Palm-oak forest hammock ("shady place"), featuring a mixed hardwood forest. There are bromeliads (epiphytes) growing on the live oak trees and a few on the cabbage, or sabal, palms. This palm is Florida’s state tree. A hammock is slightly higher ground, surrounded by wet prairies, mixed swamp, and cypress forest marshes. Such “islands” of vegetation result from having few fires, protected as they are by surrounding marshes. These two photos are in Myakka River State Park, Sarasota County, about 15 miles inland from the central Gulf Coast. [Overhead and forest-floor photos by Bobbé Christopherson.]
Global Climate Systems

Key Learning Concepts

After reading the chapter, you should be able to:

- Define climate and climatology, and explain the difference between climate and weather.
- Review the role of temperature, precipitation, air pressure, and air mass patterns used to establish climatic regions.
- Review the development of climate classification systems, and compare genetic and empirical systems as ways of classifying climate.
- Describe the principal climate classification categories other than deserts, and locate these regions on a world map.
- Explain the precipitation and moisture efficiency criteria used to determine the arid and semiarid climates, and locate them on a world map.
- Outline future climate patterns from forecasts presented, and explain the causes and potential consequences of climate change.

Earth experiences an almost infinite variety of weather—conditions of the atmosphere—at any given time and place. But if we consider the weather over many years, including its variability and extremes, a pattern emerges that constitutes climate. Think of climatic patterns as dynamic rather than static, owing to the fact that we are witnessing climate change. Climate is more than a consideration of simple averages of temperature and precipitation.
Today, climatologists know that intriguing global-scale linkages exist in the Earth-atmosphere-ocean system. For instance, strong monsoonal rains in West Africa are correlated with the development of intense Atlantic hurricanes; or, one year an El Niño in the Pacific is tied to rains in the American West, floods in Louisiana and Northern Europe, and a weak Atlantic hurricane season. Yet, the persistent La Niña in 2007 strengthened drought’s six-year hold on the West. The El Niño/La Niña phenomenon is the subject of Focus Study 10.1.

Climatologists, among other scientists, are analyzing global climate change—record-breaking global average temperatures, glacial ice melt, drying soil-moisture conditions, changing crop yields, spreading of infectious disease, changing distributions of plants and animals, declining coral reef health and fisheries, and the thawing of high-latitude lands and seas. Climatologists are concerned about observed changes occurring in the global climate, as these are at a pace not evidenced in the records of the past millennia. Climate and natural vegetation shifts during the next 50 years could exceed the total of all the past millennia. Climate and natural vegetation shifts are correlated with the development of intense Atlantic hurricanes; or, one year an El Niño in the Pacific is tied to rains in the American West, floods in Louisiana and Northern Europe, and a weak Atlantic hurricane season. Thus, changes in the polar regions of the Arctic and Antarctic.

Climate Components: Insolation, Temperature, Pressure, Air Masses, and Precipitation

The principal elements of climate are insolation, temperature, pressure, air masses, and precipitation. The first nine chapters discussed each of these elements. We review them briefly here. Insolation is the energy input for the...
climate system, but it varies widely over Earth’s surface by latitude (see Chapter 2 and Figures 2.9, 2.10, and 2.11). Daylength and temperature patterns vary diurnally (daily) and seasonally. The principal controls of temperature are latitude, altitude, land-water heating differences, and cloud cover. The pattern of world temperatures and their annual ranges are in Chapter 5 (see Figures 5.14, 5.15, 5.17, and 5.18).

Temperature variations result from a coupling of dynamic forces in the atmosphere to Earth’s pattern of atmospheric pressure and resulting global wind systems (see Figures 6.10 and 6.12). Important, too, are the location and physical characteristics of air masses, those vast bodies of homogeneous air that form over oceanic and continental source regions.

Moisture is the remaining input to climate. The hydrologic cycle transfers moisture, with its tremendous latent heat energy, through Earth’s climate system (see Figure 9.1). The moisture input to climate is precipitation in all its forms. Figure 10.2 shows the worldwide distribution of precipitation, our moisture supply. Its patterns are important, for it is a key climate control factor. Average temperatures and daylength help us approximate POTET (potential evapotranspiration), a measure of natural moisture demand.

Most of Earth’s desert regions, areas of permanent water deficit, are in lands dominated by subtropical high-pressure cells, with bordering lands grading to grasslands and to forests as precipitation increases. The most consistently wet climates on Earth straddle the equator in the Amazon region of South America, the Congo region of Africa, and Indonesia and Southeast Asia, all of which are influenced by equatorial low pressure and the intertropical convergence zone (ITCZ, see Figure 6.11).

Simply relating the two principal climatic components—temperature and precipitation—reveals general climate types (Figure 10.3). Temperature and precipitation patterns, plus other weather factors, provide the key to climate classification.

Classification of Climatic Regions

The ancient Greeks simplified their view of world climates into three zones: The “torrid zone” referred to warmer areas south of the Mediterranean; the “frigid zone” was to the north; and the area where they lived was labeled the “temperate zone,” which they considered the optimum climate. They believed that travel too close to the equator or too far north would surely end in death. But the world is a diverse place and Earth’s myriad climatic variations are more complex than these simple views.
Classification is the process of grouping data or phenomena in related categories. Such generalizations are important tools in science and are especially useful for the spatial analysis of climatic regions. Just as there is no agreed-upon climate classification system, neither is there a single set of empirical (statistical) or genetic (causal) criteria on which everyone agrees. Any classification system should be viewed as developmental, because it is always open to change and improvement.

A climate classification based on causative factors—for example, the interaction of air masses—is a genetic classification. A climate classification determined by statistical data of observed effects is an empirical classification. Climate classifications based on temperature and precipitation data are examples of empirical classifications. Genetic classifications explain climates in terms of net radiation, thermal regimes, or air mass dominance over a region. This chapter uses a system that draws on both a genetic and an empirical approach, which allows description of the climatic regions and also provides information as to why such climates are found where they occur.

One empirical classification system, published by C. W. Thornthwaite in 1948, identified moisture regions using the water-budget approach (Chapter 9) and
Focus Study 10.1
The El Niño Phenomenon—Global Linkages

Climate is the consistent behavior of weather over time, but average weather conditions also include extremes that depart from normal. The El Niño–Southern Oscillation (ENSO) in the Pacific Ocean forces the greatest interannual variability of temperature and precipitation on a global scale. The two strongest ENSO events in 120 years hit in 1997–1998 and 1982–1983. The spring wildflower bloom in Death Valley in 1998 provides visible evidence of the resultant heavy rains (Figure 10.1.1). Peruvians coined the name El Niño (“the boy child”) because these episodes seem to occur around the traditional December celebration time of Christ’s birth. Actually, El Niños can occur as early as spring and summer and persist through the year.

What Is ENSO?
Occasionally, for unexplained reasons, pressure patterns and surface ocean temperatures shift from their usual locations. Higher pressure than normal develops over the western Pacific and lower pressure develops over the eastern Pacific. Trade winds normally moving from east to west weaken and can be reduced or even replaced by an eastward (west-to-east) flow. The shifting of atmospheric pressure and wind patterns across the Pacific is the Southern Oscillation. Chapter 6 discussed the Pacific Decadal Oscillation (PDO) and its interrelation with ENSO.

Sea-surface temperatures increase, sometimes more than 8 °C (14 °F) above normal in the central and eastern Pacific during an ENSO, replacing the normally cold, upwelling, nutrient-rich water along Peru’s coastline. Such ocean-surface warming, the “warm pool,” may extend to the International Date Line. This surface pool of warm water is known as El Niño. Thus, the designation ENSO is derived—El Niño–Southern Oscillation. This condition is shown in Figure 10.1.2b in illustration and satellite image.

The thermocline (boundary of colder, deep-ocean water) lowers in depth in the eastern Pacific Ocean. The change in wind direction and warmer surface water slows the normal upwelling currents that control nutrient availability. This loss of nutrients affects the phytoplankton and food chain, depriving many fish, marine mammals, and predator birds of nourishment.

Scientists at the National Oceanographic and Atmospheric Administration (NOAA) speculate that ENSO events occurred more than a dozen times since the fourteenth century. More recently, there was an ENSO in 1982–1983 (second-strongest event), 1986–1987, 1991–1993 (one of the longest), and the most intense

FIGURE 10.1.1 El Niño’s impact on the desert.
Death Valley, southeastern California, in (a) full spring bloom following record rains triggered by the 1997–1998 El Niño and (b) the same scene in spring 2002 in its stark desert grandeur. A dramatic effect caused by changes in the distant tropics of the Pacific Ocean. [Photos by Bobbé Christopherson.]

(continued)
Focus Study 10.1 (continued)

FIGURE 10.1.2 Normal, El Niño, and La Niña changes in the Pacific.
(a) Normal patterns in the Pacific; (b) El Niño wind and weather patterns across the Pacific Ocean and TOPEX/Poseidon satellite image for November 1997 (white and red colors indicate warmer surface water—a warm pool). (c) TOPEX/Poseidon image of La Niña conditions in transition in the Pacific in October 1998 (purple and blue colors for cooler surface water—a cool pool). (d) A persistent La Niña in a March 2000 satellite image. (e) Image from June 2001 showing no El Niño as equatorial waters slowly warm with sea-surface temperature near normal. (f) The warm pool of waters retreated westward, leaving neutral or a mild La Niña off South America, July 2004 image. (g) More neutral conditions February 22, 2005. (h) La Niña growing in size, August 26, 2007. [(a) and (b) adapted and author corrected from C. S. Ramage, “El Niño.” © 1986 by Scientific American, Inc.; (b)–(e) TOPEX/Poseidon and (f, g, and h) Jason–1 images courtesy of Jet Propulsion Laboratory, NASA.]
episode in 1997–1998 that disrupted global weather. The PDO shifted into its negative phase in 1999, which seems to dampen ENSO cycles and bring drier conditions to the American West.

The expected interval for recurrence is 3 to 5 years, but the interval may range from 2 to 12 years. The frequency and intensity of ENSO events increased through the twentieth century, a topic of much research by scientists to see if there is a relation to global climate change. Recent studies suggest ENSO might be more responsive to global change than previously thought. Surface temperatures in the central tropical Pacific returned to near normal (neutral) by mid-2001 (Figure 10.1.2e).

La Niña—El Niño’s Cousin
When surface waters in the central and eastern Pacific cool to below normal by 0.4 °C (0.7 °F) or more, the condition is dubbed La Niña, Spanish for “the girl.” This is a weaker condition and less consistent than El Niño. There is no correlation in the strength or weakness of each. For instance, following the record 1997–1998 ENSO event, the subsequent La Niña was not as strong as predicted and shared the Pacific with lingering warm water.

Between 1900 and 1998 there were 13 La Niñas of note, the latest in 1988, 1995, late 1998 to 2000 (Figure 10.1.2c and d), and 2007 (Fig. 10.1.2b). According to National Center for Atmospheric Research (NCAR) scientist Kevin Trenberth, El Niños occurred 31% and La Niñas 23% of the time since 1950, with the remaining 46% of the time the Pacific being in a more neutral condition. Don’t look for symmetry and opposite effects between the two events, for there is great variability possible, except perhaps in Indonesia where remarkable drought (El Niño) and heavy rain (La Niña) correlations seem strong.

Global Effects Related to ENSO and La Niña
Effects related to ENSO and La Niña occur worldwide: droughts in South Africa, southern India, Australia, and the Philippines; strong hurricanes in the Pacific, including Tahiti and French Polynesia; and flooding in the southwestern United States and mountain states, Bolivia, Cuba, Ecuador, and Peru. In India, every drought for more than 400 years seems linked to ENSO events. The Atlantic hurricane season weakens during La Niño years and strengthens during El Niño.

Precipitation in the southwestern United States is greater in El Niño than La Niña years. The Pacific Northwest is wetter with La Niña than El Niño. El Niño-enhanced rains in 1998 produced the wildflower bloom in Death Valley pictured in Figure 10.1.1. The Colorado River flooding shown in the Chapter 9 opening photo and discussed in Chapter 15’s Focus Study 15.1 was in part attributable to the 1982–1983 El Niño. Yet, as conditions vary, other El Niños have produced drought in the very regions that flooded during a previous episode.

Since the 1982–1983 event, and with the development of remote-sensing satellites and computing capability, scientists now are able to identify the complex global interconnections among surface temperatures, pressure patterns in the Pacific, occurrences of drought in some places, excessive rainfall in others, and the disruption of fisheries and wildlife.

Discovery of these truly Earth-wide relations and spatial impacts is at the heart of physical geography. The climate of one location is related to climates elsewhere, although it should be no surprise that Earth operates as a vast integrated system. “It is fascinating that what happens in one area can affect the whole world. As to why this happens, that’s the question of the century. Scientists are trying to make order out of chaos,” says NOAA scientist Alan Strong. (For ENSO monitoring and forecasts, see the Climate Prediction Center at http://www.ncep.noaa.gov/ or the Jet Propulsion Laboratory at http://topex-www.jpl.nasa.gov/mission/jason-1.html/ or http://sealevel.jpl.nasa.gov/science/jason1 or NOAA’s El Niño Theme Page at http://www.pmel.noaa.gov/toga-tao/el-nino/nino-home.html.)
News Report 10.1

What's in a Boundary?

The boundary between mesothermal and microthermal climates is sometimes placed along the isotherm where the coldest month is \(-3^\circ\text{C} (26.6^\circ\text{F})\) or lower. That might be an accurate criterion for Europe, but for conditions in North America, the 0°C (32°F) isotherm is considered more appropriate. The difference between the 0 and \(-3^\circ\text{C}\) isotherms covers an area about the width of the state of Ohio. Remember, these isotherm lines are really transition zones and do not mean abrupt change from one temperature to another.

A line denoting at least one month below freezing runs from New York City roughly along the Ohio River, trending westward until it meets the dry climates in the southeastern corner of Colorado. In Figure 10.5 you see this boundary used. A line marking \(-3^\circ\text{C}\) as the coldest month would run farther north along Lake Erie and the southern tip of Lake Michigan. In addition, remember that from year to year, the position of the 0°C isotherm for January can shift several hundred kilometers as weather conditions vary. Climate change adds another dimension to this question of accurate placement of statistical boundaries—for they are shifting. The Intergovernmental Panel on Climate Change (IPCC, discussed later in this chapter) predicts a 150- to 550-km (90- to 350-mi) range of possible poleward shift of climatic patterns in the midlatitudes during this century. Such change in climate would place Ohio, Indiana, and Illinois within climate regimes now experienced in Arkansas and Oklahoma. As you examine North America in Figure 10.5, use the graphic scale to get an idea of the magnitude of these potential shifts. Boundaries are indeed dynamic.

FIGURE 10.4 Climate regions generalized.
Six general climate categories, keyed to the legend and coloration in the Figure 10.5 map.
Relative to the question asked about your campus and birthplace in the caption to Figure 10.3, locate these two places on this climate map.
and their regional types that provide us with a structure for our discussion in this chapter.

- Tropical (equatorial and tropical latitudes)
  - rain forest (rainy all year)
  - monsoon (6 to 12 months rainy)
  - savanna (less than 6 months rainy)
- Mesothermal (midlatitudes, mild winter)
  - humid subtropical (hot summers)
  - marine west coast (warm to cool summers)
  - Mediterranean (dry summers)
- Microthermal (high latitudes, cold winter)
  - humid continental (hot to warm summers)
  - subarctic (cool summers to very cold winters)
- Polar (high latitudes and polar regions)
  - tundra (high latitude or high altitude)
  - ice caps and ice sheets (perpetually frozen)
  - polar marine
- Highland (compared to lowlands at the same latitude, highlands have lower temperatures—recall the normal lapse rate)

Only one climate category is based on moisture efficiency as well as temperature:

- Desert (permanent moisture deficits)
  - arid deserts (tropical, subtropical hot and midlatitude cold)

Global Climate Patterns

Adding detail to Figure 10.4, we develop the world climate map presented in Figure 10.5. The following sections describe specific climates, organized around each of the main climate categories listed previously. An opening box at the beginning of each climate section gives a simple description of the climate category and causal elements that are in operation. A world map showing distribution and the featured representative cities also is in the introductory box for each climate. The names of the climates appear in italics in the chapter.

Climographs exemplify particular climates for selected cities. A climograph is a graph that shows monthly temperature and precipitation, location coordinates, average annual temperature, total annual precipitation, elevation, the local population, annual temperature range, annual hours of sunshine (if available, as an indication of cloudiness), and a location map. Along the top of each climograph are the dominant weather features that are influential in that climate.

Discussions of soils, vegetation, and major terrestrial biomes that fully integrate these global climate patterns are in Part IV. Table 20.1 synthesizes all this information and enhances your understanding of this chapter, so please place a tab on that page and refer to it as you read.

Tropical Climates (equatorial and tropical latitudes)

Tropical climates occupy about 36% of Earth’s surface, including both ocean and land areas—Earth’s most extensive climate category. The tropical climates straddle the equator from about 20° N to 20° S, roughly between the Tropics of Cancer and Capricorn, thus the designation tropical. Tropical climates stretch northward to the tip of Florida and southward to central Mexico, central India, and Southeast Asia. These climates are truly winterless. Consistent daylength and almost perpendicular Sun angle throughout the year generate this warmth. Important causal elements include:

- Consistent daylength and insolation input, which produce consistently warm temperatures;
- Intertropical convergence zone (ITCZ), which brings rain as it shifts seasonally with the high Sun;
- Warm ocean temperatures and unstable maritime air masses.

Tropical climates have three distinct regimes: tropical rain forest (ITCZ present all year), tropical monsoon (ITCZ present for 6 to 12 months), and tropical savanna (ITCZ present for less than 6 months).

Tropical Rain Forest Climates

The tropical rain forest climate is constantly moist and warm. Convectional thunderstorms, triggered by local heating and trade-wind convergence, peak each day from mid-afternoon to late evening inland and earlier in the day where marine influence is strong along coastlines. Precipitation follows the migrating intertropical convergence zone (ITCZ, Chapter 6). The ITCZ shifts northward and southward with the summer Sun throughout the
FIGURE 10.5 World climate classification.
Annotated on this map are selected air masses, near-shore ocean currents, pressure systems, and the January and July locations of the ITCZ. Use the colors in the legend to locate various climate types; some labels of the climate names appear in italics on the map to guide you.
Part II The Water, Weather, and Climate Systems

High rainfall sustains lush evergreen broadleaf tree growth, producing Earth’s equatorial and tropical rain forests (Figure 10.6). The leaf canopy is so dense that little light diffuses to the forest floor, leaving the ground surface dim and sparse in plant cover. Dense surface vegetation occurs along riverbanks, where light is abundant. (Widespread deforestation of Earth’s rain forest is detailed in Chapter 20.)

High temperature promotes energetic bacterial action in the soil so that organic material is quickly consumed. Heavy precipitation washes away certain minerals and nutrients. The resulting soils are somewhat sterile and can support intensive agriculture only if supplemented by fertilizer.

Uaupés, Brazil (Figure 10.7), is characteristic of tropical rain forest. On the climograph you can see that the lowest-precipitation month receives nearly 15 cm (6 in.), and the annual temperature range is barely 2 °C (3.6 °F). In all such climates, the diurnal (day-to-night) temperature range exceeds the annual minimum–maximum (coolest to warmest) range: Day–night temperatures can range more than 11 °C (20 °F), more than 5 times the annual monthly average range.

The only interruption of tropical rain forest climates across the equatorial region is in the highlands of the South American Andes and in East Africa (see Figure 10.7).

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Figure 10.5). There, higher elevations produce lower temperatures; Mount Kilimanjaro is less than 4° south of the equator, but at 5895 m (19,340 ft) it has permanent glacial ice on its summit (although this ice is shrinking due to higher air temperatures). Such mountainous sites fall within the highland climate category.

**Tropical Monsoon Climates**

The tropical monsoon climates feature a dry season that lasts 1 or more months. Rainfall brought by the ITCZ falls in these areas from 6 to 12 months of the year. (Remember, the ITCZ affects the tropical rain forest climate region throughout the year.) The dry season occurs when the convergence zone is not overhead. Yangon, Myanmar (formerly Rangoon, Burma), is an example of this climate type, as illustrated by the climograph and photograph in Figure 10.8. Mountains prevent cold air masses from central Asia getting into Yangon, resulting in its high average annual temperatures.

About 480 km (300 mi) north in another coastal city, Sittwe (Akyab), Myanmar, on the bay of Bengal, annual precipitation rises to 515 cm (203 in.) compared to Yangon’s 269 cm (106 in.). Therefore, Yangon is a drier tropical monsoon area than farther north along the coast but still receives more than the 250-cm criteria.

Tropical monsoon climates lie principally along coastal areas within the tropical rain forest climatic realm and experience seasonal variation of wind and precipitation. Evergreen trees grade into thorn forests on the drier margins near the adjoining savanna climates.

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**FIGURE 10.8** Tropical monsoon climate.

(a) Climograph for Yangon, Myanmar (formerly Rangoon, Burma) (tropical monsoon); city of Sittwe also noted on map. (b) The monsoonal forest near Malang, Java, at the Purwodadi Botanical Gardens.

[Photo by Tom McHugh/Photo Researchers, Inc.]
Part II  The Water, Weather, and Climate Systems

Tropical Savanna Climates

Tropical savanna climates exist poleward of the tropical rain forest climates. The ITCZ reaches these climate regions for about six months or less of the year as it migrates with the summer Sun. Summers are wetter than winters because convectional rains accompany the shifting ITCZ when it is overhead. This produces a notable dry condition when the ITCZ is farthest away and high pressure dominates. Thus, POTET (natural moisture demand) exceeds PRECIP (natural moisture supply) in winter, causing water-budget deficits.

Temperatures vary more in tropical savanna climates than in tropical rain forest regions. The tropical savanna regime can have two temperature maxima during the year because the Sun’s direct rays are overhead twice—before and after the summer solstice in each hemisphere as the Sun moves between the equator and the tropic. Dominant grasslands with scattered trees, drought resistant to cope with the highly variable precipitation, characterize the tropical savanna regions.

Arusha, Tanzania, is a characteristic tropical savanna city (Figure 10.9). This metropolitan area of more than 350,000 people is located near the foot of the highest African mountain, Mt. Kilimanjaro. The annual precipitation is about 119 cm (46.9 in.), while the annual temperature range is 4.1 °C (7.4 °F).

### Figure 10.9

(a) Climograph for Arusha, Tanzania (tropical savanna); note the intense dry period. (b) Characteristic landscape in Kenya, with plants adapted to seasonally dry water budgets. (c) Extreme northern Australia on the Cape York Peninsula; the tropical savanna features eucalyptus trees, grasses, and conical termite mounds, in an open savanna in Mungkan Kandju National Park. [Photos by (b) Stephen J. Krasemann/DRK Photo; (c) B. G. Thomson, courtesy of The Wilderness Society.]
than 1,368,000 people is east of the famous Serengeti Plains savanna and Olduvai Gorge, site of human origins, and north of Tarangire National Park. Temperatures are consistent with tropical climates, despite the elevation (1387 m) of the station. Note the marked dryness from June to October, which defines changing dominant pressure systems rather than annual changes in temperature. This region is near the transition to the dryer desert hot-steppe climates to the northeast.

Mesothermal Climates (midlatitudes, mild winters)

Mesothermal, meaning “middle temperature,” describes these warm and temperate climates where true seasonality begins and seasonal contrasts in vegetation, soil, and human lifestyle adaptations are evident. Mesothermal climates occupy the second-largest percentage of Earth's land and sea surface—more than half of Earth's oceans and about one-third of its land area. Approximately 55% of the world's population resides in these climates.

The mesothermal climates, and nearby portions of the microthermal (cold winter) climates, are regions of great weather variability, for these are the latitudes of greatest air mass interaction. Causal elements include:

- Shifting air masses of maritime and continental origin are guided by upper-air westerly winds and undulating Rossby waves and jet streams.
- Migrating cyclonic (low-pressure) and anticyclonic (high-pressure) systems bring changeable weather conditions and air mass conflicts.
- Sea-surface temperatures of offshore ocean currents influence air mass strength: cooler water temperatures along west coasts (weaken) and warmer water along east coasts (strengthen).
- Summers transition from hot to warm to cool as you move away from the tropics. Climates are humid, except where subtropical high pressure produces dry summer conditions.

Humid Subtropical Climates

The humid subtropical hot-summer climates are either moist all year or have a pronounced winter-dry period, as occurs in eastern and southern Asia. Maritime tropical air masses generated over warm waters off eastern coasts influence humid subtropical hot-summer climates during summer. This warm, moist, unstable air produces convectional showers over land. In fall, winter, and spring, maritime tropical and continental polar air masses interact, generating frontal activity and frequent midlatitude cyclonic storms. These two mechanisms produce year-round precipitation. Overall, precipitation averages 100–200 cm (40–80 in.) a year.

Nagasaki, Japan (Figure 10.10), is characteristic of an Asian humid subtropical hot-summer station, whereas Columbia, South Carolina, is characteristic of the North American climate region (Figure 10.11). Unlike the precipitation of humid subtropical hot-summer cities in the United States (Atlanta, Memphis, Norfolk, New Orleans, and Columbia), Nagasaki's winter precipitation is a bit less because of the effects of the Asian monsoon. However, the lower precipitation of winter is not quite dry enough to change its category to a winter-dry. In comparison to higher rainfall amounts in Nagasaki (196 cm, 77 in.), Columbia's precipitation totals 126.5 cm (49.8 in.); compare to Atlanta's 122 cm (48 in.) annually (Figure 10.11b).

Humid subtropical winter-dry climates are related to the winter-dry, seasonal pulse of the monsoons. They extend poleward from tropical savanna climates and have a summer month that receives 10 times more precipitation than their driest winter month. A representative station is Chengdu, China. Figure 10.12 demonstrates the strong correlation between precipitation and the high-summer Sun.

The habitability of the humid subtropical hot-summer and humid subtropical winter-dry climates and their ability to sustain populations are borne out by the concentration
of people in north-central India, the bulk of China’s 1.3 billion people, and the many who live in climatically similar portions of the United States.

The intense summer rains of the Asian monsoon can cause problems, as they did each year between 2004 and 2007, producing floods in India and Bangladesh. Occasional dramatic thunderstorms and tornadoes are notable in the southeastern United States, with tornado occurrences seemingly breaking previous records each year.

The monsoonal winter-dry climates hold several precipitation records. Cherrapunji, India, in the Assam Hills south of the Himalayas, is the all-time precipitation record holder for a single year and for every other time interval from 15 days to 2 years. Because of the summer monsoons that pour in from the Indian Ocean and the Bay of Bengal, Cherrapunji has received 930 cm (30.5 ft) of rainfall in 1 month and 2647 cm (86.8 ft) in 1 year—both records.

Marine West Coast Climates

Marine west coast climates, featuring mild winters and cool summers, dominate Europe and other middle-to-high-latitude west coasts (see Figure 10.5). In the United States, these climates with their cooler summers are in contrast to the hot-summer humid climate of the southeastern United States.

Maritime polar air masses—cool, moist, unstable—dominate marine west coast climates. Weather systems forming along the polar front and maritime polar air masses move into these regions throughout the year, making weather quite unpredictable. Coastal fog, annually totaling 30 to 60 days, is a part of the moderating marine influence. Frosts are possible and tend to shorten the growing season.

Marine west coast climates are unusually mild for their latitude. They extend along the coastal margins of the Aleutian Islands in the North Pacific, cover the southern third of Iceland in the North Atlantic and coastal Scandinavia, and dominate the British Isles. It is hard to imagine that such high-latitude locations can have average monthly temperatures above freezing throughout the year.

Unlike the extensive influence of marine west coast regions in Europe, mountains restrict this climate to coastal environs in Canada, Alaska, Chile, and Australia. The temperate rain forest of Vancouver Island is representative of these moist and cool conditions (Figure 10.13). (A temperature graph for Vancouver, British Columbia, appears in Figure 5.12 with a photo of this marine west coast city.)

The climograph for Dunedin, New Zealand, demonstrates the moderate temperature patterns and the annual temperature range for a marine west coast city in the Southern Hemisphere (Figure 10.14).
An interesting anomaly occurs in the eastern United States. In portions of the Appalachian highlands, increased elevation lowers summer temperatures in the surrounding **humid subtropical hot-summer** climate, producing a **marine west coast** cooler summer. The climograph for Bluefield, West Virginia (Figure 10.15), reveals marine west coast temperature and precipitation patterns, despite its location in the east. Vegetation similarities between the Appalachians and the Pacific Northwest have enticed many emigrants from the East to settle in these climatically familiar environments in the Northwest.

**Mediterranean Dry-Summer Climates**

Across the planet during summer months, shifting cells of subtropical high pressure block moisture-bearing winds from adjacent regions. This shifting of stable, warm to

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**FIGURE 10.11** Humid subtropical hot-summer climate, rainy all year, American region. (a) Climograph for Columbia, South Carolina (*humid subtropical*). Note the more consistent precipitation pattern compared to Nagasaki, as Columbia receives seasonal cyclonic storm activity and summer convection showers within maritime tropical air. (b) The mixed deciduous and evergreen forest in southern Georgia, typical of the humid subtropical southeastern United States. (c) This scene is from the humid subtropical portion of Argentina along the Paraná River, northwest of Buenos Aires. [(b) and (c) Photos by Bobbé Christopherson.]
FIGURE 10.12 Humid subtropical winter-dry climate. (a) Climograph for Chengdu, China (humid subtropical). Note the summer-wet monsoonal precipitation. (b) Landscape of southern interior China characteristic of this winter-dry climate. This valley is near Mount Daliang in Sichuan Province. [Photo by Jin Zuqi/Sovfoto/Eastfoto.]

FIGURE 10.13 A marine west coast climate. Temperate rain forest in the Macmillan Provincial Park, central Vancouver Island, British Columbia, Canada (marine west coast), features a Douglas fir forest, with western red cedar and hemlock. [Photo by Bobbé Christopherson.]

hot, dry air over an area in summer and away from these regions in the winter creates a pronounced dry-summer and wet-winter pattern. For example, the continental tropical air mass over the Sahara in Africa shifts northward in summer over the Mediterranean region and blocks maritime air masses and cyclonic storm tracks. The Mediterranean climate designation specifies that at least 70% of annual precipitation occurs during the winter months. This is in contrast to the majority of the world that experiences summer-maximum precipitation.

Worldwide, cool offshore ocean currents (the California current, Canary current, Peru current, Benguela current, and West Australian current) produce stability in overlying air masses along west coasts, poleward of subtropical high pressure. The world climate map (see Figure 10.5) shows Mediterranean dry-summer climates along the western margins of North America, central Chile, and the southwestern tip of Africa, as well as across southern Australia and the Mediterranean Basin—the climate’s namesake region. Examine the offshore currents along each of these regions on the world climate map.

Figure 10.16 compares the climographs of the Mediterranean dry-summer cities of San Francisco and
Chapter 10  Global Climate Systems

**FIGURE 10.14** A Southern Hemisphere marine west coast climate.
(a) Climograph for Dunedin, New Zealand (marine west coast).
(b) Meadow, forest, and mountains on South Island, New Zealand. [Photo by Brian Enting/Photo Researchers, Inc.]

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<tr>
<td>Dunedin, New Zealand</td>
<td>1.5 m (5 ft)</td>
<td>120,000</td>
<td>10.2 °C (50.3 °F)</td>
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**FIGURE 10.15** Marine west coast climate in the Appalachians of the East.
(a) Climograph for Bluefield, West Virginia (marine west coast).
(b) Characteristic mixed forest of Dolly Sods Wilderness in the Appalachian highlands. [Photo by David Muench Photography, Inc.]
Part II The Water, Weather, and Climate Systems

San Francisco Sevilla

0° 20°

40° 20°

3,000 KILOMETERS
3,000 MILES

Station: Sevilla, Spain
Lat/long: 37°22' N 6°00' W
Avg. Ann. Temp.: 18°C (64.4°F)
Total Ann. Precip.: 55.9 cm (22 in.)
Elevation: 13 m (42.6 ft)
Population: 1,764,000
Ann. Temp. Range: 16°C (28.8°F)
Ann. Hr of Sunshine: 2862

Station: San Francisco, California
Lat/long: 37°37' N 122°23' W
Avg. Ann. Temp.: 14°C (57.2°F)
Total Ann. Precip.: 47.5 cm (18.7 in.)
Elevation: 5 m (16.4 ft)
Population: 747,000
Ann. Hr of Sunshine: 2975

Precipitation in centimeters (inches)

Temperature °C (°F)

Month

(a)

(b)

(c)

(d)

FIGURE 10.16 Mediterranean climates, California and Spain.
Climographs for (a) San Francisco, California, with its cooler dry summer and (b) Sevilla, Spain, with its hotter dry summer.
(c) Central California Mediterranean landscape of oak savanna.
(d) The countryside around Olvera, Andalusia, Spain. [Photos by (c) Bobbé Christopherson; (d) Kaz Chiba/Liaison Agency, Inc.]
Sevilla (Seville), Spain. Coastal maritime effects moderate San Francisco's climate, producing a cooler summer. The transition to a hot summer occurs no more than 24–32 km (15–20 mi) inland from San Francisco. The photos in Figure 10.16 show oak-savanna landscapes near Olvera, Spain, and in central California.

The Mediterranean dry-summer climate brings summer water-balance deficits. Winter precipitation recharges soil moisture, but water use usually exhausts soil moisture by late spring. Large-scale agriculture requires irrigation, although some subtropical fruits, nuts, and vegetables are uniquely suited to these conditions. Natural vegetation features a hard-leaved, drought-resistant variety known locally as *[chaparral](#)* in the western United States. (Chapter 20 discusses local names for this type of vegetation in other parts of the world.)

<table>
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<th>Microthermal Climates (mid- and high-latitudes, cold winters)</th>
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| Humid microthermal climates have longer winters than mesothermal climates, with summer warmth. Here the term *microthermal* means cool temperate to cold. Approximately 21% of Earth’s land surface is influenced by these climates, equaling about 7% of Earth’s total surface. These climates occur poleward of the mesothermal climates and experience great temperature ranges related to continentality and air mass conflicts. Temperatures decrease with increasing latitude and toward the interior of continental landmasses and result in intensely cold winters. Precipitation varies between moist-all-year regions (the northern tier across the United States and Canada, eastern Europe through the Ural Mountains) and winter-dry regions associated with the Asian monsoon. In Figure 10.5, note the absence of microthermal climates in the Southern Hemisphere. Because the Southern Hemisphere lacks substantial landmasses, microthermal climates develop there only in highlands. Important causal elements include:
| • Increasing seasonality (daylength and Sun altitude) and greater temperature ranges (daily and annually).
| • Upper-air westerly winds and undulating Rossby waves, which bring warmer air northward and colder air southward for cyclonic activity, and convectional thunderstorms from mT air masses in summer.
| • Asian winter-dry pattern for the microthermal climates, increasing east of the Ural Mountains to the Pacific Ocean and eastern Asia.
| • Hot summers cooling northward from the mesothermal climates, and short spring and fall seasons surrounding winters that are cold to very cold.
| • Continental interiors serving as source regions for intense continental polar (cP) air masses that dominate winter, blocking cyclonic storms.
| Microthermal climates have four distinct regimes based on increasing cold with latitude and precipitation variability: *humid continental hot-summer* (Chicago, New York); *humid continental mild-summer* (Duluth, Toronto, Moscow); and *subarctic* climates featuring cool summers, such as Churchill, Manitoba, and the formidable extremes of frigid, very cold winters in Verkhoyansk and northern Siberia.

**Humid Continental Hot-Summer Climates**

*Humid continental hot-summer* climates are differentiated by their annual precipitation distribution. In the summer, maritime tropical air masses influence both humid continental moist-all-year and winter-dry climates. In North America, frequent weather activity is possible between conflicting air masses—maritime tropical and continental polar—especially in winter. The climograph for New York City and photo (Figure 10.17a, c) and Dalian, China (10.17b,d), illustrate these two hot-summer microthermal climates.

Before European settlement, forests covered the *humid continental hot-summer* climatic region of the United States as far west as the Indiana–Illinois border. Beyond that approximate line, tall-grass prairies extended westward to about the 98th meridian (98° W in central Kansas) and the approximate location of the 51-cm (20-in.) isohyet (line of equal precipitation). Further west, the short-grass prairies reflected lower precipitation receipts.

The dry winter associated with the vast Asian landmass, specifically Siberia, results from a dry-winter high-pressure anticyclone. The dry monsoons of southern and eastern Asia are produced in the winter months by this system, as winds blow out of Siberia toward the Pacific and Indian oceans. The Dalian, China, climograph demonstrates this dry-winter tendency. The intruding cold of continental air is a significant winter feature.

Deep sod made farming difficult for the first settlers of the American prairies, as did the climate. However, native grasses soon were replaced with domesticated...
FIGURE 10.17 Humid continental hot-summer climates, New York and China.
Climographs for (a) New York City (humid continental hot summer that is moist all year) and (b) Dalian, China (humid continental hot summer that is dry in winter). (c) The “Literary Walk” with a canopy of American elms in New York City’s Central Park emerging from winter just as spring and the return of leaves and warmth begin. (d) Dalian, China, cityscape and park in summer. [Photos (c) by Bobbé Christopherson; and (d) courtesy of the Paul Louis collection.]
Humid Continental Mild-Summer Climates

Soils are thinner and less fertile in the cooler microthermal climates, yet agricultural activity is important and includes dairy cattle, poultry, flax, sunflowers, sugar beets, wheat, and potatoes. Frost-free periods range from fewer than 90 days in the north to as many as 225 days in the south. Overall, precipitation is less than in the hot-summer regions to the south; however, notably heavier snowfall is important to soil-moisture recharge when it melts. Various snow-capturing strategies are in use, including fences and tall stubble left standing after harvest in fields to create snowdrifts and thus more moisture retention on the soil.

Characteristic cities are Duluth, Minnesota, and Saint Petersburg, Russia. Figure 10.19 presents a climograph for Moscow, which is at 55° N, or about the same latitude as the southern shore of Hudson Bay in Canada. The photos of landscapes near Moscow and Sebago Lake, inland from Portland, Maine, show summer and late winter scenes, respectively.

The dry-winter aspect of the mild-summer climate occurs only in Asia, in a far-eastern area poleward of the winter-dry mesothermal climates. A representative humid continental mild-summer climate along Russia's east coast is Vladivostok, usually one of only two ice-free ports in that country.

Subarctic Climates

Farther poleward, seasonal change becomes greater. The short growing season is more intense during long summer days. The subarctic climates include vast stretches of Alaska, Canada, northern Scandinavia with their cool summers, and Siberian Russia with its very cold winters. Discoveries of minerals and petroleum reserves and the Arctic Ocean sea-ice losses have led to new interest in portions of these regions.

Areas that receive 25 cm (10 in.) or more of precipitation a year on the northern continental margins and are covered by the so-called snow forests of fir, spruce, larch, and birch are the boreal forests of Canada and the taiga of Russia. These forests are in transition to the more open northern woodlands and to the tundra region of the far north. Forests thin out to the north when the warmest...
month drops below an average temperature of 10°C (50°F). During the decades ahead, the boreal forests are shifting northward into the tundra in response to climate change with higher temperatures (Figure 10.20b).

Soils are thin in these lands once scoured by glaciers. Precipitation and potential evapotranspiration both are low, so soils are generally moist and either partially or totally frozen beneath the surface, a phenomenon known as permafrost (discussed in Chapter 17).

The Churchill, Manitoba, climograph (Figure 10.20) shows average monthly temperatures below freezing for 7 months of the year, during which time light snow cover and frozen ground persist. High pressure dominates Churchill during its cold winter—this is the source region for the continental polar air mass. Churchill is representative of the subarctic climate, with a cool summer: annual temperature range of 40°C (72°F) and low precipitation of 44.3 cm (17.4 in.).

The subarctic climates that feature a dry and very cold winter occur only within Russia. The intense cold of Siberia and north-central and eastern Asia is difficult to comprehend, for these areas experience an average temperature lower than freezing for 7 months; minimum temperatures of below −68°C (−90°F) were recorded there, as described in Chapter 5. Yet summer maximum temperatures in these same areas can exceed +37°C (+98°F).

An example of this extreme subarctic climate with very cold winters is Verkhoyansk, Siberia (Figure 10.21). For 4 months of the year, average temperatures fall below −34°C (−30°F). Verkhoyansk has probably the world’s greatest annual temperature range from winter to summer: a remarkable 63°C (113.4°F). Winters feature brittle metals and plastics, triple-thick windowpanes, and temperatures that render straight antifreeze a solid.
FIGURE 10.20 Subarctic cool summer climate.
(a) Climograph for Churchill, Manitoba (subarctic, cool summer).
(b) Winter scene on the edge of the boreal forest; young pioneer spruce trees move into the tundra. (c) Lone polar bear hunkered down in a protective dugout next to a frozen pond. (d) Mom and two cubs-of-the-year in the tundra near Hudson Bay, west of Churchill; characteristic willows in the background. (e) November street scene in Churchill. [All photos by Bobbé Christopherson.]

Station: Churchill, Manitoba  
Lat/long: 58°45' N 94°04' W  
Avg. Ann. Temp.: −7°C (19.4°F)  
Total Ann. Precip.: 44.3 cm (17.4 in.)  
Elevation: 35 m (114.8 ft)  
Population: 1400  
Ann. Temp. Range: 40°C (72°F)  
Ann. Hr of Sunshine: 1732
FIGURE 10.21 Extreme subarctic cold winter climate. (a) Climograph for Verkhoyansk, Russia (subarctic, very cold winter). (b) Scene in the town of Verkhoyansk during the short summer. [Photo by Dean Conger/National Geographic Society.]

Polar and Highland Climates

The polar climates cover about 19% of Earth's total surface and about 17% of its land area. These climates have no true summer like that in lower latitudes. Poleward of the Arctic and Antarctic Circles, daylength in summer becomes continuous, yet average monthly temperatures never rise above 10°C (50°F). These temperature conditions are intolerant to tree growth. Daylength, which in part determines the amount of insolation received, and low Sun altitude in the sky are the principal climatic factors in these frozen and barren regions. Yet, in winter, the Sun drops below the horizon poleward of 66.5° latitude, producing continuous night. An extended dawn and twilight period eases this seasonal shock a little and reduces the time of true night.

Principal climatic factors in these frozen and barren regions are the following:

- Extremes of daylength between winter and summer determine the amount of insolation received.
- Low Sun altitude even during the long summer days is the principal climatic factor.
- Extremely low humidity produces low precipitation amounts—these regions are Earth’s frozen deserts.
- Light-colored surfaces of ice and snow reflect substantial energy away from the ground surface, thus reducing net radiation.

Polar climates have three regimes: tundra (high latitude, or elevation); ice caps and ice sheet (perpetually frozen); and polar marine (oceanic association, slight moderation of extreme cold).

Also in this climate category we include highland climates, for even at low latitudes the effects of elevation can produce tundra and polar conditions. Glaciers on tropical mountain summits attest to the cooling effects of elevation. Highland climates on the map follow the pattern of Earth’s mountain ranges.
Chapter 10  Global Climate Systems

Tundra Climate

In a tundra climate, land is under continuous snow cover for 8–10 months, with the warmest month above 0°C yet never warming above 10°C (50°F). Because of elevation, the summit of Mount Washington in New Hampshire (1914 m, or 6280 ft) statistically qualifies as a highland tundra climate on a small scale.

In spring when the snow melts, numerous plants appear—stunted sedges, mosses, flowering plants, and lichens. Some of the little (7.5-cm-, 3-in.-tall) willows can exceed 300 years in age. The September photo shows the emerging fall colors of these small plants (Figure 10.22a). Much of the area experiences permafrost and ground ice conditions; these are Earth’s periglacial regions (see Chapter 17).

Approximately 410,500 km² (158,475 mi²) of Greenland are ice-free, an area of tundra and rock about the size of California. The rest of Greenland is ice sheet, covering 1,756,00 km² (677,900 mi²). Despite the severe climate, a permanent population of 56,500 lives in this province of Denmark. There are only a couple of towns along Greenland’s east coast. Ittoqqortoormiit, or Scoresby Sund, has 850 permanent residents (Figure 10.22b). Here is a village on the tundra.

Global warming is bringing dramatic changes to the tundra and its plants, animals, and permafrost ground conditions. In parts of Canada and Alaska, registered temperatures as much as 5°C above average are a regular occurrence, setting many records. As organic peat deposits in the tundra thaw, vast stores of carbon are released to the atmosphere, further adding to the greenhouse gas problem. Temperatures in the Arctic are warming at a rate twice that of the global average increase.

FIGURE 10.22 Greenland tundra and a small town.
(a) Tundra is marked by an uneven, hummocky surface of mounds resulting from an active layer that freezes and thaws with the seasons, as it is here in east Greenland. Large trees are absent in the tundra; however, relatively lush vegetation for the harsh conditions includes willow, dwarf birch and shrubs, sedges, moss, lichen, and cotton grass (white tufts). (b) A town in the tundra, Scoresby Sund fjord in the distance. In the foreground, sledge dogs rest to get ready for the winter’s work ahead. [Photos by Bobbé Christopherson.]

Ice-Cap and Ice-Sheet Climate

Most of Antarctica and central Greenland fall within the ice-sheet climate, as does the North Pole, with all months averaging below freezing. Both regions are dominated by dry, frigid air masses, with vast expanses that never warm above freezing. The area of the North Pole is actually a sea covered by ice, whereas Antarctica is a substantial continental landmass covered by Earth’s greatest ice sheet. For comparison, winter minimums in central Antarctica (July) frequently drop below the temperature of solid carbon dioxide or “dry ice” (−78°C, or −109°F). Ice caps are smaller in extent than ice sheets, roughly less than 50,000 km² (19,300 mi²), yet they completely bury the landscape like an ice sheet. The Vatnajökull Ice Cap in southeastern Iceland is an example.

Antarctica is constantly snow-covered but receives less than 8 cm (3 in.) of precipitation each year. However, Antarctic ice has accumulated to several kilometers deep and is the largest repository of freshwater on Earth. Earth’s two ice sheets cover the Antarctic continent and most of the island of Greenland. Figure 10.23 shows two scenes of these repositories of multiyear ice. The status of this ice is the focus of much attention during the present International Polar Year of scientific research.

This ice contains a vast historical record of Earth’s atmosphere. Within it, evidence of thousands of past volcanic eruptions from all over the world and ancient combinations of atmospheric gases lie trapped in frozen bubbles.
Dry climates are the world's arid deserts and semiarid regions, where we consider moisture efficiency along with temperature for understanding the climate. These regions have unique plants, animals, and physical features. Arid and semiarid regions occupy more than 35% of Earth's land area and clearly are the most extensive climate over land.

Chapter 17 presents analysis of ice cores taken from Greenland and the latest one from Antarctica, which pushed the climate record to 800,000 years before the present.

Polar Marine Climate

*Polar marine* stations are more moderate than other polar climates in winter, with no month below \(-7^\circ\text{C} (20^\circ\text{F})\), yet they are not as warm as *tundra* climates.

Because of marine influences, annual temperature ranges are low. This climate exists along the Bering Sea, the southern tip of Greenland, northern Iceland, Norway, and in the Southern Hemisphere, generally over oceans between 50° S and 60° S. Macquarie Island at 54° S in the Southern Ocean, south of New Zealand, is polar marine. Precipitation, which frequently falls as sleet (ice pellets), is greater in these regions than in continental polar climates.

### Arid and Semiarid Climates (permanent moisture deficits)

Dry climates are the world's arid deserts and semiarid regions, where we consider moisture efficiency along with temperature for understanding the climate. These regions have unique plants, animals, and physical features. Arid and semiarid regions occupy more than 35% of Earth's land area and clearly are the most extensive climate over land.

The mountains, long vistas, and resilient struggle for life are all magnified by the dryness. Sparse vegetation leaves the landscape exposed; moisture demand exceeds moisture supply throughout, creating permanent water deficits (water balance is discussed in Chapter 9). The extent of this dryness distinguishes desert and steppe climatic regions. (In addition, refer to specific annual and daily desert temperature regimes, including the highest recorded temperatures, discussed in Chapter 5; surface energy budgets covered in Chapter 4; desert landscapes in Chapter 15; and desert environments in Chapter 20.)

Important causal elements in these drylands include

- Dry, subsiding air in subtropical high-pressure systems dominates.
- Midlatitude deserts and steppes form in the rain shadow of mountains, those regions to the lee of precipitation-intercepting mountains.

- Continental interiors, particularly central Asia, are far from moisture-bearing air masses.
- Shifting subtropical high-pressure systems produce semiarid steppe lands around the periphery of arid deserts.

Dry climates are distributed by latitude and the amount of moisture deficits in four distinct regimes: *arid deserts* (tropical, subtropical hot, midlatitude cold) and *semiarid steppes* (tropical, subtropical hot, midlatitude cold).
Desert Characteristics

The world climate map in Figure 10.5 reveals the pattern of Earth’s dry climates, which cover broad regions between 15° and 30° N and S latitudes. In these areas, subtropical high-pressure cells predominate, with subsiding, stable air and low relative humidity. Under generally cloudless skies, these subtropical deserts extend to western continental margins, where cool, stabilizing ocean currents operate offshore and summer advection fog forms. The Atacama Desert of Chile, the Namib Desert of Namibia, the Western Sahara of Morocco, and the Australian Desert each lie adjacent to such a coastline.

Orographic lifting intercepts moisture-bearing weather systems to create rain shadows along mountain ranges that extend these dry regions into higher latitudes (Figure 10.24). Note these rain shadows in North and South America on the climate map. The isolated interior of Asia, far distant from any moisture-bearing air masses, falls within the dry arid and semiarid climates as well.

Major subdivisions include: deserts (precipitation supply roughly less than one-half of the natural moisture demand) and semiarid steppes (precipitation supply roughly more than one-half of natural moisture demand). Important is whether precipitation falls principally in the winter with a dry summer, in the summer with a dry winter, or is evenly distributed. Winter rains are most effective because they fall at a time of lower moisture demand. Relative to temperature, the lower-latitude deserts and steppes tend to be hotter with less seasonal change than the midlatitude deserts and steppes, where mean annual temperatures are below 18°C (64.4°F) and freezing winter temperatures are possible.

Tropical, Subtropical Hot Desert Climates

Tropical, subtropical hot desert climates are Earth’s true tropical and subtropical deserts and feature annual average temperatures above 18°C (64.4°F). They generally reside on the western sides of continents, although Egypt, Somalia, and Saudi Arabia also fall within this classification. Rainfall is from local summer convectional showers. Some regions receive almost no rainfall, whereas others may receive up to 35 cm (14 in.) of precipitation a year. A representative subtropical hot desert city is Ar Riyadh (Riyadh), Saudi Arabia (Figure 10.25).

Along the Sahara’s southern margin is a drought-tortured region. Human populations suffered great hardship as desert conditions gradually expanded over their homelands. The sparse environment sets the stage for a rugged lifestyle and subsistence economies, pictured here near Timbuktu, Mali (Figure 10.25c). Chapter 15 presents the process of desertification (expanding desert conditions).

Death Valley, California, features such a hot desert climate with an average annual temperature of 24.4°C (76°F). July and August average temperatures are 46°C (115°F) and 45°C (113°F), respectively. Temperatures over 50°C (122°F) are not uncommon.
During this decade there has been much reporting from Iraq on the war and related political events. What seemed overlooked in many reports was the fact the air temperatures in Baghdad (located on the map in Figure 10.25) were actually hotter than Death Valley during some days in July and August. Soldiers and civilians experience temperatures of 50°C (122°F) and higher in the city. Such readings broke records for Baghdad in 2007. In January, averages for Death Valley (11°C; 52°F) and Baghdad (9.4°C; 49°F) are comparable. Death Valley
is drier with 5.9 cm of precipitation compared to 14 cm in Baghdad (2.33 in.; 5.5 in.), both low amounts. Baghdad’s May to September period is remarkable, with zero precipitation, dominated as it is by an intense subtropical high-pressure system. (Baghdad is 34 m elevation at 33.3°N. Death Valley is at −54 m elevation at 36.5°N.) Keep these hot desert climates in mind as you follow events.

Midlatitude Cold Desert Climates

Midlatitude cold desert climates cover only a small area: the countries along the southern border of Russia, the Gobi Desert, and Mongolia in Asia; the central third of Nevada and areas of the American Southwest, particularly at high elevations; and Patagonia in Argentina. Because of lower temperatures and lower moisture-demand values, rainfall must be low for a station to qualify as a midlatitude cold desert climate; consequently, total annual average rainfall is only about 15 cm (6 in.).

A representative station is Albuquerque, New Mexico, with 20.7 cm (8.1 in.) of precipitation and an annual average temperature of 14°C (57.2°F) (Figure 10.26). Note the summer convectional showers on the cliograph. Across central Nevada stretches a characteristic expanse of midlatitude cold desert, greatly modified by a century of livestock grazing (Figure 10.26b).

Tropical, Subtropical Hot Steppe Climates

Tropical, subtropical hot steppe climates generally exist around the periphery of hot deserts, where shifting subtropical high-pressure cells create a distinct summer-dry and winter-wet pattern. Average annual precipitation in subtropical hot steppe areas is usually below 60 cm (23.6 in.). Walgett, in interior New South Wales, Australia, provides a Southern Hemisphere example of this climate (Figure 10.27). This climate is seen around the Sahara’s periphery and in the Iran, Afghanistan, Turkmenistan, and Kazakhstan region.

Midlatitude Cold Steppe Climates

The midlatitude cold steppe climates occur poleward of about 30° latitude and the midlatitude cold desert climates. Such midlatitude steppes are not generally found in the Southern Hemisphere. As with other dry climate regions, rainfall in the steppes is widely variable and undependable, ranging from 20 to 40 cm (7.9 to 15.7 in.). Not all rainfall is convectional, for cyclonic storm tracks penetrate the continents; however, most storms produce little precipitation.

Figure 10.28 presents a comparison between Asian and North American midlatitude cold steppe. Consider Semey (Semipalatinsk) in Kazakhstan (greater temperature range, precipitation evenly distributed) and Lethbridge, Alberta (lesser temperature range, summer maximum conventional precipitation).
Global Climate Change

Significant climatic change has occurred on Earth in the past and most certainly will occur in the future. There is nothing society can do about long-term influences that cycle Earth through swings from ice ages to warmer periods. However, our global society must address short-term changes that are influencing global temperatures within the life span of present generations. This is especially true since these changes are due to human activities—an anthropogenic forcing of climate.

Record-high global temperatures have dominated the past two decades—for both land and ocean and for both day and night. The record year for warmth was 2005, and all the years since 1995 were near this record. Air temperatures are the highest since recordings began in earnest more than 140 years ago and higher than at any time in the last 120,000 years, according to the ice-core record. This warming trend is very likely due to a buildup of greenhouse gases. Understanding this warming and all its related impacts is an important applied topic of Earth systems science and an opportunity for spatial analysis in physical geography.

Global Warming

Twenty years ago, climatologists Richard Houghton and George Woodwell described the present climatic condition:

The world is warming. Climatic zones are shifting. Glaciers are melting. Sea level is rising. These are not hypothetical events from a science fiction movie; these changes and others are already taking place, and we expect them to accelerate over the next years as the amounts of carbon dioxide, methane, and other trace gases accumulating in the atmosphere through human activities increase.†

Your author knows this quote well because it has been in every edition of Geosystems since the first edition in 1992. During the intervening years, we watched global temperatures rise and climate-change science mature. There is a strong scientific consensus that global warming is occurring and that human activities are the cause, namely the burning of fossil fuels.

The 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) concluded:

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea

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As a standard scientific reference on climate change, the IPCC uses the following to indicate levels of confidence: Virtually certain >99% probability of occurrence; Extremely likely >95%; Very likely >90%; Likely >66%; More likely than not >50%; Unlikely <33%; Very unlikely <10%; and Extremely unlikely <5%.

Chapter 10  Global Climate Systems

FIGURE 10.28  Midlatitude cold steppe climates, Kazakstan and Canada.
Climograph for (a) Semey (Semipalatinsk) in Kazakstan. (b) Herders in the region near Semey.
(c) Climograph for Lethbridge in Alberta. (d) Canadian prairies and grain elevators of southern Alberta.

(a) Station: Semey (Semipalatinsk), Kazakstan
Lat/long: 50°21' N 80°15' E
Avg. Ann. Temp.: 3°C (37.4°F)
Total Ann. Precip.: 26.4 cm (10.4 in.)
Elevation: 206 m (675.9 ft)
Population: 270,500
Ann. Temp. Range: 39°C (70.2°F)

(b) Station: Lethbridge, Alberta
Lat/long: 49°42' N 110°50' W
Avg. Ann. Temp.: 2.9°C (37.3°F)
Total Ann. Precip.: 25.8 cm (10.2 in.)
Elevation: 910 m (2985 ft)
Population: 73,000
Ann. Temp. Range: 24.3°C (43.7°F)

(c) [Image of climograph]
(d) [Image of climograph]
Coordinating Global Climate Change Research


In the United States, coordination is found at the U.S. Global Change Research Program (http://www.usgcrp.gov/). An overall source for information is http://globalchange.gov, which publishes an on-line monthly summary of all related developments. Also important are programs and services at NASA agencies, such as Dr. James Hansen’s work at Goddard Institute for Space Studies (GISS, http://www.giss.nasa.gov/), Global Hydrology and Climate Center (GHCC, http://www.gccc.msfc.nasa.gov/), and at NOAA agencies at the National Climate Data Center (NCDC, http://www.ncdc.noaa.gov/) and the National Environmental Satellite, Data, and Information Service (NESDIS, http://www.nesdis.noaa.gov/), among others. The Pew Center on Global Climate Change offers credible analysis and overview and has issued several policy reports at http://www.pewclimate.org/.

The multiagency National Ice Center is at http://www.natice.noaa.gov/. Important research is done at the National Center for Atmospheric Research (http://www.nccr.ucar.edu/). For Canada, information and research is coordinated by Environment Canada (http://www.ec.gc.ca/climate/). The effect of global warming on permafrost, which involves half of Canadian land area, is found at http://www.socc.ca/.

level. . . . Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. This is an advance since the Third Assessment Report’s conclusion that “most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.” Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns.1

The IPCC, formed in 1988, is an organization operating under the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) and is the scientific organization coordinating global climate-change research, climate forecasts, and policy formulation. In 2007, the IPCC shared the Nobel Peace Prize with former Vice-President Albert Gore for their two decades of work raising understanding and awareness about global climate-change science. The Nobel Committee said that Gore is responsible “. . . for convincing world governments that climate change was real, caused by human activity, and posed a threat to society.” Various organizations and agencies coordinate and conduct global climate-change research. News Report 10.2 offers an overview and contact information for climate-change science.

The Arctic Climate Impact Assessment (ACIA) Symposium met in 2004 and released a lengthy scientific report. The ACIA summarized:

Human activities, primarily the burning of fossil fuels (coal, oil, natural gas), and secondarily the clearing of land, have increased the concentration of carbon dioxide, methane, and other heat-trapping (“greenhouse”) gases in the atmosphere . . . this is projected to lead to significant and persistent changes in climate . . . these changes are projected to lead to wide-ranging

consequences including significant impact on coastal communities, animal and plant species, water resources, and human health and well being.\textsuperscript{24}

The American Association for the Advancement of Science (AAAS) reported in “The scientific consensus on climate change” (\textit{Science} 306, December 3, 2004: 1686), the results of a survey of all 928 climate-change papers published in refereed scientific journals between 1993 and 2003. The papers were divided into six categories and analyzed. As study author Naomi Oreskes concluded, “Remarkably, none of the papers disagreed with the consensus position.” There is a consensus that human activities are heating Earth’s surface and lower atmosphere. The author concluded:

This analysis shows that scientists publishing in the peer-reviewed literature agree with IPCC, the National Academy of Sciences, and public statements of their professional societies. Politicians, economists, journalists, and others may have the impression of confusion, disagreement, or discord among climate scientists, but that impression is incorrect . . . there is a scientific consensus on the reality of anthropogenic climate change.

In terms of \textit{paleoclimatology}, the science that studies past climates (discussed in Chapter 17), proxy indicators (ice-core data, sediments, coral reefs, ancient pollen, tree-ring density, among others) point to the present time as the warmest in the last 120,000 years, and further, that the increase in temperature during the twentieth century is \textit{very likely} the largest in any century over the past 1000 years (Figure 10.29). Earth is less than 1 C° (1.8 F°) from equaling the highest average temperature over this time span. The latest Antarctic ice core at the Dome C location pushes this climatic information back 800,000 years (described in Chapter 17).

The rate of warming in the past 30 years exceeds any comparable period in the entire measured temperature record, according to NASA scientists. Figure 10.30a plots observed annual temperatures and 5-year mean temperatures from 1880 through 2006: Worldwide, 2005 was the warmest year; 2006 was fifth warmest but warmest ever for North America.

The map in 10.30b uses the same base period as the graph (1951–1980) to give you an idea of temperature anomalies across the globe in 2006. Note the Arctic region, where new records for land and water temperatures and sea-ice melt were set in 2006 and again broken in 2007. Anomalies exceeding 2.5 C° (4.5 F°) are portrayed on the map in the Canadian Arctic and portions of Greenland, Siberia, and the Antarctic Peninsula. The fact that 2007–2009 is the International Polar Year underscores the global scientific concerns about the polar climates and lands.

FIGURE 10.30 Global temperature trends. (a) Global temperature trends from 1880 to 2006. The 0 baseline represents the 1951–1980 global average. Comparing annual temperatures and 5-year mean temperatures gives a sense of overall trends. (b) Temperature map shows temperature anomalies during 2006, fifth-warmest year on record. The coloration represents °C departures from the base period 1951–1980. On the CD-ROM that accompanies this text there is a movie of temperature anomalies from 1881 to 2006 in which you can see the warming patterns over this time span. [(a) and (b) Data courtesy of Dr. James Hansen, GISS/NASA, and NCDC/NOAA.]

FIGURE 10.31 Explaining global temperature changes. Computer models accurately track observed temperature change (black line) when they factor in human-forced influences on climate (red shading). Solar activity and volcanoes do not explain the increases (blue shading). [Graphs from Climate Change 2007: The Physical Science Basis, Working Group I, IPCC Fourth Assessment Report, February 2007: Fig. SPM-4, p. 11.]
absorb and radiate longwave energy. Figure 10.32 plots changes in three of these greenhouse gases over the past 10,000 years.

These gases are transparent to light but opaque to the longer wavelengths radiated by Earth. Thus, they transmit light from the Sun to Earth but delay heat-energy loss to space. While detained, this heat energy is absorbed and emitted over and over, warming the lower atmosphere. As concentrations of these greenhouse gases increase, more heat energy remains in the atmosphere and temperatures increase.

The present CO$_2$ concentration tops anything over the last 800,000 years in the Dome C ice core. In fact, over this ice-core record, changes of as much as 30 ppm in CO$_2$ took at least 1000 years, yet, the concentration has changed 30 ppm in just the last 17 years. With 4.5% of the world's population, the United States continues to produce 24% of global CO$_2$ emissions. China, with 20% of global population, is responsible for 18% of CO$_2$ emissions and is increasing its output. Clearly, per capita CO$_2$ emissions in the United States are far above what an average person in China produces.

**Methane and Global Warming** Another radiatively active gas contributing to the overall greenhouse effect is methane (CH$_4$), which, at more than 1% per year, is increasing in concentration even faster than carbon dioxide. In ice cores, methane levels never topped 750 ppb in the past 800,000 years, yet in Figure 10.32 we see present levels at 1780 ppb. We are at an atmospheric concentration of methane that is higher than at any time in the past 800 millennia.

Methane is generated by such organic processes as digestion and rotting in the absence of oxygen (anaerobic processes). About 50% of the excess methane comes from bacterial action in the intestinal tracts of livestock and from organic activity in flooded rice fields. Burning of vegetation causes another 20% of the excess, and bacterial action inside the digestive systems of termite populations also is a significant source. Methane is thought responsible for at least 19% of the total atmospheric warming.

**Other Greenhouse Gases** Nitrous oxide (N$_2$O) is the third most important greenhouse gas that is forced by human activity—up 17% in atmospheric concentration since 1750, higher than at any time in the past 10,000 years (Figure 10.32). Fertilizer use increases the processes in soil that emit nitrous oxide, although more research is needed to fully understand the relationships. Chlorofluorocarbons (CFCs) and other halocarbons also contribute to global warming. CFCs absorb longwave energy missed by carbon dioxide and water vapor in the lower troposphere. As radiatively active gases, CFCs enhance the greenhouse effect in the troposphere and are a cause of ozone depletion and slight cooling in the stratosphere.

**Climate Models and Future Temperatures**

The scientific challenge in understanding climate change is to sense climatic trends in what is essentially a non-linear, chaotic natural system. Imagine the tremendous task of building a computer model of all climatic components and programming these linkages (shown in Figure 10.1) over different time frames and at various scales.

Using mathematical models originally established for forecasting weather, scientists developed a complex computer climate model known as a general circulation model (GCM). There are at least a dozen established GCMs now operating around the world. Submodel
programs for the atmosphere, ocean, land surface, cryosphere, and biosphere operate within the GCM. The most sophisticated models couple atmosphere and ocean sub-models and are known as Atmosphere–Ocean General Circulation Models (AOGCMs).

The first step in describing a climate is defining a manageable portion of Earth’s climatic system for study. Climatologists create dimensional “grid boxes” that extend from beneath the ocean to the tropopause, in multiple layers (Figure 10.33). Resolution of these boxes in the atmosphere is about 250 km (155 mi) in the horizontal and 1 km (0.6 mi) in the vertical; in the ocean the boxes use the same horizontal resolution and a vertical resolution of about 200 to 400 m (650–1300 ft). Analysts deal not only with the climatic components within each grid layer but also with the interaction among the layers on all sides.

A comparative benchmark among the operational GCMs is climatic sensitivity to doubling of carbon dioxide levels in the atmosphere. GCMs do not predict specific temperatures, but they do offer various scenarios of global warming. GCM-generated maps correlate well with the observed global warming patterns experienced since 1990.

The 2007 IPCC Fourth Assessment Report, using a variety of GCM forecast scenarios, predicted a range of average surface warming for this century. Figure 10.34 illustrates six of these scenarios, each with its own assumptions of economics, population, degree of global cooperation, and greenhouse gas emission levels. The orange line is the simulation experiment where greenhouse gas emissions are held at 2000 values with no increases. The gray bars give you the best estimate and likely ranges of outcomes; for example, from a “low forecast” in B1 to a “high forecast” in A1Fl. Even the “B” scenario represents a significant increase in global land and ocean temperatures and will produce consequences. Although regionally variable and subject to revision, the IPCC temperature change forecasts for the twenty-first century are:

- High forecast: 6.4°C (11.5°F)
- Middle forecast: 1.8°C–4.0°C (3.1°F–7.2°F)
- Low forecast: 1.1°C (2.0°F)

Figure 10.35 offers us a look at the world of 2020–2029 and 2090–2099 using three scenarios from several different AOGCMs. Find the three scenarios used for these three pairs of maps on the graph in Figure 10.34. You can see from the maps why scientists are concerned about temperature trends in the higher latitudes.

**Consequences of Global Warming**

The consequences of uncontrolled atmospheric warming are complex. Regional climate responses are expected as temperature, precipitation, soil-moisture, and air mass characteristics change. Although the ability to accurately forecast such regional changes is still evolving, some consequences of warming have been forecasted and in several regions are already underway. The challenge for science is to analyze such effects on a global scale.

The following list is a brief overview from the IPCC Fourth Assessment Report “Summary for Policy Makers” and other sources that summarize global impacts emerging from climate change.

- The observed pattern of tropospheric warming and stratospheric cooling is very likely due to greenhouse gas increases and stratospheric ozone depletion.
- Widespread changes in extreme temperatures have been observed over the last 50 years. Cold days, cold nights, and frost are less frequent, while hot days, hot nights, and heat waves are more frequent.
- Observations since 1961 show the average global ocean temperature increased to depths of 3000 m and the ocean absorbed more than 80% of climate system heating. Such warming causes thermal expansion of seawater, contributing to sea level rise.
- There is observational evidence of increased intensity of tropical cyclones correlated with increases of tropical sea-surface temperatures. Total “power dissipation” of these storms has doubled since 1970. Worldwide there are more category 3, 4, and 5 tropical storms than in the previous record.
- Mountain glaciers and snow cover declined on average in both hemispheres, contributing to sea-level rise.
- Mount Kilimanjaro in Africa, portions of the South American Andes, and the Himalayas will very likely lose most of their glacial ice within the next two decades, affecting local water resources. Glacial ice continues its retreat in Alaska.
The average atmospheric water vapor content has increased over land and ocean as well as in the upper troposphere. The increase is consistent with the fact that warmer air can absorb more water vapor.

Flow speed accelerated for some Greenland and Antarctic outlet glaciers as they drain ice from the interior of the ice sheets. In Greenland this rate of loss exceeds snowfall accumulation, with losses per year more than doubling between 1996 and 2005 (mass loses of 91 km³ compared to 224 km³).

Average Arctic temperatures increased at almost twice the global average rate in the past 100 years. Wintertime lower atmosphere temperatures over Antarctica are warming at nearly three times the global average, first reported in 2006.

Temperatures in the permafrost active layer increased overall since the 1980s in the Arctic up to 3°C. The maximum area of seasonally frozen ground decreased 7% in the Northern Hemisphere, with a decrease in spring of up to 15%.
Since 1978, annual average Arctic sea ice extent shrunk in summer by 7.4% per decade, according to satellite measurements. September 2007 Arctic sea ice extent retreated to its lowest area coverage in the record.

Changes in precipitation and evaporation over the oceans and the melting of ice are freshening mid- and high-latitude oceans and seas, together with increased salinity in low-latitudes. Oceans are acidifying (lower pH) in response to absorption of increasing atmospheric CO₂.

Mid-latitude westerly winds strengthened in both hemispheres since the 1960s.

More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying linked to higher temperatures and decreased precipitation observed in the Sahel, the Mediterranean, southern Africa, parts of southern Asia, Australia, and the American West.

Higher spring and summer temperatures and earlier snowmelt are extending the wildfire season and increasing the intensity of wildfires in the western U.S. and elsewhere.

The frequency of heavy precipitation events increased over most land areas, consistent with warming and observed increases of atmospheric water vapor. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe, and northern and central Asia.

Crop patterns, as well as natural habitats of plants and animals, will shift to maintain preferred temperatures. According to climate models, climatic regions in the midlatitudes could shift poleward by 150 to 550 km (90 to 350 mi) during this century.

Biosphere models predict that a global average of 30% of the present forest cover (varying regionally from 15% to 65%) will undergo major species redistribution—greatest at high latitudes and least in the tropics.

Populations previously unaffected by malaria, dengue fever, lymphatic filariasis, and yellow fever (all mosquito vector), schistosomiasis (water snail vector), and sleeping sickness (tsetse fly vector) will be at greater risk in subtropical and midlatitude areas as temperatures increase the vector ranges.

**Changes in Sea Level** Sea-level rise must be expressed as a range of values that are under constant reassessment. During the last century, sea level rose 10–20 cm (4–8 in.), a rate 10 times higher than the average rate during the last 3000 years.

The 2007 IPCC forecast scenarios for global mean sea-level rise this century, given regional variations, are:

- **Low forecast:** 0.18 m (7.1 in.)
- **Middle forecast:** 0.39 m (15.4 in.)
- **High forecast:** 0.59 m (23.2 in.)

Unfortunately the new 2006–2007 measurements of Greenland’s ice-loss acceleration did not reach the IPCC in time for its report. Scientists are considering at least a 1.2-m (3.94-ft) “high case” for estimates of sea-level rise this century as more realistic given Greenland’s present losses coupled with mountain glacial ice losses worldwide. Remember that a 0.3-m rise in sea level would produce a shoreline retreat of 30 m (98 ft) on average. Here is the concern:

The data now available raise concerns that the climate system, in particular sea level, may be responding more quickly than climate models indicate. . . . The rate of sea-level rise for the past 20 years is 25% faster than the rate of rise in any 20-year period in the preceding 115 years . . . . Since 1990 the observed sea-level has been rising faster than the rise projected by models.*

These increases would continue beyond 2100 even if greenhouse gas concentrations were stabilized. In Chapter 16, maps present what coastlines will experience in the event of a 1-m rise in sea level.

A quick survey of world coastlines shows that even a moderate rise could bring change of unparalleled proportions. At stake are the river deltas, lowland coastal farming valleys, and low-lying mainland areas, all contending with high water, high tides, and higher storm surges. Particularly tragic social and economic consequences will affect small island states, which are unable to adjust within their present country boundaries—disruption of biological systems, loss of biodiversity, reduction in water resources, and evacuation of residents are among the impacts.

There could be both internal and international migration of affected human populations, spread over decades, as people move away from coastal flooding caused by the sea-level rise—a 1-m rise will displace 130 million people. Presently, there is no body of world law that covers “environmental refugees.”

**Political Action and “No Regrets”** Reading through all this climate-change science must seem pretty “heavy.” Instead, think of this information as empowering and as motivation to take action—personally, locally, regionally, nationally, and globally.

A product of the 1992 Earth Summit in Rio de Janeiro was the United Nations Framework Convention on Climate Change (FCCC). The leading body of the Convention is the Conference of the Parties (COP) operated by the countries that ratified the FCCC, 186 countries by 2000. Meetings were held in Berlin (COP-1, 1995) and Geneva (COP-2, 1996). These meetings set the stage for COP-3 in Kyoto, Japan, in December 1997, where 10,000 participants adopted the Kyoto Protocol by consensus. Seventeen national academies of science endorsed the Kyoto Protocol. (For updates on the status of the Kyoto Protocol, see http://unfccc.int/2860.php.) The latest 2007 gathering, COP-13, was in Bali, Indonesia.

The Kyoto Protocol binds more-developed countries to a collective 5.2% reduction in greenhouse gas emissions as measured at 1990 levels for the period 2008 to 2012. Within this group goal, various countries promised cuts: Canada is to cut 6%, the European Union 8%, and Australia 8%, among many others. The Group of 77 countries plus China favor a 15% reduction by 2010. With Russian ratification in November 2004, the Kyoto Protocol is now international law, with nearly 140 national signatories; this is without United States participation.

The Intergovernmental Panel on Climate Change (IPCC) declared that “no regrets” opportunities to reduce carbon dioxide emissions are available in most countries. The IPCC Working Group III defines this as follows:

No regrets options are by definition greenhouse gas emissions reduction options that have negative net costs, because they generate direct and indirect benefits that are large enough to offset the costs of implementing the options.

Benefits that equal or exceed their cost to society include reduced energy cost, improved air quality and health, reduction in tanker spills and oil imports, and deployment of renewable and sustainable energy sources, among others. This holds true without even considering the benefits of slowing the rate of climate change. For Europe, scientists determined that carbon emissions could be reduced to less than half the 1990 level by 2030, at a negative cost. One key to “no regrets” is the untapped energy-efficiency potential.

In the United States, five Department of Energy national laboratories (Oak Ridge, Lawrence Berkeley, Pacific Northwest, National Renewable Energy, and Argonne) reported that the United States can meet the Kyoto carbon emission reduction targets with negative overall costs (cash benefit savings) ranging from \(-\$7\) to \(-\$34\) billion. (For more, see Working Group III, *Climate Change 2001, Mitigation*, London: Cambridge University Press, 2001, pp. 21, 474–76 and 506–507.)

### Summary and Review—Global Climate Systems

**Define** climate and climatology, and explain the difference between climate and weather.

Climate is dynamic, not static. **Climate** is a synthesis of weather phenomena at many scales, from planetary to local, in contrast to weather, which is the condition of the atmosphere at any given time and place. Earth experiences a wide variety of climatic conditions that can be grouped by general similarities into climatic regions. **Climatology** is the study of climate and attempts to discern similar weather statistics and identify **climatic regions**.

- climate (p. 277)
- climatology (p. 278)
- climatic regions (p. 278)

1. Define climate and compare it with weather. What is climatology?
2. Explain how a climatic region synthesizes climate statistics.
3. How does the El Niño phenomenon produce the largest interannual variability in climate? What are some of the changes and effects that occur worldwide?

**Review** the development of climate classification systems, and compare genetic and empirical systems as ways of classifying climate.

**Classification** is the process of ordering or grouping data in related categories. A **genetic classification** is based on causative factors, such as the interaction of air masses. An **empirical classification** is one based on statistical data, such as temperature or precipitation. This text analyzes climate using aspects of both approaches, with a map based on climatological elements.

- classification (p. 280)
- genetic classification (p. 280)
- empirical classification (p. 280)

4. What are the differences between a genetic and an empirical classification system?
5. What are some of the climatological elements used in classifying climates? Why each of these?

**Describe** the principal climate classification categories other than deserts, and locate these regions on a world map.

Here we focus on temperature and precipitation measures. Keep in mind these are measurable results produced by interacting elements of weather and climate. These data are plotted on a **climograph** to display the characteristics of the climate.

There are six basic climate categories. Temperature and precipitation considerations form the basis of five climate categories and their regional types:

- Tropical (equatorial and tropical latitudes)
- rain forest (rainy all year)
- monsoon (6 to 12 months rainy)
- savanna (less than 6 months rainy)
- Mesothermal (midlatitudes, mild winters)
- humid subtropical (hot summers)
maritime west coast (warm to cool summers)
Mediterranean (dry summers)
• Microthermal (mid- and high latitudes, cold winters)
humid continental (hot to warm summers)
subarctic (cool summers to very cold winters)
• Polar (high latitudes and polar regions)
tundra (high latitude or high altitude)
ice caps and ice sheets (perpetually frozen)
polar marine
• Highland (compared to lowlands at the same latitude, highlands have lower temperatures—recall the normal lapse rate)
Only one climate category is based on moisture efficiency as well as temperature:
• Desert (permanent moisture deficits)
arid deserts (tropical, subtropical hot and midlatitude cold)
semiarid steppes (tropical, subtropical hot and midlatitude cold)
climograph (p. 285)
8. List and discuss each of the principal climate categories. In which one of these general types do you live? Which category is the only type associated with the annual distribution and amount of precipitation?
9. What is a climograph, and how is it used to display climatic information?
10. Which of the major climate types occupies the most land and ocean area on Earth?
11. Characterize the tropical climates in terms of temperature, moisture, and location.
12. Using Africa's tropical climates as an example, characterize the climates produced by the seasonal shifting of the ITCZ with the high Sun.
13. Mesothermal (subtropical and midlatitude, mild winter) climates occupy the second-largest portion of Earth's entire surface. Describe their temperature, moisture, and precipitation characteristics.
14. Explain the distribution of the humid subtropical hot-summer and Mediterranean dry-summer climates at similar latitudes and the difference in precipitation patterns between the two types. Describe the difference in vegetation associated with these two climate types.
15. Which climates are characteristic of the Asian monsoon region?
16. Explain how a marine west coast climate type can occur in the Appalachian region of the eastern United States.
17. What role do offshore ocean currents play in the distribution of the marine west coast climates? What type of fog is formed in these regions?
18. Discuss the climatic conditions for the coldest places on Earth outside the poles.

Explain the precipitation and moisture efficiency criteria used to determine the arid and semiarid climates, and locate them on a world map.

The dry and semiarid climates are described by precipitation rather than temperature. Dry climates are the world's arid deserts and semiarid regions, with their unique plants, animals, and physical features. The arid and semiarid climates occupy more than 35% of Earth's land area, clearly the most extensive climate over land.

Major subdivisions are arid deserts in tropical and midlatitude areas (precipitation—natural water supply—less than one-half of natural water demand) and semiarid steppes in tropical and midlatitude areas (precipitation more than one-half of natural water demand).

19. In general terms, what are the differences among the four desert classifications? How are moisture and temperature distributions used to differentiate these subtypes?
20. Relative to the distribution of arid and semiarid climates, describe at least three locations where they occur across the globe and the reasons for their presence in these locations.

Outline future climate patterns from forecasts presented, and explain the causes and potential consequences of climate change.

Various activities of present-day society are producing climatic changes, particularly a global warming trend. The highest average annual temperatures experienced since the advent of instrumental measurements have dominated the last 25 years. There is a scientific consensus building that global warming is related to the anthropogenic impacts on the natural greenhouse effect.

The 2007 Fourth Assessment Report from the Intergovernmental Panel on Climate Change affirms this consensus. The Intergovernmental Panel on Climate Change affirms this consensus. The IPCC has predicted surface temperature response to a doubling of carbon dioxide ranging from an increase of 1.1 °C (2.0 °F) to 6.4 °C (11.5 °F) between the present and 2100. Natural climate variability over the span of Earth's history is the subject of paleoclimatology. A general circulation model (GCM) forecasts climate patterns and is evolving to greater capability and accuracy than in the past. People and their political institutions can use GCM forecasts to form policies aimed at reducing unwanted climate change.

paleoclimatology (p. 311)
general circulation model (GCM) (p. 314)
21. Explain climate forecasts. How do general circulation models (GCMs) produce such forecasts?
22. Describe the potential climatic effects of global warming on polar and high-latitude regions. What are the implications of these climatic changes for persons living at lower latitudes?
23. How is climatic change affecting agricultural and food production? Natural environments? Forests? The possible spread of disease?
24. What are the actions being taken at present to delay the effects of global climate change? What is the Kyoto Protocol? What is the current status of U.S. and Canadian government action on the protocol?
The Geosystems Student Learning Center provides on-line resources for this chapter on the World Wide Web. To begin: Once at the Center, click on the cover of this textbook, scroll the Table of Contents menu, and select this chapter. You will find self-tests that are graded, review exercises, specific updates for items in the chapter, and in “Destinations” many links to interesting related pathways on the Internet. Geosystems Student Learning Center is found at http://www.prenhall.com/christopherson/.

**Critical Thinking**

A. The text asked that you find the climate conditions for your campus and your birthplace and locate these two places on Figures 10.3, 10.4, and 10.5. Briefly describe the information sources you used: library, Internet, teacher, and phone calls to state and provincial climatologists. Now, refer to Appendix B to refine your assessment of climate for the two locations. Briefly show how you worked through the Köppen climate criteria given in the appendix that established the climate classification for your two cities.

B. Many external factors force climate. The chart “Global and annual mean radiative forcing for the year 2000, relative to 1750” is presented here (from IPCC Climate Change 2001, The Scientific Basis, Washington: Cambridge University Press, 2001, Figure 3, p. 8, and Figure 6.6, p. 392).

The estimates of radiative forcing in Watts per square meter units are given on the y-axis (vertical axis). The level of scientific understanding is noted along the x-axis (horizontal axis), arranged from “high” to “very low.” Those columns above the “0” value (in red) indicate positive forcing, such as the greenhouse gases grouped in the far-left column. Columns that fall below the “0” value (in blue) indicate negative forcing, such as the haze from sulfate aerosols, fourth column from the left. The vertical line between the markers on each column is an estimate of the uncertainty range. Where no column appears but there is instead a line denoting a range, there is no central estimate given present uncertainties, such as for mineral dust.

Assume you are a policymaker with a goal of reducing the rate of global warming, that is, reducing positive radiative forcing of the climate system. What strategies do you suggest to alter the height of the columns and adjust the mix of elements that cause warming? Assign priorities to each suggested strategy to denote most-to-least effective in moderating climate change. Brainstorm and discuss your strategies with others.