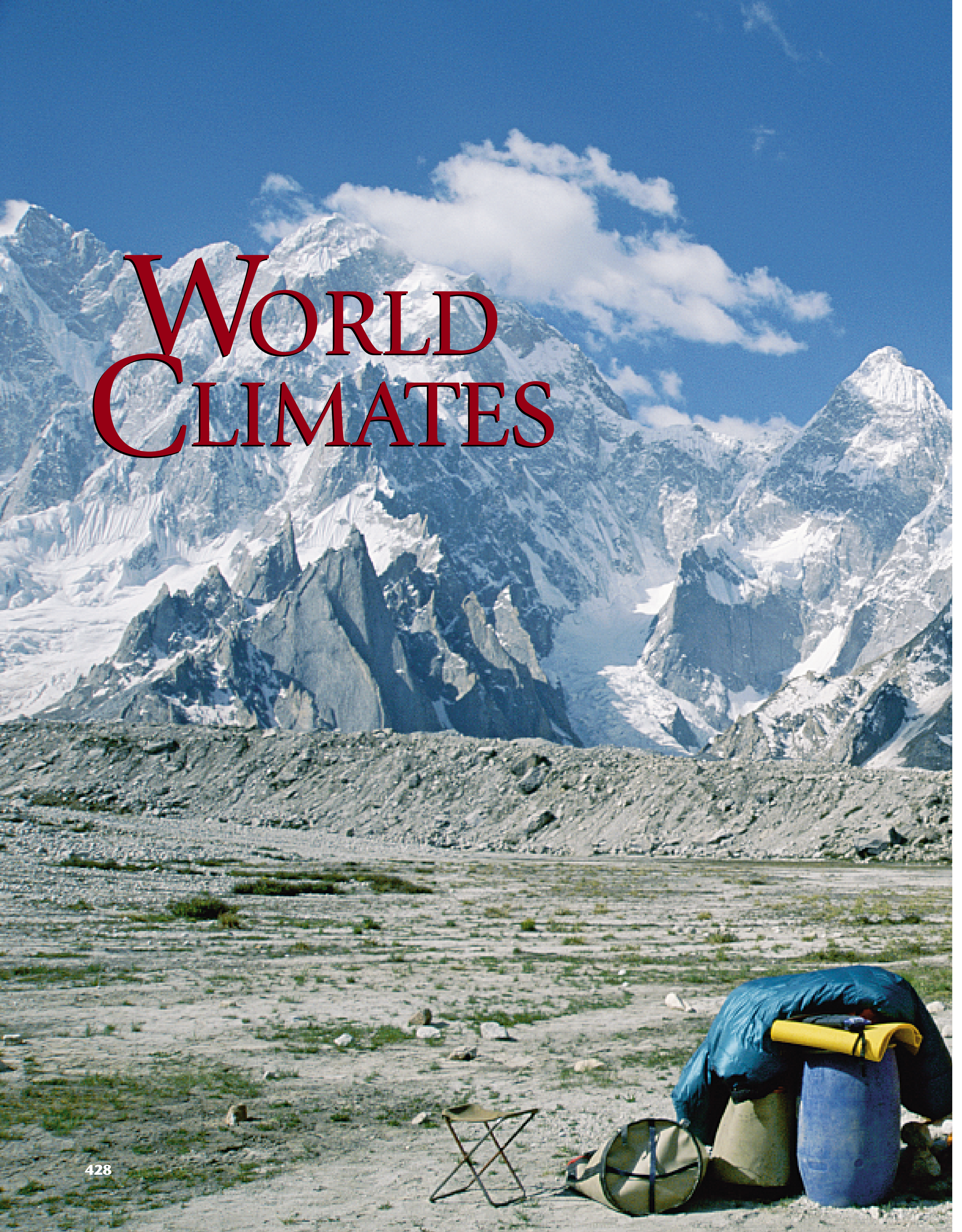
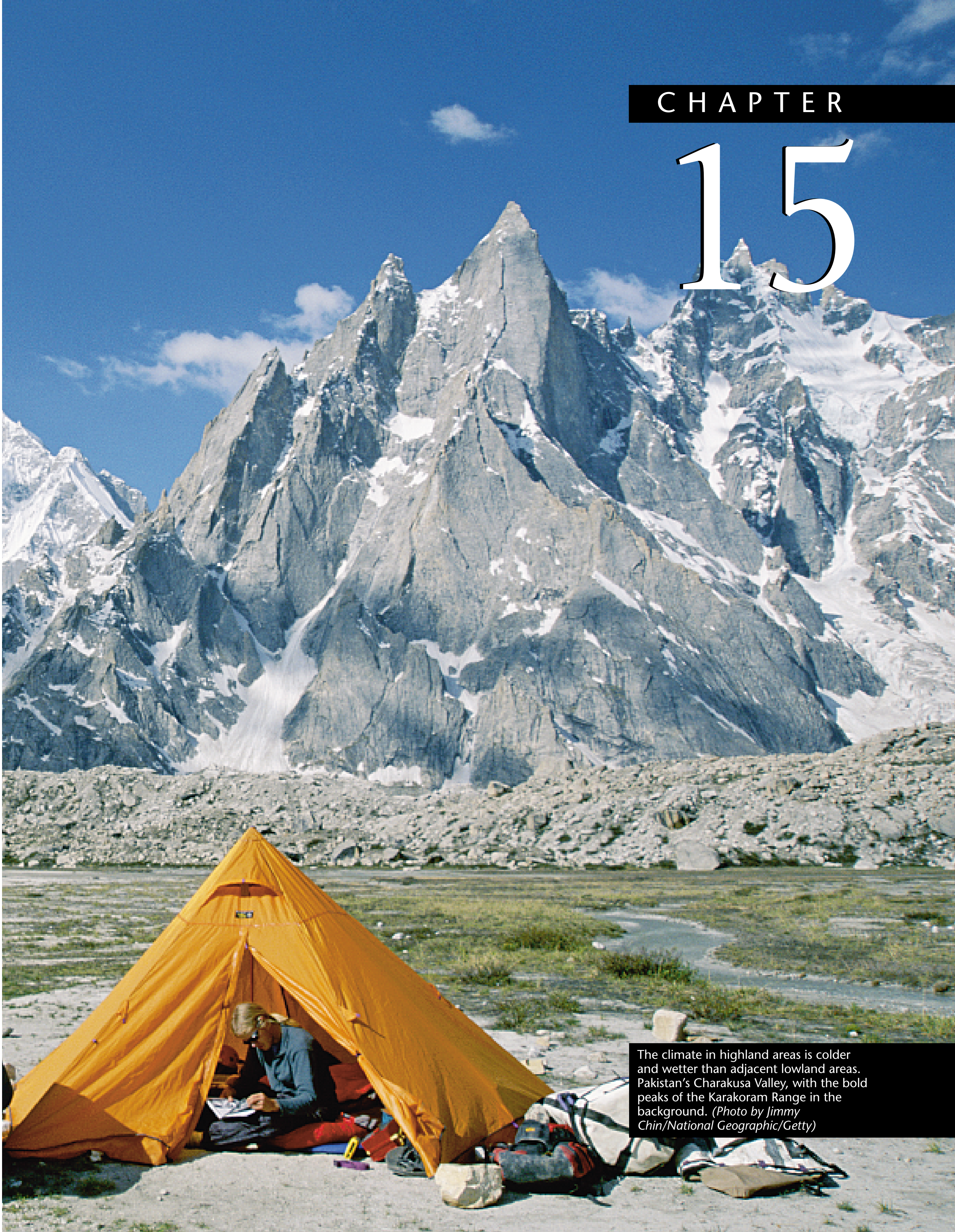
WORLD CLIMATES



CHAPTER

15



The climate in highland areas is colder and wetter than adjacent lowland areas. Pakistan's Charakusa Valley, with the bold peaks of the Karakoram Range in the background. *(Photo by Jimmy Chin/National Geographic/Getty)*

Previous chapters examined the spatial and seasonal variations in the elements of weather and climate. Now we turn to the *combined* effects of these variations in different parts of the world. The varied nature of Earth's surface (oceans, mountains, plains, ice sheets) and the many interactions that occur among atmospheric processes give every location on our planet a distinctive (sometimes unique) climate. However, we cannot describe the climatic character of countless locales; that would require many volumes.

Instead, our purpose is to introduce you to the *major climate regions* of the world. We will examine large areas and zoom in on particular places to illustrate the characteristics of these major climate regions. In addition, for those regions that are probably unfamiliar to you (the tropical, desert, and polar realms), we briefly describe the natural landscape. Keep in mind that this chapter is a general summary of world climates, using some specific examples.

In Chapter 1 we mentioned the common misconception that climate is only "the average state of the atmosphere." Although averages are certainly important to climate descriptions, variations and extremes must also be included to accurately portray the character of an area.

Temperature and precipitation are the most important elements in climate descriptions because they have the greatest influence on people and their activities and also have an important impact on the distribution of vegetation and the development of soils. Nevertheless, other factors are also important for a complete climate 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.

The first attempt at climate classification probably was made by the ancient Greeks, who divided each hemisphere into three zones: *torrid*, *temperate*, and *frigid*. (Figure 15–1) 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.

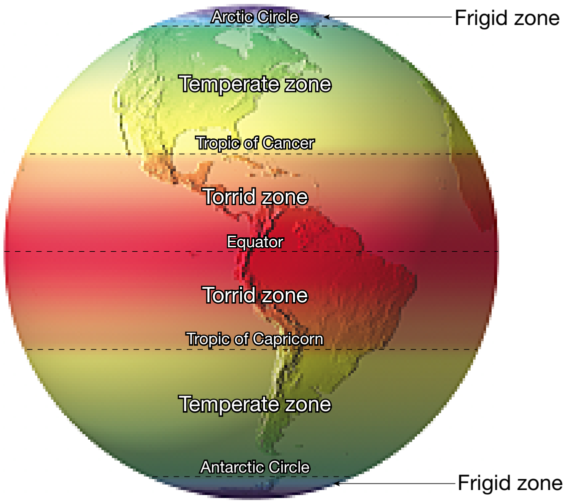


FIGURE 15-1 Probably the first attempt at climate classification was made by the ancient Greeks. They divided each hemisphere into three zones. The winterless *torrid* zone was separated from the summerless *frigid* zone by the *temperate* zone, which had features of the other two.

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.

In this chapter we use a classification devised by the 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 one, it uses easily obtained data: mean monthly and annual values of temperature and precipitation. Furthermore, the criteria are unambiguous, relatively simple to apply, and divide the world into climate regions in a realistic way.

Köppen believed that the distribution of natural vegetation was the best expression of overall climate. Consequently, the boundaries he chose were largely based on the limits of certain plant associations. He recognized five principal climate groups, each designated by a capital letter:

A *Humid tropical.* Winterless climates; all months having 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 these major groups (A, C, D, E) are defined on the basis of *temperature.* 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 Table 15–1.

TABLE 15-1 Köppen system of climate classification*

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.
	s		Same as under C
	w		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 −38°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.

*When classifying climate data using Table 15–1, you should 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 your 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.

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 their positions from one year to the next (Figure 15–2). 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 (see Box 15–1).

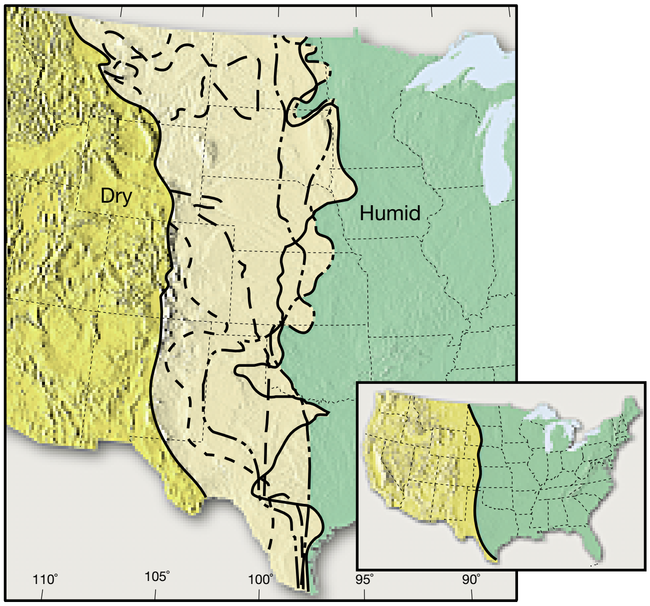
The world distribution of climates, according to the Köppen classification, is shown in Figure 15–3. We will refer you to this map several times as we examine Earth's climates in the following pages.

Climate Controls: A Summary

If Earth's surface were completely homogeneous, the map of world climates would be simple. It would look much like the ancient Greeks must have pictured it—a series of latitudinal bands girdling the globe in a symmetrical pattern on each side of the equator (Figure 15–1). Such is not the case, of course. Earth is not a homogeneous sphere, and many factors disrupt the symmetry just described.

At first glance the world climate map (Figure 15–3) reveals what appears to be a scrambled or even haphazard pattern, with similar climates located in widely separated parts of the world. A closer examination shows that although they may be far apart, similar climates generally have similar latitudinal and continental positions. This consistency suggests an order in the distribution of climate elements and that the pattern of climates is not by chance. Indeed, the climate pattern reflects a regular and dependable operation of the major climate controls. So before we examine Earth's major climates, it will be worthwhile to review each of the major controls: latitude, land and water, geographic position and prevailing winds, mountains and highlands, ocean currents, and pressure and wind systems.

FIGURE 15-2 Yearly fluctuations in the dry–humid boundary during a five-year period. The small inset shows the average position of the dry–humid boundary.



Latitude

Fluctuations in the amount of solar radiation received at Earth's surface represent the single greatest cause of temperature differences. Although variations in such factors as cloud coverage and the amount of dust in the air may be locally influential, seasonal changes in Sun angle and length of daylight are the most important factors controlling the global temperature distribution. Because all places situated along the same parallel of latitude have identical Sun angles and lengths of daylight, variations in the receipt of solar energy are largely a function of latitude. Moreover, because the vertical rays of the Sun migrate annually between the Tropic of Cancer and the Tropic of Capricorn, there is a regular latitudinal shifting of temperatures. Temperatures in the tropical realm are consistently high because the vertical rays of the Sun are never far away. As one moves farther poleward, however, greater seasonal fluctuations in the receipt of solar energy are reflected in larger annual temperature ranges.

Land and Water

The distribution of land and water must be considered second in importance only to latitude as a control of temperature. Recall that water has a greater *heat capacity* than rock and soil. Thus, land heats more rapidly and to higher temperatures than water, and it cools more rapidly and to lower temperatures than water. Consequently, variations in air temperatures are much greater over land than over water. This differential heating of Earth's surface has led to climates being divided into two broad classes—marine and continental.

Marine climates are considered relatively mild for their latitude because the moderating effect of water produces summers that are warm but not hot and winters that are cool but not cold. In contrast, **continental climates** tend to be much more extreme. Although a marine station and a continental station along the same parallel in the middle latitudes may have similar annual mean temperatures, the annual temperature *range* will be far greater at the continental station.

The differential heating and cooling of land and water can also have a significant effect on pressure and wind systems and hence on seasonal precipitation distribution as well. High summer temperatures over the continents can produce low-pressure areas that allow the inflow of moisture-laden maritime air. Conversely, the high pressure that forms over the chilled continental interiors in winter causes a reverse flow of dry air toward the oceans.

Geographic Position and Prevailing Winds

To understand fully the influence of land and water on the climate of an area, the position of that area on the continent and its relationship to the prevailing winds must be considered.

BOX 15-1 Climate Diagrams

Throughout this chapter climate diagrams accompany climate descriptions. They are useful tools for presenting the basic data needed in the study of world climates. Figure 15–A shows a typical climate diagram for St. Louis. It has 12 columns, one for each month of the year. A temperature scale is on the left side, and a red line connects monthly mean temperatures. A precipitation scale is on the right side, and blue bars show average monthly precipitation totals.

Just a glance at a climate diagram reveals whether the annual temperature range is high or low and clearly shows the seasonal distribution of precipitation. Is the station in the Northern or Southern Hemisphere? Is it near the equator? Does it experience a monsoon precipitation regime or one more characteristic of a Mediterranean climate? Such information is basic in any discussion or comparison of world climates.

The diagrams presented in this chapter include a location map in the background and other information including the latitude, longitude, and climatic classification of the station. This, however, is not always the case. Only temperature and precipitation data are essential to construct a climatic diagram.

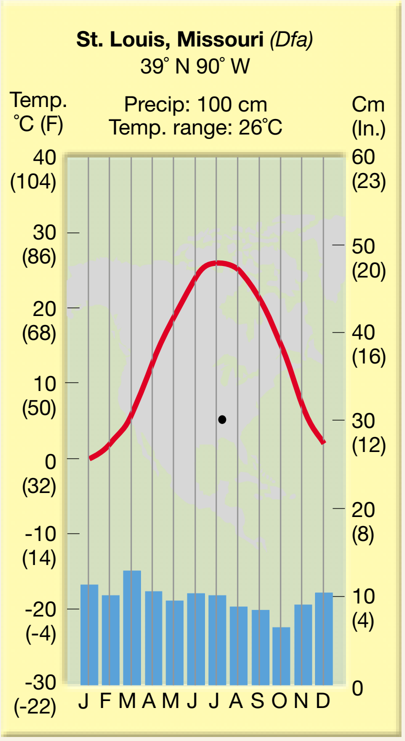


FIGURE 15-A Climate diagram for St. Louis, Missouri. Such a graph is valuable because it displays precise details of important aspects of climate for a specific place.

The moderating influence of water is much more pronounced along the windward side of a continent, for here the prevailing winds may carry the maritime air masses far inland. On the other hand, places on the lee side of a continent, where the prevailing winds blow from the land toward the ocean, are likely to have a more continental temperature regime.

Mountains and Highlands

Mountains and highlands play an important part in the distribution of climates. This impact may be illustrated by examining western North America. Because prevailing winds are from the west, the north–south trending mountain chains are major barriers. They prevent the moderating influence of maritime air masses from reaching far inland. Consequently, although stations may lie within a few hundred kilometers of the Pacific, their temperature regime is essentially continental.

Also, these topographic barriers trigger orographic rainfall on their windward slopes, often leaving a dry rain shadow on the leeward side. Similar effects may be seen in South America and Asia, where the towering Andes and the massive Himalayan system are major barriers. For comparison, Western Europe lacks a mountain barrier to obstruct the free movement of maritime air masses from the North Atlantic. As a result, moderate temperatures and sufficient precipitation mark the entire region.

Where extensive, highlands create their own climatic regions. Because of the drop in temperature with increasing altitude, areas like the Tibetan Plateau, the Altiplano of Bolivia, and the uplands of East Africa are cooler and drier than their latitudinal locations alone would indicate.

Ocean Currents

The effect of ocean currents on the temperatures of adjacent land areas can be significant. Poleward-moving currents, such as the Gulf Stream and Kuro Siwo currents in the Northern Hemisphere and the Brazilian and East Australian currents in the Southern Hemisphere, cause air

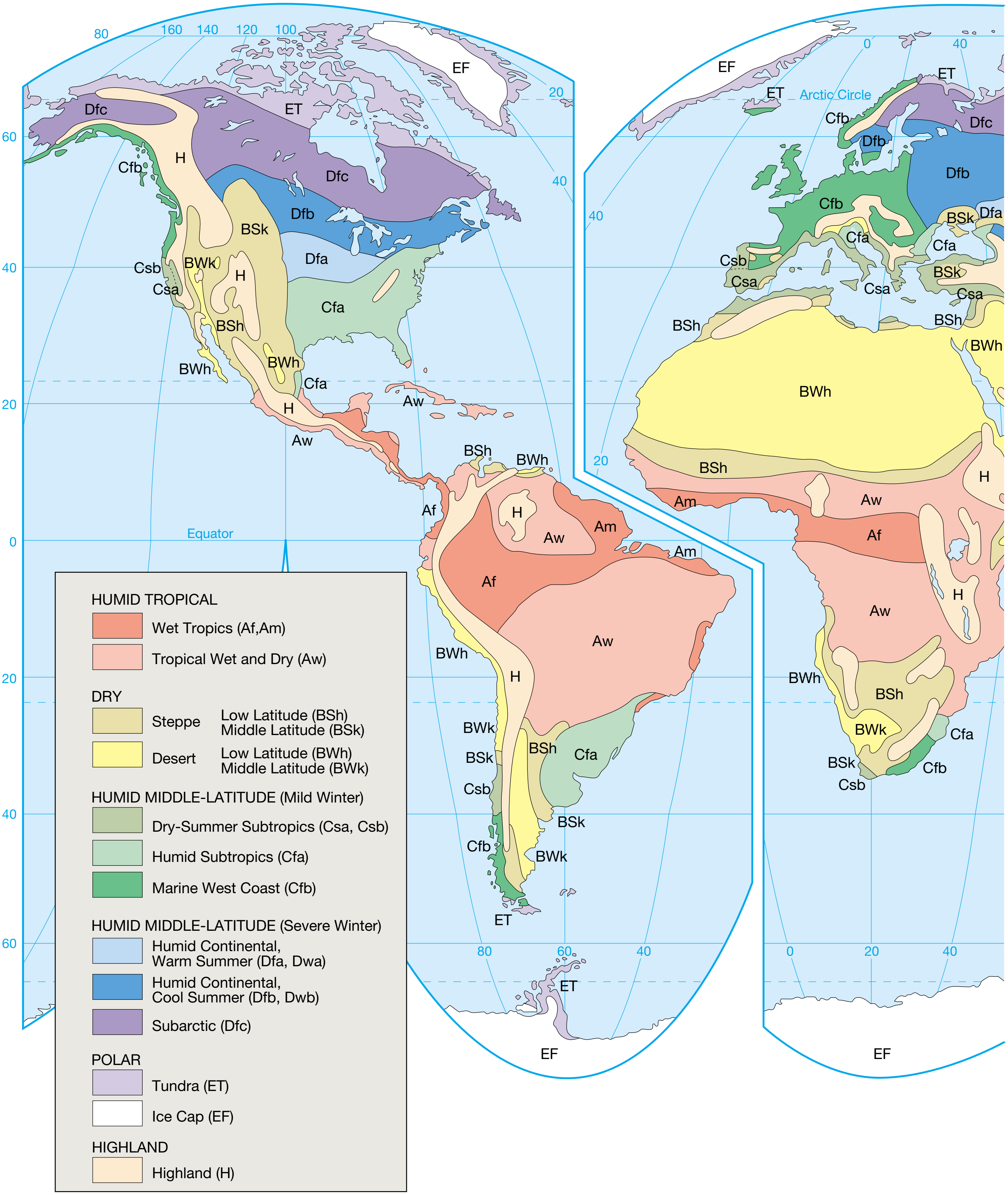


FIGURE 15-3 Climates of the world based on the Köppen classification.


80
100
120
140
160
80
ET
Dfc
H
ET
60
Dfc
Dfb
H
BSk
Dwb
BWk
BWk
Dfb
BWk
BWk
BSk
Dwa
Dfb
180
40
Cfa
H
H
Dwb
Cfa
BWh
Cfa
Tropic of Cancer
BWh
BSh
Aw
20
Af
Aw
Am
Am
Af
Aw
Af
80
BSh
0
Af
Af
Am
Af
Aw
H
Af
Aw
BSh
Af
BSh
20
Tropic of Capricorn
20
BWh
Cfa
BSh
BWh
40
Csa
Csa
Cfb
40
Cfb
60
60
100
120
140
160
60
EF
80

temperatures to be warmer than would be expected for their latitudes. This influence is especially pronounced in the winter. Conversely, the Canaries and California currents in the Northern Hemisphere and the Peruvian and Benguela currents south of the equator reduce the temperatures of bordering coastal zones. In addition, the chilling effect of these cold currents acts to stabilize the air masses moving across them. The result is marked aridity and often considerable advection fog.

Pressure and Wind Systems

The world distribution of precipitation shows a close relationship to the distribution of Earth's major pressure and wind systems. Although the latitudinal distribution of these systems does not generally take the form of simple "belts," it is still possible to identify a zonal arrangement of precipitation from the equator to the poles (see Figure 7–27. p. 225).

In the realm of the equatorial low, the convergence of warm, moist, and unstable air makes this zone one of heavy rainfall. In the regions dominated by the subtropical highs, general aridity prevails, creating major deserts. Farther poleward, in the middle-latitude zone dominated by the irregular subpolar low, the influence of the many traveling cyclonic disturbances again increases precipitation. Finally, in polar regions, where temperatures are low and the air can hold only small quantities of moisture, precipitation totals decline.

The seasonal shifting of the pressure and wind belts, which follows the movement of the Sun's vertical rays, significantly affects areas in intermediate positions. Such regions are alternately influenced by two different pressure and wind systems. A station located poleward of the equatorial low and equatorward of the subtropical high, for example, will experience a summer rainy period as the low migrates poleward, and a wintertime drought as the high moves equatorward. This latitudinal shifting of pressure belts is largely responsible for the seasonality of precipitation in many regions.

World Climates—An Overview

The remainder of this chapter is a tour of world climates. Our tour is organized like this:

- Beginning along the equator, we visit the *wet tropics* (the *A* climates), studying their temperature and precipitation characteristics, which foster the great rain forests.
- North and south of the wet tropics is the *tropical wet and dry* climate (still an *A* climate), including the monsoon areas.
- North and south of the tropical wet and dry areas are the *dry* climates (the *B* climates). Dominating large parts of the subtropics and extending into the interiors of continents in the middle latitudes, deserts and steppes cover nearly one-third of Earth's land surface.
- Moving poleward from the dry subtropical realm, we visit regions exhibiting the *humid middle-latitude* climate (one of the *C* climates). These prevail on the eastern side of continents between 25° and 40° latitude, the southeastern United States being an example.
- On the windward coasts of continents, we next visit *marine west coast* climates (also *C* climates), like that of Western Europe.
- We complete our look at *C* climates with a visit to *dry-summer subtropical* or *Mediterranean* climates, like those of Italy, Spain, and parts of California.
- In the Northern Hemisphere, where the continents extend into the middle and high latitudes, *C* climates give way to *D* climates called *humid continental.* These are "breadbasket" areas hospitable to growing grains and meat that feed much of the world.
- Verging on the polar climates are the *subarctic* climates. These vast zones of coniferous forest in Canada and Siberia are known for their long and bitter winters.
- Around the poles we visit the *polar* climates (the *E* climates). These are summerless areas of tundra and permafrost or permanent ice sheets.
- Finally, we visit some cool places that are not necessarily near the poles but are chilled by their high elevation. The *highland* climates even occur on mountaintops near the equator and are characteristic of the Rockies, Andes, Himalayas, and other mountain regions.

We begin our tour with the *wet tropics.*

The Wet Tropics (*Af, Am*)

In the wet tropics constant high temperatures and year-round rainfall combine to produce the most luxuriant vegetation in any climatic realm: the **tropical rain forest** (Figure 15–4). Unlike the forests that we North Americans are accustomed to, the tropical rain forest is made up of broadleaf trees that remain green throughout the year. In addition, instead of being dominated by a few species, these forests are characterized by many. It is not uncommon for hundreds of different species to inhabit a single square kilometer of the forest. As a consequence, the individuals of a single species are often widely spaced.

Standing on the shaded floor of the forest looking upward, one sees tall, smooth-barked, vine-entangled trees, the trunks branchless in their lower two-thirds, forming an almost continuous canopy of foliage above. A closer look reveals a three-level structure. Nearest the ground, perhaps 5 to 15 meters (16 to 50 feet) above, the narrow crowns of rather slender trees are visible. Rising above these relatively short components of the forest, a more continuous canopy of foliage occupies the height range of 20 to 30 meters (65 to 100 feet). Finally, visible through an occasional opening

FIGURE 15-4 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. Tutch River region, Sarawak, Malaysia. *(Photo by Art Wolfe/Photo Researchers, Inc.)*

in the second level, a third level may be seen at the very top of the forest. Here the crowns of the trees tower 40 meters (130 feet) or more above the forest floor.

The environment of the wet tropics just described covers almost 10 percent of Earth's land area (see Box 15–2). Figure 15–3 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 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 (3300 feet). Consequently, the major interruptions near the equator are mostly cooler highland areas.

Also note that the rainy tropics tend to have greater north–south extent along the eastern side of continents (especially South America) and along some tropical coasts. The greater span on the eastern side of a continent is due primarily to its windward position on the weak western side of the subtropical high, a zone dominated by neutral or unstable air. In other cases, as along the eastern side of Central America, the coast, backed by interior highlands, intercepts the flow of trade winds. Orographic uplift thus greatly enhances the rainfall total.

Data for some representative stations in the wet tropics are shown in Table 15–2 and Figure 15–5a and b. A brief examination of the numbers reveals the most obvious features that characterize the climate in these areas:

1. Temperatures usually average 25°C (77°F) or more each month. Not only is the annual mean high, but the annual range is also very small (note the flat temperature curves in the graphs in Figure 15–5a and b).
2. The total precipitation for the year is high, often exceeding 200 centimeters (80 inches).
3. 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.

Students Sometimes Ask…

Isn't "jungle" just another word for tropical rain forest?

No. Although both refer to vegetation in the wet tropics, they are not the same. In the tropical rain forest, there is a high canopy of foliage that does not allow much light to penetrate to the ground. As a result, plant foliage is relatively sparse on the dimly lit forest floor. By contrast, anywhere considerable light makes its way to the ground, as along riverbanks or in human-made clearings, an almost impenetrable growth of tangled vines, shrubs, and short trees exist. The familiar term "jungle" is used to describe such sites.

BOX 15-2 Clearing the Tropical Rain Forest—The Impact on Its Soils

Thick red soils are common in the wet tropics and subtropics. They are the end product of extreme chemical weathering. Because lush topical rain forests are associated with these soils, we might assume they are fertile and have great potential for agriculture. However, just the opposite is true—they are among the poorest soils for farming. How can this be?

Because rain forest soils develop under conditions of high temperature and heavy rainfall, they are severely leached. Not only does leaching remove the soluble materials such as calcium carbonate but the greatest quantities of percolating water also remove much of the silica, with the result that insoluble oxides of iron and aluminum become concentrated in the soil. Iron oxides give the soil its distinctive red color. Because bacterial activity is very high in the tropics, rain forest soils contain practically no humus. Moreover, leaching destroys fertility because the large volume of downward-percolating water removes most plant nutrients. Therefore, even though the vegetation may be dense and luxuriant, the soil itself contains few available nutrients.

Most nutrients that support the rain forest are locked up in the trees themselves. As vegetation dies and decomposes, the roots of the rain forest trees quickly absorb the nutrients before they are leached from the soil. The nutrients are continuously recycled as trees die and decompose.

FIGURE 15-B Clearing the tropical rain forest in the South American country of Surinam. The thick lateritic soil is highly leached. *(Photo by Wesley Bocxe/Photo Researchers, Inc.)*

Temperature Characteristics

Because places with an *Af* or *Am* designation lie near the equator, the reason for their uniform temperature rhythm is clear: Insolation is consistently intense. The Sun's rays are always near to vertical, and changes in day length are slight throughout the year. Therefore, seasonal temperature variations are minimal. The small difference that exists between the warmest and coolest months often reflects changes in cloud cover rather than in the position of the Sun. In the case of Belém, Brazil, for example, you can see that the highest temperatures occur during the months when rainfall (and hence cloud cover) is least.

A striking characteristic of temperatures in the wet tropics is that daily temperature variations greatly exceed seasonal differences. Whereas annual temperature ranges in the wet tropics rarely exceed 3°C (6°F), daily temperature ranges are from two to five times greater. Thus, there is a greater variation between day and night than there is seasonally. It is interesting that monthly and daily mean temperatures in the tropics are no greater than those in many U.S. cities during the summer. For example, the highest temperature recorded at Jakarta, Indonesia, over a 78-year period and at Belém, Brazil, over a 20-year period has been only 36.6°C (98°F), compared with extremes of 40.5°C (105°F) at Chicago and 41.1°C (106°F) at New York City.

Therefore, when forests are cleared to provide land for farming or to harvest the timber, most of the nutrients are removed as well (Figure 15–B). What remains is a soil that contains little to nourish planted crops.

The clearing of rain forests not only removes plant nutrients but also accelerates erosion. When vegetation is present, its roots anchor the soil, and its leaves and branches provide a canopy that protects the ground by deflecting the full force of the frequent heavy rains.

The removal of the vegetation also exposes the ground to strong direct sunlight. When baked by the Sun, these tropical soils can harden to a bricklike consistency and become practically impenetrable by water and crop roots. In only a few years, soils in a freshly cleared area may no longer be cultivable.

The term *laterite,* which is often applied to these soils, is derived from the Latin word *latere*, meaning "brick," and was first applied to the use of this material for brick-making in India and Cambodia. Laborers simply excavated the soil, shaped it, and allowed it to harden in the Sun. Ancient but still well-preserved structures built of laterite remain standing today in the wet tropics (Figure 15–C). Such structures have withstood centuries of weathering because all of the original soluble materials were already removed from the soil by chemical weathering. Laterites are therefore virtually insoluble and very stable.

In summary, we have seen that some rain forest soils are highly leached products of extreme chemical weathering in the warm, wet tropics. Although they may be associated with lush tropical rain forests, these soils are unproductive when vegetation is removed. Moreover, when cleared of plants, these soils are subject to accelerated erosion and can be baked to bricklike hardness by the Sun.

FIGURE 15-C This ancient temple at Angkor Wat, Cambodia, was built of bricks made of laterite. *(Photo by R. Ian Lloyd/Corbis/Stock Market)*

The uniqueness of the wet tropical temperature regime is its day-in and day-out, month-in and month-out regularity. Although the thermometer may not indicate abnormal or extreme conditions, the warm temperatures combined with the high humidity and meager winds make apparent temperatures particularly high. The reputation of the wet tropics as being oppressive and monotonous is mostly well deserved.

Precipitation Characteristics

The regions dominated by *Af* and *Am* climate normally receive from 175 to 250 centimeters (68 to 98 inches) of rain each year. But a glance at the data in Table 15–2 reveals more variability in rainfall than in temperature, both seasonally and from place to place. The rainy nature of the equatorial realm is partly related to the extensive heating of the region and the consequent thermal convection. In addition, this is the zone of the converging trade winds, often referred to as the **intertropical convergence zone,** or simply the **ITCZ.** The thermally induced convection, coupled with convergence, leads to widespread ascent of the warm, humid, unstable air. Conditions near the equator are thus ideal for precipitation.

Rain typically falls on more than half of the days each year. In fact, at some stations, three-quarters of the days experience rain. There is a marked daily regularity to the rainfall at many places. Cumulus clouds begin forming in late morning or early

TABLE 15-2 Data for wet tropical stations

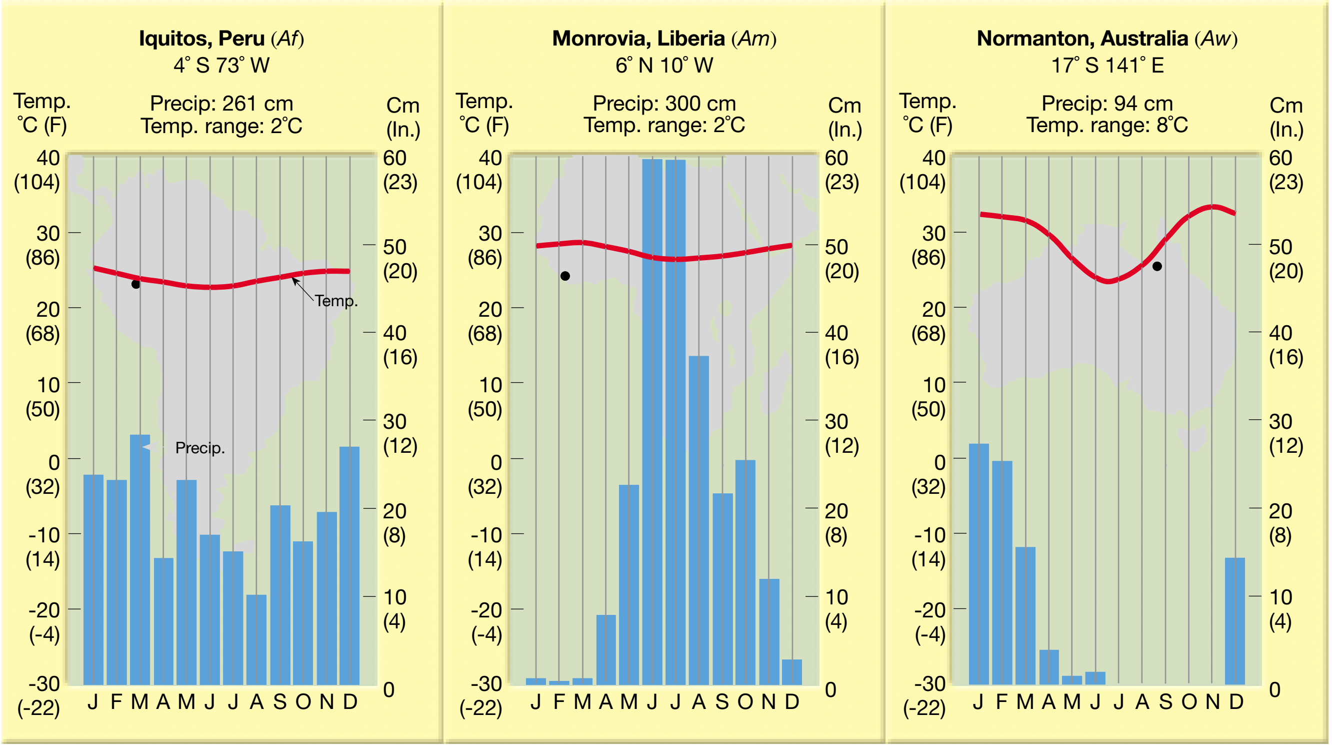
	J	F	M	A	M	J	J	A	S	O	N	D	YR
Singapore 1° 21′N; 10 m													
Temp. (°C)	26.1	26.7	27.2	27.6	27.8	28.0	27.4	27.3	27.3	27.2	26.7	26.3	27.1
Precip. (mm)	285	164	154	160	131	177	163	200	122	184	236	306	2282
Belém, Brazil 1° 18′S; 10 m													
Temp. (°C)	25.2	25.0	25.1	25.5	25.7	25.7	25.7	25.9	25.7	26.1	26.3	25.9	25.7
Precip. (mm)	340	406	437	343	287	175	145	127	119	91	86	175	2731
Douala, Cameroon 4°N; 13 m													
Temp. (°C)	27.1	27.4	27.4	27.3	26.9	26.1	24.8	24.7	25.4	25.9	26.5	27.0	26.4
Precip. (mm)	61	88	226	240	353	472	710	726	628	399	146	60	4109

afternoon. The buildup continues until about 3 or 4 P.M., the time when temperatures are highest and thermal convection is at a maximum; then the cumulonimbus towers yield showers. Figure 15–6, showing the hourly distribution of rainfall at Kuala Lumpur, Malaysia, exemplifies this pattern.

The cycle is different at many marine stations, with the rainfall maximum occurring at night. Here the environmental lapse rate is steepest and hence instability is greatest during the dark hours instead of in the afternoon. The environmental lapse rate steepens at night because the radiation heat loss from the air at heights of 600 to 1500 meters (2000 to 5000 feet) is greater than near the surface, where the air continues to be warmed by conduction and low-level turbulence created when air is heated by the warm water.

Portions of the rainy tropics are wet throughout the year. According to the Köppen scheme, at least 6 centimeters (2.3 inches) of rain falls each month. Yet extensive areas (those having the *Am* designation) are characterized by a brief dry season of one or two months. Despite the short dry season, the annual precipitation total in *Am* regions

FIGURE 15-5 By comparing these three climate diagrams, the primary differences among the *A* climates can be seen. (a) Iquitos, the *Af* station, is wet throughout the year. (b) Monrovia, the *Am* station, has a short, dry season. (c) As is true for all *Aw* stations, Normanton has an extended dry season and a greater annual temperature range than the others.



(a)

(b)

(c)

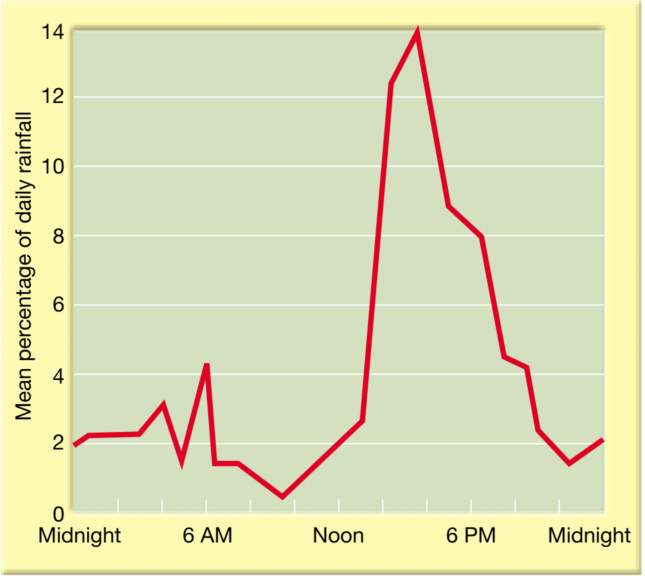


FIGURE 15-6 The distribution of rainfall by hour of the day at Kuala Lumpur, Malaysia, with its midafternoon maximum, illustrates the typical pattern at many wet tropical stations. *(After Ooi Jin-bee, "Rural Development in Tropical Areas,"* Journal of Tropical Geography, *12, no. 1 [1959])*

closely corresponds to the total in areas that are wet year-round (*Af*). Because the dry period is too brief to deplete the supply of soil moisture, the rain forest is maintained.

The seasonal pattern of precipitation in wet tropical climates is complex and not yet fully understood. Month-to-month variations are, at least in part, caused by the seasonal migration of the ITCZ, which follows the migration of the vertical rays of the Sun.

Tropical Wet and Dry (*Aw*)

Between the rainy tropics and the subtropical deserts lies a transitional climatic region referred to as **tropical wet and dry.** Along its equatorward margin, the dry season is short, and the boundary between *Aw* and the rainy tropics is difficult to define. Along the poleward side, however, the dry season is prolonged, and conditions merge into those of the semiarid realm.

Here in the tropical wet and dry climate the rain forest gives way to the **savanna,** a tropical grassland with scattered deciduous trees (Figure 15–7). In fact, *Aw* is often called the *savanna climate.* This name may not be appropriate technically, because some ecologists doubt that these grasslands are climatically induced. It is believed that woodlands once dominated this zone and that the savanna grasslands developed in response to seasonal burnings by native populations.

Temperature Characteristics

The temperature data in Table 15–3 show only modest differences between the wet tropics and the tropical wet and dry regions. Because of the somewhat higher latitude of most *Aw* stations, annual mean temperatures are slightly lower. In addition, the annual temperature range is a bit greater, varying from 3°C (5°F) to perhaps 10°C (20°F). The daily temperature range, however, still exceeds the annual variation.

Because seasonal fluctuations in humidity and cloudiness are more pronounced in *Aw* areas, daily temperature ranges vary noticeably during the year. Generally, they are small during the rainy season, when humidity and cloud cover are at a maximum, and large during droughts, when clear skies and dry air prevail. Furthermore, because of the more persistent summertime cloudiness, many *Aw* stations experience their warmest temperatures at the end of the dry season, just prior to the summer solstice. Thus, in the Northern Hemisphere, March, April, and May are often warmer than June and July.

Precipitation Characteristics

Because temperature regimes among the *A* climates are similar, the primary factor that distinguishes the *Aw* climate from *Af* and *Am* is precipitation. *Aw* stations typically receive 100 to 150 centimeters (40 to 60 inches) of rainfall each year, an amount often appreciably less than in the wet tropics. The most distinctive characteristic of this climate, however, is the *markedly seasonal character of the rainfall*—wet summers followed by dry winters. This is clearly shown by the climate diagram in Figure 15–5c.

The alternating wet and dry periods are due to the latitudinal position of the *Aw* climate region. It lies between the intertropical convergence zone, with its sultry weather and convective thundershowers, and the stable, subsiding air of the subtropical highs. Following the spring equinox, the ITCZ and the other wind and pressure belts all shift poleward as they migrate with the vertical rays of the Sun (Figure 15–8). With the advance of the ITCZ into a region, the summer rainy season commences with weather patterns typical of the wet tropics. Later, with the retreat of the ITCZ back toward the equator, the subtropical high advances into the region and brings with it intense drought.

During the dry season, the landscape grows parched and nature seems to become dormant as water-stressed trees shed their leaves and the abundant tall grasses turn brown and wither. The dry season's duration depends primarily on distance from the ITCZ. Typically, the farther an *Aw* station is from the equator, the shorter the period of ITCZ control and the longer the locale will be influenced by the stable subtropical high. Consequently, the higher the latitude, the longer the dry season and the shorter the wet period.

The movement of the ITCZ is essential to understanding rainfall distribution in the tropics. This is clear from Table 15–4, which shows precipitation data for six African stations. Notice that at Malduguri (farthest north) and Francistown (farthest south), there are single rainfall maxima that occur when the ITCZ reaches its most poleward positions. Between these stations, double maxima represent the passage of the ITCZ on its way to and from these extreme locations. It is

FIGURE 15-7 The tropical savanna in Kenya with its stunted, drought-resistant trees scattered amid a grassland may have resulted from seasonal burnings by native human populations. Serengeti National Park, Tanzania. *(Photo by Stan Osolinski/Dembinsky Photo Associates)*

important to remember that these statistics represent long-term averages and that on a year-to-year basis the movement of the ITCZ is far from regular. There is, nevertheless, no doubt that in the tropics, rainfall follows the Sun.

The Monsoon

In much of India, Southeast Asia, and portions of Australia the alternating periods of rainfall and drought characteristic of the *Aw* precipitation regime are associated with the **monsoon.** The term is derived from the Arabic word *mausim*, which means "season" and typically refers to wind systems that have a pronounced seasonal reversal of direction. During the summer, conditions are conducive to rainfall because humid, unstable air moves from the oceans toward the land. In winter this reverses, and a dry wind, having its origin over the continent, blows toward the sea.

This monsoonal circulation system develops partly in response to the differences in annual temperature variations between continents and oceans. In principle, the processes associated with the monsoon are similar to those described in connection with the land and sea breeze (Chapter 7) except that the scales, in both time and space, are much larger.

During spring in the Northern Hemisphere, an irregular area of thermally induced low pressure gradually develops over the interior of southern Asia. It is further strengthened by the poleward advance of the ITCZ (Figure 15–8). Thus, the *summertime* circulation is from the higher pressure over the ocean toward the lower pressure over the continent. As winter approaches, winds reverse direction as the ITCZ migrates southward and a deep anticyclone develops over the chilled continent. By *midwinter* dry winds blow from the continent southward to converge on Australia and southern Africa.

The *Cw* Variant

Adjacent to the wet and dry tropics in southern Africa, South America, northeastern India, and China are areas that are sometimes designated *Cw*. Although *C* has been

TABLE 15-3 Data for tropical wet and dry stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Calcutta, India 22° 32′N; 6 m													
Temp. (°C)	20.2	23.0	27.9	30.1	31.1	30.4	29.1	29.1	29.9	27.9	24.0	20.6	26.94
Precip. (mm)	13	24	27	43	121	259	301	306	290	160	35	3	1582
Cuiaba, Brazil 15°30′S 165 m													
Temp. (°C)	27.2	27.2	27.2	26.6	25.5	23.8	24.4	25.5	27.7	27.7	27.7	27.2	26.5
Precip. (mm)	216	198	232	116	52	13	9	12	37	130	165	195	1375

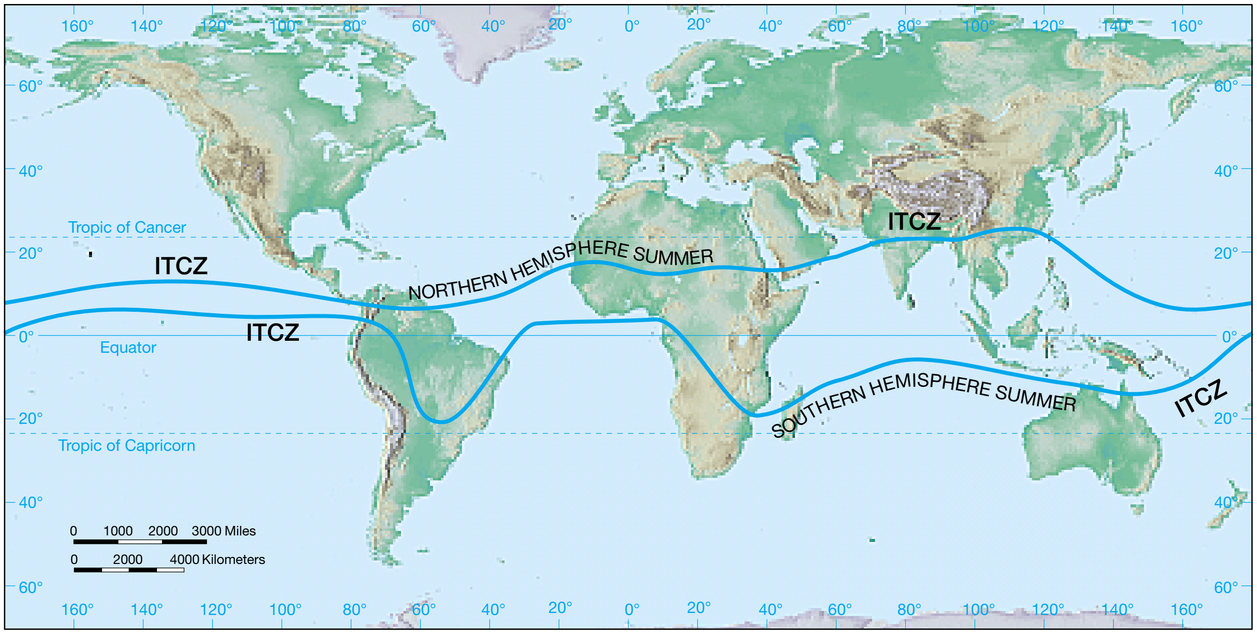


FIGURE 15-8 The seasonal migration of the ITCZ strongly influences precipitation distribution in the tropics.

substituted for *A*, indicating that these regions are subtropical instead of tropical, the *Cw* climate is nevertheless just a variant of *Aw*, for the only major difference is somewhat lower temperatures. In Africa and South America, *Cw* climates are highland extensions of *Aw*. Because they occupy elevated sites, the warmer temperatures of the adjacent wet and dry tropics are reduced. In India and China, *Cw* areas are middle-latitude extensions of the tropical monsoon realm. In some cases, especially in India, the *Cw* areas are barely poleward enough to have winter temperatures below those of the *A* climates.

The Dry Climates (*B*)

The dry regions of the world cover some 42 million square kilometers (nearly 16.5 million square miles), or about 30 percent, of Earth's land surface. No other climatic group covers so large a land area (Figure 15–9).

The most characteristic feature of dry climates, aside from their meager yearly rainfall, is that precipitation is very unreliable. Generally, the smaller the mean annual rainfall, the greater its variability. As a result, yearly rainfall averages are often misleading.

TABLE 15-4 Rainfall regimes and the movement of the ITCZ in Africa

	J	F	M	A	M	J	J	A	S	O	N	D
Malduguri, Nigeria, 11° 51′N												
Precip. (mm)	0	0	0	7.6	40.6	68.6	180.3	**220.9**	106.6	17.7	0	0
Yaounde, Cameroon, 3° 53′N												
Precip. (mm)	22.8	66.0	147.3	170.1	**195.6**	152.4	73.7	78.7	213.4	**294.6**	116.8	22.9
Kisangani, Zaire, 0° 26′N												
Precip. (mm)	53.3	83.8	**177.8**	157.5	137.2	114.3	132.0	165.1	182.9	**218.4**	198.1	83.8
Luluabourg, Zaire, 5° 54′S												
Precip. (mm)	137.2	142.2	**195.6**	193.0	83.8	20.3	12.7	58.4	116.8	165.1	**231.1**	226.0
Zomba, Malawi, 15° 23′S												
Precip. (mm)	274.3	**289.6**	198.1	76.2	27.9	12.7	5.1	7.6	17.8	17.8	134.6	**279.4**
Francistown, Botswana, 21° 13′S												
Precip. (mm)	**106.7**	78.7	71.1	17.8	5.1	2.5	0	0	0	22.9	58.4	86.4

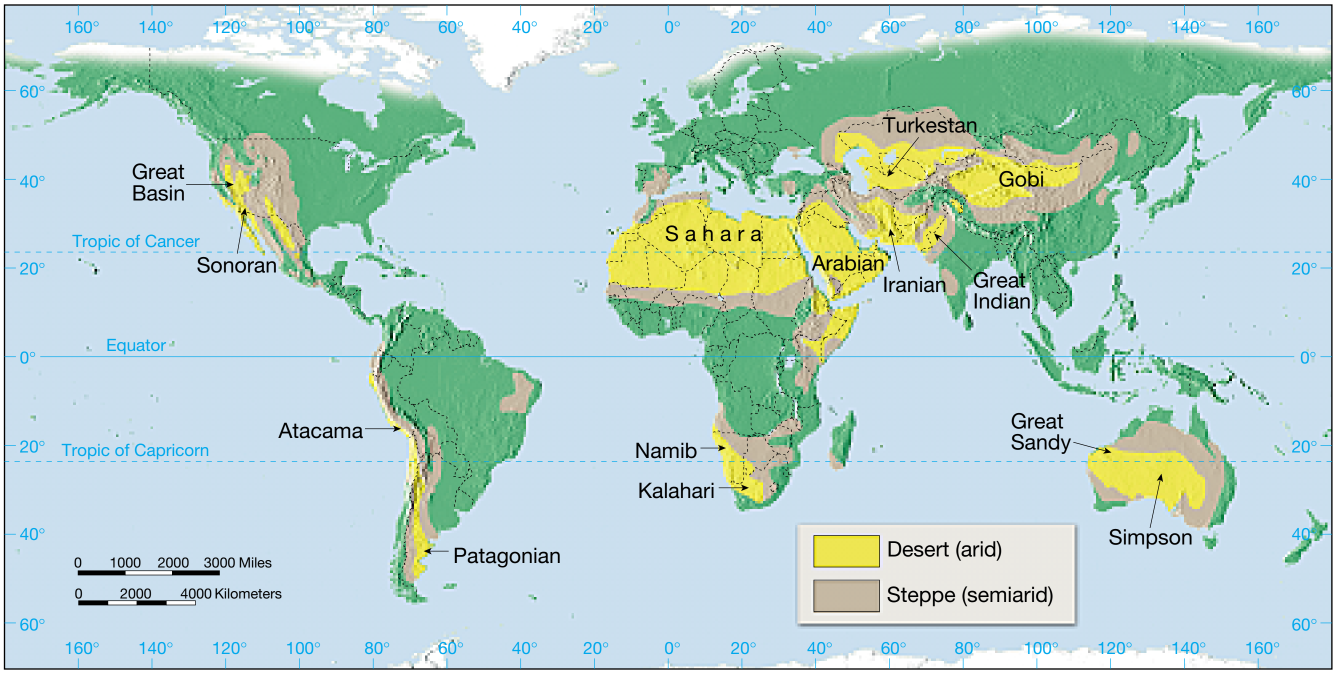


FIGURE 15-9 Arid and semiarid climates cover about 30 percent of Earth's land area. These dry *(B)* climates constitute the single largest climatic group.

For example, during one seven-year period, Trujillo, Peru, had an average rainfall of 6.1 centimeters per year (2.4 inches). Yet a closer look reveals that during the first six years and 11 months of the period, the station received a scant 3.5 centimeters (1.4 inch) (an annual average of slightly more than 0.5 centimeter). Then during the twelfth month of the seventh year, 39 centimeters (15.2 inches) of rain fell, 23 centimeters (9 inches) of it during a three-day span.

This extreme case illustrates the irregularity of rainfall in most dry regions. Also, there are usually more years when rainfall totals are below the average than years when they are above. As the foregoing example shows, the occasional wet period tends to lift the average.

Students Sometimes Ask…

I heard somewhere that deserts are expanding. Is that actually occurring?

Yes. The problem is called *desertification,* and it has come to refer to the alteration of land to desertlike conditions as the result of human activities. It commonly takes place on the margins of deserts and results primarily from inappropriate land use. It is triggered when the modest natural vegetation in marginal areas is removed by plowing or grazing. When drought occurs, as it inevitably does in these regions, and the vegetative cover has been destroyed beyond the minimum to hold the soil against erosion, the destruction becomes irreversible. Desertification is occurring in many places but is particularly serious in the region south of the Sahara Desert known as the Sahel.

What Is Meant by "Dry"?

It is important to realize that dryness is relative and simply refers to any *water deficiency.* Thus, climatologists define a **dry climate** as one in which the *yearly precipitation is less than the potential water loss by evaporation.* Dryness, then, is not only related to annual rainfall. It is also a function of evaporation, which in turn depends closely on temperature. As temperatures climb, potential evaporation also increases.

For example, 25 centimeters (10 inches) of precipitation may be sufficient to support forests in northern Scandinavia, where evaporation is slight into the cool, humid air and a surplus of water remains in the soil. However, the same amount of rain falling on Nevada or Iran supports only a sparse vegetative cover because evaporation into the hot, dry air is great. Clearly, no specific amount of precipitation can define a dry climate.

To establish a meaningful boundary between dry and humid climates, the Köppen classification uses formulas that involve three variables: (1) average annual precipitation, (2) average annual temperature, and (3) seasonal distribution of precipitation.

The use of average annual precipitation is obvious. Average annual temperature is used because it is an index of evaporation; the amount of rainfall defining the humid–dry boundary is greater where mean annual temperatures are high, and less where temperatures are low. The third variable, seasonal distribution of precipitation, is also related to this idea. If rain is concentrated in the warmest months, loss to evaporation is greater than if it is concentrated in the cooler months. Thus, considerable differences exist in the precipitation amounts received at various stations in the *B* climates.

Table 15–5 summarizes these differences. For example, if a station with an annual mean of 20°C (68°F) and a summer wet season ("winter dry") receives less than 680 millimeters (26.5 inches) of precipitation per year, it is classified as *dry*. If the rain falls primarily in winter ("summer dry"), however, the station must receive only 400 millimeters (15.6 inches) or more to be considered humid. If the precipitation is more evenly distributed, the figure defining the humid–dry boundary is between the other two.

Within the regions defined by a general water deficiency, there are two climatic types: **arid** or **desert** (***BW***) and **semiarid** or **steppe** (***BS***). Figure 15–10 presents climatic diagrams for both types. Stations a and b are in the subtropics and c and d are in the middle latitudes. Deserts and steppes 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 and represents a transition zone that surrounds the desert and separates it from the bordering humid climates (see Box 15–3). The arid–semiarid boundary is commonly set at one-half the annual precipitation separating dry regions from humid. Thus, if the humid–dry boundary happens to be 40 centimeters, the steppe–desert boundary will be 20 centimeters.

Subtropical Desert (*BWh*) and Steppe (*BSh*)

The heart of low-latitude dry climates lies along the vicinity of the Tropic of Cancer and the Tropic of Capricorn. A glance at Figure 15–9 reveals 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 (*BWh*) and steppe (*BSh*) in northern Mexico and the southwestern United States. In the Southern Hemisphere, dry climates dominate Australia. Almost 40 percent of that continent is desert, and much of the remainder is steppe.

In addition, arid and semiarid areas exist in southern Africa and make a rather limited appearance in coastal Chile and Peru. The distribution of this dry subtropical realm is primarily a consequence of the subsidence and market stability of the subtropical highs.

TABLE 15-5 Average annual precipitation (mm) at *BS*-humid boundary

Average annual temp (°C)	Summer dry season	Even distribution	Winter dry season
5	100	240	380
10	200	340	480
15	300	440	580
20	400	540	680
25	500	640	780
30	600	740	880

Precipitation. Within subtropical deserts the scanty precipitation is both infrequent and erratic. Indeed, no well-defined seasonal precipitation pattern exists in subtropical deserts. The reason is that these areas are too far poleward to be influenced by the ITCZ and too far equatorward to benefit from the frontal and cyclonic precipitation of the middle latitudes. Even during summer, when daytime heating produces a steep environmental lapse rate and considerable convection, clear skies still rule. In this case, subsidence aloft prevents the lower air, with its modest moisture content, from rising high enough to penetrate the condensation level.

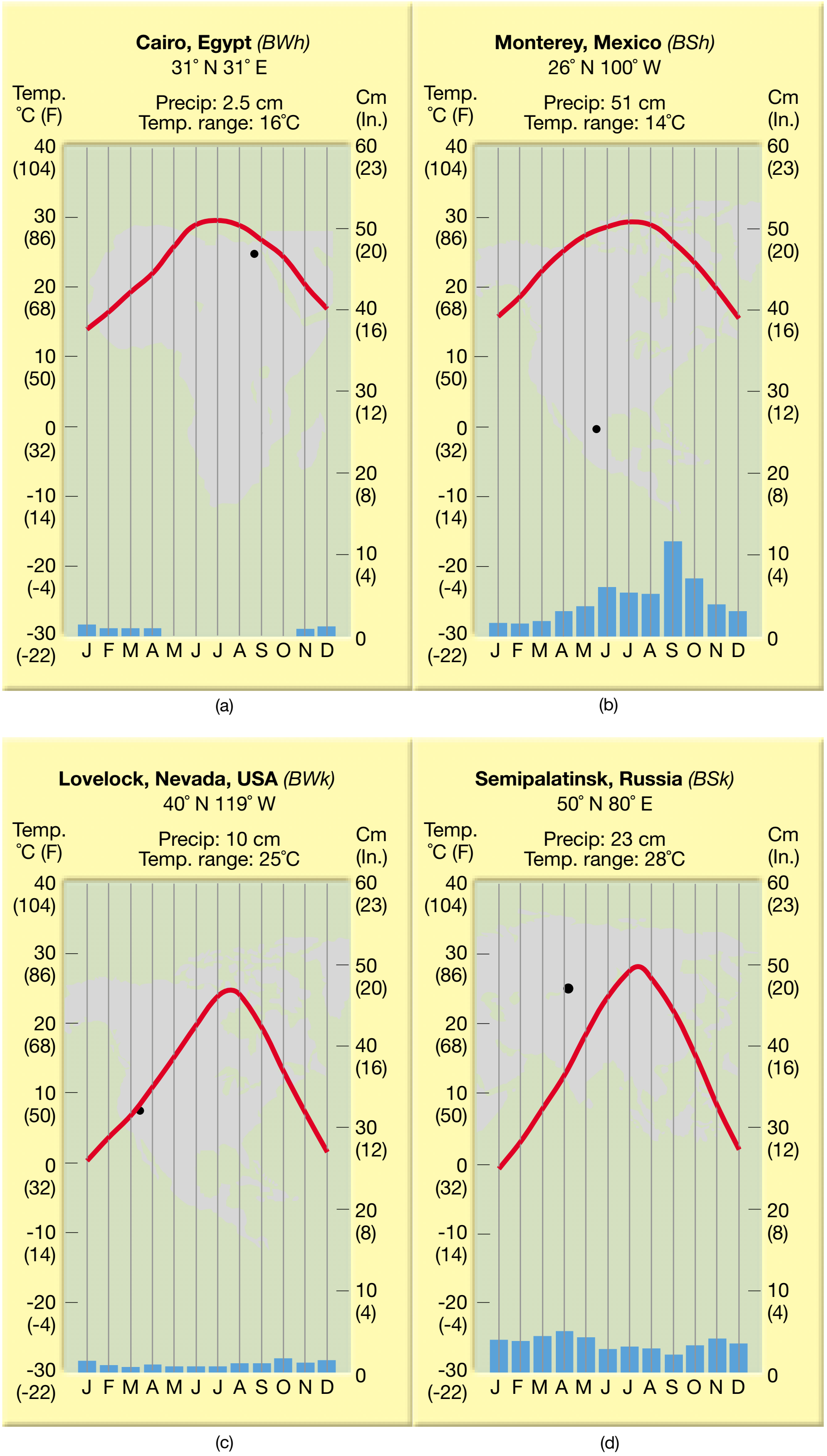
The situation is different in the semiarid transitional belts surrounding the desert. Here a seasonal rainfall pattern becomes better defined. As shown by the data for Dakar in Table 15–6, stations located on the equatorward side of low-latitude deserts have a brief period of relatively heavy rainfall during the summer, when the ITCZ is farthest poleward. The rainfall regime should look familiar, for it is similar to that found in the adjacent wet and dry tropics, except that the amount is less and the drought lasts longer.

For steppe areas on the poleward margins of the tropical deserts, the precipitation regime is reversed. As the data for Marrakech illustrate (Table 15–6), the cool season is the period when nearly all precipitation falls. At this time of year middle-latitude cyclones often take more equatorward routes and so bring occasional periods of rain.

Temperature. The keys to understanding temperatures in the desert environment are humidity and cloud cover. The cloudless sky and low humidity allow an abundance of solar radiation to reach the ground during the day and permit the rapid exit of terrestrial radiation at night. As would be expected, relative humidities are low throughout the year. Relative humidities between 10 and 30 percent are typical at midday for interior locations.

Regarding cloud cover, desert skies are almost always clear (Figure 15–11). In the Sonoran Desert region of Mexico and the United States, for example, most stations receive nearly 85 percent of the possible sunshine. Yuma, Arizona, averages 91 percent for the year, with a low of 83 percent in January and a high of 98 percent in June. The Sahara has an average winter cloud cover of about 10 percent, which in summer drops to a mere 3 percent.

During summer, the desert surface heats rapidly after sunrise, because the clear skies permit almost all the solar energy to reach the surface, as we saw in preceding examples. By midafternoon ground-surface temperatures may approach 90°C (nearly 200°F)! Under such circumstances, it is not surprising that the world's highest temperatures are recorded in the subtropical deserts. Nor is it unexpected that the daily maximums at many stations during the hot season are consistently close to the absolute maximum (the highest temperature ever recorded at a station). At Abadán, Iran, the average daily maximum in July is a scorching



(a) (b) (c) (d)

FIGURE 15-10 Climate diagrams for representative arid and semiarid stations. Cairo and Lovelock are classified as deserts; Monterey and Semipalatinsk are steppes. Stations (a) and (b) are in the subtropics, whereas (c) and (d) are middle-latitude sites.

44.7°C (112°F), or only 8.3°C (15°F) lower than the record high. Phoenix, Arizona, is not much better, recording an average July maximum of 40.5°C (105°F) compared with an absolute maximum of 47.7°C (118°F).

A contributing factor to the high ground and air temperatures is that little energy from insolation goes to power evaporation. Thus, almost all the energy goes to heating the surface. In contrast, humid regions are less likely to have such extreme ground and air temperatures, for more energy from solar radiation goes to evaporate water and less remains to heat the ground.

At night, temperatures typically drop rapidly, partly because the water vapor content of the air is fairly low. Ground-surface temperature is also a factor, however. Recall

TABLE 15-6 Data for subtropical steppe and desert stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Marrakech, Morocco, 31° 37′N; 458 m													
Temp (°C)	11.5	13.4	16.1	18.6	21.3	24.8	28.7	28.7	25.4	21.2	16.5	12.5	19.9
Precip. (mm)	28	28	33	30	18	8	3	3	10	20	28	33	242
Dakar, Senegal, 14° 44′N; 23 m													
Temp. (°C)	21.1	20.4	20.9	21.7	23.0	26.0	27.3	27.3	27.5	27.5	26.0	25.2	24.49
Precip. (mm)	0	2	0	0	1	15	88	249	163	49	5	6	578
Alice Springs, Australia, 23° 38′S, 570 m													
Temp. (°C)	28.6	27.8	24.7	19.7	15.3	12.2	11.7	14.4	18.3	22.8	25.8	27.8	20.8
Precip. (mm)	43	33	28	10	15	13	8	8	8	18	30	38	252

from the discussion of radiation in Chapter 2 that the higher the temperature of a radiating body, the faster it loses heat. Thus, applied to a desert setting, such environments not only heat up quickly by day but also cool rapidly at night.

Consequently, low-latitude deserts in the interiors of continents have the greatest daily temperature ranges on Earth. Daily ranges from 15 to 25°C (27 to 45°F) are common, and they occasionally reach even higher values. The highest daily temperature range ever recorded was at In Salah, Algeria, in the Sahara. On October 13, 1927, this station experienced a 24-hour range of 55.5°C (100°F), from 52.2 to −3.3°C (126 to 26°F).

Because most areas of *BWh* and *BSh* are poleward of the *A* climates, annual temperature ranges are the highest among the tropical climates. During the low-Sun period, averages are below those in other parts of the tropics, with monthly means of 16 to 24°C (60 to 75°F) being typical. Still, temperatures during the summer are higher than those in the humid tropics. Consequently, annual means at many subtropical desert and steppe stations are similar to those in the *A* climates.

West Coast Subtropical Deserts

Where subtropical deserts are found along the west coasts of continents, cold ocean currents have a dramatic influence on the climate. The principal west coast deserts are the Atacama in Peru and Chile and the Namib in southern and southwestern Africa. Other areas include portions of the Sonoran Desert in Baja, California, and coastal areas of the Sahara in northwestern Africa.

These areas deviate considerably from the general image we have of subtropical deserts. The most obvious effect of the cold current is reduced temperatures, as exemplified by the data for Lima, Peru, and Port Nolloth, South Africa (Table 15–7). Compared with other stations at similar latitudes, these places have lower annual mean temperatures and subdued annual and daily ranges. Port Nolloth, for example, has an annual mean of only 14°C (57°F) and an annual range of just 4°C (7.2°F). Contrast this with Durban, on the opposite side of South Africa, which has a yearly mean of 20°C (68°F) and an annual range twice that at Port Nolloth.

Although these stations are adjacent to the oceans, their yearly rainfall totals are among the lowest in the world. The

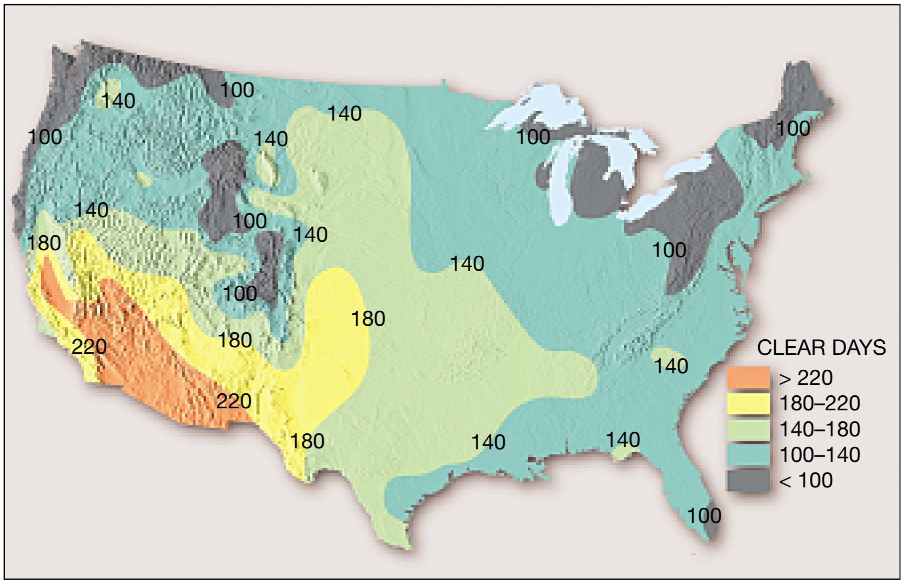
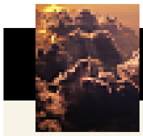


FIGURE 15-11 Average annual number of clear days. With few exceptions, desert skies are typically cloudless and hence receive a very high percentage of the possible sunlight. This is strikingly illustrated by the southwest desert.



BOX 15-3 The Disappearing Aral Sea

The Aral Sea lies on the border between Uzbekistan and Kazakhstan in central Asia (Figure 15–D). The setting is the Turkestan desert, a middle-latitude desert in the rain shadow of Afghanistan's high mountains. In this region of interior drainage, two large rivers, the Amu Darya and the Syr Darya, carry water from the mountains of northern Afghanistan across the desert to the Aral Sea. Water leaves the sea by evaporation. Thus, the size of the water body depends upon the balance between river inflow and evaporation.

In 1960 the Aral Sea was one of the world's largest inland water bodies, with an area of about 67,000 square kilometers (26,000 square miles). Only the Caspian Sea, Lake Superior, and Lake Victoria were larger. By the year 2000 the area of the Aral Sea was less than 50 percent of its 1960 size, and its volume was reduced by 80 percent. The shrinking of this water body is depicted in Figure 15–E. By about 2010 all that will remain will be three shallow remnants.

FIGURE 15-D The Aral sea lies east of the Caspian sea in the Turkestan desert. Two rivers, the Amu Darya and Syr Darya, bring water from the mountains to the south.

What caused the Aral Sea to dry up over the past 40 years? The answer is that the flow of water from the mountains that supplied the sea was significantly reduced and then all but eliminated. The waters of the Amu Darya and Syr Darya were diverted to supply a major expansion of irrigated agriculture in this dry realm.

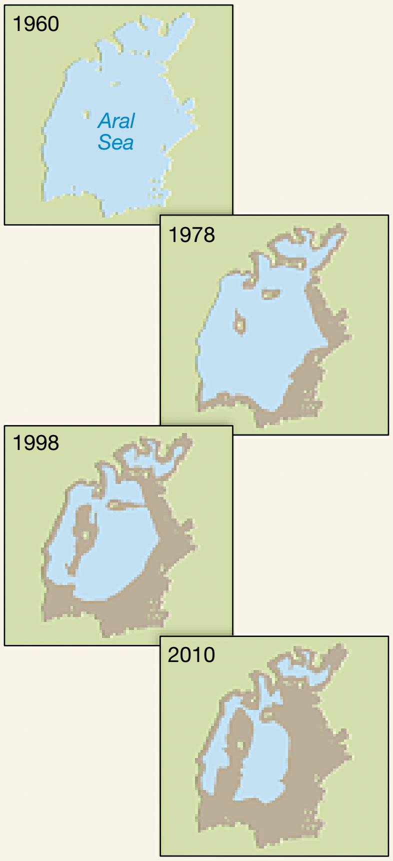


FIGURE 15-E The shrinking Aral Sea. By the year 2010 all that will remain are three small remnants.

aridity of these coasts is intensified because the lower air is chilled by the cold offshore waters and hence further stabilized. In addition, the cold currents cause temperatures often to reach the dew point. As a result, these areas are characterized by high relative humidity and much advection fog and dense stratus cloud cover.

The point is that not all subtropical deserts are sunny, hot places with low humidity and cloudless skies. Indeed, the presence of cold currents causes west coast subtropical deserts to be relatively cool, humid places, often shrouded by low clouds or fog.

Middle-Latitude Desert (*BWk*) and Steppe (*BSk*)

Unlike their low-latitude counterparts, middle-latitude deserts and steppes are not controlled by the subsiding air masses of the subtropical highs. Instead, these dry lands

TABLE 15-7 Data for west coast tropical desert stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Port Nolloth, South Africa, 29° 14′S; 7 m													
Temp. (°C)	15	16	15	14	14	13	12	12	13	13	15	15	14
Precip. (mm)	2.5	2.5	5.1	5.1	10.2	7.6	10.2	7.6	5.1	2.5	2.5	2.5	63.4
Lima, Peru, 12° 02′S; 155 m													
Temp. (°C)	22	23	23	21	19	17	16	16	16	17	19	21	19
Precip. (mm)	2.5	T	T	T	5.1	5.1	7.6	7.6	7.6	2.5	2.5	T	40.5

The intensive irrigation greatly increased agricultural productivity, but not without significant costs. The deltas of the two major rivers have lost their wetlands, and wildlife has disappeared. The once-thriving fishing industry is dead, and the 24 species of fish that once lived in the Aral Sea are no longer there. The shoreline is now tens of kilometers from the towns that were once fishing centers (Figure 15–F).

The shrinking sea has exposed millions of acres of former seabed to sun and wind. The surface is encrusted with salt and with agrochemicals brought by the rivers. Strong winds routinely pick up and deposit thousands of tons of newly exposed material every year. This process has not only contributed to a significant reduction in air quality for people living in the region but has also appreciably affected crop yields due to the deposition of salt-rich sediments on arable land.

FIGURE 15-F In the town of Jamboul, Kazakhstan, boats now lie in the sand because the Aral Sea has dried up. *(Photo by Ergun Cagatay/Getty Images, Inc./Liaison)*

The shrinking Aral Sea has had a noticeable impact on the region's climate. Without the moderating effect of a large water body, there are greater extremes of temperature, a shorter growing season, and reduced local precipitation. These changes have caused many farms to switch from growing cotton to growing rice, which demands even more diverted water.

Environmental experts agree that the current situation cannot be sustained. Could this crisis be reversed if enough fresh water were to once again flow into the Aral Sea? Prospects appear grim. Experts estimate that restoring the Aral Sea to about twice its present size would require stopping all irrigation from the two major rivers for 50 years. This could not be done without ruining the economies of the countries that rely on that water.

The decline of the Aral Sea is a major environmental disaster that sadly is of human making.

exist principally because of their position in the deep interiors of large landmasses, far removed from the main moisture source—the oceans. In addition, the presence of high mountains across the paths of the prevailing winds further separates these areas from water-bearing maritime air masses (Figure 15–12). In North America the Coast ranges, Sierra Nevada, and Cascades are the foremost barriers; in Asia the great Himalayan chain prevents the summertime monsoon flow of moist air off the Indian Ocean from reaching far into the interior (Figure 15–13).

A glance at Figure 15–9 reveals that middle-latitude desert and steppe climates are most widespread in North America and Eurasia. The Southern Hemisphere lacks extensive land areas in the middle latitudes, so it has a much smaller area of *BWk* and *BSk*. It is found only at the southern tip of South America in the rain shadow of the towering Andes.

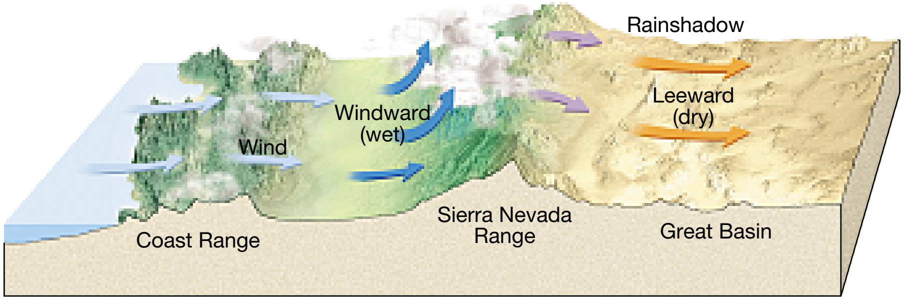


FIGURE 15-12 Mountains frequently contribute to the aridity of middle-latitude deserts and steppes by creating a rain shadow. Orographic lifting leads to precipitation on the windward slopes. By the time air reaches the leeward side of the mountains, much of the moisture has been lost. The Great Basin desert is a rain shadow desert that covers nearly all of Nevada and portions of adjacent states.

FIGURE 15-13 Scene in Nevada's Great Basin Desert. The aridity of this region is enhanced greatly by the rain shadow created by the Sierra Nevada. *(Photo by Charlie Ott/Photo Researchers, Inc.)*

Like subtropical deserts and steppes, the dry regions of the middle latitudes have meager and unreliable precipitation. Unlike the dry lands of the low latitudes, however, these more poleward regions have much lower winter temperatures and hence lower annual means and higher annual ranges of temperature.

The data in Table 15–8 illustrate this point nicely. The data also reveal that rainfall is most abundant during the warm months. Although not all *BWk* and *BSk* stations have a summer precipitation maximum, most do because in winter high pressure and cold temperatures tend to dominate the continents. Both factors oppose precipitation. In summer, however, conditions are somewhat more conducive to cloud formation and precipitation because the anticyclone disappears over the heated continent, and higher surface temperatures and greater mixing ratios prevail.

Students Sometimes Ask…

Aren't deserts mostly covered with sand dunes?

A common misconception about deserts is that they consist of mile after mile of drifting sand dunes. It is true that sand accumulations do exist in some areas and may be striking features. But, perhaps surprisingly, sand accumulations worldwide represent only a small percentage of the total desert area. For example, in the Sahara—the world's largest desert—accumulations of sand cover only *one-tenth* of its area. The sandiest of all deserts is the Arabian, one-third of which consists of sand.

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

The Köppen classification recognizes two groups of humid middle-latitude climates. One group has mild winters (the *C* climates) and the other experiences severe winters (the *D* climates). The following three sections pertain to the *C*-type mild winter group. Figure 15–14 presents climate diagrams of the three types of *C* climates.

Humid Subtropical Climate (*Cfa*)

Humid subtropical climates are found on the eastern sides of the continents, in the 25° to 40° latitude range. They dominate the southeastern United States and other similarly situated areas: all of Uruguay and portions of Argentina and southern Brazil in South America, eastern China and southern Japan in Asia, and the eastern coast of Australia.

In the summer a visitor to the humid subtropics would experience hot, sultry weather of the type expected in the rainy tropics. Daytime temperatures are generally in the lower 30s (°C) (high 80s °F), but it is not uncommon for the thermometer to reach into the upper 30s (90s°F) or even 40 (more than 100°F) on many afternoons. Because the mixing ratio and relative humidity are high, the night brings little relief. An afternoon or evening thunderstorm is possible

TABLE 15-8 Data for middle-latitude steppe and desert stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Ulan Bator, Mongolia, 47° 55′N; 1311 m													
Temp. (°C)	−26	−21	−13	−1	6	14	16	14	9	−1	−13	−22	−3
Precip. (mm)	1	2	3	5	10	28	76	51	23	7	4	3	213
Denver, Colorado, 39° 32′N; 1588 m													
Temp. (°C)	0	1	4	9	14	20	24	23	18	12	5	2	11
Precip. (mm)	12	16	27	47	61	32	31	28	23	24	16	10	327

because these areas experience them between 40 and 100 days each year, the majority during summer.

The primary reason for the tropical summer weather in *Cfa* regions is the dominating influence of maritime tropical air masses. During the summer months this warm, moist, unstable air moves inland from the western portions of the oceanic subtropical anticyclone. As the maritime tropical (*mT*) air passes over the heated continent, it becomes increasingly unstable, giving rise to the common convectional showers and thunderstorms.

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

Because the land surface is colder than the maritime air, the air becomes chilled in its lower layers as it moves poleward. Consequently, convectional showers are rare, for the stabilized *mT* air masses produce clouds and precipitation only when forced to rise.

The data for two humid subtropical stations in Table 15–9 serve to summarize the general characteristics of the *Cfa* climate. Yearly precipitation usually exceeds 100 centimeters (39 inches), and the rainfall is well distributed throughout the year. Summer normally brings the most precipitation, but there is considerable variation. In the United States, for example, precipitation in the Gulf states is very evenly distributed. But as one moves poleward or toward

FIGURE 15-14 Each of these climate diagrams represents a type of *C* climate: (a) humid subtropical, (b) marine west coast, and (c) dry-summer subtropical.

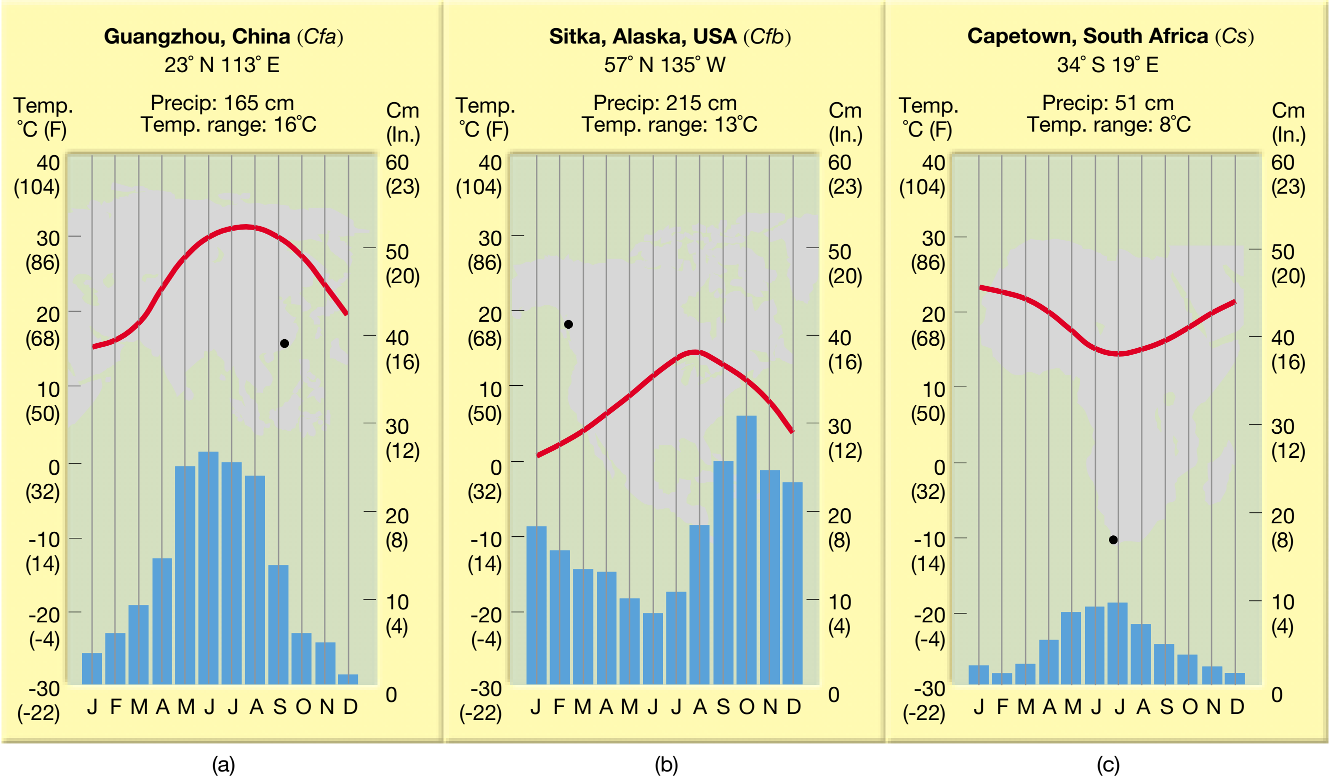


TABLE 15-9 Data for humid subtropical stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
New Orleans, Louisiana, 29° 59′N; 1 m													
Temp. (ºC)	12	13	16	19	23	26	27	27	25	21	15	13	20
Precip. (mm)	98	101	136	116	111	113	171	136	128	72	85	104	1371
Buenos Aires, Argentina, 34° 35′S; 27 m													
Temp. (ºC)	24	23	21	17	14	11	10	12	14	16	20	22	17
Precip. (mm)	104	82	122	90	79	68	61	68	80	100	90	83	1027

the drier western margins, much more falls in summer. Some coastal stations have rainfall maximums in late summer or autumn when tropical cyclones or their remnants visit the area. In Asia the well-developed monsoon circulation favors a summer precipitation maximum (see the Chinese station in Figure 15–14a).

Temperature figures show that summer temperatures are comparable to the tropics and that winter values are markedly lower. This is to be expected, because the higher-latitude position of the subtropics experiences a wider variation in Sun angle and day length, plus occasional (even frequent) invasions of continental polar (*cP*) air masses during winter.

The Marine West Coast Climate *(Cfb)*

On the western (windward) side of continents from about 40º to 65º north and south latitude is a climate region dominated by the onshore flow of oceanic air. The prevalence of maritime air masses means mild winters, cool summers, and ample rainfall throughout the year. In North America this **marine west coast climate** (***Cfb***) extends from near the U.S.–Canada border northward as a narrow belt into southern Alaska (Figure 15–15). A similar slender strip occurs in South America along the coast of Chile. In both instances high mountains parallel the coast and prevent

FIGURE 15-15 Fog is common along the rocky Pacific coastline at Olympic National Park, Washington. This area is classified as a *marine west coast climate.* As the name implies, the ocean exerts a strong influence. *(Photo by Richard J. Green/Photo Researchers, Inc.)*

the marine climate from penetrating far inland. The largest area of *Cfb* climate is in Europe, for here there is no mountain barrier blocking the movement of cool maritime air from the North Atlantic. Other locations include most of New Zealand as well as tiny slivers of South Africa and Australia.

The data for representative marine west coast stations in Table 15–10 and Figure 15–14b reveal no pronounced dry period, although monthly precipitation drops during the summer. The reduced summer rainfall is due to the poleward migration of the oceanic subtropical highs. Although the areas of marine west coast climate are too far poleward to be dominated by these dry anticyclones, their influence is sufficient to cause a decrease in warm-season rainfall.

A comparison of precipitation data for London and Vancouver (Table 15–10) also demonstrates that coastal mountains have a significant influence on yearly rainfall. Vancouver has about two and a half times that of London. In settings like Vancouver's, the precipitation totals are higher not only because of orographic uplift but also because the mountains slow the passage of cyclonic storms, allowing them to linger and drop a greater quantity of water.

The ocean is near, so winters are mild and summers relatively cool. Therefore, a low annual temperature range is characteristic of the marine west coast climate. Because *cP* air masses generally drift eastward in the zone of the westerlies, periods of severe winter cold are rare. The western edge of North America is especially sheltered from incursions of frigid continental air by the high mountains that intervene between the coast and the source regions for *cP* air masses. Because no such mountain barrier exists in Europe, cold waves there are somewhat more frequent.

The ocean's control of temperatures can be further demonstrated by a look at temperature gradients (changes in temperature per unit distance). Although this climate encompasses a wide latitudinal span, temperatures change much more abruptly moving inland from the coast than they do in a north–south direction. The transport of heat from the oceans more than offsets the latitudinal variation in the receipt of solar energy. For example, in both January and July the temperature change from coastal Seattle to inland Spokane, a distance of about 375 kilometers (230 miles), is equal to the variation between Seattle and Juneau, Alaska. Juneau is about 11° of latitude, or roughly 1200 kilometers (750 miles), north of Seattle.

The Dry-Summer Subtropical (Mediterranean) Climate *(Csa, Csb)*

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 region is transitional in character. It is the only humid climate that has a pronounced winter rainfall maximum, a feature that reflects its intermediate position (Figure 15–14c).

In summer the region is dominated by the stable eastern side of the oceanic subtropical highs. In winter, as the wind and pressure systems follow the Sun equatorward, it is within range of the cyclonic storms of the polar front. Thus, during the course of a year, these areas alternate between being a part of the dry tropics and being an extension of the humid middle latitudes. Although middle-latitude changeability characterizes the winter, tropical constancy describes the summer.

As was 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 extend to the latitudes where dry-summer climates exist, the development of this climatic type is limited on these continents as well.

Because of the arrangement of the continents and their mountain ranges, inland development occurs only in the Mediterranean basin (Figure 15–16). 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.

Temperature. Two types of Mediterranean climate are recognized and are based primarily on summertime temperatures. The cool summer type (*Csb*), as exemplified by San Francisco and Santiago, Chile (Table 15–11), is limited to coastal areas. Here the cooler summer temperatures

TABLE 15-10 Data for marine west coast stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Vancouver, British Columbia, 49° 11′N; 0 m													
Temp. (°C)	2	4	6	9	13	15	18	17	14	10	6	4	10
Precip. (mm)	139	121	96	60	48	51	26	36	56	117	142	156	1048
London, UK, 51° 28′N; 5 m													
Temp. (°C)	4	4	7	9	12	16	18	17	15	11	7	5	10
Precip. (mm)	54	40	37	38	46	46	56	59	50	57	64	48	595

FIGURE 15-16 Rolling landscape with olive trees in Tuscany (Italy). The dry-summer subtropical climate is especially well developed in the Mediterranean region. *(Photo by Grilly Bernard/Getty Images, Inc./Stone Allstock)*

one expects on a windward coast are further intensified by cold ocean currents.

The data for Izmir, Turkey, and Sacramento illustrate the features of the warm summer type (*Csa*). At both places winter temperatures are not very different from those in the *Csb* type. But Sacramento, in the Central Valley of California, is removed from the coast, and Izmir is bordered by the warm waters of the Mediterranean; consequently, summer temperatures are noticeably higher. As a result, annual temperature ranges are also higher in *Csa* areas.

Precipitation. Yearly precipitation within the dry-summer subtropics ranges between about 40 and 80 centimeters (16 and 31 inches). In many areas such amounts mean that a station barely escapes being classified as semiarid. As a result, some climatologists refer to the dry-summer climate as *subhumid* instead of humid. This is especially true along the equatorward margins because rainfall totals increase in the poleward direction. Los Angeles, for example, receives 38 centimeters (15 inches) of precipitation annually, whereas San Francisco, 400 kilo-

TABLE 15-11 Data for dry-summer subtropical stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
San Francisco, California, 37° 37′N; 5 m													
Temp. (°C)	9	11	12	13	15	16	17	17	18	16	13	10	14
Precip. (mm)	102	88	68	33	12	3	0	1	5	19	40	104	475
Sacramento, California, 38° 35′N; 13 m													
Temp. (°C)	8	10	12	16	19	22	25	24	23	18	12	9	17
Precip. (mm)	81	76	60	36	15	3	0	1	5	20	37	82	416
Izmir, Turkey, 38° 26′N; 25 m													
Temp. (°C)	9	9	11	15	20	25	28	27	23	19	14	10	18
Precip. (mm)	141	100	72	43	39	8	3	3	11	41	93	141	695
Santiago, Chile, 33° 27′S; 512 m													
Temp. (°C)	19	19	17	13	11	8	8	9	11	13	16	19	14
Precip. (mm)	3	3	5	13	64	84	76	56	30	13	8	5	360

meters (250 miles) to the north, receives 51 centimeters (20 inches) per year. Still farther north, at Portland, Oregon, the yearly rainfall average is over 90 centimeters (35 inches).

Students Sometimes Ask…

Do soils differ from one climate to another?

That's a definite yes. Climate is one of the most influential soil-forming factors. Variations in temperature and precipitation determine the type of weathering that occurs and also greatly influences the rate and depth of soil formation. For example, a hot, wet climate may produce a thick layer of chemically weathered soil in the same amount of time that a cold, dry climate produces a thin mantle of mechanically weathered debris. Also, the amount of precipitation influences the degree to which various materials are leached from the soil, thereby affecting soil fertility. Finally, climate is an important control on the type of plant and animal life present, which in turn influences the nature of the soil that forms.

Humid Continental Climates with Severe Winters (*D*)

The *C* climates just described have mild winters. By contrast, *D* climates experience severe winters. In this and the following section, two types of *D* climates are discussed—the humid continental and the subarctic. Climate diagrams of representative locations are shown in Figure 15–17.

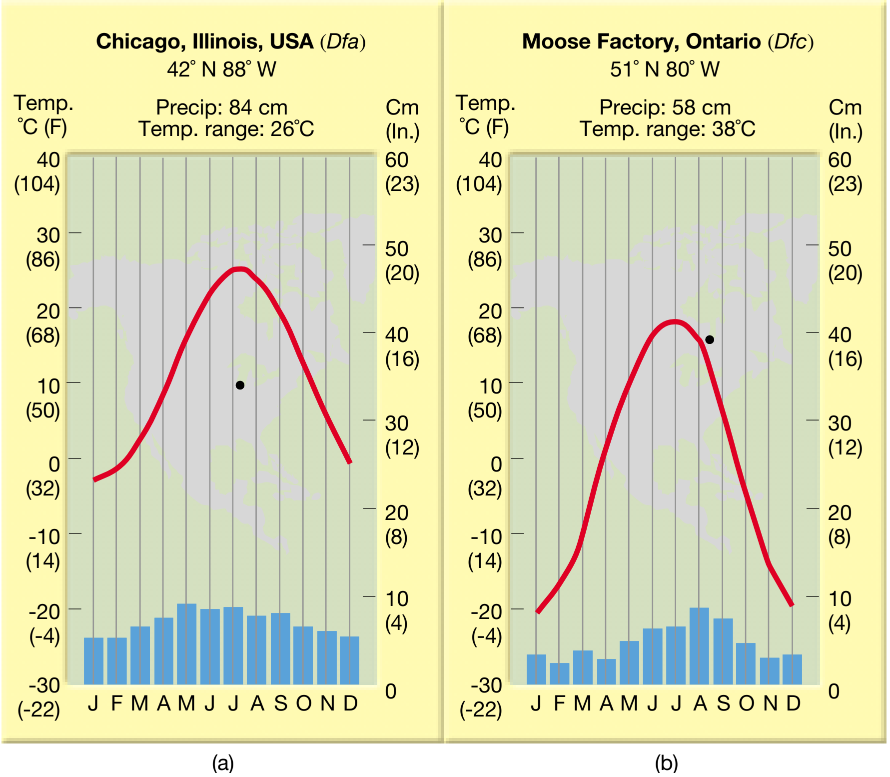
This climate region is dominated by the polar front and thus is a battleground for tropical and polar air masses. No other climate experiences such rapid nonperiodic changes in the weather. Cold waves, heat waves, droughts, blizzards, and heavy downpours are all yearly events in the humid continental realm (see Box 15–4).

Humid Continental Climate (*Dfa*)

The **humid continental climate** (*Dfa*), as its name implies, is a land-controlled climate. It is the product of broad continents located in the middle latitudes. Because continentality is a basic feature, this climate does not occur in the Southern Hemisphere, where the middle-latitude zone is dominated by the ocean. Instead, it is confined to central and eastern North America and Eurasia in the latitude range 40–50°N.

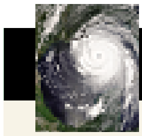
It may at first seem unusual that a continental climate should extend eastward to the margins of the ocean. However, the prevailing atmospheric circulation is from the west, so deep and persistent incursions of maritime air from the east are unlikely.

Temperature. Both winter and summer temperatures in the *Dfa* climate are relatively severe. Consequently, annual temperature ranges are great. A comparison of the stations in Table 15–12 illustrates this. July means are generally near and often above 20°C (68°F), so summertime temperatures, although lower in the north than in the south, are not markedly different.



(a) (b)

FIGURE 15-17 *D* climates are associated with the interiors of large landmasses in the mid-to-high latitudes of the Northern Hemisphere. Although winters can be harsh in Chicago's humid continental (*Dfa*) climate (a), the subarctic environment (*Dfc*) of Moose Factory is more extreme (b).



BOX 15-4 Atmospheric Hazard: Understanding Drought*

Drought is a period of abnormally dry weather that persists long enough to produce a significant hydrologic imbalance such as crop damage or water supply shortages (Figure 15–G). Drought severity depends upon the degree of moisture deficiency, its duration, and the size of the affected area.

(a) February 13, 2005

(b) February 11, 2004

FIGURE 15-G These satellite images depict drought in Portugal. In February 2005, Portugal was experiencing its worst drought in decades. Agricultural losses were devastating. In many areas, January 2005 was the driest January in more than 100 years. The dramatic impact of the drought is clear when comparing these images. The green of Portugal's forests and fields is apparent in the image captured on February 11, 2004, but is missing from the image obtained on February 13, 2005. In 2005 the landscape appears dull olive and brown as the country's vegetation withers in the face of the drought.

During the summer of 1999 parts of the eastern United States were suffering the effects of a yearlong drought. Four mid-Atlantic states experienced the driest summer since record keeping began in 1894. Crops were lost or stunted, and the water volume in many reservoirs and rivers dropped to seriously low levels. The drought, which began in 1998, included a heat wave and a rainfall deficit of 20 to 45 centimeters (8 to 18 inches) in many affected areas.

Although natural disasters such as floods and hurricanes usually generate more attention, droughts can be just as devastating and carry a bigger price tag. On the average, droughts cost the United States $6 to $8 billion annually compared to $2.4 billion for floods and $1.2 to $4.8 billion for hurricanes. Direct economic losses from a severe drought in 1988 were estimated at $40 billion.

Many people consider drought a rare and random event, yet it is actually a normal, recurring feature of climate. It occurs in virtually all climate zones, although its characteristics vary from region to region. The concept of drought differs from that of aridity. Drought is a temporary happening, whereas aridity describes regions where low rainfall is a permanent feature of the climate.

Drought is different from other natural hazards in several ways. First, it occurs in a gradual, "creeping" way, making its onset and end difficult to determine. The effects of drought accumulate slowly over an extended time span and sometimes linger for years after the drought has ended. Second, there is not a precise and universally accepted definition of drought. This adds to the confusion about whether or not a drought is actually occurring and, if it is, its severity. Third, drought seldom produces structural damages, so its social and economic effects are less obvious than damages from other natural disasters.

No single definition of drought works in all circumstances. The various definitions reflect many perspectives that use a number of different variables. Most definitions pertain to a specific region because of differences in climate characteristics. Thus, it is usually difficult to apply a definition that was developed for one region to another.

Definitions reflect four basic approaches to measuring drought: meteorological, agricultural, hydrological, and socioeconomic. *Meteorological drought* deals with the degree of dryness based on the departure of precipitation from normal values and the duration of the dry period. *Agricultural drought* is usually linked to a deficit of soil moisture. A plant's need for water depends on prevailing weather conditions, biological characteristics of the particular plant, its stage of growth, and various soil properties. *Hydrological drought* refers to deficiencies in surface and subsurface water supplies. It is measured as streamflow and as lake, reservoir, and groundwater levels (Figure 15–H). There is a time lag between the onset of dry conditions and a drop in streamflow, or the lowering of lakes, reservoirs, or groundwater levels. So, hydrological measurements are not the earliest indicators of drought. *Socioeconomic drought* is a reflection of what happens when a physical water shortage affects people. Socioeconomic drought occurs when the demand for an economic good exceeds supply as a result of a shortfall in water supply. For example, drought can result in significantly reduced hydroelectric power production, which in turn may require conversion to more expensive fuels and/or significant energy shortfalls.

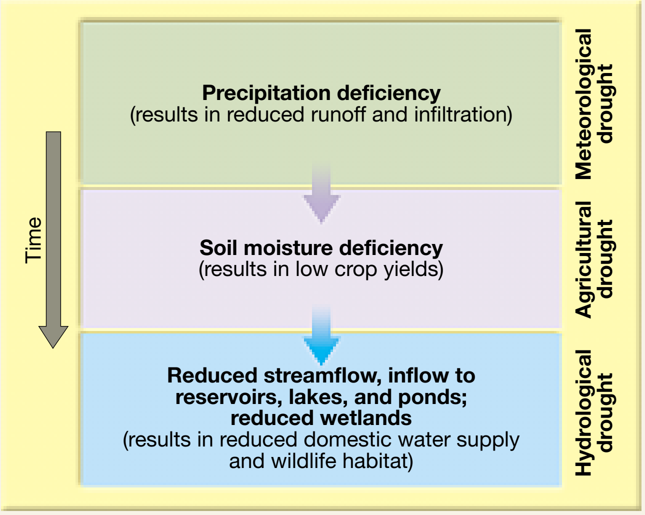
There is a sequence of impacts associated with meteorological, agricultural, and hydrological drought (Figure 15–I). When meteorological drought begins, the agricultural sector is usually the first to be affected because of its heavy dependence on soil moisture. Soil moisture is rapidly depleted during extended dry periods. If precipitation deficiencies continue, those dependent on rivers, reservoirs, lakes, and groundwater may be affected.

When precipitation returns to normal, meteorological drought comes to an end. Soil moisture is replenished first, followed by streamflow, reservoirs and lakes, and finally groundwater. Thus, drought impacts may diminish rapidly in the agricultural sector because of its reliance on soil moisture but linger for months or years in other sectors that depend on stored surface or subsurface water supplies. Groundwater users, who are often the last to be affected following the onset of meteorological drought, may also be the last to experience a return to normal water levels. The length of the recovery period depends upon the intensity of the meteorological drought, its duration, and the quantity of precipitation received when the drought ends.

The impacts suffered because of drought are the product of both the meteorological event and the vulnerability of society to periods of precipitation deficiency. As demand for water increases as a result of population growth and regional population shifts, future droughts can be expected to produce greater impacts whether or not there is any increase in the frequency or intensity of meteorological drought.

FIGURE 15-H One indicator of hydrological drought is significantly diminished streamflow. Continuous records of streamflow are collected by the U.S. Geological Survey at more than 7000 gauging stations in the United States. This station is on the Rio Grande, south of Taos, New Mexico. *(Photo by E. J. Tarbuck).*

FIGURE 15-I Sequence of drought impacts. After the onset of meteorological drought, agriculture is affected first, followed by reductions in streamflow and water levels in lakes, reservoirs, and underground. When meteorological drought ends, agricultural drought ends as soil moisture is replenished. It takes a considerably longer time span for hydrological drought to end.



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[*] Based in part on material prepared by the National Drought Mitigation Center (http://drought.unl.edu).

TABLE 15-12 Data for humid continental stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Omaha, Nebraska, 41° 18′N; 330 m													
Temp. (°C)	−6	−4	3	11	17	22	25	24	19	12	4	−3	10
Precip. (mm)	20	23	30	51	76	102	79	81	86	48	33	23	652
New York City, 40° 47′N; 40 m													
Temp. (°C)	−1	−1	3	9	15	21	23	22	19	13	7	1	11
Precip. (mm)	84	84	86	84	86	86	104	109	86	86	86	84	1065
Winnipeg, Canada, 49° 54′N; 240 m													
Temp. (°C)	−18	−16	−8	3	11	17	20	19	13	6	−5	−13	3
Precip. (mm)	26	21	27	30	50	81	69	70	55	37	29	22	517
Harbin, Manchuria, 45° 45′N; 143 m													
Temp. (°C)	−20	−16	−6	6	14	20	23	22	14	6	−7	−17	3
Precip. (mm)	4	6	17	23	44	92	167	119	52	36	12	5	557

This is illustrated by the temperature distribution map of the eastern United States in Figure 15–18a. The summer map has only a few widely spaced isotherms, indicating a weak summer temperature gradient. The winter map, however, shows a stronger temperature gradient (Figure 15–18b). The decrease in midwinter values with increasing latitude is appreciable. Confirming this, Table 15–12 reveals that the temperature change between Omaha and Winnipeg is more than twice as great in winter as in summer.

Because of the steeper winter temperature gradient, shifts in wind direction during the cold season often result in sudden large temperature changes. Such is not the case in summer, for temperatures throughout the region are more uniform.

Annual temperature ranges also vary within this climate, generally increasing from south to north and from the coast toward the interior. Comparing the data for Omaha and Winnipeg illustrates the first situation, and comparing New York City and Omaha illustrates the second.

Precipitation. Records of the four stations in Table 15–12 reveal the general precipitation pattern for *Dfa* climates. A summer maximum occurs at each station. But it is weakly defined at New York City, because the East Coast is more accessible to maritime air masses throughout the year. For the same reason, New York City also has the highest total of the four stations. Harbin, Manchuria, on the other hand, shows the most pronounced summer maximum, followed by a winter drought. This is characteristic of most eastern Asian stations in the middle latitudes and reflects the powerful control of the monsoon.

Another pattern revealed by the data is that precipitation generally decreases toward the continental interior and from south to north, primarily because of increasing distance from the sources of *mT* air. Furthermore, the more northerly stations are also influenced for a greater part of the year by drier polar air masses.

Wintertime precipitation is chiefly associated with the passage of fronts connected with traveling middle-latitude cyclones. Part of this precipitation is snow, the proportion increasing 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, and rain, of course, does not. Moreover, summer rains are often in the form of relatively short convective showers, whereas winter snows are more prolonged.

The Subarctic Climate *(Dfc, Dfd)*

North of the humid continental climate and south of the polar tundra is an extensive **subarctic climate.** It covers broad, uninterrupted expanses in North America (western Alaska to Newfoundland) and in Eurasia (Norway to the Pacific coast of Russia). It is often called the **taiga** climate, for it closely corresponds to the northern coniferous forest region of the same name (Figure 15–19). Although scrawny, the spruce, fir, larch, and birch trees in the taiga represent the largest stretch of continuous forest on Earth.

Temperature. The subarctic is well illustrated by the climate diagram in Figure 15–17b and by the data for Yakutsk, Russia, and Dawson, Yukon Territory in Table 15–13. Here in the source regions of continental polar (*cP*) air masses, the outstanding feature is the dominance of winter. Not only is it long, it is bitterly cold. Winter minimum temperatures are among the lowest recorded outside the ice caps 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, these

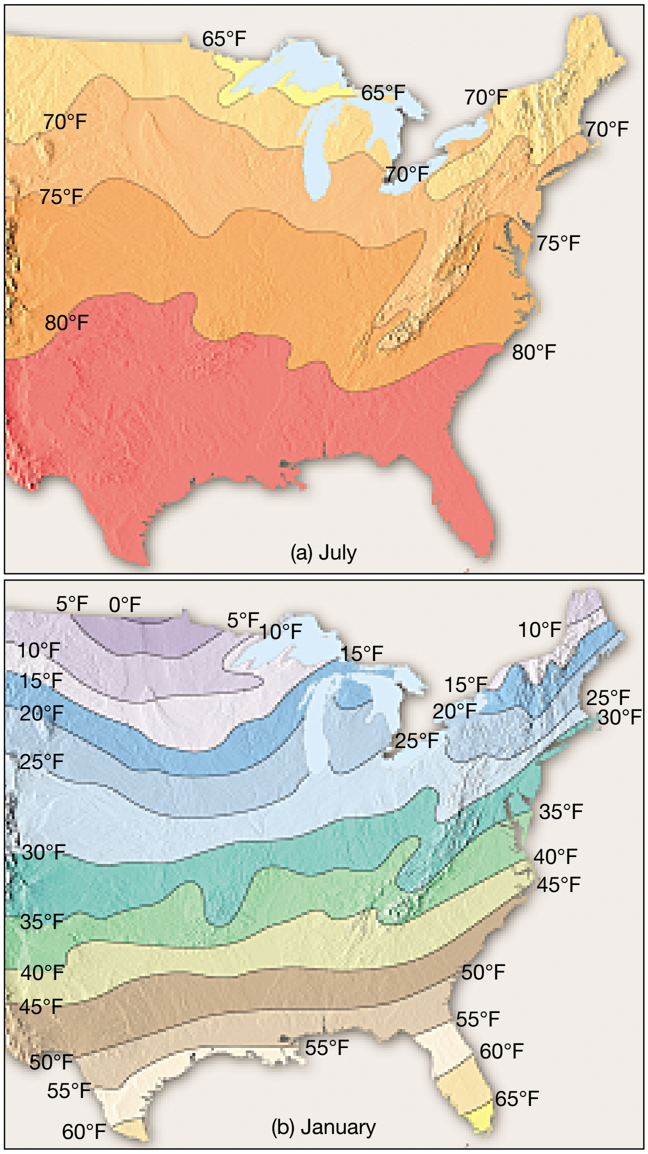

FIGURE 15-18 (a) During the summer months, north–south temperature variations in the eastern United States are small—that is, the temperature gradient is weak. (b) In winter, however, north– south temperature contrasts are sharp.

temperatures illustrate the extreme cold that envelops the taiga in winter.

In contrast, subarctic summers are remarkably warm, despite their short duration. When compared to regions farther south, however, this short season must be characterized as cool; for despite the many hours of daylight, the Sun never rises very high in the sky, so solar radiation is not intense. The extremely cold winters and the relatively warm summers of the taiga combine to produce the greatest annual temperature ranges on Earth. Yakutsk holds the distinction of having the greatest average temperature range in the world, 63°C (113°F). As the data for Dawson show, the North American subarctic is less severe.

Precipitation. Because these far northerly continental interiors are the source regions of *cP* air masses, only limited moisture is available throughout the year. Precipitation totals are therefore small, seldom exceeding 50 centimeters (20 inches). By far the greatest precipitation comes as rain from scattered summer convectional showers. Less snow falls than in the humid continental climate to the south, yet there is the illusion of more. The reason is simple: No melting occurs for months at a time, so the entire winter accumulation (up to 1 meter) is visible all at once. Furthermore, during blizzards, high winds swirl the dry, powdery snow into high drifts, giving the false impression that more snow is falling than is actually the case. So although snowfall is not excessive, a visitor to this region could leave with that impression.

The Polar Climates (*E*)

According to the Köppen classification, **polar climates** are those in which the mean temperature of the warmest month is below 10°C (50°F). Two types are recognized: the tundra climate (*ET*) and the ice cap climate (*EF*). Climate diagrams of representative stations are presented in Figure 15–20.

Just as the tropics are defined by their year-round warmth, so the polar realm is known for its enduring cold, with the lowest annual means on the planet. Because polar winters are periods of perpetual night, or nearly so, temperatures are understandably bitter. During the summer, temperatures remain cool despite the long days, because the Sun is so low in the sky that its oblique rays produce little warming. In addition, much solar radiation is reflected by the ice and snow or used in melting the snow cover. In either case, energy that could have warmed the land is lost. Although cool, summer temperatures are still much higher than those experienced during the severe winter months. Consequently, annual temperature ranges are extreme.

Although polar climates are classified as humid, precipitation is generally meager, with many nonmarine stations receiving less than 25 centimeters (10 inches) annually. Evaporation, of course, is also limited. The scanty precipitation is 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. In addition, steep lapse rates are not possible. Usually precipitation is most abundant during the warmer summer months, when the air's moisture content is highest.

The Tundra Climate (*ET*)

The **tundra climate** on land is found almost exclusively in the Northern Hemisphere. It occupies the coastal fringes of the Arctic Ocean, many Arctic islands, and the ice-free

FIGURE 15-19 The northern coniferous forest is also called the *taiga.* Denali National Park, Alaska. *(Photo by Yva Momatiuk and John Eastcott/Photo Researchers, Inc.)*

shores of northern Iceland and southern Greenland. In the Southern Hemisphere no extensive land areas exist in the latitudes where tundra climates prevail. Consequently, except for some small islands in the southern oceans, the *ET* climate occupies only the southwestern tip of South America and the northern portion of the Palmer Peninsula in Antarctica.

The 10°C (50°F) summer isotherm that marks the equatorward limit of the tundra also marks the poleward limit of tree growth. Thus, the tundra is a treeless region of grasses, sedges, mosses, and lichens (Figure 15–21a). During the long cold season, plant life is dormant, but once the short, cool summer commences, these plants mature and produce seeds with great rapidity.

Because summers are cool and short, the frozen soils of the tundra generally thaw to depths of less than a meter. Consequently, the subsoil remains permanently frozen as **permafrost** (Figure 15–21b). Permafrost blocks the downward movement of water and results in poorly drained, boggy soils that make the summer tundra landscape difficult to traverse (Figure 15–22).

The data for Point Barrow, Alaska (Table 15–14), on the shores of the frozen Arctic Ocean, exemplify the most

TABLE 15-13 Data for subarctic stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Yakutsk, Russia, 62° 05′N; 103 m													
Temp. (°C)	−43	−37	−23	−7	7	16	20	16	6	−8	−28	−40	−10
Precip. (mm)	7	6	5	7	16	31	43	38	22	16	13	9	213
Dawson, Yukon, Canada, 64° 03′N; 315 m													
Temp. (°C)	−30	−24	−16	−2	8	14	15	12	6	−4	−17	−25	−5
Precip. (mm)	20	20	13	18	23	33	41	41	43	33	33	28	346

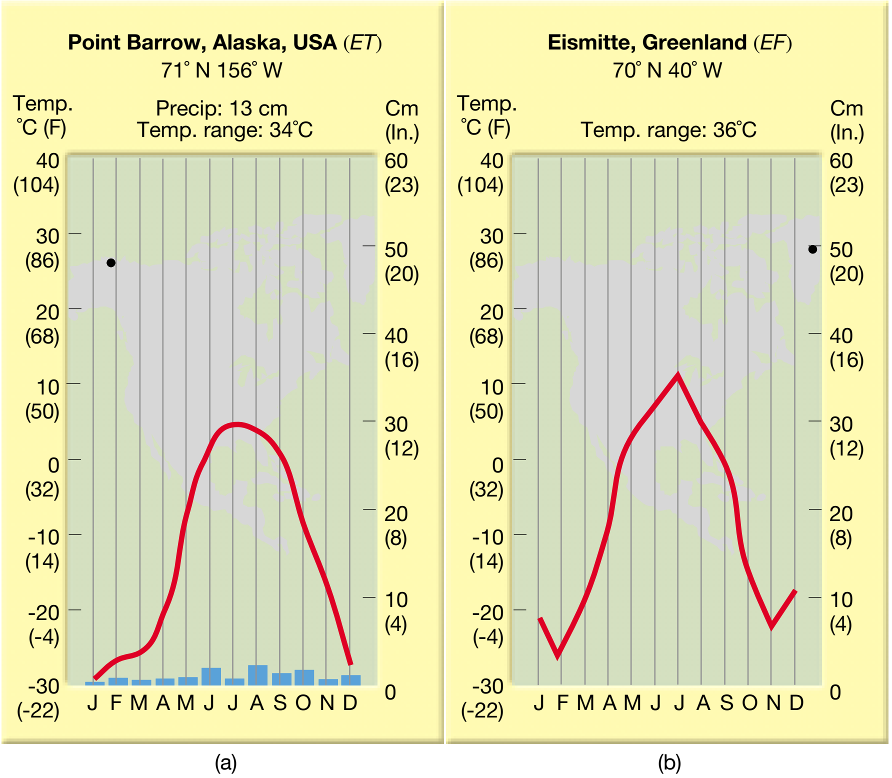

FIGURE 15-20 These climate diagrams represent the two basic polar climates. (a) Point Barrow, Alaska, exhibits a tundra (*ET*) climate. (b) Eismitte, Greenland, a station located on a massive ice sheet, is classified as an ice cap (*EF*) climate.

common type of *ET* station, where continentality prevails. The combination of high latitude and continentality makes winters severe, summers cool, and annual temperature ranges great. Yearly precipitation is small, with a modest summertime maximum.

Although Point Barrow represents the most common type of tundra setting, the data for Angmagssalik, Greenland (Table 15–14), reveal that some *ET* stations are different. Summer temperatures at both stations are equivalent, yet winters at Angmagssalik are much warmer and the annual precipitation is eight times greater than at Point Barrow. The reason is Angmagssalik's location on the southeastern coast of Greenland, where there is considerable marine influence. The warm North Atlantic Drift keeps winter temperatures relatively warm, and maritime polar (*mP*) air masses supply moisture throughout the year. Because winters are less severe at stations like Angmagssalik, annual temperature ranges are much smaller than at stations like Point Barrow, where continentality is a major control.

Note that tundra climates are not entirely confined to the high latitudes. The summer coolness of this climate is also found at higher elevations as one moves equatorward. Even in the tropics, you can find *ET* climates if you go high enough. When compared with the Arctic tundra, however, winter temperatures in these lower-latitude counterparts become milder and less distinct from summer, as the data for Cruz Loma, Ecuador (Table 15–14), illustrate.

Students Sometimes Ask…

Does permafrost ever melt?

Yes, this sometimes happens. One situation is when people disturb the surface. When the insulating mat of vegetation is removed, or roads and buildings are constructed, the delicate thermal balance can be disturbed and permafrost can thaw. Global warming over the past century is also thought to be responsible for a reduction in the extent of regions underlain by permafrost. Thawing produces unstable ground that may slide, slump, subside, or undergo severe frost heaving.

The Ice-Cap Climate *(EF)*

The **ice-cap climate,** designated by Köppen as *EF,* has no monthly mean above 0°C (32°F). 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, and aside from scattered occurrences in high mountain areas, it is largely confined to the ice sheets of Greenland and Antarctica.

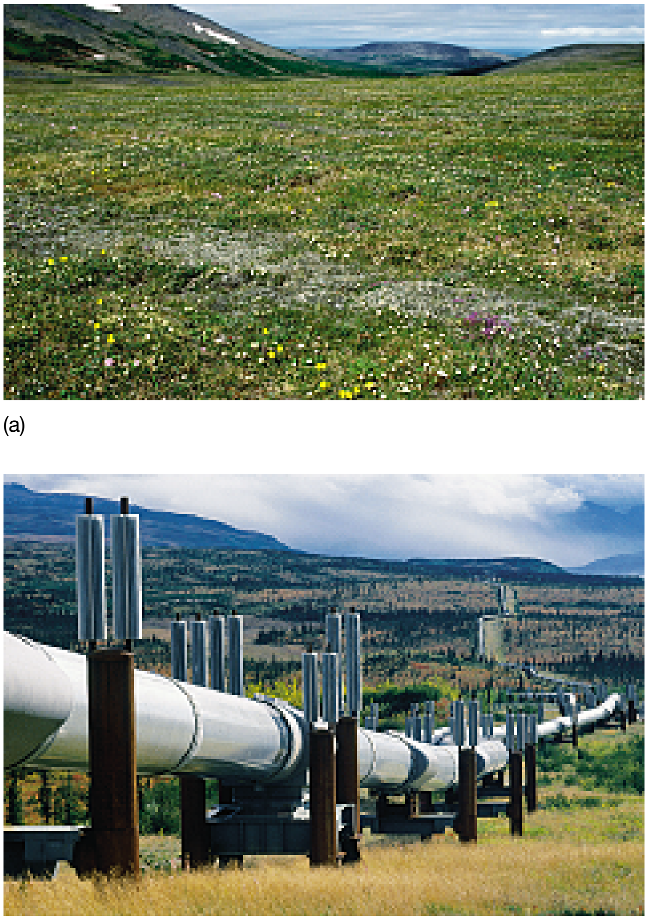

FIGURE 15-21 (a) The tundra in bloom north of Nome, Alaska. It is a region almost completely devoid of trees. Bogs and marshes are common, and plant life frequently consists of mosses, low shrubs, and flowering herbs. *(Photo by Fred Bruemmer/DRK Photo)* (b) In places in Alaska, a pipeline containing heated oil is suspended above ground to prevent melting of delicate permafrost. *(Tome & Pat Leeson/Photo Researchers)*

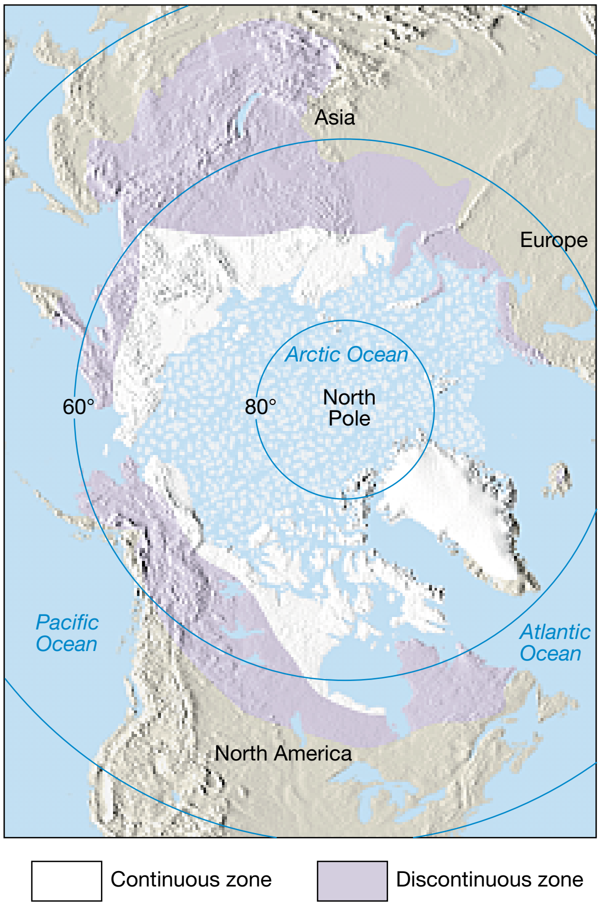

FIGURE 15-22 Distribution of permafrost in the Northern Hemisphere. More than 80 percent of Alaska and about 50 percent of Canada are underlain by permafrost. Two zones are recognized. In the continuous zone, the only ice-free areas are beneath deep lakes or rivers. In the higher-latitude portions of the discontinuous zones, there are only scattered islands of thawed ground. Moving southward, the percentage of unfrozen ground increases until all the ground is unfrozen. *(After the U.S. Geological Survey)*

Average annual temperatures are extremely low. For example, the annual mean at Eismitte, Greenland (Table 15–14), is −29°C (−20°F); at Byrd Station, Antarctica, −21°C (−6°F); and at Vostok, the Russian Antarctic Meteorological Station, −57°C (−71°F). Vostok has also experienced the lowest temperature ever recorded, −88.3°C (−127°F), on August 24, 1960.

In addition to latitude, the primary reason for such temperatures is the presence of permanent ice. Ice has a very high albedo, reflecting up to 80 percent of the meager sunlight that strikes it. The energy that is not reflected is used largely to melt the ice and so is not available for raising the temperature of air.

Another factor at many *EF* stations is elevation. Eismitte, at the center of the Greenland ice sheet, is almost 3000 meters above sea level (10,000 feet), and much of Antarctica is even higher. Thus, the permanent ice and high elevations further reduce the already low temperatures of the polar realm.

The intense chilling of the air close to the ice sheet means that strong surface-temperature inversions are common. Near-surface temperatures may be as much as 30°C (54°F) colder than air just a few hundred meters above. Gravity pulls this cold, dense air downslope, often producing strong winds and blizzard conditions. Such air movements, called *katabatic winds*, are an important aspect of ice cap weather at many locations. Where the slope is sufficient, these gravity-induced air movements can be strong enough to flow in a direction that is opposite the pressure gradient.

Highland Climates

It is well known that mountain climates are distinctly different from those in adjacent lowlands. Sites with **highland climates** are cooler and usually wetter. The world climate types already discussed consist of large, relatively homogeneous

TABLE 15-14 Data for polar stations

	J	F	M	A	M	J	J	A	S	O	N	D	YR
Eismitte, Greenland, 70° 53′N; 2953 m													
Temp. (°C)	−42	−47	−40	−32	−24	−17	−12	−11	−11	−36	−43	−38	−29
Precip. (mm)	15	5	8	5	3	3	3	10	8	13	13	25	111
Angmagssalik, Greenland, 65° 36′N; 29 m													
Temp. (°C)	−7	−7	−6	−3	2	6	7	7	4	0	−3	−5	0
Precip. (mm)	57	81	57	55	52	45	28	70	72	96	87	75	775
Point Barrow, Alaska, 71° 18′N; 9 m													
Temp. (°C)	−28	−28	−26	−17	−8	0	4	3	−1	−9	−18	−24	−12
Precip. (mm)	5	5	3	3	3	10	20	23	15	13	5	5	110
Cruz Loma, Ecuador, 0° 08′S; 3888 m													
Temp. (°C)	6.1	6.6	6.6	6.6	6.6	6.1	6.1	6.1	6.1	6.1	6.6	6.6	6.4
Precip. (mm)	198	185	241	236	221	122	36	23	86	147	124	160	1779

regions. But highland climates are characterized by a great diversity of climatic conditions over small areas. Because large differences occur over short distances, the pattern of climates in mountainous areas is a complex mosaic, too complicated to depict on a world map.

In North America highland climates characterize the Rockies, Sierra Nevada, Cascades, and the mountains and interior plateaus of Mexico. In South America the Andes create a continuous band of highland climate that extends for nearly 8000 kilometers (5000 miles). The greatest span of highland climates stretches from western China, across southern Eurasia, to northern Spain, from the Himalayas to the Pyrenees. Highland climates in Africa occur in the Atlas Mountains in the north and in the Ethiopian Highlands in the east.

The best-known climate effect of increased altitude is lower temperatures. Greater precipitation due to orographic lifting is also common at higher elevations. The precipitation map for Nevada, Figure 15–23, illustrates this nicely. The long, slender zones of highest precipitation coincide with areas of mountainous topography. 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 15–24 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 (about 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), a full 15°C (27°F) cooler. Although the temperatures at each city are quite different, the annual march of temperature for both is similar. Both experience minimum and maximum monthly means in the same months. When precipitation data are examined, both places have a similar seasonal pattern, but the amounts at Flagstaff are higher in every month. In addition, much of Flagstaff's winter precipitation is snow, whereas it only rains in Phoenix.

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 do north-facing slopes

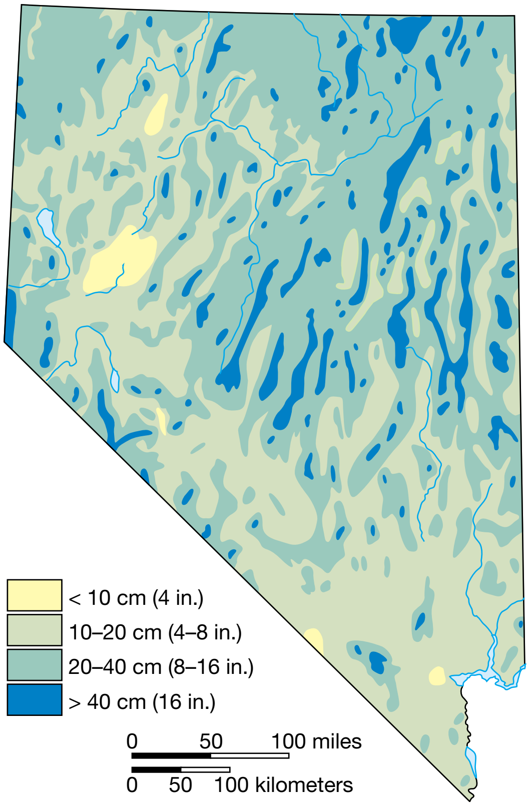

FIGURE 15-23 Precipitation map for the state of Nevada. Nevada is part of a region known as the Basin and Range that is characterized by many small mountain ranges that rise 900 to 1500 meters (3000–5000 feet) above the basins that separate them. Where there are mountains, there is more precipitation; where there are basins, there is less precipitation. The relationship is simple and straightforward.

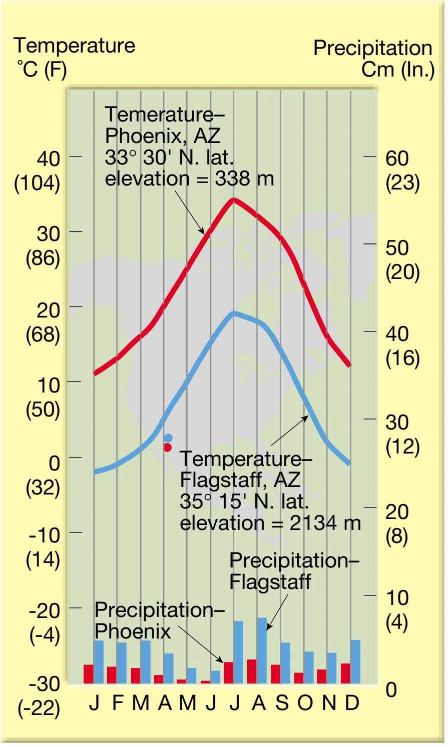

FIGURE 15-24 Climate diagrams for two Arizona stations illustrate the general influence of elevation on climate. Flagstaff is cooler and wetter because of its position on the Colorado Plateau, nearly 1800 meters (6000 feet) higher than Phoenix.

and deep valleys. Wind direction and speed in mountains can be highly variable and quite different from the movement of air aloft or over adjacent plains. 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.

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. Ascending a mountain can let us view dramatic vegetation changes that otherwise might require a poleward journey of thousands of kilometers (Figure 15–25). This occurs because altitude duplicates, in some respects, the influence of latitude on temperature and hence on vegetation types. However, we know other factors, such as slope orientation, exposure, winds, and orographic effects also play a role in controlling the climate of highlands. Consequently, although the concept of vertical life zones applies on a broad regional scale, the details within an area vary considerably. Some of the most obvious variations result from differences in rainfall or the receipt of solar radiation on opposite sides of a mountain.

To summarize, *variety* and *changeability* best describe highland climates. Because atmospheric conditions fluctuate with altitude and exposure, a nearly limitless variety of local climates occurs 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. Slopes facing the Sun are unlike those that lie mainly in the shadows.

FIGURE 15-25 (a) Only scanty drought-tolerant natural vegetation can survive in the hot, dry climate of southern Arizona, near Phoenix. *(Photo by Charlie Ott Photography/Photo Researchers, Inc.).* (b) The natural vegetation associated with the cooler, wetter highlands near Flagstaff, Arizona, is much different from the desert lowlands. *(Photo by Larry Ulrich/DRK Photo)*

(a)

(b)

Chapter Summary

- Climate is more than “the average state of the atmosphere” because a complete climate description should also include variations and extremes to accurately portray the total character of an area. The most important elements in climate descriptions are *temperature* and *precipitation* inasmuch as they have the greatest influence on people and their activities and also have an important impact on the distribution of vegetation and the development of soils.
- Perhaps the first attempt at climate classification was made by the ancient Greeks, who divided each hemisphere into three zones: *torrid, temperate*, and *frigid.* Many climate-classification schemes have been devised. The classification of climates is the product of human ingenuity and its value is determined largely by its intended use.
- For decades, a climate classification devised by Wladimir Köppen (1846–1940) has been the best-known and most used tool for presenting the world pattern of climates. The *Köppen classification* uses easily obtained data: mean monthly and annual values of temperature and precipitation. Furthermore, the criteria are unambiguous, simple to apply, and divide the world into climate regions in a realistic way. Köppen believed that the distribution of natural vegetation was the best expression of an overall climate. Consequently, the boundaries he chose were largely based on the limits of certain plant associations. Köppen recognized five principal climate groups, each designated with a capital letter: *A (humid tropical), B (dry), C (humid middle-latitude, mild winters), D (humid middle-latitude, severe winters)*, and *E (polar)*. Four groups *(A, C, D, E)* are defined by temperature. The fifth, the *B* group, has precipitation as its primary criterion.
- Order exists in the distribution of climate elements and the pattern of climates is not by chance. The world’s climate pattern reflects a regular and dependable operation of the major *climate controls*. The major controls of climate are (1) *latitude* (variations in the receipt of solar energy and temperature differences are largely a function of latitude), (2) *land/water influence (marine climates* are generally mild, whereas *continental climates* are typically more extreme), (3) *geographic position and prevailing winds* (the moderating effect of water is more pronounced along the windward side of a continent), (4) *mountains and highlands* (mountain barriers prevent maritime air masses from reaching far inland, trigger orographic rainfall, and where they are extensive, create their own climatic regions), (5) *ocean currents* (poleward-moving currents cause air temperatures to be warmer then otherwise would be expected), and (6) *pressure and wind systems* (the world distribution of precipitation is closely related to the distribution of Earth’s major pressure and wind systems).
- Situated astride the equator, the *wet tropics (Af, Am)* exhibit constant high temperatures and year-round rainfall that combine to produce the most luxuriant vegetation in any climatic realm—the *tropical rain forest*. Temperatures in these regions usually average 25ºC (77ºF) or more each month and the daily temperature variations characteristically exceed seasonal differences. Precipitation in *Af* and *Am* climates is normally from 175 to 250 centimeters (68 to 98 inches) per year and is more variable than temperature, both seasonally and from place to place. Thermally induced convection coupled with convergence along the *intertropical convergence zone (ITCZ)* leads to widespread ascent of the warm, humid, unstable air and ideal conditions for cloud formation and precipitation.
- The *tropical wet and dry* (*Aw*) climate region is a transitional zone between the rainy tropics and the subtropical steppes. Here, the rain forest gives way to the *savanna*, a tropical grassland with scattered deciduous trees. Only modest temperature differences exist between the wet tropics and the tropical wet and dry regions. The primary factor that distinguishes the *Aw* climate from *Af* and *Am* is precipitation. In *Aw* regions the precipitation is typically between 100 and 150 centimeters (40 to 60 inches) per year and exhibits some seasonal character—wet summers followed by dry winters. In much of India, southeast Asia, and portions of Australia, these alternating periods of rainfall and drought are associated with the *monsoon*, wind systems with a pronounced seasonal reversal of direction. The *Cw* climate, which is subtropical instead of tropical, is a variant of *Aw*.
- Dry regions of the world cover about 30 percent of Earth’s land area. Other than their meager yearly rainfall, the most characteristic feature of dry climates is that precipitation is very unreliable. Climatologists define a *dry climate* as one in which the yearly precipitation is less than the potential water loss by evaporation. To define the boundary between dry and humid climates, the Köppen classification uses formulas that involve three variables: (1) average annual precipitation, (2) average annual temperature, and (3) seasonal distribution of precipitation.
- The two climates defined by a general water deficiency are (1) *arid* or *desert* (*BW*), and *semiarid* or *steppe* (*BS*). The differences between deserts and steppes are primarily a matter of degree. Semiarid climates are a marginal and more humid variant of arid climates that represent transitional zones that surround deserts and separate them from the bordering humid climates. Under the strong influence of the subtropical highs, the heart of the subtropical desert *(BWh)* and steppe *(BSh)* climates lies in the vicinity of the Tropic of Cancer and the Tropic of Capricorn. Within subtropical deserts, the scanty precipitation is both infrequent and erratic. In the semiarid

transitional belts surrounding the desert, a seasonal rainfall pattern becomes better defined. Due to cloudless skies and low humidities, low-latitude deserts in the interiors of continents have the greatest daily temperature ranges on Earth. Where subtropical deserts are found along the west coasts of continents, cold ocean currents produce cool, humid conditions, often shrouded by low clouds or fog. Unlike their low-altitude counterparts, middle-latitude deserts *(BWk)* and steppes *(BSk)* are not controlled by the subsiding air masses of the subtropical highs. Instead, these lands exist principally because of their position in the deep interiors of large landmasses.

- *Humid middle-latitude climates with mild winters* (*C* climates) occur where the average temperature of the coldest month is less than 18°C (64°F) but above −3°C (27°F). Several *C* climate subgroups exist. *Humid subtropical climates (Cfa)* are on the eastern sides of the continents, in the 25- to 40-degree latitude range. Because of the dominating influence of maritime tropical air masses, summer weather within these regions is hot and sultry, and winters are mild. In North America, the *marine west coast climate (Cfb)* extends from near the United States–Canada border northward as a narrow belt into southern Alaska. The prevalence of maritime air masses means mild winters, cool summers, and ample rainfall throughout the year. *Dry-summer subtropical (Mediterranean) climates (Csa, Csb)* are typically found along the west sides of continents between latitudes 30° and 45°. In summer, the regions are dominated by the stable eastern sides of the oceanic subtropical highs. In winter, as the wind and pressure systems follow the Sun equatorward, they are within range of the cyclonic storms of the polar front.
- *Humid continental climates with severe winters* (*D* climates) experience severe winters. The average temperature of the coldest month is −3°C (27°F) or below, and the average temperature of the warmest month exceeds 10°C (50°F). *Humid continental climates (Dfa)* are land-controlled and do not occur in the Southern Hemisphere. They are confined to central and eastern North America and Eurasia in the latitude range 40° to 50°N. Both winter and summer temperatures in *Dfa* climates can be characterized as severe, and annual temperature ranges are large. Precipitation is generally greater in summer and generally decreases toward the continental interior and from south to north. Wintertime precipitation is chiefly associated with the passage of fronts connected with traveling middle-latitude cyclones. *Subarctic climates (Dfc, Dfd)*, often called *taiga* climates because they correspond to the northern coniferous forests of the same name, 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 greatest annual temperature ranges on Earth occur here.
- *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. Found almost exclusively in the Northern Hemisphere, the *tundra climate (ET)*, marked by the 10°C (50°F) summer isotherm at its equatorward limit, 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. Consequently, the growth of vegetation is prohibited, and the landscape is one of permanent ice and snow.
- *Highland climates* are characterized by a great diversity of climatic conditions over a small area. In North America highland climates characterize the Rockies, Sierra Nevada, Cascades, and the mountains and interior plateaus of Mexico. 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.

Vocabulary Review

arid or desert (*BW*) (p. 445)
continental climate (p. 432)
dry climate (p. 444)
dry-summer subtropical climate (p. 453)
highland climate (p. 462)
humid continental climate (p. 455)
humid subtropical climate (p. 450)
ice-cap climate (p. 461)
intertropical convergence zone (ITCZ) (p. 439)
Köppen classification (p. 430)
marine climate (p. 432)

marine west coast climate (p. 452)
Mediterranean climate (p. 453)
monsoon (p. 442)
permafrost (p. 460)
polar climate (p. 459)
savanna (p. 441)
semiarid or steppe (*BS*) (p. 445)
subarctic climate (p. 458)
taiga (p. 458)
tropical rain forest (p. 436)
tropical wet and dry (p. 441)
tundra climate (p. 459)

Review Questions

1. Why is classification often a necessary task in science?
2. What climate data are needed to classify a climate using the Köppen scheme?
3. Should climate boundaries, such as those shown on the world map in Figure 15–3, be regarded as fixed? Explain.
4. List the major climate controls and briefly describe their influence.
5. How does the tropical rain forest differ from a typical middle-latitude forest?
6. Distinguish between jungle and tropical rain forest.
7. Explain each of the following characteristics of the wet tropics:
    - **a.** This climate is restricted to elevations below 1000 meters.
    - **b.** Mean monthly and annual temperatures are high and the annual temperature range is low.
    - **c.** This climate is rainy throughout the year, or nearly so.
8. Why are the wet tropics considered oppressive and monotonous?
9. What is the difference between *Af* areas and *Am* areas?
10. The tropical soils described in Box 15–2 support luxuriant rain forests yet are considered to have low fertility. Explain.
11. **a.** What primary factor distinguishes *Aw* climates from *Af* and *Am*?
    - **b.** How is this difference reflected in the vegetation?
12. Describe the influence of the ITCZ and the subtropical high on the precipitation regime in the *Aw* climate.
13. In which of the following climates is the annual rainfall likely to be more consistent from year to year: *BSh*, *Aw*, *BWh*, or *Af*? In which of these climates is the annual rainfall most variable from year to year? Explain your answers.
14. In the dry (*B*) climates, there are usually more years when rainfall totals are below the average than above. Explain and give an example.
15. The amount of precipitation that defines the humid–dry boundary is variable. Why?
16. What is the primary reason (control) for the existence of the dry subtropical realm (*BWh* and *BSh*)?
17. **a.** Describe and explain the seasonal distribution of precipitation for a *BSh* station on the poleward side of a tropical desert and a *BSh* station on the equatorward side.
    - **b.** If both stations barely meet the requirements for steppe climates (that is, with only a little more rainfall, both stations would be considered humid), which station would probably have the lower rainfall total? Explain.
18. Why do ground and air temperatures reach such high values in subtropical deserts?
19. Subtropical deserts, such as the Atacama and Namib, deviate considerably from the general image that we have of deserts. In what ways are these deserts not "typical" and why?
20. What is the primary cause of middle-latitude deserts and steppes?
21. Why are desert and steppe areas uncommon in the middle latitudes of the Southern Hemisphere?
22. Describe and explain the differences between summertime and wintertime precipitation in the humid subtropics (*Cfa*).
23. 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?
24. How do temperature gradients (north–south versus east–west) reveal the strong oceanic influence along the West Coast of North America?
25. In this chapter the dry-summer subtropics were described as transitional. Explain why.
26. What other name is given to the dry-summer subtropical climate?
27. Why are summer temperatures cooler at San Francisco than at Sacramento (Table 15–11)?
28. Why is the humid continental climate confined to the Northern Hemisphere?
29. Why do coastal stations like New York City experience primarily continental climatic conditions?

30. Using the four stations shown in Table 15–12, describe the general pattern of precipitation in humid continental climates.

31. In the dry-summer subtropics precipitation totals increase with an increase in latitude, but in the humid continental climates the reverse is true. Explain.

32. Although generally characterized by small precipitation totals, subarctic and polar climates are considered humid. Explain.

33. Although snowfall in the subarctic climate is relatively scant, a wintertime visitor might leave with the impression that snowfall is great. Explain.

34. Describe and explain the annual temperature range one should expect in the realm of the taiga.

35. Although polar regions experience extended periods of sunlight in the summer, temperatures remain cool. Explain.

36. What is the significance of the 10°C (50°F) summer isotherm?

37. Why is the tundra landscape characterized by poorly drained, boggy soils?

38. Why are winter temperatures higher and the annual precipitation greater in Angmagssalik, Greenland, than at Point Barrow, Alaska?

39. The tundra climate is not confined solely to high latitudes. Under what circumstances might the *ET* climate be found in more equatorward locations?

40. Where are *EF* climates developed most extensively?

41. Besides the effect of latitude, what other factor(s) contribute to the extremely low temperatures that characterize the *EF* climate? Explain.

42. The Arizona cities of Flagstaff and Phoenix are relatively close to one another, yet have contrasting climates (see Figure 15–24). Briefly explain why the differences occur.

Problems

1. Use Table 15–1 to determine the appropriate classification for stations a, b, and c below.
2. Using the maps in Figure 15–18, determine the approximate January and July temperature gradients between the southern tip of mainland Florida and the point where the Minnesota–North Dakota border touches Canada. Assume the distance to be 3100 kilometers (1900 miles). Express your answers in °C per 100 kilometers or °F per 100 miles.

			J	F	M	A	M	J	J	A	S	O	N	D	YR
a.	Temp.	(°C)	−18.7	−18.1	−16.7	−11.7	−5.0	0.6	5.3	5.8	1.4	−4.2	−12.3	−15.8	−7.5
	Precip.	(mm)	8	8	8	8	15	20	36	43	43	33	13	12	247
b.	Temp.	(°C)	24.6	24.9	25.0	24.9	25.0	24.2	23.7	23.8	23.9	24.2	24.2	24.7	24.4
	Precip.	(mm)	81	102	155	140	133	119	99	109	206	213	196	122	1675
c.	Temp.	(°C)	12.8	13.9	15.0	16.1	17.2	18.8	19.4	22.2	21.1	18.8	16.1	13.9	15.9
	Precip.	(mm)	53	56	41	20	5	0	0	2	5	13	23	51	269

Atmospheric Science Online

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