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CLIMATE AND WEATHER

OVERVIEW

In Chapter 1, we discussed human efforts to obtain water for drinking, irrigation, navigation, and hydropower. A common theme in that chapter was the attempt to transport water to other locations by constructing canals, aqueducts, groundwater wells, and diversion dams. The question that naturally arises is: Why didn't these early civilizations simply move to wetter regions with more reliable sources of water?

Early settlers did not consider mass migration to more hospitable climates for several reasons. First, more humid regions may have been located far from existing communities. For many people, the process of relocating to unfamiliar settings, far from known sources of food and water, was probably unthinkable. Second, some areas with adequate water already had settlements with cultures very different from those of drier climates. An influx of "outsiders" looking for food, water, and jobs might not have been welcomed. Third, religion, wealth, family tradition, and fear most likely played important roles in decisions to remain in arid locations. Why else would people remain in dry, inhospitable areas? Do these same factors exist today?

CLIMATE

Climate is defined as the average weather condition of a location and can generally be predicted for centuries into the future. The climate of Egypt is hot and dry, although a few occasional wet and cool days are possible. The climate of southeastern Canada and northeastern United States is generally hot and humid during the summer months but frigid with ice and snow in winter. Several factors affect the climate of a region, but the three primary ones are air currents, ocean currents, and the tilt of the Earth's axis.

Air Currents **Global trade winds** (the word *trade* means "direction" or "course") are persistent winds caused by changes in air temperature and the rotation of the Earth. George Hadley (1685–1758), an English mathematician, pointed out in 1735 that global winds are caused by the uneven distribution of the Sun's heat on the Earth. Hadley theorized that, since more thermal energy reaches the equator than the poles, global winds would be generated as the air moves between those two regions to reach equilibrium.[18]

If the Earth were a nonrotating sphere, air circulation would be from areas of high atmospheric pressure—around the north and south poles—to areas of low atmospheric pressure around the equator. The equatorial low is established by solar heating as warm air rises, while polar cooling creates the polar high-pressure cells. The Earth's rotation disrupts this simple atmospheric pattern through a process called the **Coriolis effect.** Moving objects, such as the wind, are deflected to the right (clockwise motion) in the Northern Hemisphere and to the left (counterclockwise motion) in the Southern Hemisphere.

The Coriolis effect is named after Gaspard Gustav de Coriolis (1792–1843), a 19th-century French engineer who originally had hoped for a military career but was too frail. Instead, his contribution as a French soldier was to improve the accuracy of artillery shell trajectories. Coriolis studied the effect of an object moving above the Earth (an artillery shell) while the Earth rotated underneath that object. This phenomenon explained why artillery shells veered off target slightly.

Coriolis was the first scientist to explain, in 1835, why weather systems rotate. According to Newton's first law, a moving body that is not affected by a force will continue in a straight line. However, he deduced that since the Earth and its atmosphere make one rotation every 24 hours, and since the atmosphere at the equator has to rotate faster than the atmosphere at the poles, the force of the Earth's rotation deflects air to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.[19]

Air also moves between the equator and the poles due to temperature gradients. As a result, a low-pressure zone of convergence, called the **intertropical convergence zone (ITCZ),** is created at the equator. Air also piles up at latitudes 30°N and 30°S,,creating two belts of high pressure around those latitudes. Air in the high-pressure zones sinks back to the ground, with some air flowing back toward the poles but most returning back toward the equator.

Global air circulation patterns can be readily seen by the distribution of deserts. Approximately 25 percent of the Earth's land mass (outside the polar regions) consists of arid (desert) lands, described earlier as locations that receive less than 10 inches (250 mm) of average annual precipitation. Substantial regions of **semiarid** climate (annual precipitation of between 10 and 20 in., or between 250 and 510 mm) are found adjacent to many of the deserts in the world (Figure 2.16).

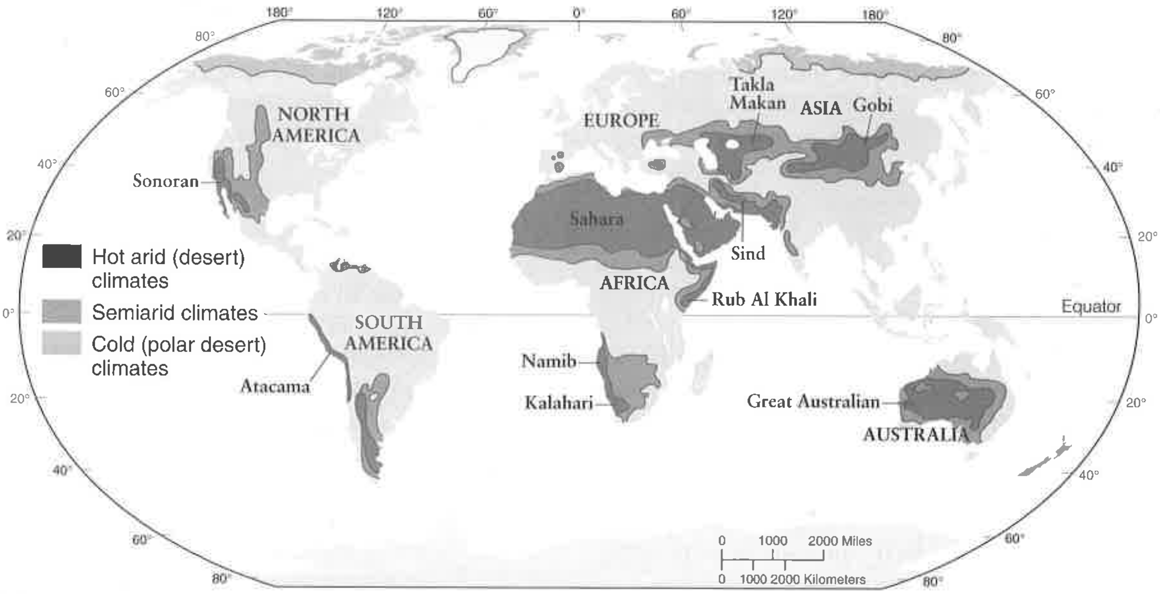

FIG. 2.16 Arid and semiarid regions of the world. Compare the desert locations shown here with the centers of early civilizations shown in Figure 1.1 in Chapter 1. What similarities do you see between climate and the locations of early civilizations? Read Jared Diamond's Pulitzer Prize winning book, *Guns, Germs, and Steel*, (W.W. Norton & Company) for a fascinating look at why civilizations evolved where they did, and how climate, vegetation, and agriculture played key roles in the course of world history.

Ocean Currents Ocean currents are broad, slow drifts of seawater in the ocean created by prevailing surface winds, ocean tides produced by the gravitational pull of the moon, the Coriolis effect caused by the Earth's rotation, and differences in water density effected by temperature or salinity variations. Ocean currents affect, and often temper, regional climates through the transfer of thermal energy. The climates in Iceland and Norway, for example, are surprisingly mild due to the relatively warm **Gulf Stream** current off its shores that originate near the equator (see Figure 2.17). By contrast, Greenland is largely covered by ice because the Gulf Stream and North Atlantic currents veer northwesterly in the vicinity of Greenland and do not flow near enough to the landmass to provide any thermal benefits.

Surface ocean currents are generally wind driven and occur in all of the world's oceans. Moving air pushes the surface of seawater and can create a current of water from 165 to 330 feet (50 to 100 m) deep. Prevailing trade winds, discussed earlier, determine the direction of these fairly shallow ocean currents. Examples of large surface currents are the Gulf Stream, the North Atlantic Current, the California Current, the Atlantic South Equatorial Current, and the Westward Drift.

Associated with these wind-driven currents are counter-surface and underlying currents. The Coriolis effect on water of the oceans is similar to its effect on the atmosphere. Water in the oceans near the equator must move faster with the Earth's rotation than does water near the poles. This causes surface ocean currents to be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The currents eventually come into contact with landmasses that deflect them again, creating giant oceanic current circles called **gyres** (pronounced *jires*).

Tidal currents, created by rising and falling tides, are especially relevant to coastal environments worldwide. The rise and fall of tides do not occur simultaneously around the world, so some locations experience higher ocean surface

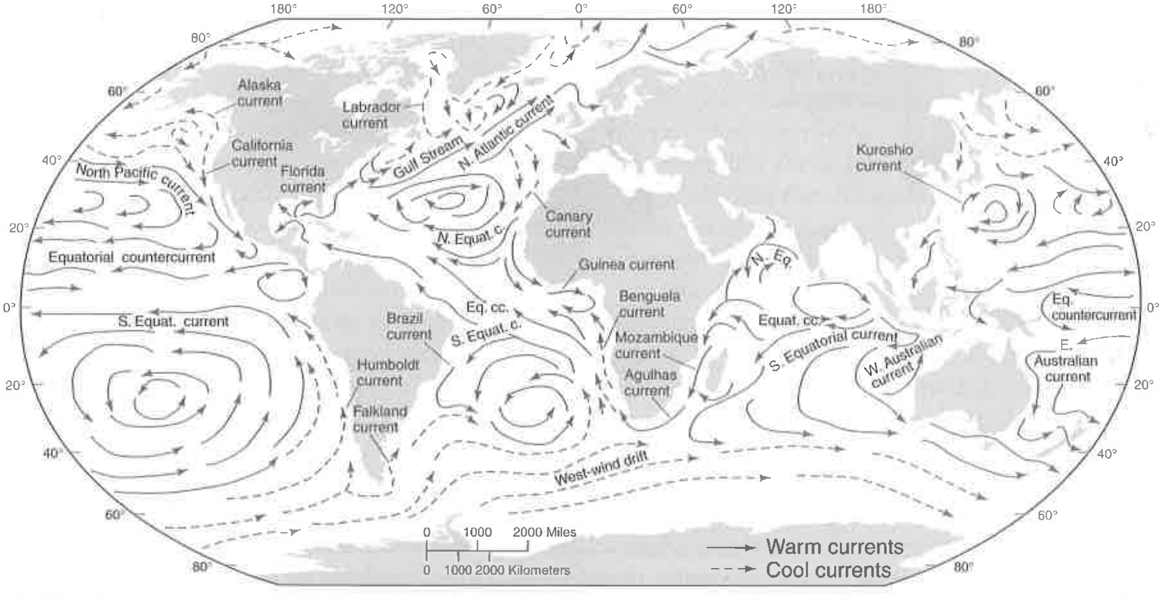

FIG. 2.17 Ocean currents have distinctive patterns that curve to the right (clockwise) in the Northern Hemisphere and to the left (counterclockwise) in the Southern Hemisphere. Continents deflect the westward flow of currents in the Atlantic and Pacific oceans and force warm, equatorial waters toward the poles.

elevations, while other regions have lower ocean surface levels. This difference in water surface elevations on the ocean creates currents as seawater attempts to create a common water level.

Vertical and ocean-bottom currents are created mainly by density differences in temperature and salinity. Cold, salty waters from the polar regions sink to the ocean bottom and move toward the opposite poles where they again surface. This is known as *upwelling* and is very important to marine life in the movement of food and nutrients. These displaced cooler waters are then replaced by the underlying bottom waters.

A CLOSER LOOK

Clipper ships first arrived in the Americas in the late 1840s and created a new era of sailing vessels for the transport of goods around the world. Speed records were constantly broken on long voyages, and knowledge of trade winds and ocean currents gave a great advantage over rival shipping companies.

During the 1840s, Matthew Fontaine Maury (1806–1873), a Tennessee farm boy who sailed around the world as a midshipman in the United States Navy, raised this science to a high level of sophistication. After one visit home while on leave, he was thrown off the top of a stagecoach and broke his leg. It never healed properly, and the Navy assigned him to a desk job at its Depot of Charts and Instruments in Washington, D.C.

In the depot's vault, Maury discovered a collection of thousands of ships' logs, including almost every one since the first voyage of a U.S. Navy vessel. The charts included the weather and sea conditions for every month of the year for oceans around the world. Maury and his staff compiled these hundreds of thousands of bits of information. Later, he persuaded the Navy to standardize observations taken of weather, winds, currents, and other hydrological and meteorological data from their entire fleet. This led to the creation of Maury's published work *Wind and Current Charts* in 1847.

Sea captains were initially skeptical of the charts created by a low-level, land-bound Navy officer who hadn't been to sea in years. However, in 1848 a merchant by the name of Jackson challenged Maury's work and decided to follow the suggested courses on the charts. To Jackson's astonishment, by following Maury's charts he cut 35 days off a round trip between Baltimore, Maryland, and Rio de Janeiro, Brazil. Word spread quickly as other naval officers reported similarly reduced travel times on other voyages.

Eventually, Maury and his staff charted all the oceans of the world and offered specialized information on trade winds, monsoons, water surface temperatures, storms, currents, and even the distribution of whales. In 1854, Maury published *Physical Geography of the Sea* and soon earned the name "Pathfinder of the Seas." For his efforts he received honors from intellectual societies and European royalty, and the gratitude of clipper captains around the world.[20]

A modern-day ocean-current-charting exercise is occurring as scientists track the epic voyages of 29,000 potential data points. In January 1992, 20 containers of rubber bath toys—rubber ducks, frogs, beavers, and turtles—were washed overboard from a cargo ship in the Pacific Ocean midway between Hong Kong and Tacoma, Washington. All were presumed lost at sea. However, in spite of windstorms, Arctic ice floes, and constant weathering, the flotilla of rubber bath toys have voyaged nearly halfway around the world, through the Bering Strait, across Arctic waters, and into the Atlantic Ocean off North America.

Six rubber toys first washed up on beaches near Sitka, Alaska, in November 1992, ten months after falling overboard in the Pacific storm. Remarkably, approximately 400 of the rubber toys have been found along the coasts of Alaska, Hawaii, Washington, and Vancouver Island and the Queen Charlotte Islands off British Columbia during the first years of their epic voyage. Three years later, the ducks were passing through the Bering Strait but became frozen in Arctic ice pack for several years. It's expected that other castaways will later be found along the coasts of Iceland and the United Kingdom. Oceanographers are tracking the location of the beached toys and are using that data to improve our knowledge of prevailing winds and ocean currents. It's a method that Matthew Maury would have found remarkable.

Tilt of the Earth's Axis The seasons of the Earth, as well as temperature variations between the equator and the poles, are created when the Earth spins around an axis that is tilted 23.5 degrees from perpendicular to the plane of the ecliptic—the imaginary surface that contains the Earth's orbit around the Sun. If the Earth were stood straight up on its axis, the equator would always face the Sun, and there would be no change in seasons.

A second minor factor that contributes to the change in seasons is the Earth's elliptical orbit around the Sun. This orbit causes the distance between the Earth and the Sun to vary slightly each day, so that we're 3 million miles (5 million km) closer to the Sun in early January than in early July. This distance change causes the Earth to receive slightly more thermal energy in January (during the Southern Hemisphere's summer) and less overall energy during the Northern Hemisphere's summer in July.

MONITORING CLIMATE CHANGE

Each year, the Earth's climate is recorded in tree rings, ice, corals, and sediment cores around the world. The study of tree rings is called **dendrochronology** (from *dendro,* Greek for "tree," and *chronology,* for the science that deals with time and dates). Trees form one growth ring per year, which varies in size, density, and chemical characteristics. Each ring reflects variations in annual climate, including precipitation and temperature (see Figure 2.18).

Andrew E. Douglas (1867–1962) was an astronomer who became the acknowledged Father of Dendrochronology. Through his work with the Harvard College Observatory in Massachusetts in the late 1800s, he hoped to find evidence of past sunspot events by studying the growth rings of coniferous trees. In the early 1900s, he began work on his theory in the forests of northern Arizona and later joined the faculty at the University of Arizona. In 1914, he presented a paper on his research to the Carnegie Institution in Washington, D.C., and from there, the science of dendrochronology evolved.[21]

Ice can provide a similar climatic record in regions where trees cannot grow, such as at the polar ice caps. Oxygen isotopes found in extracted ice cores from glaciers or polar ice caps can reveal climate changes over thousands of years. (Ice cores from depths of over 2 mi., or 3.2 km, were recently collected in Greenland and Antarctica.) Ice core temperature, dust, air bubbles, acidity, and oxygen isotopes can provide fairly detailed and accurate climate history. The Greenland and Antarctica ice cores provide climatic history going back 250,000 and 500,000 years, respectively.[22]

Ocean corals also provide information regarding historical climate data. Scientists have discovered that coral reefs contain a record of ocean

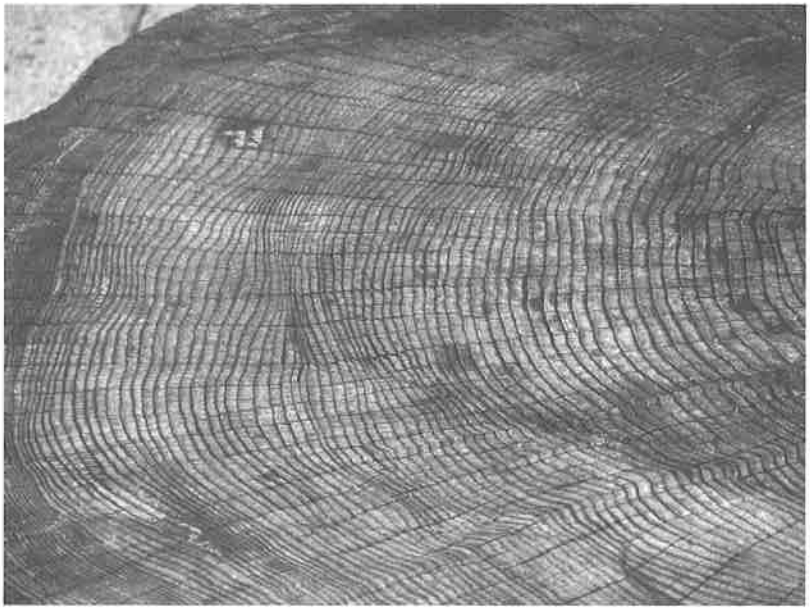

FIG. 2.18 These growth rings are from an unknown tree species at the Bristol Zoo, Bristol, England. This trunk was three feet (1 m) in diameter.

surface temperature changes for many thousands of years. Growth bands on corals provide the data for this research. Paleoclimatologists extract long cores of corals—ranging from 1 to 4 inches (3 to 10 cm) in diameter to retrieve details of past tropical ocean conditions. This is done in much the same way as dendrochronologists study tree rings to glean information about ancient climate over continents. Because corals grow close to the ocean surface, these measurements provide excellent records on tropical air and sea conditions. This is vital to study the interaction of ocean temperatures and the atmosphere—an interaction that creates and fuels the great ocean circulations and wind patterns. These, in turn, generate and push weather systems around the world. Researchers are now working to correlate ocean surface temperature records of El Niño and La Niña cycles to predict future climate changes.

Finally, sediment core analysis also has been used to assess climatic change. In Russia, for example, the study of Lake Baikal sediments began in 1993. Sediment cores of more than 320 feet (98 m) in length were collected and analyzed to reveal the climatic, environmental, and geologic history of that particular region as far back as 5 million years.[23] Drilling in ocean sediments has recorded global climate changes back to 200 million years ago.

Urban Microclimates Human development and urbanization can change local microclimates, particularly around large cities. Temperature and precipitation change in such regions can be caused by the "urban heat island effect," defined by the U.S. Environmental Protection Agency (USEPA) as "urban air and surface temperatures that are higher than nearby rural areas." Heat islands are particularly noticeable at night, when urban temperatures can be 10°F (12°C) greater than surrounding rural areas.[24] By contrast, daytime temperatures can sometimes be slightly cooler than regional readings.

Urban heat islands are caused by a variety of human actions, including paved or concrete surfaces, lack of vegetation, rooftops, and large buildings. Research is showing that urban landscapes and pollution in cities change local and regional precipitation patterns. In particular, precipitation distribution is altered over central business districts of larger cities, and downwind for about 15 to 50 miles (25 to 75 km). The following guest essay describes this phenomenon.

GUEST ESSAY

Urbanization and Its Effects on Key Atmospheric and Surface Water Cycles

by **Dr. J. Marshall Shepherd**
Department of Geography,
Atmospheric Sciences Program,
University of Georgia

Dr. Shepherd is Associate Professor at the University of Georgia and is conducting research, advising, and teaching in atmospheric sciences, climatology, water cycle processes and urban climate systems. Dr. Shepherd is currently a member of NASA's Precipitation Measurement Missions Science team. For his work on urban effects on precipitation, Dr. Shepherd received the Presidential Early Career Award, the highest federal award given to the nation's young scientists and engineers. Dr. Shepherd received his B.S., M.S., and Ph.D. in physical meteorology from Florida State University. He was the first African-American to receive a Ph.D. from the Florida State University Department of Meteorology.

Processes In 2008, more than half the world's population lived in urban areas, and by 2030, towns and cities will make up 81 percent of urban humanity (UNFPA, 2007). The National Science Foundation (2005) published "Water: Challenges at the Intersection of Human and Natural Systems." Two overarching questions were posed:

> *(1) Can human intervention in the water cycle set processes and trajectories in motion that we cannot readily see because they are masked by complexity and variation? and (2) Can we begin to put all the pieces together in a way in which we can begin to forecast environmental changes related to water—and therefore intervene before irreparable environmental or social damage is done?*

The 2007 Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (Trenberth et al., 2007) noted that Earth's mean temperature has increased in recent decades in response to primarily anthropogenic activities. Because a warmer atmosphere holds more water vapor, higher evaporation and precipitation rates accelerate the global water cycle and could increase the frequency of weather extremes such as major flood and drought episodes. In turn, the modified water cycle may impact urban infrastructure performance, requiring changes to design, management, and policy.

While discussion has focused on greenhouse gas forcing and its effects, the IPCC report noted a growing interest in what role urban land cover/land use (LCLU) and pollution have on climate change. The report called out the growing body of research linking urban-related processes with regional precipitation changes. Studies from the 1970s and 1980s (for a review, see Shepherd, 2005) suggested that urban landscape and pollution in cities alter precipitation budgets and distributions, particularly over and 25 to 75 kilometers downwind of the central business district. Figure 2.19a is a mesoscale model simulation comparing accumulated rainfall evolution with and without urban land cover (Shepherd et al., 2007). Figure 2.19b reveals a warm-season anomaly in rainfall east of Atlanta using Doppler radar climatology (Mote et al., 2007). Using emerging satellite precipitation methods, Shepherd et al. (2002) found anomalies around several cities and demonstrated the feasibility of multiple study areas.

The possible mechanisms for urbanization to affect precipitation or storms include one or a combination of the following: (1) enhanced atmospheric convergence due to increased surface roughness (buildings, structures) in the urban environment; (2) destabilization due to urban heat island (UHI)–thermal perturbation of the boundary layer and resulting downstream translation of the UHI circulation or UHI-generated convective clouds; (3) enhanced pollution in the urban environment for cloud condensation nuclei sources; or (4) bifurcation or diversion of precipitating systems by the urban building canopy.

Geophysical changes in the water cycle have perceivable impacts on the urban water cycle system. According to Dr. Dale Quattrochi (NASA Marshall Space Flight Center), "The National Weather Service (NWS) office in Charlotte, North Carolina has become very concerned that urban-enhanced precipitation events in conjunction with increased impervious surface extent within the Charlotte metro area have led to an increase in heavy runoff/urban flooding events." Engineers for other cities have similar concerns and are considering modeling studies to quantify the compounded impacts. Changnon and Westcott (2002) assessed the temporal and spatial distributions of heavy rainstorms in the Chicago area. The 12-year average was 40 percent more than in the 1948 to 1980 period. The total rainfall from the 53 heavy rainstorms maximized over the city and suggested that the city and nearby lake were likely affecting the storms. Impacts from the record-high 2001 storm season revealed that efforts to control flooding, including the Deep Tunnel system, had urban flooding in the moderate intensity storms, but the most intense storms (e.g., 100-year rainfall values) caused excessive flooding and a need to release floodwaters into Lake Michigan. Burian et al. (2004), Burian and Shepherd (2005), and Reynolds et al. (2008) discussed the implications of urban-induced precipitation on the design of urban drainage systems and surface hydrological processes (see Figure 2.20). Such examples of science knowledge transfer in the civil engineering, water resource, and planning communities must be mirrored in areas related to precision agriculture, transportation systems, weather forecasting, and other applications that may be impacted by more frequent or intense urban storms.

As concern grows about the impact of anthropogenic and natural processes on climate change, water cycle accelerations, and precipitation variability, it is important to place urban processes

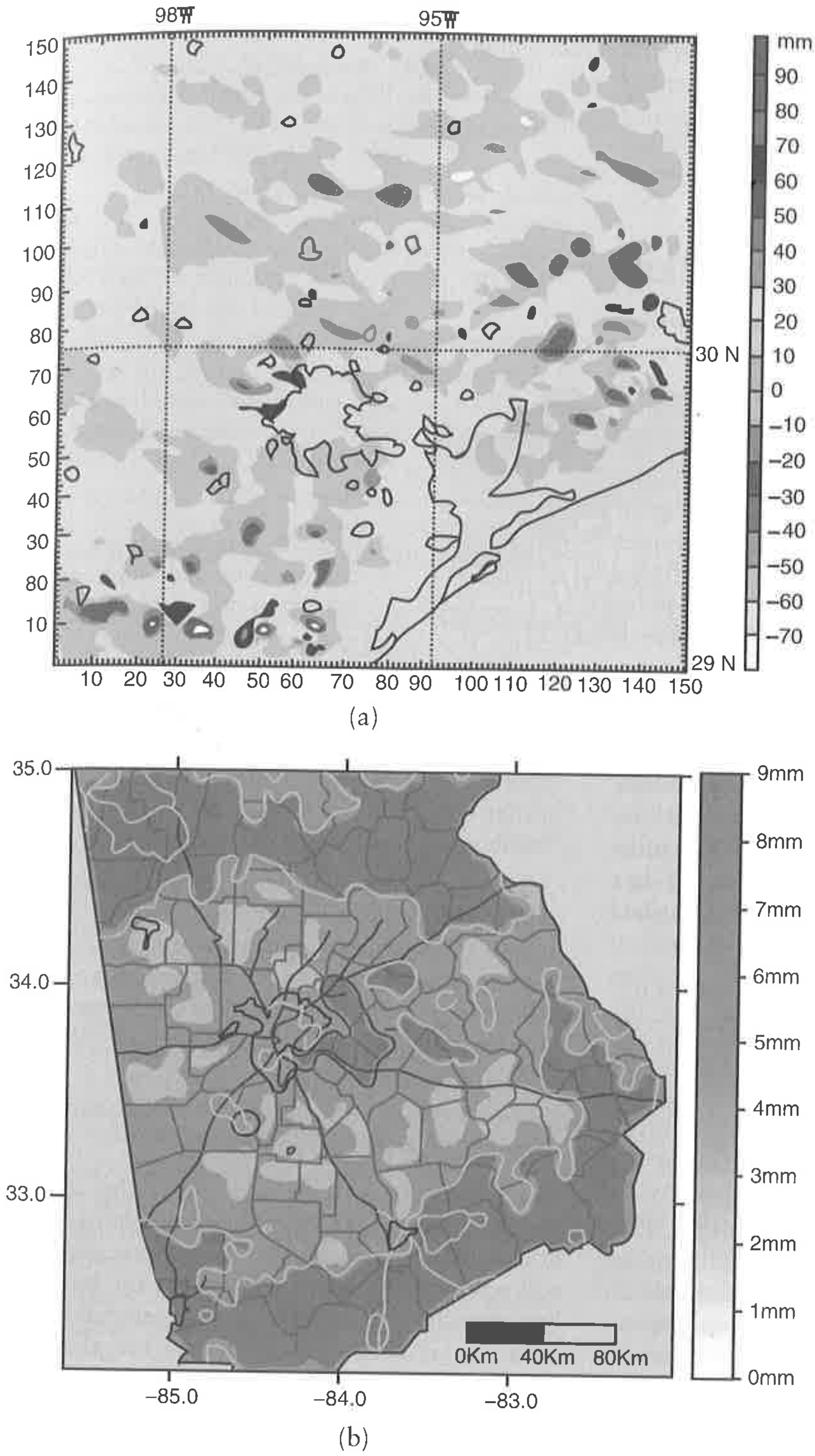

FIG. 2.19 (a) Difference in accumulated rainfall for mesoscale model simulations with and without Houston, Texas, urban land cover (following Shepherd et al., 2007). (b) Average daily precipitation (mm) during the 194 days of the study for June to August of 2002–2006 when an MT (marine tropical) air mass was present in northern Georgia as derived from the KFFC radar in Atlanta. The 4.5-millimeter and 100-hour contours are shown in the darker shades (following Mote et al., 2007).

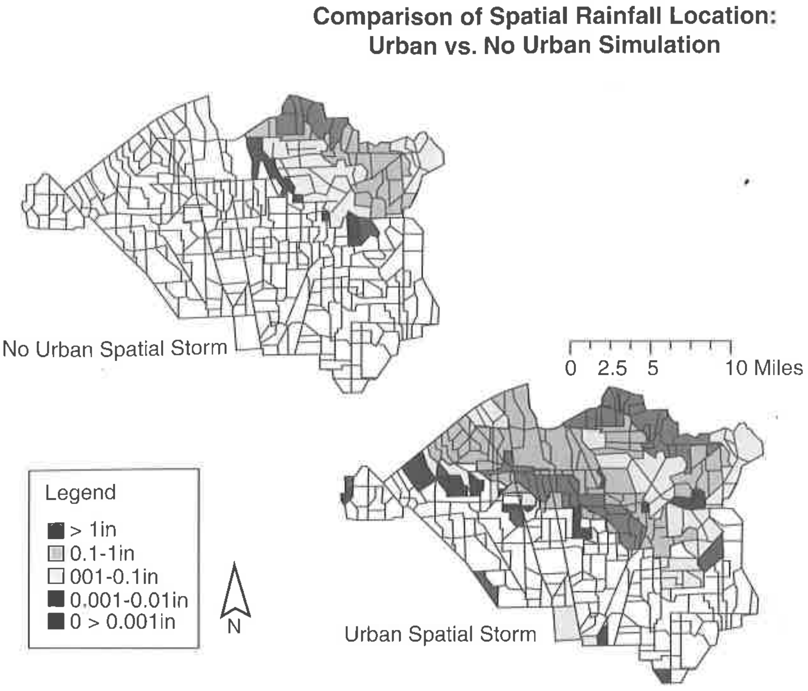

FIG. 2.20 Surface runoff from coupled weather-land-surface-hydrological model simulations of an urban watershed near Houston, Texas (Reynolds et al., 2008).

into the context of regional and global climate system processes. The debate has generally shifted from "Can urban areas affect precipitation?" to "How and why do they affect rainfall?" To fully address the relationships and interactions between the urban environment and precipitation, several things are required:

- New observing systems to monitor and track anthropogenic and natural aerosols, land cover/land use changes, cloud microphysics, and precipitation processes
- Modeling systems that explicitly resolve aerosols, cloud microphysics, complex land surfaces, and precipitation evolution so that a more conclusive understanding of the feedbacks and interactions can be attained
- Implementation of urban parameterizations at the local scale to resolve urban canyon, dynamics, and flux processes, particularly in terms of roughness, surface cover properties, low-level moisture associated with irrigation, and aerosols
- Field studies to validate remote-sensing observations and modeling simulations of urban precipitation processes and to extend basic understanding of the processes involved
- Climate-modeling systems that adequately characterize the urban environment to understand the aggregate roles of global urban surfaces on the Earth's climate system, particularly the precipitation component of the water cycle under different growth and climate change scenarios
- Assessment of the impact of urban-induced rainfall on societal applications

These efforts will certainly move the science understanding forward. Additionally, knowledge of how urban environments impact precipitation will undoubtedly have implications for how urban areas are represented in future generations of weather and climate models; how urban planners and water resource managers plan cities; how agricultural activities are carried out; and other societal applications.

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WEATHER

Weather is the state of the atmosphere at a given time and place. It is a short-term event and generally is not reliably predicted for more than a few days, because the chaotic nature of the atmosphere makes such prediction difficult. Perturbations (disturbances) in the atmosphere that may seem minor can suddenly become major events.[25] Weather is generally determined by five variables: (1) temperature, (2) air pressure, (3) humidity, (4) heating, and (5) wind speed and direction.

Temperature Carbon dioxide, water vapor, methane, ozone, and nitrous oxide create the Earth's "life-maintaining blanket." These five gases are commonly called **greenhouse gases** because they absorb infrared radiation being emitted from the surface of the Earth, much as a glass-covered greenhouse absorbs the sun's radiation. Changes in the amounts of greenhouse gases, however, can lead to changes in temperature and eventually to changes in climate.

Ocean temperatures play a significant role in global weather patterns (see Figures 2.21a and 2.21b). Anyone who has gone to the beach off the coast of Maine, Rhode Island, or Nova Scotia in the summer has experienced surprisingly cold ocean waters (often no more than 53°F, or 12°C, during the summer months). In contrast, ocean temperatures may rise above 80°F (27°C) off the coast of Florida. **Isotherms** (lines connecting points of equal temperature) show bands of ocean temperatures that generally parallel the equator. The warmest waters in August (approximately 82°F, or 28°C) are found in a zone generally between 30°N and 10°S latitude, where

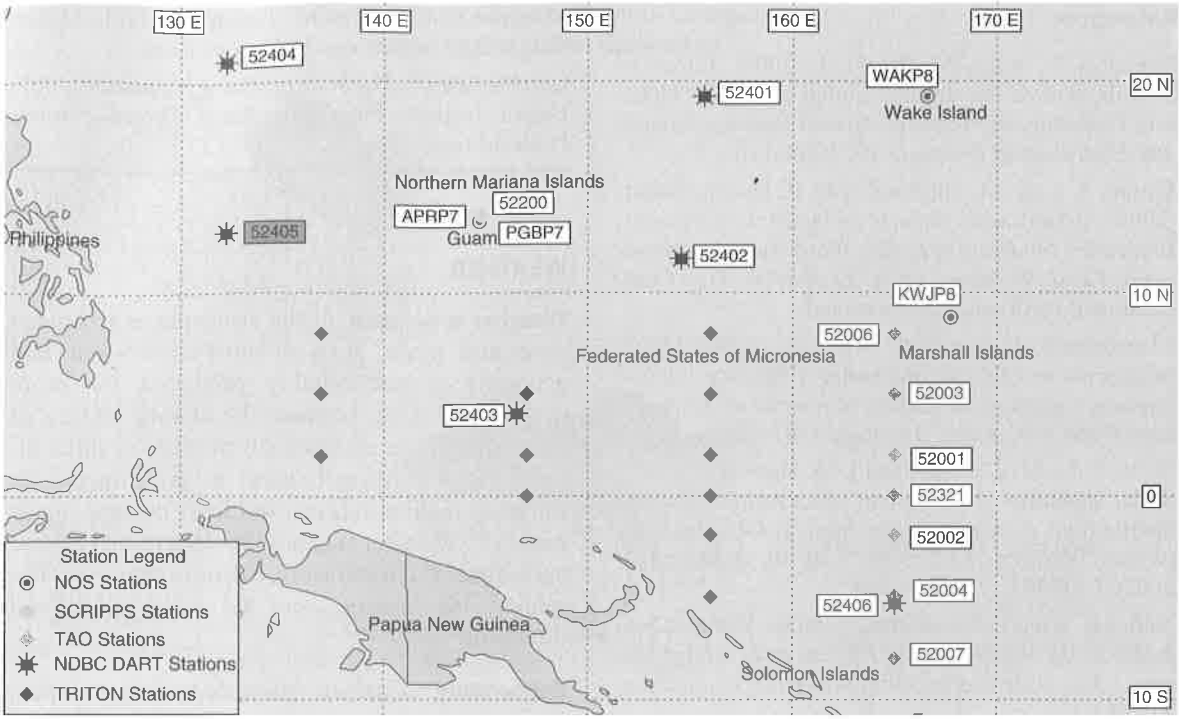


FIG. 2.21a Western Pacific buoy locations are shown that provide marine data to the National Data Buoy Center, National Oceanic and Atmospheric Administration (NOAA), Stennis Space Center, Mississippi. Go to their homepage at http://www.ndbc.noaa.gov to check out real time temperature, wind speed, ocean elevations, and other real time observations from ocean buoys deployed around the world.

solar radiation is the greatest. By January, the zone of maximum solar radiation moves to the Southern Hemisphere, followed by higher ocean temperatures.[26]

The ocean has a high capacity to hold heat and moderates coastal temperatures in many regions of the world. Land temperature extremes have ranged from 136°F (58°C) in the Libyan Desert of northern Africa to –126°F (–88°C) in central Antarctica (a variation of 262°F, or 146°C). By contrast, recorded ocean temperatures have varied by only 69°F, or 38°C. The variance has been from 97°F (36°C) in the Persian Gulf to 28°F (–2°C) in polar seas.[27]

Air and land surface temperatures also play a major role in climate, regional weather patterns, and aquatic ecosystems. The vertical motions caused by the heating of the air and oceans will be discussed later in this chapter in the section titled "Heating."

Air Pressure The Earth's **atmosphere** is composed of invisible and odorless gases and suspended particles that surround our planet. Since air pressure decreases with altitude, the density of the atmosphere (the amount of air per unit volume) decreases as altitude increases. Variations in air pressure are measured by a **barometer**.

The highest barometric pressure ever recorded on the Earth's surface was 1083.8 millibars (32.00 in., or 813 mm) at Agata, Siberia, on December 31, 1968. The temperature was –50°F (–46°C), with the extreme cold and dense

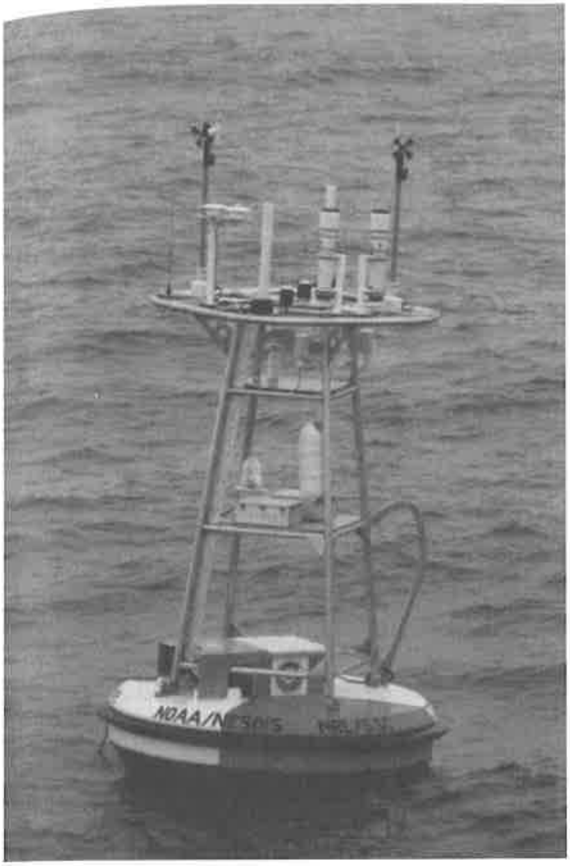


FIG. 2.21b Data are received by the National Data Buoy Center via a GOES satellite every three hours from buoys like this one. The information is used for improved ocean, weather, and climate forecasts.

air contributing to the high reading. The lowest sea level pressure recorded was 870 millibars (25.69 in., or 653 mm) on October 12, 1979, approximately 1000 miles (1609 km) east of the Philippine Islands inside Typhoon Tip. The lowest recorded atmospheric pressure in the United States was 892 millibars (26.35 in., or 669 mm) inside a 1935 Labor Day hurricane that crossed the Florida Keys. The absolute lowest pressure on Earth is probably inside a tornado.[28] The average barometric pressure, called the *standard atmosphere at sea level,* is 30.17 inches or 766 mm of mercury.

SIDEBAR

The invention of the mercury barometer is generally attributed to the Italian physicist Evangelista Torricelli (1608–1647), a student of Galileo. In 1643, Torricelli constructed a glass bulb with a neck "two cubits" long. (A cubit varies in length but is generally 17 to 21 in., or 43 to 53 cm.) The tube was filled with mercury and inverted into a basin containing more mercury. (Originally, Torricelli used water in his model, but he finally had to use a 60 ft., or 18 m, glass tube. He later used the much heavier mercury in his experiment and reduced the height of the tube to only about 3 ft., or 1 m.) Torricelli deduced from this experiment that air pressure on the mercury surface in the bowl must be holding up the column of mercury inside the glass tube. Day-to-day measurements of Torricelli's invention showed slight variations in air pressure outside the glass tube filled with mercury. This led to the discovery by Torricelli and others of air pressure changes and their relation to weather changes.[29]

Humidity The composition of air varies in different locations at the Earth's surface, owing to the presence of **aerosols** and water vapor. Aerosols are very small liquid droplets, or tiny solid particles, that remain suspended in the air. Water aerosols enter the atmosphere when ocean waves break, flowing water tumbles over rocks or other obstructions, or vapor turns to liquid (condensation). Liquid aerosols can exist in fog, while solid particles such as very small ice crystals, smoke particles from fires, dust, volcanic emissions, and industrial pollutants can be widespread. Aerosols are crucial to cloud formation and to the reflection and absorption of radiation. They act as condensation nuclei for clouds, which are basically very large aqueous aerosols. These aerosols transform radiation—from both the Sun and the land surface—in ways that affect and shape cloud development. Aerosols affect climate and are becoming an increasingly important field of study for molecular scientists and climatologists.[30]

Humidity is a measure of the amount of water vapor that exists in the atmosphere at a given location. Warm air can hold more water vapor than cold air. On a hot, humid day in the tropics, as much as 4 percent of the air by volume can be water vapor, while on a cold winter day in other regions, less than 0.3 percent water vapor may be present.[31] There are several ways of expressing humidity. One is *absolute humidity,* the weight of water vapor in a given volume of air, expressed as grams of water vapor per cubic meter of air. Another measure, *relative humidity*, is the amount of water vapor in the air at a particular temperature and atmospheric pressure compared with the maximum amount the air can hold under those conditions. It is a measure of how moist the air is at a certain time and location, and is expressed as a percentage. If air contains three-quarters of the maximum moisture content it could hold at a give temperature and pressure, the relative humidity is said to be at 75 percent. Another measurement related to humidity is the dew point temperature. The **dew point** is the temperature at which the rate of evaporation and condensation are equal—meaning the relative humidity is 100 percent.

SIDEBAR

Water is the third most abundant chemical in the Earth's atmosphere, after nitrogen and oxygen. Water, in its vapor form, is the most important greenhouse gas. This makes it a critical component in the climate of our planet.[32]

Evaporation causes water vapor to enter the atmosphere and then change back into a liquid form as part of the hydrologic cycle. When the number of water molecules that evaporate (change from a liquid to a gas) equals the number changing from a gas to a liquid in the atmosphere, the atmosphere is said to be saturated (the dew point or frost point has been reached). If this water vapor content is exceeded, precipitation will occur in the form of rain, snow, hail, or sleet.

Heating Have you ever pumped air into a bike tire and noticed that the pump became hot as you pushed down on the handle? Some of the heat you felt was generated by friction between the leather sleeves moving inside the pump cylinder. However, much of the temperature increase was caused by the compression of air inside the bike pump. In contrast, have you ever released air from a tire and noticed how cool it felt?

These two conditions—the heat generated from compressed air and the coolness of expanding air—are examples of **adiabatic processes** (from the Greek word *adiabatos,* meaning "no passage"). This term comes from the process of heating or cooling without the addition or subtraction of heat from an outside source. When air is compressed, the result is an increase in temperature. When compressed air expands, the result will be a decrease in temperature.

The adiabatic process occurs when air rises and sinks in the Earth's atmosphere. Warm air is less dense than cool air and will rise in the atmosphere. However, as the air pressure decreases and elevation increases, rising air will expand and cool. If the opposite occurs and cool air begins to sink in the atmosphere, the temperature will increase as the air is compressed at lower elevations. Rising and expanding unsaturated air will drop in temperature at a constant rate of 1°F per 183 feet (1°C per 100 m). Falling and contracting parcels of unsaturated air will increase in temperature at the same rate. These air temperature changes, caused by compression and expansion based on elevation change, are called the **adiabatic lapse rate.**[33]

The adiabatic process often creates clouds, which are composed of aerosols and/or ice crystals, and form when air rises and becomes saturated through the process of adiabatic cooling. Clouds can be classified on the basis of form and height. On the basis of form, clouds are grouped into two major classes: globular masses, or **cumuliform clouds**, and layered, or *stratiform clouds*. Clouds are categorized into four families by height: low, middle, high, and clouds with vertical development.[34]

Cumulus clouds are puffy, round, individual clouds that form when hot, humid air rises due to convection heating (the transfer of heat to the atmosphere from the land surface). Manifestations occur in cumulus clouds (stratocumulus, cumulonimbus, altocumulus, and cirrocumulus) as **convection heating** increases the elevation of warm, humid air movement.

Stratiform clouds are best known by the sheet or blanket appearance that extends across the entire sky. These cloud formations reach a certain level of water vapor content and then spread laterally instead of vertically. Nimbostratus, altostratus, and cirrostratus clouds vary from the dense, low cloud blanket to the higher-elevation cloud formations with a "wispy" appearance. Cirrus clouds are the highest stratus clouds in the sky and look like filaments or feathers. These are composed entirely of ice crystals.

Clouds are generally formed by combinations of five processes:

1. Density lifting caused by warm, low-density air rising due to convection heating (heating from the Sun) and then displacing cooler air located at higher elevations.
2. Frontal lifting caused by warm, moist air moving over cooler air. This is called a **warm front** and often causes the buildup of clouds and the generation of precipitation. A warm front is shown on a weather map by a line with semicircles extending into the cooler air. The term *front* is used because Norwegian meteorologists in World War I compared the clash of air masses above the Earth to the battle lines, or fronts, of warring armies of the time on the land surface.[35]
3. Frontal lifting caused by cool air moving under warmer air. Cold air will move in as a **cold front** and will displace warmer, less dense air by pushing it upward. This may cause cloud formation and precipitation. A cold front is designated on a map by a line with triangle-shaped points extending into the warmer air mass. (Occasionally, weather fronts will become parallel with little or no movement. These are called **stationary fronts** and are shown with triangular points on one side and semicircles on the other side of the weather front.)
4. **Orographic lifting** created when warm, moist air is forced by wind over high natural features such as mountains (see Figure 2.22). Some of the highest amounts of precipitation occur in regions that experience orographic lifting: the western coast of Tasmania in Australia, the Owen Stanley mountain range in New Guinea, and the Cascade Range in northern California, Oregon, Washington, and British Columbia.

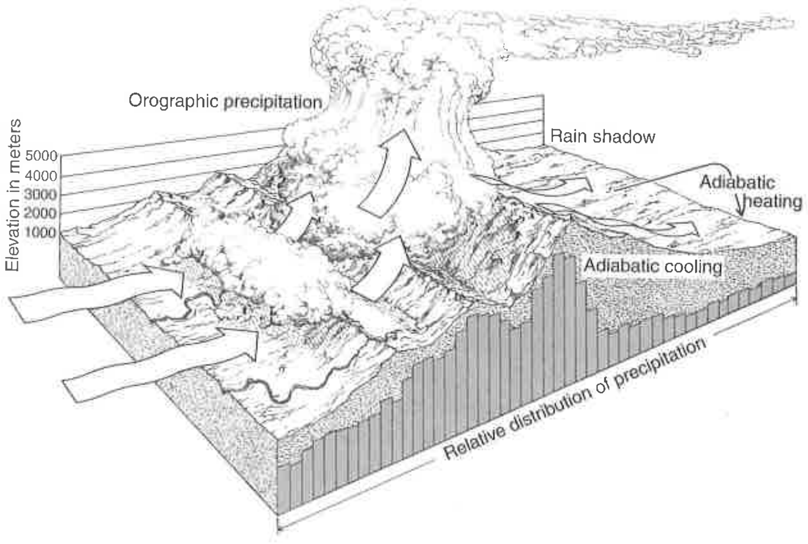


FIG. 2.22 Orographic precipitation. Rain and snowfall are heaviest on the windward slopes as compared to the dry climates of leeward, or downwind, slopes. See Figure 2.25 for the effects of this process.

5. Convergence lifting caused when two air masses collide and are both forced upward. Weather patterns along the Florida Peninsula are a good example of this process. Air flows toward land both from the Gulf of Mexico on Florida's west coast and from the Atlantic Ocean on the east coast of the state. The two air masses collide over the state and force some air to rise, resulting in frequent afternoon thunderstorms and rain showers.

All in all, the single basic reason for cloud formation and precipitation, or the lack of it, is related to vertical motions. The upward motion of air can enhance the growth of clouds, the formation of ice crystals, and the precipitation process. If the air is sinking or subsiding, the relative humidity decreases the air warms while the water content remains the same. Clouds will dissipate, and precipitation becomes sparse. When air rises, clouds form, a good field of droplets—differing in size by a factor or ten or even a thousand—become available for coalescence, ice nuclei form in the colder portion of the growing cloud, and these assist in the ice nucleation process, which is so important to precipitation.

Much of what we see as weather and climate can be explained by these vertical motions. The violence of the weather is directly related to the strength of these vertical motions. Meteorologists would love to be able to predict those vertical motions with accuracy.[36]

A CLOSER LOOK

On July 26, 1959, Lt. Col. William H. Rankin, a U.S. Marine Corps pilot, was on a routine flight between Massachusetts and South Carolina. He was flying an F8U Crusader supersonic jet at 47,000 feet (14,326 m) above a well-developed cumulonimbus cloud system, or thunderhead, when he was forced to eject due to a seized engine (a condition created when pistons expand so much due to overheating that they will not move in the cylinders, probably caused by low oil pressure).

Lt. Col. Rankin fell through the extremely cold (−70°F, or −57°C) interior of the thunderhead cloud. Violent updrafts inside the storm changed his normal 10-minute descent into a 40-minute ride of terror. Lightning flashed around him and at times seemed to pass through his body, while continual claps of thunder almost broke his eardrums. Torrential rain and pelting hailstones struck his body, which was protected only by a summer flight suit and helmet. The pilot was terrified that he might drown while still in the thunderhead due to the incredible amount of precipitation inside the cloud.

Ejection into the low atmospheric pressure at 47,000 feet caused his internal organs to swell in size, creating horrific pain. Lt. Rankin's parachute at times oscillated like a pendulum and at other times deflated from violent downdrafts of air. The harrowing aerial experience ended when he landed in a pine tree near Rich Square, North Carolina. He was the only person known to have penetrated the entire length of a severe thunderstorm and survived at that time.[37]

In February 2007, paraglider pilot Ewa Wisnierska of Germany (see Figure 2.23) was sucked up into a tornado-like thunderstorm while practicing for the Paragliding World Championships in New South Wales, Australia. She survived lightning, pounding hail the size of oranges, and −40°F (−40°C) temperatures after the storm shot her up to an altitude of 32,635 feet (9947 m)—above the altitude of Mount Everest's peak (see Figure 2.24). Wisnierska passed out due to a lack of oxygen and flew unconscious for up to an hour covered in ice, according to an onboard tracking system. She suffered from severe frostbite and bruises all over her body.

FIG. 2.23 Vice-World Champion in paragliding, Ewa Wisnierska, gliding across the vineyards near Bernkastel-Kues, Germany, in 2005. Wisnierska is the only woman among the world's top 20 paragliders. She was sucked into a thunderstorm during the World Championship in Australia in February 2007 and barely survived.

Another paraglider caught in the same cumulonimbus storm system was not as lucky. He Zhongpin, a member of the Chinese national paragliding team, was found 47 miles (75 km) from his launch site. He most likely suffocated or froze to death after being sucked up into the same storm.[38]

As mentioned earlier, the Cascade Mountains of Oregon are a topographic barrier that creates a large rain shadow over the eastern (downwind) region of the state. Portland, on the west (windward) side of the mountain range, receives approximately 36 inches (91 cm) of precipitation annually. By contrast, the city of Pendleton, Oregon, on the east side of the Cascades, is in a rain shadow and receives only 12 inches (30 cm) per year (Figure 2.25). A **rain shadow** is an area of low precipitation created when warm, moist air runs into a barrier, such as a mountain range, which causes orographic lifting and heavy precipitation on the windward side. Low precipitation occurs on the downwind side of such a range. This is the main reason why Portland receives more precipitation than Chicago, and more than Los Angeles, Phoenix, and Denver combined.

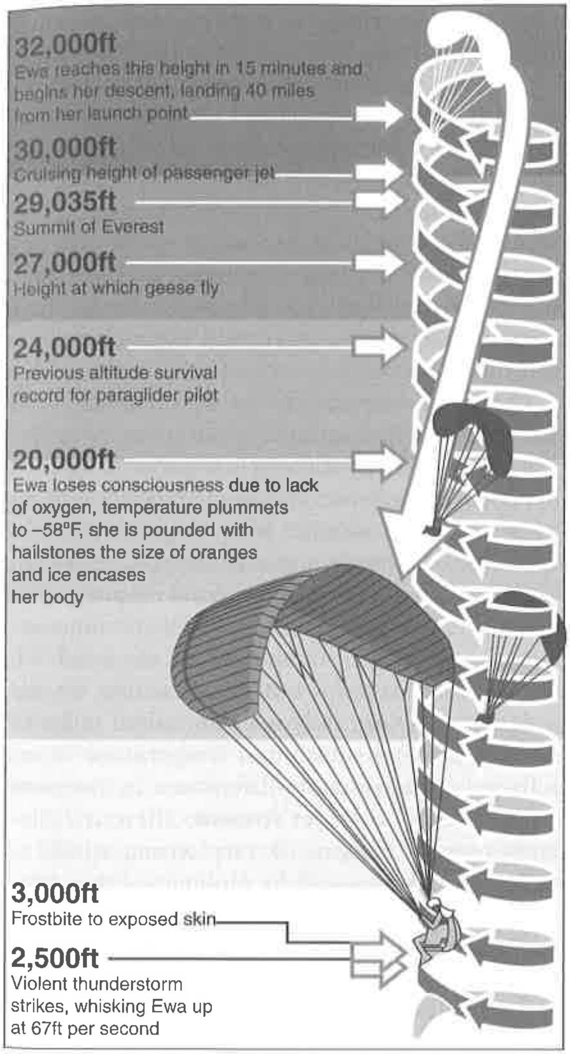


FIG. 2.24 The rise and fall of Ewa Wisnierska.

Coastal deserts can also occur along the western shores of some continents. Cold, bottom waters of an ocean often meet landmasses, causing maritime air temperatures to cool. Fog can often be the result, since the air retains too little moisture to create precipitation. Coastal deserts in Peru, Chile, and southwestern Africa are among the driest regions on Earth.

Heating caused by El Niño and La Niña events can also drastically alter weather around the world. **El Niño** (Spanish for "the Little Boy" or "Christ Child," since it often arrives around Christmas) is a natural phenomenon that occurs when a warm surface ocean current forms in the eastern Pacific Ocean off the coast of Ecuador and Peru. This warm current prevents cold, deeper water from reaching the ocean surface. El Niño is also associated with the southward displacement of the intertropical convergence zone (ITCZ) called the **southern oscillation,** a variable pattern of air pressure between the eastern and western tropical Pacific.

Strong El Niño events often produce floods in Ecuador, Peru, Cuba, and the southern United States, and drought in Australia, Indonesia, the Philippines, and southern Africa. El Niño can also generate more frequent and intense ice storms in southeastern Canada, while generally reducing Atlantic tropical storms and hurricanes.

El Niño is on an approximate cycle of two to seven years and has been monitored in South America for centuries. Peruvian farmers have predicted El Niño rainfall in December by

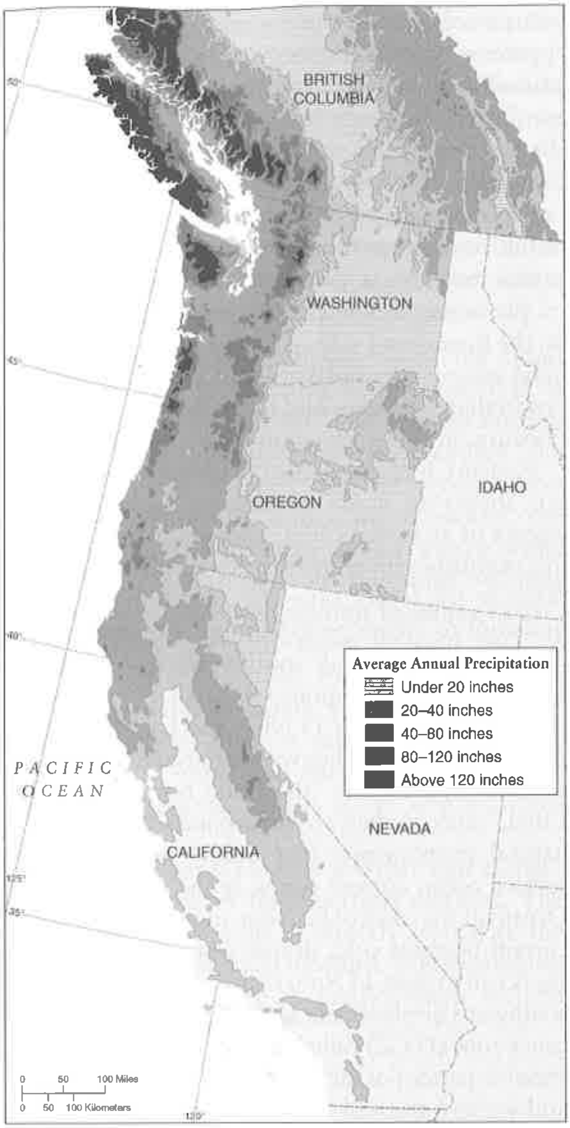


FIG. 2.25 Average annual precipitation in California, Oregon, Washington, and British Columbia. Note the dramatic drop in orographic precipitation going from west to east.

observing the brightness of stars in the Pleiades constellation in June. Brighter stars meant more rain during the growing season. It has been hypothesized that El Niño conditions in the ocean off the coast of Peru generated high cirrus clouds during the summer that veiled starlight from the constellation.[39]

La Niña ("the Little Girl") is another natural phenomenon caused by cooler water in the equatorial Pacific Ocean. It also leads to flood and drought conditions across the world, but the locations of these weather patterns tend to be opposite from the effects of El Niño.

Wind Speed and Direction **Wind** is the horizontal movement of air caused by differences in air pressure. Air is constantly moving from locations of high pressure to areas of low pressure to eliminate differences in air pressure caused by solar heating. There is always some vertical movement associated with this air movement. Air pressure gradients are determined by **isobars** (lines on a map that connect locations of equal atmospheric pressure) measured by a barometer. The area between isobars determines the air pressure gradient in a location on the ground. If isobars are close together, wind speed will increase as air moves from a region of high pressure to a nearby region of lower pressure. An area where isobars are far apart will experience little or no wind.

The spiral pattern of air flow can be seen almost daily on satellite photos or weather maps. Air rotating around a low-pressure system, in a counterclockwise motion, is labeled with an *L* for Low on a weather map. Air rotating in a clockwise motion around a high-pressure system is labeled *H* for High on the same map.

Finally, during the winter, it is not uncommon for the temperature to be 65°F (18°C) in Mississippi but near freezing on the same day in Ohio, only a few hundred miles to the north. These substantial temperature variations arise because of differences in pressure gradients that create **jet streams.** These are relatively narrow ribbons of very strong winds at higher altitudes caused by moving air that tries to even out areas between high- and low-pressure systems. High winds aloft have been compared to streams of water and are generally strongest during winter months.

WEATHER MODIFICATION

Everybody talks about the weather, but nobody does anything about it.

Mark Twain, *Hartford Courant*, August 27, 1897

Weather modification is any change in the weather caused by humans. For centuries, the idea of "controlling" the weather has been an intriguing idea. Efforts have been made to increase rainfall, reduce the size and duration of hailstorms, dissipate fog, reduce the intensity of lightning, and calm the winds of hurricanes. However, rain enhancement and hail suppression have shown the most promise.

One of the first U.S. weather modification programs began in the 1890s. Investigators noted that in the major battles of the Civil War of the 1860s, rainfall seemed to occur after artillery had been fired. The U.S. Congress appropriated $9000 for the U.S. Department of Agriculture to conduct tests near Washington, D.C., and in west Texas. Cannons were fired into the sky, dynamite was detonated, and hydrogen-filled balloons were released into the atmosphere, but the results were inconclusive.[40]

The first scientific breakthrough in weather modification occurred in 1946 when V. J. Schaeffer, a scientist with the General Electric Company (GE) in Schenectady, New York, accidentally discovered that adding dry ice (frozen carbon dioxide) into a deep freeze full of supercooled fog caused the moisture to quickly freeze and drop as snow particles. Schaeffer later found that silver iodide produced a similar effect. Before long, airplanes were dropping silver iodide into supercooled clouds above New England to increase the growth of ice crystals. (On one flight, researchers even carved a big GE into the clouds.)[41]

This process of introducing nucleating agents such as silver iodide (AgI), ammonium iodide (NH_4I), or dry ice into clouds to enhance precipitation or to reduce hail is called **cloud seeding**. Cloud seeding causes water vapor in a cloud to freeze, converting it from a gaseous to a solid state. Other moisture is then induced to form around this nucleus until these water droplets become heavy enough to fall as precipitation. Ground-based generators or specially equipped aircraft deliver the nucleating agents into clouds.

Silver iodide is often introduced into a cloud by burning silver iodide flares. The smoke particles furnish the nuclei for ice crystal formation. A cloud temperature of 10°F (–12°C) is ideal, although a range of 25°F to –22°F (–4°C to –30°C) is acceptable. Cloud temperatures warmer than 25°F (–4°C) are not sufficiently supercooled, while temperatures below –22°F (–30°C) already contain ice crystals, since spontaneous nucleation occurs at –40°F (–40°C).[42]

POLICY ISSUE

Although cloud-seeding efforts have been conducted for over a century, many people adamantly oppose the concept because cloud seeding, they believe, increases the likelihood of damaging hailstorms. Reductions in precipitation downwind of seeded storms have also been attributed, opponents argue, to enhanced rainfall upwind. Some scientists and water resource managers are skeptical of the benefits of cloud seeding, since many scientific studies are inconclusive.

Some objectors argue that cloud seeding is unethical because it interferes with natural hydrologic processes. Supporters argue that cloud seeding works and that efforts should continue regardless of political boundaries. In 1972, the United Nations Conference on the Human Environment held in Stockholm, Sweden, urged establishment of an advisory committee to consider the international concerns of weather modification.

If you were the program manager for a cloud-seeding experiment, how would you deal with these types of allegations to gain support for your program? How could you design a precipitation-monitoring network to support your project?

Concerns have been expressed over the environmental effects of using ammonium or silver iodide if large quantities accumulate on the ground after seeding efforts. Measurements have been made of the change of concentrations of silver iodide found in farm ponds, rivers, and other areas where cloud seeding is practiced. Only minor concentrations have been found, but widespread use of silver iodide could result in elevated local concentrations in precipitation and runoff.[43]

SIDEBAR

The costliest hailstorm in U.S. history occurred along the Front Range of Colorado, from Fort Collins to Colorado Springs, on July 11, 1990, with damages of $625 million. In 1984, a hailstorm in Munich, Germany, caused $1 billion in damages. The largest documented hailstone fell in Aurora, Nebraska, on June 22, 2003 (see Figure 2.26). It measured 7.0 inches (18 cm) in diameter and had a circumference of 18.75 inches (48 cm)—almost the size of a soccer ball. The monster thunderheads that produced this gigantic hailstone had tops of over 70,000 feet (21,000 m). The hailstone is now at the National Center for Atmospheric Research in Boulder, Colorado, where it will be preserved indefinitely.[44]

It is very difficult to evaluate the effectiveness of precipitation enhancement projects. Since the atmosphere does not generate identical clouds, a complex statistical dilemma is created in determining the value of such cloud-seeding programs. One method is to compare the amount and extent of rainfall in a seeded area with a region outside the area, using several different cases. This type of analysis has shown an increase in precipitation of 10 to 20 percent.[45]

FLOODS

Floods—a most deadly natural disaster—have become more common and severe due to human influence and development. Paved surfaces, road embankments, and wetlands removal can increase runoff volumes in specific locations. A flood can be caused by summer thunderstorms, melting snow, ice jams in swollen rivers, or seasonal monsoons. Storms can be totally unexpected and come with a limited time warning, such as summer floods experienced in Tucson, Arizona, or on both the North and South Islands of New Zealand. By contrast, floods can be predictable and closely monitored, like flooding along the Mississippi River in the United States or the Red River in the north-central United States and south-central Canada, after a winter and spring of excess moisture (see Figure 2.27).

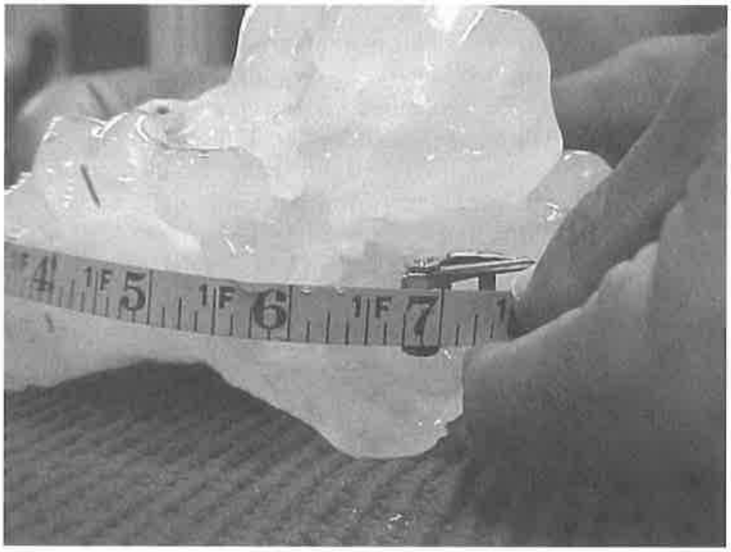


FIG. 2.26 The largest documented hailstone in the United States—7.0 inches (18 cm) in diameter and 18.75 inches (48 cm) in circumference—almost the size of a soccer ball. It fell from a thunderstorm in Aurora, Nebraska, in 2003.

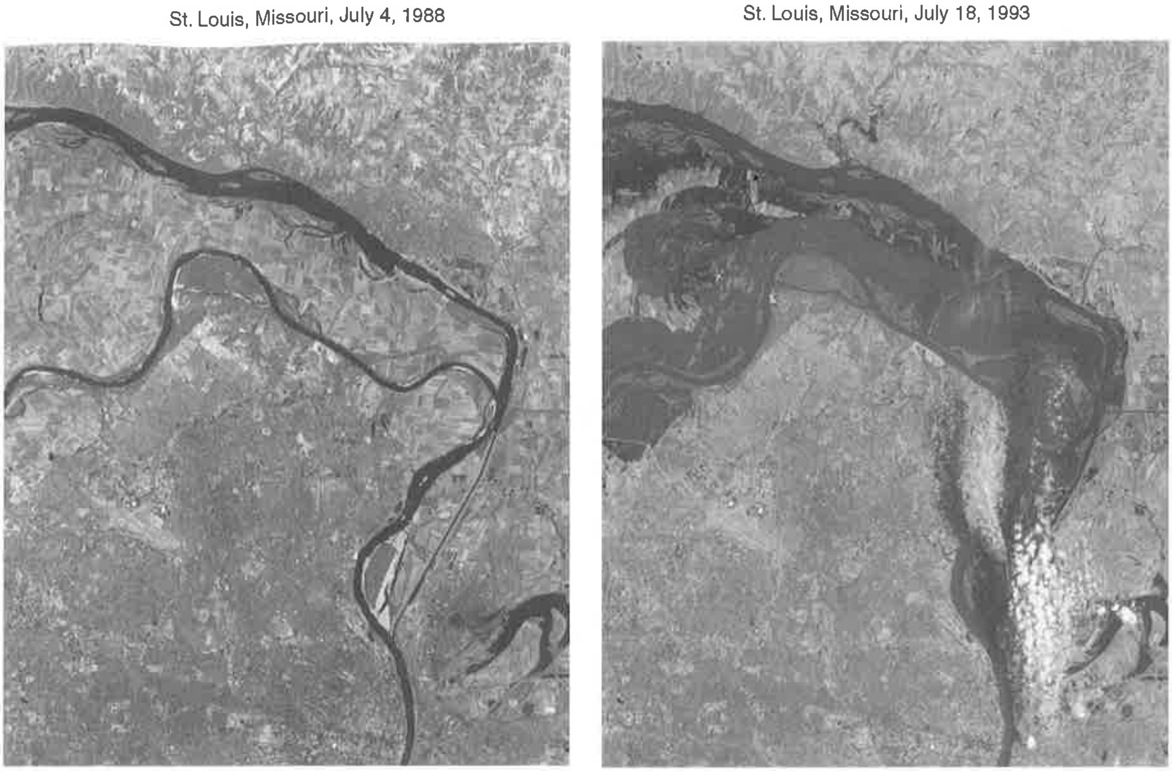
FIG. 2.27 The Sorlie Bridge between Grand Forks, North Dakota, and East Grand Forks, Minnesota, during the 1997 Red River of the North flood.

Every year thousands of floods occur around the world, with very little warning. Such an event, called a **flash flood**, happened in the Black Hills of South Dakota on June 9, 1972, when 15 inches (381 mm) of rain fell in only five hours, sweeping away more than 200 people in the unexpected floodwaters generated by the storm. In Calama, Chile, virtually no rain fell for 400 years in the city of 150,000 people located in the middle of the Atacama Desert. Then a midafternoon deluge hit on February 10, 1972, creating mudslides and catastrophic floods.

On the evening of July 31, 1976, near Estes Park, Colorado, over 12 inches (305 mm) of rain fell in just four hours above the mountainous and narrow Big Thompson River Canyon. Thousands of streamside motorists, residents, and campers were caught by surprise. Surface water runoff was so great that all stream measurement devices were washed out by a 20-foot (6 m) wall of water that crashed down the dark canyon. Loss of life was widespread as 144 people died in the flood. The death toll would have been much higher if Colorado State Patrol Sergeant Willis Hugh Purdy had not driven his patrol car down the canyon, ahead of the racing wall of water, to warn unsuspecting residents and campers. The heroic Sergeant Purdy died in the flood. Today, a plaque in his honor is located in the Big Thompson Canyon.

Flash floods are brutally swift, massive, and destructive. However, larger floods have occurred with several days and even weeks of warning from meteorologists and government authorities. In 1993, massive snowmelt and above-normal precipitation in the upper Mississippi River Basin, associated with the 1992–1993 El Niño, led to enormous amounts of surface water runoff during that spring and summer. Iowa, Missouri, and Illinois, as well as other basin states, experienced record water levels that covered substantial portions of those states (see Figure 2.28). Government agencies worked around the clock for weeks in an effort to construct levees and dikes, built of earth or sandbags, to keep floodwaters away from communities. In some cases, these efforts were successful, but in other locations, entire cities were inundated.

In the Northern Territory of Australia, cyclone season begins in early November and runs to the end of April. (Cyclones are called hurricanes or typhoons in other countries.) Rainfall and flooding can be extreme but are not unexpected during cyclone season. See http://www.bom.gov.au/info/cyclone for excellent



St. Louis, Missouri, July 4, 1988

St. Louis, Missouri, July 18, 1993

FIG. 2.28 These satellite images show the confluence of the Missouri and Mississippi rivers near St. Louis, Missouri. A normal flow pattern is shown in the July 4, 1988, photo at the left, where the area between the two rivers is dry and cultivated for crops. The July 18, 1993, photo on the right shows the rivers out of their banks because of weeks of torrential rains in the region. Farmland and communities were inundated with floodwaters, causing billions of dollars in damages.

information from the Australian Bureau of Meteorology.

DROUGHT

Author John Steinbeck wrote in *East of Eden,* "And it never failed that during the dry years the people forgot about the rich years, and during the wet years they lost all memory of the dry years. It was always that way."[46] Steinbeck wrote of the brutally dry years in Oklahoma in the 1930s and described the hardships created for farmers and businesspeople across the American Midwest.

According to the U.S. National Weather Service, **drought** is "a period of abnormally dry weather which persists long enough to produce a serious hydrologic imbalance." The severity of a drought depends on the degree of moisture deficiency, the duration of the dry weather, and the size of the affected area. Drought is very different from aridity. **Aridity** is a permanent climatic condition in a region, whereas drought is a temporary lack of moisture.

Drought is relative to a particular location. Years without rain in the Atacama Desert, located in the rain shadow of the Andes Mountains of northern Chile, would simply represent the normal aridity of the region. However, two months without moisture in Seattle, Washington, or Montreal, Quebec, could be classified as a serious drought. Droughts generally have no specific beginning or end, cover large areas, and cause little structural damage. Drought can sometimes be predicted through data obtained on developing El Niño and La Niña events.

Drought can be defined in several different ways:

Meteorological drought: Departure from normal precipitation (Annual precipitation over 5 in., or 12.7 cm, per year in some parts of northern Africa would be considered a very wet period.)

Hydrological drought: Below-normal surface and groundwater supplies

Agricultural drought: Inadequate water supplies to grow a particular crop

Socioeconomic drought: Inadequate water supplies to serve local residents

Several **drought indices** exist to measure the severity of below-average moisture in a region. A simple method used quite often is "percent of normal," a calculation that meets the needs of TV weather forecasters and general audiences. All audiences easily understand when a meteorologist says "We're 10 percent above normal in precipitation for the year," or "Precipitation is 20 percent below normal in the western part of the province."

The Palmer drought severity index, or **Palmer index**, was the first comprehensive drought index developed in the United States.[47] The U.S. Department of Agriculture uses this index to determine when to provide emergency drought assistance. It was developed by W. C. Palmer in 1965 and works best in large areas of uniform topography.

This index does not consider human alterations to the natural water balance, such as reservoir storage. An extremely wet region would have a Palmer Classification of 4.0 or more, whereas an extreme drought would be 4.0 or less (see Table 2.6). Weekly Palmer Index maps can be viewed at http://www.drought.noaa.gov/palmer.html.

TABLE 2.6 Palmer Drought Severity Index

Soil Moisture Algorithm	Weather Conditions
4.0 or more	Extremely wet
3.0 to 3.99	Very wet
2.0 to 2.99	Moderately wet
1.0 to 1.99	Slightly wet
0.5 to 0.99	Incipient wet spell
0.49 to –0.49	Near normal
–0.5 to –0.99	Incipient dry spell
–1.0 to –1.99	Mild drought
–2.0 to –2.99	Moderate drought
–3.0 to –3.99	Severe drought
–4.0 or less	Extreme drought

A **Surface Water Supply Index (SWSI)** provides a weighted index for a river basin using information on snowpack, reservoir storage levels, precipitation, and stream flow.

Drought is a naturally occurring event throughout the world. The Dust Bowl of the 1930s was probably the worst drought in recorded U.S. and Canadian history. In those years, dust storms occurred weekly (see Figure 2.29), and piled drifts of blown soil deposits up to 25 feet (8 m) high. Topsoil was blown thousands of miles from dry farmland in the Central Plains out to ships in the Atlantic Ocean. Crops withered away, livestock died, and grasshoppers arrived like the plague. Fortunately, land use practices have changed since then to protect barren ground susceptible to blowing.

Drought can be horrific and cause enormous human and environmental problems (see Figure 2.30). The dust storms of the 1930s were the worst environmental problem in the United States, whether measured in physical, human, or economic terms. Dust was so thick that pedestrians could literally bump into each other in the middle of the day. Clouds of dust rose several miles (km) high, and carried hundreds of millions of tons of topsoil thousands of miles. Homes, barns, tractors, and fields were buried under drifts of dirt. In conditions known as "black blizzards," the sky could turn black in

FIG. 2.29 In this famous photo from the Dust Bowl, farmer Arthur Coble and his two sons walk in the face of a dust storm, Cimmaron County, Oklahoma. (Arthur Rothstein, photographer, April 1936. Library of Congress.)

a matter of minutes, and dust obscured the sun for several days at a time. Some people thought they were seeing the end of the world.[48]

POLICY ISSUE

Extended drought in California from 1986 to 1993 forced residents to drastically reduce water use. Restrictions were implemented to conserve water, as a result of which lawns and crops withered and died from lack of water. A drought hit much of the eastern United States and south-central Canada in 2002 and peaked in the western regions of the two countries in 2003, when below-normal precipitation caused extensive crop loss and ravaging forest fires. Fines of up to $1000 and a six-month jail term were imposed in some locations for watering a lawn or washing a car. Other methods have been used to combat drought, such as in 1988, when Alabama Governor Guy Hunt led a statewide prayer for rain. Wet weather arrived the next day and continued for weeks.

How do you prepare for drought? Government officials can encourage residents to plant xeriscape (low water-use) plants instead of bluegrass for lawns. Emergency water allocation programs, based on priority of use, can be developed. Many cities have contingency plans for water use restrictions during periods of water shortages. Even and odd watering days are often used in drier climates, based on the last digit of a home address, to restrict lawn watering and car washing. In extreme conditions, outdoor water use is prohibited.

Drought planners often consider techniques used in arid climates. Many residents in Phoenix, Arizona, have crushed-rock lawns instead of bluegrass to reduce water use. Drip irrigation is used to reduce the amount of water needed to grow crops in southern California. Restrictions on water use are common in these dry regions. What drought contingency plans have been used in your area? Is it appropriate for government agencies to implement water rationing only during drought periods, or should government-mandated water conservation programs be a way of life?

Researchers who study tree rings have recently found evidence of a "mega-drought" in

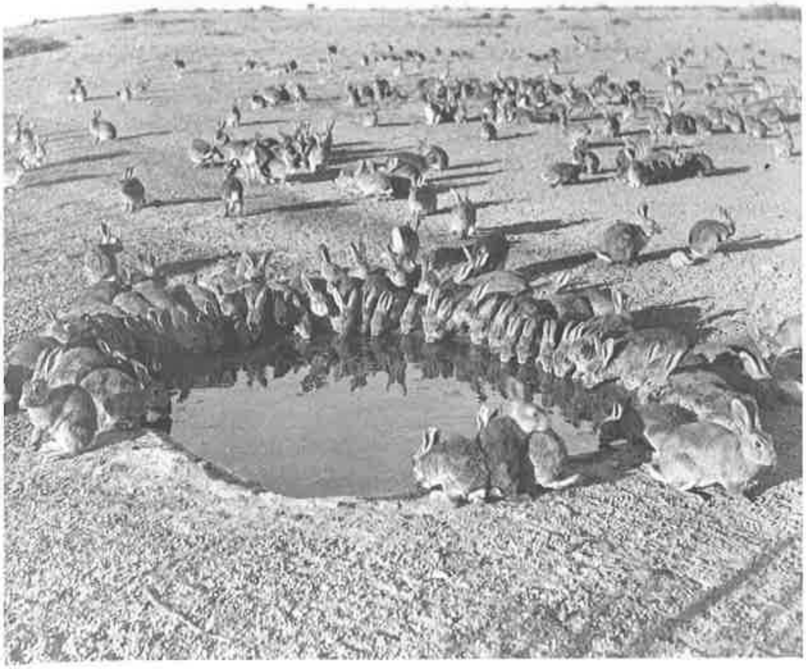


FIG. 2.30 Humans have greatly altered the habitat of Australia. In 1859, Thomas Austin imported 24 rabbits from England and released them on his property for sport hunting. With no natural predators, the animals multiplied rapidly; Australia had over 200 million rabbits in the 1990s, but that number is around 100 million today through various control methods. Unfortunately, this extreme overpopulation has created severe stress on the natural and human landscape. Here, thirsty rabbits converge on a waterhole during a drought.

the 16th century that caused havoc throughout North America. Researchers used dendrochronology to determine that severe conditions existed at times in Mexico, the southwestern United States, Wyoming, Montana, and the southeastern United States. Early English, Spanish, and Native Americans would have faced decades of severe drought in these regions. It appears that no other drought—looking back as far as A.D. 1200—was as intense, prolonged, or widespread as the mega-drought of the 1500s. Archival records for the Spanish colony of Santa Elena, located on present-day Parris Island, South Carolina, indicate a severe drought from 1566 to 1569. In 1587, the same year Sir Walter Raleigh's colony on Roanoke Island disappeared, settlers on Parris Island abandoned their colony. The severely dry weather of this period could explain why some Native American Indians abandoned the pueblos between 1540 and 1598. Records from the Chichimeca War in Mexico, which lasted from 1550 to 1590, indicate severe drought conditions.

Researchers state that the 16th-century mega-drought was not caused by global warming. However, they are unsure whether it was caused by ocean currents or another phenomenon. Further study of ocean sediments and coral reefs may reveal the ocean's role in this mega-drought. Such a drought today would wipe out certain agricultural activities and would place great strain on municipal and industrial water supplies in those regions. The good news is that, based on tree ring studies, the mega-drought of the 16th century is the only drought event of this magnitude over the past 1000 years. However, numerous droughts, each lasting lasting 5 to 10 years, have been discovered by dendrochronologists. These studies indicate that prolonged droughts have frequently occurred across the southwestern United States (one of the fastest-growing population regions in the nation) and should be expected in the future.[49]

CHAPTER SUMMARY

The hydrologic cycle is a never-ending, naturally occurring feature of our Earth and is powered by energy from the Sun. Through the processes of precipitation, runoff, storage, evaporation and condensation, water is recirculated around the world. Between natural processes of the atmosphere, the land surface, groundwater, and the oceans, the Earth's water is constantly recycled.

The locations of wet and dry regions on our planet are determined by a variety of factors, but primarily by air movement and ocean currents. The Earth's rotation generates patterns of air and ocean water movement that create extremes in precipitation around the world. Orographic barriers, such as mountain ranges in Washington, Oregon, British Columbia, and Chile, can also create extremely dry local climates.

Weather is created by the same factors that generate climate but is also affected by changes in atmospheric temperature and barometric pressure. Warm and cold fronts can greatly influence daily and weekly weather patterns. Some weather events can be predicted by observing the development of El Niño or La Niña events, while other conditions are almost unpredictable.

QUESTIONS FOR DISCUSSION

1. Name the five primary components of the hydrologic cycle.
2. What is the difference between climate and weather?
3. Why are some regions of the world much drier than other areas?
4. Discuss the role of wetlands within the hydrologic cycle.
5. Discuss orographic lifting and its effects on precipitation variability in the western United States and Canada.
6. Identify several methods used to obtain historical climate data.
7. Explain how an El Niño event develops off the coast of Peru.
8. In the Southern Hemisphere, do ocean current gyres go clockwise or counterclockwise? Why?
9. What is the difference between aridity and drought?
10. Find the current Palmer drought index for a selected region. What classification currently exists, and why?

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SUGGESTED RESOURCES FOR FURTHER STUDY

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