~250,000 residence) were forced to temporarily relocate. Although much of the population and city has since rebounded, many of the low-income communities have not. For example, the bustling neighborhood of the Lower 9th Ward, where more than 15,000 people lived prior to Katrina, had a population of just 3,000 twelve years later.[22] The residences who returned now live in sparse neighborhoods filled with empty lots and abandoned house, with very few stores and no schools (Figure 10.15a). Although the reasons for the lack of recovery in such communites are many, the most clear reason why most of the former residence did not return was they could not afford to return. For those who owned a home, many did not have flood insurance or were under insured and consequently could not afford home repair costs (Figure 10.15a). Nor was returning and renting anywhere in New Orleans an option, due to sky-rocketed rental prices driven by a historic low vacancy rate due to so many homes having been destroyed by Katrina.

Although certainly not agreed upon by all New Orleanians, many Americans feared that the loss of such communites like the 9th Ward—home to many historically famous musicians—would kill the heart and soul of the city responsible for the creation of jazz. Consequently, a number of philanthropic organizations in the decade that followed Katrina stepped in to bring back the original residence of such communities. One such example is the *Make It Right Foundation* founded by the actor Brad Pitt. He and his foundation have pledged to build 150 sustainable houses for former home owners of the Lower 9th Ward who could not afford to return after the storm. As of 2017, more than 350 former residence are back home living in the 107 houses that have been constructed thus far (Figure 10.15b).



(a)



(b)

▲ FIGURE 10.15 A Slow Painful Recovery

In 2017, more than a decade after near complete destruction by Hurricane Katrina, the Lower 9th Ward struggles still to recover. (a) This newly constructed home lies between an empty lot on the right where a Katrina damaged home was demolished, and on its left by an uninhabitable house that suffered extensive wind and water damage in 2005. (b) Sustainable home built by the *Make it Right Foundation*, which hopes to revive this struggling community by helping former owners rebuild. Note that both newly constructed homes in this figure are elevated on 1-m (~3 ft) high pylons to protect them from future flood events. (*Duane E. DeVecchio*)

CASE study

10.3 Survivor Story

Hurricane Katrina

Abdulrahman Zeitoun's Family Evacuated—He Stayed to "Mind the Damage"

After living in New Orleans for more than 30 years, contractor Abdulrahman Zeitoun has seen more than his share of tropical storms. So when forecasters began advising Gulf Coast residents to evacuate for Hurricane Katrina in late August 2005, Zeitoun declined to leave. "I say, 'Look, I'm not going. Someone has to stay behind and mind the damage.'"

On Saturday, August 27, Zeitoun waved goodbye to his wife and four children as they drove to relatives in Baton Rouge to wait out the storm. The next day, the wind and rain grew stronger and stronger, the power died, and the roof began to leak. But by late Monday, the weather had calmed and the danger seemed over. "I see water on the street a foot and a half deep, a few trees down. I call my wife, 'I say, '"Everything's done, if you want to come back."'"

In fact, the worst disaster in the history of New Orleans was only just beginning. Nearby, ocean waters surging inland started to overtop city levees, bursting through in several places to inundate entire neighborhoods.

Zeitoun heard the floodwaters before he saw them. "There were noises like when you sit by a river. I stick my head out the window and see water in the backyard rising very fast." He moved family photographs, the first-aid kit, flashlights, and small items upstairs, and then he stacked the first-floor furniture in tall piles. "I sacrificed one thing to save another one; anything I could do to minimize the damage."

The water rose for another 24 hours. Zeitoun called his wife and told her not to return, as the city would not be habitable for a long time. Then he climbed in his canoe to check on his tenants elsewhere in town.

What he saw as he paddled the silent streets was beyond his worst imaginings. Water on his block had reached the top of the stop sign, more than 6 feet high. A neighbor asked for a lift to check on his truck. They found the vehicle in water up to its roof. An older couple waving white flags asked to be rescued. Unable to fit them in the canoe, Zeitoun promised to find help. Further along, they heard a voice from a one-story house. Jumping in the water, Zeitoun managed to open the door. An elderly woman, skirts ballooning around her like a Civil War belle, stood in water up to her shoulders. To rescue her, Zeitoun and his neighbor flagged down one military boat after another, to no avail. Finally, a few civilians with a hunting boat stopped. Zeitoun positioned a ladder beneath her legs, and together the men levered the woman into the vessel. They went on to rescue the older couple and delivered all three seniors to a local hospital.

At his rental, Zeitoun found his tenant healthy and, by some miracle, in possession of a working phone. Neighborhood residents began converging to call friends and relatives.

Zeitoun helped several more people the next day, obtaining a boat to help rescue an older man in a wheelchair. In the evening, Zeitoun, his tenant, a friend, and a man using the phone were gathered at the rental when a military boat floated by. "They jump into the house with machine guns and say, 'What are you doing here?' I say, 'I own the place, it's my house,'" Zeitoun said. But the soldiers arrested all four and took them to a bus station being used as a temporary jail. They were thrown into a makeshift cage of chicken wire, interrogated for three days, and moved to a nearby prison. After spending a month behind bars, Zeitoun was released on bail. All charges—for suspected looting—have since been dropped.

Despite his ordeal, Zeitoun plans to stay in New Orleans. "My business is here. I have good relations here with my associates, friends, customers. I feel like I have a family in this city," he said.

— KATHLEEN WONG

10.3 Geographic Regions at Risk for Cyclones

In general, tropical and extratropical cyclones pose threats to different parts of the United States and Canada. Tropical cyclones have the greatest impact on coastal areas with warm offshore waters, such as the Gulf of Mexico and the Gulf Stream along the East Coast. Hurricanes pose the most serious threat to the eastern contiguous United States, Puerto Rico, the Virgin Islands, and U.S. territories in the Pacific Ocean. They are a lesser but real threat to Hawaii and Atlantic Canada. On the Pacific Coast, hurricanes frequently strike Baja California and the west coast of the Mexican mainland. Moist, unstable air from the remnants of Pacific tropical storms and hurricanes that moves inland over Mexico often contributes to torrential rains in the southwestern United States as far east as Texas.

The East and Gulf Coasts of the United States have the highest risk for tropical storms and hurricanes in North America and experience, on average, five hurricanes each year. Although hurricanes and tropical storms sometimes form in the Gulf of Mexico and Caribbean Sea, most hurricanes that threaten the East and Gulf Coasts form off the western coast of Africa and take one of three tracks (see Figure 10.8):

1. Westward toward the eastern coast of Florida, sometimes passing over Caribbean islands such as Puerto Rico and the Virgin Islands; these storms then move out to the Atlantic Ocean to the northeast without striking the North American continent.
2. Westward over Cuba and into the Gulf of Mexico to strike the Gulf Coast.
3. Westward to the Caribbean and then northeastward, skirting the East Coast; these storms may strike the continent from central Florida to New York. A few storms continue north as hurricanes to strike coastal New England or Atlantic Canada.

The geographic regions at risk for hurricanes and tropical storms include the entire Gulf Coast from southern Texas to southern Florida and the Atlantic Coast from southern Florida northward through the coastal provinces of Canada (Figure 10.16). This risk can be assessed with a map showing the probability that a hurricane will strike a particular 80 km (~50 mi.) coastal segment in a given year (Figure 10.17). Hurricane-strike probabilities are particularly high along the coasts of southern Florida, Alabama, Mississippi, Louisiana, eastern Texas, and Cape Hatteras.

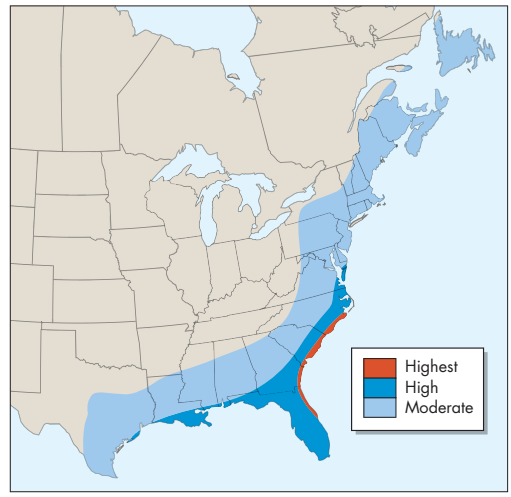


FIGURE 10.16 North American Regions at Risk for Hurricanes
Areas shown are based on the likelihood that a hurricane will pass within 160 km (~100 mi.). Highest-risk area (red area) is likely to experience 60 hurricanes, the high-risk area 40 to 60 hurricanes, and the moderate-risk area fewer than 40 hurricanes in the next 100 years. Map based on observations from 1888 to 2005. *(Based on the U.S. Geological Survey and NOAA Atlantic Oceanographic and Meteorological Laboratory)*

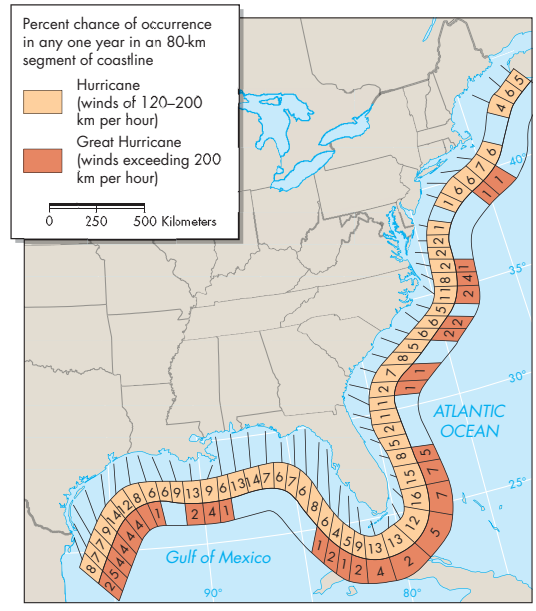


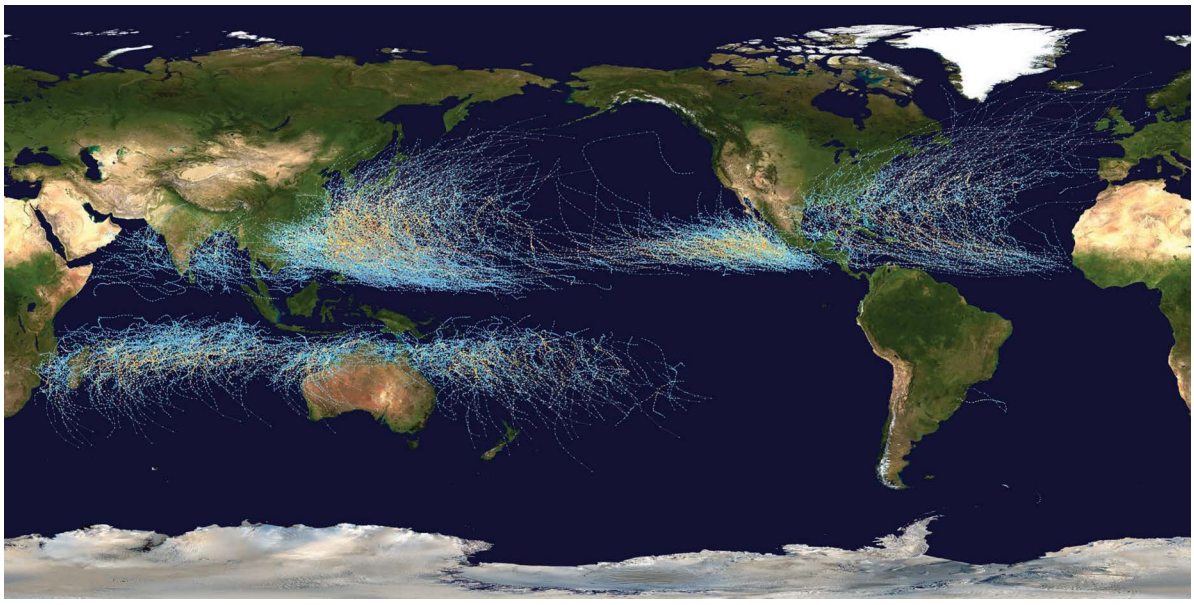
FIGURE 10.17 Major Hurricane Hazard Map
Probability that a major hurricane will strike a particular 80 km (~50 mi.) segment of Gulf and Atlantic Coasts of the United States in a given year is shown in light orange, and the probability that an intense Category 5 storm will strike is shown in darker orange. *(From Council on Environmental Quality, 1981. Environmental trends)*

With the greatest hurricane threat in the southeastern United States, the threat to New England is often underestimated. In 1815, a major hurricane made landfall on Long Island, New York, and then crossed into Massachusetts and New Hampshire. The Great Hurricane of 1938, one of the fastest-moving hurricanes on record, had an intensity and path nearly identical to the 1815 hurricane. The hurricane struck Long Island without warning and killed an estimated 680 people in New York, Connecticut, and Massachusetts. An estimated 80 percent of New England lost electrical power from the storm. Winds were clocked at 130 km (~80 mi.) per hour in New York City and 160 km (~100 mi.) per hour or more from Providence, Rhode Island, to the Boston area.[6] Then in 2012, Hurricane Sandy, the largest hurricane on record, made landfall in New Jersey just 100 km (~60 mi.) south of New York Harbor (see Applying the Fundamental Concepts: Hurricane Sandy).

Our emphasis on North America might imply that the North Atlantic Ocean is the most hazardous area for hurricanes and tropical storms. In fact, that is far from the case; the northwest Pacific generally has three times the number of hurricanes as the North Atlantic, and the Pacific and Indian Oceans overall have more hurricanes (Figure 10.18).[5] Two areas, the South Atlantic and southeast Pacific, rarely have hurricanes because of their cold surface waters. Hurricanes do not form close to the equator because of the absence of the Coriolis effect and, once formed, do not cross the equator.

Hurricanes affecting North America generally develop in the summer and early fall with the length of the hurricane season varying from year to year. The official Atlantic hurricane season starts on June 1 and ends November 30. Most Atlantic hurricanes occur in August, September, and October when the sea surface is the warmest. In contrast, the season for tropical cyclones in the Southern Hemisphere is from January to April.

In North America, the geographic region at risk from extratropical cyclones is far larger than from tropical cyclones. Severe weather from extratropical cyclones is greatest in the interior of the continent but may also occur in coastal areas. The greatest threat for this severe weather varies with location and time of year. In winter months, extratropical cyclones create strong windstorms along the Pacific Coast and nor'easters on the Atlantic Coast, as well as produce heavy snowstorms and blizzards, especially in the Sierra Nevada Mountains and within and east of the Rocky Mountains. During spring and summer months, extratropical cyclones are responsible for the severe thunderstorm and tornado hazard in much of the United States and Canada east of the Rocky Mountains (see Chapter 9).



▲ FIGURE 10.18 Typical Tropical Cyclone Paths and Regions of Formation
Most tropical cyclones develop between 5° and 20° latitude. Colored lines indicate cyclone paths, with colors correlating to storm intensity. Tropical storms are shown in blue, and cyclones with intensities from 1 to 5 on the Saffir–Simpson hurricane scale are shown in shades that range from yellow (Category 1) to red (Category 5). *(From NASA and Nilfanion)*

10.3 CHECK your understanding

1. Where are tropical cyclones most common, and why?
2. Which areas of the United States and Canada have the highest risk for hurricanes?
3. How do the chances of a Category 1 hurricane making landfall in the U.S. South (Florida–Georgia) compare with that in the Northeast (New York–Massachusetts)?

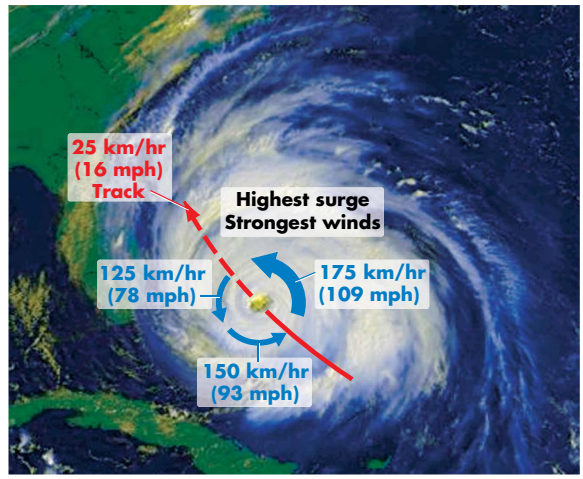
10.4 Effects of Cyclones

Tropical and extratropical cyclones claim many lives and cause enormous amounts of property damage every year. Both types of cyclones produce flooding, thunderstorms, and tornadoes, and extratropical cyclones can create snowstorms and blizzards (see Chapter 6 and 9). Three additional effects of cyclones are especially damaging: storm surge, high winds, and heavy rains. In the case of hurricanes, storm surge by far causes the greatest damage and contributes to 90 percent of all hurricane-related fatalities.[12]

STORM SURGE

Storm surge is the local rise of sea level that results primarily from water that is pushed toward the shore by the winds that swirl around a storm. Major hurricanes and intense extratropical cyclones approaching a coastline often generate storm surges of more than 3 m (~10 ft.). Storm surges of 12 m (~40 ft.) or greater have occurred with hurricanes in Bangladesh and Australia.[23] Larger and more intense cyclones build an elevated dome of water beneath the storm that often creates a higher storm surge as the storm makes landfall. Higher storm surges also develop when the coastal water depth gradually grows shallower toward shore. On these coasts, wind-driven water piles up until the wind shifts direction or decreases in speed to allow the surge to flow back to the sea. For most hurricanes in the Northern Hemisphere, the storm surge is greatest in the right forward quadrant of the storm as it makes landfall (Figure 10.19). The height of the surge is generally greatest near the time of maximum wind speed and is also greater if landfall takes place at high tide (see Applying the Fundamental Concepts: Hurricane Sandy).

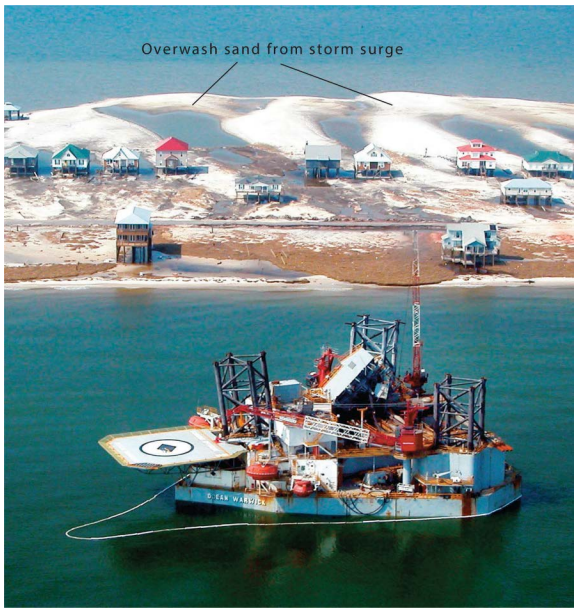
Two mechanisms in an intense cyclone cause the storm surge. The first and by far the more significant is stress exerted by wind on the water surface. As winds grow stronger, the water level rises quickly, with the height of the water proportional to the square of the wind speed. The larger the area over which the wind blows, referred to as the *fetch*, the higher the water will rise. Thus, large storms such as Hurricane Sandy in 2012 generally produce greater storm surges. The second but considerably less important mechanism is the low atmospheric pressure in the storm that pulls up the sea surface. For every millibar that atmospheric pressure drops, the sea surface rises 1 centimeter (~0.5 in.). In most intense hurricanes, the atmospheric pressure drops around 100 millibars, increasing the storm surge height by around 1 m (~3 ft.).[6]



▲ FIGURE 10.19 Hazard Greatest in Right Forward Quadrant of Atlantic Hurricanes
For hurricanes in the Northern Hemisphere, such as Hurricane Floyd shown here, the right forward quadrant of the cyclone typically has the highest storm surge, the strongest winds, most tornadoes, and heaviest rainfall. Image processed from NOAA GOES satellite. *(Goddard Space Flight Center/NASA)*

Storm surge is also affected by the shape of a coastline. In a narrow bay, lagoon, or lake, the height of the storm surge may increase as water sloshes back and forth in the enclosed or partially enclosed body of water. This produces *resonance*, a phenomenon that occurs when a wave reflecting from one shore is superimposed on a wave moving in another direction. The net effect is an amplification of the surge, similar to the amplified shaking from reflected seismic waves in a sedimentary basin (see Chapter 3).

Contrary to depictions in Hollywood movies, a storm surge is not an advancing wall of water; instead, it is a continual increase in sea level as the storm approaches landfall. Much of the storm surge damage actually comes from the large storm waves that are superimposed upon the surge. These storm waves combined with ocean currents erode beaches, islands, and roads.



< FIGURE 10.20 Hurricane Overwash Deposits
Overwash sand from Hurricane Katrina cover Dauphin Island when the storm surge overtopped the narrow strip of land. The storm surge destroyed more than half the houses on the island and damaged and displaced the oil platform in the foreground more than 106 km (~66 mi.). Although Dauphin Island was flooded by storm surges from Hurricanes Lili (2002), Ivan (2004), Dennis (2005), and Katrina (2005), some home owners want to rebuild. *(Adrien Lamarre/US Army Corps of Engineers)*

Sand eroded from the beach and coastal sand dunes is carried landward by the storm surge and forms deposits known as **overwash** (Figure 10.20). Many overwash deposits form as broad fans or deltas at the end of channels as the storm surge cuts through the beach and dunes perpendicular to the shoreline. Called *washover channels*, these features can be problematic when they cut entirely through islands or peninsulas and isolate one area from another (Figure 10.21). Most washover channels are naturally repaired by deposition of sand by coastal currents and wave action in the months following the storm. When Hurricane Allen struck South Padre Island on the Texas coast in 1980, a 4 m (~13 ft.) storm surge flooded part of the island and cut numerous washover channels. Geologists visiting the area shortly after the hurricane found that only the larger sand dunes had remained above the storm surge. When they climbed up on the dunes, they were faced with a new natural hazard—the coyotes and rattlesnakes that had taken refuge there during the storm.

HIGH WINDS

Although the storm surge from a hurricane, and sometimes an extratropical cyclone, is generally more deadly, the damage caused by high winds is more obvious, in part because the winds affect a much larger area. The Saffir–Simpson Hurricane Scale provides a good summary of the various types of wind damage that commonly occur in a hurricane (see Table 10.1). As



< FIGURE 10.21 Hatteras Island Breached by Hurricane Isabel Storm Surge
Three channels, totaling 500 m (~1649 ft.) in width, were cut through Hatteras Island, North Carolina, by Category 2 Hurricane Isabel in September 2003. The breach, located close to where the eyewall crossed the island, is just west of Cape Hatteras. These washover channels were created by a 2.3 m (~7.6 ft.) storm surge in the right forward quadrant of the storm. *(USGS)*

mentioned previously, hurricane winds will be the strongest in the eyewall and the northwest quadrant of the storm. Because of this, forecasters try to predict where the eye of the hurricane will make landfall.

The highest sustained wind speed that has been measured in a hurricane is close to 310 km (~190 mi.) per hour. This speed was recorded for three Category 5 hurricanes: Camille in the Gulf of Mexico in 1969, Tip in the northwest Pacific in 1979, and Allen in the Caribbean Sea in 1980. Even higher gusts of 320 km (~200 mi.) per hour have been estimated for three hurricanes making landfall in the United States: the Labor Day Hurricane in the Florida Keys in 1935; Camille in Mississippi in 1969; and Andrew near Homestead, Florida, in 1992 (Figure 10.22).[24] The destruction wrought by winds of 320 km (~200 mi.) per hour is nearly total. In the 1935 Labor Day Hurricane, a train carrying World War I veterans working in the Florida Keys was blown entirely off the tracks (Figure 10.23).[25] Some of the 423 people who died in the Labor Day Hurricane appeared to have been sandblasted to death by sand blown from the beach. The Labor Day Hurricane was the most intense storm to hit the United States in recorded history and served as the inspiration for the classic Humphrey Bogart movie *Key Largo*.[23]

Wind speeds in most hurricanes diminish exponentially once the storm makes landfall; wind speed is generally reduced by one half within about 7 hours after the storm crosses the coastline.[12] However, a few hurricanes do not lose all their strength when they move over land or cold water and instead transition to become extratropical cyclones. During the transition, some of these storms can maintain or even increase their wind speed. In 1954, Hurricane Hazel made landfall in North Carolina, yet it maintained 160 km (~100 mi.) per hour winds and caused extensive damage as far north as Toronto, Canada. Transition to an extratropical storm may occur if a dying hurricane merges with an upper-level extratropical cyclone or cold front or if it rapidly moves from warm to cold water.[6]

To many people's surprise, the strongest recorded wind in the United States has been from an extratropical cyclone, not a hurricane. This record was set by a 372 km (~231 mi.) per hour gust at a weather station on Mount Washington in New Hampshire's White Mountains in April 1934. On average, Mount Washington experiences



▲ FIGURE 10.23 Hurricane Blows Train off Tracks in Florida Keys

Wind gusts of more than 320 km (~200 mi.) per hour from the Labor Day Hurricane of 1935 blew the cars of this railroad train off its tracks in the Florida Keys. Hundreds of World War I veterans working in the Florida Keys were killed on the train as they were being evacuated from the storm. *(AP Photo)*



◀ FIGURE 10.22 Aerial View of Hurricane Wind Damage

This mobile home community near Homestead Air Force Base in southern Florida was devastated by wind gusts of up to 320 km (~200 mi.) per hour during Hurricane Andrew in 1992. Injuries were numerous, and 250,000 people in Florida were left homeless from the hurricane. *(AP Photo/Ray Fairall)*

hurricane-strength winds 104 days each year because of the exposed location and mountainous topography.[23]

Strong winds and heavy rains from extratropical cyclones cause most of the severe weather on the West Coast from San Diego to Vancouver. One of the most destructive of these storms was the Big Blow of 1962, which produced wind gusts of 260 km (~160 mi.) per hour along the Washington coast and 290 km (~179 mi.) per hour on the Oregon coast.[6]

In the central United States and Canada, extratropical cyclones are responsible for the high winds in blizzards and tornadoes (see Chapter 9) and for deadly windstorms on the Great Lakes. One 1913 storm sank or grounded 17,300-foot ore ships on Lakes Huron and Erie.[23] Another extratropical cyclone in 1975 sank one of the largest ore ships ever to sail on the Great Lakes, the *S.S. Edmund Fitzgerald*, killing the entire crew. Close to the time the *Fitzgerald* sank in Lake Superior, the captain of a nearby ship estimated wind gusts of more than 160 km (~100 mi.) per hour and waves up to 11 m (~36 ft.).[11]

HEAVY RAINS

An average hurricane produces about a trillion gallons of rainwater each day, nearly three times the amount of freshwater consumed in the United States each year.[6] The heaviest rainfalls in history have occurred where hurricanes have passed over, or close to, mountainous islands. La Reunion Island in the Indian Ocean has five rainfall records from tropical cyclones including 1 m (~45 in.) in 12 hours, 1.8 m (~70 in.) in 24 hours, and 2.5 m (~100 in.) in 48 hours.[6] Unlike the storm surge and very high winds that are generally limited to hurricanes and intense extratropical cyclones, heavy rains occur with cyclones of lower intensity. Tropical storms and even weaker tropical depressions can cause extensive flooding. In 2001, Tropical Storm Allison, which never became a hurricane, dumped up to 940 mm (~40 in.) of rain on Houston, Texas, and more than 690 mm (~30 in.) in southern Louisiana.[24] More than 45,000 homes and businesses were flooded in Houston, the fourth largest city in the United States. The storm killed 41 people, caused more than $5 billion in damages, and was the costliest tropical storm in U.S. history.[24] Rainfall from tropical storms and remnants of hurricanes is often most intense when the storms encounter topographic barriers, such as the Appalachian Mountains, and during nighttime hours when the rotational circulation of the storms contracts.

Intense rainfall from cyclones can cause widespread inland flooding (see Chapter 6). Four factors affect the extent of inland flooding: the storm's speed; changes in land elevation over which the storm moves; interaction with other weather systems; and the amount of water in the soil, streams, and lakes before the storm arrives.[26] In 2004, inland flooding from Hurricane Ivan extended from Georgia north through Ohio and Pennsylvania to southern New York State (see Figure 6.19). This flooding was caused, in part, by the slow movement of the storm, the hilly and mountainous terrain of the Appalachians, and saturation of the soil by heavy rains from the remnants of Hurricane Frances less than 10 days earlier. For some hurricanes, the damage and death toll associated with inland flooding exceed the storm damage to the coastal zone. Inland flooding along the coast from a hurricane often lasts for many days as floodwaters draining the land surface flow slowly into coastal bays and lagoons.

10.4 CHECK your understanding

1. What are three major causes of hurricane damage? Which is typically the most deadly?
2. Why are wind speeds the highest in the right forward quadrant of a hurricane?
3. Explain the causes and effects of storm surges. What will cause a storm surge to increase?

10.5 Linkages between Cyclones and Other Natural Hazards

Although cyclones themselves present numerous direct hazards to human life and property, their effects are magnified by linkages to other natural hazards. Cyclones are closely linked to coastal erosion, flooding, mass wasting, and other types of severe weather, such as tornadoes, severe thunderstorms, snowstorms, and blizzards. In coastal areas, and perhaps other regions, the cyclone hazard is directly linked to climate change.

Some of the fastest rates of coastal erosion occur during the landfall of cyclones. This observation applies to both hurricanes on the Gulf and East Coasts and winter extra-tropical cyclones on the West Coast. Wind-driven waves superimposed on a storm surge actively erode beaches and coastal dunes, predominantly on the Atlantic Coast, and sea cliffs, primarily on the Pacific Coast (see Chapter 11). Some of the eroded sand in beaches and dunes is replaced during fair-weather conditions, whereas other sand is removed entirely from the coastal zone by waves and currents during storms.

Most cyclones making landfall cause both saltwater flooding from a storm surge and freshwater flooding

from heavy rains. Areas where the coast has subsided are more vulnerable to both types of flooding (see Chapter 8). In other cases on land, cyclones cause destructive flooding because weak steering winds aloft allow the storms to stagnate over the same area for many days. Slow-moving cyclones often cause flash flooding because heavy rains continue to fall on already saturated soil.

In mountainous areas, heavy rains associated with cyclones can cause devastating landslides and debris flows. For example, in 1998, heavy rains from Hurricane Mitch in Guatemala, Honduras, El Salvador, and Nicaragua triggered widespread flooding, landslides, and debris flows, which killed at least 11,000 people.[27] Likewise, many landslides and debris flows in California, the Pacific Northwest, and the Appalachian Mountains are associated with heavy rains produced by extratropical cyclones.

Wind damage from hurricanes is not limited to the winds circulating around the eye of the storm. Hurricanes may generate *downbursts* of precipitation-driven winds with speeds of more than 160 km (~100 mi.) per hour and numerous tornadoes.[5] Approximately half the hurricanes that come ashore produce tornadoes. Most of these tornadoes occur within 24 hours after the hurricane makes landfall. Tornado formation is most likely from north to east-southeast of the center of the storm.[25]

Finally, as global sea-level rises because of global warming (see Chapter 12), the negative effects of cyclones will become more severe along coastlines. This will be especially true in areas of the U.S. Gulf and East Coasts that have relatively flat coastal plains. For example, along much of the Texas coast, a 0.3 m (~1 ft.) rise in sea level will result in a landward shift of the shoreline by approximately 300 m (~1000 ft.). In the coming decades, storm surges from cyclones will be able to penetrate farther inland than ever before in history.

10.5 CHECK your understanding

1. Explain how cyclones are linked with other natural hazards.

10.6 Natural Service Functions of Cyclones

Cyclones, and the weather fronts associated with them, are the primary source of precipitation in most areas of the United States and Canada. In the eastern and southern United States, hurricanes and tropical storms often provide much-needed precipitation to moisture-starved areas. This moisture may come from tropical cyclones that formed in the Atlantic Ocean and Gulf of Mexico, or it may be carried by upper-level winds from hurricanes along the Pacific Coast of Mexico. Along the West Coast, extratropical cyclones are the major source of precipitation during the winter rainy season. Extratropical cyclones are also responsible for many heavy snowstorms during winter months; many regions depend on spring snowmelt to recharge streams.

As mentioned previously, tropical cyclones also serve an important function in distributing the Sun's energy, equalizing the temperatures of our planet. Cyclones elevate warm air from the tropics and distribute it toward polar regions.

Cyclones have important natural service functions in ecosystems. Winds from these storms carry plants, animals, and microorganisms long distances, helping populate volcanic islands with flora and fauna once the islands rise above sea level. Cyclone-generated waves can also stir up deeper, nutrient-rich waters, resulting in plankton blooms in the open ocean and in estuaries. Cyclones rejuvenate ecosystems ranging from old-growth forests to tropical reefs. High winds topple weak and diseased trees in forests, and strong waves break apart some types of coral. Overall, these storms contribute to species diversity in many ecosystems.

In summary, cyclones are important sources of precipitation and contribute to the ecological health of many plant and animal communities. When viewed from space, cyclones are awe-inspiring sources of beauty and reminders of the power of natural processes.

10.6 CHECK your understanding

1. What is the primary natural service function cyclones provide the western United States?
2. Briefly summarize the contribution of cyclones to the health and diversity of Earth.

10.7 Human Interaction with Cyclones

Human interaction with cyclones, especially hurricanes, has increased markedly in the past four decades. Prior to greater population concentrations in coastal areas, and certainly before the advent of global satellite imagery, cyclones simply fulfilled their natural functions and some hurricanes went undetected for all or part of their existence.

In the past 50 years, population growth in the United States has been greatest in coastal areas that are especially vulnerable to the effects of cyclones. Today, approximately 53 percent of the people in the United States live in coastal counties.[28] Urban areas continue to expand along coastlines that have been devastated by coastal cyclones in historic times. This includes extensive development in Galveston, Texas; the greater Miami–Ft. Lauderdale and Tampa–St. Petersburg areas of Florida; and the Hamptons on eastern Long Island, to name a few. The growth in coastal population has also increased property values in coastal zones, which result in continual increases in the cost of damages from hurricanes and coastal extratropical cyclones.

As more people build in coastal counties, the nature of such construction can potentially make the cyclone hazard more dangerous and costly to humans. Destruction of coastal dunes for building sites increases the vulnerability of a shore to storm surge. Seawalls and bulkheads that are built to protect property reflect storm waves and contribute to beach erosion (see Chapter 11), further increasing the risks from storms. Finally, improperly attached building materials, such as roofing, often become projectiles in hurricane-strength winds. These projectiles damage other buildings and injure and sometimes kill people.

Many scientists have recently become concerned about the effects of our changing climate on tropical cyclones. Global warming, caused by gases that humans are putting into the atmosphere, is raising the temperature of the sea surface and contributing to rising sea level (see Chapter 12). Warm sea-surface temperature is a major factor in tropical cyclone development, and it is possible that warmer ocean water will increase hurricane intensity.[29] Rising sea level will also increase the reach of a storm surge and extend the effects of the large waves that ride the surge.

10.7 CHECK your understanding

1. Explain how population trends and global warming will interact with cyclones in coastal areas.

10.8 Minimizing the Effects of Cyclones

Since we cannot prevent the cyclone hazard, the primary way to reduce property damage and avoid loss of life is to accurately forecast these storms and issue advisories to warn people in their path. Other ways to minimize the effects, such as enforcing building codes and evacuation procedures, are adjustments to living with hazard and are discussed in the next section. Although the following discussion focuses on hurricanes, many of the challenges faced in forecasting their behavior, such as monitoring changes in storm path and intensity, also apply to intense extratropical cyclones.

FORECASTS AND WARNINGS

Minimizing property damage and casualties from hurricanes requires accurate forecasts that predict the behavior of these great storms as they approach landfall. The public must be warned in time to prepare or evacuate. Hurricanes can be difficult to forecast because they encompass many different weather processes, and they generally develop far from shore where there are few, if any, observers or weather stations. Once a hurricane has formed, meteorologists must predict if it will reach land, where and when it will strike, how strong the winds will be, how wide an area will be affected, and how much rainfall and storm surge will accompany the storm. Because of the complexity of hurricane prediction, hurricane forecast centers must use a variety of tools.

Hurricane forecast centers are located all across the globe and include the U.S. National Hurricane Center (NHC) on the campus of Florida International University in Miami, Florida, and the Canadian Hurricane Centre (CHC) in Dartmouth, Nova Scotia. The NHC watches the Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and eastern Pacific Ocean between May 15 and November 30 each year, and the CHC monitors tropical and post-tropical cyclones that are likely to affect Atlantic Canada.[30,31] Both centers issue watches and warnings to the public and support hurricane research. In the United States, a *hurricane watch* is issued when a hurricane is likely to strike within the next 48 hours and a *hurricane warning* is given when the storm is likely to make landfall within the next 36 hours or less.[32] The CHC also issues watches and warnings at appropriate times.[31] Both centers utilize information from weather satellites, hurricane-hunter aircraft, Doppler radar, weather buoys, reports from ships, and computer models to detect, forecast, and predict hurricanes.

Hurricane Forecasting Tools Weather satellites are probably the most valuable tools for hurricane detection and tracking, since the great storms form over the open ocean. Satellites can detect early warning signs of hurricanes long before the storm actually begins (see Figure 10.4b) and alert meteorologists to areas that should be watched closely. Although satellites are excellent for monitoring the growth and track of a

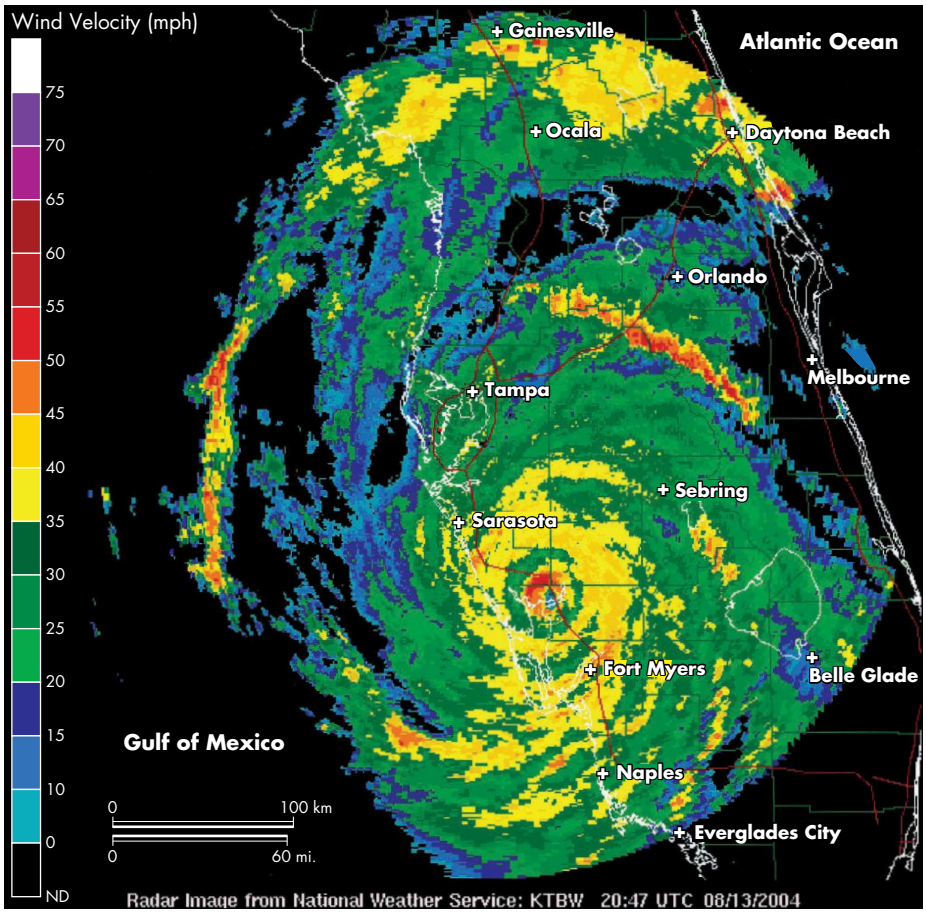
storms over the open ocean, they cannot give accurate detailed information about wind speed and other conditions within the storms. When within range, other tools are used to develop and refine predictions about the storm's behavior.

Aircraft are an invaluable tool, and special planes are flown directly into a hurricane to gather data, especially regarding intensity. U.S. Air Force hurricane-hunter aircraft perform most of the reconnaissance, although NOAA research aircraft also fly missions through hurricanes. These aircraft can begin their data collection when Atlantic tropical cyclones cross 55° W longitude, a north–south line approximately 2600 km (~1600 mi.) east of Miami, Florida (see Case Study 10.4: Professional Profile). During winter months, Air Force and NOAA aircraft also collect meteorological data on extratropical cyclones in the Pacific Ocean and along the East Coast.

Doppler radar systems provide another means of collecting data about hurricanes that come within about 320 km (~200 mi.) of the U.S. mainland and some islands, such as Puerto Rico and Key West. Radar can provide estimates of rainfall amount, wind velocity, and reveal hurricane rain bands and the eye of the storm (Figure 10.24).

Weather buoys floating along the Atlantic and Gulf Coasts are also used. These buoys are automated weather stations that continuously record weather conditions at their location and transmit information to the U.S. National Weather Service or the Meteorological Service. Some information about offshore weather conditions is also obtained from ships that are in the vicinity of a hurricane.

Meteorologists today use computer models that take into account all available data to make predictions about

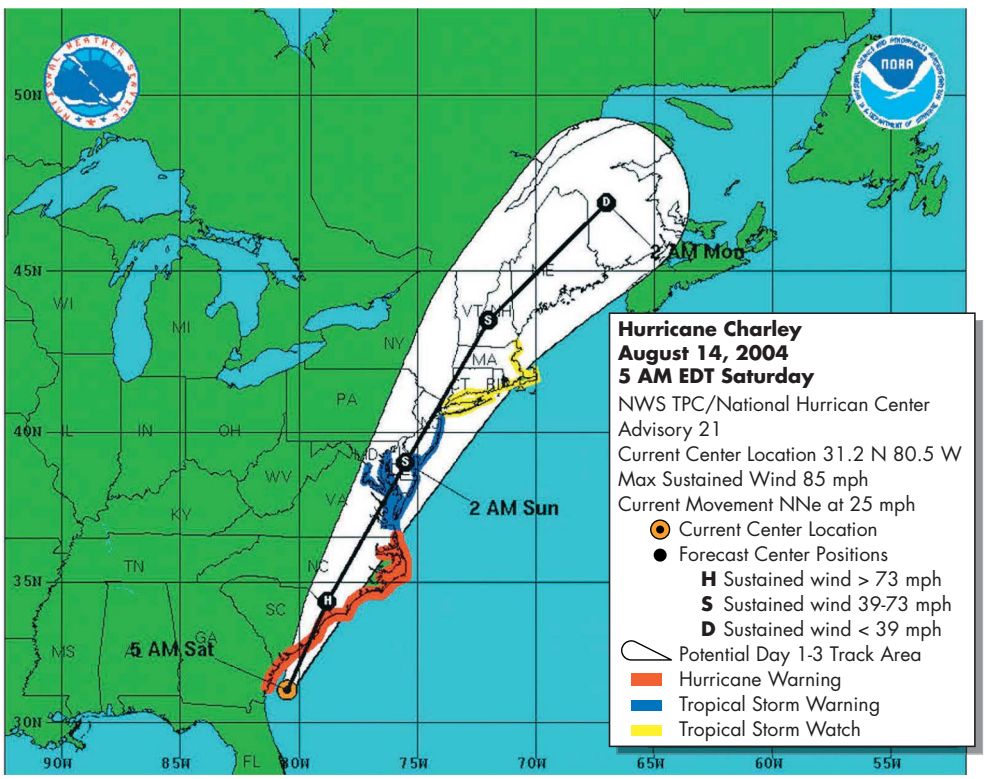


▲ FIGURE 10.24 Radar Image of Hurricane Charley

Image from the Tampa Bay weather radar after Hurricane Charley, a strong Category 4 storm, had made landfall between Fort Myers and Sarasota on the west coast of Florida in 2004. Red and orange colors in the spiraling rain bands have the highest winds. *(National Weather Service)*

hurricane tracks (Figure 10.25). Computer models are constantly being updated with millions of weather observations that are collected each day by the aforementioned tools. Processing such large amounts of data requires a team of scientists and large supercomputers. The most advanced mathematical model used by the NHC that includes weather data from around the globe is the Global Forecast System (GFS) model, which runs four times a day and can make weather predictions up to 16 days in advance. However, forecasts made by the GFS more than seven days out are not very accurate and are not widely accepted. Although such models have vastly improved our ability to predict where and when a storm will strike, they are still not completely accurate in predicting the intensity of the storm; therefore, reconnaissance flights remain an integral part of hurricane prediction.[5] Although such flights are dangerous and extremely expensive, their expense pales in comparison to the cost of evacuating additional miles of coastline with less accurate forecasts. Currently only the U.S. government uses such flights, and for hurricanes their use is limited to the western Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and an area around Hawaii.[5,33]

Storm Surge Predictions Forecasts of the track and the intensity of cyclones making landfall on coastlines are used to help predict the height and extent of the storm surge. As mentioned previously, forecasters can use wind speed, fetch, and average water depth to get a general idea of the elevation of the storm surge. Forecasters must also predict the time of day that the surge will arrive, because the additional water piled up by the storm is added to the level established by the astronomical tides. Along the Gulf of Mexico, with its tidal range of only a few feet, this is less important than in parts of New England and Atlantic Canada, where the tidal range is 3 m (~10 ft.) or more. Along these parts of the Atlantic Coast, a storm surge from a tropical or extratropical cyclone at high tide would be especially devastating.



▲ FIGURE 10.25 Hurricane Track Map

This National Hurricane Center map shows the predicted path of Hurricane Charley for the following three days. The width of the white area indicates the potential error in the predicted track. Severe weather watches and warnings are shown with red indicating a hurricane warning, blue a tropical storm warning, and yellow a tropical storm watch. *(From NOAA)*

The Hurricane Hunters

10.4 Professional Profile

CASE study

Even though amateur tornado chasers occupy an established, if eccentric, niche in the world of weather enthusiasts, hurricane hunting is still a job for the pros.

In fact, Major Chad "Hoot" Gibson boasted that his crew is the only "weather reconnaissance" squadron in the world. The aptly named "Hurricane Hunters" are a crew of Air Force members who fly planes directly into the center of hurricanes while the storms are still lingering over the ocean (Figure 10.4.A). During their wild ride, they gather important data about the strength of the storm, which the National Weather Service uses in its prediction of where the storm will strike. The crew begins 170 km (~110 mi.) out from where they estimate the eye of the hurricane will be, and they do their best to fly directly for the center in a straight line. In the course of doing so, Gibson said, they've encountered just about every form of severe weather out there: hail, updrafts and downdrafts, turbulence, and even tornadoes. "We avoid those," he said.

At the center of the hurricane is the furious eyewall, whose winds commonly blow in the neighborhood of 225 km (~140 mi.) per hour. And breaching the wall is no smooth ride. "There are times when the plane vibrates so badly that you can't read your computer screen," Gibson said.

But when they've made it through, the view from the eye, Gibson said, is awe inspiring. "Amazing. Fantastic," he said. "It's like sitting at the 50-yard line of a football stadium." In a well-formed eye, the sky is blue overhead, although the water below—the plane flies at an elevation of around 3050 m (~10,000 ft.)—still "looks like a washing machine."

The Hurricane Hunters don't dally too long in the eye. One reason is that the winds at the center are so



FIGURE 10.4.A Hurricane Hunter Aircraft
This U.S. Air Force Reserve Lockheed Martin WC-130 aircraft, based at Kessler Air Force Base in Mississippi, is specially equipped for taking weather measurements in hurricanes. WC-130 aircraft similar to this one investigate hurricanes at the direction of the National Hurricane Center. *(U.S. Air Force photo/Tech. Sgt. Ryan Labaden)*

calm, at around 4 to 7 km (~2 to 4 mi.) per hour, that the plane itself can throw off the data if it moves too much. Instead, they make a quick pass through the eye as the plane drops a dropsonde, a "weather station in a can," as Gibson described it, to take necessary measurements. Then it's back through the opposite wall and another bumpy ride.

To frame the sharp contrast in wind speed, Gibson recalled a mission through the center of Hurricane Floyd in September 1999 in which the crew entered the first eyewall, experienced 220 km (~137 mi.) per hour winds, then reached the eye 4 minutes later where the winds were blowing at 8 km (~5 mi.) per hour, and then 5 minutes later were again confronted with 225 km (~140 mi.) per hour gusts at the other side.

Not all eyes are perfectly formed, and some storms will have several smaller centers, so the hurricane hunters use the telltale 180-degree shift in the winds—the trademark of the center of a vortex—as the official core of the storm.

The squadron now flies the WC130J, a specially equipped version of the propeller-driven, Lockheed Martin Hercules military transport plane. Air Force pilots, and their predecessors in the Army Air Corps, have been flying scientific missions through hurricanes since 1944.

— CHRIS WILSON

Predicting the geographic extent of the storm surge requires detailed information about land elevation along a coastline. An airborne laser surveying technique, known as LIDAR (Light Detection and Ranging), is used to prepare detailed 3D digital elevation models of coastline elevation that are accurate to approximately 30 cm (~12 in.). This detailed survey data can be entered into sophisticated computer programs to predict both the height and the extent of the storm surge (Figure 10.26). Computer programs such as SLOSH (Sea, Land, and Overland Surges from Hurricanes) and ADCIRC (ADvanced CIRCulation) take into account the forecasts for central atmospheric pressure of the storm, its size, forward speed, track, wind speed, and the seafloor topography (i.e., bathymetry). ADCIRC, which can also take into account the wind and wave stress, tides, and additional water discharged from rivers, was used successfully to predict the storm surge for Hurricane Katrina (see Case Study 10.2: Hurricane Katrina).[14] Overall these models are accurate to within 20 percent of forecast values. This means that if the computer model calculates a 3.0 m (~10 ft.) storm surge, you can expect the observed storm surge to be between 2.5 and 3.7 m (~8 and 12 ft.).



FIGURE 10.26 Hurricane Storm Surge Flooding of Galveston, Texas
An estimated 65,500 residents live on Galveston Island, a Gulf of Mexico barrier island south of Houston, Texas. These before (a) and after (b) images of part of the island show flooding that will occur when a 5.8 m (~19 ft.) storm surge hits the island from the next Category 5 hurricane. In 1900, catastrophic storm-surge flooding by a Category 4 hurricane drowned more than 6,000 people in the most deadly natural disaster in U.S. history.
(Center for Space Research and Bureau of Economic Geology, The University of Texas at Austin)

Hurricane Prediction and the Future Until Hurricane Katrina in 2005, hurricane deaths in the United States had dropped dramatically, largely because of better forecasting, improved evacuation, and greater public awareness. Unfortunately, coastal populations are skyrocketing, and coastal development continues in hazard zones. This trend may result in more hurricane-related deaths if increased traffic slows evacuations, if inexperienced residents are not adequately prepared, or if new residents ignore evacuation procedures.[5]

Whereas increased coastal populations may lead to more hurricane-related deaths, property damage costs have already increased dramatically (Table 10.2). As more and more people build homes and businesses in the coastal zone, we can expect to see these costs continue to rise.

10.8 CHECK your understanding

1. What are the five main tools used to predict hurricanes and extratropical cyclones?
2. How do hurricane watches and warnings differ?

TABLE 10.2 Property Damage Costs Associated with Hurricanes—U.S. Atlantic and Gulf Coasts

Decade	Property Damage[a]
1900–1909	$2.4 billion
1910–1919	$5.7 billion
1920–1929	$3.6 billion
1930–1939	$9.8 billion
1940–1949	$9.0 billion
1950–1959	$21.8. billion
1960–1969	$40.5 billion
1970–1979	$34.8 billion
1980–1989	$35.1 billion
1990–1999	$92.2 billion
2000–2010	$279.5 billion

[a] In 2017 dollars.

Source: Blake, E. S., Landsea, C. W., Gibney, E. J., and I.M. Systems Group, NCDC Asheville, 2011. The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2010 (and other frequently requested hurricane facts). NOAA Technical Memorandum NWS TPC-4, Miami, FL: NOAA/National Weather Service, Tropical Prediction Center, National Hurricane Center. www.nhc.noaa.gov/pdf/nwsnhc-6.pdf. Accessed 10/30/17.

10.5 CASE study 2017 Atlantic Hurricane Season: Record Breaking

The 2017 hurricane season was catastrophic and the costliest U.S. hurricane season in history, both financially (~$300 Billion) and in loss of life (~3,000 killed). Estimates from Hurricane Harvey alone are between $180 and $200 billion (USD).[34,35] But Hurricane Harvey was just one of several hurricanes that ravaged the United States and Caribbean Islands during the record-breaking hurricane activity of September 2017 (Figure 10.27). With 17 named storms that year, 2017 was the fifth-most active season since records began, more than 160 years ago. It was also the only time that the continental United States was struck by more than one Category 4 hurricane in a single hurricane season.

Hurricane Harvey was the first Atlantic storm with hurricane strength to make landfall in the United States. Crossing the Texas shoreline 217 km (135 mi.) southwest of Houston as a Category 4 Hurricane. Persisting for almost five days after making landfall, doubling the longevity of any prior recorded hurricane on land, which consequently led to record-breaking rainfall and flooding in Texas (see Chapter 6 Applying the Fundamental Concepts). High winds and a 2–3 m (7–12 ft.) storm surge also resulted in extensive damage along the Gulf coast. By September 1 Hurricane Harvey had moved inland and was dissipating over Tennessee, and has ultimately been credited with 90 deaths in the United States—most of which were from drowning.[35]

Within one week of Harvey's dissipation, Hurricanes Irma, Jose, and Katia were fully formed and working their way westward (Figure 10.27). September 8, 2017, in meteorological records, represents the calendar day with the greatest recorded accumulated cyclone energy in the Atlantic Basin.[35] Although Jose and Katia resulted in thousands of resident evacuations of the island of Bermuda and coastal Mexico, respectively, neither storm resulted in any recorded deaths and neither hurricane made landfall in the United States. Hurricane Irma, however, is unofficially responsible for at least 90 people killed in the continental United States and more that 45 killed in the Caribbean Islands. On September 9, Irma made landfall as the first recorded Category 5 hurricane to strike the island of Cuba since 1924, and was the strongest-ever hurricane to impact the Caribbean Island (Figure 10.27).[35] Three days later, Irma made landfall in Florida as a Category 4, making it the first time that two hurricanes of this magnitude



< FIGURE 10.27 Highest Recorded Accumulated Cylcone Energy
With Hurricanes Katia (left), Irma (center), and Jose (right), September 8, 2017 holds the record for the greatest accumulated cyclone energy in the Atlantic Basin since records began. *(VIIRS image captured by the National Oceanic and Atmospheric Administration's Suomi NPP satellite)*

ever struck the United States in a single year. Unofficial estimates suggest that Hurricane Irma resulted in more that $66 billion in damage across the Caribbean and the U.S. mainland, but the Atlantic Basin had yet another final punch—Hurricane Maria.

After crossing the Caribbean Islands, headed toward Puerto Rico between September 16 and 18, tropical storm Maria doubled its wind strength to 175 km (109 mi.) per hour after making it the strongest tropical storm thus far of the 2017 Atlantic hurricane season.[35] Making landfall on September 20 as the strongest hurricane to strike Puerto Rico since 1928, Hurricane Maria caused widespread destruction across the U.S. Commonwealth. Still recovering from Hurricane Irma, which struck just 12 days earlier, more than 70,000 residence of the Puerto Rico were still without power and were about to be hit with 30 hours of high wind and rain. Subsequently, Maria completely destroyed Puerto Rico's electrical grid, and more than three months after the hurricane, 45 percent of the population (~3.5 million residence) were still without electricity and the crisis is ongoing at the time of this writing.[36] As of late 2017, the Puerto Rican death toll estimates from hurricane Maria are still unknown, and range from a few tens to several thousand. Logistical and political challenges have hindered recovery to date, but aid from around the globe is slowly flowing into the U.S. Commonwealth of Puerto Rico as of November 2017.

Fueled by anomalously high ocean sea-surface temperatures in the Atlantic Basin and in the Gulf of California, the 2017 Atlantic Hurricane Season was extraordinarily active.[35] With record levels of hurricane rainfall and total cyclone energy in the Northern Hemisphere, some scientists speculate that such weather events are a sign of what is to come, as global climate change results in seasonally warmer tropical atmospheric conditions (see Chapter 12).

10.9 Perception of and Adjustment to Cyclones

PERCEPTION OF CYCLONES

Residents of regions at risk for hurricanes or coastal extra-tropical cyclones often have significant experience with them, yet surprisingly, they do not always perceive the danger. During every hurricane, a number of people choose not to evacuate. People's perception of severe storm risks varies according to their experience. Many people now living in coastal areas are relatively new residents. Although they may have experienced a few hurricanes, they do not comprehend the threat of a major hurricane, and they may underestimate the hazard. Incorrect predictions of where or when a hurricane will strike may also lower risk perception. For example, if people are repeatedly warned of storms that never arrive, they may become complacent and ignore future warnings. As with any other hazard, accurate risk perception by planners and the public alike is key to reducing the threats associated with coastal hazards to those who live there.

ADJUSTMENT TO HURRICANES AND EXTRATROPICAL CYCLONES

Warning systems, evacuation plans and shelters, insurance, and building design are key adjustments to hurricanes. Emergency warning systems are designed to give the public the maximum possible advance notice that a potential hurricane is headed their way. Warning methods include media broadcasts of watches and warnings and, in cases of immediate danger, the local use of sirens. Efficient evacuation plans must be developed and distributed prior to hurricane season to ensure the most well-organized escape possible. At the time of evacuation, public transportation must be provided, shelters opened, and the number of outbound traffic lanes increased on evacuation routes. As was apparent with Hurricanes Katrina and Rita in 2005, it can take days to evacuate heavily populated areas, especially offshore barrier islands that require the use of ferries or have few bridges.

Homes and other buildings can be constructed to withstand hurricane-force winds and elevated to allow passage of a storm surge (Figure 10.28). Hurricane and other disaster-resistant building recommendations are available from the Partnership for Advancing Technology in Housing (PATH), a public–private partnership between homebuilding, product manufacturing, insurance, and financial industries and representatives of U.S. government agencies.

Personal adjustments for shoreline residents of the East and Gulf Coasts include being aware of the hurricane season and understanding the risks of owning and insuring shoreline property. Before the season starts, people should prepare their homes and property by trimming dead or dying branches from trees, obtaining flood insurance, and installing heavy-duty shutters that can be closed to protect windows. They should learn the evacuation routes and discuss emergency plans with their loved ones. Disaster preparedness for a hurricane is similar to that for an earthquake and includes having flashlights, spare batteries, a radio, first-aid kit, emergency food and water, can opener, cash and credit cards, essential medicines, and sturdy shoes.[37] As with a tornado watch, once a hurricane watch has been issued, it is imperative to stay tuned to local radio and/or TV stations. If an evacuation order is given, gather emergency supplies and follow the assigned evacuation route.

10.9 CHECK your understanding

1. Describe the adjustments that people need to make when living in hurricane-prone areas.



FIGURE 10.28 Hurricane-Resistant House
Home in the Florida Keys that has been constructed with strong blocks and space below the living area to allow a hurricane storm surge to pass through the building. *(Edward A. Keller)*

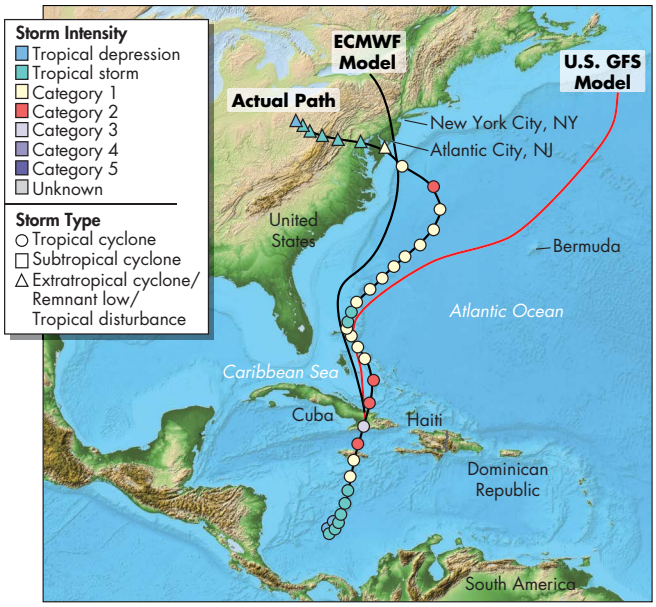
APPLYING the 5 Fundamental Concepts

Hurricane Sandy Case Study

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

Unlike Katrina, which struck early in the 2005 Atlantic hurricane season and ravaged the southern states, Hurricane Sandy developed in late October 2012 and impacted much of the eastern seaboard of the United States and Canada. On October 22, Sandy began as a tropical wave in the southern Caribbean and was quickly upgraded to a tropical storm several hours later (Figure 10.29). Strengthening to a Category 1 hurricane, Sandy's eye passed west of Haiti and the Dominican Republic but still dropped more than 20 inches of rain on the islands. With more than 400,000 Haitians still living in poorly constructed shantytowns due to a slow recovery following the 2010 Haiti earthquake (see Chapter 3), more than 50 people on the island were killed by flooding and mudslides (Figure 10.30).[38] With sustained winds of 110 mph, 1 mph less than a major Category 3 hurricane, Sandy struck Cuba on October 26. Approximately 55,000 Cubans were evacuated from the projected path of the storm and low-lying coastal areas, but on landfall waves up to 9 m (~29 ft.) pounded Cuba's southern coast and a 2 m (~7 ft.) storm surge caused extensive flooding and coastal erosion, completely destroying more than 15,000 homes and killing 11 people.

As Sandy moved northward through the Caribbean, scientists at the NHC and other weather agencies applied computer modeling to weather data to predict Sandy's eventual path. About the time Sandy was ravaging Cuba, just three days before U.S. landfall, most models were not in agreement on what path Sandy might



< FIGURE 10.29 Modeled and Actual Path of Hurricane Sandy

Computer models are the best way to predict the track of a developing storm, but just three days before Hurricane Sandy was to make landfall in New Jersey, the computer models did not agree. Although the European model (ECMWF) accurately predicted where Sandy would come ashore, the U.S. NHC model (GFS) suggested the storm would head northeast after leaving the Carribean Sea.



< FIGURE 10.30 Flooding in Haiti

Residents of Leogane, Haiti find higher ground as the water level continues to rise Friday, October 26, 2012. Residents of Leogane have had five consecutive days of rain in the aftermath of Hurricane Sandy. *(AP Photo/The Miami Herald, Carl Juste)*

take. The most trusted NHC global model (GFS) projected that Sandy would head east into the Atlantic Ocean to dissipate (see Figure 10.29). Consequently, much of the local weather media downplayed the potential impact that Sandy would have on the United States. However, the European Centre for Medium-Range Weather Forecasts (ECMWF) projected a very different outcome: Its model showed Sandy turning to the northwest in the Bahamas, followed by another turn that would take the hurricane northeast, parallel to the East Coast and making landfall near New York City.[39] Even more disconcerting, the ECMWF high-resolution forecast predicted that Sandy would join with an arctic front that was moving southward out of Canada. The rare occurrence of an arctic cold front and a hurricane joining forces was cause for great concern all over the Atlantic northeast.

On October 27 Sandy tracked northwest and then northeast, as the ECMWF model had predicted. Although the storm's eyewall was offshore, strong winds, rain, and waves caused widespread loss of power and closure of several highways due to coastal erosion and flooding in Georgia, the Carolinas, and Virginia. In Bermuda, winds from Sandy caused an F1 tornado, which touched down and damaged homes and businesses.[40]

As Sandy moved up the mid-Atlantic Coast as a Category 1 hurricane, meteorological conditions changed. Atlantic hurricanes at this latitude typically begin to lose energy as they move into cooler waters and are forced eastward into the North Atlantic by the prevailing westerly winds (see Figure 10.8). However, an anomalous intense high-pressure ridge over Greenland, due to negative North Atlantic Oscillation conditions, was blocking the westerly flow of air and deflecting Hurricane Sandy westward (Figure 10.31).[41] The high pressure region also caused the arctic cold front to remain stationary over the northeastern United States. Not only was Sandy now heading toward the Northeastern Seaboard, but by early October 28 it was clear that the hurricane would merge with the cold front, forming a hybrid "superstorm" just as the ECMWF model had predicted (Figure 10.29).

Preparations for heavy widespread snow in the Appalachian Mountains and Midwest and massive flooding in the northeastern states was not being anticipated. A power outage model built by researchers at Johns Hopkins University predicted that 10 million people from northern Virginia to Pennsylvania would lose power.[42] Government officials and power companies called on independent contractors from the southeastern states to New England to be ready to help repair downed power lines and restore electricity to the eastern seaboard in the wake of the hurricane.

Twenty-four hours before Sandy was projected to make landfall, the ECMWF model predicted that the storm would come ashore

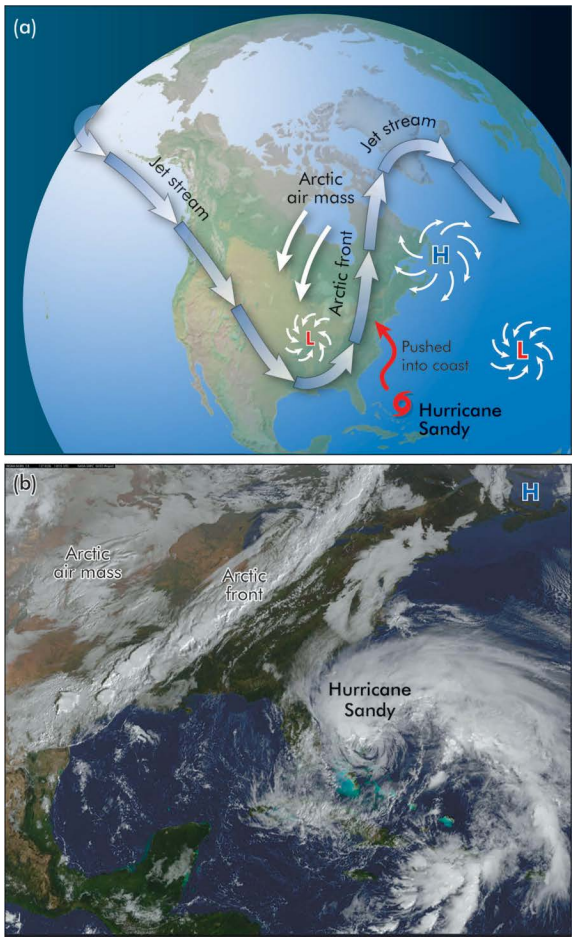


FIGURE 10.31 Hurricane Sandy's Unusual Path
(a) Hurricanes moving north along the eastern seaboard typically head back into the Atlantic away from the United States and Canadian coasts due to the prevailing westerly winds north of 35° latitude. However, in October 2012 an atypical intense high-pressure ridge over Greenland blocked Sandy's path toward the northeast and deflected the storm westward. These atmospheric conditions drove Hurricane Sandy into the U.S. Eastern Seaboard where the storm combined with an arctic cold front coming out of Canada to form a hybrid "superstorm." *(From Climate Central. Reprinted by permission.)* (b) Satellite image of Sandy in the Carribbean Sea one day after being upgraded from a tropical depression and one day before becoming a Category 1 hurricane. *(NASA)*

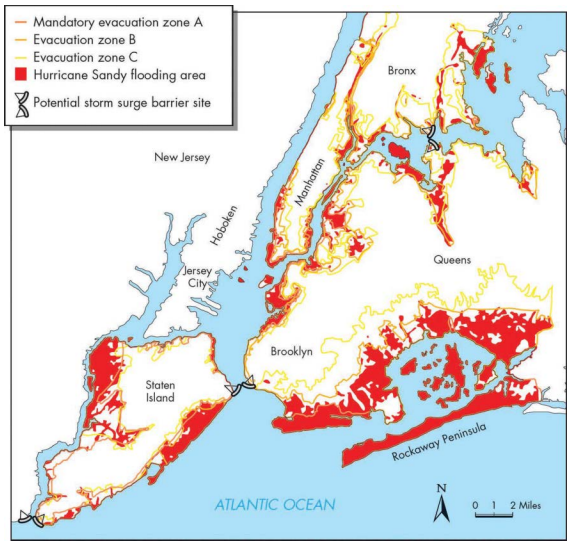
within 25 miles of Atlantic City, New Jersey (see Figure 10.29). This path would place New York City in the right forward quadrant of the hurricane, where winds would be at a maximum (see Figure 10.19). Before making landfall, however, Sandy would run across 480 km (~300 mi.) of open water, which when combined with the storm's great diameter meant a huge storm surge could be expected. Furthermore, Sandy's arrival was timed with the full moon and high tide, which would add an additional 0.6 m (~2 ft.) to the anticipated 3.6 m (~12 ft.) storm surge. Of particular concern was flooding in New York City, the largest city in the United States with a population density of more than 27,000 people per square mile!

On the afternoon of October 28, New York City Mayor Bloomberg ordered the evacuation of 375,000 citizens living in coastal and low-lying areas along rivers in Evacuation Zone A (Figure 10.32).[43] This region is susceptible to flooding from any hurricane and broadly correlates to FEMA's Flood Zone A.

As Sandy's eye came ashore in New Jersey at 8:00 P.M. on October 29, the storm no longer had sustained hurricane-strength wind velocities and was downgraded to a post-tropical cyclone.[44] However, the storm's huge size meant high winds, rain, and storm surge battered the coasts of New York and New Jersey through three 12-hour cycles of high and low tide. Sandy's storm surge in New York Harbor was the highest ever recorded at 4.3 m (~14 ft.); the previous record was 4 m (~13 ft.) in 1821.[45] The surge topped seawalls in lower Manhattan, causing widespread power outages and flooding of parts of the city's subway system and the Hugh Carey Tunnel connecting Manhattan with Brooklyn. In the community of Breezy Point on the Rockaway Peninsula, flooding triggered a six-alarm fire that destroyed 111 homes and damaged 20 more (Figure 10.32).

Of the approximately 130 U.S. citizens in eight states killed by Hurricane Sandy, 43 were in New York City, half of whom were on Staten Island (see Figure 10.32). Staten Island was particularly vulnerable to the storm surge because the Long Island and New Jersey coasts meet at a 120° angle, which focused the surge directly toward Staten Island.[46] The storm surge also ravaged much of the New Jersey coast, destroying several coastal boardwalks, numerous homes and businesses, and killing 37 people (see Figure 10.1b).

By the morning of October 30, Sandy's center had moved inland and would ultimately dissipate



< FIGURE 10.32 New York City Flood Evacuation Plan and Sandy Inundation

This map shows the areas flooded by Hurricane Sandy with respect to New York City's three flood evacuation zones. Zones are differentiated by their likelihood of flooding as a result of hurricane intensity: Zone A—potential for flooding from any hurricane; Zone B—potential for flooding from a Category 2+ hurricane; and Zone C potential for flooding from a Category 3–4 hurricane hitting just south of New York City. Evacuation of Zone A was made mandatory 24 hours before Sandy made landfall. *(Based on FEMA ABFE maps of New York City)*

over western Pennsylvania on October 31. In the wake of the hurricane, about 380,000 homes were destroyed or damaged, more than 8.5 million residences were without power over 16 states, and heavy snow blanketed five states with parts of Virginia, West Virginia, and North Carolina receiving 0.6–0.9 m (~2–3 ft.). Although the number of hurricanes in the 2012 season fell short of predictions, the season tied for the third most active season on record and Hurricane Sandy became the second most expensive hurricane to hit the United States.

As with Katrina, flooding caused the greatest monetary damage and loss of life. Building codes based on FEMA's Advisory Base Flood Elevation (ABFE) maps for New York City had been in place since 1983.[47] Structures built after 1983 that were flooded by Hurricane Sandy fared better than those built earlier, thereby saving hundreds of millions of dollars paid out by insurance companies to those living in FEMA Zone A. However, flooding was more extensive than was predicted for a storm with Sandy's wind velocities, and areas beyond Zone A were inundated (see Figure 10.32). In the aftermath of Sandy, FEMA released new ABFE maps for all of New York City and for 11 New York and New Jersey counties; this expands the area covered by Zone A in order to mitigate future flood damage.[47] For those living in the newly redistricted areas the cost of flood insurance



^ FIGURE 10.33 Storm Surge Barriers

Aerial view of storm surge barriers in the Netherlands, similar to what could be installed in critical locations to protect parts of New York and New Jersey (see Figure 10.32 for locations). Barriers are closed in this image. *(Frans Lemmens/Corbis)*

will likely rise accordingly if they choose to rebuild. Alternatively, New York Governor Cuomo proposed a more ambitious long-term plan to mitigate future damage: home buyouts at full prestorm market value for the more than 100,000 homeowners affected by Sandy, as well as for homeowners unaffected by Sandy but who live in FEMA Zone A. The land would never be built on again, with some properties turned into public parks or wetlands, dunes, and other natural buffers that would help protect coastal communities from future storms.

In addition to Governor Cuomo's proposal to buy out homeowners and businesses located in the ever-expanding flood-prone areas, more drastic mitigation procedures include constructing movable storm surge barriers (Figure 10.32).[48] These barriers would be built at three key locations (see Figure 10.32) that would stop the flooding of parts of New York and New Jersey and could protect as much as 50 percent of the areas in the flood-prone zone.[18] But with an estimated price tag of $10 billion, is the cost of these barriers too great? Or, in the aftermath of Hurricane Sandy, is the risk of inaction even greater?

APPLYING THE 5 FUNDAMENTAL CONCEPTS

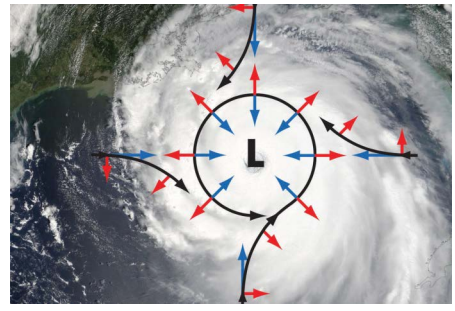
1. Explain how scientists predicted the size, path, and potential problems posed by Hurricane Sandy from its origins in the tropical Atlantic to its dissipation. What factors complicated prediction and warnings?
2. Describe the preparedness of areas affected by Hurricane Sandy in terms of risk—to what extent did the affected regions perceive the risks and act on this perception?
3. Link the various weather-related events that occurred in the Caribbean and eastern United States at the end of October 2012 to Sandy's development and movement.
4. The population density of New York city means that when any severe natural hazard strikes the region the consequences are likely to be high. Discuss a few examples of how urban development of the region has added to the risk posed by large hurricanes.
5. Provide examples of how the adverse consequences of Sandy were minimized and what new strategies have been proposed to minimize the effects of future hurricanes.

CONCEPTS in review

10.1 Introduction to Cyclones

LO:1 Describe the weather conditions that create, maintain, and dissipate cyclones.

- Cyclones, large areas of low atmospheric pressure with winds converging toward the center, are associated with most severe weather. Cyclones are described as either tropical or extratropical based on their characteristics and origin.
- Tropical cyclones have warm cores, are not associated with weather fronts, and form over tropical and subtropical oceans between 5° and 20° latitude. Called typhoons, severe tropical cyclones, or cyclonic storms in most of the Pacific and Indian Oceans, these storms are called hurricanes in the Atlantic and northeast Pacific Oceans and in this book.
- Extratropical cyclones have cool cores, develop along weather fronts, and form between 30° and 70° latitude over either the land or ocean. These midlatitude cyclones produce windstorms,



KEY WORDS

cyclone (p. 398), **cyclone intensity** (p. 398), **extratropical cyclones** (p. 398), **hurricanes** (p. 399), **tropical cyclones** (p. 398), **typhoons** (p. 399)

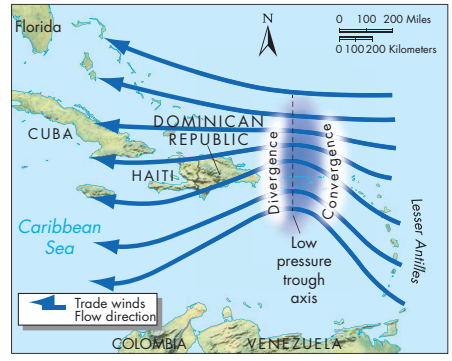
snowstorms, blizzards, and severe thunderstorm outbreaks. Both types of cyclones can have high-velocity straight-line winds, tornadoes, heavy precipitation, and coastal storm surges.

- Tropical cyclones are classified as tropical depressions, tropical storms, and hurricanes with increasing wind speed. Tropical storms must have sustained winds of at least 119 km (~74 mi.) per hour to become a hurricane. A hurricane is assigned a category based on measured or inferred sustained winds. Hurricanes reaching Category 3 or above are considered major hurricanes.
- Tropical storms and hurricanes are given names from lists for the region where they form, whereas extratropical cyclones are sometimes named for their geographic area of origin or prevailing wind direction.

10.2 Cyclone Development and Movement

LO:2 Explain why it can be difficult to forecast cyclone behavior.

- Most tropical cyclones start out as a tropical disturbance, a large thunderstorm complex associated with a low-pressure trough. In the Atlantic Ocean, many of these disturbances form off the west coast of Africa as easterly waves in the trade winds. A tropical disturbance that develops a circular wind pattern becomes a tropical depression and may become a tropical storm if winds exceed 63 km (~39 mi.) per hour. Only a few tropical storms become hurricanes.
- Hurricanes develop spiraling rain bands of clouds around a nearly calm central eye. The eye is surrounded by an eyewall cloud where the strongest winds and most intense rainfall occur. Warm, moist air condensing in rain bands and the eyewall releases latent heat and provides continual energy for the hurricane. Excess heat is vented out of the storm's top.
- Most hurricanes are steered by winds in the middle and upper troposphere and these storms generally lose intensity over land or cooler water, whereas extratropical cyclones typically form along fronts where there are strong, diverging winds in the upper troposphere.



KEY WORDS

easterly waves (p. 401), **eye** (p. 403), **eyewall** (p. 403), **North Atlantic Oscillation** (p. 405), **rain bands** (p. 403), **tropical depression** (p. 401), **tropical disturbance** (p. 401), **tropical storm** (p. 401)

10.3 Geographic Regions at Risk for Cyclones

LO:3 Locate several geographic regions at risk for hurricanes and extratropical cyclones.

- In North America, the Gulf and Atlantic Coasts are at highest risk for tropical cyclones, with hurricane-strike probabilities being the greatest in southern Florida, the northern Gulf Coast, and Cape Hatteras.
- Extatropical cyclones are the primary severe weather hazard on the Pacific Coast and cause storms on the Great Lakes. For the eastern United States and Atlantic Canada, these cyclones are known as nor'easters because of their strong northeasterly winds that cause severe weather.



10.4 Effects of Cyclones

LO:4 Give examples of the effects of cyclones in coastal and inland areas.

- Cyclones produce coastal storm surges, high winds, and heavy rains with major hurricanes and intense extratropical cyclones generating storm surges of more than 3 m (~10 ft.). Higher surges are produced by larger or more intense storms and on shallow coastlines or narrow bays.
- In the Northern Hemisphere, the greatest storm surge and highest winds are typically in the right forward quadrant of tropical cyclones. Much of the structural damage from coastal storms comes from wind-driven waves on top of the storm surge.
- Strong currents from storm surges cut channels through islands and peninsulas and deposit sand as overwash.
- Wind damage from hurricanes is more widespread but less deadly than the storm surge.
- Although hurricanes hold most rainfall records, tropical storms also produce intense rains and flooding. Inland flooding occurs from hurricane remnants if storms move slowly, encounter hills or mountains, interact with other weather systems, or track over already saturated ground.



KEY WORDS

overwash (p. 416), **storm surge** (p. 415)

10.5, 10.6, and 10.7 Linkages between Cyclones and Other Natural Hazards; Natural Service Functions of Cyclones; Human Interaction with Cyclones

LO:5 Recognize linkages between cyclones and other natural hazards.

LO:6 List the benefits derived from cyclones.

LO:7 Describe adjustments that can minimize damage and personal injury from coastal cyclones.

- Cyclones are closely linked with other severe weather, flooding, landslide, and debris flow hazards.
- The hazard posed by storm surges and erosion from coastal cyclones will increase as sea-level rises worldwide from global warming. Hurricane intensity is also projected to increase with warmer global temperatures.
- Both hurricanes and coastal extratropical cyclones will become more destructive to our society as coastal populations and per capita wealth grow. On the positive side, cyclones are major sources of precipitation, help maintain global heat flow, and contribute to long-term ecosystem health.



10.8 and 10.9 Minimizing the Effects of Cyclones Perception of and Adjustment to Cyclones

LO:8 Propose prudent actions to take for hurricane or extratropical cyclone watches and warnings.



- Accurate forecasts, effective storm warnings, strict building codes, and well-planned evacuations can minimize the effects of coastal cyclones.
- Hurricane forecasting relies on weather satellites, aircraft flights, Doppler radar, and automated weather buoys. Computer models predict hurricane tracks more accurately than their intensity. Storm surge predictions are based on wind speed, fetch, average water depth, and timing of landfall in relation to astronomical tides.
- Perception of the coastal cyclone hazard depends on individual experience and proximity to the hazard.
- Community adjustments to hurricanes in developed countries involve building protective structures or modifying people's behavior through land-use zoning, evacuation procedures, and warning systems.
- Individual adjustments to hurricanes include having emergency supplies on hand; preparing once a storm prediction is made; and if required, evacuating before the storm hits. Homes can also be constructed to withstand hurricane-force winds and elevated to allow passage of storm surges.

CRITICAL thinking questions

1. If you had to evacuate your home and go to a nearby public shelter, where would it be? If you had to evacuate your home and travel at least 160 km (~100 mi.) from where you live, where would you go? What would you take with you in either case? What problems might you or your community face in an evacuation (e.g., people in poor health or with disabilities, people without a means of transportation, visitors, pets, domesticated animals)? What would be your concerns?
2. The southern tip of Florida has a very large area of marsh and swampland—the Everglades—and a large lake, Lake Okeechobee. Based on your understanding of how a hurricane works, what effect would these wetlands have on a hurricane that was tracking across southern Florida? What effect would the hurricane have on Lake Okeechobee?
3. What conditions required for hurricane development could explain why hurricanes generally do not form between 5° N and 5° S of the equator, or in the southeastern Pacific and South Atlantic Oceans?
4. Obtain a topographic map (see Appendix C) for an ocean beach you visit or for an urban area along the Atlantic shore or Gulf Coast. Shade or color the area that would be affected by a 5 m (~20 ft.) storm surge. Examine your completed map and assess the damage that would occur, the routes people would take for evacuation, and land-use restrictions you would recommend for future development.

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