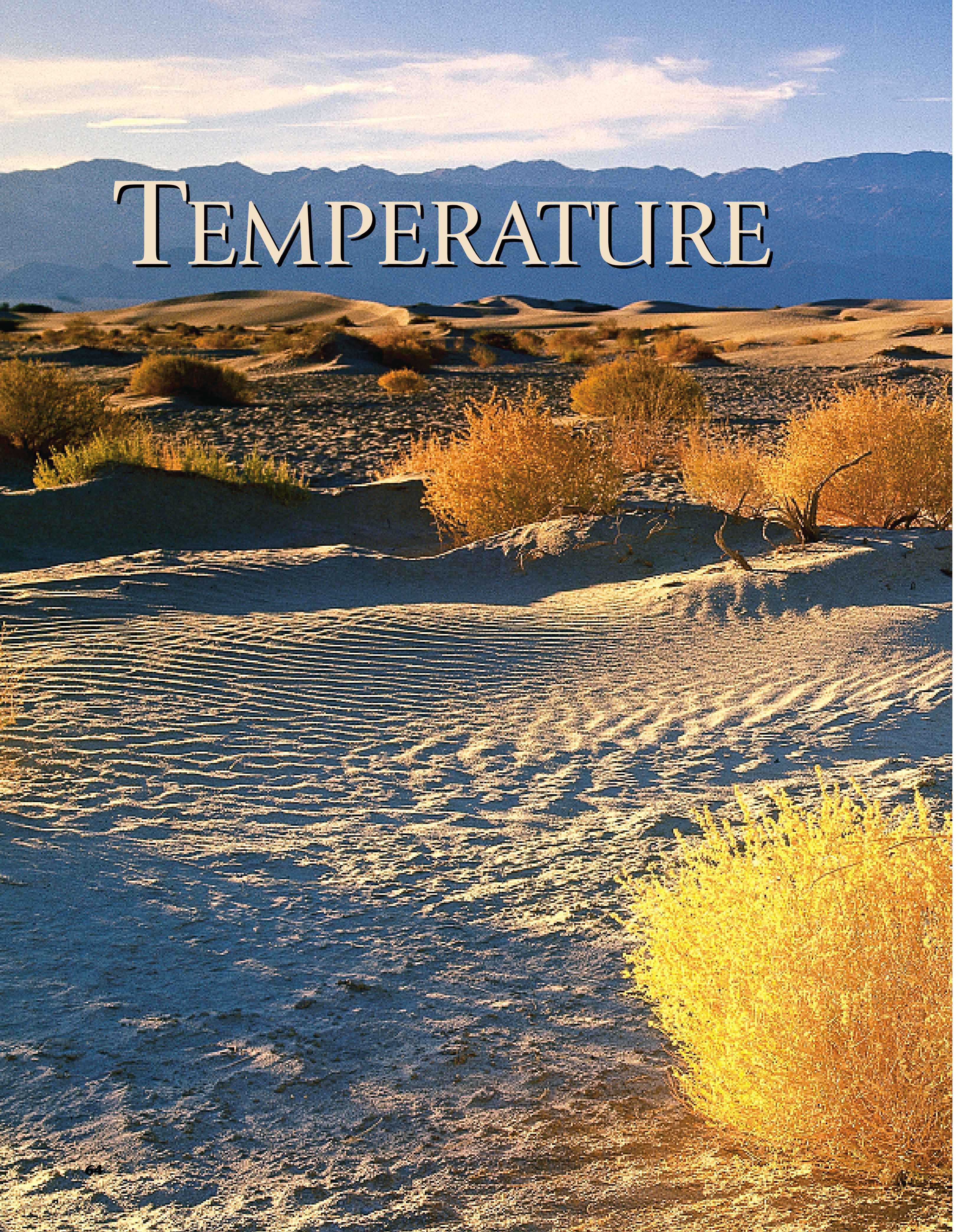
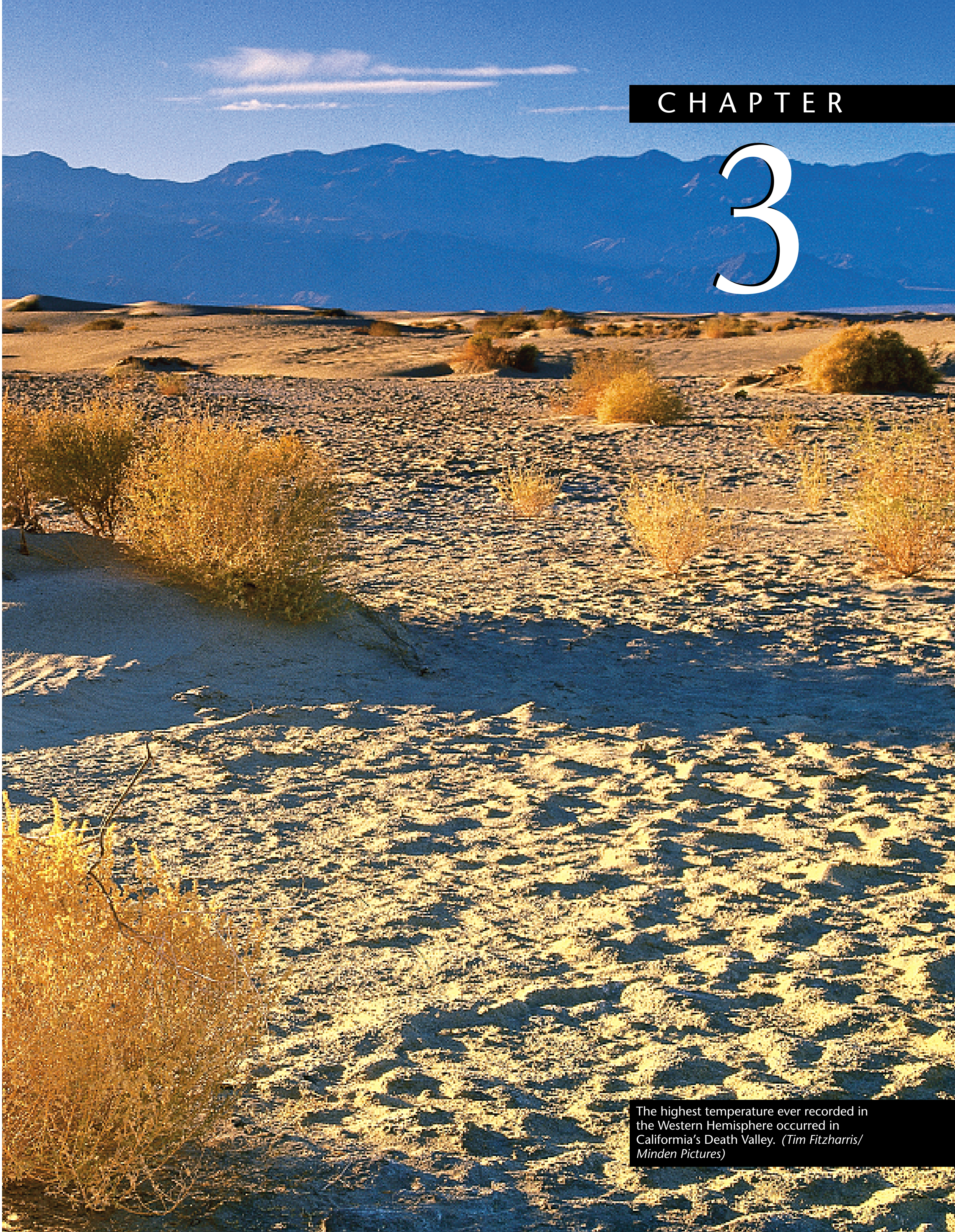
TEMPERATURE



CHAPTER 3



The highest temperature ever recorded in the Western Hemisphere occurred in California's Death Valley. *(Tim Fitzharris/ Minden Pictures)*

Temperature is one of the basic elements of weather and climate. When someone asks what the weather is like outside, air temperature is often the first element we mention (Figure 3–1). From everyday experience, we know that temperatures vary on different time scales: seasonally, daily, sometimes even hourly. Moreover, we all realize that substantial temperature differences exist from one place to another. In Chapter 2 we learned how air is heated, and we examined the role of Earth–Sun relationships in causing temperature variations from season to season and from latitude to latitude. In Chapter 3 we will focus on several other aspects of this very important atmospheric property, including factors other than Earth–Sun relationships that act as temperature controls. We will also look at how temperature is measured and expressed and see that temperature data can be of very practical value to us all. Applications include calculations that are useful in evaluating energy consumption, crop maturity, and human comfort.

For the Record: Air-Temperature Data

Temperature Data and the Controls of Temperature

▶ Basic Temperature Data

Temperatures recorded daily at thousands of weather stations worldwide provide much of the temperature data compiled by meteorologists and climatologists (see Box 3–1). Hourly temperatures may be recorded by an observer or obtained from automated observing systems that continually monitor the atmosphere. At many locations only the maximum and minimum temperatures are obtained. The **daily mean temperature** is determined by averaging the 24 hourly readings or more frequently by adding the maximum and minimum temperatures for a 24-hour period and dividing by 2. From the maximum and minimum, the **daily temperature range** is computed by finding the difference between these figures. Other data involving longer periods are also compiled:

1. The **monthly mean temperature** is calculated by adding together the daily means for each day of the month and dividing by the number of days in the month.
2. The **annual mean temperature** is an average of the 12 monthly means.
3. The **annual temperature range** is computed by finding the difference between the warmest and coldest monthly mean temperatures.

Mean temperatures are especially useful for making daily, monthly, or annual comparisons. It is common to hear a weather reporter state, "Last month was the warmest

FIGURE 3-1 At 1886 meters (6288 feet), Mount Washington is the highest peak in the White Mountains and in fact the entire Northeast. It is a popular destination for hikers and is considered by some to be "the Home of the World's Worst Weather" due to its extreme cold, heavy snows, high winds, frequent icing, and dense fog. The observatory at its summit keeps detailed weather records. *(Photo by Jim Salge/Mount Washington Observatory)*

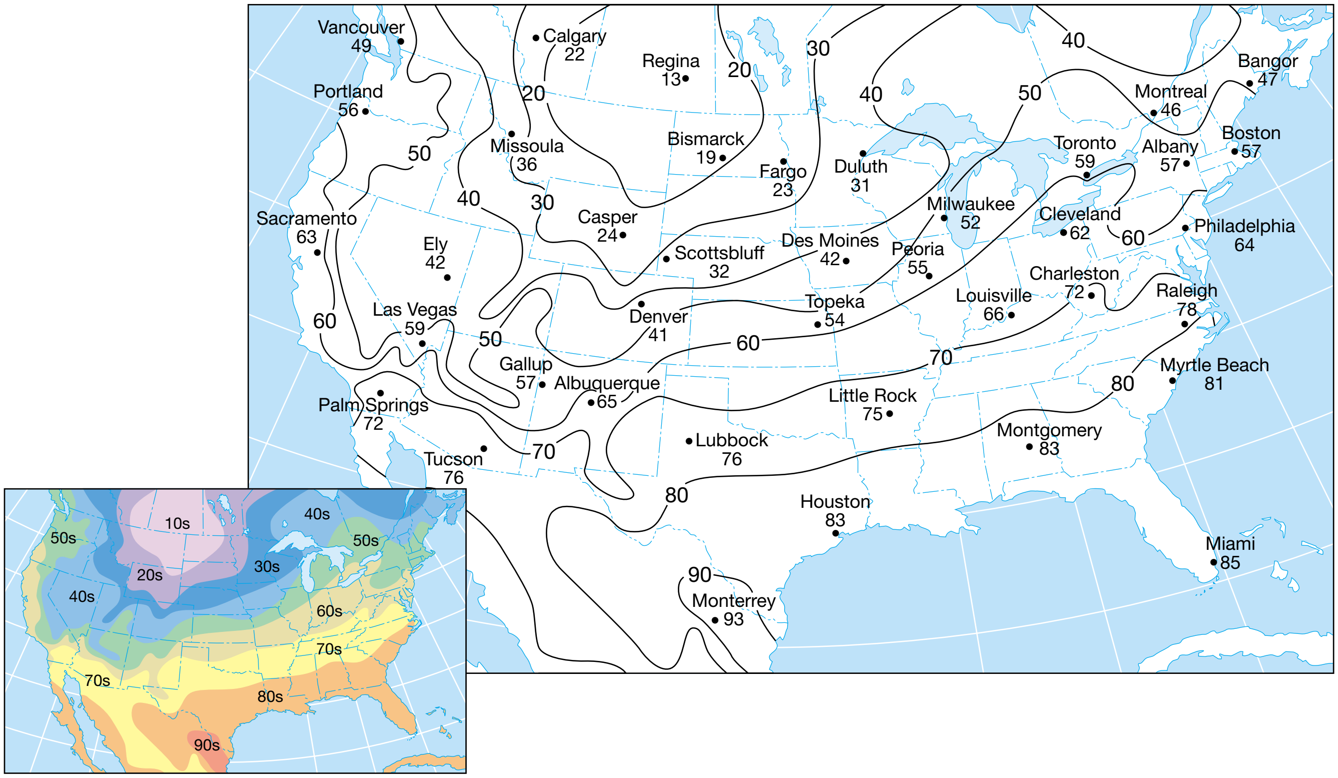


FIGURE 3-2 Isothermal map for a spring day. Isotherms are lines that connect points of equal temperature. Showing temperature distribution in this way makes patterns easier to see. On television and in many newspapers, temperature maps are in color. Rather than labeling isotherms, the area *between* isotherms is labeled. For example, the zone between the 60° and 70° isotherms is labeled "60s."

February on record" or "Today Omaha was 10 degrees warmer than Chicago." Temperature ranges are also useful statistics because they give an indication of extremes, a necessary part of understanding the weather and climate of a place or an area.

To examine the distribution of air temperatures over large areas, isotherms are commonly used. An **isotherm** is a line that connects points on a map that have the same temperature (*iso* = equal, *therm* = temperature). Therefore, all points through which an isotherm passes have identical temperatures for the time period indicated. Generally, isotherms representing 5° or 10° temperature differences are used, but any interval may be chosen. Figure 3–2 illustrates how isotherms are drawn on a map. Notice that most isotherms do not pass directly through the observing stations, because the station readings may not coincide with the values chosen for the isotherms. Only an occasional station temperature will be exactly the same as the value of the isotherm, so it is usually necessary to draw the lines by estimating the proper position between stations.

Isothermal maps are valuable tools because they clearly make temperature distribution visible at a glance. Areas of low and high temperatures are easy to pick out. In addition, the amount of temperature change per unit of distance, called the **temperature gradient,** is easy to visualize. Closely spaced isotherms indicate a rapid rate of temperature change, whereas more widely spaced lines indicate a more gradual rate of change. For example, notice in Figure 3–2 that the isotherms are closer in Colorado and Utah (steeper temperature gradient), whereas the isotherms are spread farther in Texas (gentler temperature gradient). Without isotherms a map would be covered with numbers representing temperatures at tens or hundreds of places, which would make patterns difficult to see.

Students Sometimes Ask…

What's the hottest city in the United States?

It depends on how you want to define "hottest." If average annual temperature is used, then Key West, Florida, is the hottest, with an annual mean of 25.6°C (78°F) for the 30-year span 1971–2000. However, if we look at cities with the highest July maximums during the 1971–2000 span, then the desert community of Palm Springs, California, has the distinction of being hottest. Its average daily high in July is a blistering 42.4°C (108.3°F)! Yuma, Arizona (41.7°C/107°F), Phoenix, Arizona (41.4°C/106°F), and Las Vegas, Nevada (40°C/104.1°F), aren't far behind.

Why Temperatures Vary: The Controls of Temperature

GEODe ATMOSPHERE

Temperature Data and the Controls of Temperature

▶ Controls of Temperature

The **controls of temperature** are factors that cause temperature to vary from place to place and from time to time (see Box 3–2). Chapter 2 examined the most important cause for temperature variation—differences in the receipt of solar radiation. Because variations in Sun angle and length of daylight depend on latitude, they are responsible for warm temperatures in the tropics and colder temperatures poleward. Of course, seasonal temperature changes at a given latitude occur as the Sun's vertical rays migrate toward and away from a place during the year.

But latitude is not the only control of temperature. If it were, we would expect all places along the same parallel to have identical temperatures. Such is clearly not the case. For instance, Eureka, California, and New York City are both coastal cities at about the same latitude, and both places have an annual mean temperature of 11°C (51.8°F). Yet New York City is 9.4°C (16.9°F) warmer than Eureka in July and 9.4°C (16.9°F) colder than Eureka in January. In another example, two cities in Ecuador—Quito and Guayaquil—are relatively close to one another, but the mean annual temperatures at these two cities differ by 12.2°C (22°F). To explain these situations and countless others, we must realize that factors other than latitude also exert a strong influence on temperature. In the next sections we examine these other controls, which include:

1. differential heating of land and water
2. ocean currents
3. altitude
4. geographic position
5. cloud cover and albedo

Land and Water

In Chapter 2 we saw that the heating of Earth's surface controls the heating of the air above it. Therefore, to understand variations in air temperature, we must understand the variations in heating properties of the different surfaces that Earth presents to the Sun—soil, water, trees, ice, and so on. Different land surfaces reflect and absorb varying amounts of incoming solar energy, which in turn cause variations in the temperature of the air above. The greatest contrast, however, is not between different land surfaces but between land and water. Figure 3–3 illustrates this idea nicely. This satellite image shows surface temperatures in portions of Nevada, California, and the adjacent Pacific Ocean on the afternoon of May 2, 2004, during a spring heat wave. Land-surface temperatures are clearly much higher than water-surface temperatures. The image shows the extreme high surface temperatures in southern California and Nevada in dark red.* Surface temperatures in the Pacific Ocean are much lower. The peaks of the Sierra Nevada, still capped with snow, form a cool blue line down the eastern side of California.

In side-by-side bodies of land and water, such as those shown in Figure 3–3, *land heats more rapidly and to higher temperatures than water, and it cools more rapidly and to lower temperatures than water*. Variations in air temperatures, therefore, are much greater over land than over water. Why do land and water heat and cool differently? Several factors are responsible.

1. An important reason that the surface temperature of water rises and falls much more slowly than the surface temperature of land is that *water is highly mobile*. As water is heated, convection distributes the heat through a considerably larger mass. Daily temperature changes occur to depths of 6 meters (20 feet) or more below the surface, and yearly, oceans and deep lakes experience temperature variations through a layer between 200 and 600 meters thick (650 and 2000 feet).

   In contrast, heat does not penetrate deeply into soil or rock; it remains near the surface. Obviously, no mixing can occur on land because it is not fluid. Instead, heat must be transferred by the slow process of conduction. Consequently, daily temperature changes are small below a depth of 10 centimeters (4 inches), although some change can occur to a depth of perhaps 1 meter (3 feet). Annual temperature variations usually reach depths of 15 meters (50 feet) or less. Thus, as a result of the mobility of water and the lack of mobility in the solid Earth, a relatively thick layer of water is heated to moderate temperatures during the summer. On land only a thin layer is heated but to much higher temperatures.

   During winter the shallow layer of rock and soil that was heated in summer cools rapidly. Water bodies, in contrast, cool slowly as they draw on the reserve of heat stored within. As the water surface cools, vertical motions are established. The chilled surface water, which is dense, sinks and is replaced by warmer water from below, which is less dense. Consequently, a larger mass of water must cool before the temperature at the surface will drop appreciably.
2. Because land surfaces are opaque, heat is absorbed only at the surface. This fact is easily demonstrated at a beach on a hot summer afternoon by comparing the surface temperature of the sand to the temperature just a few centimeters beneath the surface. Water, being more transparent, allows some solar radiation to penetrate to a depth of several meters.
3. The **specific heat** (the amount of heat needed to raise the temperature of 1 gram of a substance 1°C) is more than three times greater for water than for

*Realize that air temperatures are cooler than surface temperatures. For example, the surface of a sandy beach can be painfully hot even though the air temperature is comfortable.

BOX 3-1 North America's Hottest and Coldest Places

Most people living in the United States have experienced temperatures of 38°C (100°F) or more. When statistics for the 50 states are examined for the past century or longer, we find that every state has a maximum temperature record of 38°C or higher. Even Alaska has recorded a temperature this high. Its record was set June 27, 1915, at Fort Yukon, a town along the Arctic Circle in the interior of the state.

Maximum Temperature Records

Surprisingly, the state that ties Alaska for the "lowest high" is Hawaii. Panala, on the south coast of the big island, recorded 38°C on April 27, 1931. Although humid tropical and subtropical places like Hawaii are known for being warm throughout the year, they seldom experience maximum temperatures that surpass the low to mid-30s Celsius (90s Fahrenheit) (Figure 3–A).

The highest accepted temperature record for the United States as well as the entire Western Hemisphere is 57°C (134°F). This long-standing record was set at Death Valley, California, on July 10, 1913. Summer temperatures at Death Valley are consistently among the highest in the Western Hemisphere. During June, July, and August, temperatures exceeding 49°C (120°F) are to be expected. Fortunately, Death Valley has few human summertime residents.

Why are summer temperatures at Death Valley so high? In addition to having the lowest elevation in the Western Hemisphere (53 meters/174 feet below sea level), Death Valley is a desert. Although it is only about 300 kilometers (less than 200 miles) from the Pacific Ocean, mountains cut off the valley from the ocean's moderating influence and moisture. Clear skies allow a maximum of sunshine to strike the dry, barren surface. Because no energy is used to evaporate moisture as occurs in humid regions, all of the energy is available to heat the ground. In addition, subsiding air that warms by compression as it descends is also common to the region and contributes to its high maximum temperatures.

FIGURE 3-A Surprisingly, the highest temperature recorded for Hawaii is 38°C (100°F). It ties Alaska for the "lowest high." *(Photo by Mark Muench)*

Minimum Temperature Records

The temperature controls that produce truly frigid temperatures are predictable, and they should come as no surprise. We should expect extremely cold temperatures during winter in high-latitude places that lack the moderating influence of the ocean. Moreover, stations located on ice sheets and glaciers should be especially cold, as should stations positioned high in the mountains. *All* of these criteria apply to Greenland's Northice station (elevation 2307 meters/7567 feet). Here on January 9, 1954, the temperature plunged to −66°C (−87°F). If we exclude Greenland from consideration, Snag, in Canada's Yukon Territory, holds the record for North America. This remote outpost experienced a temperature of −63°C (−81°F) on February 3, 1947. When only locations in the United States are considered, Prospect Creek, located north of the Arctic Circle in the Endicott Mountains of Alaska, came close to the North American record on January 23, 1971, when the temperature plunged to −62°C (−80°F). In the lower 48 states the record of −57°C (−70°F) was set in the mountains at Rogers Pass, Montana, on January 20, 1954. Remember that many other places have no doubt experienced equally low or even lower temperatures; they just were not recorded.

BOX 3-2 Atmospheric Hazard: Heat Waves—Deadly Events*

A *heat wave* is a prolonged period of abnormally hot and usually humid weather that typically lasts from a few days to several weeks (Figure 3–B). The impact of heat waves on individuals varies greatly. The elderly are the most vulnerable because heat puts more stress on weak hearts and bodies. The poor, who often cannot afford air-conditioning, also suffer disproportionally. Studies also show that the temperatures at which death rates increase varys from city to city. In Dallas, Texas, a temperature of 39°C (103°F) is required before the death rate climbs. In San Francisco the key temperature is just 29°C (84°F).

Heat waves are deadly events.

> Heat is the deadliest of all atmospheric phenomena. From 1979 to 1999, the deaths of 8,015 Americans were directly associated with excessive heat exposure. This toll underestimates heat's true impact, however, as there is no consensus on what constitutes a "heat-related death," and death certificates often do not identify when heat has acted as a catalyst in exacerbating preexisting cardiovascular, respiratory, and other conditions. Indeed, during the hot summer of 1980, across the United States some 10,000 deaths may have been associated with the oppressive heat, and the hot summer of 2003 in Europe may have claimed nearly 15,000 lives in France.**

The dangerous impact of summer heat is reinforced when examining Figure 3–C, which shows average annual weather-related deaths for the 10-year period 1994–2003. A com-

FIGURE 3-B Getting some relief during a heat wave in Washington, D.C. *(Photo by Mark Reinstein/The Image Works)*

*For a related discussion, see Box 4–4, "Humidity and Heat Stress," p. 112

**Scott C. Sheridan and Laurence S. Kalkstein, "Progress in Heat Watch-Warning System Technology," *Bulletin of the American Meteorological Society*, Vol. 85, No. 12, December 2004, p. 1931.

land. Thus, water requires considerably more heat to raise its temperature the same amount as an equal quantity of land.

4. Evaporation (a cooling process) from water bodies is greater than from land surfaces. Energy is required to evaporate water. When energy is used for evaporation, it is not available for heating.*

*Evaporation is an important process that is discussed more thoroughly in the section on "Water's Changes of State" in Chapter 4.

All these factors collectively cause water to warm more slowly, store greater quantities of heat energy, and cool more slowly than land.

Monthly temperature data for two cities will demonstrate the moderating influence of a large water body and the extremes associated with land (Figure 3–4). Vancouver, British Columbia, is located along the windward Pacific coast, whereas Winnipeg, Manitoba, is in a continental position far from the influence of water. Both cities are at about the same latitude and thus experience similar sun angles and lengths

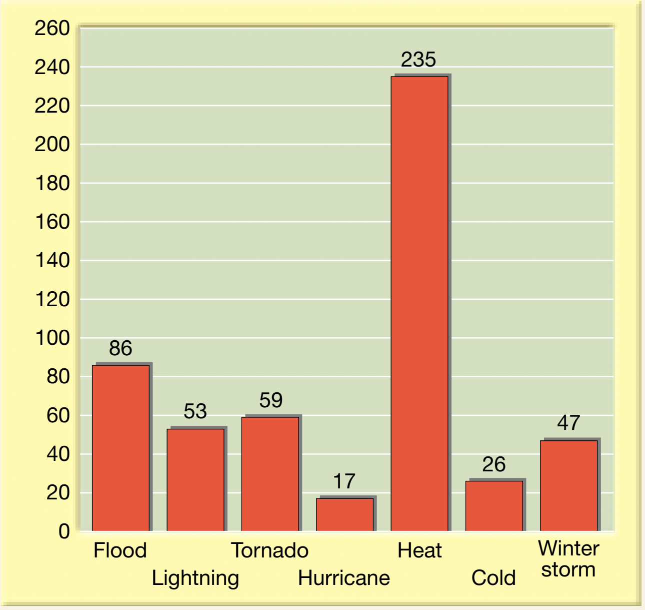


FIGURE 3-C Average annual weather-related fatalities for the 10-year period 1994–2003. *(After NOAA)*

parison of values reveals that the number of heat deaths far surpasses those of any other weather condition.

In July 1995 a brief but intense heat wave developed in the central United States. A total of 830 deaths were attributed to this severe five-day event, the worst in 50 years in the northern Midwest. The greatest loss of life occurred in Chicago, where there were 525 fatalities. The *Chicago Tribune* appropriately labeled the event "a citywide tragedy."

The severity of heat waves is usually greater in cities because of the *urban heat island* (see Box 3–4). Large cities do not cool off as much at night during heat waves as rural areas do, and this can be a critical difference in the amount of heat stress within the inner city. In addition, the stagnant atmospheric conditions usually associated with heat waves trap pollutants in urban areas and add the stresses of severe air pollution to the already dangerous stresses caused by the high temperatures.

In addition to the tragic loss of life, the 1995 Midwest heat wave had many other impacts, including the following:

- Energy use vastly increased. This resulted in some power failures during peak stress hours and, of course, in substantially higher electric bills.
- Highways and railroads were damaged due to heat-induced heaving and buckling of roadway joints and rails.
- Many companies reported a substantial reduction in employee work efficiency.
- Shopping declined dramatically.
- In rural areas, livestock were affected. For example, on July 14 the *Wisconsin Journal* reported that 850 dairy cattle had died, major flocks of poultry were killed, and milk production was off by 25 percent.

Not everyone is adversely affected by a heat wave. In response to the 1995 event, tourism from Chicago to nearby (and cooler) Wisconsin increased 10 percent. As we would expect, sales of air conditioners in the Midwest rose as well—more than 50 percent over the previous year.

The 1995 heat wave in the upper Midwest was the most intense in half a century. It provided a sobering lesson by focusing attention on the need for more effective warning and response plans, especially in major urban areas where heat stress is greatest.

of daylight. Winnipeg, however, has a mean January temperature that is 20°C lower than Vancouver's. Conversely, Winnipeg's July mean is 2.6°C higher than Vancouver's. Although their latitudes are nearly the same, Winnipeg, which has no water influence, experiences much greater temperature extremes than does Vancouver. The key to Vancouver's moderate year-round climate is the Pacific Ocean.

On a different scale, the moderating influence of water may also be demonstrated when temperature variations in the Northern and Southern hemispheres are compared. The views of Earth in Figure 3–5 show the uneven distribution of land and water over the globe. Water covers 61 percent of the Northern Hemisphere; land represents the remaining 39 percent. However, the figures for the Southern Hemisphere (81 percent water, 19 percent land) reveal why it is correctly called the *water hemisphere*. Between 45° north and 79° north latitude there is actually more land than water, whereas between 40° south and 65° south latitude there is almost no land to interrupt the oceanic and atmospheric circulation. Table 3–1 portrays the considerably smaller annual temperature ranges in the water-dominated Southern Hemisphere compared with the Northern Hemisphere.

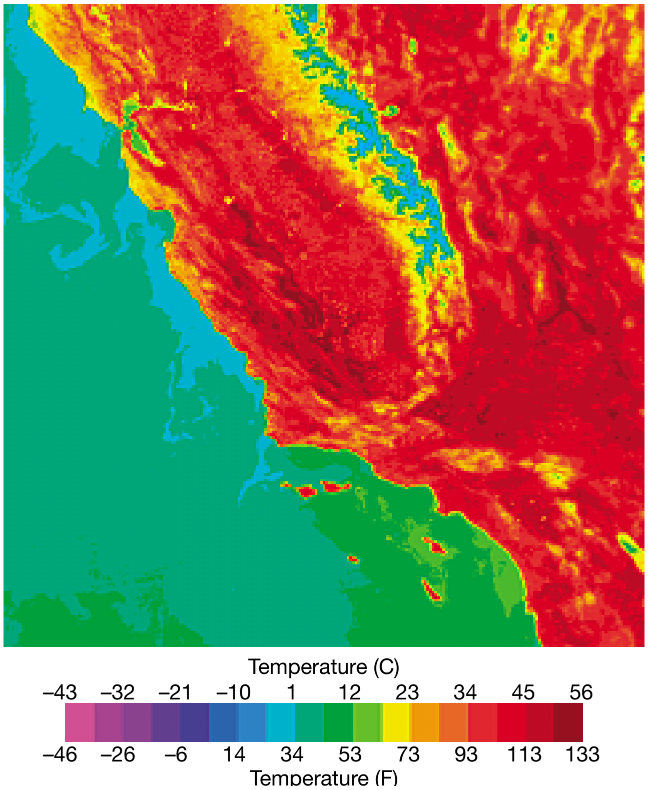


FIGURE 3-3 The differential heating of land and water is an important control of air temperatures. In this satellite image from the afternoon of May 2, 2004, water-surface temperatures in the Pacific Ocean are much lower than land-surface temperatures in California and Nevada. *(NASA image)*

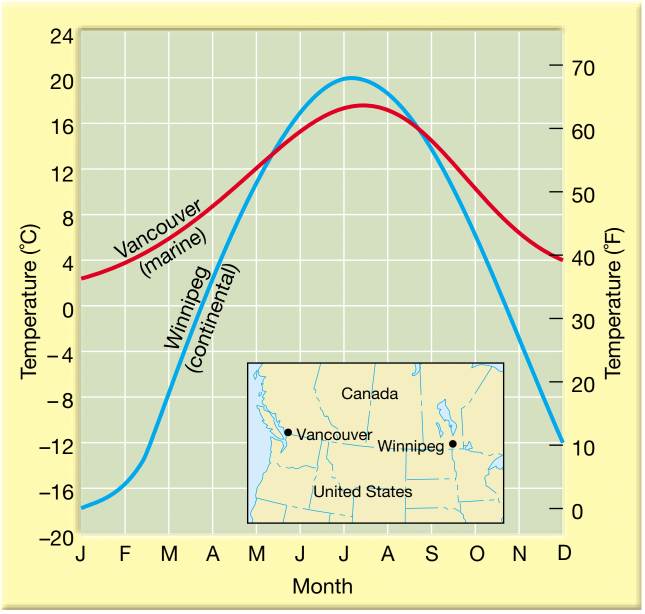


FIGURE 3-4 Mean monthly temperatures for Vancouver, British Columbia, and Winnipeg, Manitoba. Vancouver has a much smaller annual temperature range owing to the strong marine influence of the Pacific Ocean. Winnipeg illustrates the greater extremes associated with an interior location.

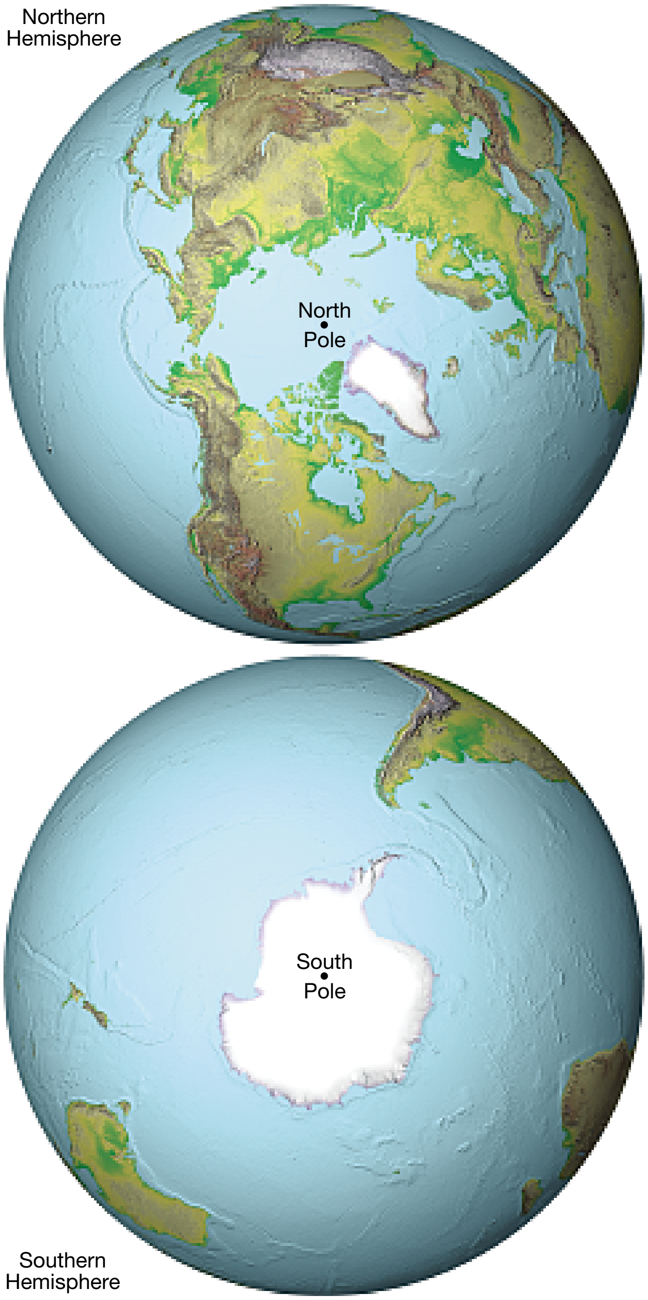


FIGURE 3-5 The uneven distribution of land and water between the Northern and Southern hemispheres. Almost 81 percent of the Southern Hemisphere is covered by the oceans—20 percent more than the Northern Hemisphere.

TABLE 3-1 Variation in mean annual temperature range (°C) with latitude.

Latitude	Northern Hemisphere	Southern Hemisphere
0	0	0
15	3	4
30	13	7
45	23	6
60	30	11
75	32	26
90	40	31

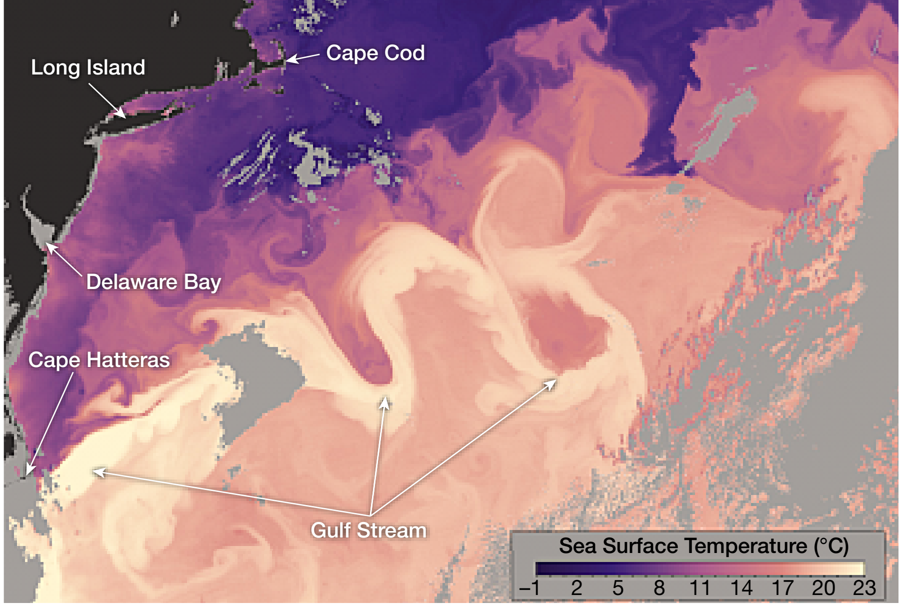


FIGURE 3-6 This satellite image shows sea-surface temperatures off the East Coast of the United States on April 18, 2005. The warm waters of the Gulf Stream (lighter shades) extend diagonally from bottom left to top right. The current transports heat from the tropics far into the North Atlantic. This image shows several deep bends in the path of the Gulf Stream. In fact, the northernmost of the two deep bends actually loops back on itself, creating a closed-off eddy. On the northern side of the current, cold waters (blue) dip southward into the Gulf Stream's warmth. Gray areas indicate clouds. *(NASA image)*

Ocean Currents

You probably have heard of the Gulf Stream, an important surface current in the Atlantic Ocean that flows northward along the East Coast of the United States (Figure 3–6). Surface currents like this one are set in motion by the wind. At the water surface, where the atmosphere and ocean meet, energy is passed from moving air to the water through friction. As a consequence, the drag exerted by winds blowing steadily across the ocean causes the surface layer of water to move. Thus, major horizontal movements of surface waters are closely related to the circulation of the atmosphere, which in turn is driven by the unequal heating of Earth by the Sun (Figure 3–7).*

Surface ocean currents have an important effect on climate. It is known that for Earth as a whole, the gains in solar energy equal the losses to space of heat radiated from the surface. When most latitudes are considered individually, however, this is not the case. There is a net gain of energy in lower latitudes and a net loss at higher latitudes. Because the tropics are not becoming progressively warmer, nor the polar regions colder, there must be a large-scale transfer of heat from areas of excess to areas of deficit. This is indeed the case. *The transfer of heat by winds and ocean currents equalizes these latitudinal energy imbalances.* Ocean water movements account for about a quarter of this total heat transport, and winds the remaining three-quarters.

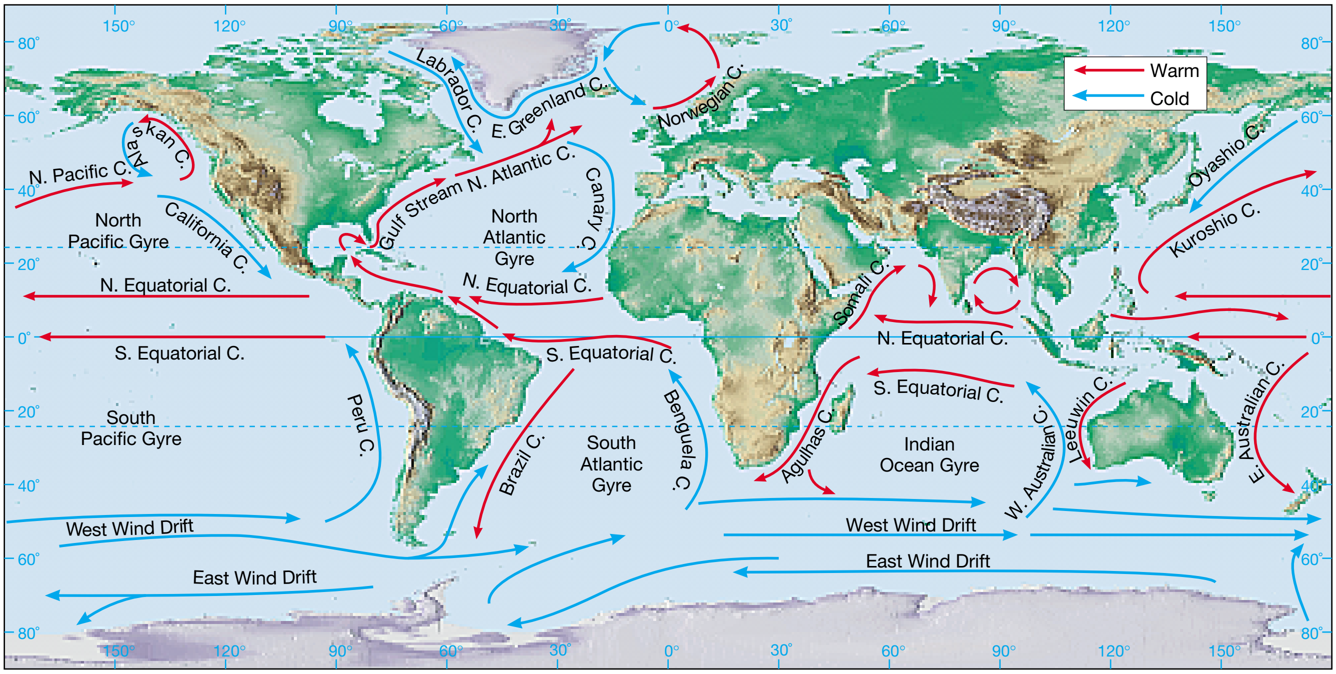


FIGURE 3-7 Major surface ocean currents. Poleward-moving currents are warm, and equatorward-moving currents are cold. Surface ocean currents are driven by global winds and play an important role in redistributing heat around the globe. Note that cities mentioned in the text discussion are shown on this map.

*The relationship between global winds and surface ocean currents is examined in Chapter 7.

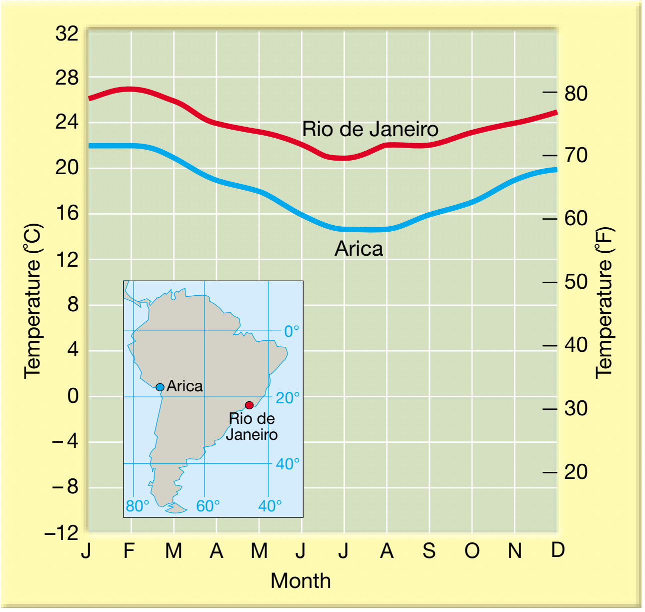


FIGURE 3-8 Monthly mean temperatures for Rio de Janeiro, Brazil, and Arica, Chile. Both are coastal cities near sea level. Even though Arica is closer to the equator than Rio de Janeiro, its temperatures are cooler. Arica is influenced by the cold Peruvian Current, whereas Rio de Janeiro is adjacent to the warm Brazilian Current.

The moderating effect of poleward-moving warm ocean currents is well known. The North Atlantic Drift, an extension of the warm Gulf Stream, keeps wintertime temperatures in Great Britain and much of Western Europe warmer than would be expected for their latitudes (London is farther north than St. John's, Newfoundland). Because of the prevailing westerly winds, the moderating effects are carried far inland. For example, Berlin (52° north latitude) has a mean January temperature similar to that experienced at New York City, which lies 12° latitude farther south. The January mean at London (51° north latitude) is 4.5°C (8.1°F) higher than at New York City.

In contrast to warm ocean currents like the Gulf Stream, the effects of which are felt most during the winter, cold currents exert their greatest influence in the tropics or during the summer months in the middle latitudes. For example, the cool Benguela Current off the western coast of southern Africa moderates the tropical heat along this coast. Walvis Bay (23° south latitude), a town adjacent to the Benguela Current, is 5°C (9°F) cooler in summer than Durban, which is 6° latitude farther poleward but on the eastern side of South Africa, away from the influence of the current (Figure 3–7). The east and west coasts of South America provide another example. Figure 3–8 shows monthly mean temperatures for Rio de Janeiro, Brazil, which is influenced by the warm Brazilian Current and Arica, Chile, which is adjacent to the cold Peruvian Current. Closer to home, because of the cold California current, summer temperatures in subtropical coastal southern California are lower by 6°C (10.8°F) or more compared to East Coast stations.

Altitude

The two cities in Ecuador mentioned earlier, Quito and Guayaquil, demonstrate the influence of altitude on mean temperature. Both cities are near the equator and relatively close to one another, but the annual mean temperature at Guayaquil is 25.5°C (77.9°F) compared with Quito's mean of 13.3°C (55.9°F). The difference may be understood when the cities' elevations are noted. Guayaquil is only 12 meters (39 feet) above sea level, whereas Quito is high in the Andes Mountains at 2800 meters (9200 feet) (Figure 3–9).

Recall that temperatures drop an average of 6.5°C per kilometer (3.5°F per 1000 feet) in the troposphere; thus, cooler temperatures are to be expected at greater heights. Yet the magnitude of the difference is not totally explained by the nor-

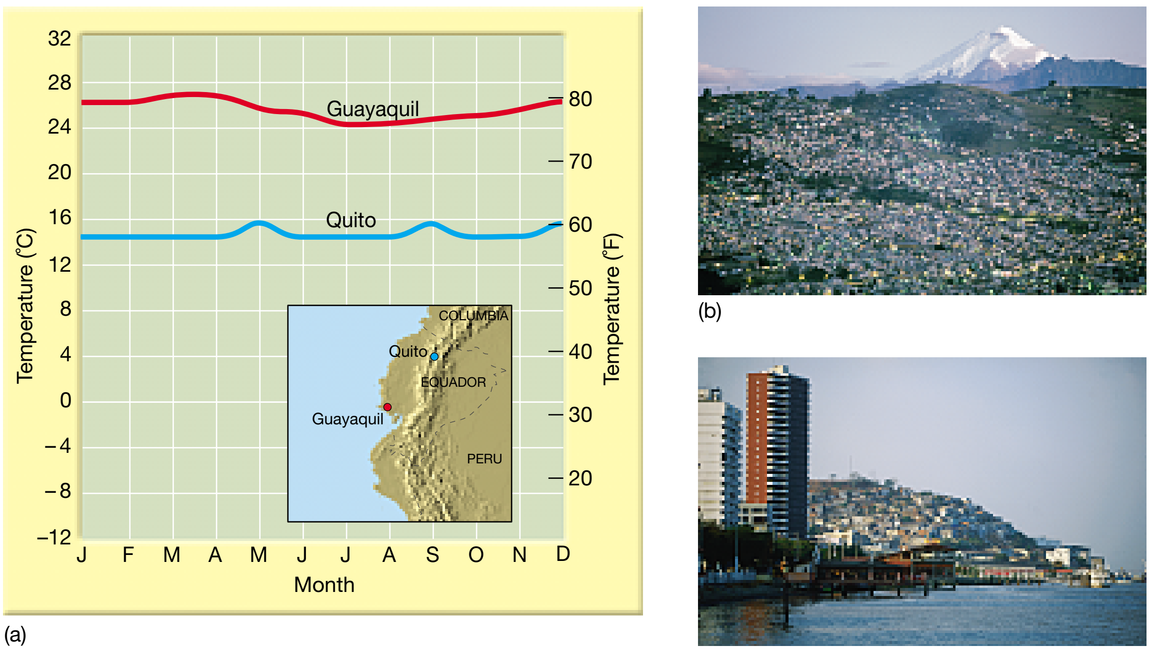


FIGURE 3-9 (a) Graph comparing monthly mean temperatures at Quito and Guayaquil, Ecuador. (b) Because Quito is high in the Andes, it experiences much cooler temperatures than Guayaquil, which is near sea level. *(Photo by Pablo Corral Vega/CORBIS)* *(c)* Although Guayaquil is not far from Quito, it is near sea level and therefore significantly warmer. *(Photo by Jeff Greenberg/ Omni-Photo Communications, Inc.)*

mal lapse rate. If this figure were used, we would expect Quito to be about 18.2°C (32.7°F) cooler than Guayaquil, but the difference is only 12.2°C (22°F). The fact that high-altitude places, such as Quito, are warmer than the value calculated using the normal lapse rate results from the absorption and reradiation of solar energy by the ground surface.

In addition to the effect of altitude on mean temperatures, the daily temperature range also changes with variations in height. Not only do temperatures drop with an increase in altitude but atmospheric pressure and density also diminish. Because of the reduced density at high altitudes, the overlying atmosphere absorbs and reflects a smaller portion of the incoming solar radiation. Consequently, with an increase in altitude, the intensity of solar radiation increases, resulting in relatively rapid and intense daytime heating. Conversely, rapid nighttime cooling is also the rule in high mountain locations. Therefore, stations located high in the mountains generally have a greater daily temperature range than do stations at lower elevations.

Students Sometimes Ask...

Can high mountain areas in the tropics be cold enough for glaciers?

Yes. Glaciers do indeed occur in the tropics at high elevations. Near the equator, glaciers sometimes form above about 5000 meters (16,400 feet). Examples of equatorial glaciers include those atop Mount Kenya and Mount Kilimanjaro in East Africa and those in the tall mountains of New Guinea.

Geographic Position

The geographic setting can greatly influence the temperatures experienced at a specific location. A coastal location where prevailing winds blow from the ocean onto the shore (a *windward* coast) experiences considerably different temperatures than does a coastal location where prevailing winds blow from the land toward the ocean (a *leeward* coast). In the first situation the windward coast will experience the full moderating influence of the ocean—cool summers and mild winters—compared to an inland station at the same latitude.

A leeward coastal situation, however, will have a more continental temperature regime because the winds do not carry the ocean's influence onshore. Eureka, California, and New York City, the two cities mentioned earlier, illustrate this aspect of geographic position (Figure 3–10). The annual temperature range at New York City is 19°C (34°F) greater than Eureka's.

Seattle and Spokane, both in the state of Washington, illustrate a second aspect of geographic position: mountains acting as barriers. Although Spokane is only about 360 kilometers (225 miles) east of Seattle, the towering Cascade Range separates the cities. Consequently, Seattle's temperatures show a marked marine influence, but Spokane's are more typically continental (Figure 3–11). Spokane is 7°C (12.6°F) cooler than Seattle in January and 4°C (7.2°F) warmer than Seattle in July. The annual range at Spokane is 11°C (nearly 20°F) greater than at Seattle. The Cascade Range effectively cuts off Spokane from the moderating influence of the Pacific Ocean.

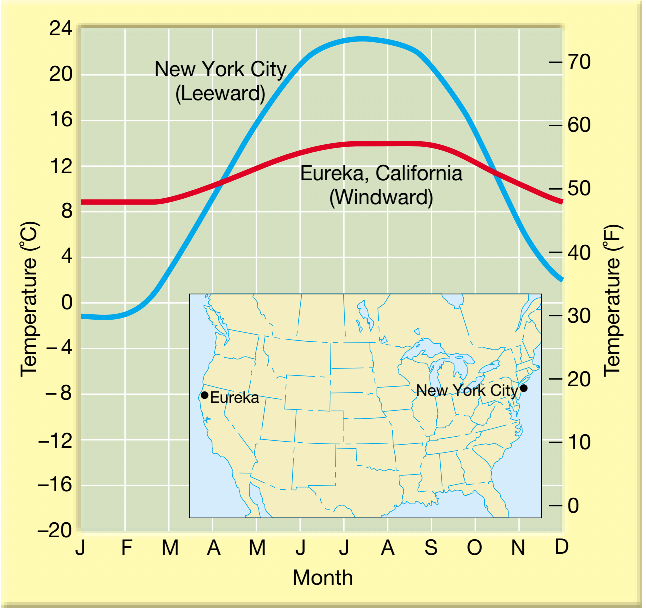


FIGURE 3-10 Monthly mean temperatures for Eureka, California, and New York City. Both cities are coastal and located at about the same latitude. Because Eureka is strongly influenced by prevailing winds from the ocean and New York City is not, the annual temperature range at Eureka is much smaller.

Cloud Cover and Albedo

You may have noticed that clear days are often warmer than cloudy ones and that clear nights usually are cooler than cloudy ones. This demonstrates that cloud cover is another

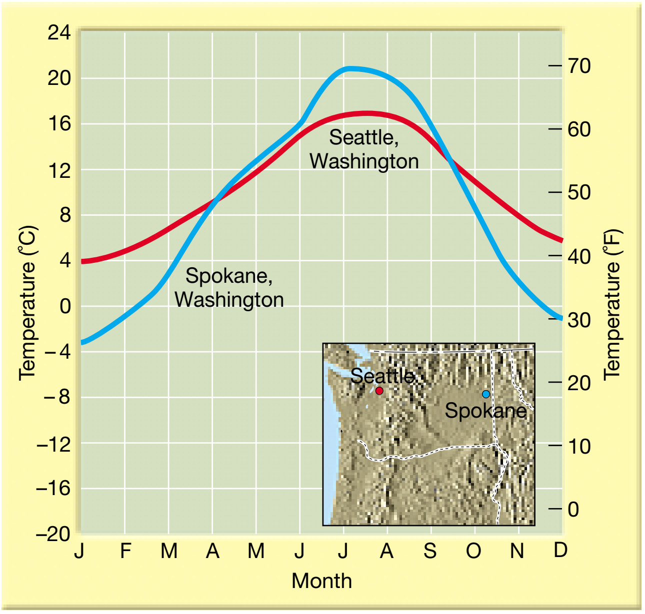


FIGURE 3-11 Monthly mean temperatures for Seattle and Spokane, Washington. Because the Cascade Mountains cut off Spokane from the moderating influence of the Pacific Ocean, its annual temperature range is greater than Seattle's.

(a) (b)

FIGURE 3-12 (a) It is obvious when you are above thick, dense clouds that a great deal of light is reflected that otherwise would reach Earth's surface. (b) When there is a dense overcast, maximum temperatures at the surface are lower than they would be if the sky was clear. *(Photo (a) by Detlev Ravenswaay/Photo Researchers, Inc.; photo (b) by David Muench)*

factor that influences temperature in the lower atmosphere. Studies using satellite images show that at any particular time about half of our planet is covered by clouds. Cloud cover is important because many clouds have a high albedo and therefore reflect a significant proportion of the sunlight that strikes them back to space. By reducing the amount of incoming solar radiation, daytime temperatures will be lower than if the clouds were absent and the sky were clear (Figure 3–12). As was noted in Chapter 2, the albedo of clouds depends on the thickness of the cloud cover and can vary from 25 to 80 percent (see Figure 2–15, page 49).

At night, clouds have the opposite effect as during daylight. They absorb outgoing Earth radiation and emit a portion of it toward the surface. Consequently, some of the heat that otherwise would have been lost remains near the ground. Thus, nighttime air temperatures do not drop as low as they would on a clear night. The effect of cloud cover is to reduce the daily temperature range by lowering the daytime maximum and raising the nighttime minimum. This is illustrated nicely in Figure 3–13.

The effect of cloud cover on reducing maximum temperatures can also be detected when monthly mean temperatures are examined for some stations. For example, each year much of southern Asia experiences an extended period of relative drought during the cooler low-Sun period; it is then followed by heavy monsoon rains.* The graph for Yangon, Myanmar (Rangoon, Burma), illustrates this pattern (Figure 3–14). Notice that the highest monthly mean temperatures occur in April and May, before the summer solstice, rather than in July and August, as normally occurs at most stations in the Northern Hemisphere. Why?

*This pattern is associated with the monsoon circulation and is discussed in Chapter 7.

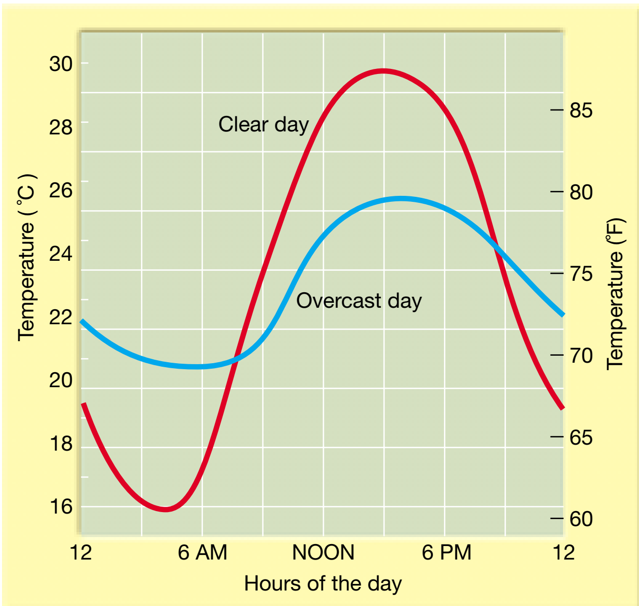


FIGURE 3-13 The daily cycle of temperature at Peoria, Illinois, for two July days. On the clear day the maximum temperature was higher, and the minimum temperature was lower than on the cloudy day.

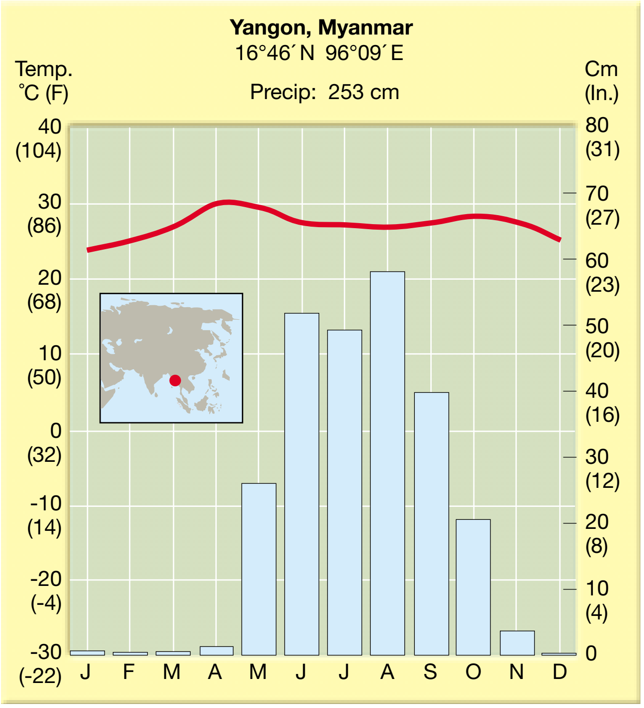


FIGURE 3-14 Monthly mean temperatures (curve) and monthly mean precipitation (bar graph) for Yangon, Myanmar. The highest mean temperature occurs in April, just before the onset of heavy summer rains. The abundant cloud cover associated with the rainy period reflects back into space the solar energy that otherwise would strike the ground and raise summer temperatures.

The reason is that during the summer months when we would usually expect temperatures to climb, the extensive cloud cover increases the albedo of the region, which reduces incoming solar radiation. As a result, the highest monthly mean temperatures occur in late spring when the skies are still relatively clear.

Cloudiness is not the only phenomenon that increases albedo and thereby reduces air temperature. We also recognize that snow- and ice-covered surfaces have high albedos. This is one reason why mountain glaciers do not melt away in the summer and why snow may still be present on a mild spring day. In addition, during the winter when snow covers the ground, daytime maximums on a sunny day are cooler than they otherwise would be, because energy that the land would have absorbed and used to heat the air is reflected and lost.

World Distribution of Temperatures

Take a moment to study the two world isothermal maps (Figures 3–15 and 3–16). From hot colors near the equator to cool colors toward the poles, these maps portray sea-level temperatures in the seasonally extreme months of January and July. On these maps you can study global temperature patterns and the effects of the controls of temperature, especially latitude, the distribution of land and water, and ocean currents (see Box 3–3). Like most isothermal maps of large regions, all temperatures on these world maps have been reduced to sea level to eliminate the complications caused by differences in altitude.

On both maps the isotherms generally trend east and west and show a decrease in temperatures poleward from the tropics. They illustrate one of the most fundamental aspects of world temperature distribution: that the effectiveness of incoming solar radiation in heating Earth's surface and the atmosphere above it is largely a function of latitude.

Moreover, there is a latitudinal shifting of temperatures caused by the seasonal migration of the Sun's vertical rays. To see this, compare the color bands by latitude on the two maps. For example, on the January map the "hot spots" of 30°C are *south* of the equator, but in July they have shifted *north* of the equator.

If latitude were the only control of temperature distribution, our analysis could end here, but this is not the case. The added effect of the differential heating of land and water is clearly reflected on the January and July temperature maps. The warmest and coldest temperatures are found over land—note the coldest area, a purple oval in Siberia, and the hottest areas, the deep orange ovals—all over land. Consequently, because temperatures do not fluctuate as much over water as over land, the north–south migration of isotherms is greater over the continents than over the oceans. In addition, it is clear that the isotherms in the Southern Hemisphere, where there is little land and where the oceans predominate, are much more regular than in the Northern Hemisphere, where they bend sharply northward in July and southward in January over the continents.

Isotherms also reveal the presence of ocean currents. Warm currents cause isotherms to be deflected toward the poles, whereas cold currents cause an equatorward bending. The horizontal transport of water poleward warms the overlying air and results in air temperatures that are higher than would otherwise be expected for the latitude. Conversely, currents moving toward the equator produce cooler-than-expected air temperatures.

Figures 3–15 and 3–16 show the seasonal extremes of temperature, so comparing them enables us to see the annual range of temperature from place to place. Comparing the two maps shows that a station near the equator has a very small annual range because it experiences little variation in the length of daylight and it always has a relatively high Sun angle. A station in the middle latitudes, however, experiences wide variations in Sun angle and length of daylight and hence large variations in temperature. Therefore, we can state that the annual temperature range increases with an increase in latitude (see Box 3–30).

Moreover, land and water also affect seasonal temperature variations, especially outside the tropics. A continental location must endure hotter summers and colder winters

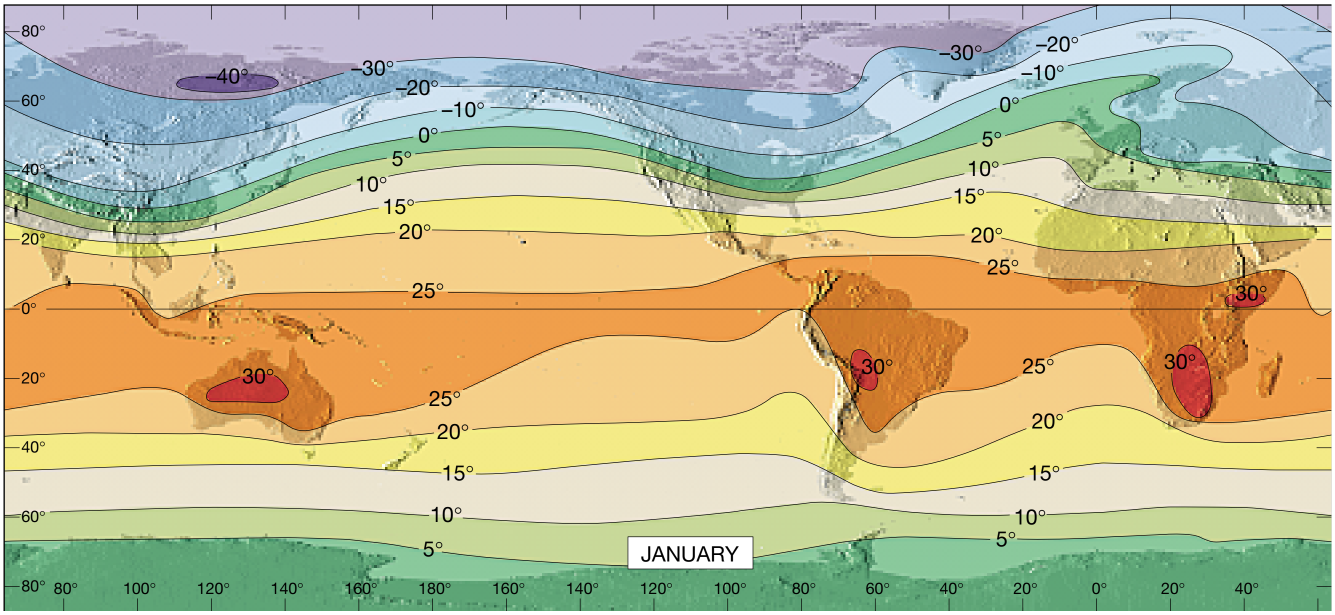


FIGURE 3-15 World mean sea-level temperatures in January in degrees Celsius.

than a coastal location. Consequently, outside the tropics the annual range will increase with an increase in continentality.

Figure 3–17, which shows the global distribution of annual temperature ranges, serves to summarize the preceding two paragraphs. By examining this map, it is easy to see the influence of latitude and continentality on this temperature statistic. The tropics clearly experience small annual temperature variations. As expected, the highest values occur in the middle of large landmasses in the subpolar latitudes. It is also obvious that annual temperature ranges in the ocean-dominated Southern Hemisphere are much smaller than in the Northern Hemisphere with its large continents.

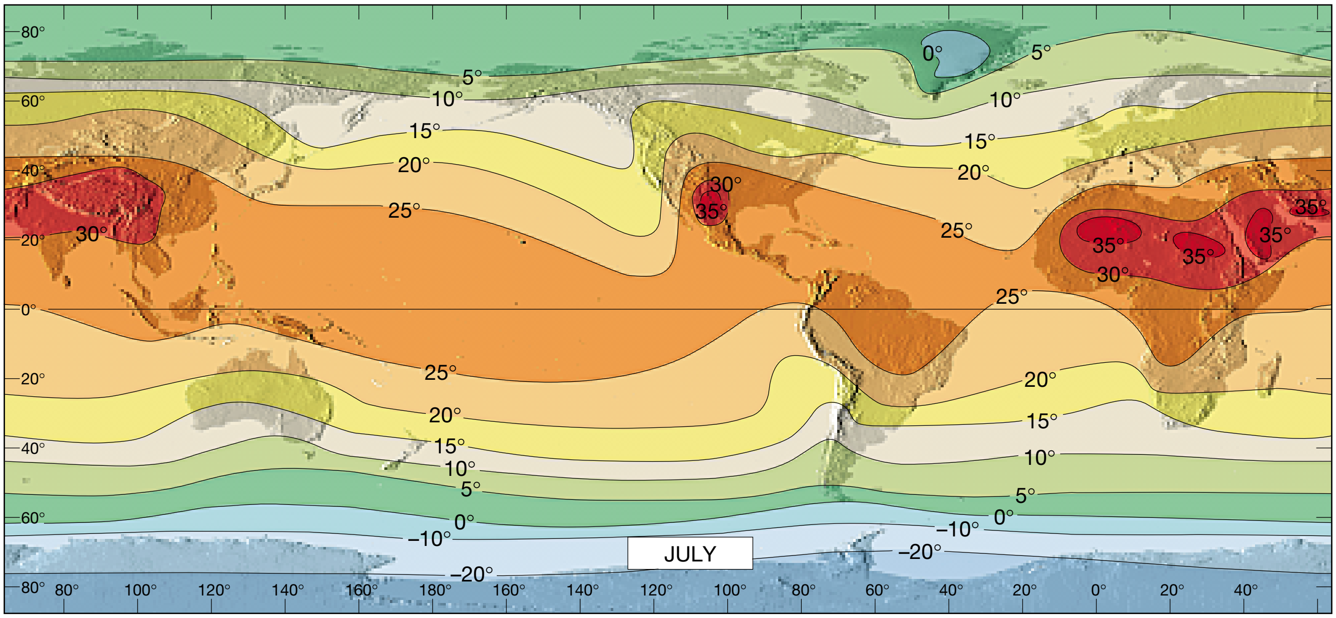


FIGURE 3-16 World mean sea-level temperatures in July in degrees Celsius.

BOX 3-3 Latitude and Temperature Range

*Gregory J. Carbone**

Latitude, because of its influence on Sun angle, is the most important temperature control. Figures 3–15 and 3–16 clearly show higher temperatures in tropical locations and lower temperatures in polar regions. The maps also show that higher latitudes experience a greater range of temperatures during the year than do lower latitudes. Notice also that the temperature gradient between the subtropics and the poles is greatest during the winter season. A look at two cities—San Antonio, Texas, and Winnipeg, Manitoba—illustrates how seasonal differences in Sun angle and day length account for these temperature patterns. Figure 3–D shows the annual march of temperature for the two cities, whereas Figure 3–E illustrates the Sun angles for the June and December solstices.

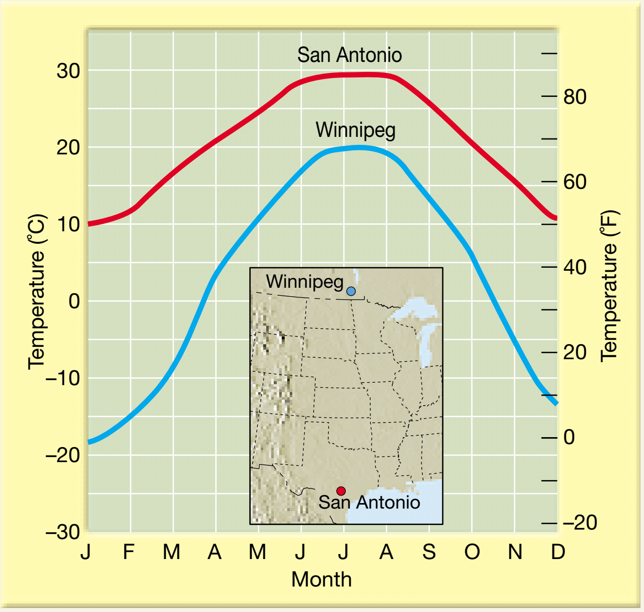


FIGURE 3-D The annual temperature range at Winnipeg is much greater than at San Antonio.

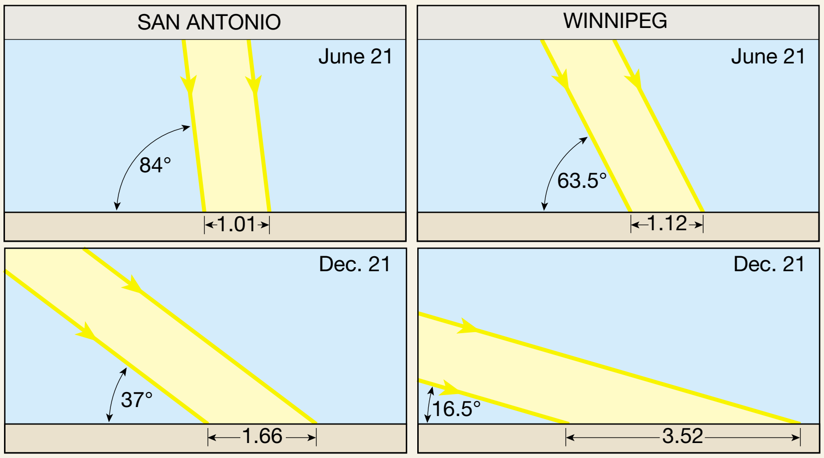


FIGURE 3-E A comparison of Sun angles (solar noon) for summer and winter solstices at San Antonio and Winnipeg. The space covered by a 90° angle = 1.00.

San Antonio and Winnipeg are a fixed distance apart (approximately 20.5° latitude), so the difference in Sun angles between the two cities is the same throughout the year. However, in December, when the Sun's rays are least direct, this difference more strongly affects the intensity of solar radiation received at Earth's surface. Therefore, we expect a greater difference in temperatures between the two stations in winter than in summer. Moreover, the seasonal difference in intensity (spreading out of the light beam) at Winnipeg is considerably greater than at San Antonio. This helps to explain the greater annual temperature range at the more northerly station. Table 2–2, Chapter 2, shows that seasonal contrasts in day length also contribute to different temperature patterns at the two cities.

*Professor Carbone is a faculty member in the Department of Geography at the University of South Carolina.

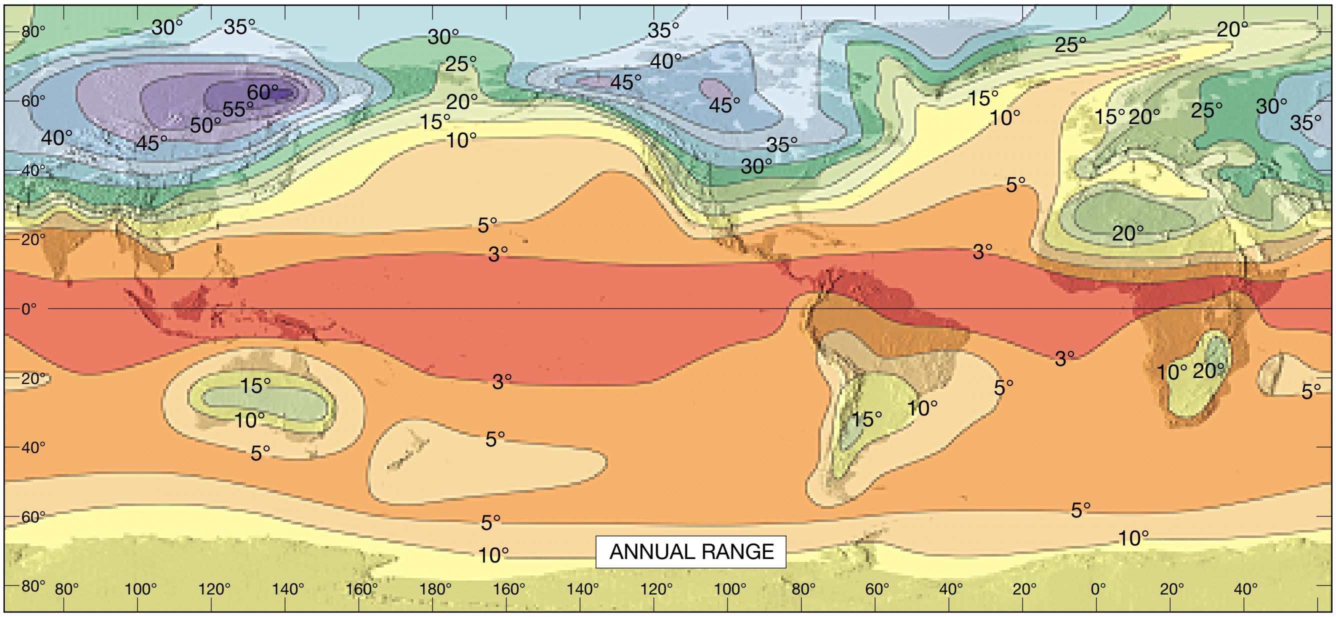


FIGURE 3-17 Global annual temperature ranges in degrees Celsius. Annual ranges are small near the equator and increase toward the poles. Outside the tropics, annual temperature ranges increase as we move away from the ocean toward the interior of large landmasses. *(After Robert W. Christopherson,* Geosystems: An Introduction to Physical Geography, *Fifth Edition, Prentice Hall, 2003)*

Students Sometimes Ask...

Where in the world would I experience the greatest contrast between summer and winter temperatures?

Among places for which records exist, it appears as though Yakutsk, a station in the heart of Siberia, is the best candidate. The latitude of Yakutsk is 62° north, just a few degrees south of the Arctic Circle. Moreover, it is far from the influence of water. The January mean at Yakutsk is a frigid −43°C (−45°F), whereas its July mean is a pleasant 20°C (68°F). The result is an average annual temperature range of 63°C (113°F), among the highest anywhere on the globe.

Cycles of Air Temperature

You know from experience that a rhythmic rise and fall of air temperature occurs almost every day. Your experience is confirmed by thermograph records like the one in Figure 3–18 (a thermograph is an instrument that continuously records temperature). The temperature curve reaches a minimum around sunrise (Figure 3–19). It then climbs steadily to a maximum between 2 P.M. and 5 P.M. The temperature then declines until sunrise the following day.

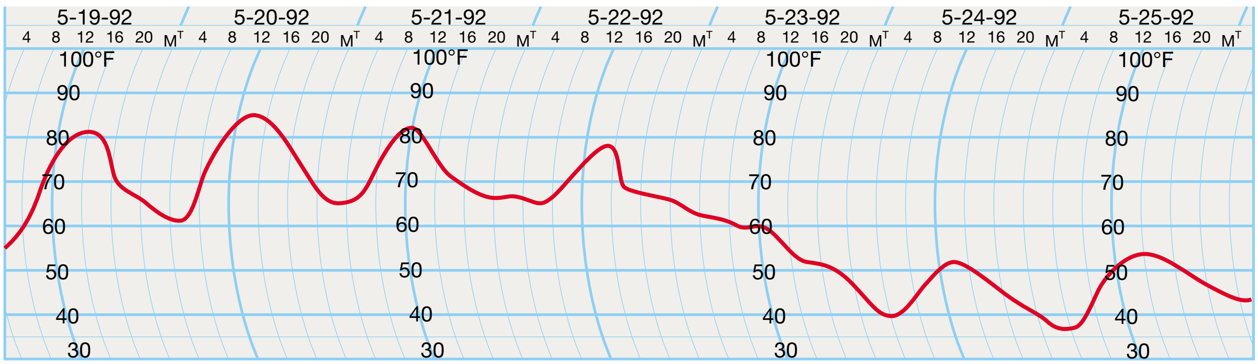


FIGURE 3-18 Thermograph of temperatures in Peoria, Illinois, during a seven-day span in May 1992. The typical daily rhythm, with minimums around sunrise and maximums in mid- to late afternoon, occurred on most days. The obvious exception occurred on May 23, when the maximum was reached at midnight and temperatures dropped throughout the day.

(a)

(b)

FIGURE 3-19 The minimum daily temperature usually occurs near the time of sunrise. As the ground and air cool during the nighttime hours, familiar early morning phenomena such as the frost in photo (a) and the ground fog in photo (b) may form. *(Photo (a) by AP Photo/Daily Telegram/Jed Carlson. Photo (b) by Michael Collier)*

Daily Temperature Variations

The primary control of the daily cycle of air temperature is as obvious as the cycle itself: It is Earth's daily rotation, which causes a location to move into daylight for part of each day and then into darkness. As the Sun's angle increases throughout the morning, the intensity of sunlight also rises, reaching a peak at local noon and gradually diminishing in the afternoon.

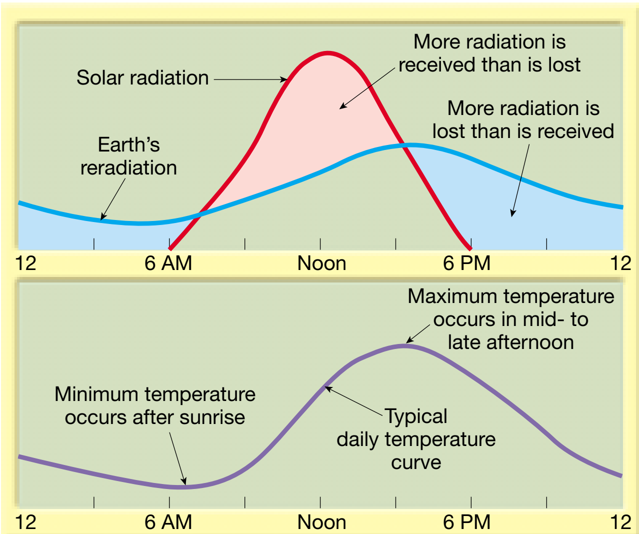


FIGURE 3-20 The daily cycle of incoming solar radiation, Earth's radiation, and the resulting temperature cycle. This example is for a midlatitude site around the time of an equinox. As long as solar energy gained exceeds outgoing energy emitted by Earth, the temperature rises. When outgoing energy from Earth exceeds the input of solar energy, temperature falls. Note that the daily temperature cycle *lags* behind the solar radiation input by a couple of hours.

Figure 3–20 shows the daily variation of incoming solar energy versus outgoing Earth radiation and the resulting temperature curve for a typical middle-latitude location at the time of an equinox. During the night the atmosphere and the surface of Earth cool as they radiate heat away that is not replaced by incoming solar energy. The minimum temperature, therefore, occurs about the time of sunrise, after which the Sun again heats the ground, which in turn heats the air.

It is apparent that the time of highest temperature does not generally coincide with the time of maximum radiation. By comparing Figures 3–18 and 3–20, you can see that the curve for incoming solar energy is symmetrical with respect to noon, but the daily air temperature curves are not. The delay in the occurrence of the maximum until mid- to late afternoon is termed the *lag of the maximum*.

Although the intensity of solar radiation drops in the afternoon, it still exceeds outgoing energy from Earth's surface for a period of time. This produces an energy surplus for up to several hours in the afternoon and contributes substantially to the lag of the maximum. In other words, as long as the solar energy gained exceeds the rate of Earth radiation lost, the air temperature continues to rise. When the input of solar energy no longer exceeds the rate of energy lost by Earth, the temperature falls.

The lag of the daily maximum is also a result of the process by which the atmosphere is heated. Recall that air is a poor absorber of most solar radiation; consequently, it is heated primarily by energy reradiated from Earth's surface. The rate at which Earth supplies heat to the atmosphere through radiation, conduction, and other means, however, is not in balance with the rate at which the atmosphere radiates heat away. Generally, for a few hours after the period of maximum solar radiation, more heat is supplied to the atmosphere by Earth's surface than is emitted by the atmosphere to space. As a result, most locations experience an increase in air temperature during the afternoon.

In dry regions, particularly on cloud-free days, the amount of radiation absorbed by the surface will generally be high. Therefore, the time of the maximum temperature at these locales will often occur quite late in the afternoon. Humid locations, in contrast, will frequently experience a shorter time lag in the occurrence of their temperature maximum.

Magnitude of Daily Temperature Changes

The magnitude of daily temperature changes is variable and may be influenced by locational factors, or local weather conditions, or both (see Box 3–4). Four common examples illustrate this point. The first two relate to location, and the second two pertain to local weather conditions.

1. Variations in Sun angle are relatively great during the day in the middle and low latitudes. However, points near the poles experience a low Sun angle all day. Consequently, the temperature change experienced during a day in the high latitudes is small.
2. A windward coast is likely to experience only modest variations in the daily cycle. During a typical 24-hour period the ocean warms less than 1°C. As a result, the air above it shows a correspondingly slight change in temperature. For example, Eureka, California, a windward coastal station, consistently has a lower daily temperature range than Des Moines, Iowa, an inland city at about the same latitude. Annually the daily range at Des Moines averages 10.9°C (19.6°F) compared with 6.1°C (11°F) at Eureka, a difference of 4.8°C (8.6°F).
3. As mentioned earlier, an overcast day is responsible for a flattened daily temperature curve (see Figure 3–13). By day, clouds block incoming solar radiation and so reduce daytime heating. At night the clouds retard the loss of radiation by the ground and air. Therefore, nighttime temperatures are warmer than they otherwise would have been.
4. The amount of water vapor in the air influences daily temperature range because water vapor is one of the atmosphere's important heat-absorbing gases. When the air is clear and dry, heat rapidly escapes at night, and the temperature falls rapidly. When the air is humid, absorption of outgoing long-wavelength radiation by water vapor slows nighttime cooling, and the temperature does not fall to as low a value. Thus, dry conditions are associated with a higher daily temperature range because of greater nighttime cooling.

Although the rise and fall of daily temperatures usually reflects the general rise and fall of incoming solar radiation, such is not always the case. For example, a glance back at Figure 3–18 reveals that on May 23 the maximum temperature occurred at midnight, after which temperatures fell throughout the day. If records for a station are examined for a period of several weeks, apparently random variations are seen. Obviously these are not Sun-controlled. Such irregularities are caused primarily by the passage of atmospheric disturbances (weather systems) that are often accompanied by variable cloudiness and winds that bring air having contrasting temperatures. Under these circumstances, the maximum and minimum temperatures may occur at any time of the day or night.

Annual Temperature Variations

In most years the months with the highest and lowest mean temperatures do not coincide with the periods of maximum and minimum incoming solar radiation. Poleward of the tropics the greatest intensity of solar radiation occurs at the time of the summer solstice in June, yet the months of July and August are generally the warmest of the year in the Northern Hemisphere. Conversely, a minimum of solar energy is received in December at the time of the winter solstice, but January and February are usually colder.

The fact that the occurrence of annual maximum and minimum radiation does not coincide with the times of temperature maximums and minimums indicates that the amount of solar radiation received is not the only factor determining the temperature at a particular location. Recall from Chapter 2 that places equatorward of about 38° N and 38° S receive more solar radiation than is lost to space and that the opposite is true of more poleward regions. Based on this imbalance between incoming and outgoing radiation, any location in the southern United States, for example, should continue to get warmer late into autumn.

But this does not occur, because more poleward locations begin experiencing a negative radiation balance shortly after the summer solstice. As the temperature contrasts become greater, the atmosphere and ocean currents "work harder" to transport heat from lower latitudes poleward.

Temperature Measurement

GEODe ATMOSPHERE

Temperature Data and the Controls of Temperature

▸ Basic Temperature Data

Thermometers are "meters of therms": They measure temperature. Thermometers measure temperature either mechanically or electrically.

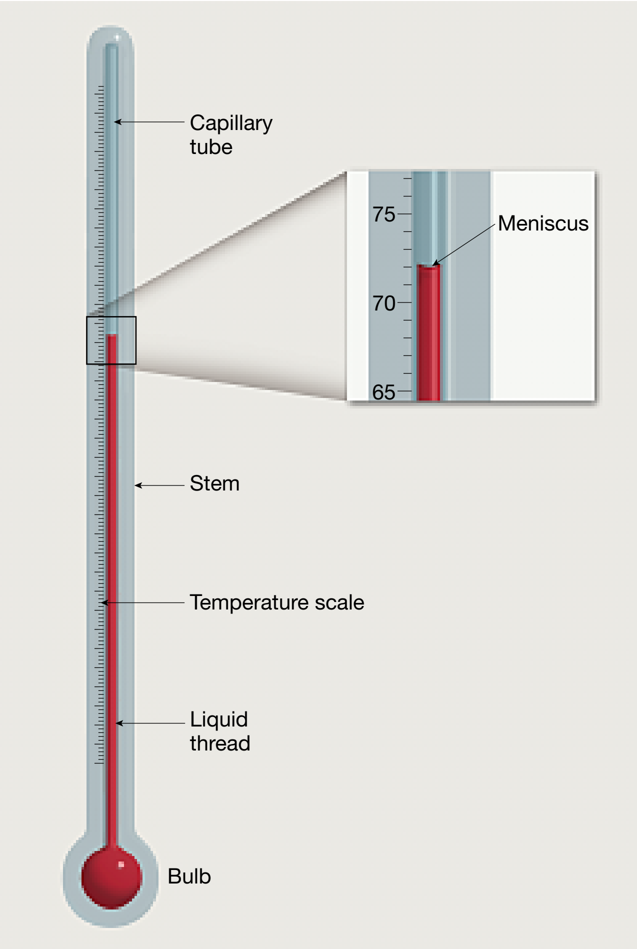


FIGURE 3-21 The main components of a liquid-in-glass thermometer.

Mechanical Thermometers

Most substances expand when heated and contract when cooled, so many common thermometers are based on this property. More precisely, they rely on the fact that different substances react to temperature changes differently.

The **liquid-in-glass thermometer** shown in Figure 3–21 is a simple instrument that provides relatively accurate readings over a wide temperature range. Its design has remained essentially unchanged ever since it was developed in the late 1600s. When temperature rises, the molecules of fluid grow more active and spread out (the fluid expands). Expansion of the fluid in the bulb is much greater than the expansion of the enclosing glass. As a consequence, a thin "thread" of fluid is forced up the capillary tube. Conversely, when temperature falls, the liquid contracts and the thread of fluid moves back down the tube toward the bulb. The movement of the end of this thread (known as the *meniscus*) is calibrated against an established scale to indicate the temperature.

The highest and lowest temperatures that occur each day are of considerable importance and are often obtained by using specially designed liquid-in-glass thermometers. Mercury is the liquid used in the **maximum thermometer,** which has a narrowed passage called a *constriction* in the bore of the glass tube just above the bulb (Figure 3–22a). As the temperature rises, the mercury expands and is forced through the constriction. When the temperature falls, the constriction prevents a return of mercury to the bulb. As a result, the top of the mercury column remains at the highest point (maximum temperature attained during the measurement period). The instrument is reset by shaking or by whirling it to force the mercury through the constriction back into the bulb. Once the thermometer is reset, it indicates the current air temperature.

In contrast to a maximum thermometer that contains mercury, a **minimum thermometer** contains a liquid of low density, such as alcohol. Within the alcohol, and resting

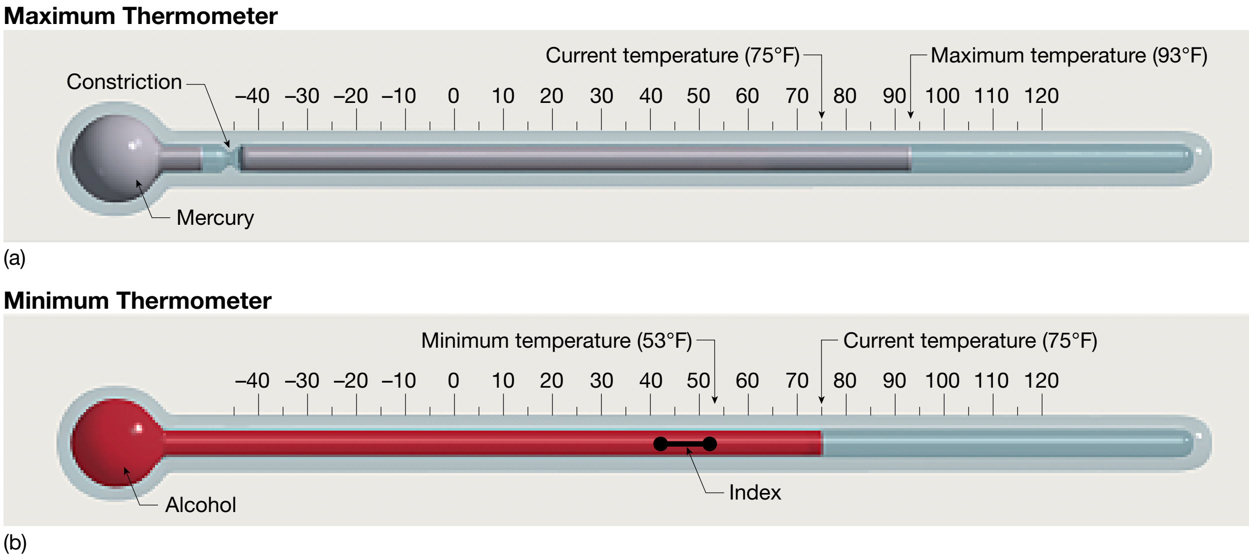


FIGURE 3-22 (a) Maximum thermometer and (b) minimum thermometer.

BOX 3-4 How Cities Influence Temperature: The Urban Heat Island

The most apparent human impact on climate is the modification of the atmospheric environment by the building of cities. The construction of every factory, road, office building, and house destroys microclimates and creates new ones of great complexity (Figure 3–F).

The most studied and well-documented urban climatic effect is the *urban heat island*. The term refers to the fact that temperatures within cities are generally higher than in rural areas. The heat island is evident when temperature data such as that which appears in Table 3–A are examined. As is typical, the data for Philadelphia show the heat island is most pronounced when minimum temperatures are examined. The magnitude of the temperature differences shown by Table 3–A is probably even greater than the figures indicate, because temperatures observed at suburban airports are usually higher than those in truly rural environments.

FIGURE 3-F Cities modify practically every climate element. One of the most studied and best documented effects is called the *urban heat island*. *(Photo by Daniel Philippe/Photo Researchers, Inc.)*

Figure 3–G, which shows the distribution of average minimum temperatures in the Washington, D.C., metropolitan area for the three-month winter period (December through February) over a five-year span, also illustrates a well-developed heat island. The warmest winter temperatures occurred in the heart of the city, whereas the suburbs and surrounding countryside experienced average minimum temperatures that were as much as 3.3°C (6°F) lower. Remember that these temperatures are averages. On many clear, calm nights the temperature difference between the city center and the countryside was considerably greater, often 11°C (20°F) or more. Conversely, on many overcast or windy nights the temperature differential approached zero degrees.

TABLE 3-A Average temperatures (°C) for suburban Philadelphia Airport and downtown Philadelphia (10-year averages)

	Airport	Downtown
Annual mean	12.8	13.6
Mean June max	27.8	28.2
Mean December max	6.4	6.7
Mean June min	16.5	17.7
Mean December min	−2.1	−0.4

Source: After H. Neuberger and J. Cahir, Principles of Climatology *(New York: Holt, Rinehart and Winston, 1969), 128.*

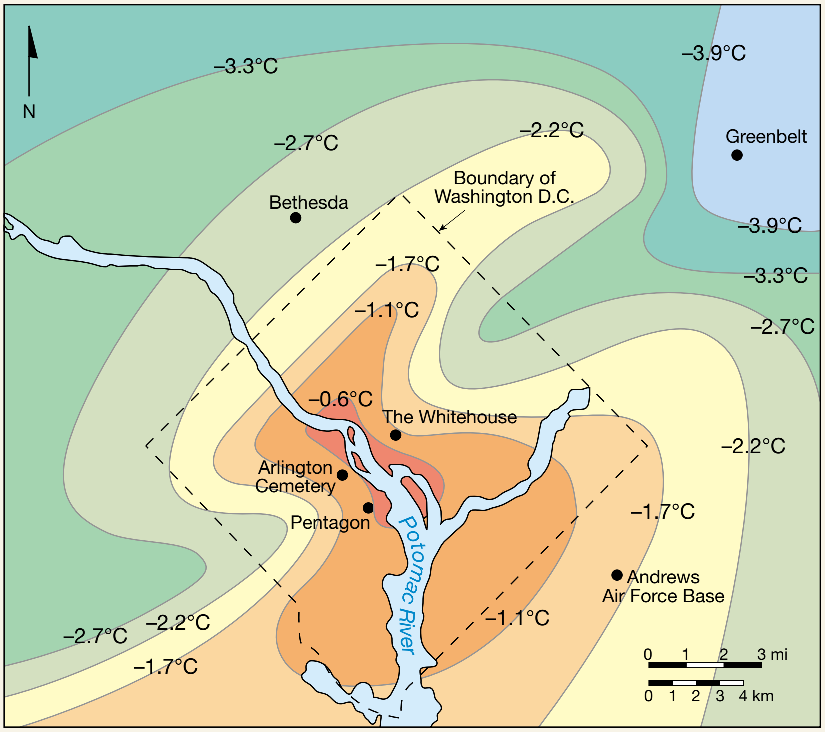


FIGURE 3-G The heat island of Washington, D.C., as shown by the average minimum temperatures (°C) during the winter season (December through February). The city center had an average minimum that was nearly 4°C higher than some outlying areas. *(After Clarence A. Woolum, "Notes from the Study of the Microclimatology of the Washington, D.C. Area for the Winter and Spring Seasons," Weatherwise, 17, no. 6 (1964), 264, 267.)*

A recent study indicates that one effect of the urban heat island is to influence the biosphere by extending the plant cycle.* After examining data for 70 cities in eastern North America, researchers found that the growing cycle in cities was about 15 days longer than surrounding rural areas. Plants began the growth cycle an average of about seven days earlier in spring and continued growing an average of eight days longer in fall.

Why are cities warmer? The radical change in the surface that results when rural areas are transformed into cities is a significant cause of the urban heat island. First, the tall buildings and the concrete and asphalt of the city absorb and store greater quantities of solar radiation than do the vegetation and soil typical of rural areas. In addition, because the city surface is impermeable, the runoff of water following a rain is rapid, resulting in a significant reduction in the evaporation rate. Hence, heat that once would have been used to convert liquid water to a gas now goes to increase further the surface temperature. At night, as both the city and countryside cool by radiative losses, the stonelike surface of the city gradually releases the additional heat accumulated during the day, keeping the urban air warmer than that of the outlying areas.

A portion of the urban temperature rise is also attributed to waste heat from sources such as home heating and air-conditioning, power generation, industry, and transportation. In addition, the "blanket" of pollutants over a city contributes to the heat island by absorbing a portion of the upward-directed long-wave radiation emitted by the surface and reemitting some of it back to the ground.

*Reported in *Weatherwise,* Vol. 57, No. 6, Nov/Dec 2004, p. 20.

at the top of the column, is a small dumbbell-shaped index (Figure 3–22b). As the air temperature drops, the column shortens and the index is pulled toward the bulb by the effect of surface tension with the meniscus. When the temperature subsequently rises, the alcohol flows past the index, leaving it at the lowest temperature reached. To return the index to the top of the alcohol column, the thermometer is simply tilted. Because the index is free to move, the minimum thermometer must be mounted horizontally; otherwise the index will fall to the bottom.

Another commonly used mechanical thermometer is the **bimetal strip.** As the name indicates, this thermometer consists of two thin strips of metal that are bonded together and have widely different expansion properties. When the temperature changes, both metals expand or contract, but they do so unequally, causing the strips to curl. This change corresponds to the change in temperature.

The primary meteorological use of the bimetal strip is in the construction of a **thermograph,** an instrument that continuously records temperature. The changes in the curvature of the strip can be used to move a pen arm that records the temperature on a calibrated chart that is attached to a clock-driven, rotating drum (Figure 3–23). Although very convenient, thermograph records are generally less accurate than readings obtained from a mercury-in-glass thermometer. To obtain the most reliable values, it is necessary to check and correct the thermograph periodically by comparing it with an accurate, similarly exposed thermometer.

Electrical Thermometers

Some thermometers do not rely on differential expansion but instead measure temperature electrically.

A resistor is a small electronic part that resists the flow of electrical current. A **thermistor** (thermal resistor) is similar, but its resistance to current flow varies with temperature. As temperature increases, so does the resistance of the thermistor, reducing the flow of current. As temperature drops, so does the resistance of the thermistor, allowing more current to flow. The current operates a meter or digital display that is calibrated in degrees of temperature. The thermistor thus is used as a temperature sensor—an electrical thermometer.

Thermistors are rapid-response instruments that quickly register temperature changes. Therefore, they are commonly used in radiosondes where rapid temperature changes are often encountered. The National Weather Service also uses a thermistor system for ground-level readings. The sensor is mounted inside a shield made of louvered plastic rings, and a digital readout is placed indoors (Figure 3–24).

Instrument Shelters

How accurate are thermometer readings? It depends not only on the design and quality of the instruments but also on where they are placed. Placing a thermometer in the direct sunlight will give a grossly excessive reading, because the instrument itself absorbs solar energy much more efficiently than the air. Placing a thermometer near a heat-radiating surface, such as a building or the ground, also yields inaccurate readings. Another way to assure false readings is to prevent air from moving freely around the thermometer.

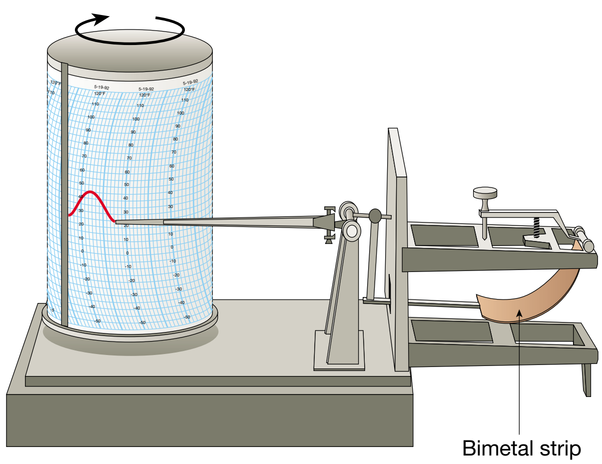


FIGURE 3-23 A common use of the bimetal strip is in the construction of a thermograph, an instrument that continuously records temperatures.

FIGURE 3-24 This modern shelter contains an electrical thermometer called a *thermistor*. *(Photo by Bobbé Christopherson)*

FIGURE 3-25 This traditional standard instrument shelter is white (for high albedo) and louvered (for ventilation). It protects instruments from direct sunlight and allows for the free flow of air. *(Courtesy of Qualimetrics, Inc.)*

So where should a thermometer be placed to read air temperature accurately? The ideal location is an instrument shelter (Figure 3–25). The shelter is a white box that has louvered sides to permit the free movement of air through it, while shielding the instruments from direct sunshine, heat from the ground, and precipitation. Furthermore, the shelter is placed over grass whenever possible and as far away from buildings as circumstances permit. Finally, the shelter must conform to a standardized height so that the thermometers will be mounted at 1.5 meters (5 feet) above the ground.

Students Sometimes Ask…

What are the highest and lowest temperatures ever recorded at Earth's surface?

The world's record-high temperature is nearly 59°C (136°F)! It was recorded on September 13, 1922, at Azizia, Libya, in North Africa's Sahara Desert. The lowest recorded temperature is −89°C (−129°F). It should come as no surprise that this incredibly frigid temperature was recorded in Antarctica, at the Russian Vostok Station, on July 21, 1983.

Temperature Scales

In the United States, TV weather reporters give temperatures in degrees Fahrenheit. But scientists as well as most people outside of the United States use degrees Celsius. Scientists sometimes also use the Kelvin or absolute scale. What are the differences among these three temperature scales? To make quantitative measurement of temperature possible, it was necessary to establish scales. Such temperature scales are based on the use of reference points, sometimes called **fixed points.** In 1714, Gabriel Daniel **Fahrenheit,** a German physicist, devised the temperature scale that bears his name. He constructed a mercury-in-glass thermometer in which the zero point was the lowest temperature he could attain with a mixture of ice, water, and common salt. For his second fixed point he chose human body temperature, which he arbitrarily set at 96°.

On this scale, he determined that the melting point of ice (the **ice point**) was 32° and the boiling point of water (the **steam point**) was 212°. Because Fahrenheit's original reference points were difficult to reproduce accurately, his scale is now defined by using the ice point and the steam point. As thermometers improved, average human body temperature was later changed to 98.6°F.*

In 1742, 28 years after Fahrenheit invented his scale, Anders Celsius, a Swedish astronomer, devised a decimal scale on which the melting point of ice was set at 0° and the boiling point of water at 100°.** For many years it was called the *centigrade scale*, but it is now known as the **Celsius scale,** after its inventor.

Because the interval between the melting point of ice and the boiling point of water is 100° on the Celsius scale and 180° on the Fahrenheit scale, a Celsius degree (°C) is larger than a Fahrenheit degree (°F) by a factor of 180/100, or 1.8. So, to convert from one system to the other, allowance must be made for this difference in the size of the degrees. Also, conversions must be adjusted because the ice point on the Celsius scale is at 0° rather than at 32°. This relationship is shown graphically in Figure 3–26.

The Celsius–Fahrenheit relationship also is shown by the following formulas:

$$°F = (1.8 \times °C) + 32$$

or

$$°C = \frac{°F - 32}{1.8}$$

*This traditional value for "normal body temperature" was established in 1868. A recent assessment places the value at 98.2°F with a range of 4.8°F.

**The boiling point referred to in the Celsius and Fahrenheit scales pertains to pure water at standard sea-level pressure. It is necessary to remember this fact, for the boiling point of water gradually decreases with altitude.

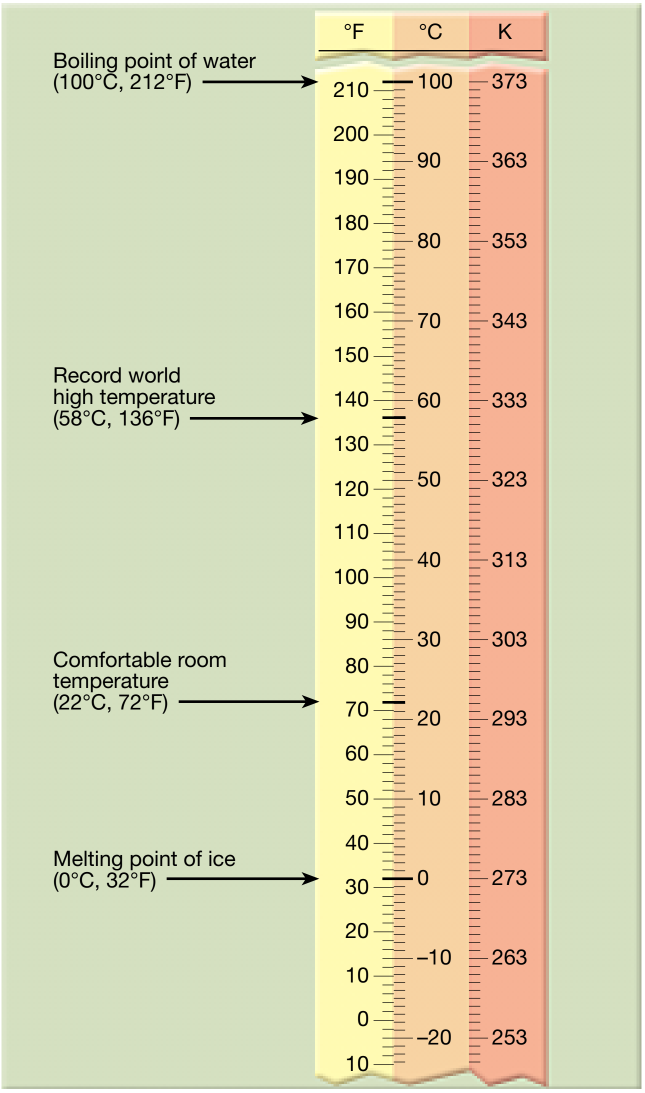


FIGURE 3-26 The three temperature scales compared.

You can see that the formulas adjust for degree size with the 1.8 factor, and adjust for the different 0° points with the ±32 factor.

The Fahrenheit scale is best known in the United States, where its official use is declining along with the British system of weights and measures. In other parts of the world as well as in the scientific community, where the metric system is used, the Celsius temperature scale is also used.

For some scientific purposes a third temperature scale is used, the **Kelvin** or **absolute scale.** On this scale, degrees Kelvin are called *Kelvins* (abbreviated K). It is similar to the Celsius scale because its divisions are exactly the same; there are 100° separating the melting point of ice and the boiling point of water. However, on the Kelvin scale, the ice point is set at 273 and the steam point at 373 (see Figure 3–26). The reason is that the zero point represents the temperature at which all molecular motion is presumed to cease (called **absolute zero**). Thus, unlike the Celsius and Fahrenheit scales, it is not possible to have a negative value when using the Kelvin scale, for there is no temperature lower than absolute zero. The relationship between Kelvin and Celsius scales is easily written as follows:

$$^{\circ}C = K\ 273 \quad \text{or} \quad K = {}^{\circ}C + 273$$

Applications of Temperature Data

To make weather data more useful to people, many different applications have been developed over the years. In this section, we examine some commonly used practical applications. First, we will look at three indices that all have the term *degree-days* as part of their name: heating degree-days, cooling degree-days, and growing degree-days. The first two are relative measures that allow us to evaluate the weather-produced needs and costs of heating and cooling. The third is a simple index used by farmers to estimate the maturity of crops.

Heating Degree-Days

Developed by heating engineers early in the twentieth century, **heating degree-days** represent a practical method for evaluating energy demand and consumption. It starts from the assumption that heating is not required in a building when the daily mean temperature is 65°F (18.3°C) or higher.* Simply, each degree of temperature below 65°F is counted as 1 heating degree-day. Therefore, heating degree-days are determined each day by subtracting the daily mean below 65°F from 65°F. Thus, a day with a mean temperature of 50°F has 15 heating degree-days ($65 - 50 = 15$), and one with an average temperature of 65°F or higher has none.

The amount of heat required to maintain a certain temperature in a building is proportional to the total heating degree-days. This linear relationship means that doubling the heating degree-days usually doubles the fuel consumption. Consequently, a fuel bill will generally be twice as high for a month with 1000 heating degree-days as for a month with just 500. When seasonal totals are compared for different places, we can estimate differences in seasonal fuel consumption (Table 3–2). For example, more than five times as much fuel is required to heat a building in Chicago (nearly 6500 total heating degree-days) than to heat a similar building in Los Angeles (almost 1300 heating degree-days). This statement is true, however, only if we assume that building construction and living habits in these areas are the same.

*Because the National Weather Service and the news media in the United States still compute and report degree-day information in Fahrenheit degrees, we will use the Fahrenheit scale throughout this discussion.

TABLE 3-2 Average annual heating and cooling degree-days for selected cities (1971–2000)*

City	Heating degree-days	Cooling degree-days
Anchorage, AK	10470	3
Baltimore, MD	3807	1774
Boston, MA	5630	777
Chicago, IL.	6498	830
Denver, CO	6128	695
Detroit, MI.	6422	736
Great Falls, MT	7828	288
International Falls, MN	10269	233
Las Vegas, NV	2239	3214
Los Angeles, CA	1274	679
Miami, FL	149	4361
New York City, NY	4754	1151
Phoenix, AZ	1125	4189
San Antonio, TX	1573	3038
Seattle, WA	4797	173

*Source: NOAA, National Climatic Data Center

Each day, the previous day's accumulation is reported as well as the total thus far in the season. For reporting purposes the heating season is defined as the period from July 1 through June 30. These reports often include a comparison with the total up to this date last year or with the long-term average for this date or both, and so it is a relatively simple matter to judge whether the season thus far is above, below, or near normal.

Cooling Degree-Days

Just as fuel needs for heating can be estimated and compared by using heating degree-days, the amount of power required to cool a building can be estimated by using a similar index called the **cooling degree-day.** Because the 65°F base temperature is also used in calculating this index, cooling degree-days are determined each day by subtracting 65°F from the daily mean. Thus, if the mean temperature for a given day is 80°F, 15 cooling degree-days would be accumulated. Mean annual totals of cooling degree-days for selected cities are shown in Table 3–2. By comparing the totals for Baltimore and Miami, we can see that the fuel requirements for cooling a building in Miami are almost two and a half times as great as for a similar building in Baltimore. The "cooling season" is conventionally measured from January 1 through December 31. Therefore, when cooling degree-day totals are reported, the number represents the accumulation since January 1 of that year.

Although indices that are more sophisticated than heating and cooling degree-days have been proposed to take into account the effects of wind speed, solar radiation, and humidity, degree-days continue to be widely used.

Growing Degree-Days

Another practical application of temperature data is used in agriculture to determine the approximate date when crops will be ready for harvest. This simple index is called the **growing degree-day.**

The number of growing degree-days for a particular crop on any day is the difference between the daily mean temperature and the base temperature of the crop, which is the minimum temperature required for it to grow. For example, the base temperature for sweet corn is 50°F and for peas it is 40°F. Thus, on a day when the mean temperature is 75°F, the number of growing degree-days for sweet corn is 25 and the number for peas is 35.

Starting with the onset of the growth season, the daily growing degree-day values are added. Thus, if 2000 growing degree-days are needed for that crop to mature, it should be ready to harvest when the accumulation reaches 2000 (Figure 3–27). Although many factors important to plant growth are not included in the index, such as moisture conditions and sunlight, this system nevertheless serves as a simple and widely used tool in determining approximate dates of crop maturity.

Temperature and Comfort

A more familiar use of temperature data relates to human perception of temperature. Television weather reports use indices that attempt to portray levels of human comfort and discomfort. Such indices are based on the fact that our sensation of temperature is often quite different from the actual air temperature recorded by a thermometer.

FIGURE 3-27 Growing degree-days are used to determine the approximate date when crops will be ready for harvest. *(Photo by Alice Garik/Peter Arnold, Inc.)*

The human body is a heat generator that continually releases energy. Anything that influences the rate of heat loss from the body also influences our sensation of temperature, thereby affecting our feeling of comfort. Several factors control the thermal comfort of the human body, and certainly air temperature is a major one. Other environmental conditions are also significant, such as relative humidity, wind, and solar radiation.

Because evaporation is a cooling process, the evaporation of perspiration from skin is a natural means of regulat-

FIGURE 3-28 Strong winds make winter days seem much colder. New Yorkers had to cope with frigid temperatures, strong winds, and lots of snow during this January blizzard in 1996. *(Photo by Kaz Chiba Photography/Getty Images, Inc.-Liaison)*

ing body temperature. When the air is very humid, however, heat loss by evaporation is reduced. As a result, a hot and humid day feels warmer and more uncomfortable than a hot and dry day. This is the basis for a commonly used expression of summertime discomfort known as the *heat stress index* or simply the *heat index*. Because of its link to humidity, this index is the focus of a special-interest box in Chapter 4.

Wind is another significant factor affecting the sensation of temperature. A cold and windy winter day may feel much colder than the air temperature indicates (Figure 3–28). Box 3–5 focuses on this frequently used wintertime application known as *windchill*.

Students Sometimes Ask…

What impact does windchill have on exposed water pipes or my car's radiator?

The only effect windchill has on inanimate objects, such as the ones you mentioned, is to shorten the amount of time it takes for the object to cool. The inanimate object will not cool below the actual air temperature. For example, if the temperature outside is –5°F and the windchill temperature is –31°F, then your car's radiator will not drop lower than –5°F.

Chapter Summary

- Temperature is one of the basic elements of weather and climate. The *daily mean temperature* is determined by averaging the 24 hourly readings or by adding the maximum and minimum temperatures for a 24-hour period and dividing by two. The *daily temperature range* is computed by finding the difference between the maximum and minimum temperatures. Other temperature data involving longer periods include the *monthly mean temperature* (the sum of the daily means for each day of the month divided by the number of days in the month), the *annual mean temperature* (the average of the twelve monthly mean temperatures), and the *annual temperature range* (the difference between the warmest and coldest monthly mean temperatures).
- The *controls of temperature*—those factors that cause temperature to vary from place to place—are (1) differential heating of land and water; (2) ocean currents; (3) altitude; (4) geographic position; and (5) cloud cover and albedo.
- On maps illustrating the world distribution of temperature, *isotherms*, lines that connect points of equal temperature, generally trend east and west and show a decrease in temperature poleward. Moreover, the isotherms illustrate a latitudinal shifting of temperatures caused by the seasonal migration of the Sun's vertical rays and also reveal the presence of ocean currents. The north-south migration of isotherms is more pronounced over the continents because the temperatures do not fluctuate as much over water.
- Annual temperature range is small near the equator and increases with an increase in latitude. Outside the tropics, annual temperature range also increases with an increase in continentality.
- The primary control of the daily cycle of air temperature is Earth's rotation. However, the magnitude of these changes is variable and influenced by locational factors, local weather conditions, or both.
- As a consequence of the mechanism by which Earth's atmosphere is heated, the months of the highest and lowest temperatures do not coincide with the periods of maximum and minimum incoming solar radiation. In the Northern Hemisphere the greatest intensity of solar radiation occurs at the time of the summer solstice, yet the months of July and August are generally the warmest of the year. Conversely, in the Northern Hemisphere a minimum of solar energy is received in December at the time of the winter solstice, but January and February are usually colder.
- *Thermometers* measure temperature either mechanically or electrically. Most *mechanical thermometers* are based on the ability of a substance to expand when heated and contract when cooled. One type of mechanical thermometer, the liquid-in-glass thermometer, includes maximum thermometers, which use mercury, and minimum thermometers, which contain a liquid of low density, such as alcohol. A bimetal strip mechanical thermometer is frequently used in a thermograph, an instrument that continuously records temperature. *Electrical thermometers* use a thermistor (a thermal resistor) to measure temperature.
- Temperature scales use reference points, called *fixed points*. Three common temperature scales are (1) the *Fahrenheit scale*, which is defined by using the ice point (32°) and steam point (212°), (2) the *Celsius scale*, a decimal scale on which the melting point of ice is set at 0° and the boiling point of water at 100°, and (3) the *Kelvin* or *absolute scale*, where the zero point represents the temperature at which all molecular motion is presumed to cease (called *absolute zero*), the ice point is set at 273, and the steam point at 373.
- Three common applications of temperature data are (1) *heating degree-days*, where each degree of temperature below 65°F is counted as one heating degree day, (2) *cooling degree-days*, which are determined by subtracting 65°F from the daily mean, and (3) *growing degree-days*,

BOX 3-5 Windchill: The Cooling Power of Moving Air

Most everyone is familiar with the wintertime cooling power of moving air. When the wind blows on a cold day, we realize that comfort would improve if the wind were to stop. A stiff breeze penetrates ordinary clothing and reduces its capacity to retain body heat while causing exposed parts of the body to chill rapidly. Not only is cooling by evaporation heightened in this situation but the wind is also acting to carry heat away from the body by constantly replacing warmer air next to the body with colder air.

On November 1, 2001, the U.S. National Weather Service (NWS) and the Meteorological Services of Canada (MSC) implemented a new Wind Chill Temperature (WCT) index that is designed to more accurately calculate how the wind and cold feel on human skin (Figure 3–H). The index formerly used by the United States and Canada was developed in the 1940s and based on research conducted in Antarctica. The experiments measured the cooling rate of water in a container hanging from a tall pole outside.

FIGURE 3-H This windchill chart came into use in November 2001. Fahrenheit temperatures are used here because this is how the National Weather Service and the news media in the United States commonly report windchill information. The shaded areas on the chart indicate frostbite danger. Each shaded zone shows how long a person can be exposed before frostbite develops. *(After NOAA, National Weather Service)*

Temperature (°F)

Wind (mph)	Calm	40	35	30	25	20	15	10	5	0	–5	–10	–15	–20	–25	–30	–35	–40	–45
	5	36	31	25	19	13	7	1	–5	–11	–16	–22	–28	–34	–40	–46	–52	–57	–63
	10	34	27	21	15	9	3	–4	–10	–16	–22	–28	–35	–41	–47	–53	–59	–66	–72
	15	32	25	19	13	6	0	–7	–13	–19	–26	–32	–39	–45	–51	–58	–64	–71	–77
	20	30	24	17	11	4	–2	–9	–15	–22	–29	–35	–42	–48	–55	–61	–68	–74	–81
	25	29	23	16	9	3	–4	–11	–17	–24	–31	–37	–44	–51	–58	–64	–71	–78	–84
	30	28	22	15	8	1	–5	–12	–19	–26	–33	–39	–46	–53	–60	–67	–73	–80	–87
	35	28	21	14	7	0	–7	–14	–21	–27	–34	–41	–48	–55	–62	–69	–76	–82	–89
	40	27	20	13	6	–1	–8	–15	–22	–29	–36	–43	–50	–57	–64	–71	–78	–84	–91
	45	26	19	12	5	–2	–9	–16	–23	–30	–37	–44	–51	–58	–65	–72	–79	–86	–93
	50	26	19	12	4	–3	–10	–17	–24	–31	–38	–45	–52	–60	–67	–74	–81	–88	–95
	55	25	18	11	4	–3	–11	–18	–25	–32	–39	–46	–54	–61	–68	–75	–82	–89	–97
	60	25	17	10	3	–4	–11	–19	–26	–33	–40	–48	–55	–62	–69	–76	–84	–91	–98

Frostbite Times: 30 minutes · 10 minutes · 5 minutes

which are determined from the difference between the daily mean temperature and the base temperature of the crop, the minimum temperature required for it to grow.

- One familiar use of temperature data relates to human perception of temperature. The *heat stress index* (or *heat index*), a commonly used expression of summertime discomfort, links humidity and temperature to determine the thermal comfort of the human body. *Windchill,* a typical wintertime index, uses both wind and air temperature to calculate the human sensation of temperature.

Vocabulary Review

absolute zero (p. 88)
annual mean temperature (p. 66)
annual temperature range (p. 66)
bimetal strip (p. 86)
Celsius scale (p. 87)
controls of temperature (p. 68)
cooling degree-day (p. 89)
daily mean temperature (p. 66)
daily temperature range (p. 66)
Fahrenheit scale (p. 87)
fixed points (p. 87)
growing degree-days (p. 89)
heating degree-days (p. 88)
ice point (p. 87)
isotherm (p. 67)
Kelvin or absolute scale (p. 88)
liquid-in-glass thermometer (p. 83)
maximum thermometer (p. 83)
minimum thermometer (p. 83)
monthly mean temperature (p. 66)
specific heat (p. 68)
steam point (p. 87)
temperature gradient (p. 67)
thermistor (p. 86)
thermograph (p. 86)
thermometers (p. 82)

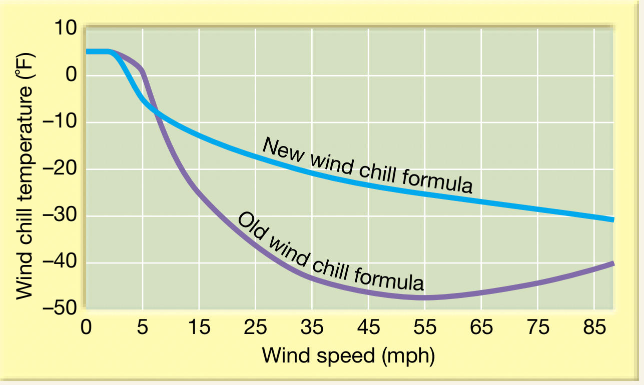


FIGURE 3-I This graph compares windchill temperatures using the old and new calculations, assuming the air temperature is 5°F. Overall, the new index is significantly warmer than the previous index, especially when wind speeds exceed 15 miles per hour. *(After NOAA, National Weather Service)*

Because a container of water freezes faster than flesh, the previous windchill index *underestimated* the time to freezing and *overestimated* the chilling effect of the wind (Figure 3-I).

The new index accounts for wind effects at face level and more accurately portrays body heat–loss estimates. Moreover, it was tested on human subjects in a chilled wind tunnel. The results of those trials were used to validate and improve the accuracy of the new formula.

Unlike the previous index, the new Wind Chill Chart includes a frostbite indicator, showing the points where temperature, wind speed, and exposure time will produce frostbite on humans (Figure 3–I). For example, a temperature of 0°F and a wind speed of 15 miles per hour will produce a windchill temperature of −19°F. Under these conditions, exposed skin can freeze in 30 minutes.

It is worth pointing out that in contrast to a cold and windy day, a calm and sunny day in winter feels *warmer* than the thermometer reading. In this situation the warm feeling is caused by the absorption of direct solar radiation by the body. Currently the new index does not take into account any offsetting effect for windchill due to solar radiation. Such a factor may be added at a later date.

It is important to remember that the windchill temperature is only an *estimate* of human discomfort. The degree of discomfort felt by different people will vary because it is influenced by many factors. Even if clothing is assumed to be the same, individuals vary widely in their responses because of such factors as age, physical condition, state of health, and level of activity. Nevertheless, as a relative measure, WCT is useful because it allows people to make more informed judgments regarding the potential harmful effects of wind and cold.

*Based in part on material prepared by the U.S. National Weather Service.

Review Questions

1. How are the following temperature data calculated: daily mean, daily range, monthly mean, annual mean, and annual range?
2. What are isotherms and what is their purpose?
3. Why are summertime maximum temperatures so high in Death Valley, California? (See Box 3–1.)
4. **a.** State the relationship between the heating and cooling of land versus water.
   b. List and explain the factors that cause the difference between the heating and cooling of land and water.
   c. We are studying the atmosphere, so why are we concerned with the heating characteristics at Earth's surface?
5. How does the annual temperature range near the equator compare with the annual temperature ranges in the middle to high latitudes? Explain.
6. Three cities are at the same latitude (about 45° N). One city is located along a windward coast, another in the center of the continent, and the third along a leeward coast. Compare the annual temperature ranges of these cities.
7. Quito, Ecuador, is on the equator and is not a coastal city. It has an annual mean temperature of only 13°C. What is the likely cause for this low annual mean temperature?
8. How does the daily march of temperature on a completely overcast day compare with that on a cloudless, sunny day? Explain your answer.
9. Examine Figure 3–14 and explain why Yangon's monthly mean temperature for April is higher than the July monthly mean.
10. Answer the following questions about world temperature distribution (you may wish to refer to the January and July isotherm maps).

a. Isotherms generally trend east–west. Why?
b. Isotherms bend (poleward, equatorward) over continents in summer. Underline the correct answer and explain.
c. Isotherms shift north and south from season to season. Why?
d. Where do isotherms shift most, over land or water? Explain.
e. How do isotherms show ocean currents? How can you tell if the current is warm or cold?
f. Why are the isotherms more irregular in the Northern Hemisphere than in the Southern Hemisphere?

11. Which area on Earth experiences the highest annual temperature range? (Refer to Figure 3–17). Why is the annual range so high in this region?

12. Although the intensity of incoming solar radiation is greatest at local noon, the warmest part of the day is most often midafternoon. Why? Use Figure 3–20 to explain your answer.

13. List at least three factors that contribute to the urban heat island. (See Box 3–4.)

14. The magnitude of the daily temperature range can vary significantly from place to place and from time to time. List and describe at least three factors that might cause such variations.

15. Describe how each of the following thermometers works: liquid-in-glass, maximum, minimum, bimetal strip, and thermistor.

16. What is a thermograph? Which one of the thermometers listed in Question 15 is commonly used in the construction of a thermograph?

17. In addition to having an accurate thermometer, which other factors must be considered to obtain a meaningful air temperature reading?

18. **a.** What is meant by the terms *steam point* and *ice point*?
b. What values are given these points on each of the three temperature scales presented in this chapter?

19. Why is it not possible to have a negative value when using the Kelvin temperature scale?

20. When heating and cooling degree-day totals for different places are examined to compare fuel consumption, what important assumption is made?

21. How are growing degree-days calculated? For what purpose is this index used?

Problems

1. If you were asked to identify the coldest city in the United States (or any other designated region), what statistics could be used? Can you list at least three different ways of selecting the coldest city?

2. Refer to the thermograph record in Figure 3–18. Determine the maximum and minimum temperature for each day of the week. Use these data to calculate the daily mean and daily range for each day.

3. By referring to the world maps of temperature distribution for January and July (Figures 3–15 and 3–16), determine the approximate January mean, July mean, and annual temperature range for a place located at 60° north latitude, 80° east longitude, and a place located at 60° south latitude, 80° east longitude.

4. Calculate the annual temperature range for three cities in Appendix F. Try to choose cities with different ranges and explain these differences in terms of the controls of temperature.

5. Referring to Figure 3–H in Box 3–5, determine windchill temperatures under the following circumstances:
a. Temperature = 5°F, wind speed = 15 mph.
b. Temperature = 5°F, wind speed = 30 mph.

6. The mean temperature is 55°F on a particular day. The following day the mean drops to 45°F. Calculate the number of heating degree-days for each day. How much more fuel would be needed to heat a building on the second day compared with the first day?

7. Use the appropriate formula to convert the following temperatures:

20°C = ____ °F

−25°C = ____ K

59°F = ____ °C

Atmospheric Science Online

The Atmosphere 10e web site uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by meteorology instructors, this site will help improve your understanding of meteorology. Visit **http://www.prenhall.com/lutgens** and click on the cover of *The Atmosphere 10e* to find:

- **Online review quizzes**
- **Critical thinking exercises**
- **Links to chapter-specific web resources**
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