20

World Climates and Global Climate Change

FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

20.1 List the five parts of the climate system and provide examples of each.

20.2 Explain why classification is a necessary process when studying world climates. Discuss the criteria used in the Köppen system of climate classification.

20.3 Compare the two broad categories of tropical climates.

20.4 Contrast low-latitude dry climates and middle-latitude dry climates.

20.5 Distinguish among five different humid middle-latitude climates.

20.6 Contrast ice cap and tundra climates.

20.7 Summarize the characteristics associated with highland climates.

20.8 Summarize the nature and cause of the atmosphere's changing composition since about 1750. Describe the climate's response.

20.9 Contrast positive- and negative-feedback mechanisms and provide examples of each.

20.10 Discuss the possible impacts of aerosols on climate change.

20.11 Describe some possible consequences of global warming.

Mauna Loa Observatory is an important atmospheric research facility on Hawaii's Big Island. It has been collecting data and monitoring atmospheric change since the 1950s. (Photo by Forrest M. Mimms III)

The focus of this chapter is *climate*, the long-term aggregate of weather. Climate is more than just an expression of average atmospheric conditions. In order to accurately portray the character of a place or an area, variations and extremes must also be included. Climate strongly influences the nature of plant and animal life, the soil, and many external geologic processes. Climate influences people as well.

Although climate has a significant impact on people, we are learning that people also have a strong influence on climate. In fact, today global climate change caused by humans is an important global environmental issue. Unlike changes in the geologic past, which represented natural variations, modern climate change is dominated by human influences that are sufficiently large that they exceed the bounds of natural variability. Moreover, these changes are likely to continue for many centuries. The effects of this venture into the unknown with climate could be very disruptive not only to humans but to many other life-forms as well.

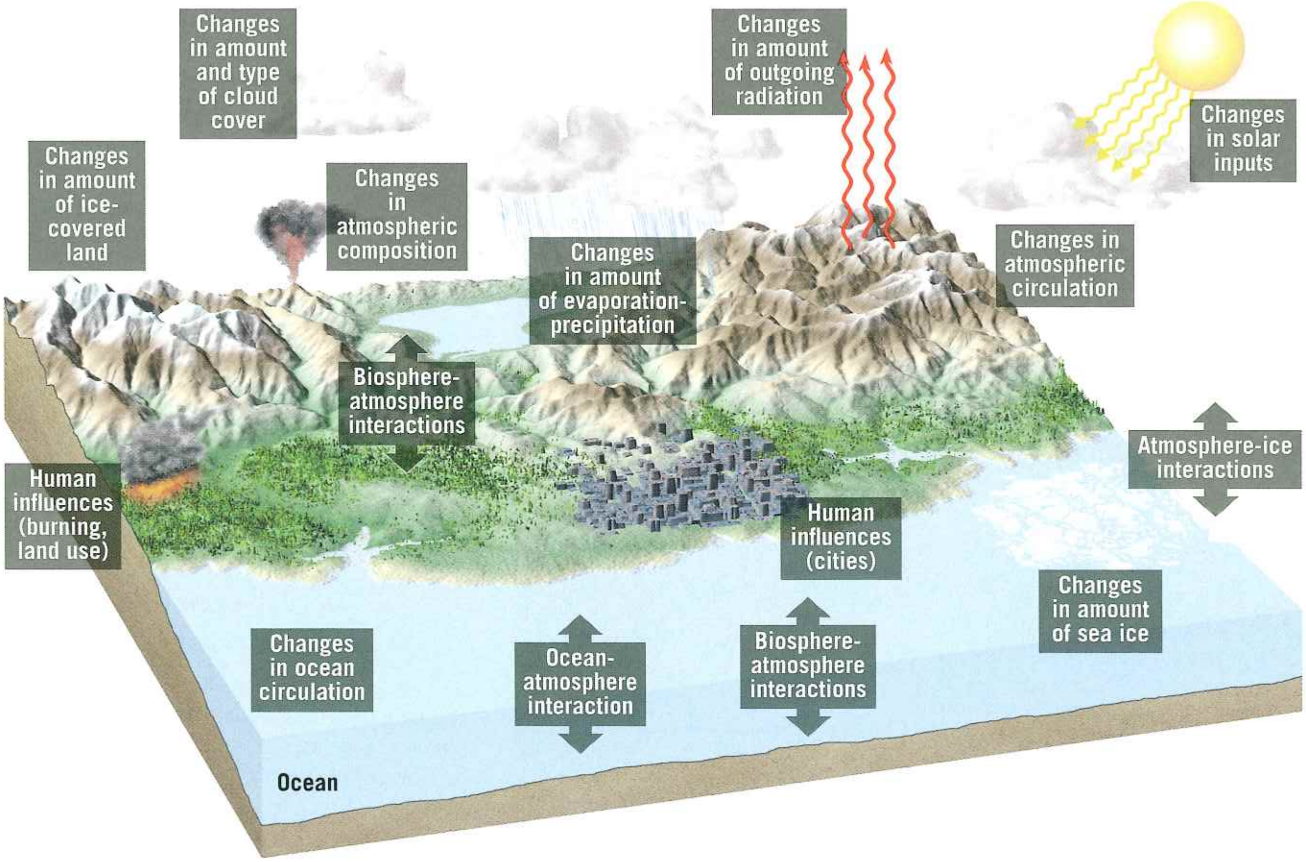
20.1 THE CLIMATE SYSTEM

List the five parts of the climate system and provide examples of each.

Throughout this book, you have been reminded that Earth is a multidimensional system that consists of many interacting parts. A change in any one part can produce changes in any or all of the other parts—often in ways that are neither obvious nor immediately apparent. This fact is certainly true when it comes to the study of climate and climate change.

To understand and appreciate climate, it is important to realize that climate involves more than just the atmosphere. Indeed, we must recognize that there is a **climate system** that includes the atmosphere, hydrosphere, geosphere, biosphere, and cryosphere. (The *cryosphere* refers to the ice and snow that exist at Earth's surface.) The climate system *involves the exchanges of energy and moisture that occur among the five spheres.* These exchanges link the atmosphere to the other spheres so that the whole functions as an extremely complex, interactive unit. Changes to the climate system do not occur in isolation. Rather, when one part of it changes, the other components also react. The major components of the climate system are shown in **FIGURE 20.1**.

IGURE 20.1 Earth's limate System Schematic ew showing several mponents of Earth's imate system. Many teractions occur among the arious components on a ide range of space and time cales, making the system xtremely complex.



Climate has a profound impact on many of Earth's external processes. When climate changes, these processes respond. A glance back at the rock cycle in Chapter 3 (page 61) reminds us about many of the connections. Of course, rock weathering has an obvious climate connection, as do processes that operate in arid, tropical, and glacial landscapes. Phenomena such as debris flows and river flooding are often triggered by atmospheric events such as periods of extraordinary rainfall. Clearly, the atmosphere is a basic link in the hydrologic cycle. Other connections involve the impact of internal processes on the atmosphere. For example, the particles and gases emitted by volcanoes can change the composition of the atmosphere, and mountain building can have a significant impact on regional temperature, precipitation, and wind patterns.

The study of sediments, sedimentary rocks, and fossils clearly demonstrates that, through the ages, practically every place on our planet has experienced wide swings in climate, from ice ages to conditions associated with subtropical coal swamps or desert dunes. Chapter 12 reinforces this fact. Time scales for climate change vary from decades to millions of years.

20.1 CONCEPT CHECKS

1. What are the five major parts of the climate system?
2. List at least five connections between climate and Earth's external and internal processes.

20.2 WORLD CLIMATES

Explain why classification is a necessary process when studying world climates. Discuss the criteria used in the Köppen system of climate classification.

Previous chapters have already presented the spatial and seasonal variations of the major elements of weather and climate. Chapter 16 examined the controls of temperature and the world distribution of temperature. In Chapter 18, you studied the general circulation of the atmosphere and the global distribution of precipitation. You are now ready to investigate the *combined* effects of these variations in different parts of the world. The varied nature of Earth's surface and the many interactions that occur among atmospheric processes give every location on our planet a distinctive, even unique, climate. However, we are not going to describe the unique climatic character of countless different locales. Instead, we introduce the major climate regions of the world. The discussion in this chapter examines large areas and uses particular places only to illustrate the characteristics of these major climate regions.

Temperature and precipitation are the most important elements in a climate description because they have the

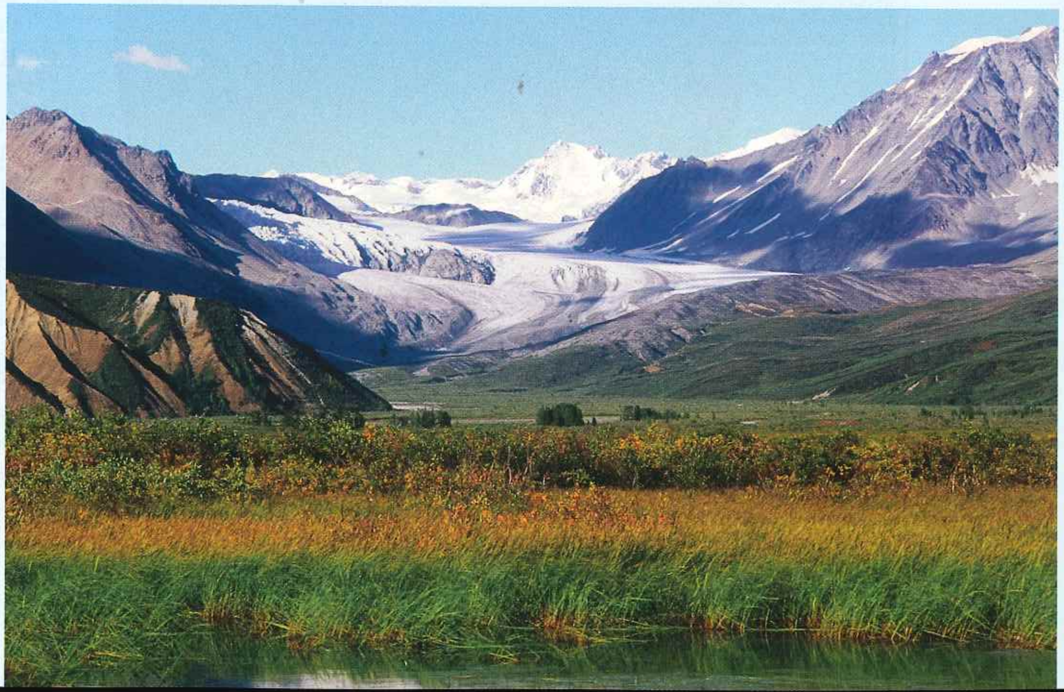
EYE ON EARTH

This image shows a portion of Alaska's Delta Range, a mountainous area southeast of Fairbanks. (Photo by Michael Collier)

QUESTION 1 *What are the five major parts of the climate system?.*

QUESTION 2 *Which of the five parts are represented in this photo?*

QUESTION 3 *Speculate on how climate change in the coming decades might cause change to the area shown here.*



greatest influence on people and their activities, and they also have an important impact on the distribution of such phenomena as vegetation and soils. Nevertheless, other factors are also important for a complete climatic description. When possible, some of these factors are introduced into our discussion of world climates.

Climate Classification

The worldwide distribution of temperature, precipitation, pressure, and wind is, to say the least, complex. Because of the many differences from place to place and time to time, it is unlikely that any two places that are more than a very short distance apart can experience identical weather. The virtually infinite variety of places on Earth makes it apparent that the number of different climates must be extremely large. Having such a diversity of information to investigate is not unique to the study of the atmosphere. It is a problem basic to all science. (Consider astronomy, which deals with billions of stars, and biology, which studies millions of complex organisms.) To cope with such variety, we must devise some means of *classifying* the vast array of data to be studied. By establishing groups of items that have common characteristics, order and manageability are introduced. Bringing order to large quantities of information not only aids comprehension and understanding but also facilitates analysis and explanation.

One of the first attempts at climate classification was made by the ancient Greeks, who divided each hemisphere into three zones: *torrid*, *temperate*, and *frigid* (**FIGURE 20.2**).

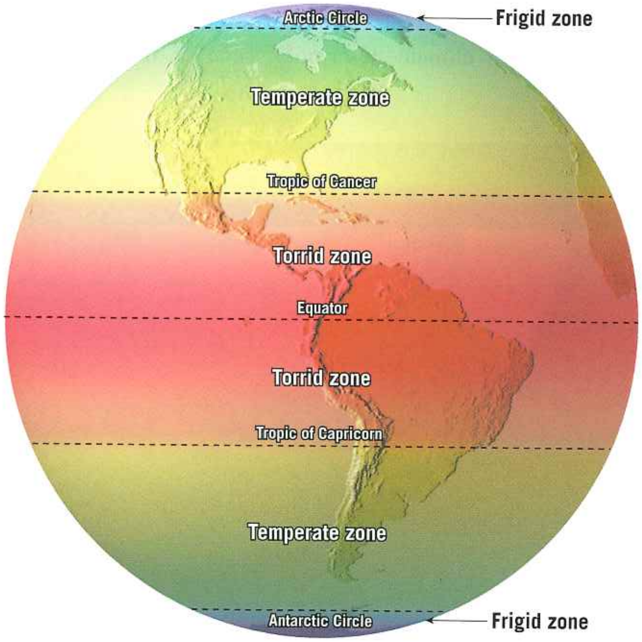


FIGURE 20.2 An Early Climate Classification Among the first attempts at climate classification was one made by the ancient Greeks. They divided each hemisphere into three zones. The winterless *torrid* zone was separated from the summerless *frigid* zone by the *temperate* zone, which had features of the other two.

The basis of this simple scheme was Earth–Sun relationships. The boundaries were the four astronomically important parallels of latitude: the Tropic of Cancer (23.5° north), the Tropic of Capricorn (23.5° south), the Arctic Circle (66.5° north), and the Antarctic Circle (66.5° south). Thus, the globe was divided into winterless climates and summerless climates and an intermediate type that had features of the other two.

Few other attempts were made until the beginning of the twentieth century. Since then, many climate-classification schemes have been devised. Remember that the classification of climates (or of anything else) is not a natural phenomenon but the product of human ingenuity. The value of any particular classification system is determined largely by its *intended use*. A system designed for one purpose may not work well for another.

The Köppen Classification

In this chapter, we use a classification devised by Russian-born German climatologist Wladimir Köppen (1846–1940). As a tool for presenting the general world pattern of climates, the **Köppen classification** has been the best-known and most used system for decades. It is widely accepted for many reasons. For example, it uses only easily obtained data: mean monthly and annual values of temperature and precipitation. Furthermore, the criteria are unambiguous, are relatively simple to apply, and divide the world into climate regions in a realistic way.

Köppen believed that the distribution of natural vegetation is an excellent expression of the totality of climate. Consequently, the boundaries he chose were largely based on the limits of certain plant associations. Five principal groups were recognized, and each group was designated by a capital letter, as follows:

A. **Humid tropical.** Winterless climates; all months have a mean temperature above 18°C (64°F).
B. **Dry.** Climates where evaporation exceeds precipitation; there is a constant water deficiency.
C. **Humid middle-latitude, mild winters.** The average temperature of the coldest month is below 18°C (64°F) but above –3°C (27°F).
D. **Humid middle-latitude, severe winters.** The average temperature of the coldest month is below –3°C (27°F), and the warmest monthly mean exceeds 10°C (50°F).
E. **Polar.** Summerless climates; the average temperature of the warmest month is below 10°C (50°F).

Notice that four of the major groups (A, C, D, and E) are defined on the basis of temperature characteristics, and the fifth, the B group, has precipitation as its primary criterion. Each of the five groups is further subdivided by using the criteria and symbols presented in **FIGURE 20.3**.

Letter Symbol 1st	2nd	3rd	
A			Average temperature of the coldest month is 18°C or higher.
	f		Every month has 6 cm of precipitation or more.
	m		Short dry season; precipitation in driest month less than 6 cm but equal to or greater than $10 - R/25$ (R is annual rainfall in cm).
	w		Well-defined winter dry season; precipitation in driest month less than $10 - R/25$.
	s		Well-defined summer dry season (rare).
B			Potential evaporation exceeds precipitation. The dry–humid boundary is defined by the following formulas: (Note: R is the average annual precipitation in cm, and T is the average annual temperature in °C.) $R < 2T + 28$ when 70% or more of rain falls in warmer 6 months. $R < 2T$ when 70% or more of rain falls in cooler 6 months. $R < 2T + 14$ when neither half year has 70% or more of rain.
	S		Steppe The BS–BW boundary is 1/2 the dry–humid boundary.
	W		Desert
		h	Average annual temperature is 18°C or greater.
		k	Average annual temperature is less than 18°C.
C			Average temperature of the coldest month is under 18°C and above –3°C.
	w		At least 10 times as much precipitation in a summer month as in the driest winter month.
	s		At least three times as much precipitation in a winter month as in the driest summer month; precipitation in driest summer month less than 4 cm.
	f		Criteria for w and s cannot be met.
		a	Warmest month is over 22°C; at least 4 months over 10°C.
		b	No month above 22°C; at least 4 months over 10°C.
		c	One to 3 months above 10°C.
D			Average temperature of coldest month is –3°C or below; average temperature of warmest month is greater than 10°C.
	w		Same as under C.
	s		Same as under C.
	f		Same as under C.
		a	Same as under C.
		b	Same as under C.
		c	Same as under C.
		d	Average temperature of the coldest month is –3°C or below.
E			Average temperature of the warmest month is below 10°C.
	T		Average temperature of the warmest month is greater than 0°C and less than 10°C.
	F		Average temperature of the warmest month is 0°C or below.

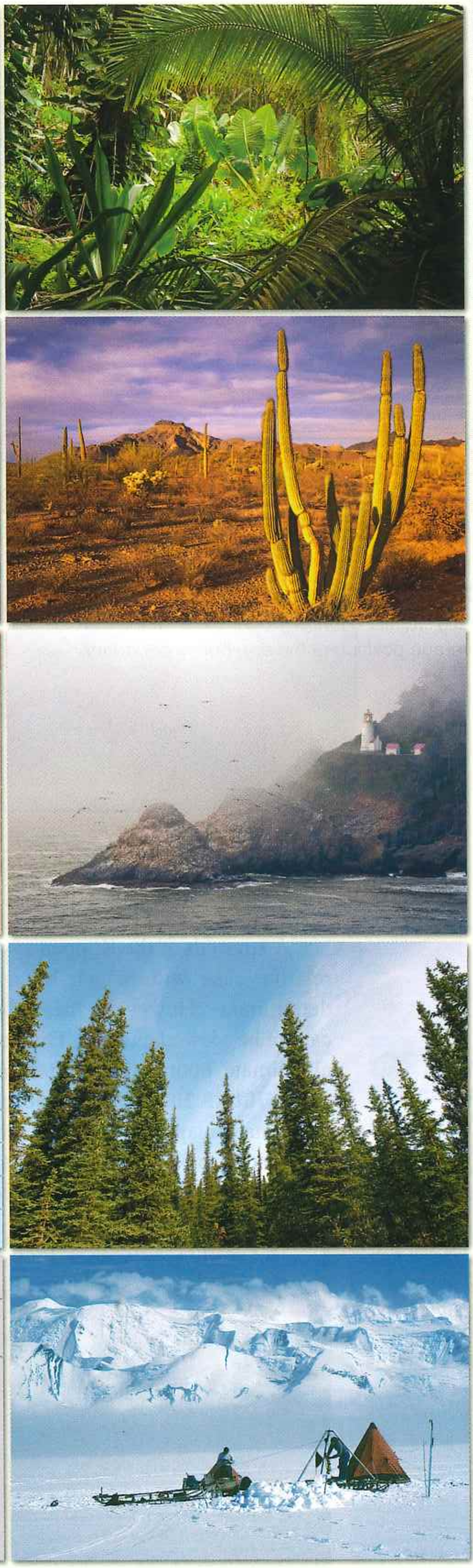
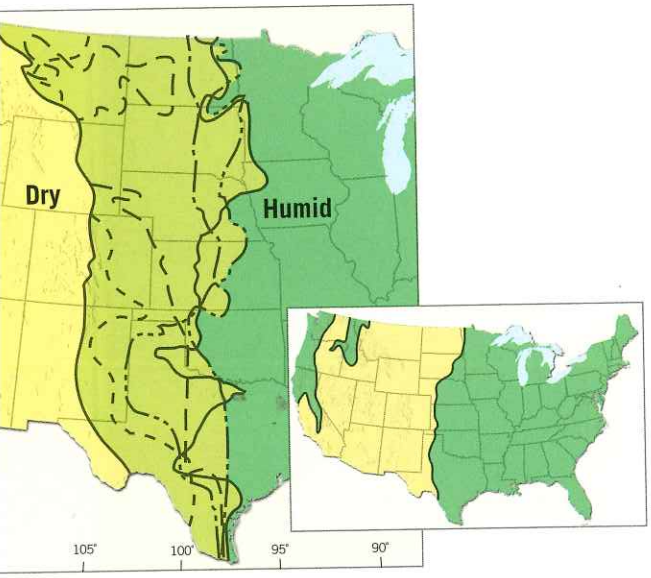


FIGURE 20.3 The Köppen System of Climate Classification This system uses easily obtained data: mean monthly and annual values of temperature and precipitation. When using this figure to classify climate data, first determine whether the data meet the criteria for the E climates. If the station is not a polar climate, proceed to the criteria for B climates. If the data do not fit into either the E or B groups, check the data against the criteria for A, C, and D climates, in that order. (Photos, in order from A–E, are by Michael Collier, Marek Zak/Alamy Images, Ed Reschke/Getty Images, Michael Collier, J.G. Paren/Science Source)



RE 20.4 Conditions Change from Year to Year Yearly ations in the dry–humid boundary during a 5-year period. The small shows the average position of the dry–humid boundary.

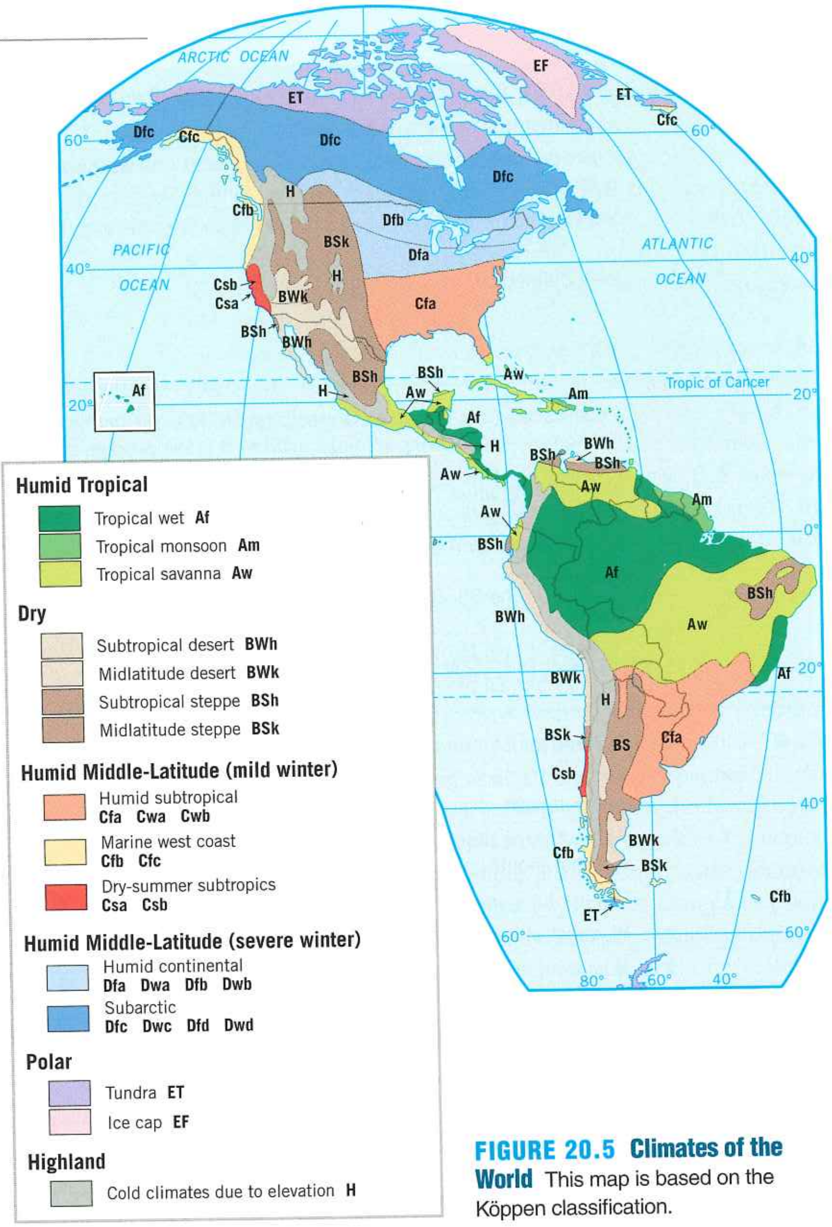


FIGURE 20.5 Climates of the World This map is based on the Köppen classification.

A strength of the Köppen system is the relative ease with which boundaries are determined. However, these boundaries cannot be viewed as fixed. On the contrary, all climate boundaries shift from year to year (**FIGURE 20.4**). The boundaries shown on climate maps are simply average locations based on data collected over many years. Thus, a climate boundary should be regarded as a broad transition zone and not a sharp line.

The world distribution of climates according to the Köppen classification is shown in **FIGURE 20.5**. You will refer to this map several times as Earth's climates are discussed in the following pages.

20.2 CONCEPT CHECKS

1. Why is classification often a necessary task in science?
2. What climate data are needed to classify a climate using the Köppen system?
3. Should climate boundaries, such as those shown on the world map in Figure 20.5, be regarded as fixed? Explain.

20.3 HUMID TROPICAL (A) CLIMATES

Compare the two broad categories of tropical climates.

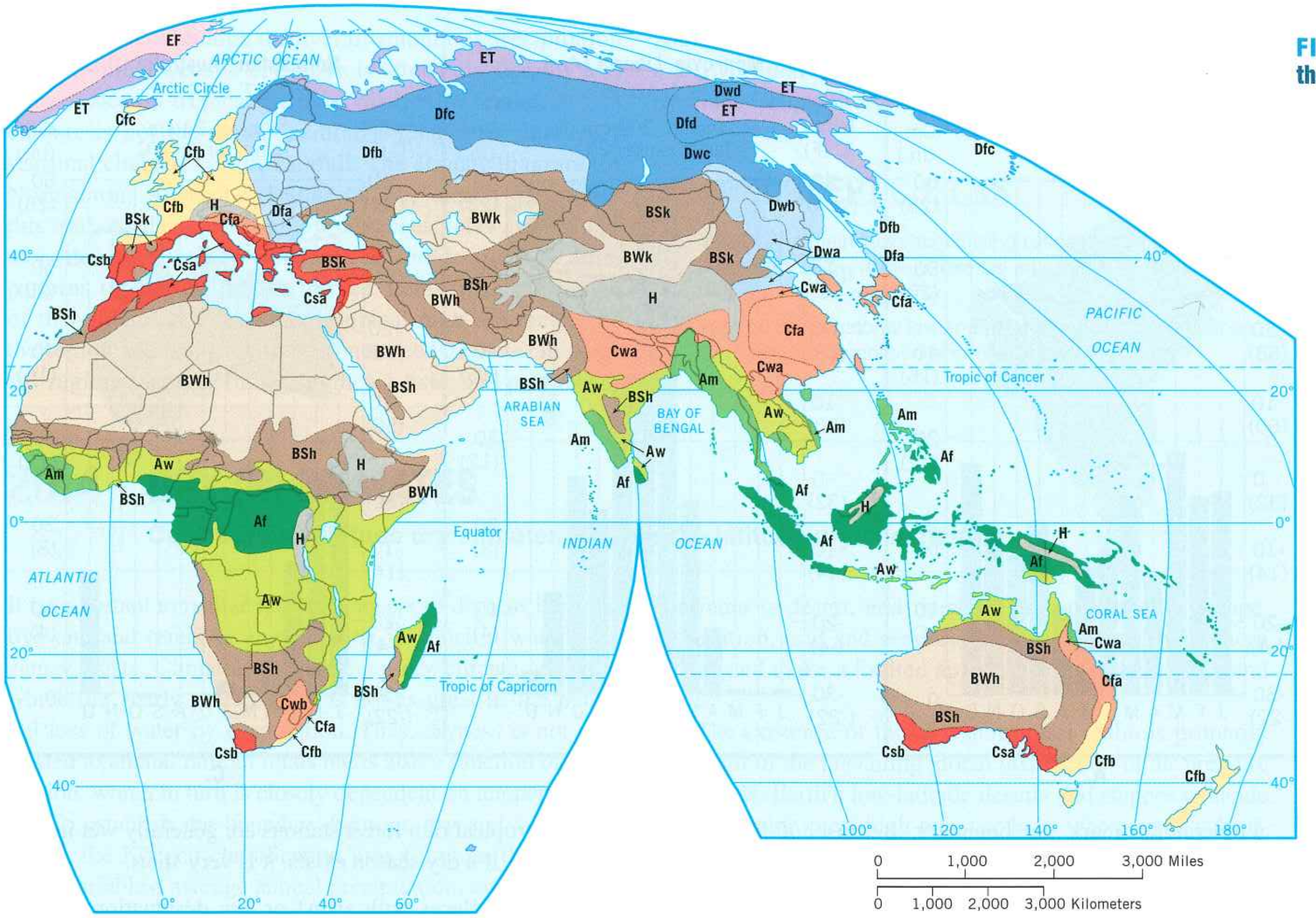
Within the A group of climates, two main types are recognized: wet tropical climates (Af and Am) and tropical wet and dry (Aw).

The Wet Tropics

The constantly high temperatures and year-round rainfall in the wet tropics combine to produce the most luxuriant vegetation found in any climatic realm: the **tropical rain forest** (**FIGURE 20.6**).

The environment of the wet tropics characterizes almost 10 percent of Earth's land area. An examination of Figure 20.5 shows that Af and Am climates form a discontinuous belt astride the equator that typically extends 5° to 10° into each hemisphere. The poleward margins are most often marked by diminishing rainfall, but occasionally decreasing

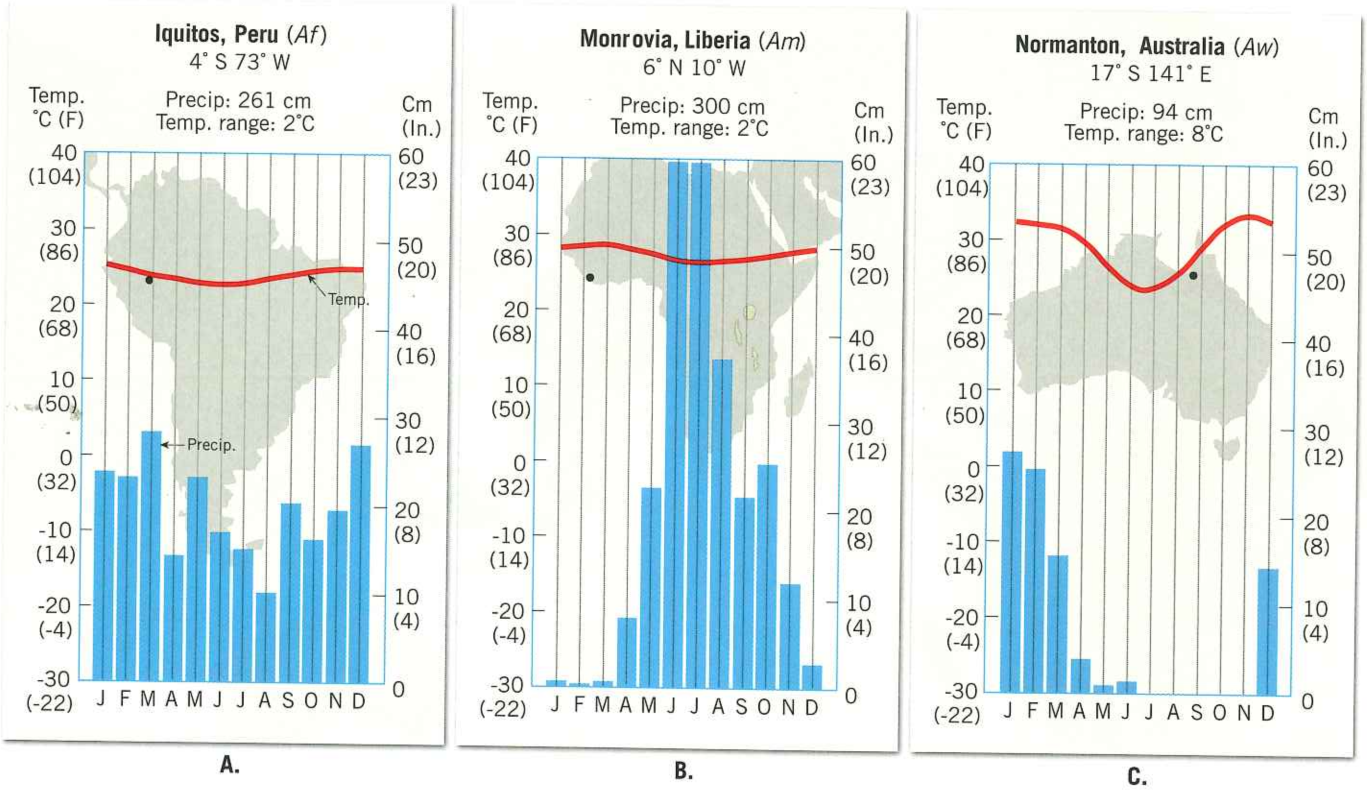
FIGURE 20.5 Climates of the World (*continued*)



MODIFIED GOODE'S HOMOLOSINE EQUAL-AREA PROJECTION

SmartFigure 20.6 Tropical Rain Forest Unexcelled in luxuriance and characterized by hundreds of different species per square kilometer, the tropical rain forest is a broadleaf evergreen forest that dominates the wet tropics. This image shows Borneo's Segama River passing through virgin tropical rain forest. (Photo by Peter Lilja/AGE Fotostock)

URE 20.7 Humid ical Climates By paring these three atic diagrams, the ary differences ng the A climates be seen. uitos, the ation, is wet ughout the year. onrovia, the Am on, has a short eason. **C.** As is for all Aw stations, nanton has an nded dry season a higher annual erature range the others.



temperatures mark the boundary. Because of the general decrease in temperature with height in the troposphere, this climate region is restricted to elevations below 1000 meters (nearly 3300 feet). Consequently, the major interruptions near the equator are principally cooler highland areas.

Data for some representative stations in the wet tropics are shown in **FIGURE 20.7A,B**. A brief examination reveals the most obvious features that characterize the climate in these areas:

- Temperatures usually average 25°C (77°F) or more each month. Consequently, not only is the annual mean temperature high, but the annual temperature range is very small.
- The total precipitation for the year is high, often exceeding 200 centimeters (80 inches).
- Although rainfall is not evenly distributed throughout the year, tropical rain forest stations are generally wet in all months. If a dry season exists, it is very short.

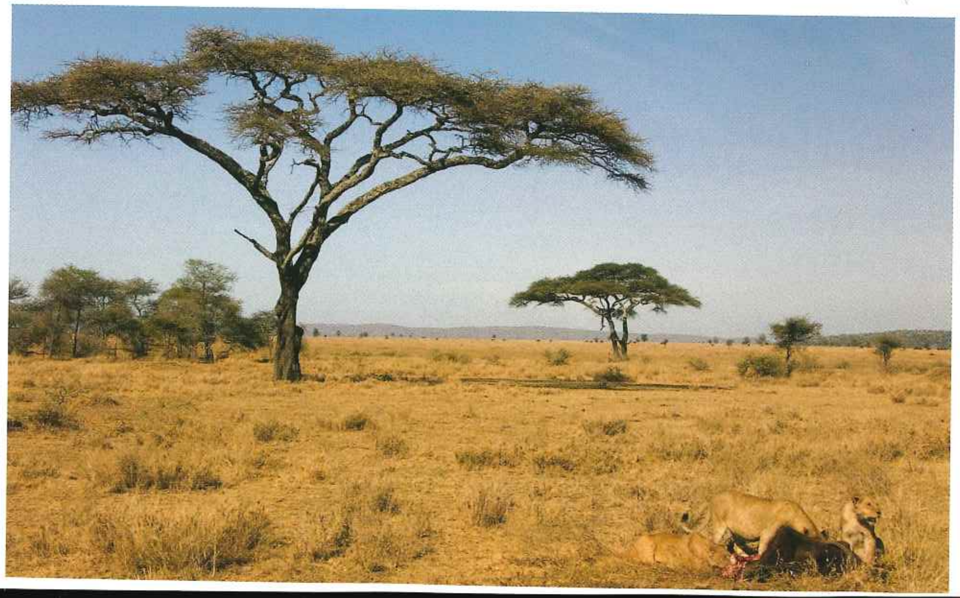
Because places with an Af or Am designation lie near the equator, the reason for the uniform temperature rhythm experienced in such locales is clear: The intensity of solar radiation is consistently high. The vertical rays of the Sun are always relatively close, and changes in the length of daylight throughout the year are slight; therefore, seasonal temperature variations are minimal.

The region is strongly influenced by the equatorial low. Its converging trade winds and the accompanying ascent of warm, humid, unstable air produce conditions that are ideal for the formation of precipitation.

Tropical Wet and Dry

In the latitude zone poleward of the wet tropics and equatorward of the subtropical deserts lies the transitional **tropical wet and dry climate**. Here the rain forest gives way to the *savanna*, a tropical grassland with scattered drought-tolerant trees (**FIGURE 20.8**). Because temperature characteristics among all A climates are quite similar, the primary factor that distinguishes the Aw climate from Af and Am is

RE 20.8 Tropical nna Grassland This al savanna in Tanzania's geti National Park, with nted, drought-resistant was probably strongly nced by seasonal ngs carried out by native n populations. (Photo by chov Vladimir/Shutterstock)



precipitation. Although the overall amount of precipitation in the tropical wet and dry realm is often considerably less than in the wet tropics, the most distinctive feature of this climate is not the annual rainfall total but the markedly seasonal character of the rainfall. The climate diagram for Normanton, Australia (**FIGURE 20.7C**), clearly illustrates this trait. As the equatorial low advances poleward in summer, the rainy season commences and features weather patterns typical of the wet tropics. Later, with the retreat of the equatorial low, the subtropical high advances into the region and brings with it pronounced dryness. In some Aw regions, such as India, Southeast Asia, and portions of Australia, the alternating periods of rainfall and dryness are associated with a well-established monsoon circulation (see Chapter 18).

20.3 CONCEPT CHECKS

1. What is the main factor that distinguishes Aw climates from Af and Am? How is this difference reflected in the vegetation of these climate regions?
2. How do the equatorial low and the subtropical high influence the seasonal distribution of rainfall in the Aw climate?

20.4 DRY (B) CLIMATES

Contrast low-latitude dry climates and middle-latitude dry climates.

It is important to realize that the concept of dryness is a relative one and refers to any situation in which a water deficiency exists. Climatologists define a dry climate as one in which the yearly precipitation is not as great as the potential loss of water by evaporation. Thus, dryness is not only related to annual rainfall totals but is also a function of evaporation, which in turn is closely dependent on temperature.

To establish the boundary between dry and humid climates, the Köppen classification uses formulas that involve three variables: average annual precipitation, average annual temperature, and seasonal distribution of precipitation. The use of average annual temperature reflects its importance as an index of evaporation. The amount of rainfall defining the humid–dry boundary increases as the annual mean temperature increases. The use of seasonal precipitation as a variable is also related to this idea. If rain is concentrated in the warmest months, loss to evaporation is greater than if the precipitation is concentrated in the cooler months.

Within the regions defined by a general water deficiency are two climatic types: **arid**, or **desert** (BW), and **semiarid**, or **steppe** (BS). These two groups have many features in common; their differences are primarily a matter of degree. The semiarid is a marginal and more humid variant of the arid climate type and represents a transition zone that surrounds the desert and separates it from the bordering humid climates (see Figure 6.30, page 193).

Low-Latitude Deserts and Steppes

The heart of low-latitude dry climates lies in the vicinities of the Tropics of Cancer and Capricorn. A glance at Figure 20.5 shows a virtually unbroken desert environment stretching for more than 9300 kilometers (nearly 6000 miles) from the Atlantic coast of North Africa to the dry lands of northwestern India. In addition to this single great expanse, the Northern Hemisphere contains another, much smaller area of subtropical desert and steppe in northern Mexico and the southwestern United States. In the Southern Hemisphere, dry climates dominate Australia. Almost 40 percent of the continent is desert, and much of the remainder is steppe. In addition, arid and semiarid areas are found in southern Africa and make a limited appearance in coastal Chile and Peru.

The existence of this dry subtropical realm is primarily the result of the prevailing global distribution of air pressure and winds. Earth's low-latitude deserts and steppes coincide with the subtropical high-pressure belts where air is subsiding (see Figure 18.17, page 561). When air sinks, it is compressed and warmed. Such conditions are opposite of what is needed for cloud formation and precipitation. Therefore, clear skies, a maximum of sunshine, and dryness are to be expected. The classic view of Africa and the Arabian Peninsula from space in **FIGURE 20.9** reinforces this idea. The climate diagrams for Cairo, Egypt, and Monterrey, Mexico (**FIGURE 20.10A,B**), illustrate the characteristics of low-latitude dry climates.

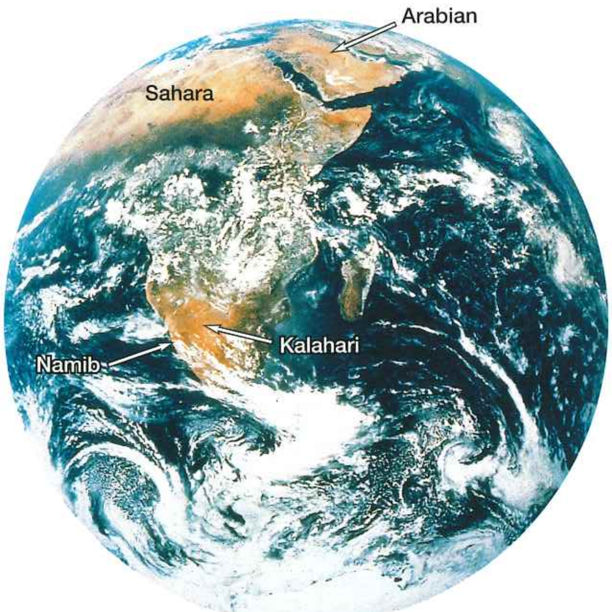
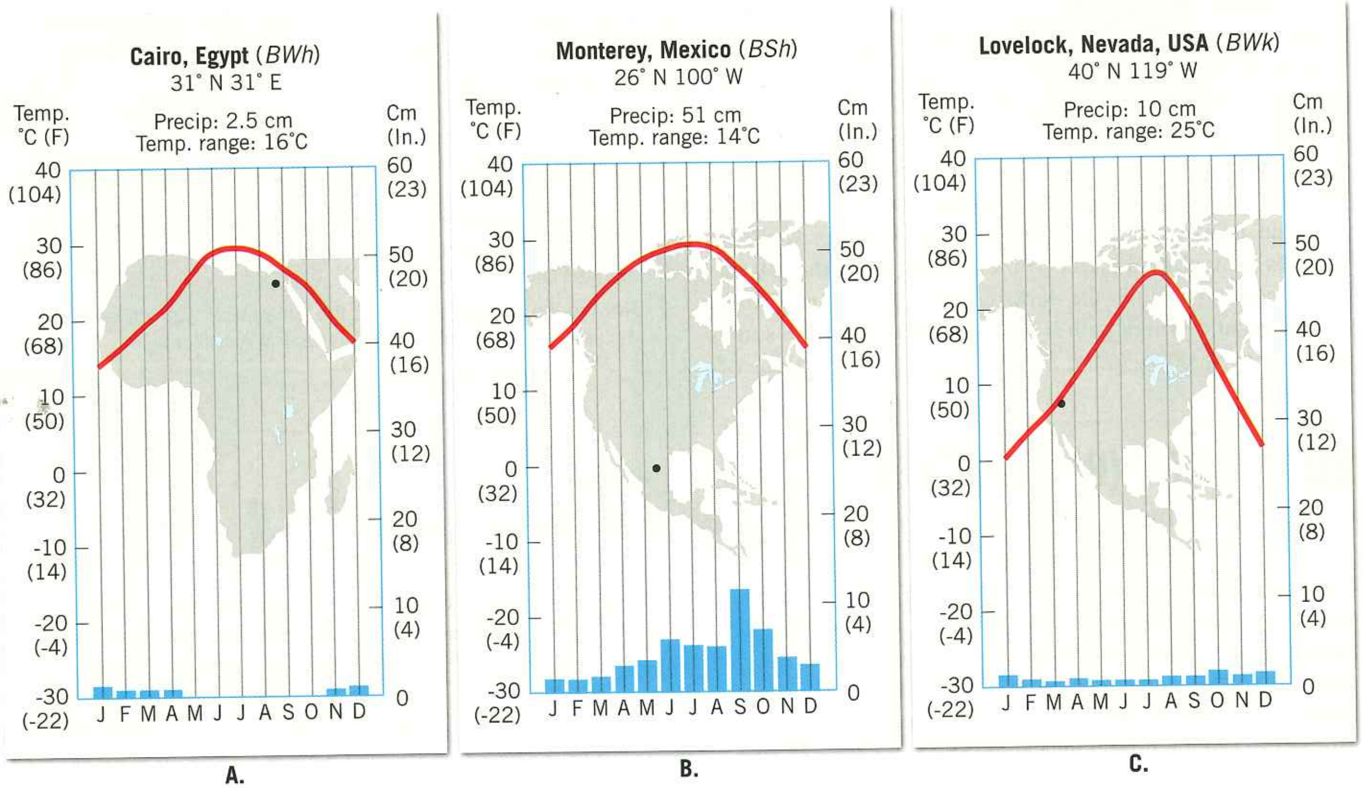


FIGURE 20.9 Deserts of Africa and the Arabian Peninsula In this view of Earth from space, North Africa's Sahara Desert, the adjacent Arabian Desert, and the Kalahari and Namib Deserts in southern Africa are clearly visible as tan-colored, cloud-free zones. These low-latitude deserts are dominated by the dry, subsiding air associated with pressure belts known as the *subtropical highs.* By contrast, the band of clouds that extends across central Africa and the adjacent oceans coincides with the equatorial low-pressure belt, the rainiest region on Earth. (NASA)

GURE 20.10
imate Diagrams for id and Semiarid ations Stations and **B.** are in the btropics, whereas is in the middle titudes. Cairo and ovelock are classified s deserts; Monterrey a steppe. Lovelock, evada, may also be alled a rain shadow esert.


Cairo, Egypt (*BWh*) 31° N 31° E

Monterey, Mexico (*BSh*) 26° N 100° W

Lovelock, Nevada, USA (*BWk*) 40° N 119° W

Middle-Latitude Deserts and Steppes

Unlike their low-latitude counterparts, middle-latitude deserts and steppes are not controlled by the subsiding air masses associated with high pressure. Instead, these dry lands exist principally because of their positions in the deep interiors of large landmasses far removed from the oceans, which are the ultimate source of moisture for cloud formation and precipitation. In addition, the presence of high mountains across the paths of prevailing winds further acts to separate these areas from water-bearing maritime air masses.

Windward sides of mountains are often wet. As prevailing winds meet mountain barriers, the air is forced to ascend, producing clouds and precipitation. By contrast, the leeward sides of mountains are usually much dryer and are often arid enough to be referred to as rain shadow deserts (see Figure 17.11, page 526). Because

EYE ON EARTH

This classic view of Earth from space was taken in December 1968 by an *Apollo 8* astronaut. The image shows the Western Hemisphere. Dense clouds cover much of North America. A large portion of South America is also cloud covered. However, the western margin of South America is cloud free. As you answer the following questions, you will find it helpful to consult Figure 6.30 (page 193) and Figures 15.2 and 15.3 (pages 455–456) and the discussions that relate to these figures.

QUESTION 1 *What is the name of the desert that occupies the cloudless area along the western margin of South America?*

QUESTION 2 *An ocean current flows just offshore of this desert area. Is it warm or cold? Toward what direction must the current flow—toward or away from the equator?*

QUESTION 3 *How does this desert's close proximity to the Pacific Ocean influence its aridity?*

NASA

many middle-latitude deserts occupy sites on the leeward sides of the mountains, they can also be classified as rain shadow deserts (**FIGURE 20.10C**). In North America, the Coast Ranges, Sierra Nevada, and Cascades are the foremost mountain barriers. In Asia, the great Himalayan chain prevents the summertime monsoon flow of moist Indian Ocean air from reaching the interior. Because the Southern Hemisphere lacks extensive land areas in the middle latitudes, only a small area of desert and steppe is found in this latitude range, existing primarily in the rain shadow of the towering Andes.

In the case of middle-latitude deserts, we have an example of the impact of tectonic processes on climate. Rain shadow deserts exist because of the mountains produced when plates collide. Without such mountain-building episodes, wetter climates would prevail where many dry regions exist today.

20.4 CONCEPT CHECKS

1. Why is the amount of precipitation that defines the boundary between humid and dry climates variable?
2. What is the primary reason (control) for the existence of the dry subtropical realm (BWh and BSh)?
3. What factors contribute to the existence of middle-latitude deserts and steppes?

20.5 HUMID MIDDLE-LATITUDE CLIMATES (C AND D CLIMATES)

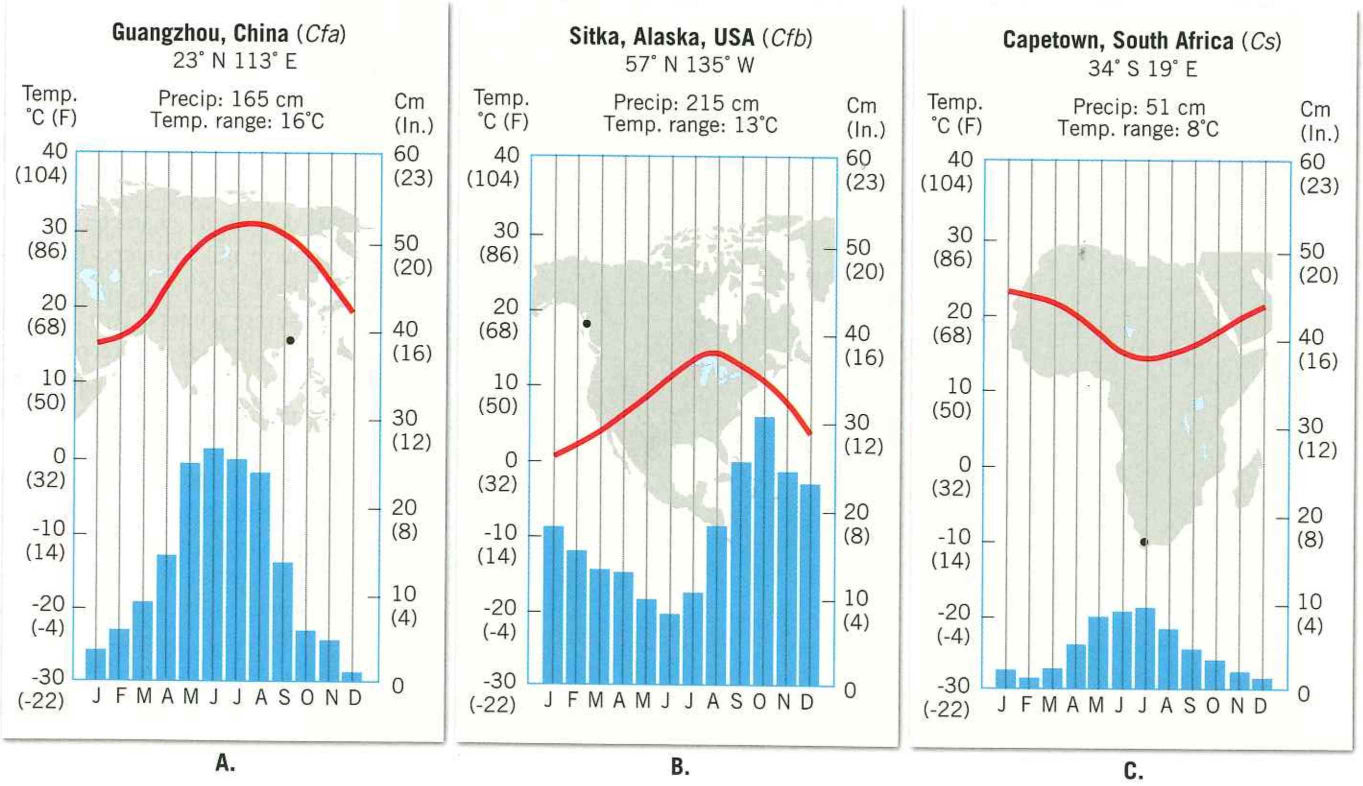
Distinguish among five different humid middle-latitude climates.

The humid middle-latitude climates dominate large portions of North America, Europe, and Asia. Humid middle-latitude climates are divided into two categories: C climates, which have mild winters, and D climates, which have severe winters.

Humid Middle-Latitude Climates with Mild Winters (C Climates)

Although the term *subtropical* is often used for the C climates, it can be misleading. Although many areas with C climates do indeed possess some near-tropical characteristics, other regions do not. For example, we would be stretching the use of the term *subtropical* to describe the climates of coastal Alaska and Norway, which belong to the C group. Within the C group of climates, several subgroups are recognized.

Humid Subtropics Located on the eastern sides of the continents, in the 25° to 40° latitude range, the **humid subtropical climate** dominates the southeastern United States, as well as other similarly situated areas around the world (see Figure 20.5). The climate diagram for Guangzhou, China (**FIGURE 20.11A**), shows a typical example. In summer, the humid subtropics experience hot, sultry weather of the type one expects to find in the rainy tropics. Daytime temperatures



A.

B.

C.

FIGURE 20.11 Examples of C Climates **A.** humid subtropical, **B.** marine west coast, and **C.** dry-summer subtropical.

are generally high, and because both mixing ratio and relative humidity are high, the night brings little relief. An afternoon or evening thunderstorm is also possible, for these areas experience such storms on an average of 40–100 days each year, the majority during the summer months.

As summer turns to autumn, the humid subtropics lose their similarity to the rainy tropics. Although winters are mild, frosts are common in the higher-latitude Cfa areas and occasionally plague the tropical margins as well. The winter precipitation is also different in character from the summer. Some is in the form of snow, and most is generated along fronts of the frequent middle-latitude cyclones that sweep over these regions.

Marine West Coast Situated on the western (windward) side of continents, from about 40° to 65° north and south latitude, is a climate region dominated by the onshore flow of oceanic air (**FIGURE 20.12**). In North America, the **marine west coast climate** extends from near the U.S.–Canadian border northward as a narrow belt into southern Alaska (**FIGURE 20.11B**). The largest area of Cfb climate is found in Europe because there are no mountain barriers blocking the movement of cool maritime air from the North Atlantic.

The prevalence of maritime air masses means that mild winters and cool summers are the rule, as is an ample amount of rainfall throughout the year. Although there is no pronounced dry period, there is a drop in monthly precipitation totals during the summer. The reason for the reduced summer rainfall is the poleward migration of the oceanic subtropical highs. Although the areas of marine west coast climate are situated too far poleward to be dominated by these dry anticyclones, their influence is sufficient to cause a decrease in warm season rainfall.

Dry-Summer Subtropics The **dry-summer subtropical climate** is typically located along the west sides of continents between latitudes 30° and 45°. Situated between the marine west coast climate on the poleward side and the subtropical steppes on the equatorward side, this climate is best described as transitional in character. It is unique because it is the only humid climate that has a strong winter rainfall maximum, a feature that reflects its intermediate position (**FIGURE 20.11C**). In summer, the region is dominated by stable conditions associated with the oceanic subtropical highs. In winter, as the wind and pressure systems follow the Sun equatorward, the region is within range of the cyclonic storms of the polar front. Thus, during the course of a year, these areas alternate between becoming a part of the dry subtropics and an extension of the humid middle latitudes. Whereas middle-latitude changeability characterizes the winter, subtropical constancy describes the summer.

As is the case for the marine west coast climate, mountain ranges limit the dry-summer subtropics to a relatively narrow coastal zone in both North and South America. Because Australia and southern Africa barely reach to the latitudes where dry-summer climates exist, the development of this climatic type is limited on those continents as well. Consequently, because of the arrangement of the continents and their mountain ranges, inland development occurs only in the Mediterranean basin. Here the zone of subsidence extends far to the east in summer; in winter, the sea is a major route of cyclonic disturbances. Because the dry-summer climate is particularly extensive in this region, the name *Mediterranean climate* is often used as a synonym.

URE 20.12 Marine st Coast Climate Fog ommon along the rocky cific coastline at Olympic tional Park, Washington. the name of this climate plies, the ocean exerts trong influence. (Photo by hard J. Green/Science Source)

Humid Middle-Latitude Climates with Severe Winters (D Climates)

The C climates that were just described characteristically have mild winters. By contrast, D climates experience severe winters. Two types of D climates are recognized: the humid continental and the subarctic climates. Climatic diagrams of representative locations are shown in **FIGURE 20.13**. The D climates are land-controlled climates, the result of broad continents in the middle latitudes. Because continentality is a basic feature, D climates are absent in the Southern

Hemisphere, where the middle-latitude zone is dominated by the oceans.

Humid Continental The **humid continental climate** is confined to the central and eastern portions of North America and Eurasia in the latitude range between approximately 40° and 50° north latitude. It may at first seem unusual that a continental climate should extend eastward to the margins of the ocean. However, because the prevailing atmospheric circulation is from the west, deep and persistent incursions of maritime air from the east are not likely to occur.

Both winter and summer temperatures in the humid continental climate can be characterized as relatively severe. Consequently, annual temperature ranges are high throughout the climate.

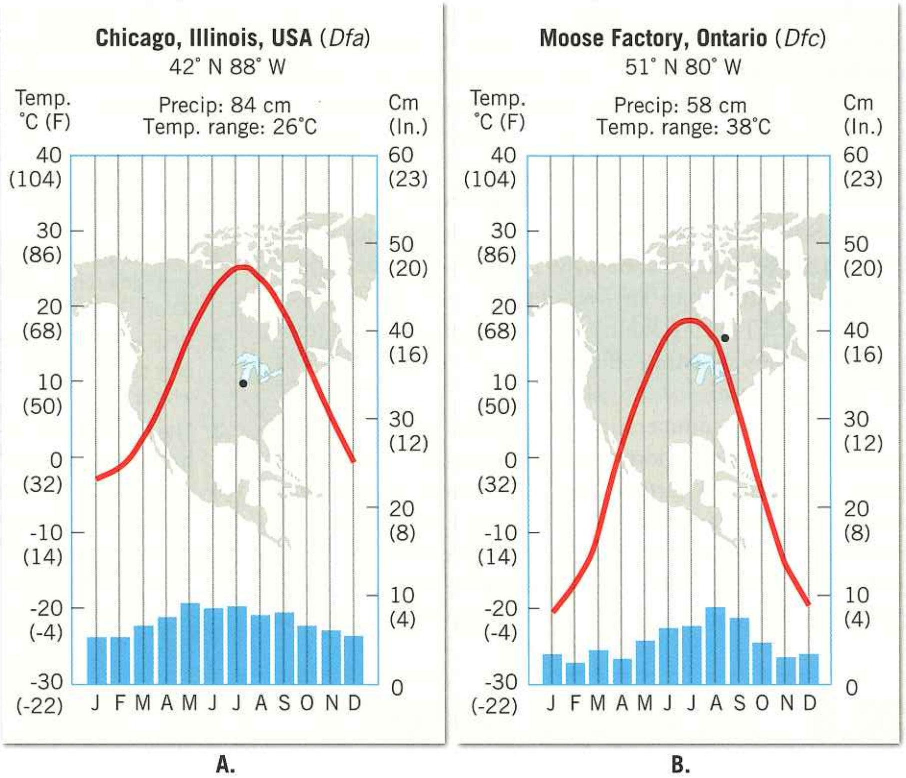


FIGURE 20.13 Examples of D Climates Climates in this category are associated with the interiors of large landmasses in the mid- to high latitudes of the Northern Hemisphere. Winters can be harsh in Chicago's humid continental (Dfa) climate, and the subarctic environment (Dfc) of Moose Factory is more extreme.

Precipitation is generally greater in summer than in winter. Precipitation totals generally decrease toward the interior of the continents, as well as from south to north, primarily because of increasing distance from the sources of maritime tropical (mT) air. Furthermore, the more northerly stations are also influenced for a greater part of the year by drier polar air masses.

Wintertime precipitation in humid continental climates is chiefly associated with the passage of fronts connected with traveling midlatitude cyclones. Part of this precipitation is in the form of snow, and the proportion of snow increases with latitude. Although precipitation is often considerably less during the cold season, it is usually more conspicuous than the greater amounts that fall during summer. An obvious reason is that snow remains on the ground, often for extended periods.

Subarctic Situated north of the humid continental climate and south of the polar tundra is an extensive **subarctic climate** region covering broad, uninterrupted expanses from western Alaska to Newfoundland in North America and from Norway to the Pacific coast of Russia in Eurasia (see Figure 20.5). It is often referred to as the *taiga* climate, for its extent closely corresponds to the northern coniferous forest region of the same name (**FIGURE 20.14**). Although scrawny, the spruce, fir, larch, and birch trees in the taiga represent the largest stretch of continuous forest on the surface of Earth.

FIGURE 20.14 Subarctic Climate The northern coniferous forest, also called the taiga, is associated with subarctic climates. This climate typically experiences the highest annual temperature ranges on Earth. This scene is in Quebec's Gaspésie Peninsula. (Photo by Michael P. Gadomski/Science Source)

Here in the source regions of continental polar air masses, the outstanding feature is certainly the dominance of winter. Winter is long, and temperatures are bitterly cold. Winter minimum temperatures are among the lowest ever recorded outside the ice sheets of Greenland and Antarctica. In fact, for many years, the world's coldest temperature was attributed to Verkhoyansk in east-central Siberia, where the temperature dropped to –68°C (–90°F) on February 5 and 7, 1892. Over a 23-year period, this same station had an average monthly minimum of –62°C (–80°F) during January. Although exceptional temperatures, they illustrate the extreme cold that envelops the taiga in winter.

By contrast, summers in the subarctic are remarkably warm, despite their short duration. However, when compared with regions farther south, this short season must be characterized as cool. The extremely cold winters and relatively warm summers combine to produce the highest annual temperature ranges on Earth. Because these far northerly continental interiors are the source regions for cP air masses, there is very limited moisture available throughout the year. Precipitation totals are therefore small, with a maximum occurring during the warmer summer months.

20.5 CONCEPT CHECKS

1. Describe and explain the differences between summertime and wintertime precipitation in the humid subtropical climate (Cfa).
2. Why is the marine west coast climate (Cfb) represented by only slender strips of land in North and South America, and why is it very extensive in Western Europe?
3. The dry-summer subtropics are described as transitional. Explain why this is true.
4. Why is the humid continental climate confined to the Northern Hemisphere?
5. Describe and explain the annual temperature range you should expect in the realm of the *taiga*.

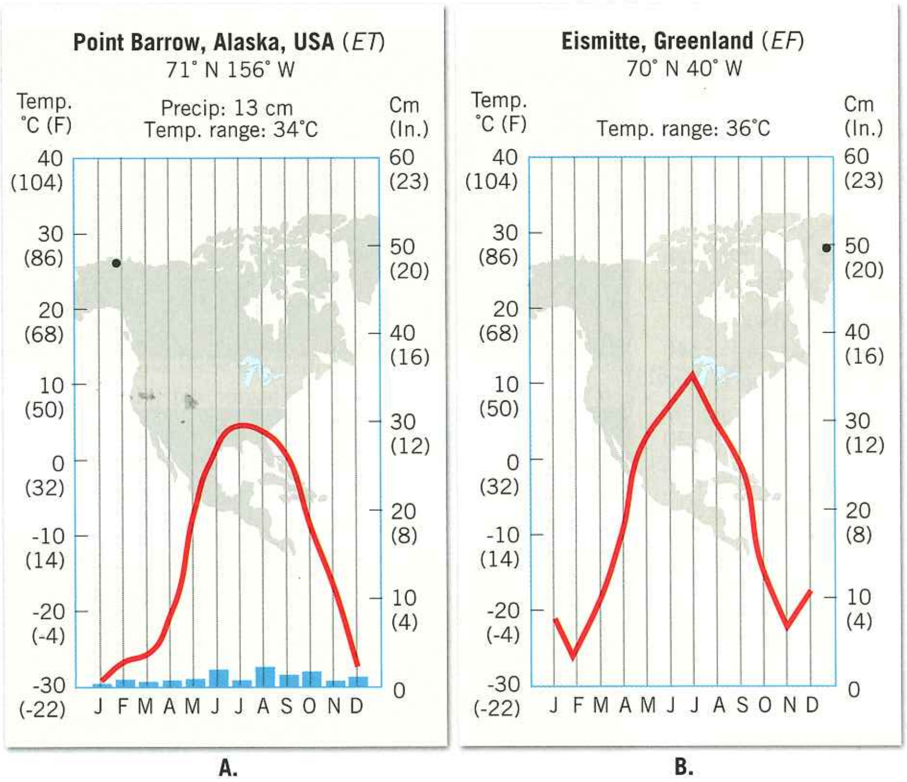
20.6 POLAR (E) CLIMATES

Contrast ice cap and tundra climates.

Polar climates are those in which the mean temperature of the warmest month is below 10°C (50°F). Thus, just as the tropics are defined by their year-round warmth, the polar realm is known for its enduring cold. As winters are periods of perpetual night, or nearly so, temperatures at most polar locations are understandably bitter. During the summer months temperatures remain cool despite the long days, because the Sun is so low in the sky that its oblique rays are not effective in bringing about a genuine warming. Although polar climates are classified as humid, precipitation is generally meager. Evaporation, of course, is also limited. The scanty precipitation totals are easily understood in view of the temperature characteristics of the region. The amount of water vapor in the air is always small because low mixing ratios must accompany low temperatures. Usually precipitation is most abundant during the warmer summer months, when the moisture content of the air is highest.

Two types of polar climates are recognized. The **tundra climate** (ET) is a treeless climate found almost exclusively in the Northern Hemisphere (**FIGURE 20.15**). Because of the combination of high latitude and continentality, winters are severe, summers are cool, and annual temperature ranges are

IGURE 20.15 Ice Cap Climate Greenland and ntarctica are the major examples of this extreme limate. In this image, scientists are conducting esearch on the Greenland ice sheet. (Photo by Dr. Joel arper)



SmartFigure 20.16
Examples of E Climates These climatic diagrams represent the two basic types of polar climates. **A.** Barrow, Alaska, exhibits a tundra (ET) climate. **B.** Eismitte, Greenland, a station located on a massive ice sheet, is classified as an ice cap (EF) climate.

high (**FIGURE 20.16A**). Furthermore, yearly precipitation is small, with a modest summer maximum.

The **ice cap climate** (EF) does not have a single monthly mean above 0°C (32°F) (**FIGURE 20.16B**). Consequently, because the average temperature for all months is below freezing, the growth of vegetation is prohibited, and the landscape is one of permanent ice and snow. This climate of perpetual frost covers a surprisingly large area of more than 15.5 million square kilometers (6 million square miles), or about 9 percent of Earth's land area. Aside from scattered occurrences in high mountain areas, it is confined to the ice sheets of Greenland and Antarctica (see Figure 6.2, page 173).

20.6 CONCEPT CHECKS

1. Although polar regions experience extended periods of sunlight in the summer, temperatures remain cool. Explain.
2. Why are precipitation totals low in polar climates? Which season has the most precipitation? Why?
3. Where are EF climates most extensively developed?

20.7 HIGHLAND CLIMATES

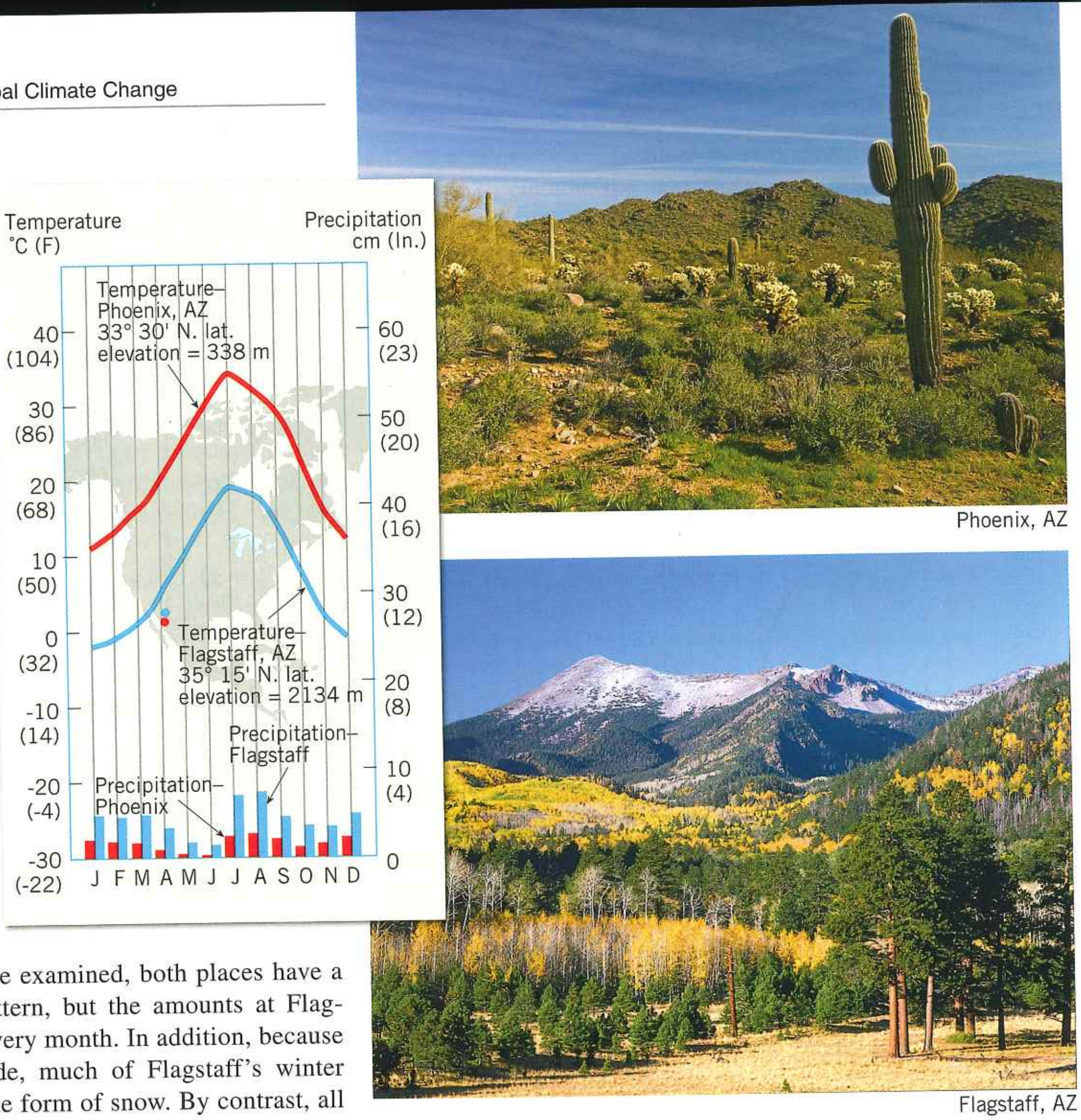
Summarize the characteristics associated with highland climates.

It is a well-known fact that mountains have climate conditions that are distinctly different from those found in adjacent lowlands. Compared to nearby places at lower elevations, sites with **highland climates** are cooler and usually wetter. Unlike the world climate types already discussed, which consist of large, relatively homogeneous regions, the outstanding characteristic of highland climates is the great diversity of climatic conditions that occur.

The best-known climatic effect of increased altitude is lower temperatures. In addition, an increase in precipitation due to orographic lifting usually occurs at higher elevations. Despite the fact that mountain stations are colder and often wetter than locations at lower elevations, highland climates are often very similar to those in adjacent lowlands in terms of seasonal temperature cycles and precipitation distribution. **FIGURE 20.17** illustrates this relationship.

Phoenix, at an elevation of 338 meters (1109 feet), lies in the desert lowlands of southern Arizona. By contrast, Flagstaff is located at an altitude of 2100 meters (7000 feet) on the Colorado Plateau in northern Arizona. When summer averages climb to 34°C (93°F) in Phoenix, Flagstaff is experiencing a pleasant 19°C (66°F), which is a full 15°C (27°F) cooler. Although the temperatures at each city are quite different, the pattern of monthly temperature changes for each place is similar. Both experience their minimum and maximum monthly means in the same months. When

artFigure 20.17 **Highland**
Diagrams for two stations in Arizona
he general influence of elevation on
lagstaff is cooler and wetter because of
n on the Colorado Plateau, nearly 1800
000 feet) higher than Phoenix. Only
ought-tolerant natural vegetation can
the hot, dry climate of southern Arizona,
enix. (Photo by Design Pics/
) The natural vegetation
ed with the cooler, wetter
s near Flagstaff, Arizona,
different from the desert
. (Photo by Jim Cole/Alamy)



precipitation data are examined, both places have a similar seasonal pattern, but the amounts at Flagstaff are higher in every month. In addition, because of its higher altitude, much of Flagstaff's winter precipitation is in the form of snow. By contrast, all of the precipitation at Phoenix is rain.

Because topographic variations are pronounced in mountains, every change in slope with respect to the Sun's rays produces a different microclimate. In the Northern Hemisphere, south-facing slopes are warmer and dryer because they receive more direct sunlight than north-facing slopes and deep valleys. Wind direction and speed in mountains can be highly variable. Mountains create various obstacles to winds. Locally, winds may be funneled through valleys or forced over ridges and around mountain peaks. When weather conditions are fair, mountain and valley breezes are created by the topography itself.[1]

We know that climate strongly influences vegetation, which is the basis for the Köppen system. Thus, where there are vertical differences in climate, we should expect a vertical zonation of vegetation as well. By ascending a mountain, we can view dramatic vegetation changes that otherwise might require a poleward journey of thousands of kilometers (see Figure 20.17). This occurs because altitude duplicates, in some respects, the influence of latitude on the distribution of vegetation.

Perhaps the terms *variety* and *changeability* best describe mountain climates. Because atmospheric conditions fluctuate rapidly with changes in altitude and exposure, a nearly limitless variety of local climates occur in mountainous regions. The climate in a protected valley is very different from that of an exposed peak. Conditions on windward slopes contrast sharply with those on the leeward sides, whereas slopes facing the Sun are unlike those that lie mainly in the shadows.

20.7 CONCEPT CHECKS

1 The Arizona cities of Flagstaff and Phoenix are relatively close to one another yet have contrasting climates. Briefly describe the differences and why they occur.

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[1] Mountain and valley breezes are described in the section "Local Winds" in Chapter 18. Also see Figure 18.20, page 564.

20.8 HUMAN IMPACT ON GLOBAL CLIMATE

Summarize the nature and cause of the atmosphere's changing composition since about 1750. Describe the climate's response.

Proposals to explain global climate change are many and varied. In Chapter 6, we examined some possible causes for ice-age climates. These hypotheses, which involved plate tectonics and variations in Earth's orbit, were natural causes. Another natural cause, discussed in Chapter 9, is the possible role of explosive volcanic eruptions in modifying the atmosphere. It is important to remember that these mechanisms, as well as others, were not only responsible for climate change in the geologic past but will also contribute to future shifts in climate.

When relatively recent and future changes in our climate are considered, we must also examine the impact of human beings. In this section, we examine how humans contribute to global climate change. One impact largely results from the addition of carbon dioxide and other greenhouse gases to the atmosphere. A second impact is related to the addition of human-generated aerosols to the atmosphere.

Human influence on regional and global climate did not just begin with the onset of the modern industrial period. There is good evidence that people have been modifying the environment over extensive areas for thousands of years. The use of fire and the overgrazing of marginal lands by domesticated animals have both reduced the abundance and distribution of vegetation. By altering ground cover, humans have modified such important climate factors as surface albedo, evaporation rates, and surface winds.

Rising CO_2 Levels

In Chapter 16 you learned that carbon dioxide (CO_2) represents only about 0.0397 percent (397 parts per million) of the gases that make up clean, dry air. Nevertheless, it is a very significant component meteorologically. Carbon dioxide is influential because it is transparent to incoming short-wavelength solar radiation, but it is not transparent to some of the longer-wavelength outgoing Earth radiation. A portion of the energy leaving the ground is absorbed by atmospheric CO_2. This energy is subsequently re-emitted, part of it back toward the surface, thereby keeping the air near the ground warmer than it would be without CO_2. Thus, along with water vapor, carbon dioxide is largely responsible for the *greenhouse effect* of the atmosphere. Carbon dioxide is an important heat absorber, and it follows logically that any change in the air's CO_2 content could alter temperatures in the lower atmosphere.

Earth's tremendous industrialization of the past two centuries has been fueled—and still is fueled—by burning fossil fuels: coal, natural gas, and petroleum (**FIGURE 20.18**). Combustion of these fuels has added great quantities of carbon dioxide to the atmosphere. Figure 16.5 (page 489) shows changes in CO_2 concentrations at Hawaii's Mauna Loa Observatory, where measurements have been made since 1958. The graph shows an annual seasonal cycle and

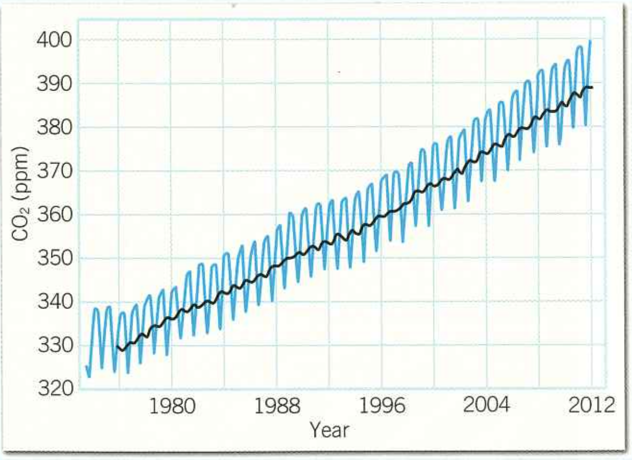
EYE ON EARTH

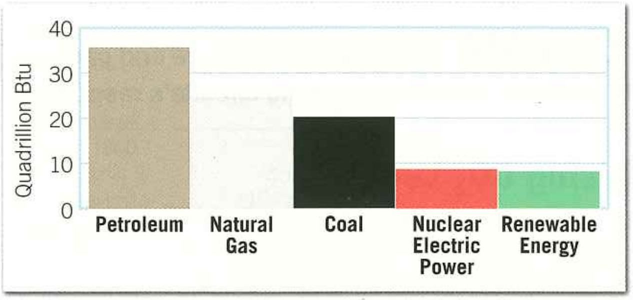
Amundsen–Scott South Pole Station is an American research facility. Among the phenomena that are monitored there are variations in atmospheric composition. The accompanying graph shows changes in the air's CO_2 content at South Pole Station (90° south latitude) and at a similar facility at Barrow, Alaska (71° north latitude). (Photo by Vicky Beaver/Alamy)

QUESTION 1 *Describe how the two lines on the graph differ.*

QUESTION 2 *Which line on the graph represents the South Pole, and which represents Barrow, Alaska?*

QUESTION 3 *Explain how you were able to determine which line is which.*





RE 20.18 U.S. y Consumption The shows energy mption in 2011. The as 97.5 quadrillion Btu. drillion is 10 raised to th power, or a million . The burning of fossil epresents slightly more 2 percent of the total. om U.S. Energy Information stration)

FIGURE 20.19 Tropical Deforestation Clearing the tropical rain forest is a serious environmental issue. In addition to causing a loss of biodiversity, it is a significant source of carbon dioxide. Fires are frequently used to clear the land. This scene is in Brazil's Amazon basin. (Photo by Pete Oxford/Nature Picture Library)

a steady upward trend over the years. The up-and-down of the seasonal cycle is due to the vast land area of the Northern Hemisphere, which contains the majority of land-based vegetation. During spring and summer in the Northern Hemisphere, when plants are absorbing CO_2 as part of photosynthesis, concentrations decrease. The annual increase in CO_2 during the cold months occurs as vegetation dies and leaves fall and decompose, which releases CO_2 back into the air.

The use of coal and other fuels is the most prominent means by which humans add CO_2 to the atmosphere, but it is not the only way. The clearing of forests also contributes substantially because CO_2 is released as vegetation is burned or decays. Deforestation is particularly pronounced in the tropics, where vast tracts are cleared for ranching and agriculture or are subjected to inefficient commercial logging operations (**FIGURE 20.19**). According to United Nations estimates, nearly 10.2 million hectares (25.1 million acres) of tropical forest were permanently destroyed each year during the 1990s. Between the years 2000 and 2005, the average figure increased to 10.4 million hectares (25.7 million acres) per year.

Some of the excess CO_2 is taken up by plants or is dissolved in the ocean. It is estimated that about 45 percent remains in the atmosphere. **FIGURE 20.20** is a graphic record of changes in atmospheric CO_2 extending back more than 400,000 years. Over this long span, natural fluctuations have varied from about 180 to 300 ppm. As a result of human activities, the present CO_2 level is about 30 percent higher than its highest level over at least the past 650,000 years. The rapid increase in CO_2 concentrations since the onset of industrialization is obvious. The annual rate at which atmospheric CO_2 concentrations are growing has been increasing over the past several decades.

The Atmosphere's Response

Given the increase in the atmosphere's carbon dioxide content, have global temperatures actually increased? The answer is "yes." According to the Intergovernmental Panel on Climate Change (IPCC), 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 sea level.[2] Most of the observed increase in global average temperatures since the mid-twentieth century is *very likely* due to the observed increase in human-generated greenhouse gas concentrations. (As used by the IPCC, *very likely* indicates a probability of 90–99 percent.) Global warming since the mid-1970s is now about 0.6°C (1°F), and total warming in

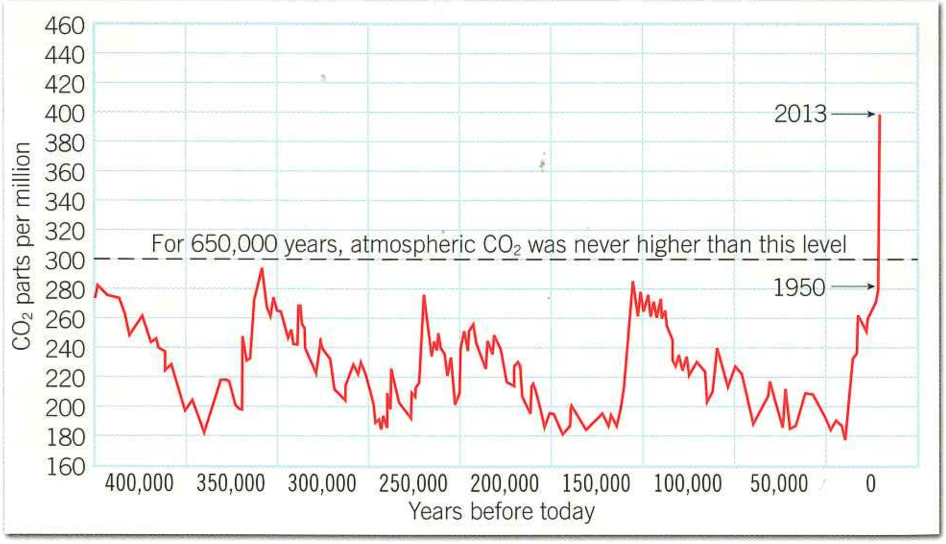


FIGURE 20.20 CO_2 Concentrations over the Past 400,000 Years Most of these data come from the analysis of air bubbles trapped in ice cores. The record since 1958 comes from direct measurements at Mauna Loa Observatory, Hawaii. The rapid increase in CO_2 concentrations since the onset of the Industrial Revolution is obvious. (NOAA)

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[2] IPCC, "Summary for Policy Makers." In *Climate Change 2013: The Physical Science Basis*. The Intergovernmental Panel on Climate Change is an authoritative group that provides advice to the world community through periodic reports that assess the state of knowledge of causes of climate change. More than 259 authors and 1089 scientific reviewers from more than 55 countries contributed to the 2013 report.

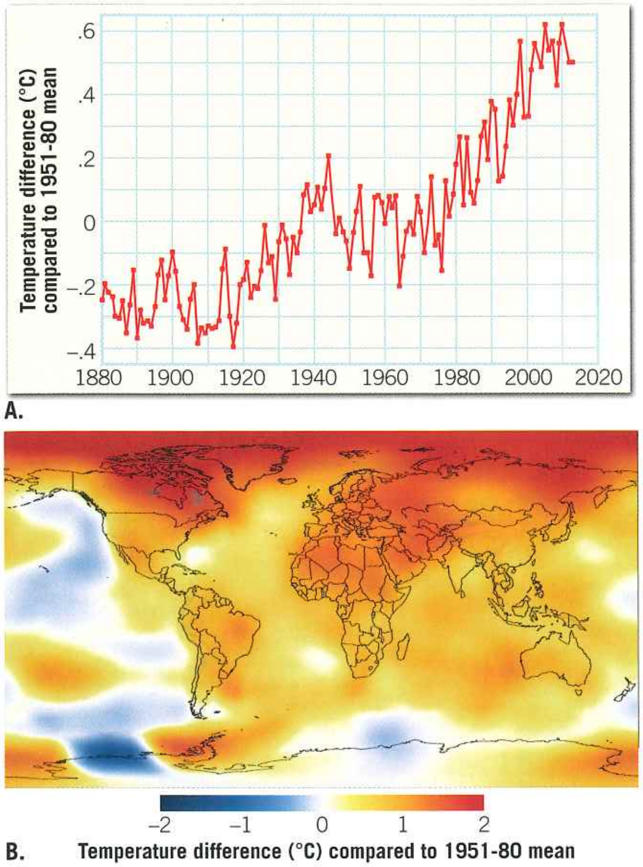


FIGURE 20.21 Global Temperatures The year 2012 was among the 10 warmest years on record. **A.** The graph depicts global temperature change in degrees Celsius since the year 1880. **B.** The world map shows global temperature differences averaged from 2008 through 2012 compared to the mean for the 1951–1980 base period. The high latitudes in the Northern Hemisphere clearly stand out. (NASA/Goddard Institute for Space Studies)

the past century is about 0.8°C (1.4°F). The upward trend in surface temperatures is shown in **FIGURE 20.21A**. The world map in **FIGURE 20.21B** compares surface temperatures for 2012 to the base period (1951–1980). You can see that the greatest warming has been in the Arctic and neighboring high-latitude regions. Here are some related facts:

- When we consider the 132-year span for which there are instrumental records (since 1880), the 10 warmest years have all occurred since 1998.
- Global mean temperature is now higher than at any time in at least the past 500 to 1000 years.
- The average temperature of the global ocean has increased to depths of at least 3000 meters (10,000 feet).

Are these temperature trends caused by human activities, or would they have occurred anyway? The scientific consensus of the IPCC is that human activities were *very likely* responsible for most of the temperature increase since 1950.

What about the future? Projections for the years ahead depend in part on the quantities of greenhouse gases that are emitted. **FIGURE 20.22** shows the best estimates of global warming for several different scenarios. The IPCC estimates that if there is a doubling of the preindustrial level of carbon dioxide (280 ppm) to 560 ppm, the "likely" temperature increase will be in the range of 2° to 4.5°C (3.5° to 8.1°F). The increase is "very unlikely" (1 to 10 percent probability) to be less than 1.5°C (2.7°F), and values higher than 4.5°C (8.1°F) are possible.

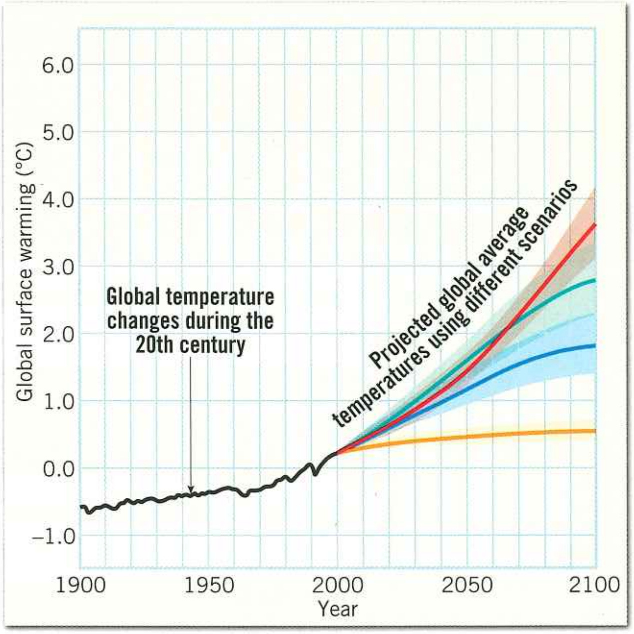


FIGURE 20.22 Temperature Projections to 2100 The right half of the graph shows projected global warming based on different emissions scenarios. The shaded zone adjacent to each colored line shows the uncertainty range for each scenario. The basis for comparison (0.0 on the vertical axis) is the global average for the period 1980 to 1999. The orange line represents the scenario in which CO_2 concentrations were held constant at values for the year 2000. (NOAA)

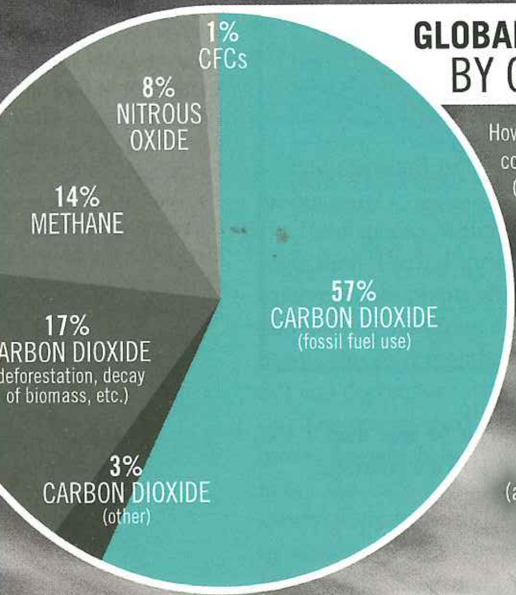
The Role of Trace Gases

Carbon dioxide is not the only gas that contributes to the global increase in temperature. In recent years, atmospheric scientists have come to realize that the industrial and agricultural activities of people are causing a buildup of several trace gases that also play significant roles. The substances are called *trace gases* because their concentrations are much lower than the concentration of carbon dioxide. The trace gases that are most important are methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). These gases absorb wavelengths of outgoing radiation from Earth that would otherwise escape into space (**FIGURE 20.23**). Although individually their impact is

FIGURE 20.23 Methane Methane is produced by anaerobic bacteria in wet places, where oxygen is scarce. (*Anaerobic* means "without air," specifically oxygen.) Such places include swamps, bogs, wetlands, and the guts of termites and grazing animals such as cattle and sheep. Methane is also generated in flooded paddy fields ("artificial swamps") used for growing rice. Coal mining and drilling for oil and natural gas are other sources of methane. (Photo by Robert Harding/SuperStock)

Greenhouse Gas (GHG) Emissions

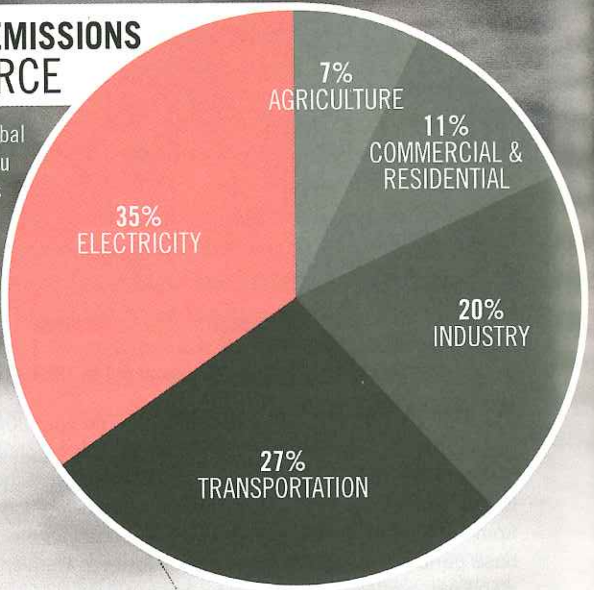
GLOBAL GREENHOUSE GAS EMISSIONS BY GAS

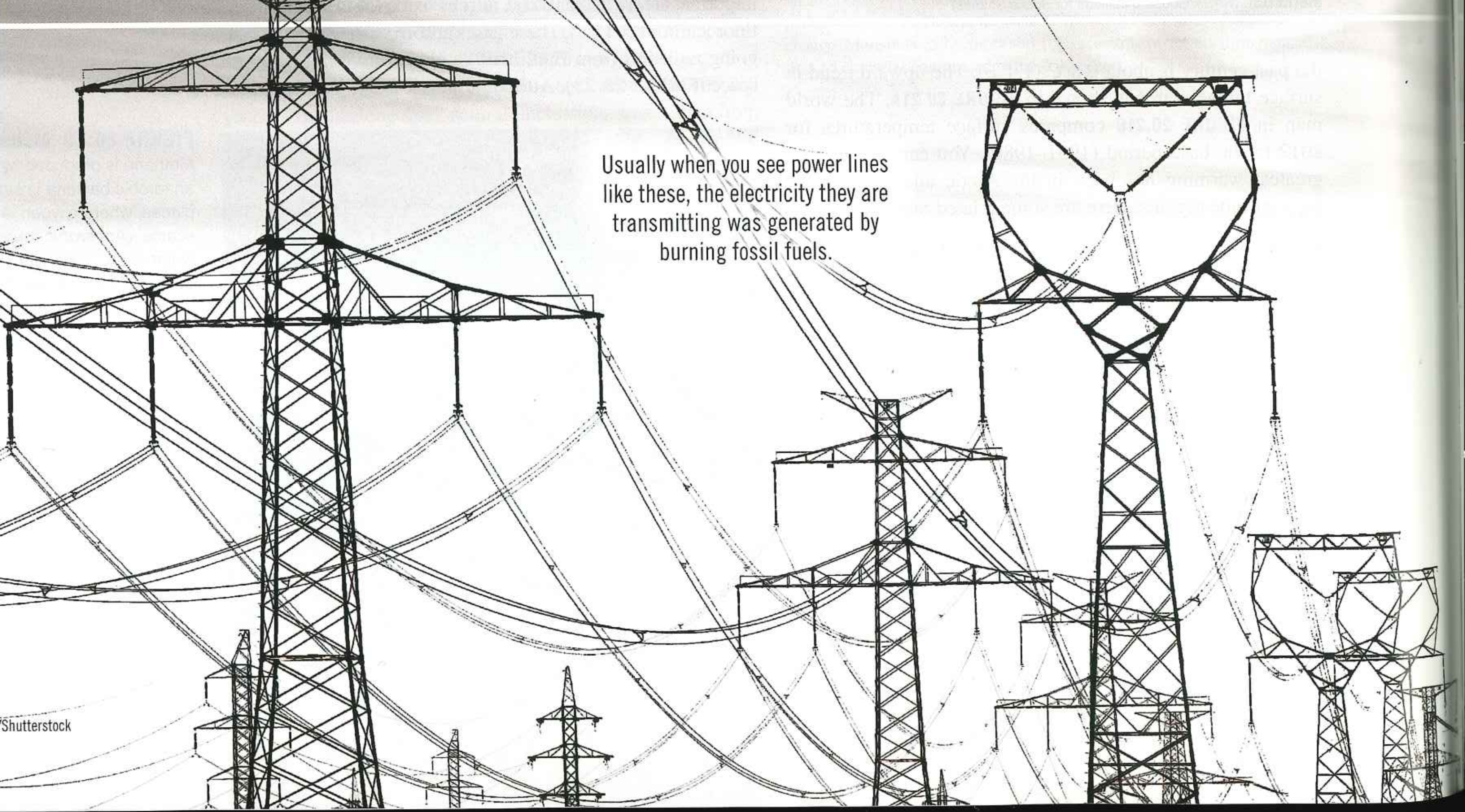


How can we compare different GHGs when some are more effective at warming the atmosphere than others? To make comparisons it is necessary to use a unit that takes into account these differing impacts. The preferred unit, called CO_2 equivalent, expresses the impact of a GHG in terms of the impact of an equivalent amount of CO_2.

UNITED STATES GREENHOUSE GAS EMISSIONS BY SOURCE

Compare the sources of United States emissions with the global figures and you will see some significant differences. Can you explain the difference in the transportation category? Forests and land use are a source for global emissions but are not listed for the U.S. Why? Land areas can act as a sink (absorbing CO_2 from the air) or a source of GHG emissions. In the U.S. since 1990, managed forests and other lands have absorbed more CO_2 from the atmosphere than they emit.



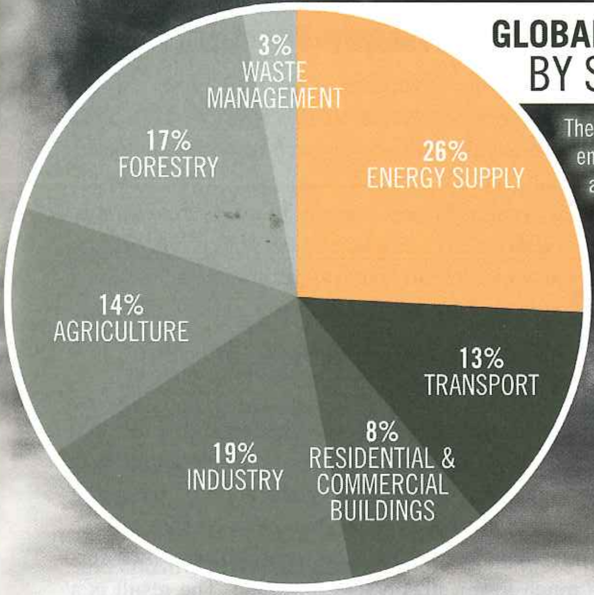


Usually when you see power lines like these, the electricity they are transmitting was generated by burning fossil fuels.

Shutterstock

The ever-escalating emissions of greenhouse gases (GHG) can be traced to all parts of the planet and to all sections of society and the economy.

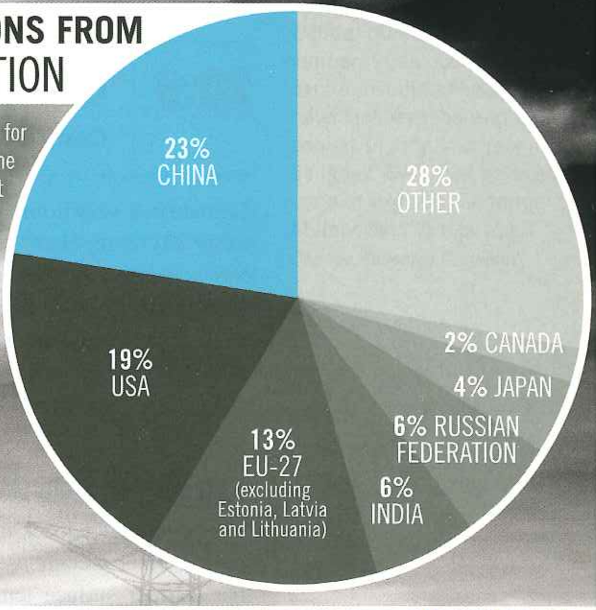
GLOBAL GREENHOUSE GAS EMISSIONS BY SOURCE



The burning of fossil fuels is a major part of emissions from energy supply, industry, transport, and residential and commercial buildings.

GLOBAL CO_2 EMISSIONS FROM FOSSIL FUEL COMBUSTION

Notice that the U.S. is responsible for 19 percent of global emissions. The U.S. population represents about 4.5 percent of the world total.



HOW MUCH CO_2 DOES AN AVERAGE AMERICAN PRODUCE?

17,000 POUNDS OF CO_2
by using **1,100 kilowatt-hours of electricity**
per month

8,800 POUNDS OF CO_2
by using **6,300 cubic feet of natural gas**
per month

1,000 POUNDS OF CO_2
by creating **4.5 pounds of trash**
per day

1,000 POUNDS OF CO_2
by **driving 160 miles**
per week

8,900 POUNDS OF CO_2
by **flying 1,900 miles**
per year

RelaXimages/SuperStock

modest, taken together, these trace gases play a significant role in warming the troposphere.

Sophisticated computer models show that the warming of the lower atmosphere caused by CO_2 and trace gases will not be the same everywhere. Rather, the temperature response in polar regions could be two to three times greater than the global average. One reason is that the polar troposphere is very stable, which suppresses vertical mixing and thus limits the amount of surface heat that is transferred upward. In addition, the expected reduction in sea ice will contribute to the greater temperature increase. This topic will be explored more fully in the next section.

20.8 CONCEPT CHECKS

1. Why has the CO_2 level of the atmosphere been increasing over the past 200 years?
2. How has the atmosphere responded to the growing CO_2 levels?
3. How are temperatures in the lower atmosphere likely to change as CO_2 levels continue to increase?
4. Aside from CO_2, what trace gases are contributing to global temperature change?

20.9 CLIMATE-FEEDBACK MECHANISMS

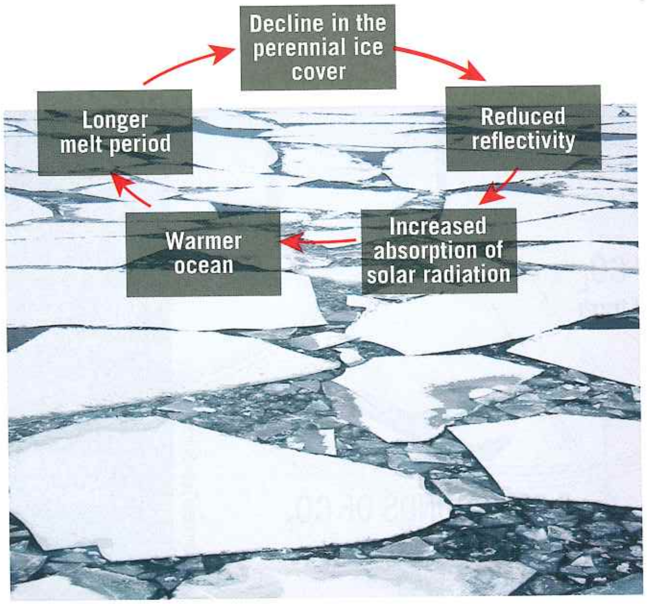
Contrast positive- and negative-feedback mechanisms and provide examples of each.

Climate is a very complex interactive physical system. Thus, when any component of the climate system is altered, scientists must consider many possible outcomes, some of which amplify the initial effect and some of which balance it out. These possible outcomes are called **climate-feedback mechanisms**. They complicate climate-modeling efforts and add greater uncertainty to climate predictions.

Types of Feedback Mechanisms

What climate-feedback mechanisms are related to carbon dioxide and other greenhouse gases? One important mechanism is that warmer surface temperatures increase evaporation rates. This in turn increases the atmosphere's water vapor content. Remember that water vapor is an even more powerful absorber of radiation emitted by Earth than is carbon dioxide. Therefore, with more water vapor in the air, the temperature increase caused by carbon dioxide and the trace gases is reinforced.

Recall that the temperature increase at high latitudes may be two to three times greater than the global average. This projection is based in part on the likelihood that the area covered by sea ice will decrease as surface temperatures rise. Because ice reflects a much larger percentage of incoming solar radiation than does open water, the melting of the sea ice causes a surface having a high albedo to be replaced by a surface with a much lower albedo (**FIGURE 20.24**). The result is a substantial increase in the solar energy absorbed at the surface. This in turn feeds back to the atmosphere and magnifies the initial temperature increase created by higher levels of greenhouse gases.



IGURE 20.24 Sea e As a Feedback echanism The image ows the springtime eakup of sea ice near ntarctica. The diagram ows a likely feedback op. A reduction in sea ice cts as a positive-feedback echanism because surface bedo decreases, and the mount of energy absorbed t the surface increases. hoto by Radius Images/Alamy)

So far, the climate-feedback mechanisms discussed have magnified the temperature rise caused by the buildup of carbon dioxide. Because these effects reinforce the initial change, they are called **positive-feedback mechanisms**. However, other effects must be classified as **negative-feedback mechanisms** because they produce results that are just the opposite of the initial change and tend to offset it.

One probable result of a global temperature rise would be an accompanying increase in cloud cover due to the higher moisture content of the atmosphere. Most clouds are good reflectors of solar radiation. At the same time, however, they are also good absorbers and emitters of radiation emitted by Earth. Consequently, clouds produce two opposite effects. They are a negative-feedback mechanism because they increase the reflection of solar radiation and thus diminish the amount of solar energy available to heat the atmosphere. On the other hand, clouds act as a positive-feedback mechanism by absorbing and emitting radiation that would otherwise be lost from the troposphere.

Which effect, if either, is stronger? Scientists still are not sure whether clouds will produce net positive or negative feedback. Although recent studies have not settled the question, they seem to lean toward the idea that clouds do not dampen global warming but rather produce a small positive feedback overall.[3]

Global warming caused by human-induced changes in atmospheric composition continues to be one of the most-studied aspects of climate change. Although no models yet incorporate

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[3] A. E. Dessler, "A Determination of the Cloud Feedback from Climate Variations over the Past Decade," *Science* 330: 1523–1526, December 10, 2010.

the full range of potential factors and feedbacks, there is strong scientific consensus that the increasing levels of atmospheric carbon dioxide and trace gases have already warmed the planet and will continue to do so into the foreseeable future.

Computer Models of Climate: Important yet Imperfect Tools

Earth's climate system is amazingly complex. Comprehensive state-of-the-science climate simulation models are among the basic tools used to develop possible climate-change scenarios. Called *general circulation models* (*GCMs*), they are based on fundamental laws of physics and chemistry and incorporate human and biological interactions. The models simulate many variables, including temperature, rainfall, snow cover, soil moisture, winds, clouds, sea ice, and ocean circulation over the entire globe through the seasons and over spans of decades.

In many other fields of study, hypotheses can be tested by direct experimentation in the laboratory or by observations and measurements in the field. However, this is often not possible in the study of climate. Rather, scientists must construct computer models of how our planet's climate system works. If we understand the climate system correctly and construct a model appropriately, then the behavior of the model climate system should mimic the behavior of Earth's climate system (**FIGURE 20.25**).

What factors influence the accuracy of climate models? Clearly, mathematical models are *simplified* versions of the real Earth and cannot capture its full complexity, especially at smaller geographic scales. Moreover, when computer models are used to simulate future climate change, many assumptions have to be made that significantly influence the outcome. They must consider a wide range of possibilities for future changes in population, economic growth, consumption of fossil fuels, technological development, improvements in energy efficiency, and more.

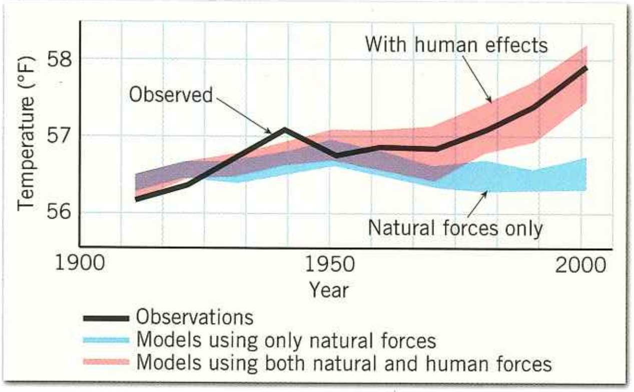

FIGURE 20.25 Computer Models The blue band shows how global average temperatures would have changed due to natural forces only, as simulated by climate models. The red band shows model projections of the effects of human and natural forces combined. The black line shows actual observed global average temperatures. As the blue band indicates, without human influences, temperatures over the past century would actually have first warmed and then cooled slightly over recent decades. Bands of color are used to express the range of uncertainty. (U.S. Global Change Research Program)

Despite many obstacles, our ability to use supercomputers to simulate climate continues to improve. Although today's models are far from infallible, they are powerful tools for understanding what Earth's future climate might be like.

20.9 CONCEPT CHECKS

1. Distinguish between positive and negative climate-feedback mechanisms.
2. Provide at least one example of each type of feedback mechanism.
3. List some factors that influence the accuracy of computer models of climate.

20.10 HOW AEROSOLS INFLUENCE CLIMATE

Discuss the possible impacts of aerosols on climate change.

Increasing the levels of carbon dioxide and other greenhouse gases in the atmosphere is the most direct human influence on global climate. But it is not the only impact. Global climate is also affected by human activities that contribute to the atmosphere's aerosol content. **Aerosols** are the tiny, often microscopic, liquid and solid particles that are suspended in the air. Unlike cloud droplets, aerosols are present even in relatively dry air. Atmospheric aerosols are composed of many different materials, including soil, smoke, sea salt, and sulfuric acid. Natural sources are numerous and include such phenomena as dust storms and volcanoes.

Most human-generated aerosols come from the sulfur dioxide emitted during the combustion of fossil fuels and as a consequence of burning vegetation to clear agricultural land. Chemical reactions in the atmosphere convert the sulfur dioxide into sulfate aerosols, the same material that produces acid precipitation. The satellite images in **FIGURE 20.26** provide an example.

How do aerosols affect climate? Aerosols act directly by reflecting sunlight back to space and indirectly by making clouds "brighter" reflectors. The second effect relates to the fact that many aerosols (such as those composed of salt or sulfuric acid) attract water and thus are especially effective as cloud condensation nuclei. The large quantity of aerosols produced by human activities (especially industrial emissions) trigger an increase in the number of cloud droplets that form within a cloud. A greater number of small droplets increases the cloud's brightness, causing more sunlight to be reflected back to space.

One category of aerosols, called **black carbon**, is soot generated by combustion processes and fires. Unlike most other aerosols, black carbon warms the atmosphere because it is an effective absorber of incoming solar radiation. In addition, when deposited on snow and ice, black carbon reduces surface albedo, thus increasing the amount of light absorbed. Nevertheless, despite the warming effect of black carbon, the overall effect of atmospheric aerosols is to cool Earth.

Studies indicate that the cooling effect of human-generated aerosols offsets a portion of the global warming caused by the growing quantities of greenhouse gases in the

20.26 Human-
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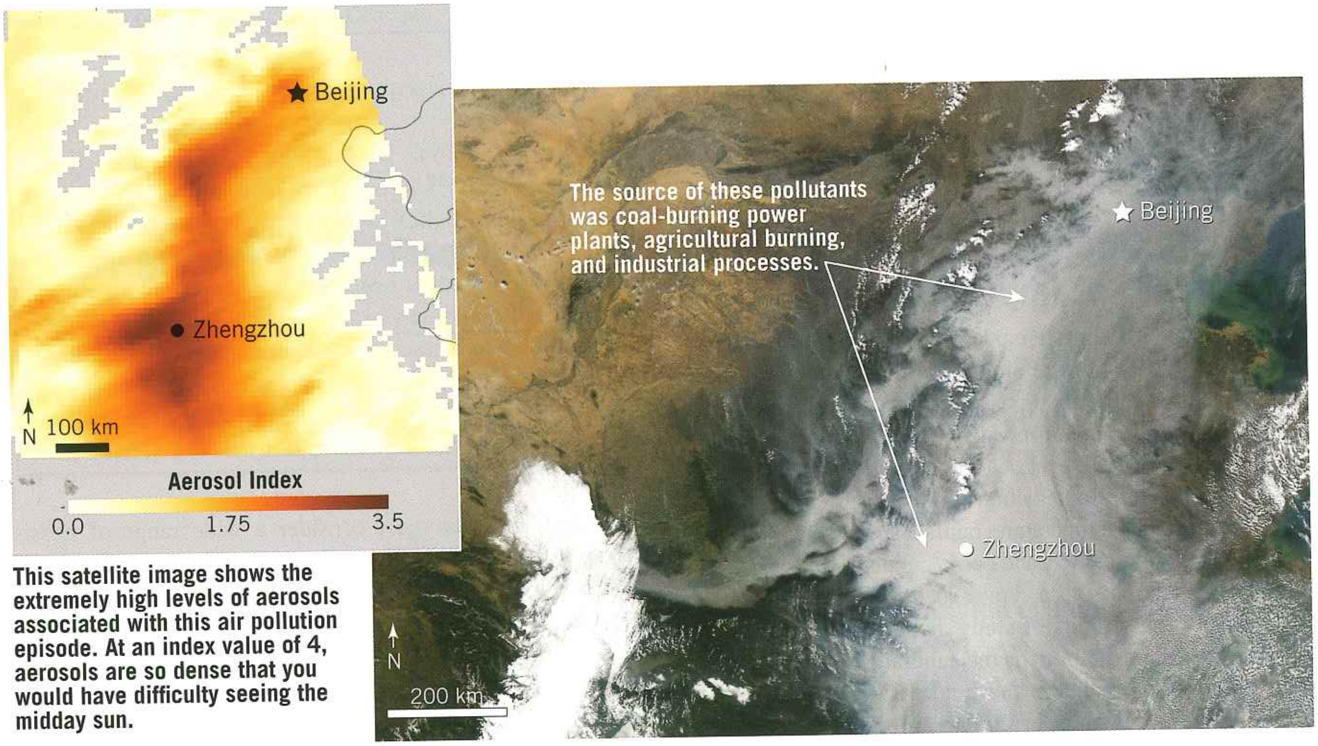
nages show a
r pollution episode
ed China on
, 2010. (NASA)



The source of these pollutants was coal-burning power plants, agricultural burning, and industrial processes.

This satellite image shows the extremely high levels of aerosols associated with this air pollution episode. At an index value of 4, aerosols are so dense that you would have difficulty seeing the midday sun.

atmosphere. The magnitude and extent of the cooling effect of aerosols is uncertain. This uncertainty is a significant hurdle in advancing our understanding of how humans alter Earth's climate.

It is important to point out some significant differences between global warming by greenhouse gases and aerosol cooling. After being emitted, greenhouse gases, such as carbon dioxide, remain in the atmosphere for many decades. By contrast, aerosols released into the troposphere remain there for only a few days or, at most, a few weeks before they are "washed out" by precipitation. Because of their short lifetime in the troposphere, aerosols are distributed unevenly over the globe. As expected, human-generated aerosols are concentrated near the areas that produce them—namely industrialized regions that burn fossil fuels and land areas where vegetation is burned.

The lifetime of aerosols in the atmosphere is short. Therefore, the effect of aerosols on today's climate is determined by the amount emitted during the preceding couple weeks. By contrast, the carbon dioxide and trace gases released into the atmosphere remain for much longer spans and thus influence climate for many decades.

20.10 CONCEPT CHECKS

1. What are the main sources of human-generated aerosols?
2. What effect does black carbon have on atmospheric temperatures?
3. What is the net effect of aerosols on temperatures in the troposphere?
4. How long do aerosols remain in the atmosphere before they are removed?
5. How does the residence time of aerosols compare to that of CO_2?

20.11 SOME POSSIBLE CONSEQUENCES OF GLOBAL WARMING

Describe some possible consequences of global warming.

What consequences can be expected if the carbon dioxide content of the atmosphere reaches a level that is twice what it was early in the twentieth century? Because the climate system is complex, predicting the distribution of particular regional changes can be speculative. It is not yet possible to pinpoint specifics, such as where or when it will become drier or wetter. Nevertheless, plausible scenarios can be given for larger scales of space and time.

As noted, the magnitude of the temperature increase will not be the same everywhere. The temperature rise will probably be smallest in the tropics and increase toward the poles. As for precipitation, the models indicate that some regions will experience significantly more precipitation and runoff, whereas others will experience a decrease in runoff due to reduced precipitation or greater evaporation caused by higher temperatures.

TABLE 20.1 summarizes some of the most likely effects and their possible consequences. The table also provides the IPCC's estimate of the probability of each effect. Levels of confidence for these projections vary from "likely" (67 to 90 percent probability) to "very likely" (90 to 99 percent probability) to "virtually certain" (greater than 99 percent probability).

TABLE 20.1 Projected Changes and Effects of Global Warming in the Twenty-First Century

Projected Changes and Estimated Probability*	Examples of Projected Impacts
Higher maximum temperatures; more hot days and heat waves over nearly all land areas (*virtually certain*)	Increased incidence of death and serious illness in older age groups and urban poor. Increased heat stress in livestock and wildlife. Shift in tourist destinations. Increased risk of damage to a number of crops. Increased electric cooling demand and reduced energy supply reliability.
Higher minimum temperatures; fewer cold days, frost days, and cold waves over nearly all land areas (*virtually certain*)	Decreased cold-related human morbidity and mortality. Decreased risk of damage to a number of crops and increased risk to others. Extended range and activity of some pest and disease vectors. Reduced heating energy demand.
Increases in frequency of heavy precipitation events over most areas (*very likely*)	Increased flood, landslide, avalanche, and debris flow damage. Increased soil erosion. Increased flood runoff could increase recharge of some floodplain aquifers. Increased pressure on government and private flood insurance systems and disaster relief.
Increases in area affected by drought (*likely*)	Decreased crop yields. Increased damage to building foundations caused by ground shrinkage. Decreased water-resource quantity and quality. Increased risk of wildfires.
Increases in intense tropical cyclone activity (*likely*)	Increased risks to human life, risk of infectious-disease epidemics, and many other risks. Increased coastal erosion and damage to coastal buildings and infrastructure. Increased damage to coastal ecosystems, such as coral reefs and mangroves.

* *Virtually certain* indicates a probability greater than 99 percent, *very likely* indicates a probability of 90–99 percent, and *likely* indicates a probability of 67–90 percent.

Source: Adapted from Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.3. IPCC, Geneva, Switzerland.

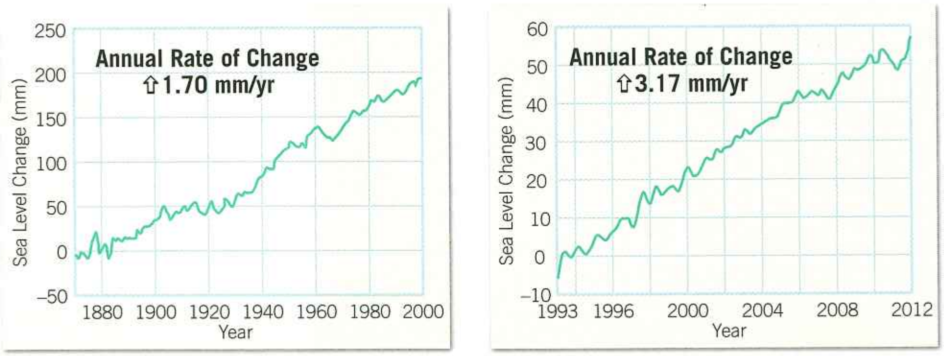
Sea-Level Rise

A significant impact of human-induced global warming is a rise in sea level. As this occurs, coastal cities, wetlands, and low-lying islands could be threatened with more frequent flooding, increased shoreline erosion, and saltwater encroachment into coastal rivers and aquifers.

Research indicates that sea level has risen about 25 centimeters (9.75 inches) since 1870. As **FIGURE 20.27** indicates, the rate of sea-level rise has been greater in recent years. Some models indicate that additional rise may approach or even exceed 50 centimeters (20 inches) by the end of the twenty-first century. Such a change may seem modest, but scientists realize that any rise in sea level along a *gently* sloping shoreline, such as the Atlantic and Gulf coasts of the United States, will lead to significant erosion and severe and permanent inland flooding (**FIGURE 20.28**). If this happens, many beaches and wetlands will be eliminated, and coastal civilization will be severely disrupted. Low-lying and densely populated places such as Bangladesh and the small island nation of the Maldives are especially vulnerable. The average elevation in the Maldives is 1.5 meters (less than 5 feet), and its highest point is just 2.4 meters (less than 8 feet) above sea level.

How is a warmer atmosphere related to a rise in sea level? One significant factor is thermal expansion. Higher air temperatures warm the adjacent upper layers of the ocean, which in turn causes the water to expand and sea level to rise.

Perhaps a more easily visualized contributor to global sea-level rise is melting glaciers. With few exceptions, glaciers around the world have been retreating at unprecedented rates over the past century. Some mountain glaciers have disappeared altogether. A recent 18-year satellite study showed that the mass of the Greenland and Antarctic Ice Sheets dropped an average of 475 gigatons per year. (A gigaton is 1 billion metric tons.) That is enough water to raise sea level 1.5 millimeters (0.05 inch) per year. The loss of ice was not steady but was occurring at an accelerating rate during the study period. Each year over the course of the study period, the two ice sheets lost a combined average of 36.3 gigatons more than they did the year before. During the same span, mountain

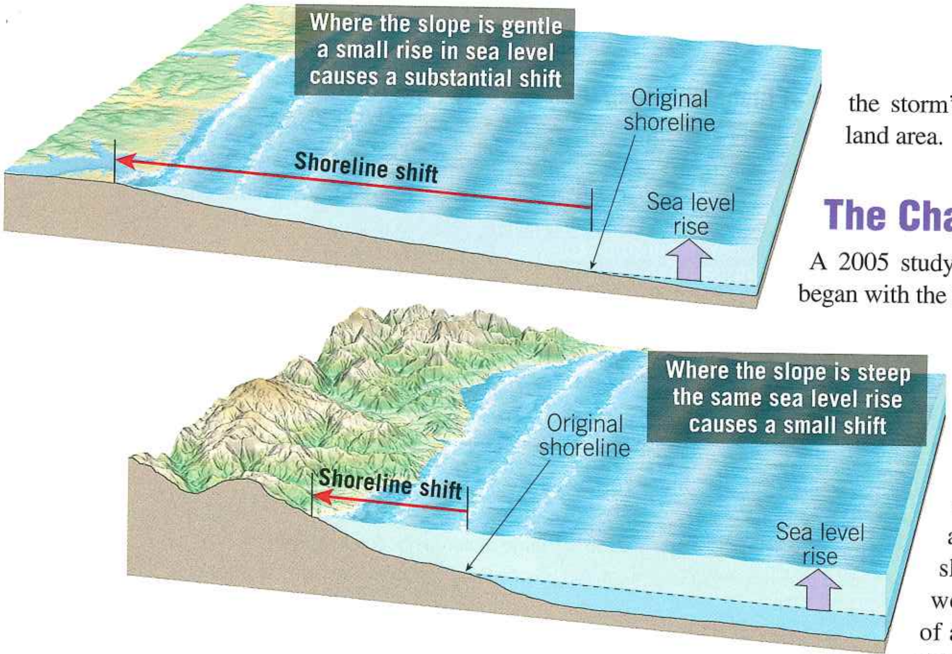


A. Sea Level Change 1870 to 2000

B. Sea Level Change 1993 to 2012

FIGURE 20.27 Rising Sea Level These graphs show sea-level change from 1870 until 2012. Note the difference in the rate of change between the two graphs. **A.** This graph shows historical sea-level data derived from coastal tide gauges. **B.** This graph shows the average sea level since 1993, derived from global satellite measurements. (NASA)

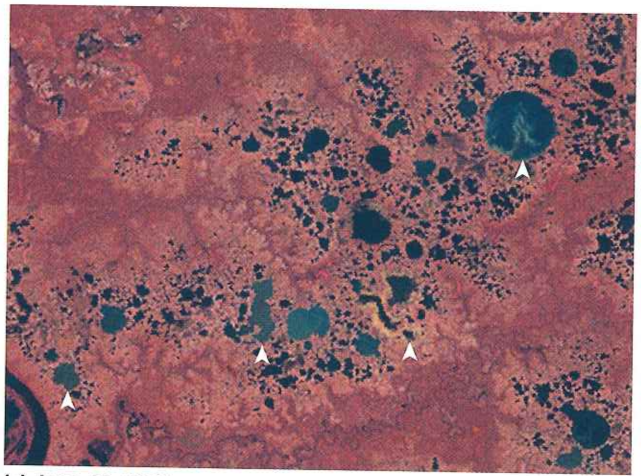
SmartFigure 20.28 Slope of the Shoreline The slope of the shoreline is critical to determining the degree to which sea-level changes will affect it. As sea level gradually rises, the shoreline retreats, and structures that were once thought to be safe from wave attack become vulnerable.



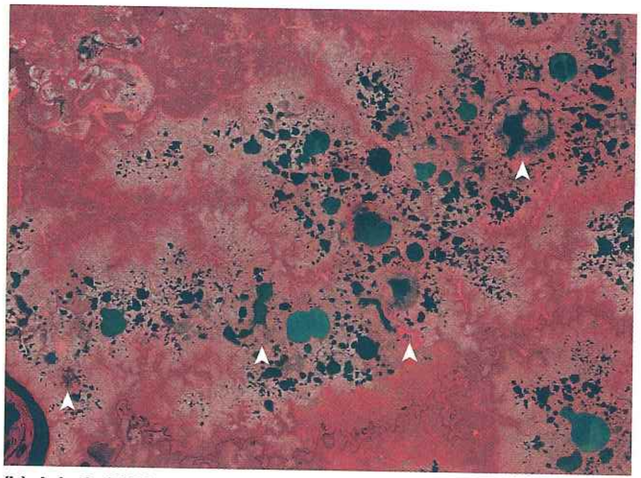
glaciers and ice caps lost an average of slightly more than 400 gigatons per year.

Because rising sea level is a gradual phenomenon, coastal residents may overlook it as an important contributor to shoreline erosion problems. Rather, the blame may be assigned to other forces, especially storm activity. Although a given storm may be the immediate cause, the magnitude of its destruction may result from the relatively small sea-level rise that allowed the storm's power to cross a much greater land area.

IGURE 20.29 Siberian akes This false-color nage pair shows lakes otting the tundra in 1973 nd 2002. The tundra egetation is colored a faded d, whereas lakes appear ue or blue-green. Many kes disappeared or shrunk onsiderably between 1973 nd 2002. After studying atellite imagery of about ,000 large lakes in a 0,000-square-kilometer 95,000-square-mile) area northern Siberia, scientists ocumented an 11 percent ecline in the number of kes, at least 125 of which sappeared completely. ASA)



(a) June 27, 1973



(b) July 2, 2002

The Changing Arctic

A 2005 study of climate change in the Arctic began with the following statement:

> For nearly 30 years, Arctic sea ice extent and thickness have been falling dramatically. Permafrost temperatures are rising and coverage is decreasing. Mountain glaciers and the Greenland ice sheet are shrinking. Evidence suggests we are witnessing the early stage of an anthropogenically induced global warming superimposed on natural cycles, reinforced by reductions in Arctic ice.[4]

Arctic Sea Ice Climate models are in general agreement that one of the strongest signals of global warming should be a loss of sea ice in the Arctic. This is indeed occurring. The area covered by sea ice naturally grows during the frigid Arctic winters and shrinks when temperatures climb in the spring and summer. Since 1979, satellites have observed a 13 percent decline per decade in the minimum summertime extent of sea ice in the Arctic. The thickness of the ice has also been declining.

The map in Figure 14.3A (page 435) compares the average sea ice extent for early September 2012 to the long-term average for the period 1979–2000. The extent of sea ice in September 2012 set a record. On that date the extent was less than 4 million square kilometers (1.54 million square miles)—70,000 square kilometers (27,000 square miles) less than the previous record low set in September 2007. The trend is also clear when you examine the graph in Figure 14.3B. Is it possible that this trend may be part of a natural cycle? Yes, but it is more likely that the sea ice decline represents a combination of natural variability and human-induced global warming, with the latter becoming increasingly evident in coming decades. As was noted in the section "Climate-Feedback Mechanisms," a reduction in sea ice represents a positive-feedback mechanism that reinforces global warming.

Permafrost During the past decade, mounting evidence has indicated that the extent of permafrost in the Northern Hemisphere has decreased, as would be expected under long-term warming conditions. **FIGURE 20.29** presents one example which shows that such a decline is occurring.

In the Arctic, short summers thaw only the top layer of frozen ground. The permafrost beneath this *active layer* is like the cement bottom of a swimming pool. In summer, water cannot percolate downward, so it saturates the soil

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[4] J. T. Overpeck, et al., "Arctic System on Trajectory to New, Seasonally Ice-Free States," *EOS, Transactions, American Geophysical Union*, 86(34): 309, August 23, 2005.

above the permafrost and collects on the surface in thousands of lakes. However, as Arctic temperatures climb, the bottom of the "pool" seems to be "cracking." Satellite imagery shows that over a 20-year span, a significant number of lakes have shrunk or disappeared altogether. As the permafrost thaws, lake water drains deeper into the ground.

Thawing permafrost represents a potentially significant positive-feedback mechanism that may reinforce global warming. When vegetation dies in the Arctic, cold temperatures inhibit its total decomposition. As a consequence, over thousands of years, a great deal of organic matter has become stored in the permafrost. When the permafrost thaws, organic matter that may have been frozen for millennia comes out of "cold storage" and decomposes. The result is the release of carbon dioxide and methane—greenhouse gases that contribute to global warming.

The Potential for "Surprises"

You have seen that climate in the twenty-first century, unlike in the preceding 1000 years, is not expected to be stable. Rather, a constant state of change is very likely. Many of the changes will probably be gradual environmental shifts, imperceptible from year to year. Nevertheless, the effects, accumulated over decades, will have powerful economic, social, and political consequences.

Despite our best efforts to understand future climate shifts, there is also the potential for "surprises." This simply means that, due to the complexity of Earth's climate system, we might experience relatively sudden, unexpected changes or see some aspects of climate shift in an unexpected manner. The report *Climate Change Impacts on the United States* describes the situation like this:

> Surprises challenge humans' ability to adapt, because of how quickly and unexpectedly they occur. For example, what if the Pacific Ocean warms in such a way that El Niño events become much more extreme? This could reduce the frequency, but perhaps not the strength, of hurricanes along the East Coast, while on the West Coast, more severe winter storms, extreme precipitation events, and damaging winds could become common. What if large quantities of methane, a potent greenhouse gas currently frozen in icy Arctic tundra and sediments, began to be released to the atmosphere by warming, potentially creating an amplifying "feedback loop" that would cause even more warming? We simply do not know how far the climate system or other systems it affects can be pushed before they respond in unexpected ways.
>
> There are many examples of potential surprises, each of which would have large consequences. Most of these potential outcomes are rarely reported, in this study or elsewhere. Even if the chance of any particular surprise happening is small, the chance that at least one such surprise will occur is much greater. In other words, while we can't know which of these events will occur, it is likely that one or more will eventually occur.[5]

The impact on climate of an increase in atmospheric carbon dioxide and trace gases is obscured by some uncertainties. Yet climate scientists continue to improve our understanding of the climate system and the potential impacts and effects of global climate change. Policymakers are confronted with responding to the risks posed by emissions of greenhouse gases, knowing that our understanding is imperfect. However, they are also faced with the fact that climate-induced environmental changes cannot be reversed quickly, if at all, due to the lengthy time scales associated with the climate system.

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[5] National Assessment Synthesis Team, *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change* (Washington, DC: U.S. Global Research Program, 2000), p. 19.

20.11 CONCEPT CHECKS

1. List and describe the factors that are causing sea level to rise.
2. Is global warming greater near the equator or near the poles? Explain.
3. Based on Table 20.1, what projected changes relate to something other than temperature?

20 CONCEPTS IN REVIEW
World Climates and Global Climate Change

20.1 THE CLIMATE SYSTEM

List the five parts of the climate system and provide examples of each.

KEY TERM: climate system

- Climate is the aggregate of weather conditions for a place or region over a long period of time.
- Earth's climate system involves the exchanges of energy and moisture that occur among the atmosphere, hydrosphere, solid Earth, biosphere, and *cryosphere* (the ice and snow that exist at Earth's surface).

Q Which sphere of the climate system dominates this image? What other sphere or spheres are present?


James Balog/Getty Images

.2 WORLD CLIMATES

Explain why classification is a necessary process when studying world climates. Discuss the criteria used in the Köppen system of climate classification.

TERM: Köppen classification

Climate classification brings order to large quantities of information, which aids comprehension and understanding and facilitates analysis and xplanation.

The most important elements in climate descriptions are temperature and precipitation because they have the greatest influence on people and their ctivities, and they also have an important impact on the distribution of vegetation and the development of soils.

- An early attempt at climate classification by the Greeks divided each hemisphere into three zones: torrid, temperate, and frigid. Many climate classifications have been devised, with the value of each determined by its intended use.
- The Köppen classification, which uses mean monthly and annual values of temperature and precipitation, is a widely used system. The boundaries Köppen chose were largely based on the limits of certain plant associations.
- Five principal climate groups, each with subdivisions, were recognized. Each group is designated by a capital letter. Four of the climate groups—A, C, D, and E—are defined on the basis of temperature characteristics, and the fifth, the B group, has precipitation as its primary criterion.

Q Why are three different formulas used to determine whether a climate is considered dry?

.3 HUMID TROPICAL (A) CLIMATES

Compare the two broad categories of tropical climates.

TERMS: tropical rain forest, tropical wet and dry

Humid tropical (A) climates are winterless, with all months having a mean temperature above 18°C (64°F).

Wet tropical climates (Af and Am), which lie near the equator, have constantly high temperatures and enough rainfall to support the most luxuriant vegetation (tropical rain forest) found in any climatic ealm.

Tropical wet and dry climates (Aw) are found poleward of the wet tropics and equatorward of the ubtropical deserts, where the rain forest gives way o the tropical grasslands and scattered drought-olerant trees of the savanna. The most distinctive eature of this climate is the seasonal character of the rainfall.

When does the rainy season occur in a tropical wet and dry climate: winter or summer? Explain.

20.4 DRY (B) CLIMATES

Contrast low-latitude dry climates and middle-latitude dry climates.

KEY TERMS: arid (desert), semiarid (steppe)

- Dry (B) climates, in which the yearly precipitation is less than the potential loss of water by evaporation, are subdivided into two types: arid or desert (BW) and semiarid or steppe (BS).
- Differences between desert and steppe are primarily a matter of degree, with semiarid being a marginal and more humid variant of arid.
- Low-latitude deserts and steppes coincide with the clear skies caused by subsiding air beneath the subtropical high-pressure belts.
- Middle-latitude deserts and steppes exist principally because of their position in the deep interiors of large landmasses far removed from the ocean. Because many middle-latitude deserts occupy sites on the leeward sides of mountains, they can also be classified as rain shadow deserts.


Dennis Tasa

Q This photo was taken in Nevada's Great Basin Desert, looking west toward the Sierra Nevada. What is the basic cause of the arid conditions in this region?

.5 HUMID MIDDLE-LATITUDE CLIMATES (C AND D CLIMATES)

Distinguish among five different humid middle-latitude climates.

TERMS: humid subtropical climate, marine west coast climate, dry-summer subtropical climate, humid continental climate, subarctic climate

Middle-latitude climates with mild winters (C climates) occur where the average temperature of the coldest month is below 18°C (64°F) but above –3°C 27°F). Three C climate subgroups exist.

Humid subtropical climates (Cfa) are located on the eastern sides of the continents, in the 25°–40° latitude range. Summer weather is hot and sultry, and winters are mild. In North America, the marine west coast climate (Cfb, Cfc) extends from near the U.S.–Canada border northward as a narrow belt into outhern Alaska. The prevalence of maritime air masses means that mild winters and cool summers are the rule. Dry-summer subtropical climates (Csa, Csb) are typically located along the west sides of continents between latitudes 30° and 45°. In summer, the regions are dominated by stable, dry conditions ssociated with the oceanic subtropical highs. In winter, they are within range of the cyclonic storms of the polar front.

Humid middle-latitude climates with severe winters (D climates) are land-controlled climates that are absent in the Southern Hemisphere. The D climates ave severe winters. The average temperature of the coldest month is –3°C (27°F) or below, and the warmest monthly mean exceeds 10°C (50°F).

Humid continental climates (Dfa, Dfb, Dwa, Dwb) are confined to the eastern portions of North America and Eurasia in the latitude range between approximately 40° and 50° north latitude. Both winter and summer temperatures can be characterized as relatively severe. Precipitation is generally greater n summer than in winter. Subarctic climates (Dfc, Dfd, Dwc, Dwd) are situated north of the humid continental climates and south of the polar tundras. The outstanding feature of subarctic climates is the dominance of winter. By contrast, summers in the subarctic are remarkably warm, despite their short duration. The highest annual temperature ranges on Earth occur here.

20.6 POLAR (E) CLIMATES

Contrast ice cap and tundra climates.

KEY TERMS: polar climate, tundra climate, ice cap climate

- Polar climates (ET, EF) are those in which the mean temperature of the warmest month is below 10°C (50°F). Annual temperature ranges are extreme, with the lowest annual means on the planet. Although polar climates are classified as humid, precipitation is generally meager, with many nonmarine stations receiving less than 25 centimeters (10 inches) annually. Two types of polar climates are recognized.
- The tundra climate (ET) is found almost exclusively in the Northern Hemisphere. The 10°C (50°F) summer isotherm represents its equatorward limit. It is a treeless region of grasses, sedges, mosses, and lichens with permanently frozen subsoil, called permafrost.
- The ice cap climate (EF) does not have a single monthly mean above 0°C (32°F). Consequently, the growth of vegetation is prohibited, and the landscape is one of permanent ice and snow. The ice sheets of Greenland and Antarctica are important examples.

20.7 HIGHLAND CLIMATES

Summarize the characteristics associated with highland climates.

KEY TERM: highland climates

- Highland climates are characterized by a great diversity of climatic conditions over a small area. Although the best-known climatic effect of increased altitude is lower temperatures, greater precipitation due to orographic lifting is also common. Variety and changeability best describe highland climates. Because atmospheric conditions fluctuate with altitude and exposure to the Sun's rays, a nearly limitless variety of local climates occur in mountainous regions.

Q Which of the local winds discussed in Chapter 18 are likely associated with highland climates?

20.8 HUMAN IMPACT ON GLOBAL CLIMATE

Summarize the nature and cause of the atmosphere's changing composition since about 1750. Describe the climate's response.

- Humans have been modifying the environment for thousands of years. By altering ground cover with the use of fire and the overgrazing of land, people have modified such important climatic factors as surface albedo, evaporation rates, and surface winds.
- Human activities produce climate change through the release of carbon dioxide (CO_2) and trace gases. Humans release CO_2 when they cut down forests and when they burn fossil fuels such as coal, oil, and natural gas. A steady rise in atmospheric CO_2 levels has been documented at Mauna Loa, Hawaii, and other locations around the world.
- More than half of the carbon released by humans is absorbed by new plant matter or dissolved in the oceans. About 45 percent remains in the atmosphere, where it can influence climate for decades. Air bubbles trapped in glacial ice reveal that there is currently about 30 percent more CO_2 than the atmosphere has contained in the past 650,000 years.
- As a result of the extra heat retention due to added CO_2, Earth's atmosphere has warmed by about 0.8°C (1.4°F) in the past 100 years, most of it since the 1970s. Temperatures are projected to increase by another 2° to 4.5°C (3.6° to 8.1°F) in the future.
- Trace gases such as methane, nitrous oxide, and CFCs also play a significant role in increasing global temperature.

20.9 CLIMATE-FEEDBACK MECHANISMS

Contrast positive- and negative-feedback mechanisms and provide examples of each.

KEY TERMS: climate-feedback mechanism, positive-feedback mechanism, negative-feedback mechanism

- A change in one part of the climate system may trigger changes in other parts of the climate system that amplify or diminish the initial effect. These climate-feedback mechanisms are called positive-feedback mechanisms if they reinforce the initial change and negative-feedback mechanisms if they counteract the initial effect.
- The melting of sea ice due to global warming (decreasing albedo and increasing the initial effect of warming) is one example of a positive-feedback mechanism. The production of more clouds (blotting out incoming solar radiation, leading to cooling) is an example of a negative-feedback mechanism.
- Computer models of climate give scientists a tool for testing hypotheses about climate change. Although these models are far simpler than the real climate system, they are useful tools for predicting the future climate.

Michael Collier

Q Changes in precipitation and temperature due to climate change can increase the risk of forest fires. Describe two ways that the event shown in this photo could contribute to global warming.

0.10 HOW AEROSOLS INFLUENCE CLIMATE

Discuss the possible impacts of aerosols on climate change.

Y TERMS: aerosols, black carbon

- Aerosols are tiny liquid and solid particles that are suspended in the air. Global climate is affected by human activities that contribute to the atmosphere's aerosol content.
- Most aerosols reflect a portion of incoming solar radiation back to space and therefore have a cooling effect.
- Overall, aerosols have a cooling effect, yet some aerosols called black carbon (soot from combustion processes and fires) absorb incoming solar radiation and warm the atmosphere. When black carbon is deposited on snow and ice, it reduces surface albedo and increases the amount of light absorbed at the surface.

Do aerosols spend more or less time in the atmosphere than greenhouse gases such as carbon dioxide? What is the significance of this difference in residence time? Explain.

20.11 SOME POSSIBLE CONSEQUENCES OF GLOBAL WARMING

Describe some possible consequences of global warming.

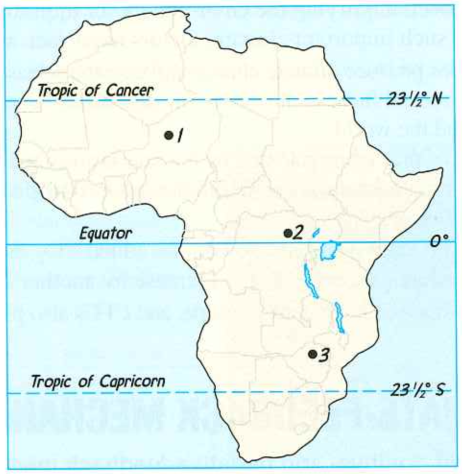
- In the future, Earth's surface temperature is likely to continue to rise. The temperature increase will likely be greatest in the polar regions and least in the tropics. Some areas will get drier, and other areas will get wetter.
- Sea level is predicted to rise for several reasons, including the melting of glacial ice and thermal expansion (a given mass of seawater takes up more volume when it is warm than when it is cool). Low-lying, gently sloped, highly populated coastal areas are most at risk.
- Sea ice cover and thickness in the Arctic have been declining since satellite observations began in 1979.
- Because of the warming of the Arctic, permafrost is melting, releasing CO_2 and methane to the atmosphere in a positive-feedback mechanism.
- Because the climate system is complicated, dynamic, and imperfectly understood, it could produce sudden, unexpected changes with little warning.

IVE IT SOME THOUGHT

Refer to Figure 20.1, which illustrates various components of Earth's climate system. Boxes represent interactions or changes that occur in the climate system. Select three boxes and provide an example of an interaction or change associated with each. Explain how these interactions may influence temperature.

2. Describe one way in which changes in the biosphere can cause changes in the climate system. Next, suggest one way in which the biosphere is affected by changes in some other part of the climate system. Finally, indicate one way in which the biosphere records changes in the climate system.

3. Refer to the monthly rainfall data (in millimeters) for three cities in Africa. Their locations are shown on the accompanying map. Match the data for each city to the correct location (1, 2, or 3) on the map. How were you able to figure this out? *Bonus:* Which figure in Chapter 18 would be especially useful in explaining or illustrating why these places have rainfall maximums and minimums when they do?



	J	F	M	A	M	J	J	A	S	O	N	D
CITY A	81	102	155	140	133	119	99	109	206	213	196	122
CITY B	0	2	0	0	1	15	88	249	163	49	5	6
CITY C	236	168	86	46	13	8	0	3	8	38	94	201

4. Refer to Figure 20.5, which shows climates of the world. Humid continental (Dfb and Dwb) and subarctic (Dfc) climates are usually described as being "land controlled"—that is, they lack marine influence. Nevertheless, these climates are found along the margins of the North Atlantic and the North Pacific oceans. Explain why this occurs.

5. It has been suggested that global warming over the past several decades likely would have been greater were it not for the effect of certain types of air pollution. Explain how this could be true.

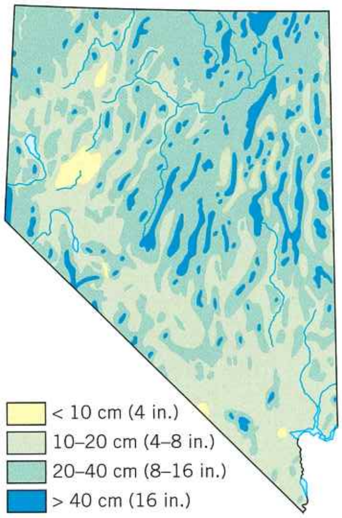
6. Motor vehicles are a significant source of CO_2. Using electric cars, such as the one pictured here, is one way to reduce emissions from this source. Although these vehicles emit little or no CO_2 or other air pollutants directly into the air, can they still be connected to such emissions? If so, explain.

David Pearson/Alamy

7. If a fellow student who, unlike you, had not studied climate were to ask, "Isn't the greenhouse effect a bad thing because it's responsible for global warming?" how would you respond?
8. During a conversation, an acquaintance indicates that he is skeptical about global warming. When you ask why he feels that way, he says, "The past couple of years in this area have been among the coolest I can remember." While you assure this person that it is useful to question scientific findings, you suggest to him that his reasoning in this case may be flawed. Use your understanding of the definition of *climate* along with one or more graphs in the chapter to persuade this person to reevaluate his reasoning.

EXAMINING THE **EARTH SYSTEM**

1. The Köppen climate classification is based on the fact that there is an excellent association between natural vegetation (biosphere) and climate (atmosphere). Briefly describe the climate conditions (temperature and precipitation) and natural vegetation associated with each of the following Köppen climates: Af, BWh, Dfc, and ET.
2. Examine the precipitation map for the state of Nevada. Notice that the areas receiving the most precipitation resemble long, slender "islands" scattered across the state. Provide an explanation for this pattern. Are average temperatures in these wetter areas likely different from those in nearby less rainy places? Why or why not? A look back at Section 6.9 and Figure 6.32 (page 195) might be helpful.



3. How might the burning of fossil fuels, such as the gasoline to run your car, influence global temperature? If such a temperature change occurs, how might sea level be affected? How might the intensity of hurricanes change? How might these changes impact people who live on a beach or barrier island along the Atlantic or Gulf coasts?
4. This satellite image from August 2007 shows the effects of tropical deforestation in a portion of the Amazon basin in western Brazil. Intact forest is dark green, whereas cleared areas are tan (bare ground) or light green (crops and pasture). Notice the relatively dense smoke in the left center of the image. How does deforestation of tropical forests change the composition of the atmosphere? Describe the effect that tropical deforestation has on global warming.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