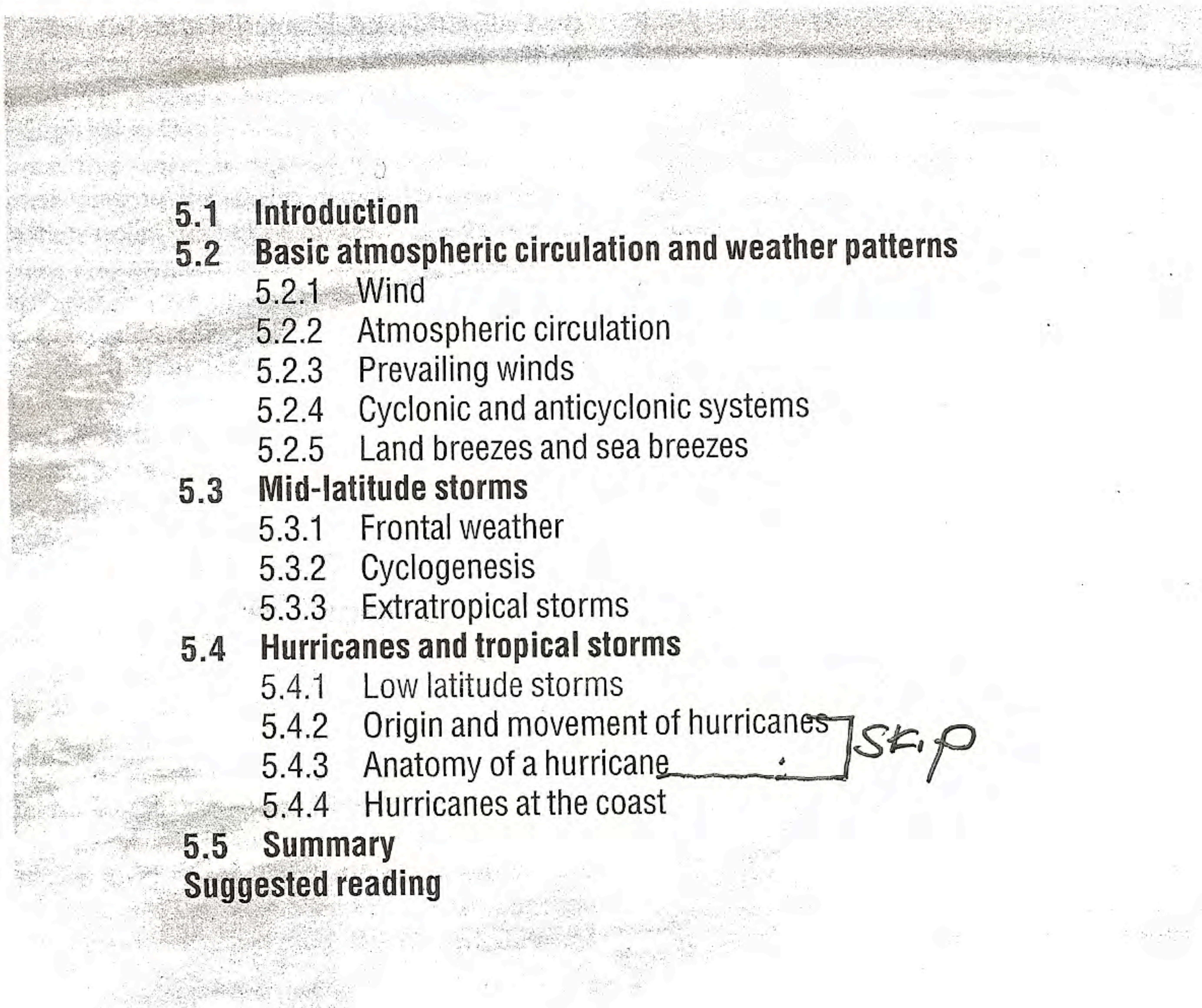
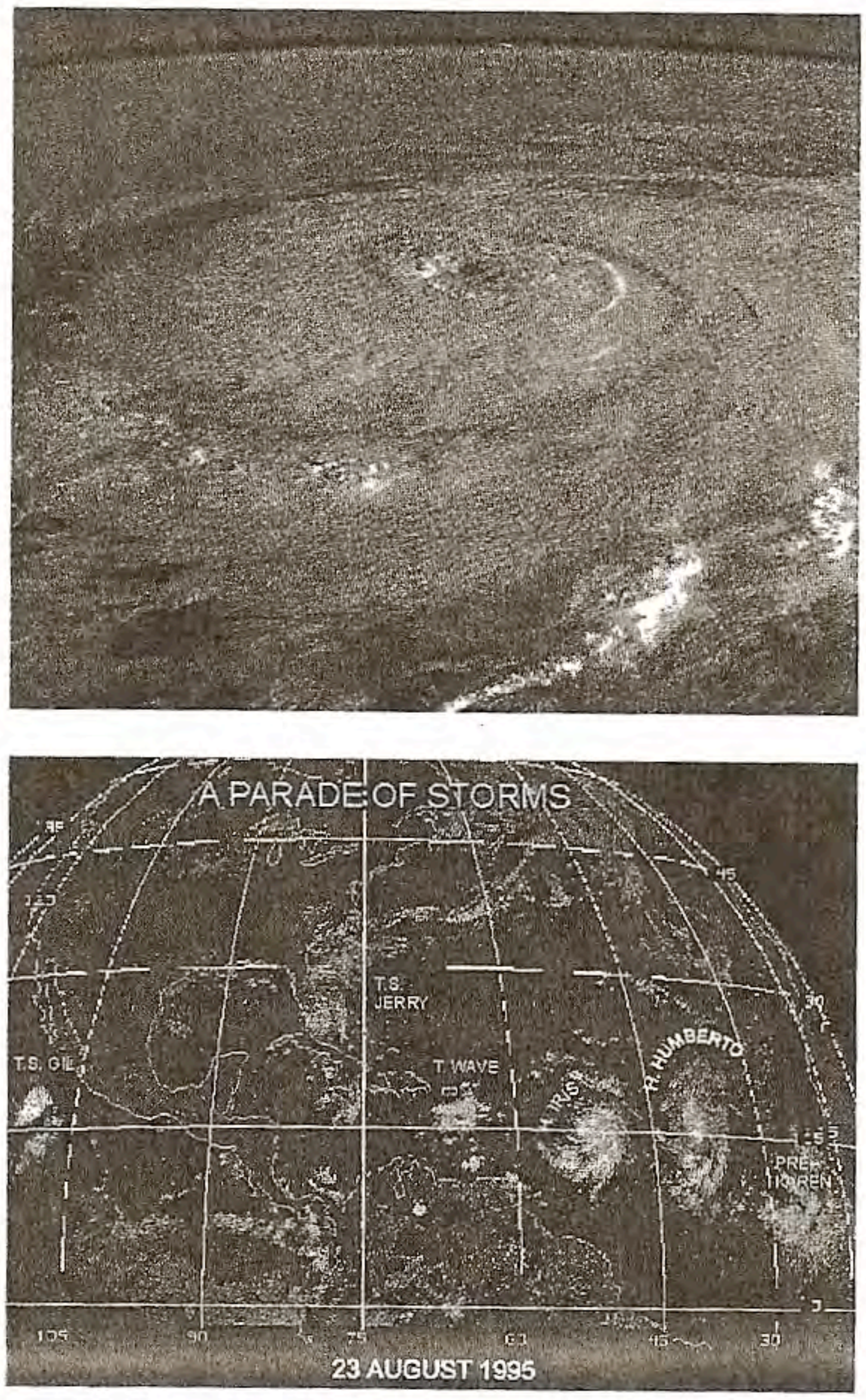
5 Weather systems, extratropical storms, and hurricanes



5.1 Introduction

Storms are a frightening but fascinating manifestation of the Earth's surface energy (Fig. 5.1). They have a dramatic influence on coastlines, in terms of both sediment movement along the coast and damage to homes and other structures. Storm waves and storm-induced currents are the primary agents responsible for removing sand from beaches and for causing long-term shoreline recession. In a matter of hours storms can produce dramatic changes in coastal morphology, as evidenced by the breaching of barriers, relocation of tidal channels, formation of dune scarps, and deposition of extensive aprons of sand along the landward side of barriers.



(a) (b)

Fig. 5.1 (a) Photograph of Hurricane Elena taken in 1985 from Space Shuttle Discovery (from http://www.wvwi.net/hurricane.htm). (b) In late August 1995 five major storms were present simultaneously in the Atlantic Ocean, while another storm, tropical storm Gil, existed in the Pacific Ocean (from http://obs-us.com/people/karen/storms/stormstuff.htm). Most Atlantic storms are born off the coast of northwest Africa and are steered westward by the easterlies or trade winds.

Property damage resulting from major hurricanes can be enormous. In 1988, Hurricane Gilbert cut a wide swath through the Caribbean Islands, resulting in US$6.5 billion of damage in Jamaica alone. In the wake of Hurricane Hugo, which hit Charleston, South Carolina, in 1989, $3 billion were spent in reparations. Three years later Hurricane Iniki (1992) swept through the Hawaiian Islands, causing a billion dollars in damage. During the same year Hurricane Andrew produced a staggering $30 billion in property damage as it crossed over southern Florida into the Gulf of Mexico. Eventually it made a second landfall in western Louisiana, where it wreaked devastation totaling another $1.5 billion.

As recorded in history and well chronicled during the past decade, the passage of major hurricanes does not only result in substantial property loss; these storms have also proved to be "killers" to the unprepared coastal population. The greatest loss of life in the United States due to natural causes is attributed to the 1900 hurricane that killed at least 6000 people on Galveston Island along the Texas coast. Most of these deaths were due to drowning resulting from a 6 m high storm surge that covered the island, most of which was less than 2.5 m in height. The storm surge is the super-elevation of the water surface produced by the hurricane's strong onshore winds and low pressure (Fig. 5.2). In response to this Galveston disaster a substantial seawall was constructed along the ocean shoreline and at the same time much of the island was raised some 1.5 m using sediment dredged from a nearby site.

The storm-related deaths that occurred in Galveston pale in comparison to the loss of life that has taken place in Bangladesh, located in the apex of the Bay of Bengal. Similar to the state of Louisiana, the southern part this country has been built through deltaic sedimentation. Much of the lower portion of the Ganges–Brahmaputra delta

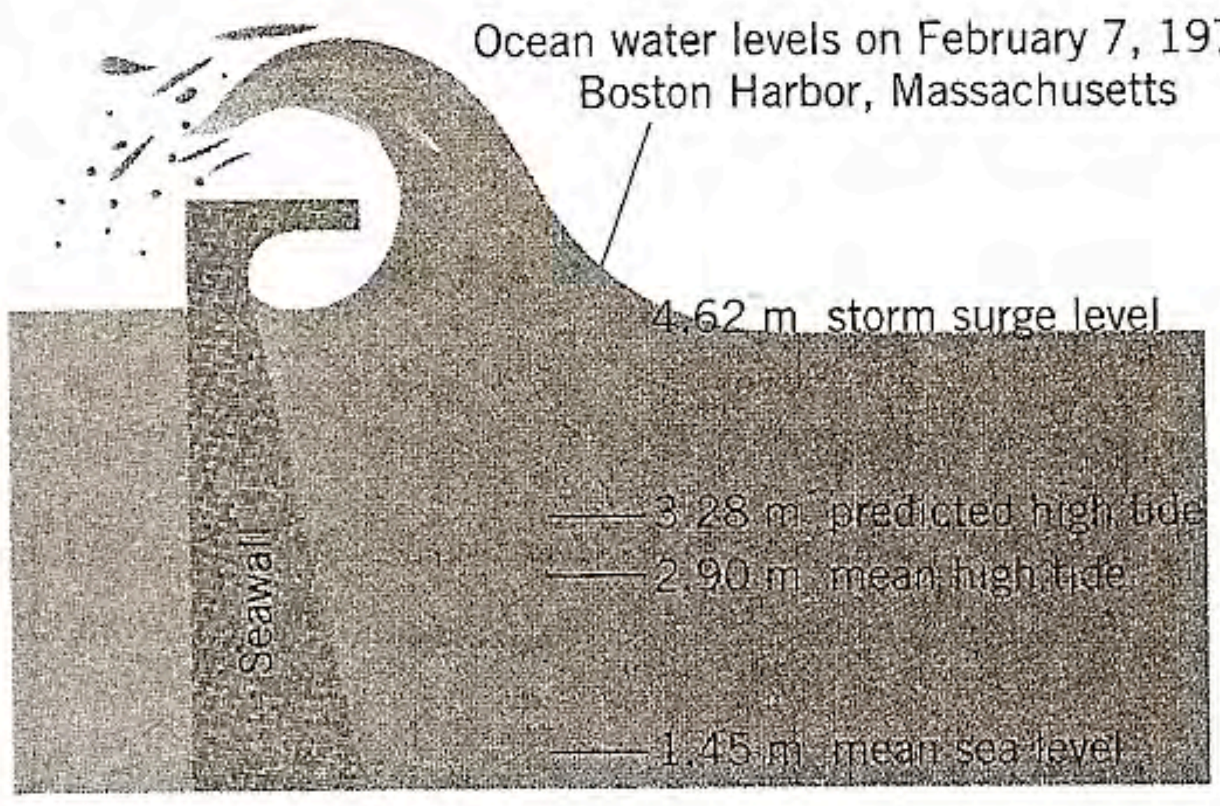


Fig. 5.2 During the Blizzard of 1978, the storm of record for much of northern New England, large astronomic tidal conditions combined with record storm surges caused significant lowland flooding and extensive coastal damage. The high tide levels allowed large storm waves to break over seawalls, against fore dune ridges, and across barrier systems.

in Bangladesh is highly populated. Most of these people live on land that is less than 4 m above sea level. An intense cyclone in 1970 moved through the northern Bay of Bengal and pushed a dome of water onshore that reached 10 m above normal water levels. An estimated half million people lost their lives as a result of this storm. A view of the area after floodwaters subsided revealed a land almost completely stripped of human occupation. A second tropical cyclone in 1991 (Cyclone Gorky) took another 100,000 lives. What makes barriers and other depositional coasts so vulnerable to intense storms is the combination of storm-induced elevated water levels and the inherent low elevation of these coastal regions.

This chapter describes fundamental atmospheric circulation because global wind patterns largely control the pathways of storms and major weather fronts. A basic discussion of air flow associated with high and low pressure systems provides a foundation for understanding the two primary types of coastal storms: those that form above the tropics, called extratropical cyclones, and those that are generated in the tropics, named tropical cyclones. Typically, these storms have different strengths and modes of formation. Similar factors, such as storm path, speed, and magnitude, as well as the configuration of the coast, govern the extent and type of damage resulting from these storms. Case histories of various storms are useful in illustrating these points. Classifications of the hurricanes and extratropical storms are presented so that the effects of various magnitude storms can be compared. The discussion emphasizes hurricanes that impact the Gulf of Mexico and eastern Atlantic Ocean, although similar storms elsewhere in the world are also included. Likewise, primary attention is given to the northeast storms that affect the northeast coast of the United States.

5.2 Basic atmospheric circulation and weather patterns

5.2.1 Wind

Wind is defined as the horizontal movement of air. It is caused by differences in atmospheric pressure. In turn, pressure gradients are produced by differential heating or cooling of air masses. On weather maps the distribution of atmospheric pressure is presented by isobars (Fig. 5.3). Isobars are lines connecting points of equal pressure. As seen on weather maps, wind flows at a slight angle to the isobars toward the central low pressure. Wind velocity increases as isobars become more closely spaced. The pressure gradient can be thought of as the slope of a hill. A ball rolling down the hill will attain a greater velocity the steeper the slope. Likewise, the greater the contrast in pressure (pressure gradient) the stronger the wind velocity.

5.2.2 Atmospheric circulation

The movement of air masses over the surface of the Earth represents one of the processes whereby temperature differences between the equator and poles are balanced. The Sun's preferential heating of the equatorial region compared to polar areas causes the strong temperature gradient that exists between the low and high latitudes. A simple heat budget of the Earth reveals that between approximately 35° N and 40° S of the equator, more energy is absorbed from incoming solar radiation than is

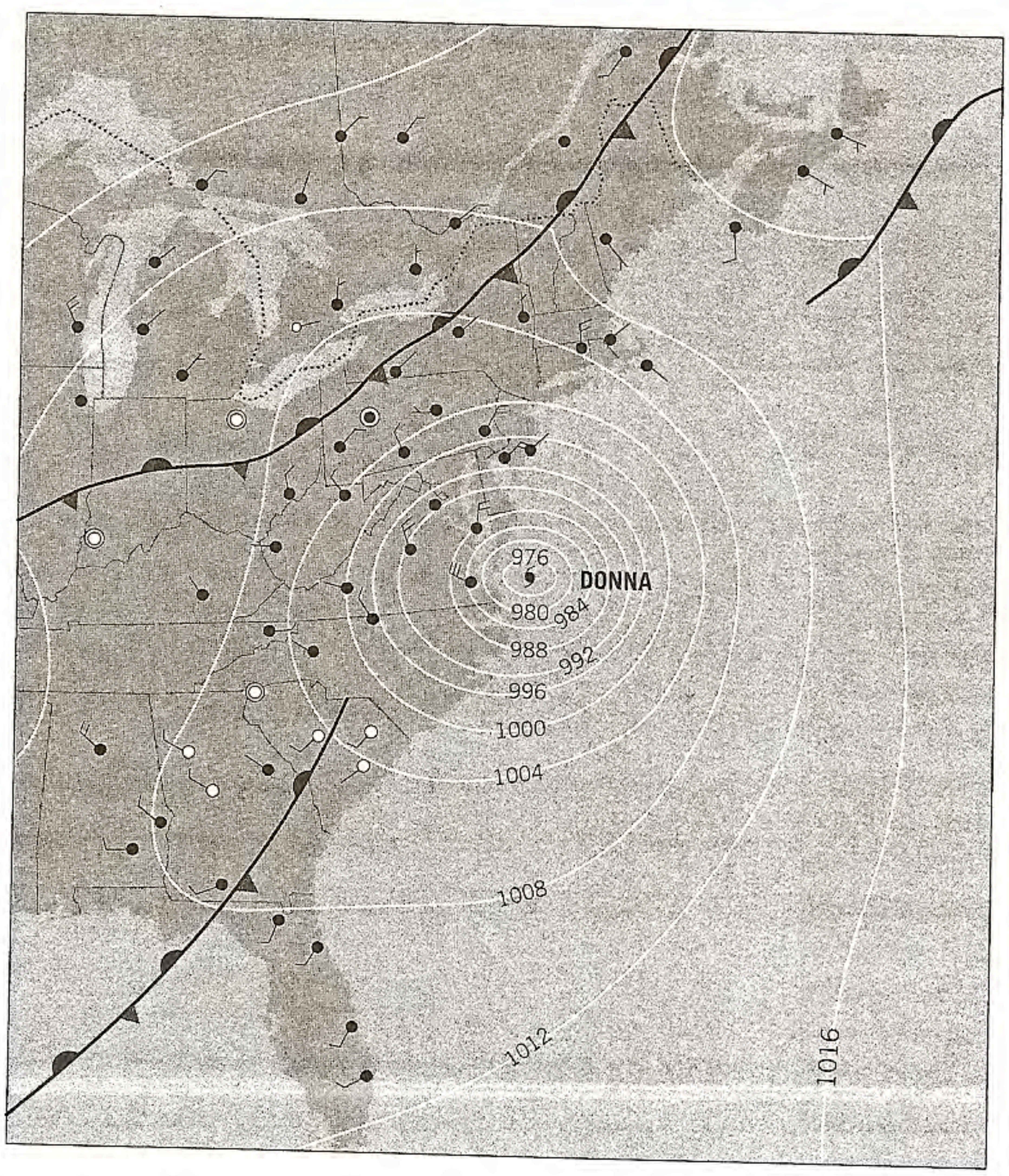


Fig. 5.3 Atmospheric pressure is measured in millibars (equal to 100 newtons per square meter). Standard sea-level pressure is 1013.25 millibars. Individual dots indicate the amount of total sky cover (black dot means totally cloudy). The arrow shaft shows the direction from which the wind is blowing. A full barb on the arrow equals 10 knots. Commonly, weather maps show concentric isobars around low and high-pressure systems.

radiated back into space (Fig. 5.4). Above these latitudes the curvature of the Earth produces a deficit of heat caused by a combination of less incoming radiation per unit area and greater reflectance of solar radiation by the ice-covered poles. While the uneven heating of the Earth has always existed, the equator does not grow warmer with time, nor do the poles grow colder. Offsetting the heat imbalance are mechanisms of heat transfer involving both the atmosphere and oceans that move heat poleward and cold toward the equator. The California Current, which transports cold water southward along the Pacific coast, and the Gulf Stream, which moves warm water northward along the Atlantic coast, are examples of this heat transfer. The north–south movement of air masses accomplishes the same task of equilibrating energy over the Earth's surface as seen when polar air invades southern Canada and the continental United States during winter or when hurricanes move into the north Atlantic during late summer and early fall.

The global wind patterns are also a product of differential heating. The Sun's concentrated incoming radiation in the equatorial latitudes heats the surrounding air and evaporates water from the oceans. As this warm moist air rises, it expands and cools, resulting in water condensation and rainfall in equatorial regions. In a highly simplistic case involving a non-rotating Earth one would expect that the dry air would flow outward from the equator toward the poles, resulting in further cooling of the air. At the poles the now dense cold dry air would sink and then flow southward along the Earth's surface toward the equator. In this ideal model two convection cells would operate, one each in the northern and southern hemispheres

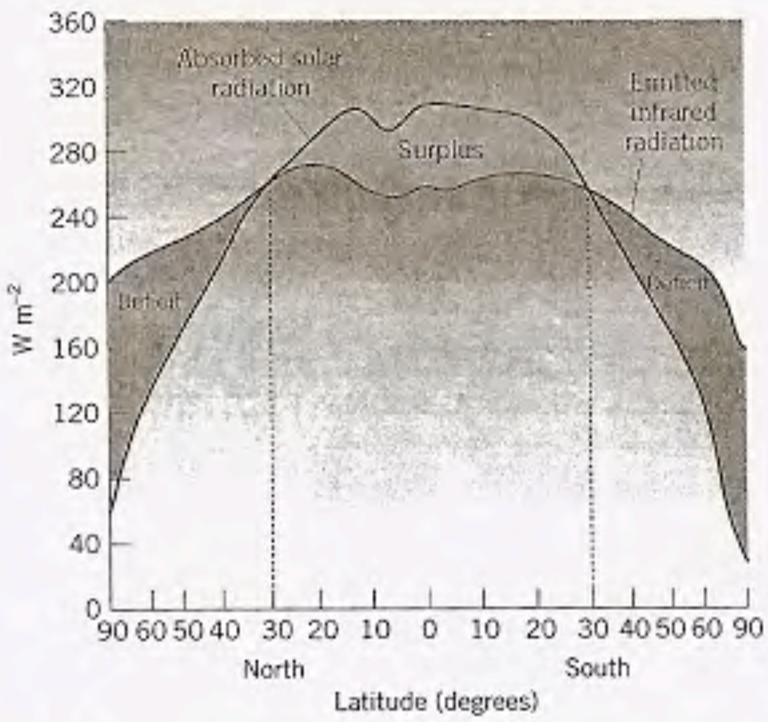


Fig. 5.4 Over the Earth's surface there is an uneven distribution of incoming solar radiation and outgoing infrared radiation. Ocean currents and weather systems are responsible for equalizing the geographic heat imbalance.

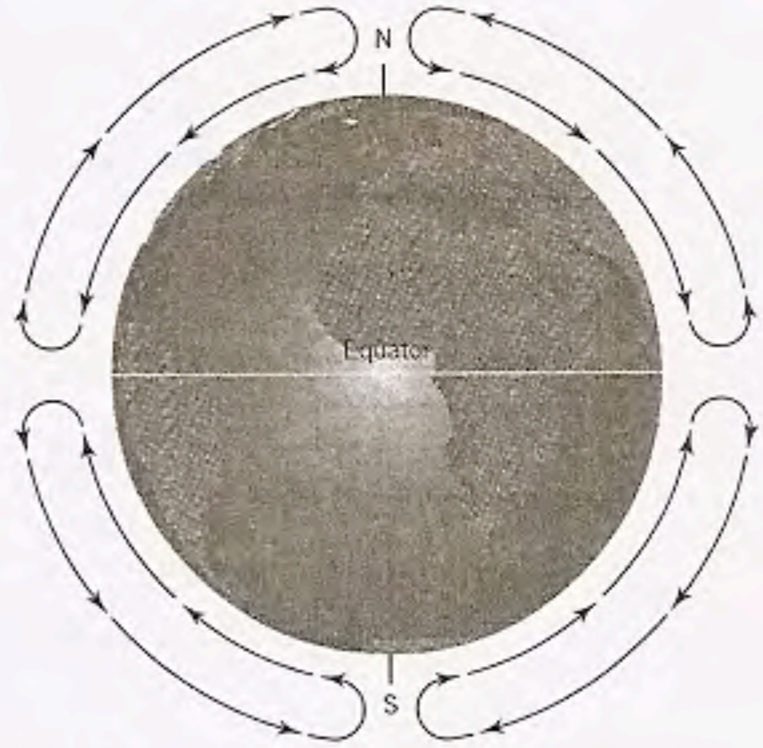


Fig. 5.5 Hypothetical model of air convection due to uneven solar heating on a non-rotating Earth.

(Fig. 5.5). However, due to the Coriolis effect, the actual global air circulation is much more complex. The Coriolis effect is produced by the Earth's rotation and causes all moving objects to be deflected to the right in the northern hemisphere and to left in the southern hemisphere. The Coriolis effect applies to ocean currents, moving air masses, and even jet planes flying across the globe.

Differential heating of the atmosphere coupled with the Coriolis effect produces a global air circulation model with six convection cells: three each in the northern and southern hemisphere (Fig. 5.6). As described in the simplistic model, preferential heating causes warm moist air to rise in the equatorial region. The rising air is replaced by surface air flowing toward the equator from the northern and southern latitudes. This rising air expands and cools, producing precipitation. Thus, the equatorial region is noted for hot temperatures, low pressure, water-laden clouds, and rain. High above the equator the air mass flows northward and southward where it continues to cool and lose moisture. At about 30° latitude the air mass descends, thus completing an atmospheric circulation cell known as the Hadley cell. As the air sinks at 30°, it compresses, producing high pressure, dry air, and variable winds. These are known as the horse latitudes. Folklore tells us they are so named because ships sailing into these latitudes became becalmed. As the ship expended its animal feed and began running out of water, the crew was forced to throw horses and other farm stock overboard. A second convection cell exists between 30 and 60° latitude, which is called the Ferrel cell. This cell is formed because some of the air that sinks at 30° latitude flows northward upon reaching Earth's surface. At the same time a secondary low pressure system stationed at about 60° latitude coincides with a rising air mass and precipitation. Aloft, this air mass cools and moves southward. The polar cell is the third circulation cell and occurs between 60 and 90°. It results from upper air masses moving northward and descending at the poles, while at the same time surface air flows south.

5.2.3 Prevailing winds

Now that the atmospheric circulation has been established, we can use air flow along the Earth's surface to understand the global prevailing wind

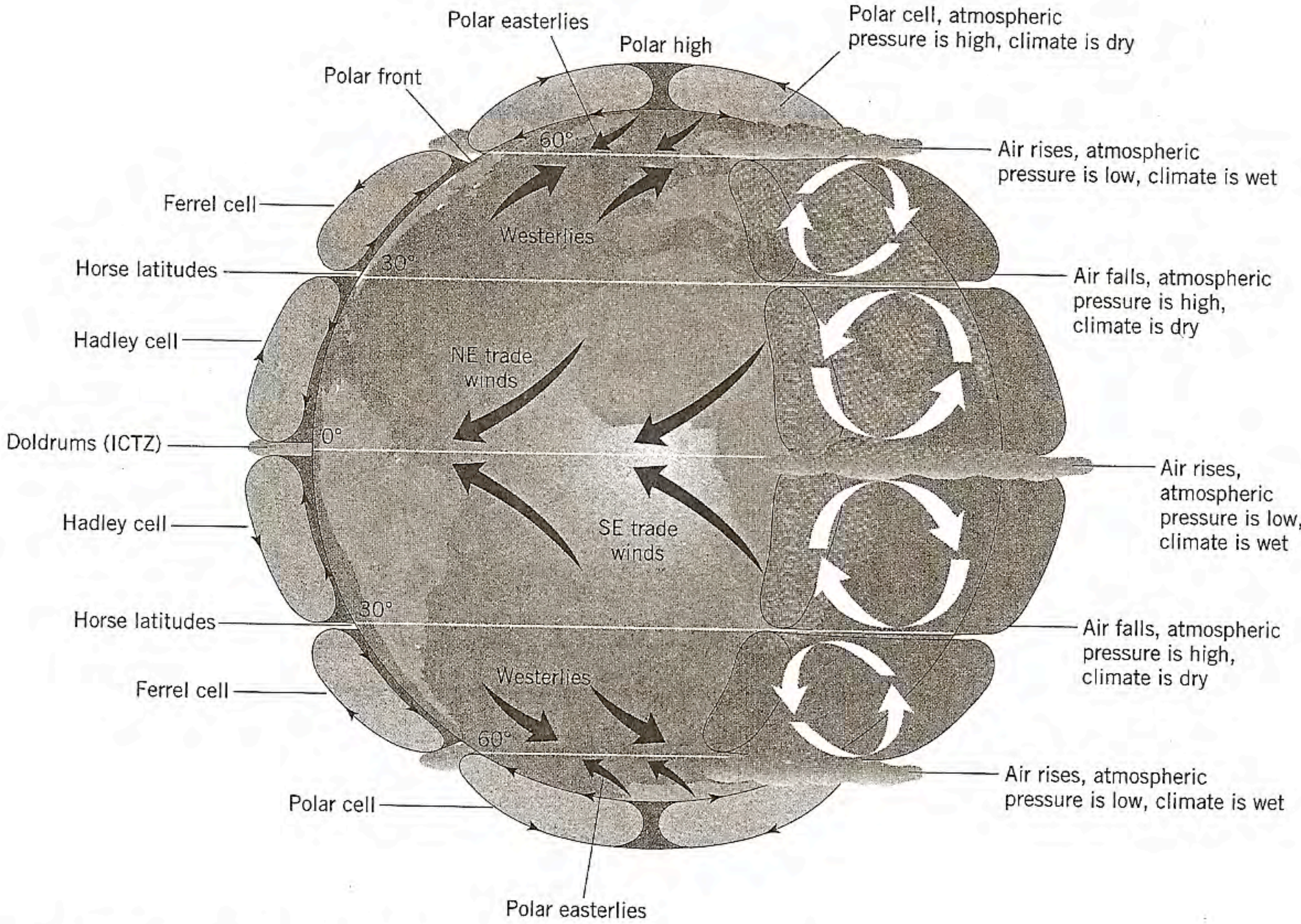


Fig. 5.6 Simplified air circulation model for a rotating Earth containing the Hadley, Ferrel, and polar convection cells north and south of the equator.

patterns (Fig. 5.6). In the northern hemisphere circulation in the Hadley convection cell would seem to indicate that air should flow from north to south between 30 and 0° latitude. Remembering, however, that the Coriolis effect causes all moving masses to be deflected to the right (in the northern hemisphere), the flow of air is actually from the easterly quadrant toward the west. These winds are called the easterlies because the winds blow from the east. They are also referred to as the "trade winds." The early merchants who sailed from Europe bound for the New World gave them this name. The word "trade" was used by the English of that day to mean constant and steady, and this is how they described the winds that helped them sail across the Atlantic. In the southern hemisphere the pattern is repeated, resulting in the convergence of the northeast and southeast trade winds at the equator. This region is called the intertropical convergence zone (ITCZ) and scientists have shown that it profoundly affects ocean currents and weather patterns in the equatorial area.

In the mid-latitudes, surface winds associated with the Ferrel circulation cell are deflected to the east by Coriolis. These winds are known as the westerlies and affect most of the continental United States. The west coast is known as a windward coast because the westerlies blow onshore, augmenting the wave energy in this region. Conversely, the east coast is a leeward coast because the westerlies blow offshore. The prevailing winds diminish wave energy, partially explaining why average shallow water wave heights are more than twice as large on the west coast as they are along the east coast. The westerlies are also responsible for steering the weather systems, including hurricanes.

In the northern hemisphere, air flowing southward from the pole forms the polar easterlies. At about 50–60° latitude the polar easterlies meet the westerlies, establishing the polar front. This convergent zone produces a near permanent boundary separating the polar cold dense air from the warm tropical air mass. The variable weather that characterizes much of the United States reflects a latitudinal wandering of the polar front.

5.2.4 Cyclonic and anticyclonic systems

Although exceptions do exist, low atmospheric pressure is most often associated with rainy or stormy weather, whereas high pressure is a sign of fair weather. A well developed low pressure system is characterized by a gyre of air that rotates in a counterclockwise direction (in the northern hemisphere; clockwise in the southern hemisphere) around a central low pressure cell (Fig. 5.7). These are called **cyclonic systems** and may be hundreds of kilometers is diameter. The counterclockwise movement of air is produced by the convergence of surface currents. Low pressure systems contain ascending air masses, which many people have observed in film footage of tornadoes. As air streams in to replace the rising air, the currents are deflected to the right by the Coriolis effect, producing the counterclockwise circulation. Hurricanes, extratropical storms, and tornadoes are all types of cyclonic systems, although tornadoes are considerably smaller systems.

High pressure systems occur where air masses are sinking. As the air mass descends toward the ground, it flows outward from a central high pressure cell. In the northern hemisphere the outward flowing currents are deflected to the right due to Coriolis, resulting in a rotating air mass that circulates in a clockwise direction. These are called anticyclones. The Bermuda High is an example of an anticyclonic system. This high pressure system stabilizes over Bermuda during mid-summer and is responsible for transporting the uncomfortable hot, hazy, humid air from the Gulf of Mexico to the northeastern Atlantic seaboard.

5.2.5 Land breezes and sea breezes

Anyone who has spent the summer along the seashore or has sailed along the coast is familiar with the systematic breezes that characterize the coastal zone. The onshore and offshore winds are a result of differential heating of the land surface versus that of the ocean. Under fair weather conditions when the sun has just risen, the air is usually calm because the air over the ocean and land has similar temperatures. However, as the Sun ascends in the sky, the land surface preferentially warms compared to that of the ocean. In turn, the land surface warms the overlying air, causing it to rise. Over the ocean the air remains cool and dense. Thus, a pressure gradient develops between the relatively low pressure over

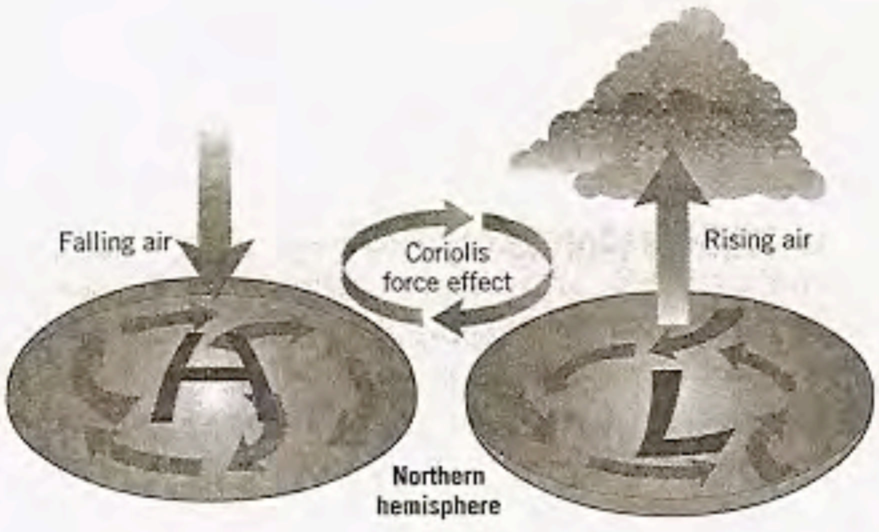


Fig. 5.7 Gyres of moving air are created around low- and high-pressure systems due to the Coriolis effect. Air masses in the northern hemisphere flow in a counterclockwise direction in low-pressure systems (cyclonic circulation) and a clockwise direction in high-pressure systems (anticyclonic circulation).

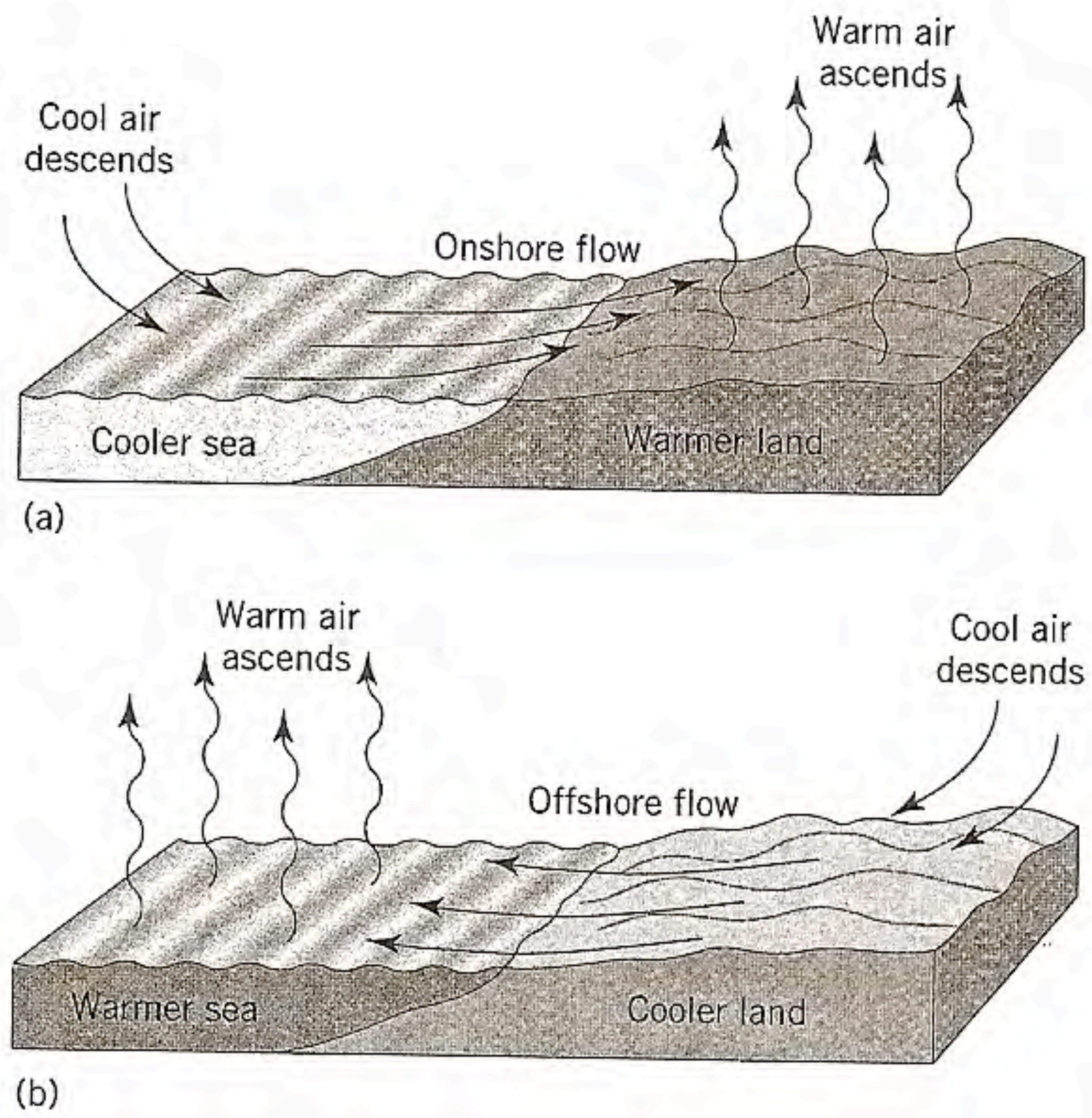


Fig. 5.8 (a) Sea and (b) land breezes are a common diurnal pattern of winds along many coasts. They are formed due to temperature differences between the land and adjacent seawater.

the land and the higher pressure over the ocean. This results in an onshore flow of air that is referred to as a sea breeze (Fig. 5.8). The sea breeze strengthens during mid-day and reaches a maximum during mid to late afternoon, before diminishing by late evening. During the night, the land surface radiates heat back to the atmosphere at a much higher rate than the ocean, which reverses the temperature and pressure gradients along the shore. This results in a flow of air from the land toward the ocean, which is called a land breeze. The extent and magnitude of the land and sea breezes are a function of ocean and daytime temperatures, coastal morphology, vegetation, and other factors.

5.3 Mid-latitude storms

Whereas tropical storms and hurricanes dominate coasts of low latitudes, extratropical storms and weather fronts are the major weather systems impacting mid-latitudes coasts. A transition zone exists between these two regions where both weather systems are common. As the name implies, extratropical cyclones form north of the Tropic of Cancer or, in the case of the southern hemisphere, south of the Tropic of Capricorn. These storms are associated with low pressure systems and affect the Pacific, Gulf, and Atlantic coasts of the United States and other mid-latitude coastlines of the world. Like all cyclonic weather systems, extratropical storms are air masses that rotate around a central low pressure with a counterclockwise circulation (Fig. 5.7). Another important type of mid-latitude weather system is the **front**. The passage of frontal systems along the Gulf coast strongly influences the coastal processes of this region. Frontal systems are discussed first, as they are the precursors to extratropical cyclone development.

5.3.1 Frontal weather

A front is defined as a narrow transition zone (25–250 km wide) between two air masses with different densities (Fig. 5.9). Fronts may extend for more than 1000 km. One air mass is usually warmer and more humid than the adjacent air mass. The boundary between the two is usually inclined, with the warmer lighter air rising over the colder, denser air. A cold front is one in which the cold air mass advances, thereby displacing the position of the warm air. The opposite occurs during the passage of a warm front. Generally, the two air masses travel with nearly the same velocity and in about the same direction. Cold fronts usually advance at a slightly more rapid rate (35 km h^{-1}) than warm fronts (25 km h^{-1}). In addition, cold fronts tend to be accompanied by more energetic weather and often contain concentrated precipitation and severe wind.

In North America, cold fronts commonly are initiated by cold air (polar air mass) sweeping down from Canada meeting warm air from the south (Fig. 5.10). Fronts travel west to east across the country and may extend all the way to the Gulf of Mexico, where they can produce strong winds and surf. The northern Gulf region experiences more than twenty cold fronts each year, lasting from 12 to 24 hours depending on the speed of the storm and whether it becomes stalled or not. Due to the overall low tidal

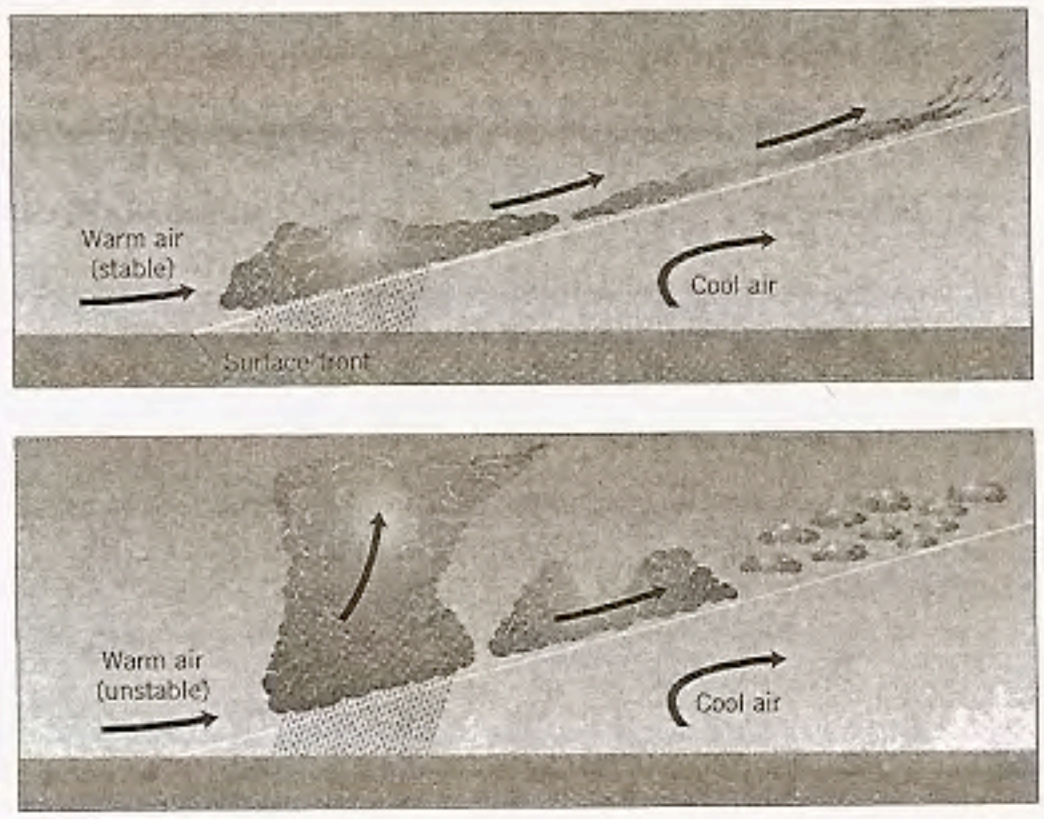


Fig. 5.9 Weather fronts are formed at the boundary between two air masses that have contrasting densities, usually due to differences in temperature. Fronts mark a change in the weather and are generally associated with moderate to intense precipitation.

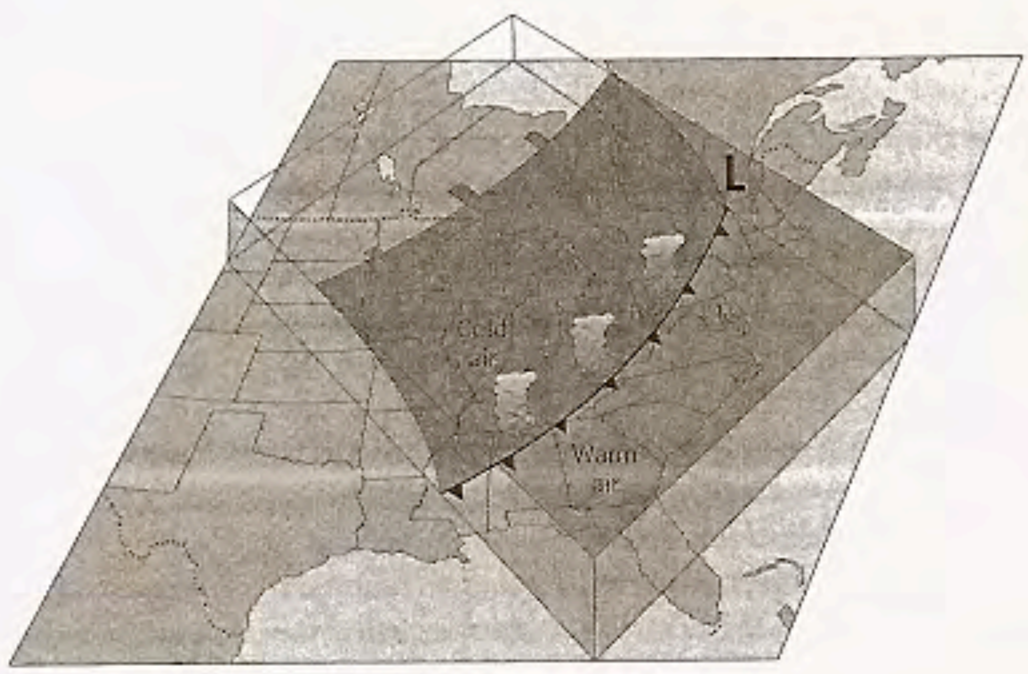


Fig. 5.10 Cold fronts in the central United States are caused by polar air moving south from Canada, displacing a warm air mass. The front moves eastward across the country and may stretch from the Gulf of Mexico to the Great Lakes.

range of most of the Gulf coast (<1 m), cold fronts can be effective agents in substantially augmenting or diminishing tidal elevations. Along the Louisiana coast cold fronts create westerly to southwesterly winds, which cause higher tide levels than would be expected due to astronomic forcing alone. This condition allows storm waves to break higher along the beach, leading to the overwashing of low barriers. At the same time, elevated tides increase the flow of ocean water into the bays and marsh systems that back the barrier islands. This generates strong landward currents through the tidal inlets during the passage of the front and strong seaward currents when the floodwaters exit the inlets. As the front passes, there is a dramatic shift from southerly to northerly winds that occurs within a few hours or less. Strong northerly winds surpress the waves in the nearshore of the Gulf-facing beaches, while at the same time generating substantial waves in the larger bays behind the barriers. In fact, scientists

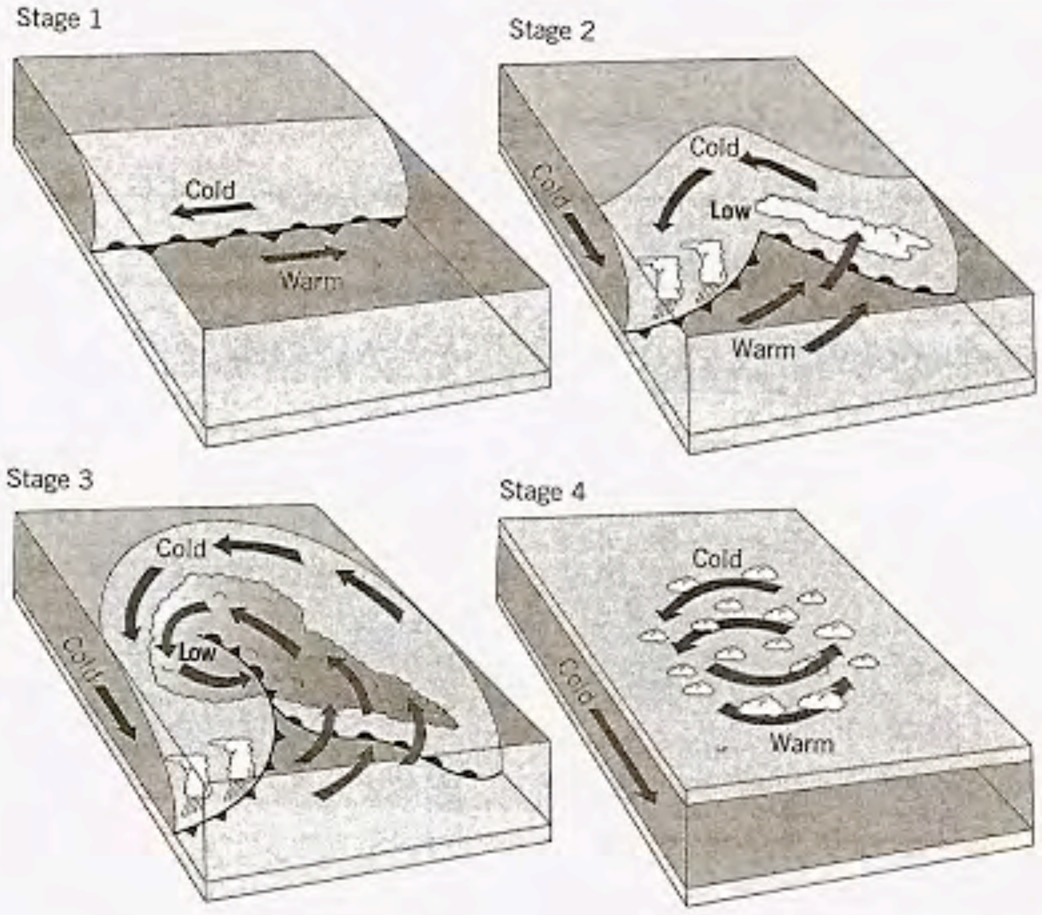


Fig. 5.11 Model of cyclogenesis as proposed by Norwegian scientists and published by J. Bjerknes.

have shown that these bay waves, which can approach 3 m in height, are responsible for chronic shoreline erosion on the backside of barriers along long stretches of the northern Gulf of Mexico. Thus, cold fronts are important agents in modifying beaches and tidal inlets in the Gulf coast region.

5.3.2 Cyclogenesis

The process of extratropical cyclone formation, cyclogenesis, was first described by Norwegian scientists during the First World War and eventually the theory was published by J. Bjerknes in 1918. Even though it was devised using limited ground observations, the basic tenets of the model are still deemed acceptable today despite major advances in the collection and analysis of weather data. Cyclones develop along advancing frontal systems in which the two air masses have a slight component of differential movement. At the surface of the front this condition is manifested by the two air masses moving in opposite directions to one another (Stage 1, Fig. 5.11). The next stage of cyclogenesis coincides with a disturbance along the front that is produced by topographic irregularities, such as mountain ranges, temperature differences, or other factors. The end result of the disturbance is a wave-like form, similar to a breaking ocean wave, in which the warm low-density air penetrates into the cold air mass (Stage 2, Fig. 5.11). Extratropical cyclone formation also appears to be strongly linked with upper air circulation where currents flow west to east in long meanders. This pattern serves to initiate or reinforce the counterclockwise rotation of air around a central low pressure (Stage 3, Fig. 5.11). The demise of a cyclone occurs when the cold air supplants the rising warm air, the sloping gradient between the two air masses ceases, and the storm runs out of energy (Stage 4, Fig. 5.11).

5.3.3 Extratropical storms

Occurrence and storm tracts

Although extratropical cyclones can occur in the mid-latitudes at any time of the year, they happen most frequently in the hemisphere that is going through winter, because this is when the temperature contrasts between the polar air masses of high

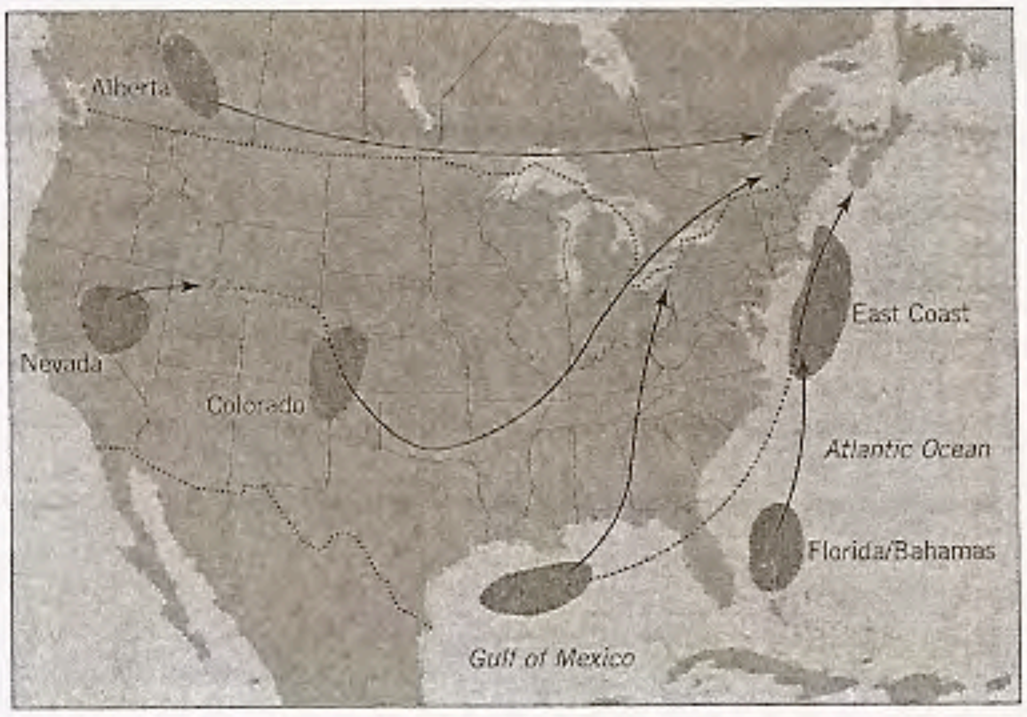


Fig. 5.12 Extratropical cyclones develop in many regions across the United States. Regardless of their origin, their pathway of these storms is towards northeast Canada and the northern Atlantic Ocean.

latitudes and the warmer air of the lower latitudes reach their maximum. In the United States extratropical storms are most common from late fall through early spring. The weather conditions that lead to extratropical cyclone formation often originate in the Pacific Ocean. Full development of the storm is associated with several locations throughout North America due to the complexity of the factors governing the weather there. These sites include the continental Southwest, Midwest, and Southeast United States, southern Alberta, Canada, and in the Gulf of Mexico and the Florida–Bahamas regions (Fig. 5.12). The continental storms travel in an eastward path across the country, eventually moving northeastward into the northern Atlantic, where they dissipate. Those that pass through the Gulf of Mexico and in the Florida–Bahamas region move northward along the eastern seaboard. Other storms track through the Great Lakes and into the Gulf of Saint Lawrence. Because most extratropical storms track along the east coast, they are major storm producers of this region, particularly north of North Carolina. Hurricanes have a greater frequency and influence along the coastal states south of Virginia.

Northeasters

Northeaster is the name given to the extratropical cyclones that pound the northeast coast of the United States and Canada with driving rain, strong winds, elevated tide levels, and storm waves. During the winter, northeasters can produce blizzard conditions, blanketing the northeast with more than two feet (60 cm) of snow. They are called northeasters because the winds associated with these storms come from the northeast (Fig. 5.13). Remember that winds are named for the direction from which they blow. In fact, it is the path of the extratropical cyclone that determines the wind direction as well as the type and severity of the storm. Northeast storms occur when the eye of the storm tracks in a northeasterly path offshore of the coast, eventually moving east of Cape Cod and Nova Scotia. Under these conditions the counterclockwise air circulation associated with the cyclone generates onshore winds that blow out of the easterly quadrant. The eastern seaboard of the United States is particularly susceptible to these storms because most of this coast faces eastward and is directly exposed to northeast winds and waves.

The Ash Wednesday Storm of 1962 was one of the most powerful and damaging northeasters ever to strike the east coast of the United States during historic times. The storm lasted for more than five tidal cycles and impacted 1000 km of mid-Atlantic coastline stretching from North Carolina to Long Island, New York. Wind gusts exceeded hurricane

Fig. 5.13 Along the eastern seaboard of the United States, particularly in New England, extratropical cyclones travel offshore of the coast and generate strong winds and storm waves from the northeast. The weather map illustrates the conditions that existed during a northeast storm on January 25, 1979. In the Boston, Massachusetts, area winds reached 60 km h^{-1} (40 m.p.h.) and the region was blanketed with over two feet (60 cm) of snow. Pressure measured in Millibars. Contour interval 4 millibars.

force, producing deepwater wave heights greater than 10 m. The storm hit during perigean spring tides, which contributed to the elevated water levels. The large storm surge and erosive waves removed beaches and carved deeply into adjacent dunes. Along many shorelines storm waves carried beach sands across barriers, forming extensive overwash deposits. The storm breached numerous barriers, creating more than a dozen ephemeral tidal inlets. Along populated sections of shoreline, rows of houses and other buildings were destroyed. Ultimately the "storm of the century" caused more than \$300 million in damage and accounted for numerous deaths.

A classification of northeasters has been devised by Robert Dolan and Robert Davis, who have studied 1347 storms affecting the North Carolina coast over a 42-year period. Their scheme is based on the power of the northeaster, which is calculated by multiplying the storm's duration by the square of the maximum significant wave height (Table 5.1). They have divided storms into five classes, with the weakest storms, Class 1 and 2, comprising about 75% of all northeasters impacting the Outer Banks of North Carolina. As seen in Table 5.1, Class 4 northeasters have a frequency of 2.4%, with a significant deepwater wave height of 5 m and an average duration of 63 hours. The extreme northeaster, Class 5, has a recurrence interval of 67 years. These storms have a significant wave height of 7 m, an average duration of 96 hours, and are agents

Table 5.1 The Dolan–Davis classification of northeast storms.

Storm class	Frequency of storms		Significant wave height (m)	Duration (h)	Power (m^2 h)	
	Number	Percentage			Mean	Range
1 Weak	670	49.7	2.0	8	32	≤71.63
2 Moderate	340	25.2	2.5	18	107	>71.63 to 163.51
3 Significant	298	22.1	3.3	34	353	>163.51 to 929.03
4 Severe	32	2.4	5.0	63	1455	>929.03 to 2322.58
5 Extreme	7	0.1	7.0	96	4548	>2322.58
	1347					

of permanent change along the coast, such as the Ash Wednesday Storm of 1962.

Shoreline vulnerability

Many of the factors that control the severity of hurricanes also apply to the impact of northeasters. The storm's size and intensity are of paramount importance, as these elements control wave height, magnitude of the storm surge, and to some extent the storm's duration. Astronomic tidal conditions can significantly augment or reduce the effects of the storm surge, thereby affecting the elevation where waves break along a shoreline. For example, the Blizzard of 1978, which is the storm of record along much of the New England coast, occurred during extraordinarily high tidal elevations in which the predicted mean high tide was 60 cm higher than mean high water levels. The high astronomic tides coinciding with the blizzard were a major factor contributing to coastal flooding, beach erosion, overwashing of barriers, inlet formation, and wave-induced damage (Fig. 5.14).

Although the majority of extratropical cyclones travel in a northeasterly path offshore of the coast, producing northeasterly winds and waves, some low-pressure systems take an inland track, such as through the Hudson or Connecticut valleys. In some instances, storms move through the Gulf of Saint Lawrence. In these circumstances the cyclonic wind regime produces wind from the southerly quadrant. In New England the shorelines have a variety of orientations and exposures to wave energy. In this region the storm track is particularly important in determining the impact of storm processes. The passage of the common northeaster primarily affects the eastward facing shorelines of outer Cape Cod and the north and south shores of Massachusetts Bay as well as the New Hampshire and southern Maine coasts. Storms that travel west of New England generate southerly wind and waves that impact the southward shores of Rhode Island, Cape Cod, and the central peninsular coast of Maine.

Another factor that influences the vulnerability of beaches to storm erosion and damage to adjacent structures is the interval between storms. The width and elevation of the berm strongly affects erosion of the abutting dune during storms. Beaches with wide accretionary berms can withstand the onslaught of an intense northeaster because the berm constitutes a large quantity of sacrificial sand that can be eroded before the dune or adjacent dwelling is destroyed. If a previous storm has removed the sand buffer, then the impact of the next storm will be much greater than that of the first. One of the reasons why the Halloween Eve Storm of 1991 caused significant damage to New England was that Hurricane Bob, which passed through the region a month and half earlier, had left many of the shorelines with little sand on the beaches.

Fig. 5.14 View of houses destroyed in Scituate, Massachusetts, during the Blizzard of 1978. Storm waves and the onshore movement of gravel toppled foundations, leading to the collapse of numerous houses along this section of coast.

5.4 Hurricanes and tropical storms

5.4.1 Low latitude storms

Hurricanes and their forerunners, tropical storms, are the major storms of the tropics. Similarly to other weather systems, they commonly move beyond their typical latitudinal range given the right set of circumstances. Most of us are familiar with tropical storms and hurricanes due to the wide media coverage they receive, particularly when a major coastal region in the United States is impacted.

Tropical storms and hurricanes are known by different names in other parts of the world. In the western Pacific they are called typhoons, in the Indian Ocean they are known as cyclones, and in Australia they are given the name "willi-willis." Tropical storms are low-latitude cyclonic systems that may intensify to a hurricane if wind velocities surpass 119 km h^{-1}. During an average year, approximately 20 tropical storms form in the equatorial Atlantic and of these eight to ten reach hurricane strength. Most hurricanes that make landfall in the United States do so in the Gulf of Mexico or along the Florida and North Carolina coasts. In a study of hurricane frequency for the southeast United States coast, Robert Muller and Gregory Stone of Louisiana State University showed that Morgan City, Louisiana, and the Florida Keys have the shortest recurrence of major hurricanes (wind velocity >179 km h^{-1}, 111 m.p.h.) (Table 5.2). The Florida Keys (including Key West and Key Largo) have survived over 32 hurricanes during the past century and seven of these were major hurricanes.

Table 5.2 Hundred-year summary of hurricane strikes and return periods.

	Hurricane strikes	Major hurricane strikes	Hurricane return period (years)	Major hurricane return period (years)
South Padre Island, TX	8	3	12	33
Port Aransas, TX	9	2	11	50
Port O'Connor, TX	13	2	8	50
Galveston, TX	13	3	8	33
Cameron, LA	5	2	20	50
Morgan City, LA	10	7	10	14
Boothville, LA	16	5	6	20
Gulfport, MS	10	2	10	50
Dauphin Island AL	15	4	14	25
Pensacola Beach, FL	14	2	7	50
Destin, FL	10	3	10	33
Panama City Beach, FL	10	2	10	50
Apalachicola, FL	11	0	9	100
Cedar Key, FL	3	1	33	100
St Petersburg, FL	5	1	20	100
Sanibel Island, FL	8	1	12	100
Marco Island, FL	12	3	8	33
Key West, FL	17	2	6	50
Key Largo, FL	15	5	7	20
Miami Beach, FL	15	2	7	50
Palm Beach, FL	13	4	8	25
Vero Beach, FL	10	1	10	100
Cocoa Beach, FL	4	0	25	100
Daytona Beach, FL	3	0	33	100
Jacksonville Beach, FL	2	0	50	100
St Simons Island, GA	1	0	100	100
Tybee Island, GA	5	0	20	100
Folly Beach, SC	3	1	33	100
Myrtle Beach, SC	7	2	14	50
Wrightsville Beach, NC	11	2	9	50
Atlantic Beach, NC	10	3	10	33
Cape Hatteras, NC	15	3	7	33

TX, Texas; LA, Louisiana; MS, Mississippi; AL, Alabama; FL, Florida; GA, Georgia; SC, South Carolina; NC, North Carolina.
Source: Study of hurricane frequency of the southeastern USA by Robert Muller and Gregory Stone of Louisiana State University.

in the bathymetry of the inner continental shelf and the configuration of coast.

Most people are aware that hurricanes are named. This practice was initiated because of the confusion surrounding situations of multiple hurricanes at one time. Prior to naming, storms were identified by their location: latitude and longitude. The first names were given during the Second World War and were in alphabetical order, such as Able, Baker, Charlie – the commonly used designations for the alphabet by the military. This practice continued until 1953, when female names were used, also in alphabetical order. This style of designating storms lasted for 25 years, and then in 1978 the policy was changed to include both male and female names. A set of names is chosen years in advance, with the first one alternating between male and female and continuing through the alphabet. Names of hurricanes that have severely impacted the United States are permanently retired from the list. Hurricanes that have achieved this status include Camille (1969), Hugo (1989), and Andrew (1992). Different names are used for the north Atlantic and eastern Pacific storms. The name is applied from the time it achieves tropical storm level until it has completely dissipated.

Hurricanes lose their power when they move over cool ocean waters or onto land. Generally by 40° latitude the waters are too cold to supply the large amounts of moisture needed to fuel the storm. Likewise, when a hurricane moves over land, sources of water vapor are greatly reduced. The ability of the storm to take up moisture is further lessened by the cooling effect of the land. Finally, the friction imparted by the land surface rapidly diminishes the low-level storm winds. These factors contribute to an increase in barometric pressure and a spreading out of the storm, leading to its general unraveling and loss of identity. Hurricanes typically last about a week to ten days but some have been known to last as long as a month.

5.4.4 Hurricanes at the coast

Many coastal regions around the world, including numerous sites along the Gulf coast and eastern seaboard of the United States, are low-lying and moderately to densely populated, with numerous dwellings, buildings, and other infrastructure. This combination presents a highly vulnerable situation to a major storm. Devastation to natural environments, destruction of property, and injury or even death to people are all typical hurricane impacts to the coastal zone. This section considers what happens when a hurricane approaches and passes over a coastal area.

Factors affecting their severity

The strength, speed, and size of the storm are major elements in determining how the hurricane will affect the coast. In addition, the gradient and width of the inner continental shelf are important considerations. In some regions, such as New York Bight, the configuration of the coast is also a critical factor. All of these variables contribute to the size of the waves, magnitude of the storm surge, and overall impact of the hurricane. Remember that storm surge, or storm tide as meteorologists frequently call it, is the super-elevation of the ocean water surface above the predicted tide level. It is the storm surge that allows the high-energy storm waves to break high against a dune ridge, across a barrier, or over a seawall. We can better assess the impact and behavior of different hurricanes, and compare those of increasingly higher category, if first we understand the factors that influence them:

1 Magnitude. Encompasses both hurricane size and intensity. Hurricane size governs the length of coast that is affected by the storm as well as the duration of high velocity winds and high-energy waves. The greater the intensity of the hurricane, the stronger the wind velocities and the larger the wave heights and storm surge.

2 Speed of storm. Determines the amount of time over which storm winds can transfer energy to the water surface waves and pile water onshore. Generally, slower moving storms produce higher waves and larger storm surges than faster moving storms of equal magnitude.

3 Path of storm. Determines the landfall of a hurricane and areas along the coast of greatest storm impact. In the northern hemisphere, when a hurricane moves onshore, areas to the right of its landfall will experience the strongest winds and greatest storm damage.

4 Coastline configuration. This is an important factor in large deeply embayed coastlines. In this setting certain hurricane tracks can significantly amplify storm surge levels as water is forced into the funnel-shaped embayment.

The circulation of wind within a hurricane and its speed and pathway toward land dictate the relative intensity of the storm and the amount of damage the hurricane will inflict along a given stretch of coast. In the northern hemisphere the wind orbiting the central low pressure of the hurricane travels in a counterclockwise direction. At the same time that this wind is blowing in a circular fashion, the hurricane is also moving over the ocean surface with a velocity that ranges from 5 to 40 km h^{-1}. This forward movement of the hurricane has an additive effect on wind blowing in the same direction as the path of the storm and a subtractive effect where the storm wind is blowing in the direction opposite to the storm's forward motion.

To illustrate this point, consider a moderate-sized hurricane in the Gulf of Mexico with an average wind velocity of 180 km h^{-1} (Fig. 5.19). The storm is moving northward with a speed of 30 km h^{-1}. East of the storm's eye the hurricane wind blows in a northerly direction with a velocity of 210 km h^{-1} (180 + 30 km h^{-1}). At the same time, wind west of the eye blows southward with an effective velocity of only 150 km h^{-1} (210 – 30 km h^{-1}). Not only is the effective wind velocity different on either side of the storm, but also as the storm passes the coast the shoreline east and west of the eye experiences very different wind and wave conditions. East of the eye there is a wind "set-up" where wind continues to blow onshore building the storm surge. Conversely, west of the eye there is a "set-down" producing lower water level and waves due to the wind blowing offshore. Damage from a hurricane is always greater to the right of the landfall than to the left of the landfall.

Hurricane Frederick was a moderate-sized storm that struck the Mississippi coast in 1979. Meteorologic and oceanographic data collected during the storm illustrate the relationships among the storm's

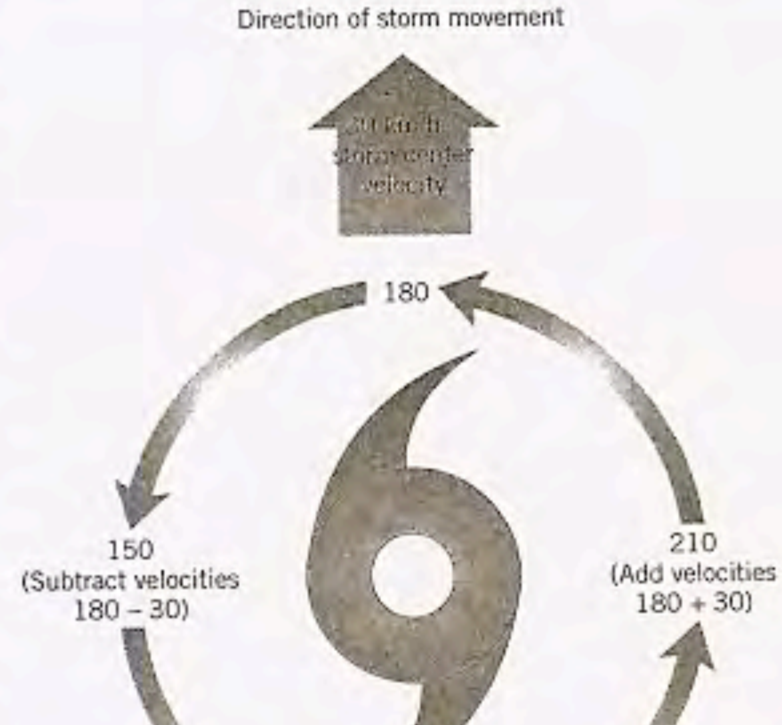


Fig. 5.19 The forward speed of a hurricane increases wind velocities on the advancing right side of the storm while diminishing wind velocities on the advancing left side of the storm.

low pressure, its wind velocity, and the storm surge pattern (Fig. 5.20). The hurricane moved onshore from the Gulf of Mexico at an average forward speed of 15 km h^{-1}. The eye of the storm made landfall at Dauphin Island, which is located along the western flank of Mobile Bay. As seen in Fig. 5.21, the highest wind velocity that was recorded at the coast, 126 km h^{-1}, coincided with the period of lowest pressure. Generally the lowest pressure is found near the eye of the hurricane and it gradually increases toward the perimeter of the storm. The strongest wind corresponds with the steepest pressure gradient, which occurs just beyond the eye of the storm. During the passage of Hurricane Frederick maximum tidal elevations recorded along the coast ranged from 1.0 to 3.8 m above mean sea level. As illustrated in Fig. 5.22, water elevations were much greater east of Dauphin Island than in the coastal regions to the west. Note that the greatest storm surge took place approximately 30 km east of the eye. This pattern of higher water level, flooding,

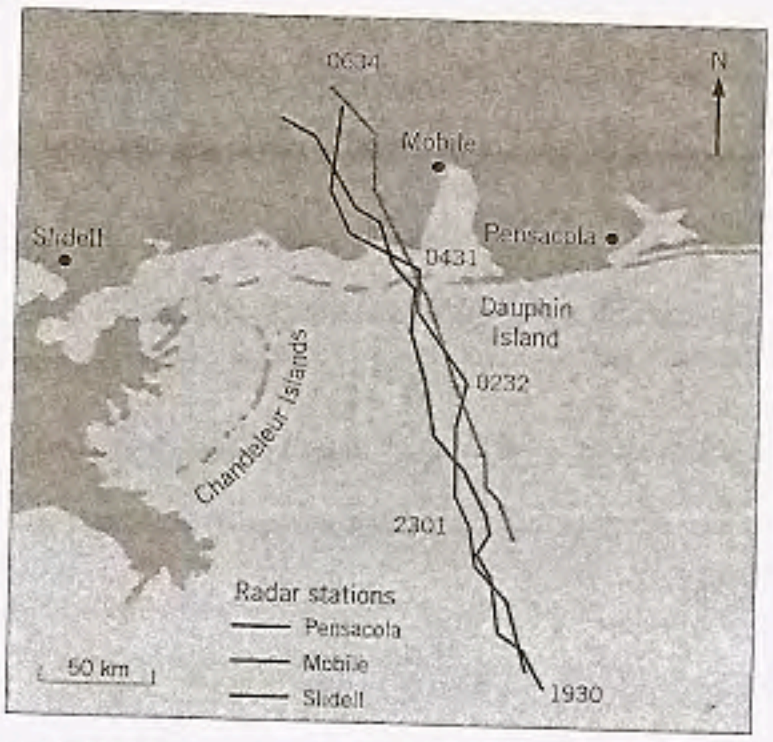


Fig. 5.20 Storm track of Hurricane Frederick, which struck Dauphin Island along the Mississippi coast on September 13, 1979. (Courtesy of Shea Penland, University of New Orleans.)

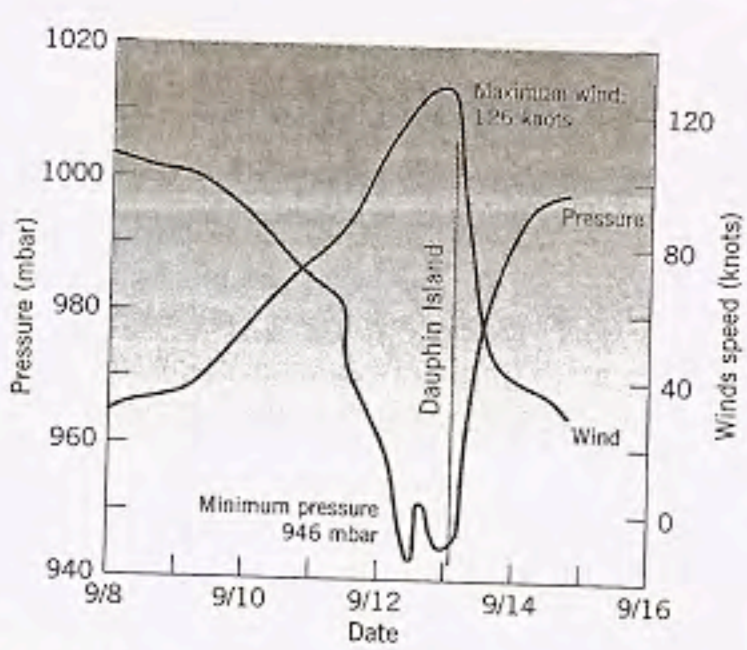


Fig. 5.21 Graph of atmospheric conditions at Dauphin Island, Mississippi, during the passage of Hurricane Frederick. Maximum wind velocities coincided with lowest atmospheric pressures. (Courtesy of Shea Penland, University of New Orleans.)

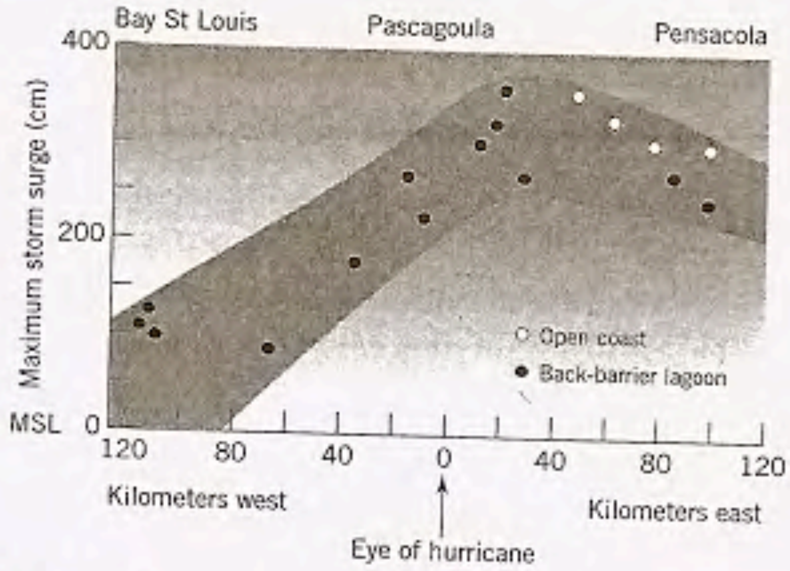


Fig. 5.22 Storm surge values along the Gulf coast from Mississippi to the panhandle of Florida resulting from Hurricane Frederick. (Courtesy of Shea Penland, University of New Orleans.)

and damage that occurs east of the storm center is due to the hurricane's counterclockwise wind circulation. When the hurricane was centered over Dauphin Island wind was still blowing onshore east of the island. At the same time, wind was already blowing offshore along the coasts of eastern Louisiana and western Mississippi. The longer the time during which hurricane winds blow onshore, the greater the storm surge and resulting damage.

The importance of coastline configuration has been clearly demonstrated in a study of New York Bight by Nicolas Coch of Queens College (New York). Eastern Long Island and northern New Jersey meet at near right angles to one another, forming a funnel-shaped embayment. Coastlines with this type of configuration are susceptible to amplification of the storm surge as waters are constricted by the adjoining landmasses. Dr Coch has shown that if a moderate-sized hurricane tracked in a northwesterly direction across northern New Jersey, the storm surge would be heightened from 1 m at the inner shelf to more than 6 m at the mouth of the Hudson River (Fig. 5.23). It is obvious that if (when) this hurricane scenario occurs, New York City would be devastated! The large storm surges associated with extensive loss of life in Bangladesh have been caused in part by the same funneling effect that is produced in the upper Bay of Bengal.

Hurricane categories

The strength of a hurricane is formally classified using the Saffir–Simpson Scale and is based on the maximum wind velocity, barometric pressure, storm

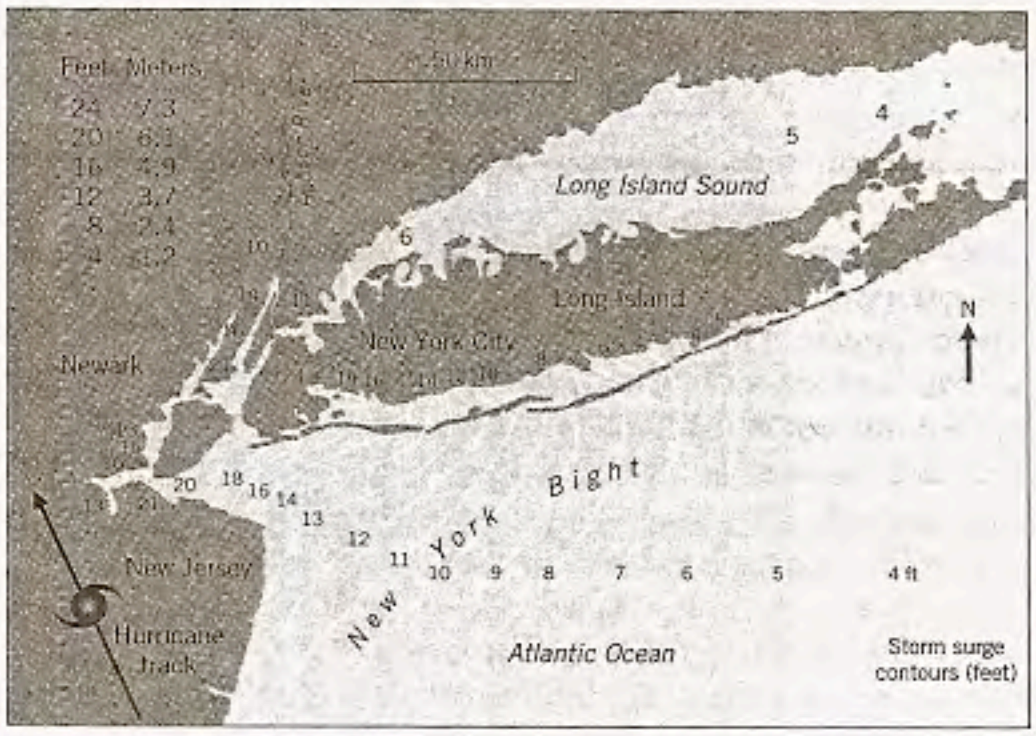


Fig. 5.23 Predicted storm surge values for the New York Bight. The contours are based on the SLOSH hurricane computer model. (From N. K. Coch, 1995, *Geohazards Natural and Human*. Englewood Cliffs, NJ: Prentice Hall, p. 444, Fig. 16.19.)

Table 5.3 Storm genesis.

Tropical disturbance	Prevalence of thunderstorms, infancy stage of tropical cyclone
Tropical depression	Cyclonic wind pattern, wind velocities up to 61 km h^{-1} (38 m.p.h.)
Tropical storm	Highly organized ocean storm visible in satellite imagery, velocities from 61 to 119 km h^{-1} (38 to 73 m.p.h.)
Hurricane	Spiraling cloud pattern around a central eye, wind velocities exceed 119 km h^{-1} (73 m.p.h.)

surge level, and expected damage (Table 5.4). The scale has five categories and each higher level represents a substantial increase in hurricane intensity (Table 5.5). A list of the most intense hurricanes in the United States in terms of loss of life and property damage is provided in Table 5.6. It is evident from this table that death tolls have decreased in recent times as meteorological forecasts and evacuation procedures have improved.

Most hurricanes fall within categories 1 to 3. One of the difficulties of accurately determining the maximum wind in severe storms such as a category 4 or 5 hurricane is the inability of instruments to withstand the storm. As an example, there has been considerable disagreement about the maximum wind velocity of Hurricane Andrew as it struck south of Miami in August 1992. Instrumentation at the National Hurricane Center in Coral Gables measured sustained wind of 210 km h^{-1} (125 m.p.h.), with gusts of about 275 km h^{-1} (165 m.p.h.) at the time that it became disabled. Calculations indicate that peak sustained wind velocities were probably greater than 235 km h^{-1} (140 m.p.h.). Inland from the shoreline high-velocity wind exerts the greatest influence on vegetation and manmade structures. The path of a hurricane is often evidenced by broken and uprooted trees, destroyed homes, and public infrastructure in complete disarray.

Damage to structures due to hurricanes is associated with lowland flooding, wave attack, and strong wind. Because of the current stringent rules and regulations regarding construction in the coastal zone, there are usually few problems with wind damage. In hurricane-prone areas, most damage is now confined to roofs, where shingles are commonly torn from roofs. Under extreme conditions such as during a category 4 or 5 hurricane, damage can be much greater and the building itself can be

Table 5.5 Comparative destructive level of hurricanes, by Saffir–Simpson category.

Category	Relative hurricane destruction potential
1	1 (reference level)
2	4 times the damage of a category 1 hurricane
3	40 times the damage
4	120 times the damage
5	240 times the damage

Source: Based on empirical analysis over the past 42 years by Dr William M. Gray, Colorado State University meteorologist.

destroyed. A good example of how recent construction codes have protected dwellings during the passage of moderate hurricanes is illustrated by the impact of Hurricane Opal in 1995. This severe storm made landfall in the panhandle of Florida just east of Pensacola. Of the nearly 1500 homes subjected to the storm's fury, approximately half were constructed prior to the new regulations and the other half were built in compliance with new building codes. There were hundreds of homes severely damaged or destroyed during the storm, but all of those built under present guidelines received only minor damage.

Storm surges and the accompanying large waves can, however, cause major damage, including the destruction of structures. For this reason, current zoning in Florida requires that the first level of occupancy must be above the 100-year storm surge level. This level is based on existing data and predicted frequency of storm surge. For example, the Gulf coast of central and southern Florida is predicted to experience a 4 m storm surge on a 100-year return interval. This is based in part on historical data of previous storms and in part on computer modeling of storm conditions using variables such as shelf gradient, wind velocity, and wave size, among others. Qualification for federally supported insurance in the coastal zone requires compliance with these regulations.

Table 5.6 The deadliest and costliest hurricanes in US history.

Hurricane	Year	Category	Pressure (millibars)	Damage (US$ billion)*	Deaths
Camille (Mississippi, Louisiana)	1969	5	909	6.10	256
Florida (Keys)	1935	5	892		408
Andrew (SE Florida, SE Louisiana)	1992	4	922	30.48	15
Audrey (SW Louisiana, N Texas)	1957	4	945	0.80	390
Florida (Keys), S Texas	1919	4	927		600†
Florida (Lake Okeechobee)	1928	4	929		1836
Florida (Miami, Pensacola), Mississippi, Alabama	1926	4	935	4.83	243
Hugo (South Carolina)	1989	4	918	7.00	57
Louisiana (Grand Isle)	1909	4	931		350
Louisiana (New Orleans)	1915	4	931		275
Texas (Galveston)	1900	4	931	0.81	6000†
Texas (Galveston)	1915	4	945	1.35	243
Mississippi, Alabama, Pensacola	1906	3			134
NE USA	1944	3	947	1.06	390
New England	1938	3	946	4.14	600
SE Florida	1906	2			164
Diane (NE USA)	1955	1	969		184

*Adjusted to 1996 dollars on the basis of US Department of Commerce implicit price deflator for construction.
†Minimum estimates.
Source: National Hurricane Center (http://www.nhc.noaa.gov/pastall.html).

5.5 Summary

Hurricanes and extratropical cyclones are a dramatic expression of the Earth's weather system. Through recorded history severe storms have accounted for permanent changes to the coastal landscape, billions of dollars of damage, and the unfortunate loss of many lives. Hurricanes are tropical storms with wind velocities exceeding 119 km h^{-1}. The largest hurricanes have storm surges greater than 7 m and winds attaining 220 km h^{-1}. They form in the tropics and are steered by the prevailing global wind patterns. Hurricanes affecting the United States are initiated off the west coast of Africa. They intensify over the warm Atlantic Ocean waters and travel in an easterly direction until they make landfall along the Gulf of Mexico and along the east coast, most commonly from Florida north to the Outer Banks of North Carolina. Rarely do hurricanes strike the west coast of the United States. They degenerate after moving over land or cold water.

Extratropical cyclones form above the tropics and are commonly associated with cold fronts. These storms are usually weaker than hurricanes, but occur more frequently. They develop over the continental United States, in southwestern Canada, in the Gulf of Mexico, and off the east coast of Florida. These storms generally move eastward and northward, eventually traveling offshore of New England and passing east of Nova Scotia. They generate northeasterly winds and waves and therefore are called "northeasters." Northeasters last for one to two days and are accompanied by wind velocities of 40–65 km h^{-1} and storm surges ranging from 0.2 to 1.2 m.

Both hurricanes and extratropical storms are low-pressure systems with counterclockwise wind patterns. The strength, speed, and size of these cyclonic systems control the severity of the storm, including the amount of erosion and structural damage. Storm track, gradient of the shelf, configuration of the shoreline, and astronomic tidal conditions are other important factors governing storm processes.

Suggested reading

Abbott, P. L. (1996) *Natural Disasters*. Dubuque, IA: W. C. Brown Publishers (Chapters 9 and 10).

Coch, N. L. (1995) *Geohazards: Natural and Human*. Englewood Cliffs, NJ: Prentice Hall.

Dunn, G. E. & Miller, B. I. (1960) *Atlantic Hurricanes*. Baton Rouge: Louisiana State University Press.

Elsner, J. & Kara, A. B. (1999) *Hurricanes of the North Atlantic: Climate and Society*. Oxford: Oxford University Press.

Henry, J. A., Portier, K. M. & Coyne, J. (1994) *The Climate and Weather of Florida*. Sarasota, FL: Pineapple Press.

Pielke, R. A. Jr & Pielke, J. A. Sr (1997) *Hurricanes: Their Nature and Impacts on Society*. New York: Wiley.

Simpson, R. H. & Riehl, H. (1981) *The Hurricane and Its Impact*. Baton Rouge: Louisiana State University Press.

Williams, J. M. & Duedall, I. W. (1997) *Florida Hurricanes and Tropical Storms*, rev. edn. Gainesville: University Press of Florida.