HURRICANES

CHAPTER 11

Hurricane Rita became a Category 5 hurricane late on September 21, 2005, with sustained winds of 275 kilometers (170 miles) per hour and a central pressure of 897 millibars, making it the third most powerful Atlantic basin storm ever measured. When this image was taken about mid-day on September 22, the storm was slightly weaker. *(NASA image)*

The whirling tropical cyclones that occasionally have wind speeds exceeding 300 kilometers (185 miles) per hour are known in the United States as **hurricanes**—the greatest storms on Earth. Hurricanes are among the most destructive of natural disasters. When a hurricane reaches land, it is capable of annihilating coastal areas and killing tens of thousands of people. On the positive side, however, these storms provide essential rainfall over many areas they cross. Consequently, a resort owner along the Florida coast may dread the coming of hurricane season, but a farmer in Japan may welcome its arrival.

The vast majority of hurricane-related deaths and damage are caused by relatively infrequent yet powerful storms. Table 11–1 lists the deadliest hurricanes to strike the United States between 1900 and 2005. The storm that pounded an unsuspecting Galveston, Texas, in 1900 was not just the deadliest U.S. hurricane ever, but the deadliest natural disaster *of any kind* to affect the United States. Of course, the deadliest and most costly storm in recent memory occurred in August 2005, when Hurricane Katrina devastated the Gulf Coast of Louisiana, Mississippi, and Alabama (Figure 11–1). Although hundreds of thousands fled before the storm made landfall, thousands of others were caught by the storm. In addition to the human suffering and tragic loss of life that were left in the wake of Hurricane Katrina, the financial losses caused by the storm are practically incalculable. Up until August 2005, the $25 billion in damages associated with Hurricane Andrew in 1992 represented the costliest natural disaster in U.S. history. This figure will be exceeded many times over when Katrina's economic impact is finally calculated. Although imprecise, some suggest that the final accounting could reach or exceed $300 billion.

The devastating hurricane season of 2005 came on the heels of an extraordinary 2004 season. Storms claimed more than 3100 lives (mostly in Haiti), and property losses in the United States topped $44 billion. The most notable storms were hurricanes Charley, Frances, Ivan, and Jeanne, all of which struck the state of Florida in August and September. Three of the storm tracks (Charley, Frances, and Jeanne) intersected in central Florida, whereas Hurricane Ivan struck the state's panhandle as it made landfall along the Gulf Coast (Figure 11–2). The Bahamas and many Caribbean islands were also hit hard. Each hurricane season, storms like those just described remind us of our vulnerability to these great forces of nature.

Profile of a Hurricane

Most of us view the weather in the tropics with favor. Places like Hawaii and the islands of the Caribbean are known for their lack of significant day-to-day variations. Warm breezes,

TABLE 11-1 The 20 deadliest U.S. hurricanes, 1900–2005

Ranking	Hurricane	Year	Category	Deaths
1.	Texas (Galveston)	1900	4	8000*
2.	Florida (Lake Okeechobee)	1928	4	1836
3.	Katrina	2005	4	1300**
4.	Florida (Keys)/S. Texas	1919	4	600†
5.	New England	1938	3	600
6.	Florida (Keys)	1935	5	408
7. (tie)	Audrey (SW Louisiana/Texas)	1957	4	390
7. (tie)	NE United States	1944	3	390‡
9.	Louisiana (Grand Isle)	1909	4	350
10. (tie)	Louisiana (New Orleans)	1915	4	275
10. (tie)	Texas (Galveston)	1915	4	275
12.	Camille (Mississippi/Louisiana)	1969	5	256
13.	Florida (Miami)/Mississippi/Alabama/ Florida (Pensacola)	1926	4	243
14.	Diane (NE United States)	1955	1	184
15.	SE Florida	1906	2	164
16.	Mississippi/Alabama/Florida (Pensacola)	1906	3	134
17.	Agnes (NE United States)	1972	1	122
18.	Hazel (North Carolina/South Carolina)	1954	4	95
19. (tie)	Betsy (SE Florida/SE Louisiana)	1965	3	75
19. (tie)	Floyd (North Carolina)	1999	2	75

* May actually have been as high as 10,000 to 12,000.
** Estimated figure.
† Over 500 of these lost on ships at sea; 600 to 900 estimated deaths.
‡ Some 344 of these lost on ships at sea.

FIGURE 11-1 An estimated 80 percent of New Orleans was flooded after several levees failed in the wake of Hurricane Katrina. The storm surge caused the level of Lake Pontchartrain to rise, straining the levee system protecting the city. *(AP Photo/David J. Phillip)*

steady temperatures, and rains that come as heavy but brief tropical showers are expected. It is ironic that these relatively tranquil regions sometimes produce the most violent storms on Earth.

Most hurricanes form between the latitudes of 5° and 20° over all the tropical oceans except the South Atlantic and the eastern South Pacific (Figure 11–3). The North Pacific has the greatest number of storms, averaging 20 per year. Fortunately for those living in the coastal regions of the southern and eastern United States, fewer than five hurricanes, on the average, develop each year in the warm sector of the North Atlantic.

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

Although many tropical disturbances develop each year, only a few reach hurricane status. By international agreement a hurricane has sustained wind speeds of at least 119 kilometers (74 miles) per hour and a rotary circulation.* Mature hurricanes average about 600 kilometers (375 miles) across, although they can range in diameter from 100 kilometers (60 miles) up to about 1500 kilometers (930 miles). From the outer edge of the hurricane to the center, the barometric pressure has sometimes dropped 60 millibars, from 1010 to 950 millibars. The lowest pressures ever recorded in the Western Hemisphere are associated with these storms.

A steep pressure gradient like that shown in Figure 11–4 generates the rapid, inward spiraling winds of a hurricane. As the air moves closer to the center of the storm, its velocity increases. This acceleration is explained by the law of conservation of angular momentum (see Box 11–1).

As the inward rush of warm, moist surface air approaches the core of the storm, it turns upward and ascends in a ring of cumulonimbus towers (Figure 11–5). This doughnut-shaped wall of intense convective activity surrounding the center of the storm is called the **eye wall.** It is here that the greatest wind speeds and heaviest rainfall occur. Surrounding

**Sustained winds* are defined as the wind averaged over a one-minute interval.

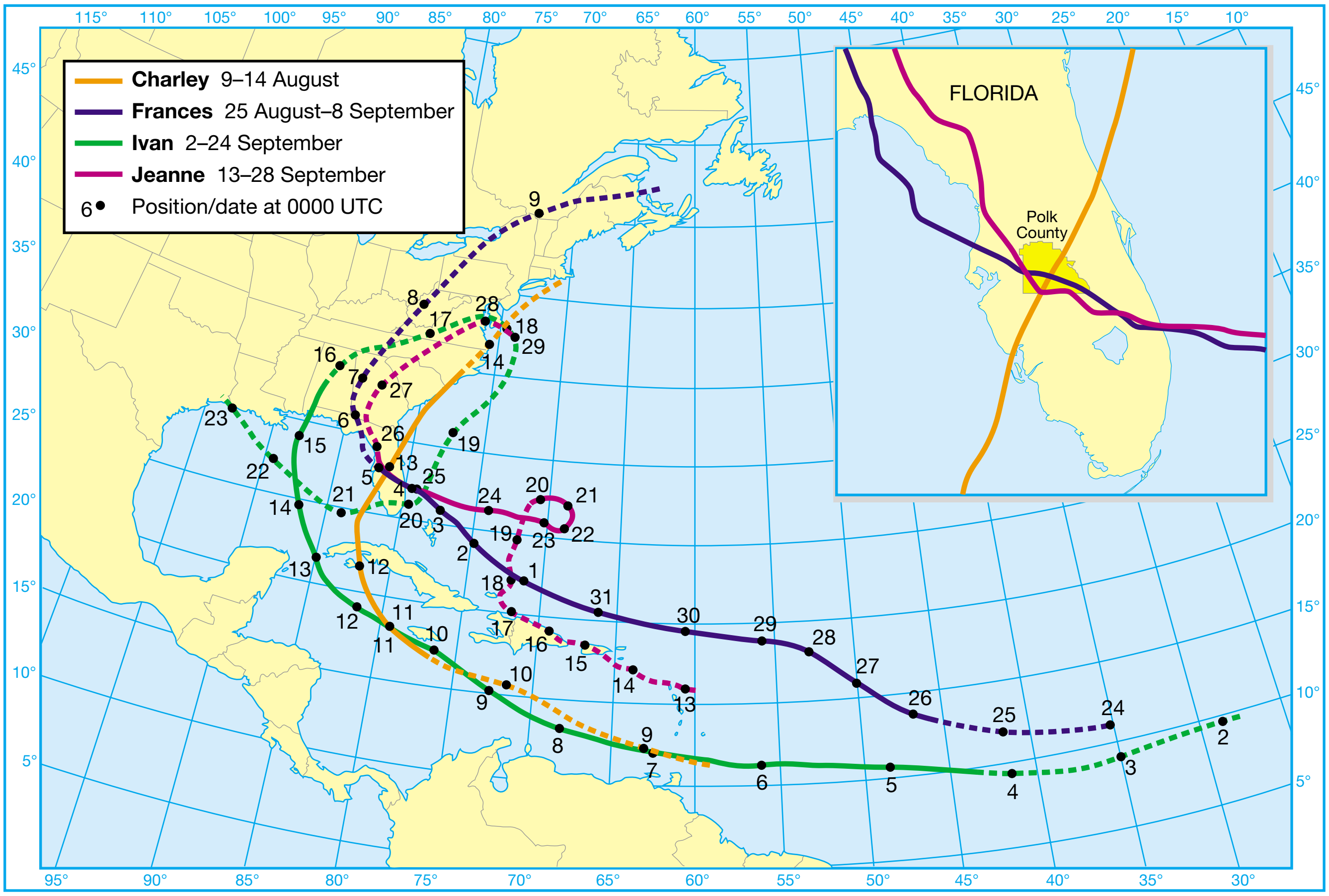
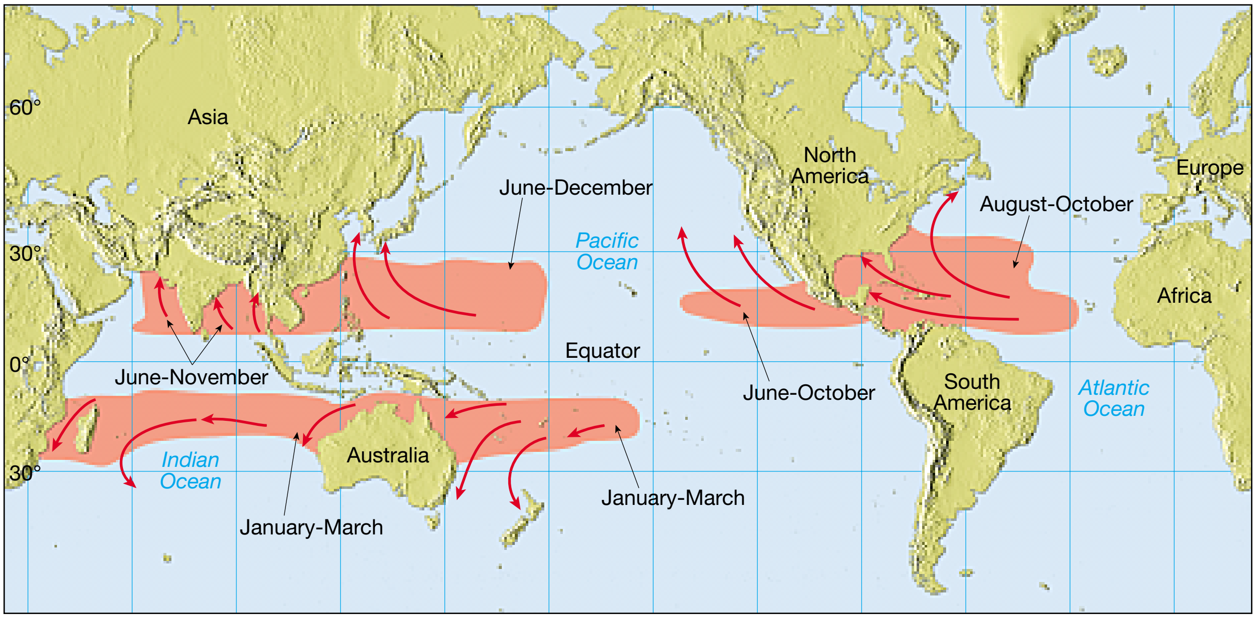


FIGURE 11-2 Tracks of the four major hurricanes to hit Florida in 2004. Hurricanes Charley, Frances, and Jeanne intersected over Polk County, Florida (see inset). Ivan made landfall near Mobile, Alabama, but greatly affected Florida's western panhandle. Each solid line shows the path of a storm when it had hurricane status. The dashed portion of each line traces the storm's path before and after hurricane stage. *(After National Hurricane Center)*

FIGURE 11-3 This world map shows the regions where most hurricanes form as well as their principal months of occurrence and the most common tracks they follow. Hurricanes do not develop within about 5° of the equator because the Coriolis force is too weak. Because warm surface ocean temperatures are necessary for hurricane formation, they seldom form poleward of 20° latitude nor over cool waters of the South Atlantic and the eastern South Pacific.



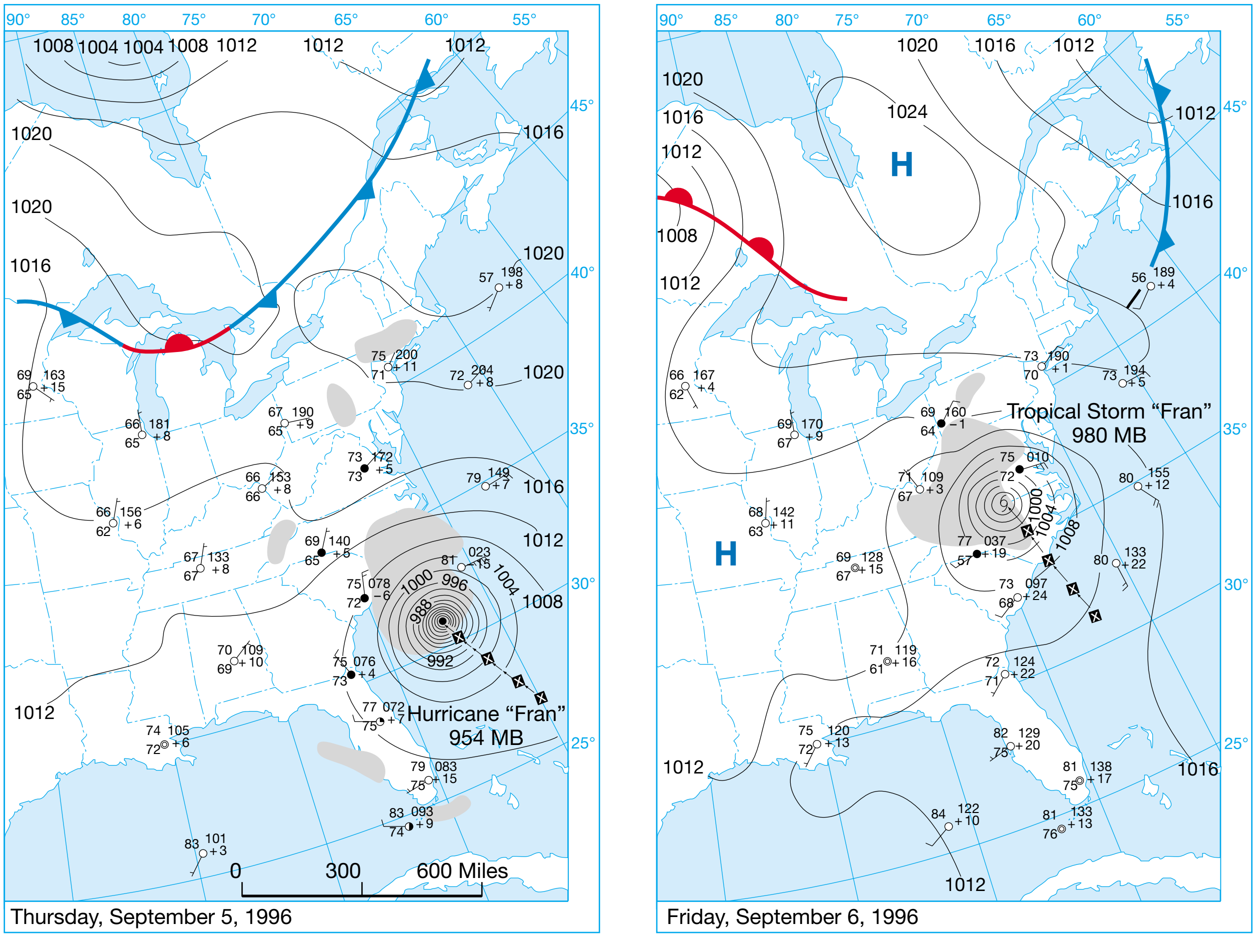


FIGURE 11-4 Weather maps showing Hurricane Fran at 7 A.M., EST, on two successive days, September 5 and 6, 1996. On September 5, winds exceeded 190 kph. As the storm moved inland, heavy rains caused flash floods, killed 30 people, and caused more than $3 billion in damages. The station information plotted off the Gulf and Atlantic coasts is from data buoys, which are remote floating instrument packages.

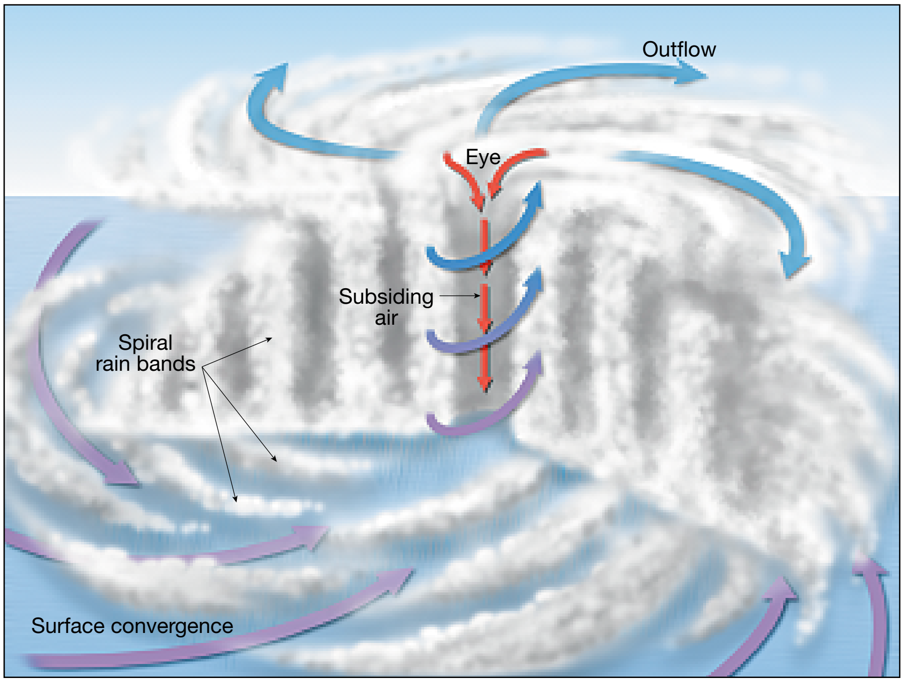


FIGURE 11-5 Cross section of a hurricane. Note that the vertical dimension is greatly exaggerated. The eye, the zone of relative calm at the center of the storm, is a distinctive hurricane feature. Sinking air in the eye warms by compression. Surrounding the eye is the eye wall, the zone where winds and rain are most intense. Tropical moisture spiraling inward creates rain bands that pinwheel around the storm center. Outflow of air at the top of the hurricane is important because it prevents the convergent flow at lower levels from "filling in" the storm. *(After NOAA)*

BOX 11-1 The Conservation of Angular Momentum

Why do winds blowing around a storm move faster near the center and more slowly near the edge? To understand this phenomenon, we must examine the *law of conservation of angular momentum.* This law states that the product of the velocity of an object around a center of rotation (axis) and the distance of the object from the axis is constant.

Picture an object on the end of a string being swung in a circle. If the string is pulled inward, the distance of the object from the axis of rotation decreases and the speed of the spinning object increases. The change in radius of the rotating mass is balanced by a change in its rotational speed.

Another common example of the conservation of angular momentum occurs when a figure skater starts whirling on the ice with both arms extended (Figure 11–A). Her arms are traveling in a circular path about an axis (her body). When the skater pulls her arms inward, she decreases the radius of the circular path of her arms. As a result, her arms go faster and the rest of her body must follow, thereby increasing her rate of spinning.

In a similar manner, when a parcel of air moves toward the center of a storm, the product of its distance and velocity must remain unchanged. Therefore, as air moves inward from the outer edge, its rotational velocity must increase.

Let us apply the law of conservation of angular momentum to the horizontal movement of air in a hypothetical hurricane. Assume that air with a velocity of 5 kilometers per hour begins 500 kilometers from the center of the storm. By the time it reaches a point 100 kilometers from the center, it will have a velocity of 25 kilometers per hour (assuming there is no friction). If this same parcel of air were to continue to advance toward the storm's center until its radius was just 10 kilometers, it would be traveling at 250 kilometers per hour. Friction reduces these values somewhat.

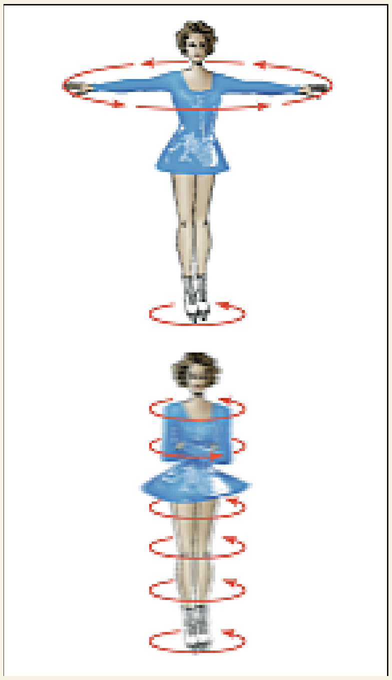


FIGURE 11-A When the skater's arms are extended, she spins slowly. When her arms are pulled in, she spins much faster.

the eye wall are curved bands of clouds that trail away in spiral fashion. Near the top of the hurricane the airflow is outward, carrying the rising air away from the storm center, thereby providing room for more inward flow at the surface.

At the very center of the storm is the **eye** of the hurricane. This well-known feature is a zone where precipitation ceases and winds subside. The graph in Figure 11–6 shows changes in wind speed and air pressure as Cyclone Monty came ashore at Mardie Station in Western Australia between February 29 and March 2, 2004. The very steep pressure gradient and strong winds associated with the eye wall are evident, as is the relative calm of the eye.

The eye offers a brief but deceptive break from the extreme weather in the enormous curving wall clouds that surround it. The air within the eye gradually descends and heats by compression, making it the warmest part of the storm. Although many people believe that the eye is characterized by clear blue skies, this is usually not the case because the subsidence in the eye is seldom strong enough to produce cloudless conditions. Although the sky appears much brighter in this region, scattered clouds at various levels are common.

Students Sometimes Ask…

Why do hurricanes hit the Gulf and Atlantic coasts but not the Pacific Coast?

There are two main reasons. One is that after hurricanes form in the subtropics, they tend to move toward the west or northwest. In the Atlantic and Gulf of Mexico, this movement sometimes brings storms into the vicinity of the mainland. In the northeast Pacific, however, a west or northwest track moves hurricanes farther offshore, away from the coast (see Figure 11–3). The second factor is the difference in water temperatures between America's coasts. Along the Gulf and Atlantic, water temperatures in summer and fall are warm (more than 27°C or 80°F) and provide the needed heat and moisture to sustain hurricanes. By contrast, along the U.S. West Coast, ocean temperatures rarely exceed the low 20s Celsius (70s Fahrenheit). These cool temperatures are not sufficient to sustain a hurricane. Thus, when an occasional northeast Pacific hurricane moves toward the West Coast, the cool waters quickly reduce the storm's strength.

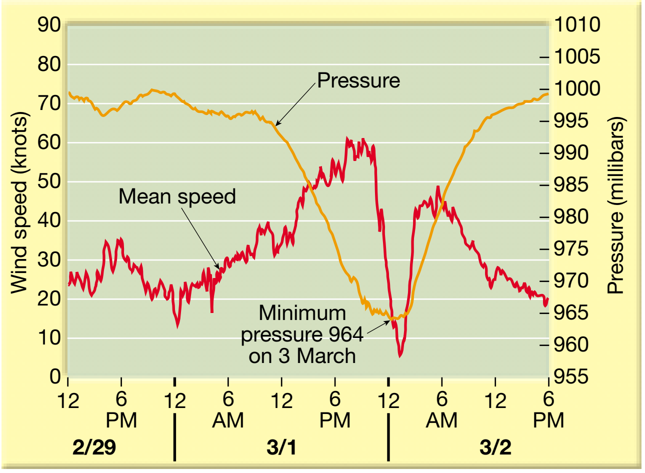


FIGURE 11-6 Measurements of surface pressure and wind speed during the passage of Cyclone Monty at Mardie Station in Western Australia between February 29 and March 2, 2004. The strongest winds are associated with the eye wall, and the weakest winds and lowest pressure are found in the eye. *(Data from World Meteorological Organization)*

Hurricane Formation and Decay

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

Hurricanes develop most often in the late summer when ocean waters have reached temperatures of 27°C (80°F) or higher and are thus able to provide the necessary heat and moisture to the air. This ocean-water temperature requirement accounts for the fact that hurricanes do not form over the relatively cool waters of the South Atlantic and the eastern South Pacific (Figure 11–7). For the same reason, few hurricanes form poleward of 20 degrees of latitude (see Figure 11–3). Although water temperatures are sufficiently high, hurricanes do not form within 5 degrees of the equator, because the Coriolis force is too weak to initiate the necessary rotary motion.

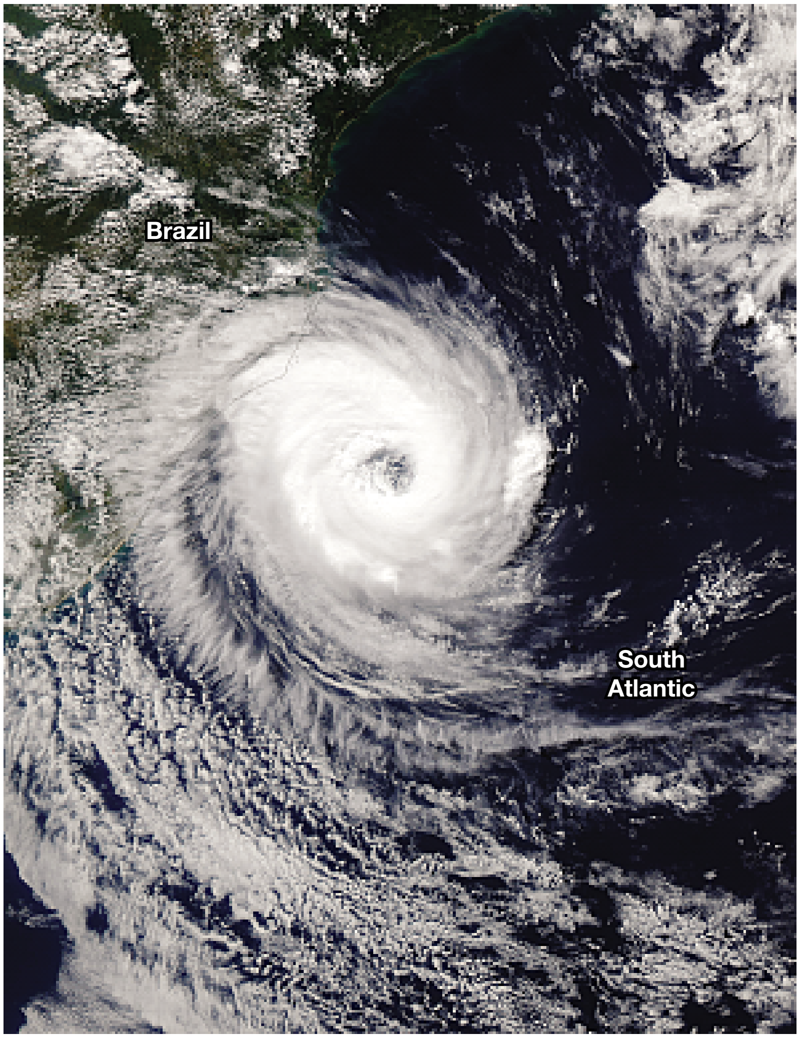


FIGURE 11-7 Since the beginning of the satellite era in the mid-1960s, no hurricane had ever been observed in the South Atlantic—that is, until March 2004. On the morning of March 28, 2004, a Category 1 hurricane, with winds between 121–129 kilometers (75–80 miles) per hour, struck the east coast of Brazil. (For an explanation of hurricane categories, see Table 11–2, p. 329.) Although there was minimal loss of life, coastal property damage approached $330 million. The clouds show the clockwise spiral associated with Southern Hemisphere storms. *(NASA image)*

Hurricane Formation

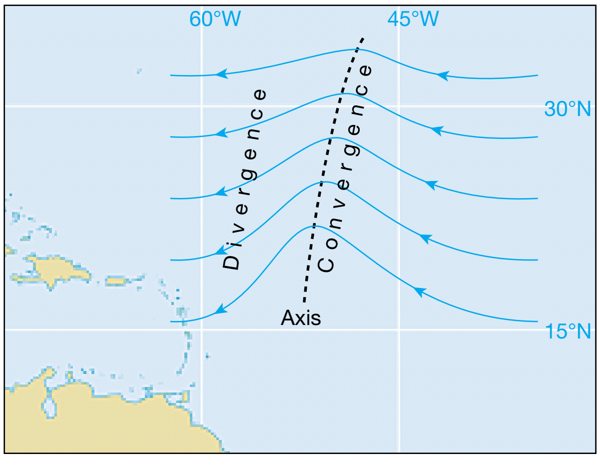
Many tropical storms achieve hurricane status in the western parts of oceans, but their origins often lie far to the east. There disorganized arrays of clouds and thunderstorms, called **tropical disturbances,** sometimes develop and exhibit weak pressure gradients and little or no rotation. Most of the time these zones of convective activity die out. However, occasionally tropical disturbances grow larger and develop a strong cyclonic rotation.

Several different situations can trigger tropical disturbances. They are sometimes initiated by the powerful convergence and lifting associated with the intertropical convergence zone (ITCZ). Others form when a trough from the middle latitudes intrudes into the tropics. Tropical disturbances that produce many of the strongest hurricanes that enter the western North Atlantic and threaten North America often begin as large undulations or ripples in the trade winds known as **easterly waves,** so named because they gradually move from east to west.

Figure 11–8 illustrates an easterly wave. The lines on this simple map are not isobars. Rather, they are *streamlines,* lines drawn parallel to the wind direction used to depict surface airflow. When middle-latitude weather is analyzed, isobars are usually drawn on the weather map. By contrast, in the tropics the differences in sea-level pressure are quite small, so isobars are not always useful. Streamlines are helpful because they show where surface winds converge and diverge.

To the east of the wave axis the streamlines move poleward and get progressively closer together, indicating that the surface flow is convergent. Convergence, of course, encourages air to rise and form clouds. Therefore, the tropical disturbance is located on the east side of the wave. To the west of the wave axis, surface flow diverges as it turns toward the equator. Consequently, clear skies are the rule here.

FIGURE 11-8 Easterly wave in the subtropical Atlantic. Streamlines show low-level airflow. To the east of the wave axis, winds converge as they move slightly poleward. To the west of the axis, flow diverges as it turns toward the equator. Tropical disturbances are associated with the convergent flow of the easterly wave. Easterly waves extend for 2000 to 3000 kilometers (1200 to 1800 miles) and move from east to west with the trade winds at rates between 15 and 35 kilometers (10 and 20 miles) per hour. At this rate, it takes an imbedded tropical disturbance a week or 10 days to move across the North Atlantic.



Easterly waves frequently originate as disturbances in Africa. As these storms head westward with the prevailing trade winds, they encounter the cold Canaries current (see Figure 3–7, p. 73). If the disturbance survives the trip across the cold stabilizing waters of the current, it is rejuvenated by the heat and moisture of the warmer water of the mid-Atlantic. From this point on, a small percentage develop into more intense and organized systems, some of which may reach hurricane status.

Even when conditions seem to be right for hurricane formation, many tropical disturbances do not strengthen. One circumstance that may inhibit further development is a temperature inversion called the *trade wind inversion.* It forms in association with the subsidence that occurs in the region influenced by the subtropical high.[†] A strong inversion diminishes air's ability to rise and thus inhibits the development of strong thunderstorms. Another factor that works against the strengthening of tropical disturbances is strong upper-level winds. When present, a strong flow aloft disperses the latent heat released from cloud tops, heat that is essential for continued growth and development.

What happens on those occasions when conditions favor hurricane development? As latent heat is released from the clusters of thunderstorms that make up the tropical disturbance, areas within the disturbance get warmer. As a consequence, air density lowers and surface pressure drops, creating a region of weak low pressure and cyclonic circulation. As pressure drops at the storm center, the pressure gradient steepens. In response, surface wind speeds increase and bring additional supplies of moisture to nurture storm growth. The water vapor condenses, releasing latent heat, and the heated air rises. Adiabatic cooling of rising air triggers more condensation and the release of more latent heat, which causes a further increase in buoyancy. And so it goes.

Meanwhile, higher pressure develops at the top of the developing tropical depression.[‡] This causes air to flow outward (diverge) from the top of the storm. Without this outward flow up top, the inflow at lower levels would soon raise surface pressures and thwart further storm development.

Although many tropical disturbances occur each year, only a few develop into full-fledged hurricanes. Recall that tropical cyclones are called hurricanes only when their winds reach 119 kilometers (74 miles) per hour. By international agreement, lesser tropical cyclones are given different names based on the strength of their winds. When a cyclone's strongest winds do not exceed 61 kilometers (37 miles) per hour, it is called a **tropical depression.** When sustained

[†]In the troposphere, a temperature inversion exists when temperatures in a layer of air increase with an increase in altitude rather than by decreasing with height, which is usually the case. For more on how subsidence can produce an inversion, see the section on "Inversions Aloft" in Chapter 13, p. 392–93.

[‡]See Figure 6–11 and the discussion of the sea–land breeze in the section on "Pressure Gradient Force" in Chapter 6.

winds are between 61 and 119 kilometers (37 and 74 miles) per hour, the cyclone is termed a **tropical storm.** It is during this phase that a name is given (Andrew, Fran, Opal, etc.). Should the tropical storm become a hurricane, the name remains the same (see Box 11–2). Each year between 80 and 100 tropical storms develop around the world. Of them, usually half or more eventually reach hurricane status.

Students Sometimes Ask…

When is hurricane season?

Hurricane season is different in different parts of the world. People in the United States are usually most interested in Atlantic storms. The Atlantic hurricane season officially extends from June through November. More than 97 percent of tropical activity in that region occurs during this six-month span. The "heart" of the season is August through October. During these three months, 87 percent of the minor hurricane (category 1 and 2) days and 96 percent of the major hurricane (category 3, 4, and 5) days occur. Peak activity is in early to mid-September.

Hurricane Decay

Hurricanes diminish in intensity whenever they (1) move over ocean waters that cannot supply warm, moist tropical air, (2) move onto land, or (3) reach a location where the large-scale flow aloft is unfavorable. Richard Anthes describes the possible fate of hurricanes in the first category as follows:

> Many hurricanes approaching the North American or Asian continents from the southeast are turned toward the northeast, away from the continents, by the steering effect of an upper-level trough. This recurvature carries the storms toward higher latitudes where the ocean temperatures are cooler and an encounter with cool, dry polar air masses is more likely. Often the tropical cyclone and a polar front interact, with cold air entering the tropical cyclone from the west. As the release of latent heat is diminished, the upper-level divergence weakens, mean temperatures in the core fall and the surface pressure rises.*

Whenever a hurricane moves onto land, it loses its punch rapidly. For example, in Figure 11–4 notice how the isobars show a much weaker pressure gradient on September 6 after Hurricane Fran moved ashore than on September 5 when it was over the ocean. The most important reason for this rapid demise is the fact that the storm's source of warm, moist air is cut off. When an adequate supply of water vapor does not exist, condensation and the release of latent heat must diminish.

In addition, the increased surface roughness over land results in a rapid reduction in surface wind speeds. This factor causes the winds to move more directly into the center of the low, thus helping to eliminate the large pressure differences.

Hurricane Destruction

Although the amount of damage caused by a hurricane depends on several factors, including the size and population density of the area affected and the nearshore bottom configuration, certainly the most significant factor is the strength of the storm itself.

Based on the study of past storms, the **Saffir–Simpson scale** was established to rank the relative intensities of hurricanes (Table 11–2). Predictions of hurricane severity and damage are usually expressed in terms of this scale. When a tropical storm becomes a hurricane, the National Weather Service assigns it a scale (category) number. Category assignments are based on observed conditions at a particular stage in the life of a hurricane and are viewed as estimates of the amount of damage a storm would cause if it were to make landfall without changing size or strength. As conditions change, the category of a storm is reevaluated so that public-safety officials can be kept informed. By using the Saffir–Simpson scale, the disaster potential of a hurricane can be monitored and appropriate precautions can be planned and implemented.

A rating of 5 on the scale represents the worst storm possible, and a 1 is least severe. Storms that fall into Category 5 are rare. Only three storms this powerful are known to have hit the continental United States: Andrew struck Florida in 1992, Camille pounded Mississippi in 1969, and a Labor Day hurricane struck the Florida Keys in 1935. Damage caused by hurricanes can be divided into three classes: (1) storm surge, (2) wind damage, and (3) inland freshwater flooding.

Students Sometimes Ask…

Are larger hurricanes stronger than smaller hurricanes?

Not necessarily. Actually, there is very little correlation between intensity (either measured by maximum sustained winds or by central pressure) and size (either measured by the radius of gale force winds or the radius of the outer closed isobar). Hurricane Andrew is a good example of a very intense storm (recently reevaluated and upgraded to the most intense category 5 level) that was also relatively small (gale-force winds extended only 150 kilometers/90 miles from the eye). Research has shown that changes in intensity and size are essentially independent of one another.

**Tropical Cyclones: Their Evolution, Structure, and Effects,* Meteorological Monographs, Vol. 19, no. 41 (1982), p. 61. Boston: American Meteorological Society.

BOX 11-2 Naming Tropical Storms and Hurricanes

Tropical storms are named to provide ease of communication between forecasters and the general public regarding forecasts, watches, and warnings. Tropical storms and hurricanes can last a week or longer, and two or more storms can be occurring in the same region at the same time. Thus, names can reduce the confusion about what storm is being described.

During World War II, tropical storms were informally assigned women's names (perhaps after wives and girlfriends) by U.S. Army Corps and Navy meteorologists who were monitoring storms over the Pacific. From 1950 to 1952, tropical storms in the North Atlantic were identified by the phonetic alphabet—Able, Baker, Charlie, and so forth. In 1953 the U.S. Weather Bureau (now the National Weather Service) switched to women's names.

The practice of using feminine names continued until 1978, when a list containing both male and female names was adopted for tropical cyclones in the eastern Pacific. In the same year a proposal that both male and female names be adopted for Atlantic hurricanes, beginning with the 1979 season, was accepted by the World Meteorological Organization (WMO).

The WMO has created six lists of names for tropical storms over ocean areas. The names used for Atlantic, Gulf of Mexico, and Caribbean hurricanes are shown in Table 11–A. The names are ordered alphabetically and do not contain names that begin with the letters Q, U, X, Y, and Z because of the scarcity of names beginning with those letters. When a tropical depression reaches tropical storm status, it is assigned the next unused name on the list. At the beginning of the next hurricane season, names from the next list are selected even though many names may not have been used the previous season.

The names for Atlantic storms are used over again at the end of each six-year cycle unless a hurricane was particularly noteworthy. This is to avoid confusion when storms are discussed in future years. For example, the names of the four hurricanes that struck Florida in 2004 (Charley, Frances, Ivan, and Jeanne) were replaced by Colin, Fiona, Igor, and Julia on the list for the year 2010.

TABLE 11-A Tropical storm and hurricane names for the Atlantic, Gulf of Mexico, Caribbean Sea*

2005	2006	2007	2008	2009	2010
Arlene	Alberto	Andrea	Arthur	Ana	Alex
Bret	Beryl	Barry	Bertha	Bill	Bonnie
Cindy	Chris	Chantal	Cristobal	Claudette	Colin
Dennis	Debby	Dean	Dolly	Danny	Danielle
Emily	Ernesto	Erin	Edouard	Erika	Earl
Franklin	Florence	Felix	Fay	Fred	Fiona
Gert	Gordon	Gabrielle	Gustav	Grace	Gaston
Harvey	Helene	Humberto	Hanna	Henri	Hermine
Irene	Isaac	Ingrid	Ike	Ida	Igor
Jose	Joyce	Jerry	Josephine	Joaquin	Julia
Katrina	Kirk	Karen	Kyle	Kate	Karl
Lee	Leslie	Lorenzo	Laura	Larry	Lisa
Maria	Michael	Melissa	Marco	Mindy	Matthew
Nate	Nadine	Noel	Nana	Nicholas	Nicole
Ophelia	Oscar	Olga	Omar	Odette	Otto
Philippe	Patty	Pablo	Paloma	Peter	Paula
Rita	Rafael	Rebekah	Rene	Rose	Richard
Stan	Sandy	Sebastien	Sally	Sam	Shary
Tammy	Tony	Tanya	Teddy	Teresa	Tomas
Vince	Valerie	Van	Vicky	Victor	Virginie
Wilma	William	Wendy	Wilfred	Wanda	Walter

*If the entire alphabetical list of names for a given year is exhausted, the naming system moves on to using letters of the Greek alphabet (alpha, beta, gamma, etc). This issue never arose until the record-breaking 2005 hurricane season when Tropical Storm Alpha, Hurricane Beta, tropical storms Gamma and Delta, Hurricane Epsilon, and Tropical Storm Zeta occurred after Hurricane Wilma.

TABLE 11-2 Saffir–Simpson hurricane scale

Scale number (category)	Central pressure (millibars)	Wind speed (kph)	Wind speed (mph)	Storm surge (meters)	Storm surge (feet)	Damage
1	980	119–153	74–95	1.2–1.5	4–5	*Minimal.* No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Also, some coastal-road flooding and minor pier damage.
2	965–979	154–177	96–110	1.6–2.4	6–8	*Moderate.* Some roofing material, door, and window damage to buildings. Some trees blown down. Considerable damage to mobile homes. Coastal and low-lying escape routes flood 2 to 4 hours before arrival of the hurricane center. Small craft in unprotected anchorages break moorings.
3	945–964	178–209	111–130	2.5–3.6	9–12	*Extensive.* Some structural damage to small residences and utility buildings. Large trees blown down. Mobile homes are destroyed. Flooding near the coast destroys smaller structures with larger structures damaged by battering of floating debris. Terrain lower than 2 meters above sea level may be flooded inland 13 km or more. Evacuation of low-lying residences within several blocks of the shoreline may be required.
4	920–944	210–250	131–155	3.7–5.4	13–18	*Extreme.* Some complete roof structure failures on small residences. Extensive damage to doors and windows. Low-lying escape routes may be cut 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 meters above sea level may be flooded, requiring massive evacuation of residential areas as far inland as 10 km.
5	<920	>250	>155	>5.4	>18	*Catastrophic.* Complete roof failure on many residences and industrial buildings. Some complete building failures. Severe window and door damage. Low-lying escape routes are cut by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of all structures located less than 5 meters above sea level and within 500 meters of the shoreline. Massive evacuation of residential areas on low ground within 8 to 16 km of the shoreline may be required.

Storm Surge

Without question, the most devastating damage in the coastal zone is caused by the storm surge. It not only accounts for a large share of coastal property losses but is also responsible for 90 percent of all hurricane-caused deaths. A **storm surge** is a dome of water 65 to 80 kilometers (40 to 50 miles) wide that sweeps across the coast near the point where the eye makes landfall. If all wave activity were smoothed out, the storm surge would be the height of the water above normal tide level (Figure 11–9). In addition, tremendous wave activity is superimposed on the surge. We can easily imagine the damage that this surge of water could inflict on low-lying coastal areas (Figure 11–10). The worst surges occur in places like the Gulf of Mexico, where the continental shelf is very shallow and gently sloping. In addition, local features such as bays and rivers can cause the surge height to double and increase in speed.

In the delta region of Bangladesh, for example, most of the land is less than 2 meters (6.5 feet) above sea level. When a storm surge superimposed on normal high tide inundated that area on November 13, 1970, the official death toll was 200,000; unofficial estimates ran to 500,000. It was one of the worst natural disasters of modern times. In May 1991 a similar event again struck Bangladesh. This time the storm took the lives of at least 135,000 people and devastated coastal towns in its path.

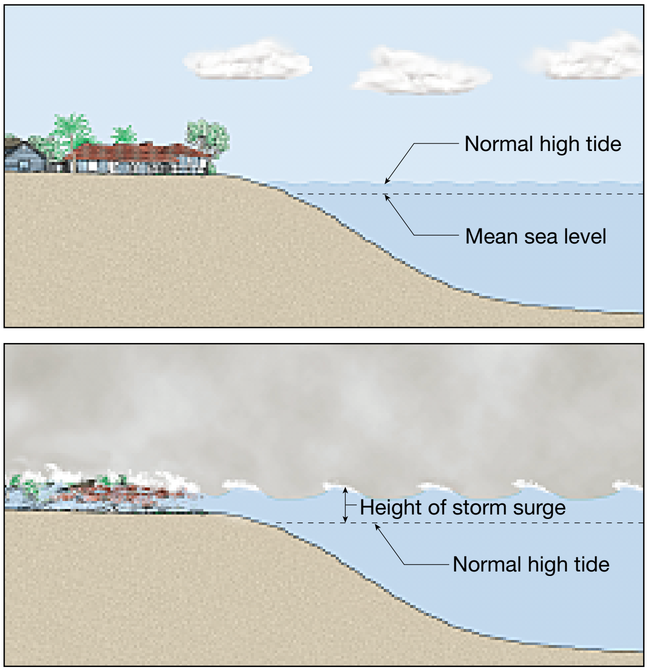


FIGURE 11-9 Superimposed upon high tide, a storm surge can devastate a coastal area. The worst storm surges occur in coastal areas where there is a very shallow and gently sloping continental shelf extending from the beach. The Gulf Coast is such a place.

A common misconception about the cause of hurricane storm surges is that the very low pressure at the center of the storm acts as a partial vacuum that allows the ocean to rise up in response. However, this effect is relatively insignificant. The most important factor responsible for the development of a storm surge is the piling up of ocean water by strong onshore winds. Gradually the hurricane's winds push water toward the shore, causing sea level to elevate while also churning up violent wave activity.

As a hurricane advances toward the coast in the Northern Hemisphere, storm surge is always most intense on the right side of the eye where winds are blowing *toward* the shore. In addition, on this side of the storm the forward movement of the hurricane also contributes to the storm surge. In Figure 11–11, assume a hurricane with peak winds of 175 kilometers (109 miles) per hour is moving toward the shore at 50 kilometers (31 miles) per hour. In this case, the net wind speed on the right side of the advancing storm is 225 kilometers (140 miles) per hour. On the left side, the hurricane's winds are blowing opposite the direction of storm movement, so the net winds are *away* from the coast at 125 kilometers (78 miles) per hour. Along the shore facing the left side of the oncoming hurricane, the water level may actually decrease as the storm makes landfall.

Wind Damage

Destruction caused by wind is perhaps the most obvious of the classes of hurricane damage. Debris such as signs, roofing materials, and small items left outside become dangerous flying missiles in hurricanes. For some struc-

(a)

(b)

FIGURE 11-10 Storm surge damage along the Mississippi coast caused by Hurricane Katrina. At some locations the surge exceeded 7.5 meters (25 feet). (a) This concrete slab is all that remains of an apartment house in Biloxi. *(Photo by Barry Williams/Getty Images)* (b) Houses and vehicles litter the railway near Pass Christian. *(AP Photo/Phil Coale)*

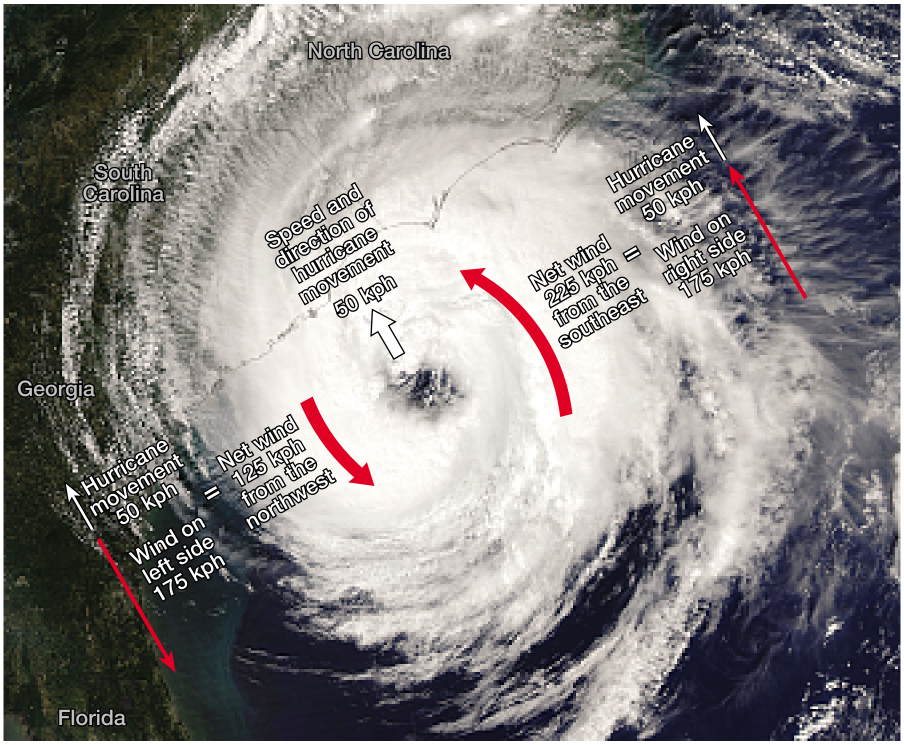


FIGURE 11-11 Winds associated with a Northern Hemisphere hurricane that is advancing toward the coast. This hypothetical storm, with peak winds of 175 kilometers (109 miles) per hour, is moving toward the coast at 50 kilometers (31 miles) per hour. On the right side of the advancing storm, the 175-kilometer-per-hour winds are in the same direction as the movement of the storm (50 kilometers per hour). Therefore, the *net* wind speed on the right side of the storm is 225 kilometers (140 miles) per hour. On the left side, the hurricane's winds are blowing opposite the direction of storm movement, so the *net* winds of 125 kilometers (78 miles) per hour are away from the coast. Storm surge will be greatest along that part of the coast hit by the right side of the advancing hurricane.

tures, the force of the wind is sufficient to cause total ruin. Just read the descriptions of category 3, 4, and 5 storms in Table 11–2. Mobile homes are particularly vulnerable. High-rise buildings are also susceptible to hurricane-force winds. Upper floors are most vulnerable because wind speeds usually increase with height. Recent research suggests that people should stay below the tenth floor but remain above any floors at risk for flooding. In regions with good building codes, wind damage is usually not as catastrophic as storm-surge damage. However, hurricane-force winds affect a much larger area than storm surge and can cause huge economic losses. For example, in 1992 it was largely the winds associated with Hurricane Andrew that produced more than $25 billion of damage in southern Florida and Louisiana.

Hurricanes sometimes produce tornadoes that contribute to the storm's destructive power. Studies have shown that more than half of the hurricanes that make landfall produce at least one tornado. In 2004 the number of tornadoes associated with tropical storms and hurricanes was extraordinary. Tropical Storm Bonnie and five landfalling hurricanes—Charley, Frances, Gaston, Ivan, and Jeanne—produced nearly 300 tornadoes that affected the southeast and mid-Atlantic states (Table 11–3). Hurricane Frances produced the most tornadoes ever reported from one hurricane. The large number of hurricane-generated tornadoes in 2004 helped make this a record-breaking year—surpassing the previous record by more than 300.*

*K. L. Gleason, et al. "U.S. Tornado Records" in *Bulletin of the American Meteorological Society,* Vol. 86, No. 6, June 2005, p. 551.

Inland Flooding

The torrential rains that accompany most hurricanes represent a third significant threat—flooding. The 2004 hurricane season was very deadly, with a loss of life that exceeded 3000 people. Nearly all of the deaths occurred in Haiti as a result of flash floods and mudflows caused by the heavy rains associated with then Tropical Storm Jeanne.

Hurricane Agnes (1972) illustrates that even modest storms can have devasting results. Although it was only a category 1 storm on the Saffir–Simpson scale, it was one of the costliest hurricanes of the twentieth century, creating more than $2 billion in damage and taking 122 lives. The greatest destruction was attributed to flooding in the northeastern portion of the United States, especially in Pennsylvania, where record rainfalls occurred. Harrisburg received nearly 32 centimeters (12.5 inches) in 24 hours and western Schuylkill County measured more than 48 centimeters (19 inches) during the same span. Agnes's rains were not as devastating elsewhere. Prior to reaching Pennsylvania, the storm caused some flooding in Georgia, but most farmers welcomed the rain because dry conditions had been

TABLE 11–3 Number of tornadoes spawned by hurricanes and tropical storms in the United States, 2004

Tropical Storm Bonnie	30
Hurricane Charley	25
Hurricane Frances	117
Hurricane Ivan	104
Hurricane Jeanne	16

plaguing them earlier. In fact, the value of the rains to crops in the region far exceeded the losses caused by flooding.

Another well-known example is Hurricane Camille (1969). Although this storm is best known for its exceptional storm surge and the devastation it brought to coastal areas, the greatest number of deaths associated with this storm occurred in the Blue Ridge Mountains of Virginia two days after Camille's landfall. Here many places received more than 25 centimeters (10 inches) of rain and severe flooding took more than 150 lives.

To summarize, extensive damage and loss of life in the coastal zone can result from storm surge, strong winds, and torrential rains. When loss of life occurs, it is commonly caused by the storm surge, which can devastate entire barrier islands or zones within a few blocks of the coast. Although wind damage is usually not as catastrophic as the storm surge, it affects a much larger area. Where building codes are inadequate, economic losses can be especially severe. Because hurricanes weaken as they move inland, most wind damage occurs within 200 kilometers (125 miles) of the coast. Far from the coast, a weakening storm can produce extensive flooding long after the winds have diminished below hurricane levels. Sometimes the damage from inland flooding exceeds storm-surge destruction.

Estimating the Intensity of a Hurricane

The Saffir–Simpson Hurricane Scale appears to be a straightforward tool. However, the accurate observations needed to correctly portray hurricane intensity at the surface are sometimes difficult to obtain. Estimating hurricane intensity is difficult because direct surface observations in the eye wall are rarely available. Therefore, winds in this most intense part of the storm have to be estimated. One of the best ways to estimate surface intensity is to adjust the wind speeds measured by reconnaissance aircraft.

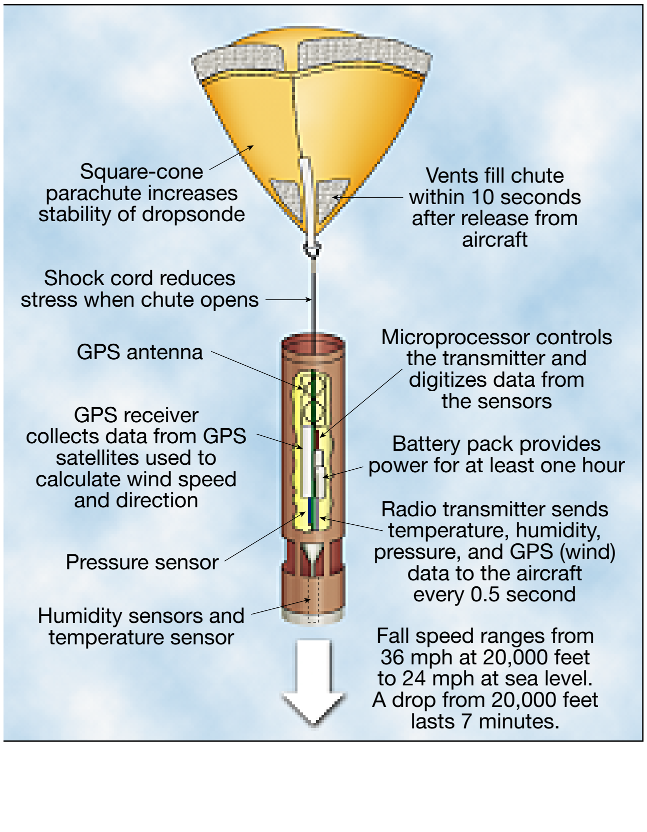
Winds aloft are stronger than winds at the surface. Therefore, the adjustment of values determined for winds aloft to values expected at the surface involves *reducing* the measurements made aloft. However, until the late 1990s, determining the proper adjustment factor was problematic because surface observations in the eye wall were too limited to establish a broadly accepted relationship between flight-level and surface winds. In the early 1990s the reduction factors commonly used ranged from 75 to 80 percent (that is, surface wind speeds were assumed to be between 75 and 80 percent of the speed at 3000 meters/10,000 feet). Some scientists and engineers even maintained that surface winds were as low as 65 percent of flight-level winds.

Beginning in 1997 a new instrument, called a *Global Positioning System (GPS) dropwindsonde*, came into use (sometimes just called a *dropsonde*). After being released from the aircraft, this package of instruments, slowed by a small parachute, drifts downward through the storm (Figure 11–12). During the descent, it continuously transmits data on temperature, humidity, air pressure, wind speed, and wind direction. The development of this technology for the first time provided a way to accurately measure the strongest winds in a hurricane from flight level all the way to the surface.

Over a span of several years, hundreds of GPS dropwindsondes were released in hurricanes. The data accumulated from these trials showed that the speed of surface winds in the eye wall averaged about 90 percent of the flight-level winds, not 75 to 80 percent. Based on this new understanding, the National Hurricane Center now uses the 90 percent figure to estimate a hurricane's maximum surface winds from flight-level observations. This means that the winds in some storms in the historical record were underestimated.

For example, in 1992 the surface winds in Hurricane Andrew were estimated to be 233 kilometers (145 miles) per hour. This was 75 to 80 percent of the value measured at 3000 meters by the reconnaissance aircraft. When scientists at the National Hurricane Center reevaluated the storm using the 90 percent value, they concluded that the maximum-sustained surface winds had been 266 kilometers (165 miles) per hour—33 kilometers (20 miles) per hour faster than the original 1992 estimate. Consequently, in August 2002 the intensity of Hurricane Andrew was officially changed from category 4 to category 5. The upgrade makes Hurricane Andrew only the third category 5 storm on record to strike the continental United States. (Recall that the other

FIGURE 11-12 The Global Positioning System (GPS) dropwindsonde is frequently just called a dropsonde. This cylindrical instrument package is roughly 7 cm (2.75 in) in diameter, 40 cm (16 in) long, and weighs about 0.4 kg (0.86 lb). The instrument package is released from the aircraft and falls through the storm via a parachute, making and transmitting measurements of temperature, pressure, winds, and humidity every half-second. *(After NASA)*



two were the "Florida Keys 1935 Hurricane" and Hurricane Camille in 1969.)

Students Sometimes Ask...

If a Category 1 hurricane produces only "minimal" damage, are tropical storms any sort of significant weather threat?

The answer is a definite yes. Although tropical storm winds are less intense than winds in a hurricane, rainfall amounts can be prodigious. For example, in June 2001, Tropical Storm Allison dropped 93.95 centimeters (36.99 inches) of rain at the Port of Houston, Texas. At Houston Intercontinental Airport, 41.83 centimeters (16.47 inches) fell on June 10, 2001—roughly four times the normal June precipitation—making it the wettest June on record. The previous wettest June occurred in 1989 when 41.35 centimeters (16.28 inches) of rain fell, mostly from another tropical storm, named Allison! The 2001 storm caused nearly $5 billion in damages in the Houston area, making it the costliest tropical storm in U.S. history. In addition, the flooding, lightning, and tornadoes associated with Allison claimed more than 40 lives.

Detecting and Tracking Hurricanes

By examining Figures 11–2 and 11–3, you can see some of the typical paths followed by tropical storms and hurricanes in the North Atlantic. What determines these tracks? The storms can be thought of as being steered by the surrounding environmental flow throughout the depth of the troposphere. The movement of hurricanes has been likened to a leaf being carried along by the currents in a stream, except that for a hurricane the "stream" has no set boundaries.

In the latitude zone equatorward of about 25° north, tropical storms and hurricanes commonly move to the west with a slight poleward component. (Look at the storm tracks in Figure 11–2 and in Figure 11–G, for example.) This occurs because of the semipermanent cell of high pressure (called the *Bermuda High*) that is positioned poleward of the storm (see Figure 7–10b, p. 209). On the equatorward side of this high-pressure center, easterly winds prevail that guide the storms westward. If this high-pressure center is weak in the western Atlantic, the storm often turns northward. On the poleward side of the Bermuda High, westerly winds prevail that steer the storm back toward the east. Often it is difficult to determine whether the storm will curve back out to sea or whether it will continue straight ahead and make landfall.

A location only a few hundred kilometers from a hurricane—just a day's striking distance away—may experience clear skies and virtually no wind. Before the age of weather satellites, such a situation made it difficult to warn people of impending storms. The worst natural disaster in U.S. history came as a result of a hurricane that struck an unprepared Galveston, Texas, on September 8, 1900. The strength of the storm, together with the lack of adequate warning, caught the population by surprise and cost the lives of 6000 people in the city and at least 2000 more elsewhere (Figure 11–13).*

*For a facinating account of the Galveston storm, read *Isaac's Storm* by Erik Larson, New York: Crown Publishers, 1999.

FIGURE 11-13 Aftermath of the Galveston hurricane of 1900. Entire blocks were swept clean, while mountains of debris accumulated around the few remaining buildings. *(AP Photos)*

(a) (b)

BOX 11-3 Atmospheric Hazard: Examining Hurricane Katrina from Space

Satellites allow us to track the formation, movement, and growth of hurricanes. In addition, their specialized instruments provide data that can be transformed into images that allow scientists to analyze the internal structure and workings of these huge storms. The images and captions in this box provide a unique perspective of Hurricane Katrina, the most devastating storm to strike the United States in more than a century.

Figures 11–B, 11–C, 11–D, and 11–E are from NASA's *Terra* satellite and are relatively "traditional" images that show Katrina at various stages of its development and dissipation.

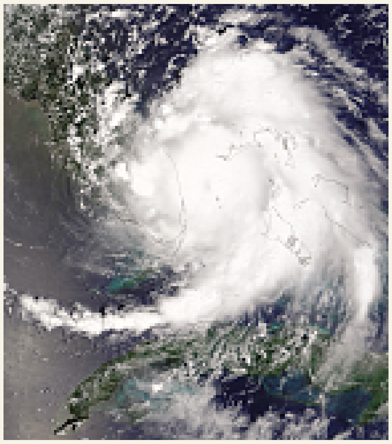


FIGURE 11-C The storm on August 25, 2005 at 12:30 P.M. EDT, just 12 hours and 40 minutes later than the image in 11–B. By this time Katrina is a Category 1 hurricane. Because the storm moved slowly, just 10 kilometers (6 miles) per hour, heavy rainfall totals were expected. See Figure 11–H to view the rainfall pattern. *(NASA image)*

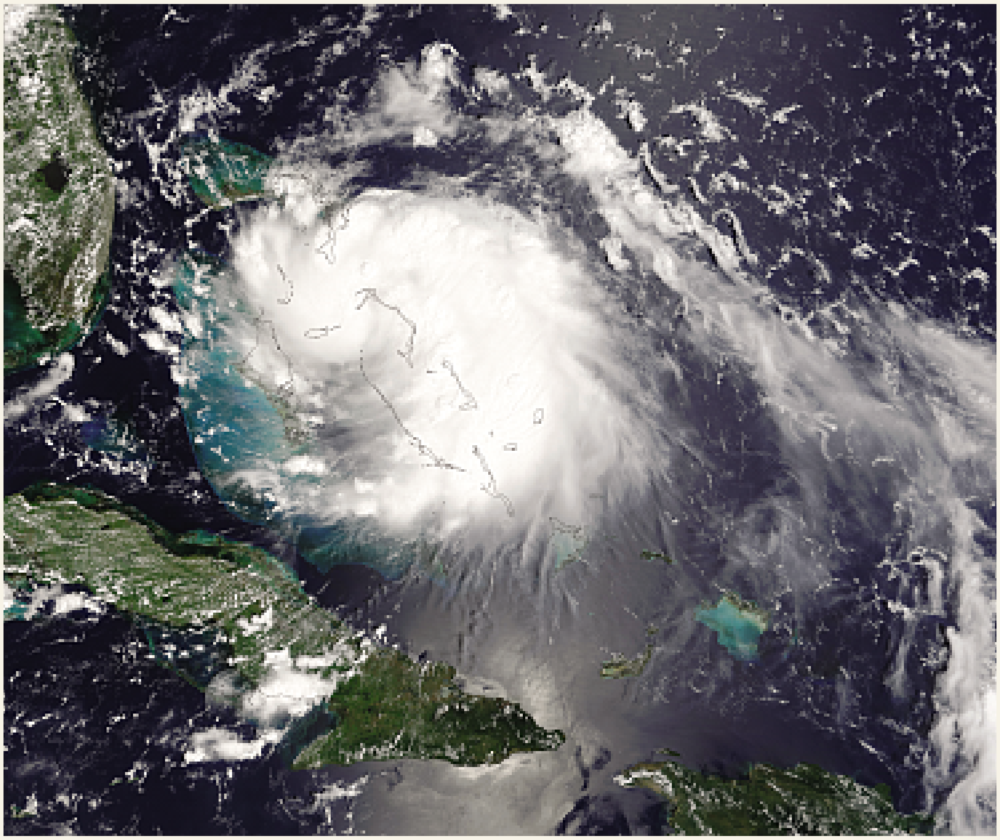


FIGURE 11-B Image of Tropical Storm Katrina on August 24, 2005, at 11:50 A.M. EDT, shortly after it became the eleventh named storm of the 2005 Atlantic hurricane season. The storm formed late on August 23 and developed quickly into a tropical storm by 11 A.M. the next morning. When this image was taken, Katrina had winds of 64 kilometers (40 miles) per hour, and was just beginning to take on the recognizable swirling shape of a hurricane. *(NASA image)*

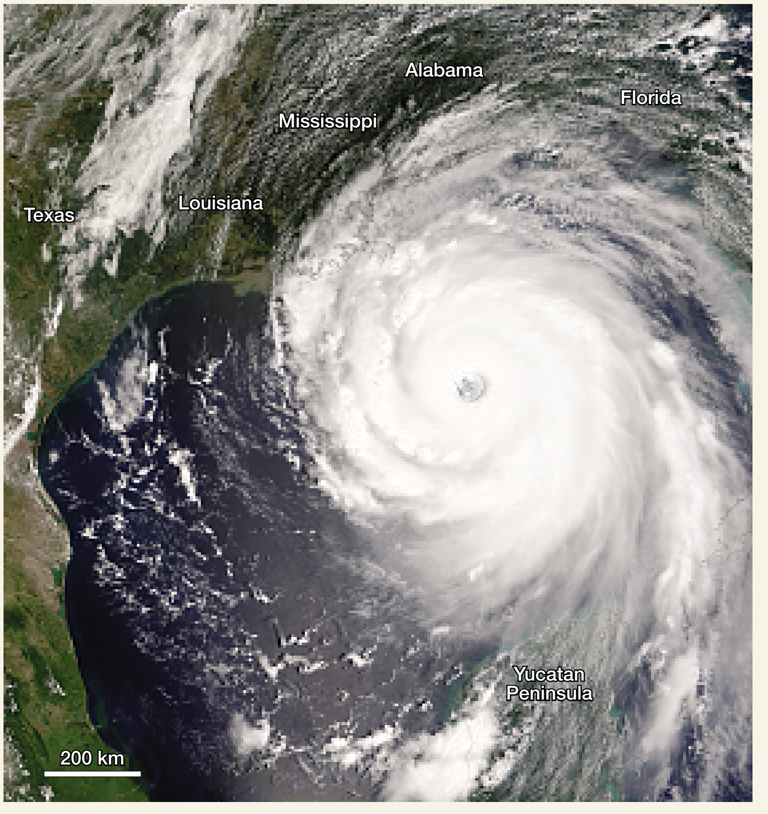


FIGURE 11-D This image shows Katrina at 1 P.M. EDT on Sunday, August 28, 2005, as a massive storm covering much of the Gulf of Mexico. After passing over Florida as a Category 1 hurricane, Katrina entered the Gulf and intensified into a Category 5 storm with winds of 257 kilometers (160 miles) per hour and even stronger gusts. Air pressure at the center of the storm measured 902 millibars. When Katrina came ashore the next day, it was a slightly less vigorous Category 4 storm. *(NASA image)*

FIGURE 11-E In this image from 3:15 P.M. EDT on August 29, 2005, Katrina measured about 1260 kilometers (780 miles) across and is sprawled over all or part of 16 states. After coming ashore as a Category 4 storm, it was still a Category 1 after being over land for nearly 8 hours. *(NASA image)*

BOX 11-3 Atmospheric Hazard: Examining Hurricane Katrina from Space (continued)

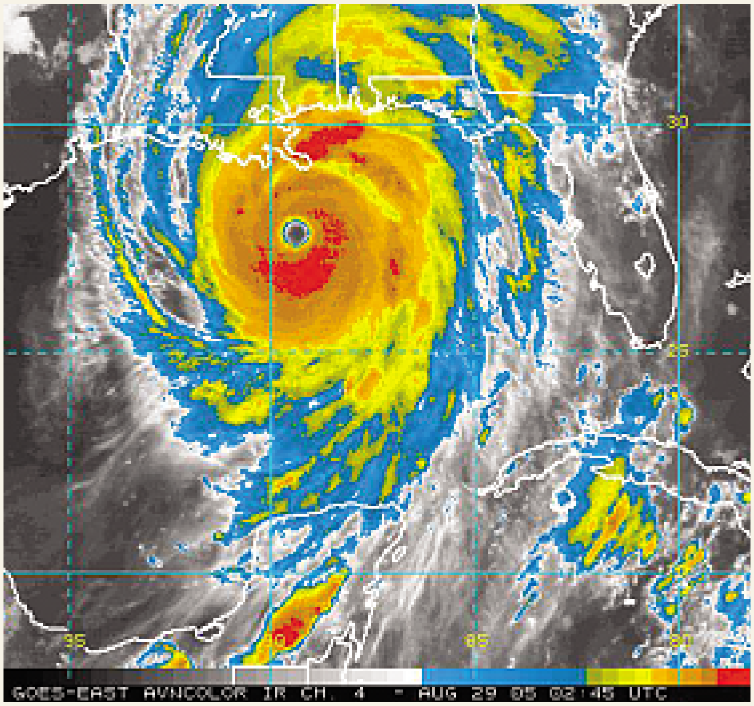


FIGURE 11-F Color-enhanced infrared image from the *GOES-East* satellite of Hurricane Katrina several hours before making landfall on August 29, 2005. The most intense activity is associated with red and orange. *(NOAA)*

Figure 11–F is a color-enhanced infrared (IR) image from the *GOES-East* satellite. (For an explanation of infrared imaging, see Box 2–5 on p. 53). Cold cloud tops, and thus the most intense storms, are easily seen in this image of Hurricane Katrina taken a few hours before landfall. Color-enhanced imagery is a method meteorologists use to aid them with satellite interpretation. The colors enable them to easily and quickly see features that are of special interest.

Figure 11–G from NASA's *QuikSCAT* satellite is very different in appearance. It provides a detailed look at Katrina's surface winds shortly before the storm made landfall. This image depicts relative wind speeds rather than actual values. The satellite sends out high-frequency radio waves, some of which bounce off the ocean and return to the satellite. Rough, storm-tossed seas create a strong signal, whereas a smooth surface returns a weaker signal. In order to match wind speeds with the type of signal that returns to the satellite, scientists compare wind measurements taken by data buoys in the ocean to the strength of the signal received by the satellite. When there are too few data buoy measurements to compare to the satellite data, exact wind speeds cannot be determined. Instead, the image provides a clear picture of relative wind speeds.

Finally, Figure 11–H shows the *Multi-satellite Precipitation Analysis (MPA)* of the storm. This image, which also depicts the track of storm, shows the overall pattern of rainfall. It was constructed from data collected over several days by the *Tropical Rainfall Measuring Mission (TRMM)* satellite and other satellites. For yet another satellite perspective of Katrina, see Figure 11–I in Box 11–4.

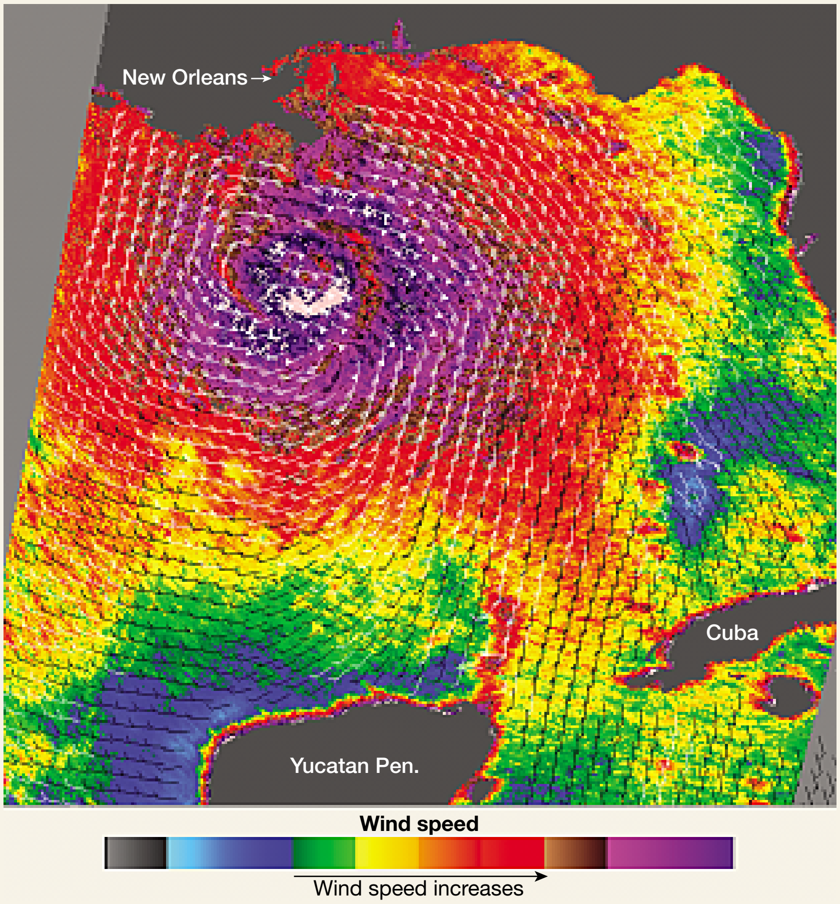
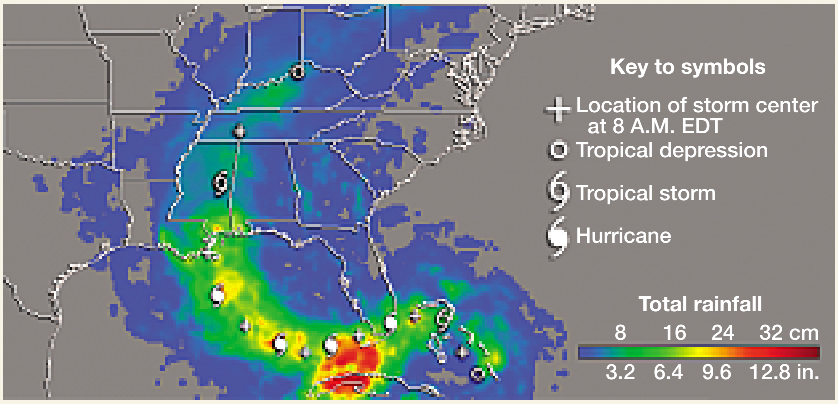


FIGURE 11-G NASA's *QuikSCAT* satellite was the source of data for this image of Hurricane Katrina on August 28, 2005. The image depicts relative wind speeds. The strongest winds, shown in shades of purple, circle a well-defined eye. The barbs show wind direction. *(NASA image)*

FIGURE 11-H Storm track and rainfall values for Hurricane Katrina for the period August 23 to 31, 2005. Rainfall amounts are derived from satellite data. The highest totals (dark red) exceeded 30 centimeters (12 inches) over northwestern Cuba and the Florida Keys. Amounts over southern Florida (green to yellow) were 12–20 centimeters (5–8 inches). Rainfall along the Mississippi coast (yellow to orange) was between 15–23 centimeters (6–9 inches). After coming ashore, Katrina moved through Mississippi, western Tennessee, and Kentucky and into Ohio. Because the storm moved rapidly, rainfall totals (green to blue) in these areas were generally less than 13 centimeters (5 inches). *(NASA image)*



In the United States, early warning systems have greatly reduced the number of deaths caused by hurricanes. At the same time, however, an astronomical rise has occurred in the amount of property damage. The primary reason for this latter trend is the rapid population growth and accompanying development in coastal areas.

The Role of Satellites

Today many different tools provide data that are used to detect and track hurricanes. This information is used to develop forecasts and to issue watches and warnings. The greatest single advancement in tools used for observing tropical cyclones has been the development of meteorological satellites.

Because the tropical and subtropical regions that spawn hurricanes consist of enormous areas of open ocean, conventional observations are limited. The needs for meteorological data from these vast regions are now met primarily by satellites. Even before a storm begins to develop cyclonic flow and the spiraling cloud bands so typical of a hurricane, it can be detected and monitored by satellites.

The advent of weather satellites has largely solved the problem of detecting tropical storms and has significantly improved monitoring (see Box 11–3, pp. 334–337). However, satellites are remote sensors, and it is not unusual for wind-speed estimates to be off by tens of kilometers per hour and for storm-position estimates to have errors. It is still not possible to precisely determine detailed structural characteristics. A combination of observing systems is necessary to provide the data needed for accurate forecasts and warnings.

Aircraft Reconnaissance

Aircraft reconnaissance represents a second important source of information about hurricanes. Ever since the first experimental flights into hurricanes were made in the 1940s, the aircraft and the instruments employed have become quite sophisticated (Figure 11–14). When a hurricane is within range, specially instrumented aircraft can fly directly into a threatening storm and accurately measure details of its position and current state of development. Data transmission can be made directly from an aircraft in the midst of a storm to the forecast center where input from many sources is collected and analyzed.

Measurements from reconnaissance aircraft are limited because they cannot be taken until the hurricane is relatively close to shore. Moreover, measurements are not taken continuously or throughout the storm. Rather, the aircraft provides sample "snapshots" of small parts of the hurricane. Nevertheless, the data collected are critical in analyzing the current characteristics needed to forecast the future behavior of the storm.

A major contribution to hurricane forecasting and warning programs has been an improved understanding of the structure and characteristics of these storms. Although advancements in remote sensing from satellites have been made, measurements from reconnaissance aircraft will be required for the foreseeable future to maintain the present level of accuracy for forecasts of potentially dangerous tropical storms.

Radar and Data Buoys

Radar is a third basic tool in the observation and study of hurricanes (Figure 11–15). When a hurricane nears the coast, it is monitored by land-based Doppler weather radar.* These radars provide detailed information on hurricane wind fields, rainfall intensity, and storm movement. As a result, local NWS offices are able to provide short-term warnings for floods, tornadoes, and high winds for specific areas. Sophisticated mathematical calculations provide forecasters with important information derived from the radar data, such as estimates of rainfall amounts. A limitation of radar is that it cannot "see" farther than about 320 kilometers (200 miles) from the coast, and hurricane watches and warnings must be issued long before the storm comes into range (see Box 11–4).

Data buoys represent a fourth method of gathering data for the study of hurricanes (see Figure 12–3, p. 349). These remote, floating instrument packages are positioned in fixed locations all along the Gulf Coast and Atlantic Coast of the United States. When you examine the weather maps in Figure 11–4, you can see data buoy information plotted at several offshore stations. Ever since the early 1970s, data

*For a more complete discussion of this important tool, see the section "Doppler Radar" in Chapter 10.

FIGURE 11-14 In the Atlantic basin, most operational hurricane reconnaissance is carried out by the U.S. Air Force Weather Reconnaissance Squadron based at Keesler AFB, Mississippi, where they maintain a fleet of 10 C-130 aircraft. Pilots fly through the hurricane to its center, measuring all basic weather elements as well as providing an accurate location of the eye. The National Oceanic and Atmospheric Administration also flies aircraft into hurricanes mostly on research missions to aid scientists in better understanding these storms. The P3 Orion aircraft shown here and state-of-the-art high-altitude jet aircraft complement the reconnaissance function of the U.S. Air Force. *(Photo by Getty Images, Inc.)*

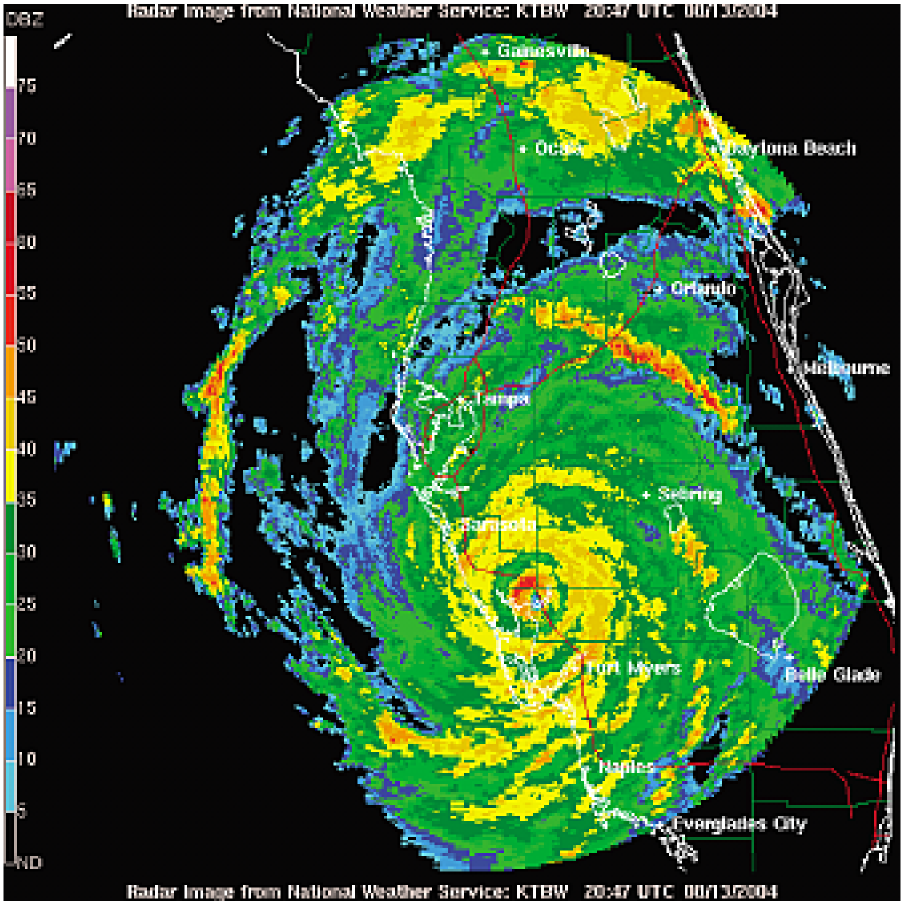


FIGURE 11-15 Doppler radar image of Hurricane Charley over Charlotte Harbor, Florida, just after landfall on August 13, 2004. The range of coastal radar is about 320 kilometers (200 miles). *(NOAA/National Weather Service)*

provided by these units have become a dependable and routine part of daily weather analysis as well as an important element of the hurricane warning system. The buoys represent the only means of making nearly continuous direct measurements of surface conditions over ocean areas.

Hurricane Watches and Warnings

Using input from the observational tools that were just described in conjunction with sophisticated computer models, meteorologists attempt to forecast the movements and intensity of a hurricane. The goal is to issue timely watches and warnings.

A **hurricane watch** is an announcement aimed at specific coastal areas that a hurricane poses a possible threat, generally within 36 hours. By contrast, a **hurricane warning** is issued when sustained winds of 119 kilometers (74 miles) per hour or higher are expected within a specified coastal area in 24 hours or less. A hurricane warning can remain in effect when dangerously high water or a combination of dangerously high water and exceptionally high waves continue, even though winds may be less than hurricane force.

Two factors are especially important in the watch-and-warning decision process. First, adequate lead time must be provided to protect life and, to a lesser degree, property. Second, forecasters must attempt to keep overwarning at a minimum. This, however, is a difficult task. A policy statement from the American Meteorological Society describes the situation as follows:

> Consistent with current forecast accuracy, it is necessary to issue hurricane warnings for rather large coastal areas. Warnings issued 24 hours before hurricane landfall average 300 nautical miles (560 kilometers) in length. Normally, the swath of damage encompasses about one-third of the warned area so the ratio of affected area to warned area is about one to three. In other words, approximately two-thirds of the area is, in effect, "overwarned." Such overwarning is not only costly, but also results in a loss of credibility in the warnings.*

Clearly, the decision to issue a warning represents a delicate balance between the need to protect the public on the one hand and the desire to minimize the degree of overwarning on the other.

*"Hurricane Detection, Tracking and Forecasting," *Bulletin of the American Meteorological Society,* 67, no. 7 (July 1993), a policy statement of an organization.

BOX 11-4 Atmospheric Hazard: A 3-D Look Inside a Hurricane

Seeing the pattern of rainfall in different parts of a hurricane is very useful to forecasters because it helps determine the strength of the storm. Scientists have developed a way to process radar data from the Tropical Rainfall Measuring Mission (TRMM) satellite within 3 hours and display it in 3-D. Because changes can occur rapidly in hurricanes, meteorologists need data as fast as possible.

TRMM is a unique satellite that is able to estimate rainfall intensity from space. In 2004, research confirmed that when cumulonimbus towers reach a certain height in the eye wall, the storm is strengthening. Images from the TRMM satellite can identify these "hot towers" of cloud development.

Because the TRMM satellite covers the tropical areas of the entire globe, the Precipitation Radar (PR) instrument takes snapshots of storms as it passes by. Every time it passes over a named tropical cyclone anywhere in the world, the PR will send data to create a 3-D "snapshot" of the storm.

The hurricane snapshot shows forecasters information on how heavy the rain is falling in different parts of the storm, such as the eye wall versus the outer rain bands. It also gives a 3-D look at the cloud heights and "hot towers" inside the storm. Higher hot towers in the eye wall usually indicate a strengthening storm.

The snapshot also gives valuable information about how the storm is put together. For example, when scientists studying a snapshot see that the body of the hurricane may be "tilted" inward, it could give clues as to whether a wind shear (a sudden change in the direction of winds near the top of the storm) may impact the storm's strength. Normally, when a hurricane runs into a strong wind shear, it weakens.

Figure 11–I is an image from the TRMM satellite showing Hurricane Katrina early on August 28, 2005. At the time of the image, Katrina was still a category 3 storm with maximum sustained winds of 185 kilometers (115 miles) per hour. The 3-D perspective shows the height of rain columns within the hurricane. Tall rain columns provide a clue that the storm is strengthening. Two isolated towers (in red) are visible: one in an outer rain band and the other in the northeastern part of the eye wall. The eye wall tower rises 16 kilometers (10 miles) above the surface of the ocean and is associated with an area of intense rainfall. Towers this tall near the core are often an indication the storm is intensifying. Katrina grew from a Category 3 to a Category 4 storm soon after this image was taken.

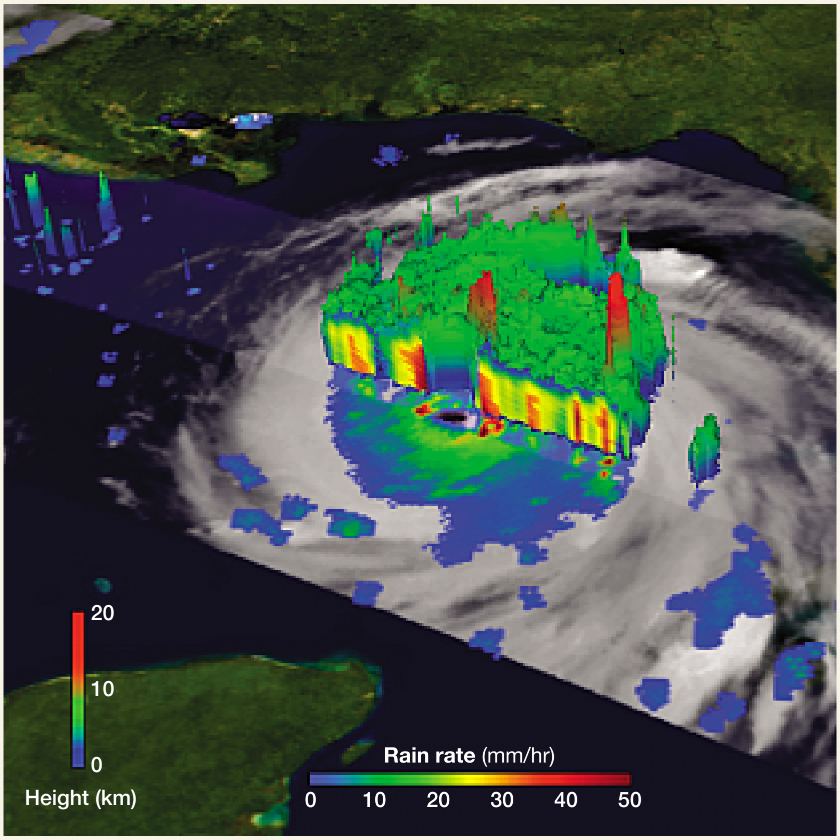


FIGURE 11-I Image from the Tropical Rainfall Measuring Mission (TRMM) satellite of Hurricane Katrina early on August 28, 2005, as the storm was gaining strength. This cutaway view of the inner portion of the storm shows cloud height on one side and rainfall rates on the other. *(NASA image)*

Chapter Summary

- The vast majority of hurricane deaths and damage are caused by relatively infrequent, yet powerful storms.
- Most hurricanes form between the latitudes of 5° and 20° over all tropical oceans except the South Atlantic and eastern South Pacific. The North Pacific has the greatest number of storms, averaging 20 per year. In the western Pacific, hurricanes are called *typhoons,* and in the Indian ocean, they are referred to as *cyclones.*
- A steep pressure gradient generates the rapid, inward spiraling winds of a hurricane. As the warm, moist air approaches the core of the storm, it turns upward and ascends in a ring of cumulonimbus towers and forms a doughnut-shaped wall called the *eye wall.* At the very center of the storm, called the *eye,* the air gradually descends, precipitation ceases, and winds subside.
- A hurricane is a heat engine fueled by the latent heat liberated when huge quantities of water vapor condense. They develop most often in late summer when ocean waters have reached temperatures of 27°C (80°F) or higher and are thus able to provide the necessary heat and moisture to the air. The initial stage of a tropical storm's life cycle, called a *tropical disturbance,* is a disorganized array of clouds that exhibits a weak pressure gradient and little or no rotation. Tropical disturbances that produce many of the strongest hurricanes that enter the western North Atlantic and threaten North America often begin as large undulations or ripples in the trade winds known as *easterly waves.*
- Each year, only a few tropical disturbances develop into full-fledged hurricanes that require minimum wind speeds of 119 kilometers per hour. When a cyclone's strongest winds do not exceed 61 kilometers per hour, it is called a *tropical depression.* When winds are between 61 and 119 kilometers per hour, the cyclone is termed a *tropical storm.* Hurricanes diminish in intensity whenever they (1) move over cool ocean waters that cannot supply warm, moist tropical air, (2) move onto land, or (3) reach a location where large-scale flow aloft is unfavorable.
- Although damages caused by a hurricane depend on several factors, including the size and population density of the area affected and the nearshore bottom configuration, the most significant factor is the strength of the storm itself. The *Saffir–Simpson* scale ranks the relative intensities of hurricanes. A 5 on the scale represents the worst storm possible, and a 1 is the least severe. Damage caused by hurricanes can be divided into three categories: (1) *storm surge,* which is most intense on the right side of the eye where winds are blowing toward the shore, occurs when a dome of water sweeps across the coast near the point where the eye makes landfall, (2) *wind damage,* and (3) *inland freshwater flooding,* which is caused by torrential rains that accompany most hurricanes.
- North Atlantic hurricanes develop in the trade winds, which generally move these storms from east to west. Today, because of early warning systems that help detect and track hurricanes, the number of deaths associated with these violent storms have been greatly reduced. Because the tropical and subtropical regions that spawn hurricanes consist of enormous areas of open oceans, meteorological data from these vast regions are provided primarily by *satellites.* Other important sources of hurricane information are *aircraft reconnaissance, radar,* and remote, floating instrument platforms called *data buoys.* Using data from these observational tools, meteorologists can issue an announcement, called a *hurricane watch,* aimed at specific coastal areas threatened by a hurricane, generally within 36 hours. By contrast, a *hurricane warning* is issued when sustained winds of 119 kilometers per hour or higher are expected within a specified coastal area in 24 hours or less. Two important factors in the watch and warning decision process are (1) adequate lead time and (2) attempting to keep overwarning at a minimum.

Vocabulary Review

easterly wave (p. 326)
eye (p. 324)
eye wall (p. 321)
hurricane (p. 320)
hurricane warning (p. 335)
hurricane watch (p. 335)
Saffir–Simpson scale (p. 327)
storm surge (p. 329)
tropical depression (p. 326)
tropical disturbance (p. 326)
tropical storm (p. 327)

Review Questions

1. Why might people in some parts of the world welcome the arrival of the hurricane season?
2. When a parcel of air approaches the center of a hurricane, how does its speed change? What law explains this change? (See Box 11–1.)
3. Which of these statements about the eye of a hurricane are true and which are false?
   - **a.** It is typically the warmest part of the storm.
   - **b.** It is usually characterized by clear, blue skies.
   - **c.** It is in the eye that winds are strongest.
4. During what time of year do most of the hurricanes that affect North America form? Why is hurricane formation favored at this time?
5. Tropical storms that form near the equator do not acquire a rotary motion as cyclones of higher latitudes do. Why?
6. What are streamlines? How do streamlines indicate an easterly wave in the North Atlantic?
7. List two factors that inhibit the strengthening of tropical disturbances.
8. Which has the stronger winds, a tropical storm or a tropical depression?
9. Why does the intensity of a hurricane diminish rapidly when it moves onto land?
10. What is the purpose of the Saffir–Simpson scale?
11. Hurricane damage can be divided into three broad categories. Name them. Which one of the categories is responsible for the greatest percentage of hurricane-related deaths?
12. Great damage and significant loss of life can take place a day or more after a hurricane has moved ashore and weakened. When this occurs, what is the likely cause?
13. In 1992 Hurricane Andrew was classified as a Category 4 storm. Ten years later its intensity was officially changed to Category 5 by the National Hurricane Center. Why was the storm reclassified?
14. List four tools that provide data used to track hurricanes and develop forecasts.
15. A hurricane has slower wind speeds than a tornado, but a hurricane inflicts more total damage. How might this be explained?
16. Briefly describe the potential problem of “overwarning” that is related to the issuing of hurricane warnings.
17. Although observational tools and hurricane forecasts continue to improve, the potential for loss of life due to hurricanes is growing. Explain this apparent contradiction.

Problems

The questions that follow refer to the weather maps of Hurricane Fran in Figure 11–4.

1. On which of the two days were Fran’s wind speeds probably highest? How were you able to determine this?
2. **a.** How far did the center of the hurricane move during the 24-hour period represented by these maps?
   b. At what rate did the storm move during this 24-hour span? Express your answers in miles per hour.
3. The middle-latitude cyclone shown in Figure 9–20 has an east–west diameter of approximately 1200 miles (when the 1008-mb isobar is used to define the outer boundary of the low). Measure the diameter (north–south) of Hurricane Fran on September 5. Use the 1008-mb isobar to represent the outer edge of the storm. How does this figure compare to the middle-latitude cyclone?
4. Determine the pressure gradient for Hurricane Fran on September 5. Measure from the 1008-mb isobar at Charleston, to the center of the storm. Express your answer in millibars per 100 miles.
5. The weather map in Figure 9–20 shows a well-developed middle-latitude cyclone. Calculate the pressure gradient of this storm from the 1008-mb isobar at the Wyoming–Idaho border to the center of the low. Assume the pressure at the center of the storm to be 986 mb and the distance to be 625 miles. Express your answer in millibars per 100 miles. How does this answer compare to your answer to problem 4?

Atmospheric Science Online

The Atmosphere 10e web site uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by meteorology instructors, this site will help improve your understanding of meteorology. Visit **http://www.prenhall.com/lutgens** and click on the cover of *The Atmosphere 10e* to find:

- **Online review quizzes**
- **Critical thinking exercises**
- **Links to chapter-specific web resources**
- **Internet-wide key term searches**

http://www.prenhall.com/lutgens