Figure 1.1 *Self-regulating climate*: Clouds form as moisture in thermals updrafts condenses upon meeting cooler air aloft, shading the land and limiting further warming. Gulf of Carpentaria, Northern Australia.

(PHOTO: © Reg Morrison)

Source: Reg Morrison, *The Climate Debate*, 2009, <homepage.mac.com/gregalchin/rm/pdfs/climate%20debate.pdf> .

CHAPTER 1

WEATHER

1.1 SUN AND EARTH

The thin line of life that surrounds the globe is defined by the precise juxtaposition of Earth's orbit around the Sun, its orientation in its orbital eccentricity, and Moon's gravitational balance. Earth's geological history, atmosphere of oxygen and water, and magnetic field contribute to the conditions that created and sustain our biological life. Earth's axial tilt and annual rotation around the Sun define our climates and seasons. The Sun's radiant energy and thermal flux of lands and oceans drive the daily progression of water within the atmosphere and regions of the globe.

Earth has just the right mass, chemical composition, and distance from the Sun to permit water to exist as a liquid, solid, or gas, freely changing its state as it is transported through our atmosphere. Not a drop of liquid water has been found elsewhere in the solar system. This was not always so. Channels on Mars suggest that early in its history, its climate was warmer and it too had free-flowing water.

To understand flooding, one must understand water. To understand water, one must understand climate and weather. Variations that we experience on Earth in climate, weather, and water begin with Sun–Earth geometry. Viewed from a hypothetical position above the North Pole, the Earth orbits the Sun counterclockwise in an elliptical orbit, close to a perfect circle. The average distance to the Sun is 93 million miles (150 million km). This distance is called 1 *astronomical unit of length* (AU), defined by the International Astronomical Union as the mean distance between the Earth and Sun over 1 orbit of the Earth. (Figure 1.2.)

Earth's axis is tilted 23.4° with respect to its orbital plane, defined by the line between the Sun and Earth. The *angle of incidence* is the angle formed between the Sun's parallel rays and earth's surface. This angle is known to designers familiar with requirements for window shading and solar control: For any building at any latitude, the range of solar altitude in degree angles is 23.4° + 23.4° = 46.8°.

Due to the Earth's axial tilt, the amount of sunlight reaching the surface of Earth varies over the course of the year, and heat imbalance is created between the poles, generating conditions for global thermal flows in atmosphere and oceans. By convention, the seasons of the calendar are determined by the *summer and winter solstice*—when the tilt of Earth's axis is most inclined toward or away from the Sun—and the *vernal* and *autumnal equinox*, when the angle of the tilt is perpendicular to the Sun–Earth line and the Sun directly overhead along the equator.

The average distance between Earth and Moon is approximately 240,000 miles (386,000 km) or, for purposes of visualization, approximately 30 times Earth's diameter. Earth is held in orbit by the gravitational force of the Sun. Earth and Moon are influenced by mutual gravitation that counteracts their centrifugal forces. The world's ocean mass is pulled by lunar gravity that influences tides more than the Sun's gravitation field. (Figures 1.3 and 1.4.)

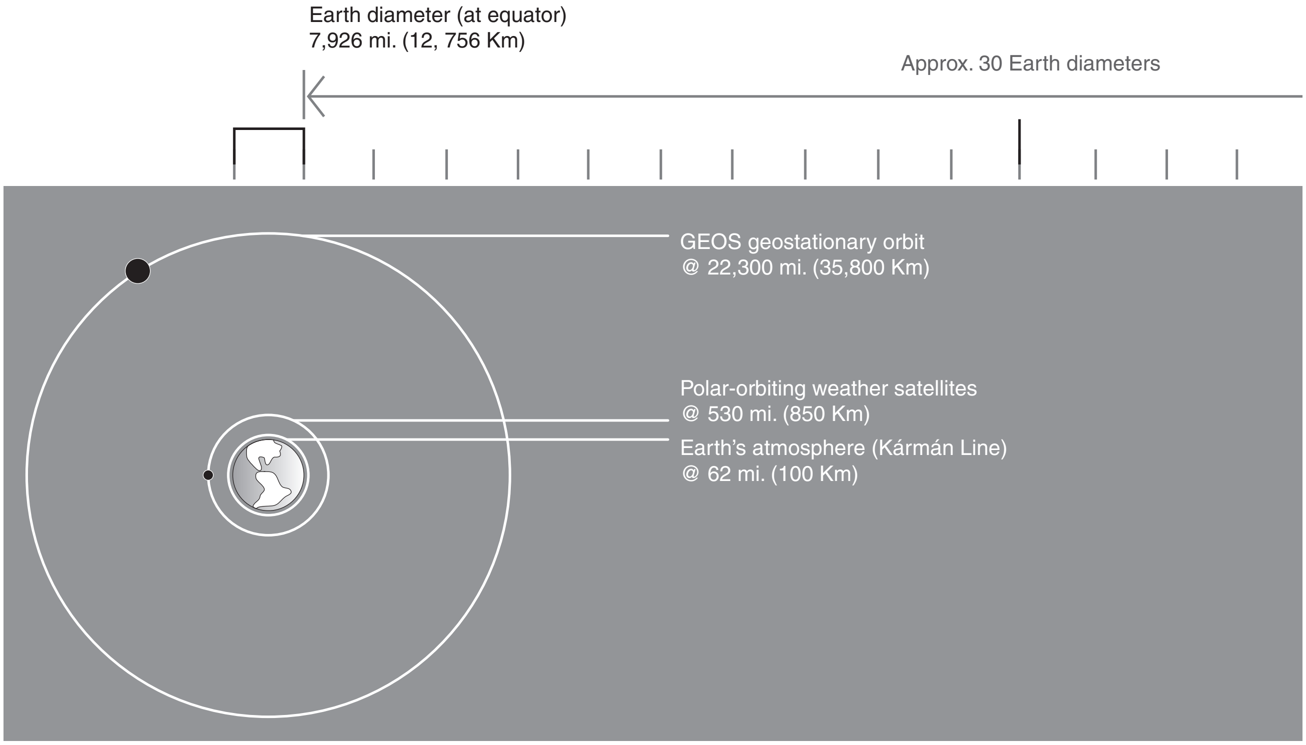

Figure 1.2 *Earth, Moon, and Sun* shown in scale of size and distance.

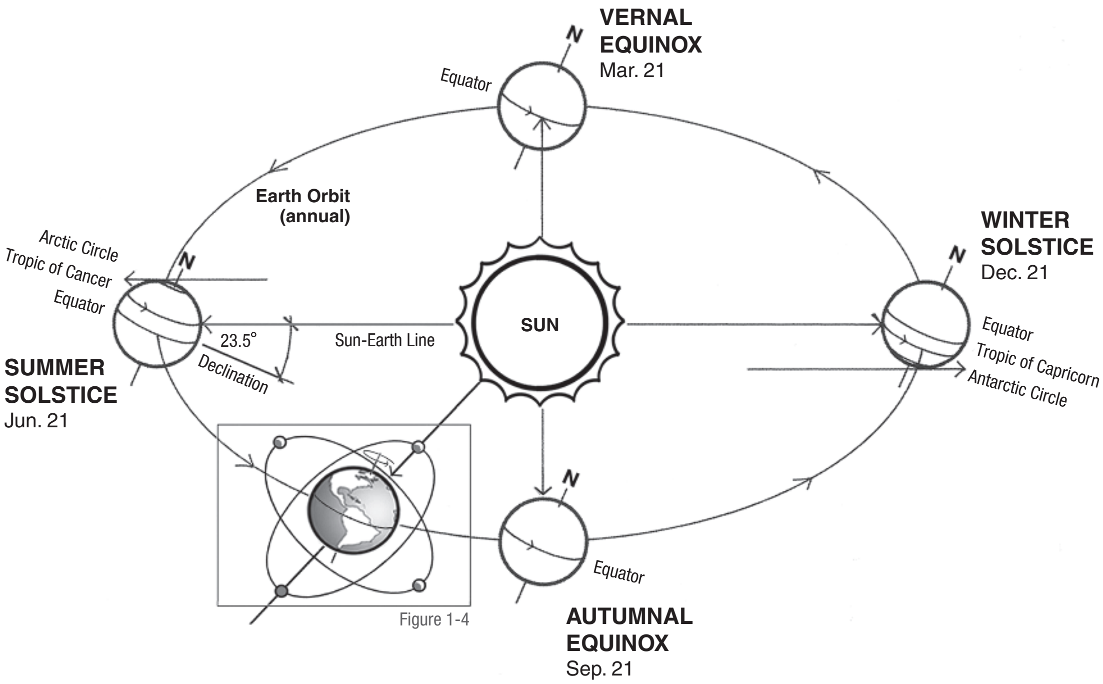

Figure 1.3a *Solar geometry:* Earth's fixed angle of tilt as it orbits the Sun accounts for seasonal climate and weather.

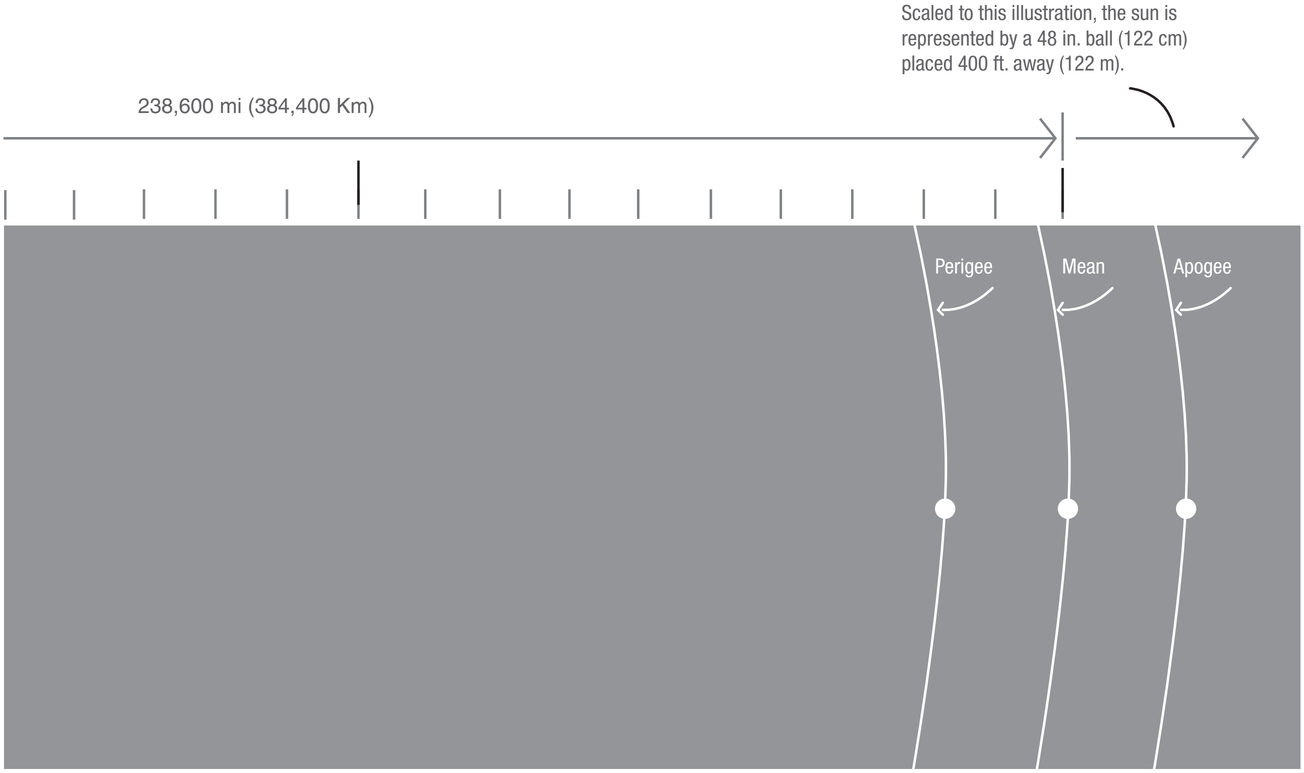

Figure 1.3b *Midnight Sun:* Time lapse of the Sun tracing a line just above the horizon, defining the Arctic Circle, Summer Solstice.

(PHOTO: © J. Farley)

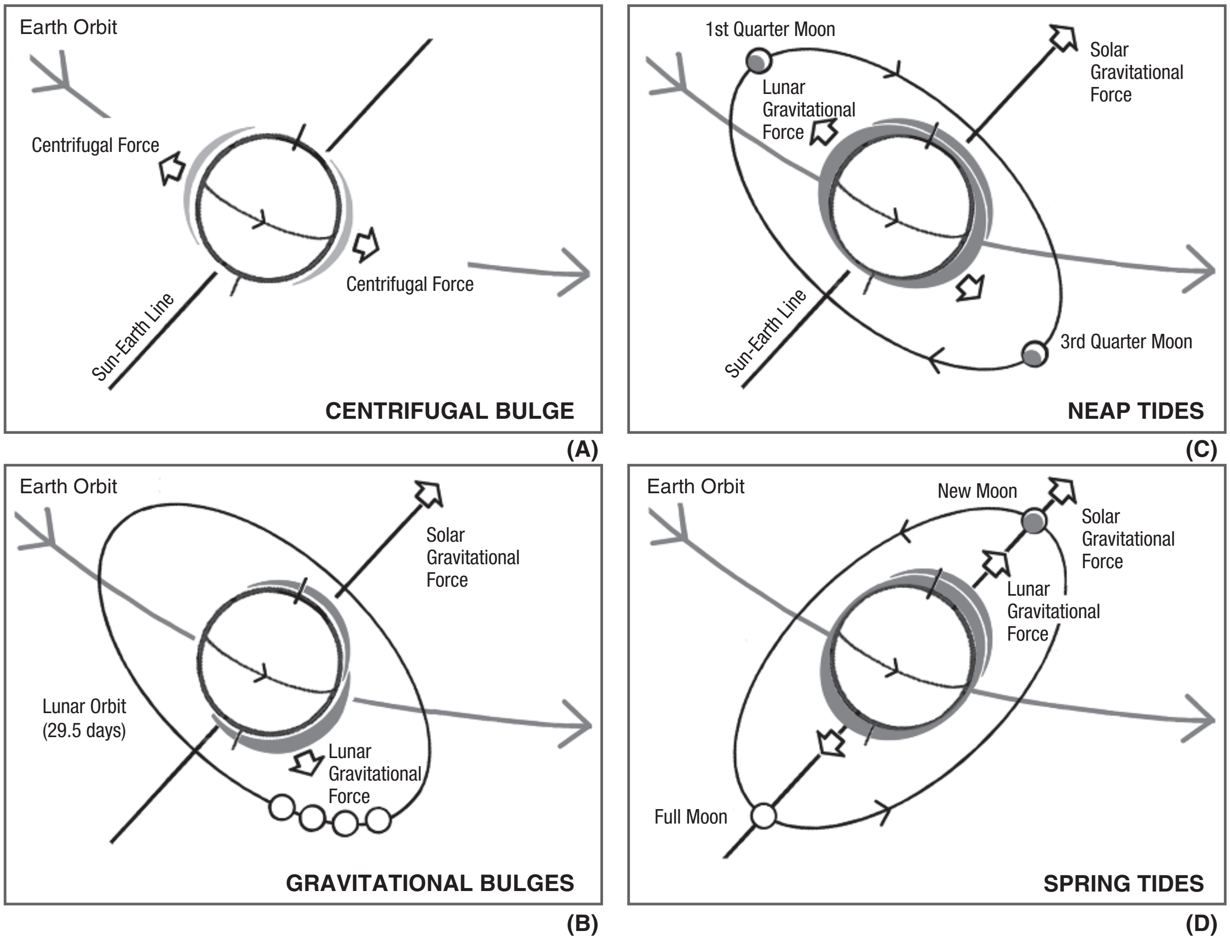

Figure 1.4 *Tides and time:* The ebb and flow of tides result from the 19-year *metonic cycle* of solar and lunar gravitational forces.

1.2 THE ATMOSPHERE

Earth is enveloped by an atmosphere comprised of gases, water, and fine dust retained by gravity and characterized by different layers of distinct temperature and composition. The atmosphere is captured by the gravitational force of its mass and density. The chemical composition of our atmosphere has been created over geologic time by compounds outgassed from Earth's crust, or possibly from impacts of volatile compounds from comets. The atmosphere is composed of 78% nitrogen, 21% oxygen, and small amounts of carbon dioxide, argon, and other gases and an average of 1% water vapor. The oxygen is the product of organic plant growth. (Table 1.1.)

The atmosphere expands and contracts as a function of season and magnetic and solar fluxes. It constantly loses molecules of lighter gases, such as helium and hydrogen. The outer limit has no clear boundary because the layer becomes increasingly thinner with altitude until it merges with outer space. (Figure 1.5 and Table 1.2.)

TABLE 1.1 EARTH ATMOSPHERE AIR COMPOSITION BY VOLUME

Nitrogen	78.08%
Oxygen	20.95%
Argon	0.93%
Carbon dioxide	0.03%

Traces: neon: 0.0012%; krypton: 0.00005%; xenon: 0.000006%; helium: 0.0003%; also nitrous oxide, methane, and carbon monoxide.

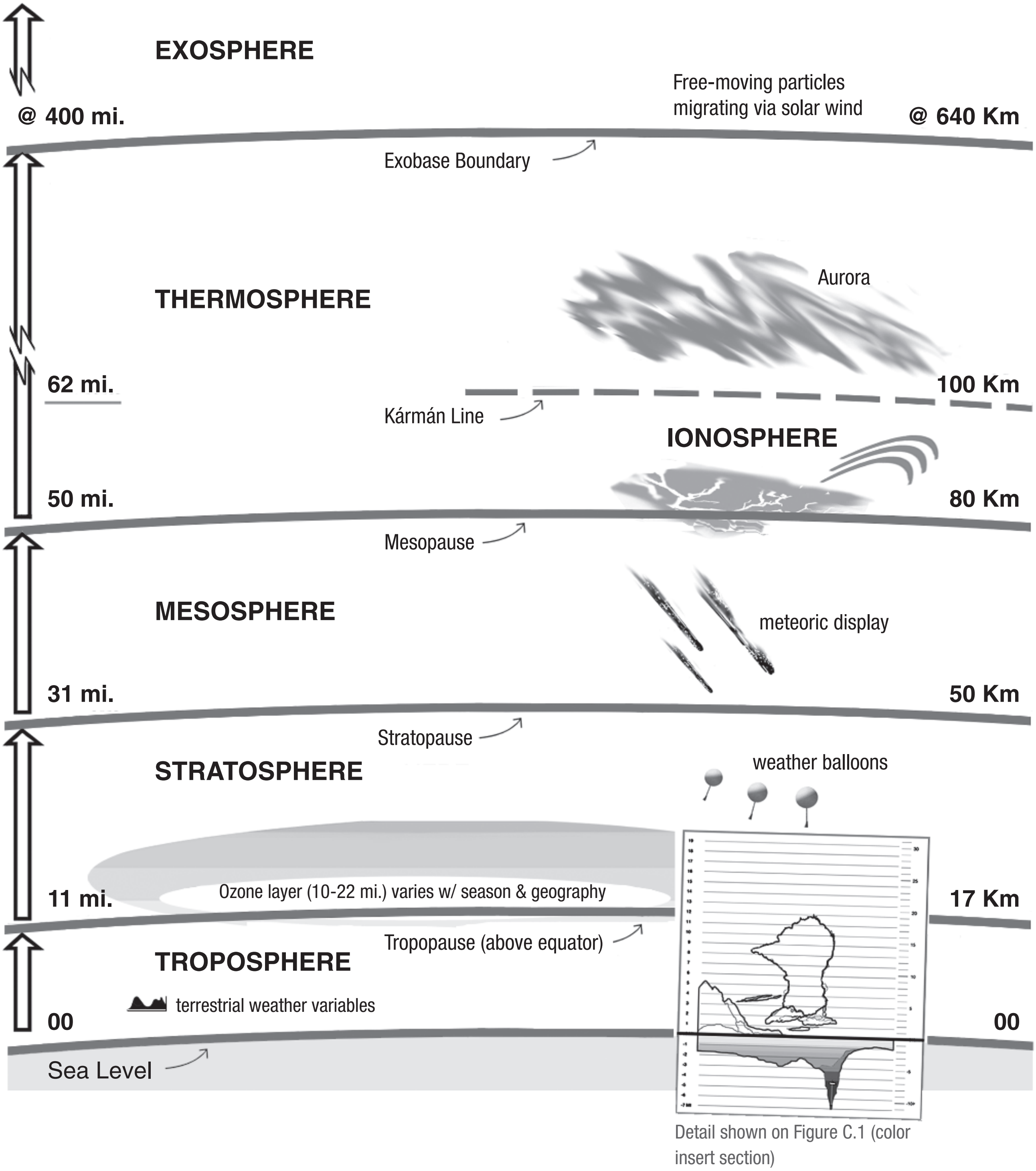

Figure 1.5 *Dimensions of the atmosphere.*

TABLE 1.2 EARTH'S ATMOSPHERIC LAYERS

Layer	Height	Temperature Range	
		Fahrenheit	*Celsius*
Exosphere	440–625 miles	3600°F	< 2000°C
Thermosphere	50–440 miles	–100°F–3,600°F	38°C–2000°C
Mesosphere	31–50 miles	32°F– −100°F	0°C–38°C
Stratosphere	7.5–31 miles	–75°F−32°F	−59°C–0°C
Troposphere	Up to 7.5 miles	65°F– −75°F	18°C–24°C

Exosphere. The outermost layer of the atmosphere in which gases get thinner and thinner and drift off into space.

Thermosphere. Temperatures generally increase with altitude, influenced by solar radiation. The gases of the thermosphere are thin but sufficient to absorb ultraviolet light from the Sun. Within the thermosphere, the *ionosphere* contains gas particles that are electrically charged by the Sun's ultraviolet rays and bounce radio signals transmitted from Earth.

Mesosphere. Temperatures generally decrease with height because thinning gases do not absorb much of the Sun's heat. The air density is sufficient to slow down meteorites hurtling into the atmosphere.

Stratosphere. Freezing temperatures gradually increase with height to about 32°F (0°C). The stratosphere contains 19% of the atmosphere's gases, which move slowly and contain little moisture, so that clouds rarely form. Within the stratosphere is the *ozone layer*, a band of ozone gas that absorbs the Sun's harmful ultraviolet rays.

Troposphere. Lowest major atmospheric layer, containing 75% of the atmospheric mass and 99% of water vapor and aerosols. Named after the Greek *tropos*, meaning "mixing," it is turbulent and influenced by the surface of the Earth. The height of the troposphere varies with latitude, ranging between 5 miles (8 km) at the poles to 10.5 miles (17 km) at the equator.

The *Kármán line* is the adopted reference for the boundary between atmosphere and space, defined by the International Federation of Aeronautics as the "edge of space" at an altitude of 62 miles (100 km) above Earth's surface.

All of Earth's weather occurs in the troposphere. Energy from the Sun heats this layer and the land and oceans below, causing expansion of the air. This lower-density air then rises and is replaced by cooler, higher-density air. The resulting atmospheric circulation drives the weather through redistribution of heat energy and water in all its forms.

Earth's surface has altered the troposphere through interactive processes of weather, water, dust, and oxygen. Photosynthesis evolved 2.7 billion years ago, creating the primarily nitrogen-oxygen atmosphere that exists today. This enabled the proliferation of aerobic organisms as well as the formation of the ozone layer that, together with Earth's magnetic field, blocks ultraviolet solar radiation, which permits life to exist.

Greenhouse Effect

In the 1820s, French scientist J. J. Fourier recognized the atmosphere's role in maintaining climate conditions livable for humans. Without this heat-retention effect, the average surface temperature would be 0°F (–18°C), much colder and essentially a frozen planet compared to actual temperature of 59°F (15°C). Swedish chemist S. Arrhenius published a "hot-house theory" in the early twentieth century, which became known as the greenhouse effect.

About 80% to 90% of Earth's natural greenhouse gas (GHG) effect is due to water vapor (H_2O). The remainder is due to trace molecules of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and a few other minor gases. Carbon dioxide is the greenhouse gas climate experts are most concerned about because the increase in human-related CO_2 emissions since the Industrial Revolution is now linked to the current global warming trend.

These trace molecules are transparent to light and shortwave solar rays but opaque to longer-wave thermal heat rays. They capture thermal energy emitted from the ground, raising the average air temperature and retarding the radiation of heat from the Earth back to space.

Carbon dioxide concentrations are increasing in the atmosphere due to fossil fuel combustion as well as rain forest burning. These concentrations represent an anthropogenic (human-made) contribution to greenhouse gas concentrations, believed to be responsible for accelerated global warming of the last 150 years. Additionally, the atmospheric concentration of methane has increased in recent decades. Reasons are uncertain, but may be ascribable to deforestation and agriculture and also to releases from deep ocean deposits and disintegration of marine and tundra hydrates.

Biosphere and Hydrosphere

The planet's life-forms sometimes are said to exist within and thus define the *biosphere*, a term originally used in geology in early nineteenth century. *Biosphere* was the title of a 1926 book by Russian Geologist V. I. Vernadsky, who defined ecology as the science of the biosphere, encompassing the life and earth sciences.

Earth is the only place in the universe where life is known to exist, which is believed to have begun to evolve about 3.5 billion years ago. The biosphere is divided into a number of biomes, inhabited by broadly similar plants and animals. Terrestrial biomes lying within arctic and polar regions or at high altitudes are relatively barren of plant and animal life. The greatest species diversity is found in tropical zones along the equator.

Bacteria play a major role in the biosphere including formation of rain-bearing clouds. Water droplets that form clouds require a nucleus where water vapor can condense and accumulate. The land supplies these nuclei in the form of dust and the bacteria that escape from plants. The ocean provides nuclei for rain in the form of dimethyl sulfide vapor (DMS) produced by photosynthesis of marine plankton. Such bacteria are a major component of the organisms that drift within the biosphere as aerial plankton.[1]

The term *hydrosphere* refers to the realm of water in all its forms on Earth. It can be said to coincide generally with the biospheric realm of living organisms sustained by water. The hydrosphere consists chiefly of the oceans but technically includes the troposphere and all water surfaces in the world, including lakes, rivers, and underground waters down to a depth of about 6,560 feet (2,000 m). The heat capacity of the oceans buffers Earth's surface from large temperature changes such as those that occur on the Moon.

Climate and Weather

Climate refers to the characterization of long-term temperature of air and ground, humidity, wind, rain, and other meteorological statistics of regions of the earth. *Weather* defines short-term variations, typically one day to several weeks. Climate and its seasons are determined by the position of the globe in its annual migration around the Sun and resulting global and continental patterns of wind and moisture transport. *Microclimate*, of direct relevance to environmental design, landscape design, and architecture, is essentially climate near the ground within 3 feet (1 m), with minute variations influenced by soil, vegetation, and moisture. Weather is determined by tropospheric conditions at regional and microclimatic scales.

Ocean currents, elevation, and latitude influence climate and weather, along with global and regional patterns of winds and storms. Masses of air and weather patterns on the surface of the Earth experience the *Coriolis effect*. The Coriolis effect—named after Gaspard-Gustave Coriolis, a French scientist who gave the force a mathematical expression in 1835—is evident in both water and air masses. At the global atmospheric scale, the Coriolis effect creates the rotation of large cyclones, appearing to veer to the right in the northern hemisphere and to the left in the southern hemisphere. At the equator, wind flow tracks east or west, with a polar tendency. As a result, tropical cyclones, typhoons, and hurricanes never cross the equator. (Figures 1.6 and 1.7.)

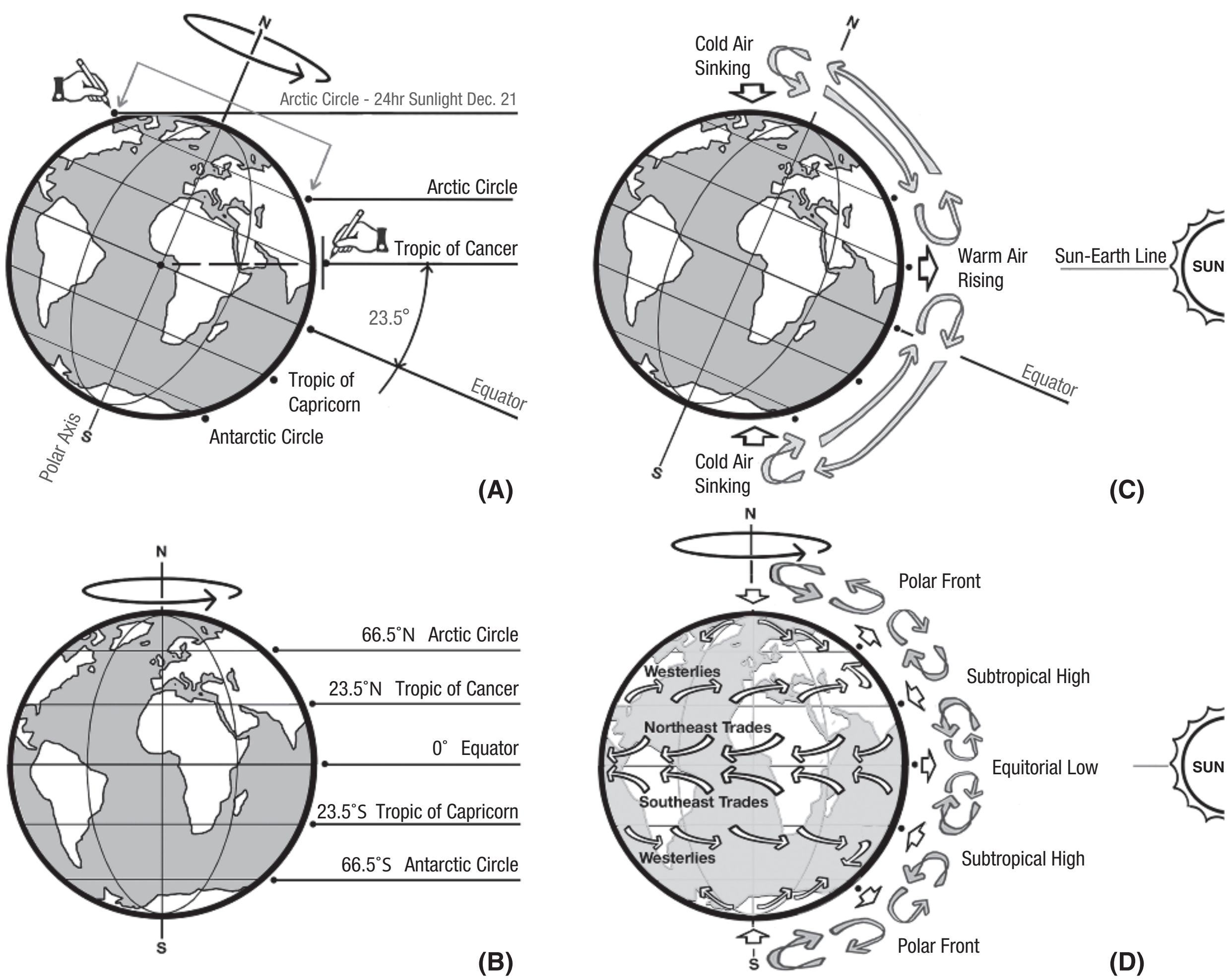

Figure 1.6 *Global wind patterns* are set in motion by thermal differences that result from Earth's solar orientation, rotation, and the *Coriolis effect.*

Meteorology

Meteorology is the study of the changes in temperature, air pressure, moisture, and wind direction in the troposphere. Meteorology addresses both description of weather and prediction of weather events.

Like all indigenous peoples, Native Americans were astute observers of the sky, climate, and weather. The first systematic weather observation beginning in the colonial era in the United States is credited to the Reverend J. Campanius Holm in 1644 in Wilmington, Delaware. Benjamin Franklin, George Washington, James Madison, and Thomas Jefferson were also keen weather observers and kept personal weather diaries. In 1814 a network of weather observations was established at army posts across the country. By 1848 Joseph Henry, considered the "father" of the U.S. Weather Service, established a meteorological program at the Smithsonian Institution calling for "a system of extended meteorological observations for solving the problem of American storms." He employed the newly developed telegraph and hundreds of volunteer weather observers located through North America, Mexico, and the Caribbean. The volunteer program was taken over by the U.S. Army Signal Service in 1874 and then transferred in 1881 to the newly established U.S. Weather Bureau, establishing the weather data network supported by governments across the globe.[2]

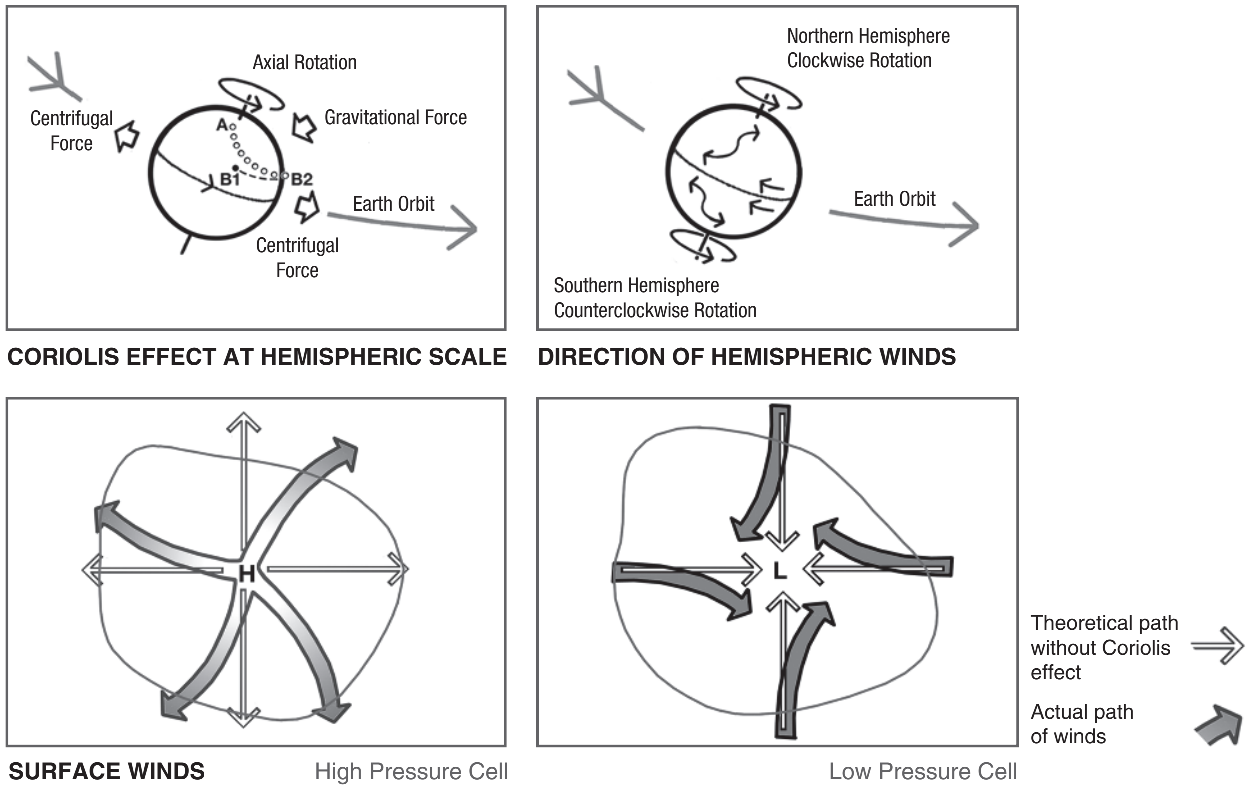

Figure 1.7 *The Coriolis effect* creates the rotation and direction of prevailing winds at continental and regional scales.

Weather satellite digital instrumentation records visible, infrared, and microwave radiation. There are two types of weather satellites, defined by their orbits. Geostationary orbiting satellites (GEOS) are placed in orbit at 22,236 miles (35,786 km) directly over the equator. At this altitude, the satellites orbit Earth once in 24 hours following the planet's rotation rate, so that the satellite appears to be fixed over a single spot; thus the word *geosynchronous* or *geostationary*, meaning "motionless in the sky if viewed from Earth." (Figures 1.8 and 1.9.)

Polar-orbiting satellites are placed in a low-altitude orbits about 500 miles (805 km) near the North Pole and the South Pole. Unlike the geostationary orbit, the polar orbit allows complete coverage as Earth rotates beneath.

Weather measurements are also recorded twice each day by radio transmission from weather balloons. Launched each day at the same time, balloon flights transmit data to the National Centers for Environmental Prediction (NCEP) in Washington, DC, creating a global picture of weather every 12 hours. Additional measurements are recorded at surface stations. All measurements are transmitted to different weather modeling centers throughout the world to produce projected weather patterns. The resulting data are provided to weather forecasters for interpretation and broadcast.

Cloud Formation

Water vapor is water in its gaseous state, typically of minute size and totally invisible. Water vapor is transported by circulatory patterns in the atmosphere in the form of clouds, mist, and precipitation distributed by global weather.

Clouds form when convective condensation reacts with rising air. When air over the warmest part of the land rises and meets cooler air, the water vapor it contains condenses into cloud droplets. The congealing air mass will continue to rise as long as its temperature is higher than the air around it. For both ancient seafarers and modern meteorologists, cloud formations have signaled weather conditions developing on the horizon. (Figure 1.10.)

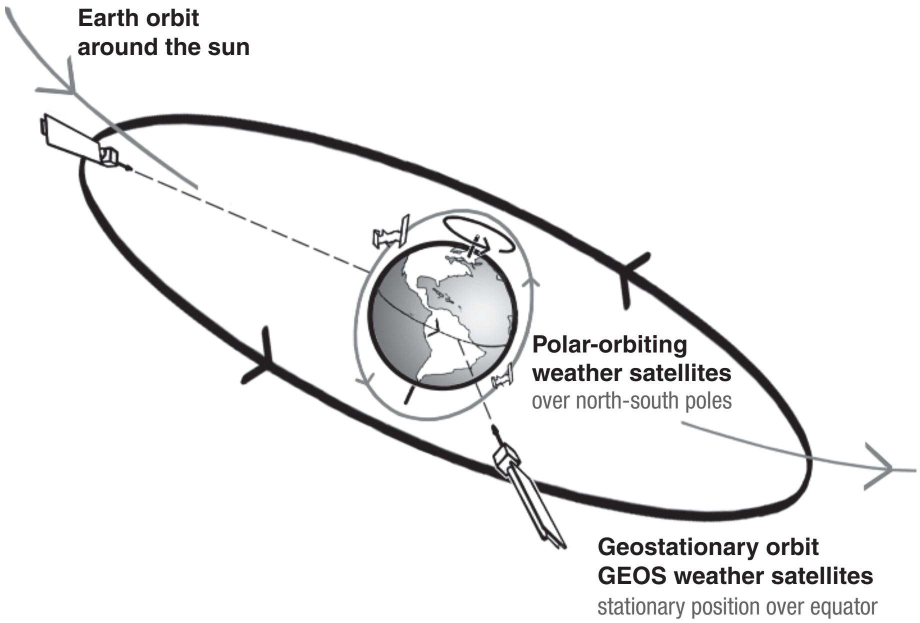

Figure 1.8 *Weather satellites* enable real-time tracking of global weather.

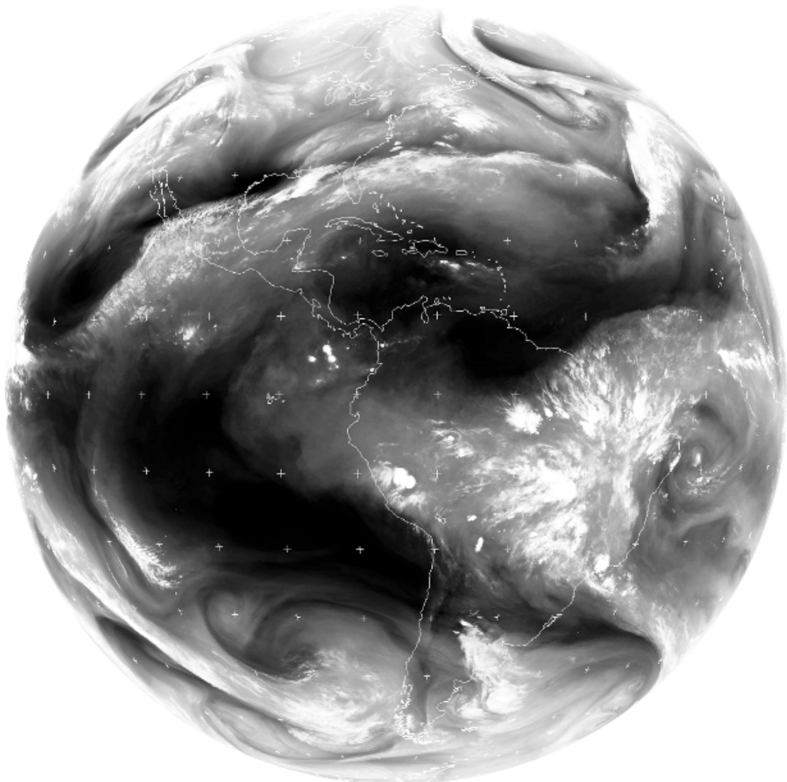

Figure 1.9 *Images from space:* Images constructed from digitized data from GEOS satellites depict global moisture, clouds, and temperatures.

Source: NASA Earth Satellite Office, <www.ghcc.msfc.nasa.gov/GOES/>; also NEODAAS Dundee Satellite Receiving Station. <www.sat.dundee.ac.uk>.

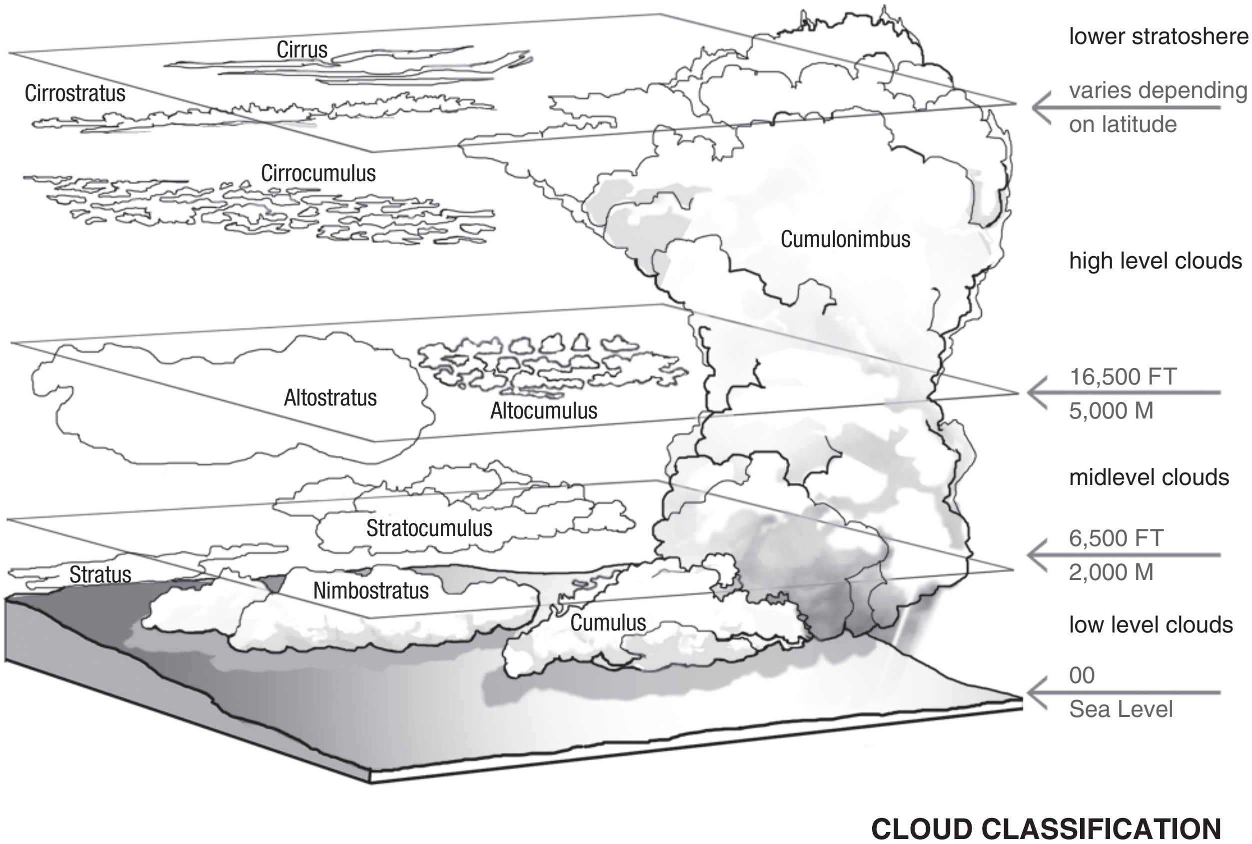

Figure 1.10 *Cloud formations* are defined by their altitude and influence on regional and local weather patterns.

Source: Illustration adapted from Bruce Buckley, Edward J. Hopkins, and Richard Whitaker, *Weather: A Visual Guide* Buffalo (New York: Firefly Books, 2008).

Basic Cloud Types

Alto. Derived from the word "high," but in meteorology used to refer to middle-level clouds.

Cirrus. Meaning "filament of hair" and used to identify high-level clouds.

Cumulus. From a term meaning "pile" or "heap," used to refer to a "tall" cloud or great height.

Nimbus. Meaning "rain," so used to refer to rain-bearing clouds. Commonly used as a suffix.

Stratus. Derived from *stratum*, or layer, used to refer to low-level clouds; also used as a suffix for a set of cloud types that have a layered appearance.

Specific Cloud Types

Cirrostratus. Combination of *cirrus* and *stratus*. Cirrostratus clouds are generally recognizable by a transparent white sheet or veil of ice crystals forming high-level clouds that appear as layered streamers.

Cirrocumulus. Combination of *cirrus* and *cumulus*. High-level ice-crystal clouds consisting of a layer of small white puffs or ripples.

Altostratus. Stratiform clouds with the "alto-" prefix indicate middle-level altitude. Altostratus clouds consist primarily of water droplets that appear as a relatively uniform white or gray layered sheet.

Altocumulus. A middle-level cloud type that has some vertical development indicated by the suffix "-cumulus." Altocumulus clouds have a layered appearance but also consist of white to gray puffs.

Stratocumulus. Low-level layer clouds, as suggested by the prefix "strato-," but having some vertical development, indicated by the suffix "-cumulus." Stratocumulus clouds consist of a layer of large rolls or merged puffs.

Cumulonimbus. Vertically developed clouds (indicated by the "cumulo-" prefix) that are rain producers (indicated by the "-nimbus" suffix). These "tall" high clouds usually extend to the troposphere and have a puffy lower portion and flattened anvil-shape top. These clouds may produce heavy rain or hail.

Nimbostratus. Rain-producing ("nimbus-") layered ("-stratus") clouds. Nimbostratus are low- to mid-level clouds that give the appearance of a uniform gray cloud.

Weather on the Ground

Winds and precipitation are the principal features of weather systems that affect both land and sea. Most weather of consequence occurs in storms, in which the key ingredient is water in any of its forms: ice, liquid, or vapor. (Figure 1.11.)

Ocean currents contribute to global climate and weather, particularly *thermohaline circulation* (*THC*). Also called the global conveyor belt, it is a global circulation pattern that distributes heat energy from the equatorial oceans to the polar regions. The circulation is driven by thermal and saline density gradients in ocean surface currents and deep oceanic "submarine rivers."[3] Cold, salty water sinks into the deep ocean in the north Atlantic, flows south and then east across the south Pacific to resurface as it is warmed in the Indian and north Pacific oceans. Surface currents carry warmer water back through the Pacific and south Atlantic, eventually to return to polar deep water via the Atlantic Gulf Stream. The round trips take between 500 and 2,000 years. (Figure 1.12.)

The primary atmospheric winds consist of the *trade winds* in the equatorial region below 30° latitude and the *westerlies* between 30° and 60° latitudes. The three general conditions in an atmospheric system that lead to widespread participation are described as *convectional, cyclonic*, and *orographic*.

Convectional precipitation usually is associated with thunderstorms. Warm, moist air rises as an unstable air mass and cools adiabatically. The rising parcel is commonly called a thermal. As it reaches cooler air and lower pressure, condensation creates precipitation. The updrafts of wind recirculate, and wind flow on the ground may be turbulent and violent. Convective thunderstorms are the most common type of atmospheric instability that produces lightning followed by thunder. (Figure 1.13.)

Mid-latitude cyclones develop when polar air moves largely within the 30° to 60° latitude range; thus they are referred to as *tropical cyclones*. Lows develop and compete with highs as both types of systems are moved by jet streams and other global patterns of wind and water transport. Development typically follows successive stages beginning with advance of an Arctic cold front into cooler air (to the south in the northern hemisphere). These massive storms may be characterized as tropical disturbances, typhoons, or hurricanes that affect Europe and Asia, North America, and to a lesser extent the southern continents.

Orographic precipitation results from moisture-laden wind as it ascends mountain elevations, such as the West Coast, interior West, and the flanks of the Appalachian Range. The moist air is cooled and precipitation ensues, typically as thunderstorms in summer or as snowstorms in winter. This mass moves down the opposite slope as dry and then warmer air, described as a rain shadow. (Figure 1.14.)

Rainfall amount is recorded as the amount of water captured by a rain gauge at an observing station during a

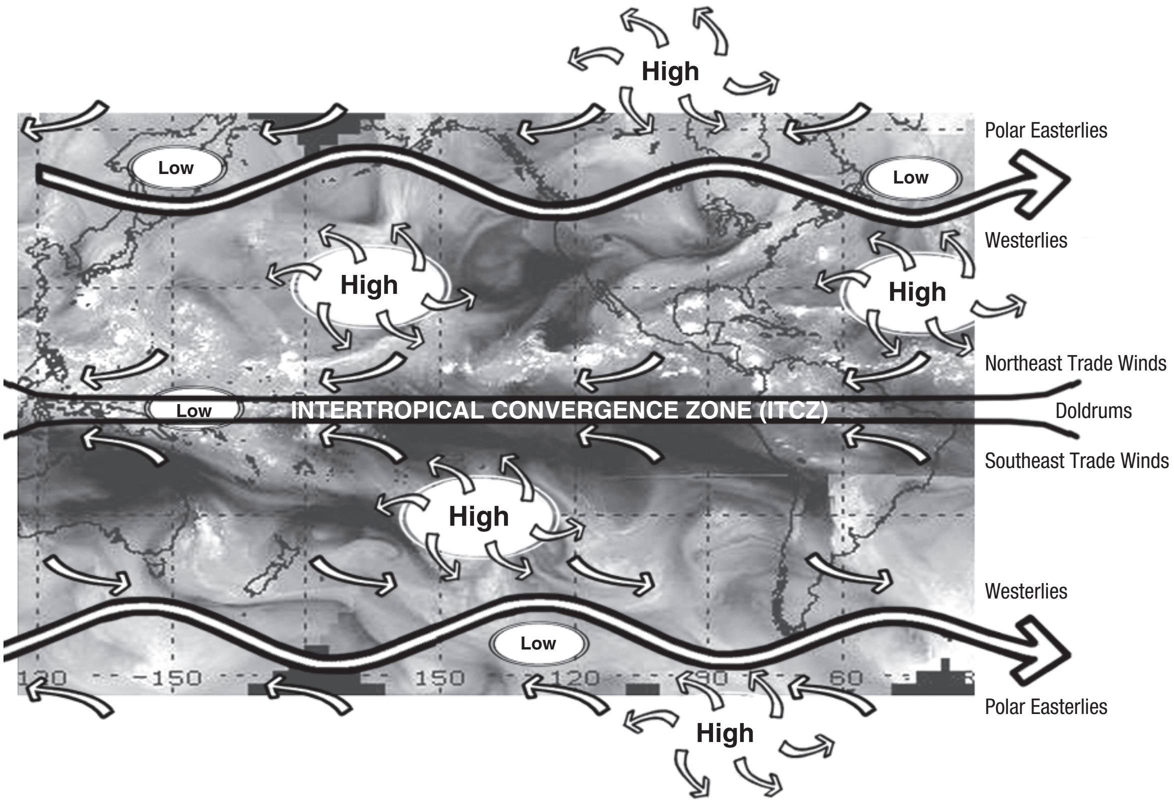

Figure 1.11 *Global weather patterns*.

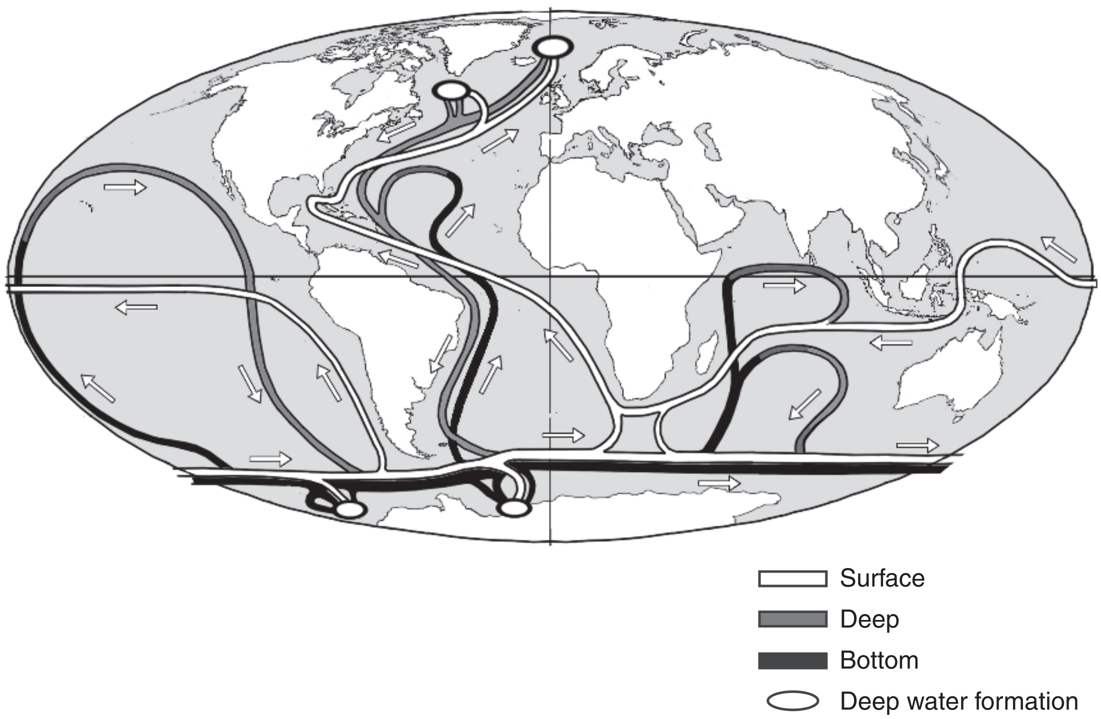

Figure 1.12 *Thermohaline circulation*: Variability in the strength of the global conveyor belt impacts global oceans and climate change.

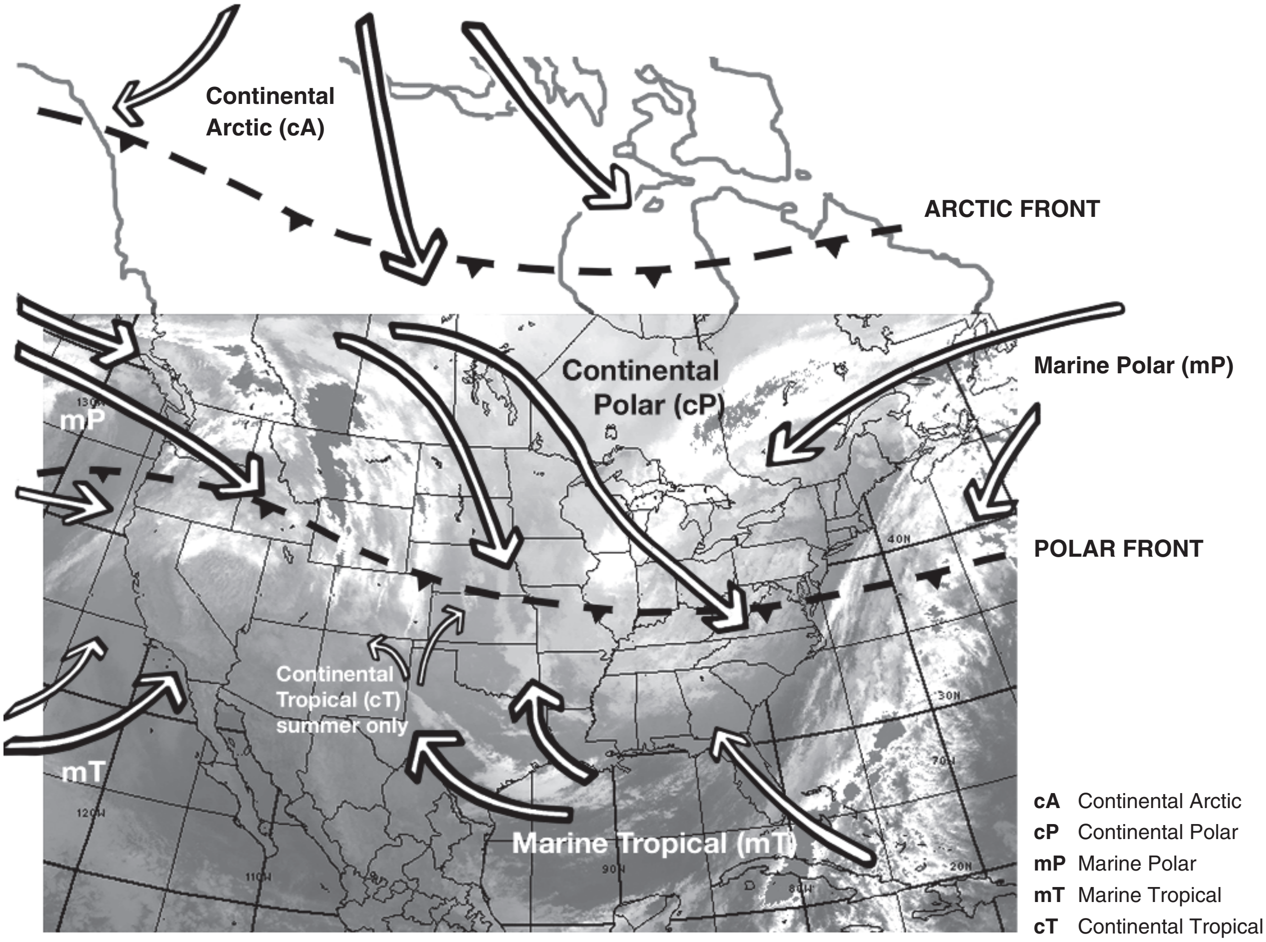

Figure 1.13 *U.S. continental weather patterns.*

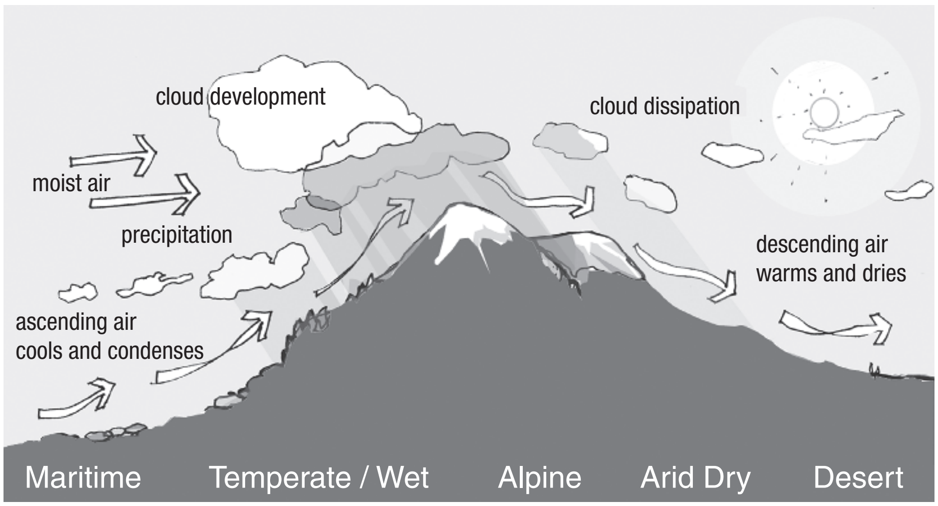

Figure 1.14 *Orthographic precipitation* creates contrasting microclimates in mountain regions, most evident in windward (wet) and leeward elevations (arid).

TABLE 1.3 TYPES OF PRECIPITATION			
Type	*Size*	*State*	*Characteristics*
Mist	0.005–0.05 mm	Liquid	Droplet large enough to be felt on the face when air is moving 1 meter/second. Associated with stratus clouds.
Drizzle	Less than 0.5 mm	Liquid	Small uniform drops that fall from stratus clouds, generally for several hours.
Rain	0.5–5 mm	Liquid	Generally produced by nimbostratus or cumulonimbus clouds. When heavy, size can be highly variable from one place to another.
Sleet	0.5–5 mm	Solid	Small, spherical to lumpy ice particles that form when raindrops freeze while falling through a layer of subfreezing air. Because the ice particles are small, damage is generally minor. Sleet can make travel hazardous.
Glaze	Layers 1 mm–2 cm thick	Solid	Produced when supercooled raindrops freeze on contact with solid objects. Glaze can form a thick coating of ice having sufficient weight to seriously damage trees and power lines.
Rime	Variable accumulations	Solid	Deposits usually consisting of ice feathers that point into the wind. These delicate frostlike accumulations form as a supercooled cloud of fog droplets encounter objects and freeze on contact.
Snow	1 mm–2 cm	Solid	The crystalline nature of snow allows it to assume many shapes, including six-sided crystals, plates, and needles. Snow is produced in supercooled clouds where water vapor is deposited as ice crystals that remain frozen during their descent.
Hail	5 mm–10 cm or larger	Solid	Precipitation in the form of hard rounded pellets or irregular lumps of ice. Produced in large cumulonimbus clouds, where frozen ice particles and supercooled water coexist.
Graupel	2 mm–5 mm	Solid	Sometimes called soft hail, graupel forms as rime collects on snow crystals to produce irregular masses of "soft" ice. Because these particles are softer than hailstones, they normally flatten on impact.

24-hour period. Rainfall rate may be used to describe a heavy rainstorm—for example, "two inches per hour." The hourly rate data typically are identified by Doppler radar, then calculated to predict how much precipitation a storm might produce if stalled. Upper and lower atmosphere temperatures are contingent factors in predicting the anticipated form of precipitation. (Table 1.3.)

1.3 WEATHER

High- and Low-Pressure Areas

Atmospheric pressure results from the total weight of air above any point of measurement, decreasing with height, measured by a barometer. Natural variations in barometric pressure occur at any one altitude as a consequence of weather. Atmospheric pressure differences are an indication of weather trends useful for forecasting.

Highs are high-pressure cells with more atmospheric pressure above their mass at ground level. Highs initiate airflow downward and outward due to higher internal density, inducing cooler and drier air to descend from higher altitudes, clearing the skies above. Due to the Coriolis effect, airflow around a high is clockwise in the northern hemisphere.

Lows are low-pressure cells characterized by less atmospheric mass above, resulting in converging airflow at the ground surface to rise. Air moving upward in a low may condense and initiate clouds and precipitation. Due to the Coriolis effect, airflow around the low is counterclockwise in the northern hemisphere.

An *occluded front* typically forms when a faster-moving cold front catches up to a slower-moving warm front. When the air behind the cold front is colder than the air ahead of the warm front, the occluded front will behave like a cold front, with brief, heavy rainfall and a wind shift to the west or northwest. When the air behind the cold front is not as cold as the air ahead of the warm front, lighter but more prolonged precipitation can be expected, similar to the overrunning precipitation produced by warm fronts. (Figure 1.15.)

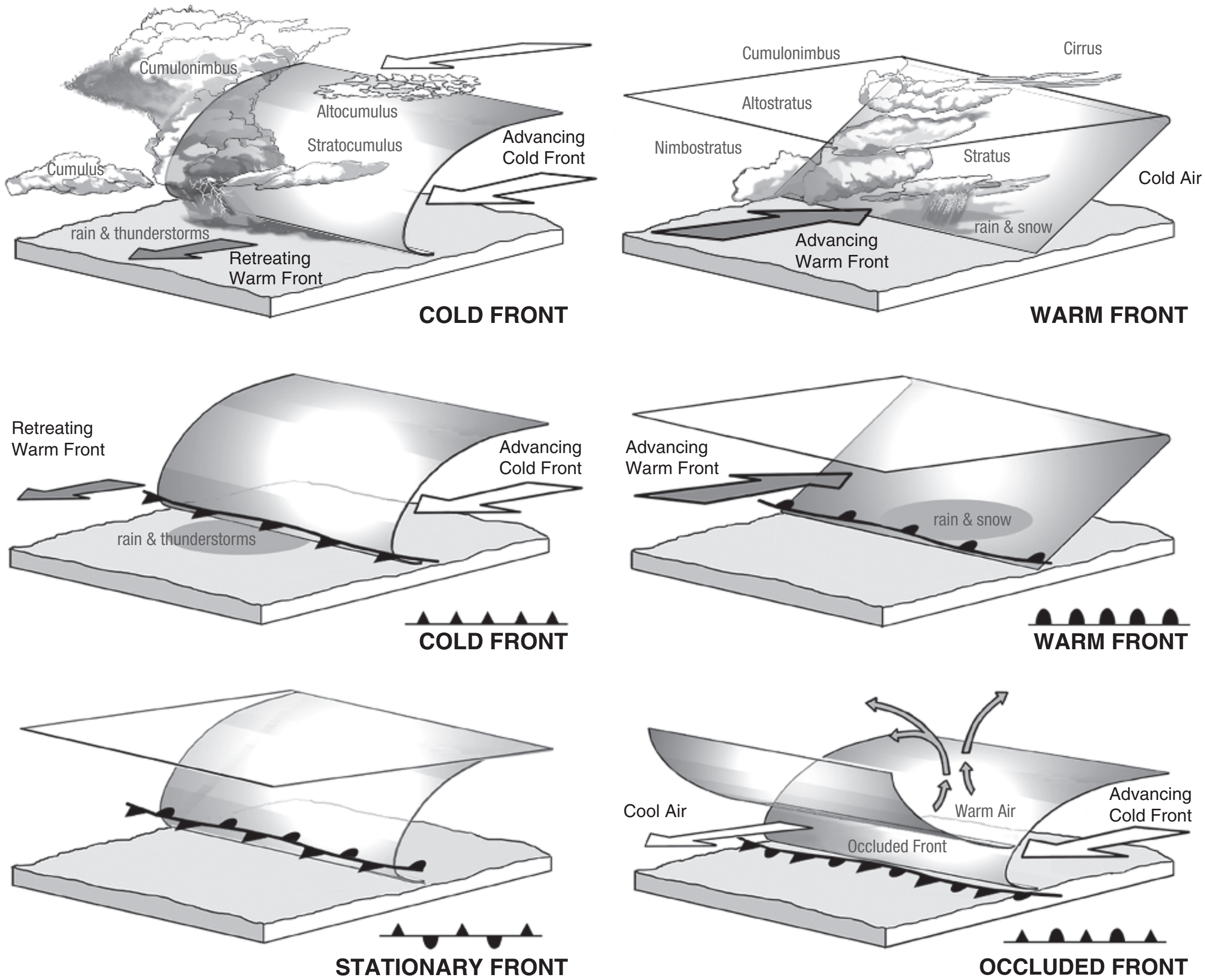

Figure 1.15 *Regional weather patterns* are established by cold and warm fronts.

Wind

Winds accompany most precipitation and storm events, described in weather forecasts in terms of origin, direction, and scale. In building and landscape design, prevailing winds may provide criteria for building form and landscape that deflect winter and storm winds or accommodate summer cooling breezes. For storm protection and hurricane-resistant design, wind design is among the most critical engineering determinants, governed by building codes and subject to professional judgment in assessing additional safety factors.

The *Beaufort Scale* has been developed based on empirical observation of winds and storms. It was first defined by British Navy administrator Admiral Francis Beaufort in 1806 and used as a reference in ship's logs. Its modern version is applicable to description of storms and anticipated risks to safety and property damage. (Table 1.4.)

TABLE 1.4 MODERN BEAUFORT SCALE

Beaufort		*Speed*				
Force	*Description*	*Knots*	*km/h*	*mph*	*Appearance on Water*	*Appearance on Land*
0	Calm	Less than 1	Less than 1	Less than 1	Sea like a mirror.	Smoke rises vertically.
1	Very light	1–3	1–5	1–3	Ripples with appearance of scales, no foam crests	Direction of wind shown by smoke drift but not by wind vanes.
2	Light breeze	4–6	6–11	4–7	Wavelets, small but pronounced. Crests with glassy appearance but do not break.	Wind felt on face, leaves rustle, ordinary wind vane moved by wind.
3	Gentle breeze	7–10	12–19	8–12	Large wavelets, crests begin to break. Glassy-looking foam, occasional whitecaps	Leaves and small twigs in constant motion, wind extends white flag.
4	Moderate breeze	11–16	20–29	13–18	Small waves becoming longer, frequent white horses.	Wind raises dust and loose paper, small branches move.
5	Fresh breeze	17–21	30–39	19–24	Moderate waves of pronounced long form. Many whitecaps, some spray.	Small trees in leaf start to sway crested wavelets on inland waters.
6	Strong breeze	22–27	40–50	25–31	Some large waves, extensive white foam crests, some spray.	Large branches in motion, umbrellas used with difficulty.
7	Near gale	28–33	51–61	32–38	Sea heaped up, white foam from breaking waves blowing in streaks with the wind.	Whole trees in motion, difficult to walk against wind.

(continued)

TABLE 1.4 (*CONTINUED*)

Beaufort		*Speed*				
Force	*Description*	*Knots*	*km/h*	*mph*	*Appearance on Water*	*Appearance on Land*
8	Gale	34–40	62–74	39–46	Moderately high and long waves. Crests break into spin drift, blowing foam in well marked streaks.	Twigs break from trees, difficult to walk.
9	Strong gale	41–47	75–87	47–54	High waves; dense foam streaks in wind; wave crests topple, tumble, and roll over. Spray reduces visibility.	Slight structural damage occurs, chimney pots and slates removed.
10	Storm	48–55	88–101	55–63	Very high waves with long overhanging crests. Dense blowing foam, sea surface appears white. Heavy tumbling of sea, shocklike, poor visibility.	Trees uprooted, considerable structural damage occurs.
11	Violent storm	56–63	102–117	64–73	Exceptionally high waves, sometimes concealing small and medium-size ships. Sea completely covered with long white patches of foam. Wave crest edges blow into froth. Poor visibility.	Widespread damage.
12	Hurricane	> 64	> 119	> 74	Air filled with foam and spray, sea white with driving spray, very poor visibility	Widespread damage.

Cyclogenesis

Cyclogenesis is an umbrella term for several weather processes that result in the development of some sort of cyclone. In regions outside of the tropics, cyclones may be initiated as waves along weather fronts before developing (occluding) as cold core cyclones, typical of winter storms. (Figure 1.16.)

Thunderstorms

Thunderstorms are formed as cumulus clouds that accumulate and extend throughout the troposphere, forming mountains of moisture that can reach altitudes up to 50,000 feet (1.5 km). The wedge of cold air associated with the advancing cold front drives under the existing air mass, producing

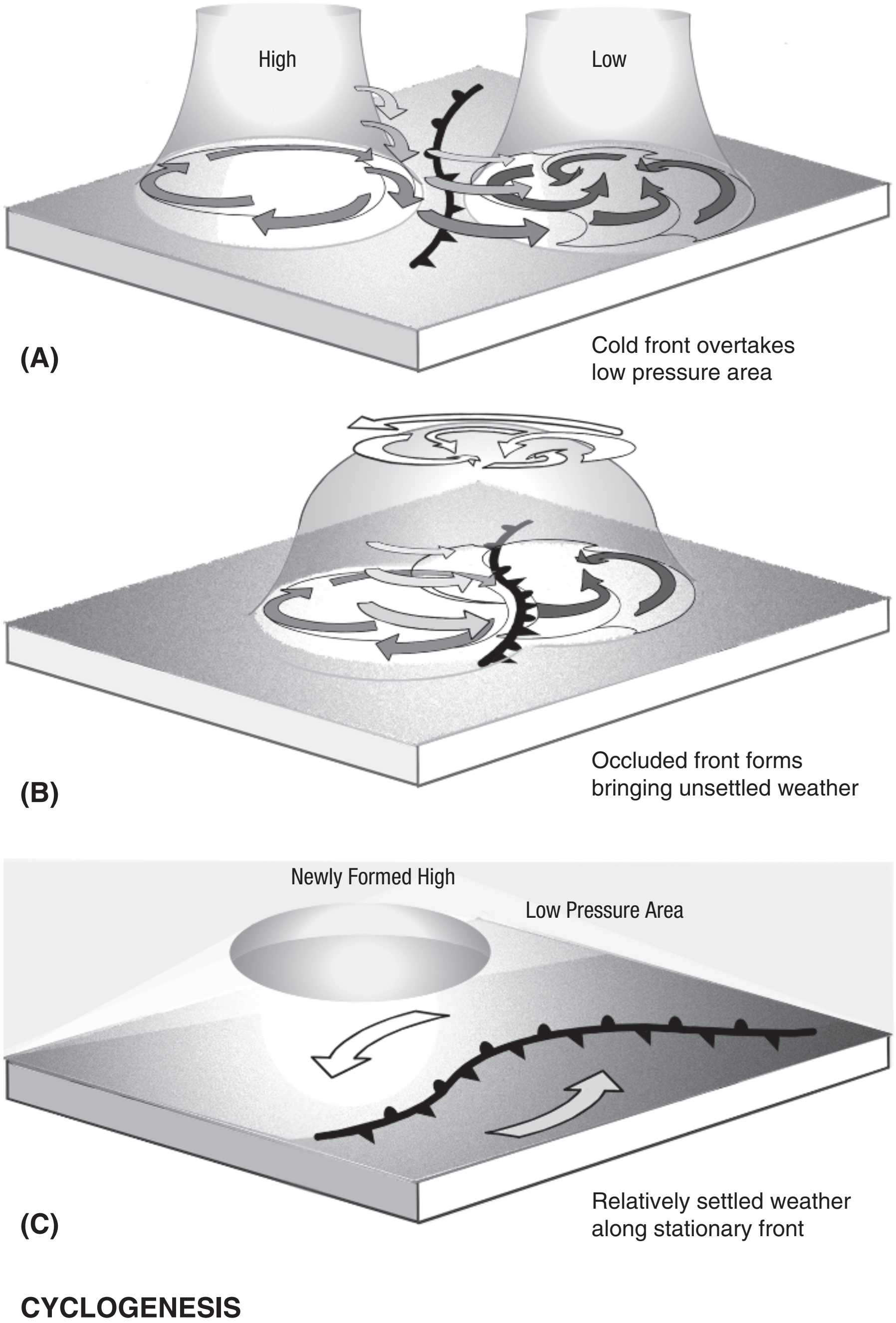

Figure 1.16 *Cyclogenesis*—interacting high- and low-pressure systems—initiates formation of mid-latitude cyclonic storms.

an upward motion in the air. As the thunderstorm develops, updrafts and downdrafts form. The cloud flattens as it reaches the top of the troposphere. Very often the higher levels of the clouds are formed into an anvil shape. Blasts of air that reach the ground from thunderstorm downdrafts gust in excess of 100 miles per hour [mph] (160 km/h). (Figure 1.17.)

Tropical Storms

A *tropical cyclone* is a storm system that originates in the tropics and is characterized by a large low-pressure center ("warm core") and thunderstorms, strong winds, and heavy rain, with counterclockwise rotation in the northern hemisphere and clockwise rotation in the southern hemisphere. The terms used for tropical cyclones differ from one region

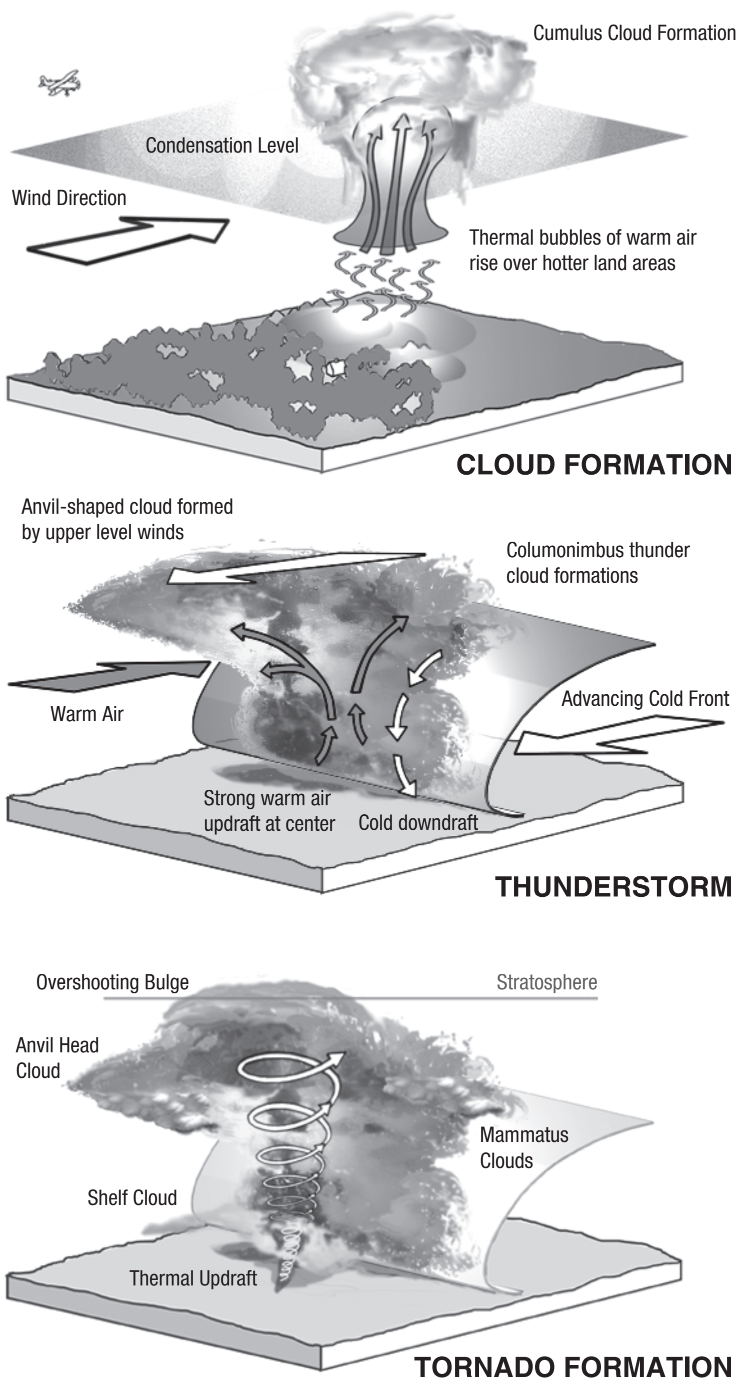

Figure 1.17 *Cloud and storm formations.*

Source: Illustration adapted from Buckley, Hopkins, and Whitaker, *A Visual Guide*.

to another globally. For most ocean basins, the average wind speed is used to determine the tropical cyclone category. A storm of any intensity can inflict damage and threat to life. Depending on location and strength, a tropical cyclone is referred to by names such as *hurricane, typhoon, tropical storm, cyclonic storm, tropical depression*, or, simply, *cyclone*.

Hailstorms

Hailstorms develop from severe thunderstorms, most typically in summertime, forming in rising air currents that carry water droplets high into a thunderstorm. There they freeze and grow as other drops collide with them. Hailstones grow until they are too large for the storm

Classification of Tropical Cyclones

Tropical disturbance, tropical wave. Unorganized mass of thunderstorms with very little, if any, organized wind circulation.

Tropical depression. Evidence of closed wind circulation around a center organized system of clouds and thunderstorms with maximum sustained winds* of 38 mph (33 kt) or less.

Tropical storm. An organized system of strong thunderstorms with a defined surface circulation and maximum sustained winds of 39 to 73 mph (34–63 kt). A storm is named once it reaches tropical storm strength.

Hurricane. An intense tropical weather system of strong thunderstorms with a well-defined surface circulation and maximum sustained winds of 74 mph (64 kt) or higher.

Source: NOAA, "Hurricane Basics," <www.nhc.noaa.gov/HAW2/english/basics.shtml>.

* Sustained winds are defined as a 1-minute average wind measured at about 33 ft (10 m) above the surface.

updrafts to hold them aloft; then they fall to the ground. Hailstones can fall at speeds well over 100 mph (87 kt).

Hailstorms generate balls or lumps of ice capable of damaging agricultural crops, buildings, and vehicles. Severe hailstorms can damage roofing shingles and tiles, metal roofs, roof sheeting, skylights, glazing, and other building components. Accumulation of hail on flat or low-sloped roofs can lead to significant vertical loads.

Northeaster

A *northeaster*—colloquially called a nor'easter—is an intense low-pressure area that forms in the winter along the East Coast of the United States, producing strong northeasterly winds and often heavy snowfall and rainfall. These storms often travel northward along the coast, eventually affecting the entire eastern seaboard. Persistent strong winds associated with these storms can cause beach erosion and damage to houses along the coast from large waves and high water levels that result from the ocean water being piled up against the coast by the wind. A northeaster typically is followed by unusually cold weather as the cold high-pressure area that created the strong winds moves into the region. (Table 1.5.)

Ice Storm

An *ice storm* is generated when rain falls from or into a layer of air that is above freezing. This can cause pellets of ice to form as sleet or glaze, which is capable of covering outdoor surfaces and tree branches with a layer of ice. Electric power and wire communication disruptions are common effects of ice storms. (Table 1.6.)

Tornadoes

A *tornado* is a rapidly rotating funnel of air that extends to the ground from a cumulonimbus cloud. Tornadoes are characterized by powerful updrafts that may extend to the top of the cloud, producing a bulge in an anvil shape, called an *overshoot*. Tornadoes are the most intense of all atmospheric storms, spawned by severe thunderstorms and hurricanes. Tornadoes often form in the right forward quadrant of a hurricane, far from the hurricane eye. The strength and number of tornadoes are not related to the strength of the hurricane that generates them. The weakest hurricanes often produce the most tornadoes.

Most tornadoes last from 5 to 10 minutes, although they can exist for as few as several seconds to more than an hour. Approximately 75% of tornadoes are classified as weak and only 1% as violent in the extreme. But this 1% is responsible for the greatest percentage of deaths from any storm events, including earthquakes.

The Fujita scale was developed by T. Theodore Fujita in the early 1970s. The scale was enhanced in 2007, defined by rankings EF-0 to EF-5 (Enhanced Fujita). (Table 1.7.) The scale is a set of wind estimates that may have been reached in a tornado, based on forensic observation of postevent damage rather than actual wind measurements which would be practically impossible to record during the actual event.

TABLE 1.5 CLASSIFICATION FOR NORTHEASTERS

Storm Class	*Storm Description*	*Storm Duration*	*Storm Impacts on Beaches and Dunes*	*Property Damage*
1	Weak	1 tidal cycle	Minor beach erosion.	Little or none.
2	Moderate	2–3 tidal cycles	Moderate beach erosion; dune scarping begins; minor flooding and shallow overwash in low areas, especially street ends.	Undermining of seaward ends of dune walkovers; undermining of slab foundations on or near the active beach; some damage to erosion control structures.
3	Significant	3–4 tidal cycles	Significant beach erosion; dune scarping with complete loss of small dunes; increased depth of flooding and overwash in low areas.	Widespread damage to dune walkovers and boardwalks; increased damage to erosion control structures; undermining of beachfront slab foundations and shallow post or pile foundations; burial of roads and inland property by overwash.
4	Severe	4–5 tidal cycles	Severe beach erosion and dune scarping; widespread dune breaching in vulnerable areas; coalescing of overwash fans; occasional inlet formation.	Damage to poorly sited, elevated, or constructed coastal buildings is common; frequent damage to erosion control structures; flood-borne debris loads increase; overwash burial depths increase.
5	Extreme	> 5 tidal cycles	Widespread and severe beach erosion and dune loss; widespread flooding of low-lying areas; massive overwash; inlet formation is common.	Widespread damage to buildings with inadequate elevations or foundations, and to buildings with inadequate setbacks from the shoreline or inlets; widespread damage to low-lying roads and infrastructure.

Source: FEMA, *Coastal Construction Manual: Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas* (FEMA 55) (August 2005), <www.fema.gov/rebuild/mat/fema55.shtm>.

Design for tornadoes is beyond the scope of this book, except to include tornadoes as a design consideration along with hurricane and related storm events. Given the extreme force of tornado wind and wind-driven precipitation, it is considered practically impossible to provide property protection in the direct path of a tornado. Precautionary measures focus on life safety; advance warning and evacuation; and when evacuation is not possible, the provision of tornado safe rooms and community shelters.[5]

TABLE 1.6 SPERRY-PILTZ ICE STORM INDEX

Ice Index	*Radial Ice Amount (inches)*	*Wind (mph)*	*Damage and Impact Descriptions*
1	< 0.25	15–25	Some localized utility interruptions possible, typically lasting 1 or 2 hours maximum.
	0.25–0.50	< 10	
2	< 0.25	> = 25	Scattered utility interruptions expected, typically lasting less than 8 to 12 hours maximum.
	0.25–0.50	15–25	
	0.50–1.00	< 10	
3	0.25–0.50	> = 25	Numerous utility interruptions, with some damage to main feeder lines expected, with outages lasting from 1 to 5 days.
	0.50–0.75	15–25	
	0.75–1.00	< 10	
4	0.50–0.75	> = 25	Prolonged and widespread utility interruptions, with extensive damage to main distribution feeder lines and possibly some high-voltage transmission lines. Outages lasting 5 to 10 days.
	0.75–1.00	15–25	
	1.00–1.50	> 10	
5	0.75–1.00	> = 25	Catastrophic damage to entire utility systems, including both distribution and transmission. Outages may last from 1 to several weeks in some areas. Shelters needed.
	1.00–1.50	15–25	
	> 1.50	< 10	

Source: S. F. McManus et al., "Development and Testing of an Ice Accumulation Algorithm," *Oklahoma Climatological Survey* (Norman, OK: University of Oklahoma Press, 2008).

TABLE 1.7 ENHANCED FUJITA SCALE

Scale	*Wind mph*	*Knots (kt)*	*Damage*
EF-0	65–85	57–74	Causes some damage to siding and shingles.
EF-1	86–110	75–95	Considerable roof damage. Winds can uproot trees and overturn singlewide mobile homes. Flagpoles bend.
EF-2	111–135	96–117	Most singlewide mobile homes destroyed. Permanent homes can shift off foundations.
EF-3	136–165	118–143	Hardwood trees debarked. All but small portions of houses destroyed.
EF-4	166–200	144–174	Complete destruction of well-built residences, large sections of school buildings.
EF-5	Above 200	Above 174	Significant structural deformation of mid- and high-rise buildings.

Source: NOAA Storm Prediction Center, <www.nhc.noaa.gov/>.

Hurricanes

A *hurricane* is a type of tropical cyclone, which is a generic term for a low-pressure system that generally forms in the tropics. Hurricanes are one of the ways that Earth's atmosphere keeps its heat budget balanced: by moving excess heat from the tropics to the middle latitudes. Hurricanes convert the warmth of the tropical oceans and atmosphere into wind and waves. Hurricanes also distribute rain and moisture throughout the eastern continental landmass of North America.

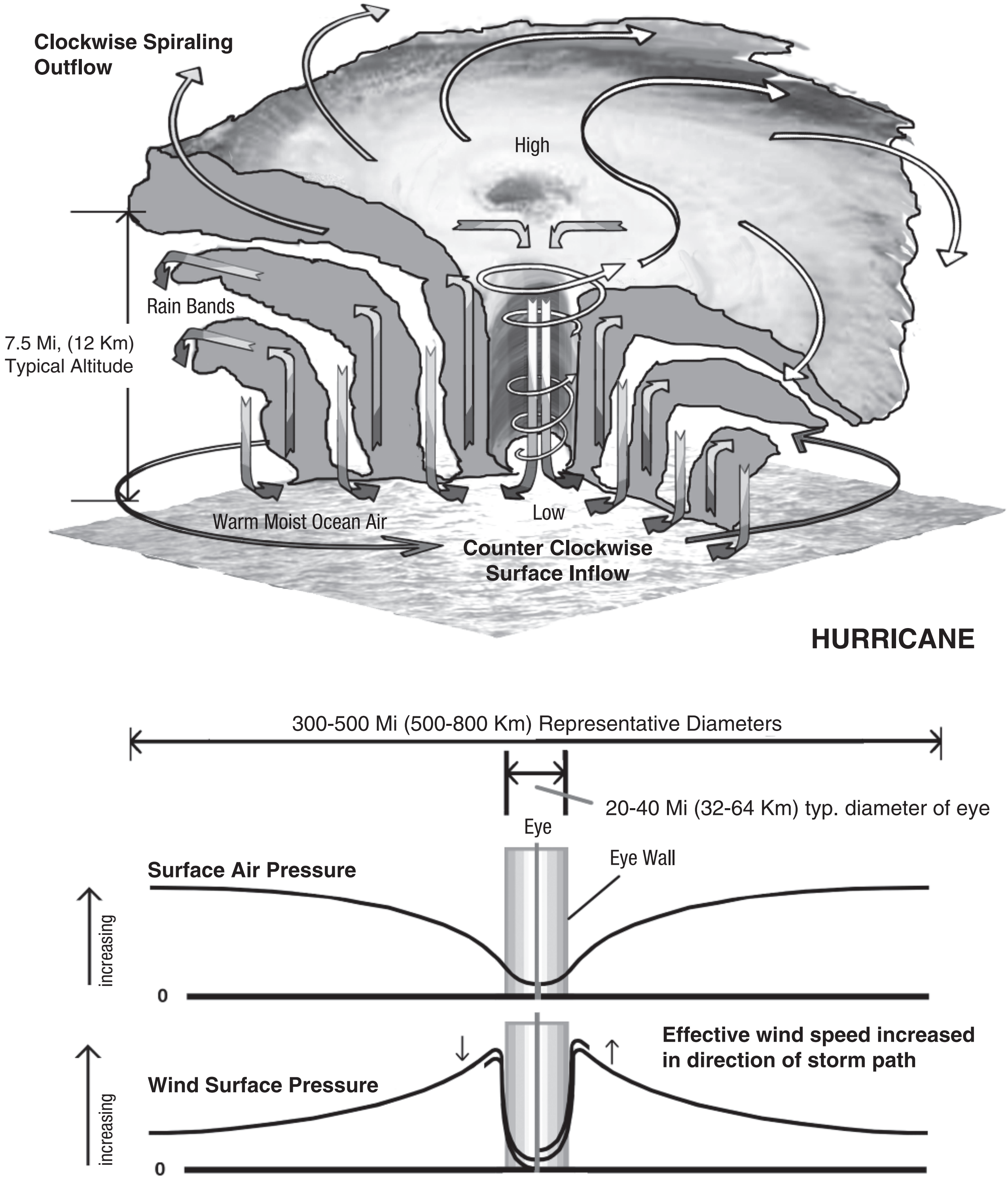

Figure 1.18 *Hurricane formation.*

Hurricanes are a more extreme development of a tropical disturbances. They begin as atmospheric depressions in the tropics, growing and gaining strength as warm humid air near the ocean's surface rises through cooler air above, generating spiraling convection currents in the atmosphere. The warm and saturated air mass spirals (counterclockwise in the northern hemisphere and clockwise in the southern hemisphere) into the center, or eye, of the developing hurricane, accelerating as it develops. The air mass spirals upward as torrential rain, producing an eyewall cloud that surrounds the eye of the storm. In the upper levels, the air spirals outward away from the center. (Figure 1.18.)

SAFFIR-SIMPSON HURRICANE WIND SCALE (EXPERIMENTAL) The Saffir-Simpson Hurricane Wind Scale is a 1 to 5 categorization based on the hurricane's estimated intensity. It is called experimental because it is newly published in its present form, eliminating estimates of storm surge that were included in prior versions. Storm surge is the most dangerous component of a hurricane. Storm surge is not always correlated with the category or severity of a hurricane because other factors determine the extent of the storm surge, including surge elevations, such as forward speed of the storm, tide cycle, and shore profile. A tropical storm or moderate hurricane may be accompanied by extreme and dangerous surge.

In general, damage risk rises by about a factor of 4 for every category increase. The damage descriptions are generalized and subject to variables of local topography, building structures, age of buildings, and extent of enforcement of flood regulations.[6] Category numbers are assigned soon after a storm becomes a hurricane, almost always based on data gathered by specially equipped NOAA "Hurricane Hunter" aircraft. (Table 1.8.)

TABLE 1.8 SAFFIR-SIMPSON HURRICANE WIND SCALE (EXPERIMENTAL) MILES PER HOUR (MPH) AND KNOTS (KT)

Category	*Sustained Winds*	*Damage*	*Description*
1	74–95 mph (64–82 kt or 119–153 km/hr)	Damaging winds are expected.	Some damage to building structures could occur, primarily to unanchored mobile homes (mainly pre-1994 construction). Some damage is likely to poorly constructed signs. Loose outdoor items will become projectiles, causing additional damage. Persons struck by windborne debris risk injury and possible death. Numerous large branches of healthy trees will snap. Some trees will be uprooted, especially where the ground is saturated. Many areas will experience power outages with some downed power poles.
2	96–110 mph (83–95 kt or 154–177 km/hr)	Very strong winds will produce widespread damage.	Some roofing material, door, and window damage of buildings will occur. Considerable damage to mobile homes (mainly pre-1994 construction) and poorly constructed signs is likely. A number of glass windows in high-rise buildings will be dislodged and become airborne. Loose outdoor items will become projectiles, causing additional damage. Persons struck by windborne debris risk injury and possible death. Numerous large branches will break. Many trees will be uprooted or snapped. Extensive damage to power lines and poles will likely result in widespread power outages that could last a few to several days.

(continued)

TABLE 1.8 (*CONTINUED*)

Category	*Sustained Winds*	*Damage*	*Description*
3	111–130 mph (96–113 kt or 178–209 km/hr)	Dangerous winds will cause extensive damage.	Some structural damage to houses and buildings will occur with a minor amount of wall failures. Mobile homes (mainly pre-1994 construction) and poorly constructed signs are destroyed. Many windows in high-rise buildings will be dislodged and become airborne. Persons struck by windborne debris risk injury and possible death. Many trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
4	131–155 mph (114–135 kt or 210–249 km/hr)	Extremely dangerous winds causing devastating damage are expected.	Some wall failures with some complete roof structure failures on houses will occur. All signs are blown down. Complete destruction of mobile homes (primarily pre-1994 construction). Extensive damage to doors and windows is likely. Numerous windows in high-rise buildings will be dislodged and become airborne. Windborne debris will cause extensive damage, and persons struck by the wind-blown debris will be injured or killed. Most trees will be snapped or uprooted. Fallen trees could cut off residential areas for days to weeks. Electricity will be unavailable for weeks after the hurricane passes.
5	Greater than 155 mph (135 kt or 249 km/hr).	Catastrophic damage is expected.	Complete roof failure on many residences and industrial buildings will occur. Some complete building failures with small buildings blown over or away are likely. All signs blown down. Complete destruction of mobile homes (built in any year). Severe and extensive window and door damage will occur. Nearly all windows in high-rise buildings will be dislodged and become airborne. Severe injury or death is likely for persons struck by wind-blown debris. Nearly all trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months.

Source: National Weather Service, "The Saffir-Simpson Hurricane Wind Scale (Experimental)," 2009, <*www.nhc.noaa.gov/aboutsshs.shtml*>.

UNIT CONVERSIONS

1 kilometer (km):
- 0.62 mile
- 0.54 nautical mile

1 mile (m):
- 1.61 kilometer
- 0.87 nautical mile

1 nautical Mile (nm):
- 1/60 degree latitude
- 1.85 kilometer
- 1.15 mile

1 knot (kt):
- 1 nautical mile per hour
- 1.85 km per hour
- 1.15 mile per hour (mph)

Notes

1. Reg Morrison, The Climate Debate, 2009, homepage.mac.com/gregalchin/rm/pdfs/climate%20debate.pdf.
2. Frank Rivers Millikan, "Joseph Henry's Grand Meteorological Crusade," Weatherwise 50 (October/November 1997).
3. Stefan Rahmstorf, "Thermohaline Circulation: The Current Climate," *Nature* 421 (February 2003).
4. NOAA, "Hurricane Basics," www.nhc.noaa.gov/HAW2/english/basics.shtml.
5. FEMA, "Taking Shelter from the Storm: Building a Safe Room for Your Home or Small Business," FEMA Report 320, 2008, www.fema.gov/plan/prevent/saferoom/fema320.shtm.
6. National Weather Service, "The Saffir-Simpson Hurricane Wind Scale (Experimental)," 2009, www.nhc.noaa.gov/aboutsshws.shtml.