# Introducing Weather and Climate

# 1

In the last weeks of 1997 and the first weeks of 1998, extreme weather across the globe killed around 2100 people and caused $33 billion worth of property damage. Forest fires raged in Sumatra and Borneo, while large portions of Australia and the East Indies were plunged into drought. Torrential rains drenched Peru and Ecuador, and ice storms left four million people in Quebec and the northeastern United States stranded without power. This devastation was partly the result of climate changes induced by changes in the tropical Pacific known as El Niño.


Global Locator

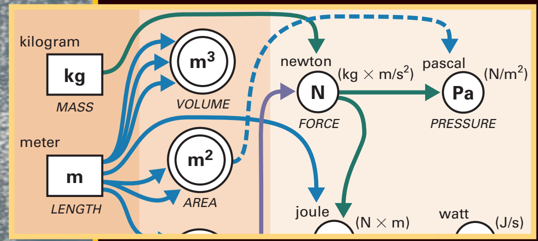
An El Niño occurs every 3–7 years and lasts for 6–12 months. It was given the Spanish name El Niño (meaning "the little boy" or "Christ Child") by Peruvian fishermen whose anchovy harvests plummeted around Christmas. Under normal conditions in the tropical Pacific region, strong winds blow westward, "piling up" very warm ocean water in the western Pacific while cool, bottom water rises to the surface along the South American coast. During an El Niño, however, the westward winds weaken, and warm waters spread eastward across the Pacific. The subsequent changes in the overlying atmosphere set in motion by an El Niño can induce changes in weather around the globe, from droughts in Australia and Brazil to flooding in California and Chile. This series of changes is one of the most striking examples of the interaction between weather and climate and how the two can affect our lives here on the Earth.

As the El Niño of 2006–2007 began, fires similar to those of 1997–1998 swept across the vast Indonesian island of Borneo.

## CHAPTER OUTLINE







# Introducing Weather and Climate

**Learning Objectives**

**Define** weather.

**Define** climate.

**Explain** different ways that weather and climate are related.

To gain a perspective of the topics covered in this text, it might be helpful to take a step back––way back. Imagine that you are an astronaut on a lunar base station in 2050 looking back toward the Earth (Figure 1.1). What do you see? From your lunar viewpoint, the first thing you notice is that the right-hand edge of the disk is in shadow, and you see the dramatic contrast between the day and night portions of the globe. The land and water masses of the illuminated side bask in the sunlight, and here the temperature of this portion of the Earth is slowly increasing. On the shadowed side of the planet, however, the heat of the oceans, atmosphere, and continents is continuously being lost—radiated into outer space both day and night. Without the offsetting heat provided by sunlight, the Earth's surface cools.

Over the next few hours, you notice the planet's slow rotation. The continent of Africa, seen in the figure, glides toward the edge of darkness, then disappears. Eventually South America emerges at the left side of the disk and slowly moves toward the center. Africa and South America receive the lion's share of the sunlight striking the Earth. These continents lie near the Equator, where they meet the strong, near-vertical rays of the Sun. North America and Europe, on the other hand, are shortchanged because they lie farther toward the pole and intercept the Sun's rays at a low angle. At the lower rim of the Earth's disk, the stark, white continent of Antarctica rotates slowly but remains sunlit, experiencing 24-hour daylight.

As the Earth days go by, you often gaze at your planet, marking the changes. Away from the Equator, huge swirls of clouds form, dissolve, and re-form in its atmosphere, making their way eastward across the disk. First one portion of a continent, and then another, is obscured. These swirls mark the passage of weather fronts and storms that are moved eastward by persistent winds high above the surface.

**The Earth from space** Figure 1.1

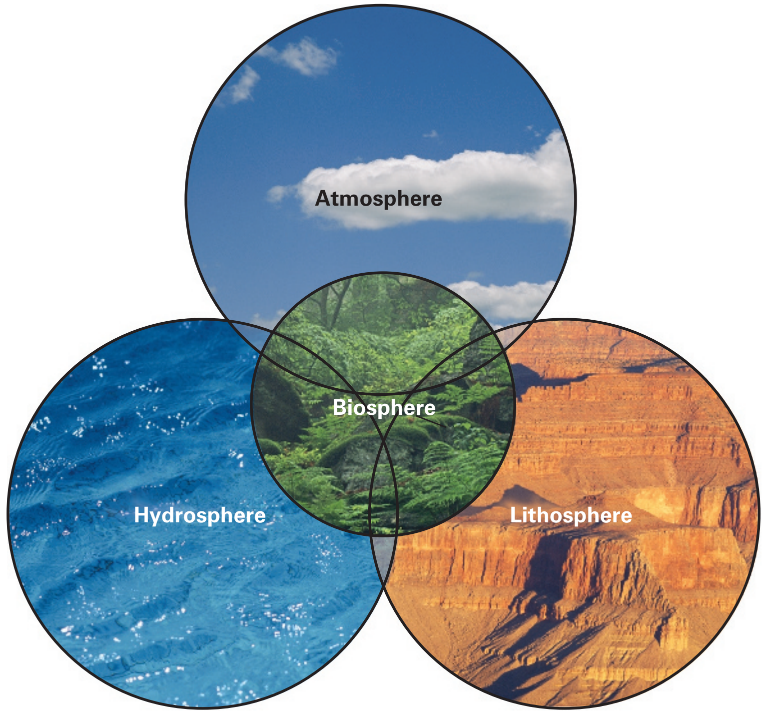
This image shows the Earth as seen from the surface of the Moon. White regions represent clouds and snow. Blue regions are oceans. The reddish-brown areas are the vast deserts of Africa. In this photo, only the left portion of the Earth receives sunlight; the right side of the Earth is experiencing night.

Near the Earth's Equator in Africa, you notice a band of patchy, persistent cloudiness bracketed north and south by reddish-brown areas of the Earth that are normally clear. The clouds result when warm, moist air is heated by excess solar energy and rises. As the air rises, it cools, and the moisture it contains condenses, forming clouds and producing rain. The lush, green landscape that is occasionally visible underneath the cloud belt seems to thrive on the warm temperature and abundant rainfall it receives. The reddish-brown areas are vast deserts. The air that rises over the Equator begins to descend in these regions, inhibiting cloud formation and rainfall. As the air descends toward the desert, it also warms. Showing the colors of rock and soil, the hot, dry deserts are barren of plants.

If you were to stay on the lunar base another six months, you would watch the slow changes of the planet with the seasons. By June, the Earth has changed its position with respect to the Sun. Antarctica has moved below the southern rim. The sunlit northern rim of the disk now includes northern Canada, Siberia, and the Arctic Ocean. The storm systems you saw buffeting the coastal regions of the United States and Europe have weakened and moved north. Now, however, a new set of storms, generated in the lower latitudes off western Africa, slowly migrate westward, occasionally strengthening as they go. A few of these may eventually grow into terrifying vortices of spiraling air hundreds of kilometers across—hurricanes.

In addition, during this time, a green wave of vegetation sweeps northward, up and across North America, Europe, and eastern Asia, following the warming temperatures of spring. The band of tropical cloudiness also moves northward, bringing along a green wave in Africa. Clearly, each region of the Earth has its unique climate, responding to the rhythm of the seasons in different ways.

What you have witnessed are the day-to-day and month-to-month changes in the circulation of the atmosphere across the globe. It is important to remember that the atmosphere is only one of the four spheres of the Earth, which include: the atmosphere, the lithosphere, the hydrosphere, and the biosphere (FIGURE 1.2).




**The Earth's spheres FIGURE 1.2**

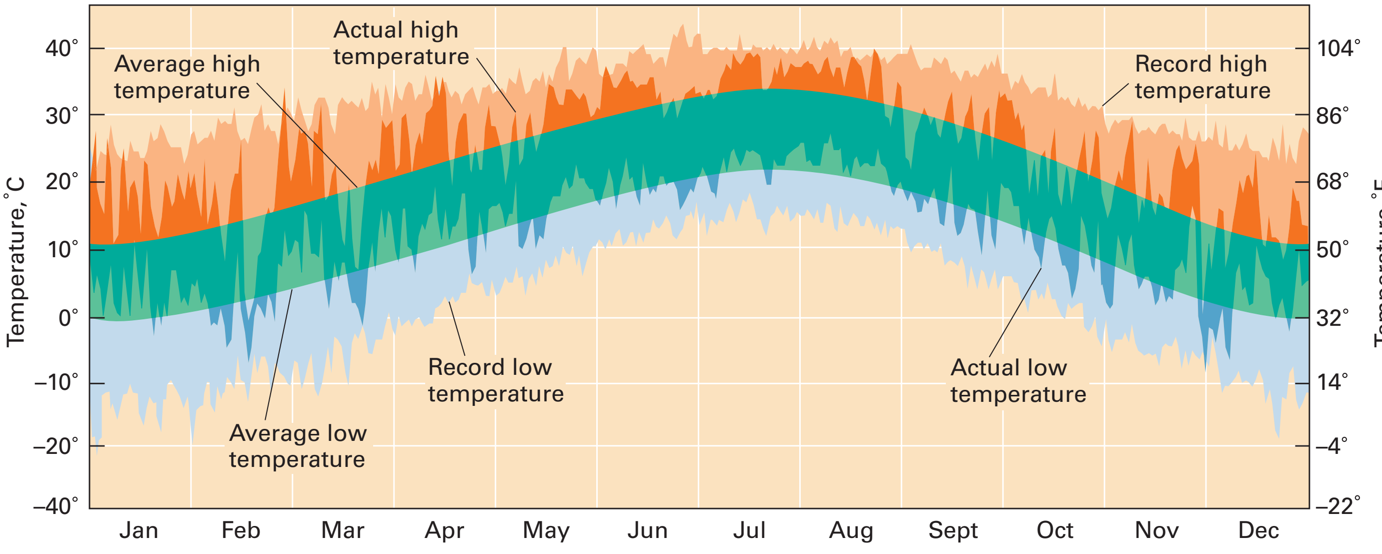
There are four great realms, or spheres of the Earth: **A** the atmosphere, **B** the lithosphere, **C** the hydrosphere, and **D** the biosphere.

The **atmosphere** is a gaseous layer that surrounds the Earth. It receives heat and moisture from the surface and redistributes them, returning some heat and all the moisture to the surface. The atmosphere also supplies vital elements—carbon, hydrogen, oxygen, and nitrogen—that are needed to sustain life-forms.

The outermost solid layer of the Earth, or **lithosphere**, provides the platform for most earthly life-forms. The solid rock of the lithosphere bears a shallow layer of soil in which nutrient elements become available to organisms. The surface of the lithosphere is sculpted into landforms. These features—such as mountains, hills, and plains—provide varied habitats for plants, animals, and humans and influence local weather.

**atmosphere** Layers of gases surrounding the Earth and bound to it by the Earth's gravity.

**lithosphere** The solid portion of the Earth's surface, extending 100 km deep and comprising the ocean basins and continents.




**Time cycles of temperature at Wichita Falls, Texas** FIGURE 1.3

This plot shows the daily temperatures at Wichita Falls, Texas, during 2006.

The liquid realm of the Earth is the **hydrosphere**, which is principally the mass of water in the world's oceans. It also includes solid ice in mountain and continental glaciers, which, like liquid water, is subject to flow under the influence of gravity. Within the atmosphere, water occurs as gaseous vapor, as well as liquid droplets and solid ice crystals that fall to the earth as *precipitation*. In the lithosphere, water is found in the uppermost layers in soils and in ground-water reservoirs.

The **biosphere** encompasses all living organisms of the Earth. Life-forms on the Earth utilize the gases of the atmosphere, the water of the hydrosphere, and the nutrients of the lithosphere, and so the biosphere is dependent on all three of the other great realms.

While our emphasis in this text will be on the atmosphere, we will often refer to the other three realms that interact with it.

**hydrosphere** Total water realm of the Earth's surface, including the oceans, surface waters of the lands, ground water, and water held in the atmosphere.

**biosphere** The network of all living organisms found on the Earth. Also that portion of the Earth in which life can exist.

You also may have noticed that many of the changes in the atmosphere exhibit different *time cycles*—rhythms in which processes change in a regular and repeatable fashion. For example, the annual revolution of the Earth around the Sun, coupled with the tilt of the Earth's axis of rotation, generates a time cycle of incoming solar energy flow. We speak of this cycle as the *rhythm of the seasons*. The rotation of the Earth on its axis sets up the night-and-day cycle of darkness and light. The Moon, in its monthly orbit around the Earth, sets up its own time cycle. We see the lunar cycle in the timing and range of tides, with higher high tides and lower low tides ("spring tides") occurring both at full moon and at new moon.

The astronomical time cycles of Earth rotation and solar revolution—which are reflected in local temperatures, for instance (FIGURE 1.3)—will appear at several places throughout this text. Other time cycles with durations of a few years describe changes in the global interactions of the ocean with the atmosphere, which can have profound impacts upon temperatures and rainfall ranging from California to Australia. Still others, with durations of tens to hundreds of thousands of years, describe the alternate growth and shrinkage of the great ice sheets.

These time cycles (or *time scales*) also allow us to differentiate processes that affect the *weather* from those that affect *climate*. In general, we can think of weather as the changes that occur over time cycles of minutes to hours to days. Climate, on the other hand, is related to changes that occur over time cycles from months to years to millennia. While we will see that changes in weather and changes in climate can influence each other, for right now let us consider them separately.

## WEATHER

When we looked down on the Earth from space, we identified two types of weather phenomena. In the midlatitudes, we saw inspiraling bands of clouds and clear skies—called *midlatitude* (or extratropical) *cyclones*; in other regions, the spiral direction is reversed and we find *midlatitude anticyclones*. In the lower latitudes, we saw smaller, more concentrated spirals of clouds and winds—called *tropical cyclones*. These are only two of the many weather phenomena you will encounter in this text.

What is weather? **Weather** is the state of the atmosphere at a particular place and time, typically described by temperature, moisture, wind, and precipitation conditions. Weather can change from minute to minute, but we usually speak of weather as the prevailing conditions of a day or two.

Another important concept is that of *weather systems*—recurring atmospheric circulation patterns and their associated weather changes. While any given change in weather is the result of a unique combination of interacting large-scale and small-scale processes, in this text we focus on weather systems, which produce similar types of weather changes. A few examples of the different types of weather systems you will encounter in this text (see **Figure 1.4**, on pages 8–9) include:

- *Midlatitude cyclones and anticyclones.* Large (hundreds of kilometers) inspirals and outspirals of surface air that repeatedly form, intensify, and dissolve as they move slowly across the mid- and high-latitude regions of the globe
- *Fronts.* The boundary along which two large bodies of air with very different temperature and moisture characteristics interact, producing lifting and cooling of air leading to cloud formation and precipitation
- *Tropical cyclones.* Vast (approximately 100 km) inspiraling systems of very high winds and heavy rainfall that develop over very warm tropical oceans and move westward in lower latitudes, affecting the eastern coasts of most continents
- *Thunderstorms.* Storms spanning a few kilometers to a hundred kilometers in which intense vertical circulations develop, resulting in heavy precipitation, lightning and thunder, and sometimes severe winds
- *Tornadoes.* Small (from 100 m up to 2 km), intense vortices around which air spirals at speeds capable of causing total destruction of any structures and life-forms in their paths

**weather** The state of the atmosphere at a particular location and time, usually determined by temperature, moisture, precipitation, and winds.

**climate** The average or prevailing weather for a given region, characterized by temperature, moisture, precipitation, and winds.

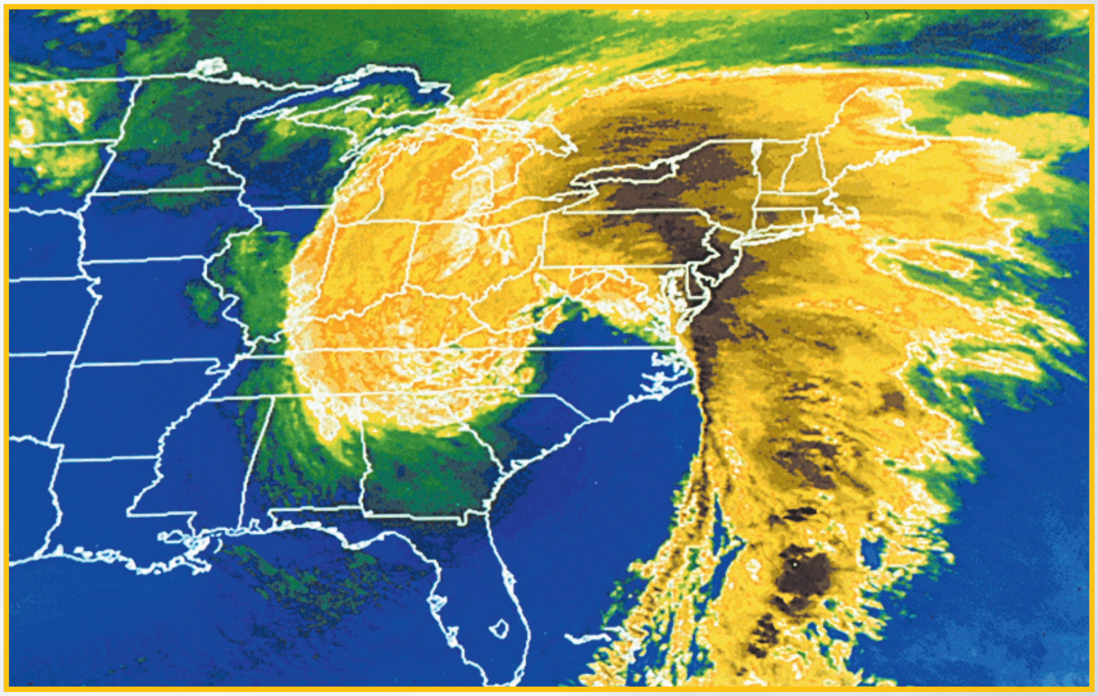
## CLIMATE

We use the term *weather* to describe how the state of the atmosphere changes from one hour to the next and from one day to the next. What about on longer time cycles—for instance, from one year to the next? In these cases, we refer to the state of the atmosphere in a given region as the **climate** of the region. While we can describe the state of the atmosphere using the same quantities—temperature, moisture, wind, and precipitation—there is one important difference. When we talk about what the climate of a region is like, we talk about its *average* characteristics and how these characteristics change over time. The average characteristics, however, are simply the average of all the different weather events that occurred at that location on a particular day (or month or even year).

# Visualizing

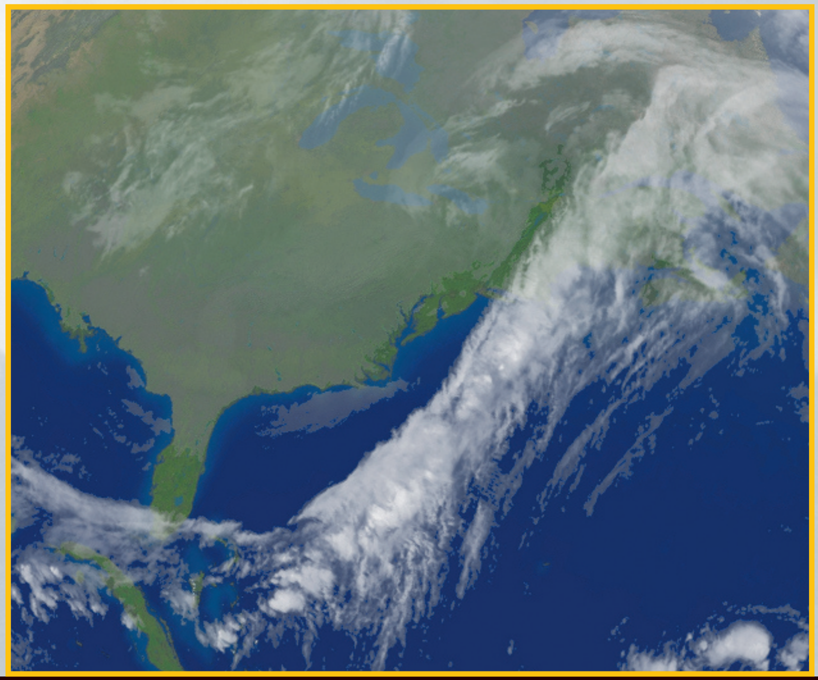
## Weather systems FIGURE 1.4

Weather systems are recurring atmospheric patterns that produce similar types of weather with each occurrence. Shown here are some that we will cover in this book.



### ▲ Midlatitude cyclones

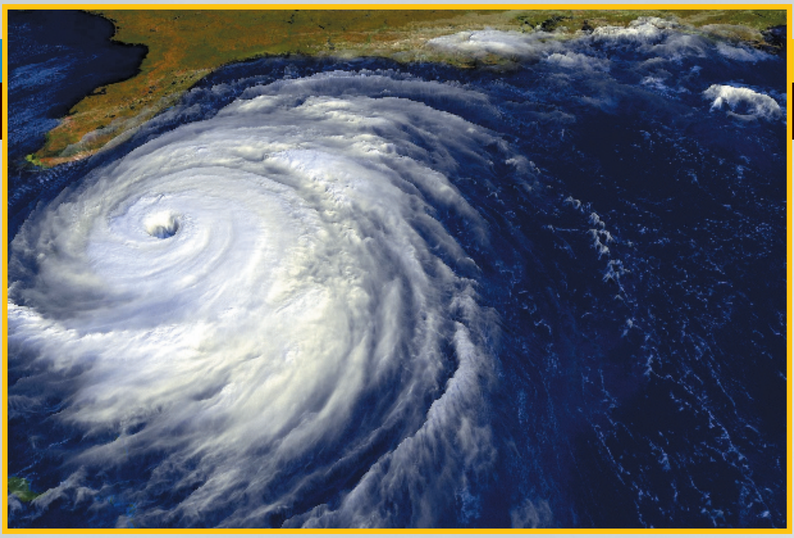
This satellite image shows a storm that struck the eastern U.S. in March of 1993. Note the characteristic "comma" shape and distinct regions of cloudy (yellow/black) and clear (blue) skies.



### Fronts ▶

This satellite image shows a cold front pushing out across the Atlantic Ocean. The front represents a boundary between very cold, dry air to the west and warmer air to the east. It is marked by the sharp boundary between clear and cloudy skies.

NATIONAL GEOGRAPHIC



◀ **Tropical cyclones**

Hurricane Floyd sits poised off the coast of Florida. With winds peaking at 250 km/h (150 mph), it traveled parallel to the coast before making landfall in North Carolina on September 16, 1999.

**Thunderstorms** ▶

A massive thunderstorm threatens a house in Connecticut. These storms can bring heavy rain, high winds, lightning, and tornadoes.

◀ **Tornadoes**

An archetypical tornado descends from the base of a thunderstorm. The rapidly spinning winds kick up dust, seen at the bottom of the tornado. Although benign looking, the winds surrounding this tornado can be faster than 90 m/s (200 mph).

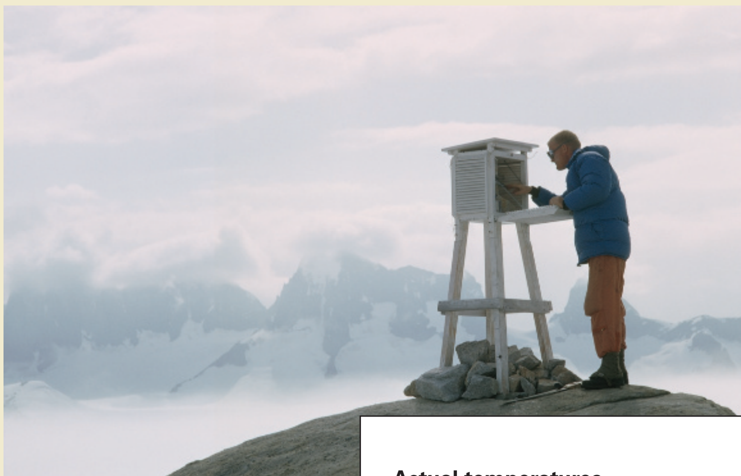
Thus when we talk about the climate of a region, we are really talking about what the average weather conditions are like in that region. For example, if we ask what the temperature in Juneau, Alaska, is in June, we are talking about the average temperature in June, measured over many years (usually around 30). On any given day in June in any given year, however, the actual temperature can be very different from the average temperature, as described in *What a Scientist Sees: Actual Temperatures and Temperature Departures*.

What a Scientist Sees

## Actual Temperatures and Temperature Departures

Scientists install and record data from weather instruments, such as thermometers, in specific locations, such as this one in Juneau, Alaska. These thermometers will record the daily temperatures for a number of years before the average temperature of the location can be determined. Each actual measurement tells us something about the temperature on a given day. However, if scientists want to know whether it is colder or warmer than normal, they look at temperature departures.

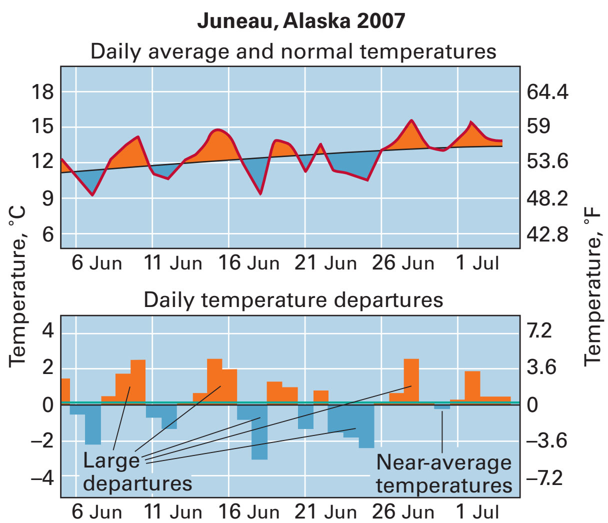
To calculate a departure from normal—also called an *anomaly*—a scientist will subtract the average value from the actual value. This allows the scientist to identify which days (or years) were much warmer than normal and which were much cooler than normal. As seen here, on most days the actual temperature does not match the average temperature.



**Weather station**
A shelter containing thermometers and other weather instruments is installed in Juneau, Alaska. These instruments take measurements over many days and years, allowing scientists to determine the average temperature for a given day, as well as the temperature departures on a specific day.

**Actual temperatures**
The measured temperatures are shown by the colored line. The average temperatures for the given day are provided by the smooth line. When temperatures are higher than average, the curve is red; when they are lower, the curve is blue.

**Temperature departures**
The departures of measured temperatures from average temperatures are shown by the colored bars. When the value is close to 0, it means the temperature for that day was close to the average.



**Wheat fields** FIGURE 1.5

Wheat prefers to grow in locations with relatively little moisture, warm conditions, and plenty of sunshine.

Why, then, do we concern ourselves with climate if there is no guarantee that the temperature (or rainfall or winds) on a given day will be the same as the average conditions? It is because many of the processes we as humans care about operate according to the climate of a region.

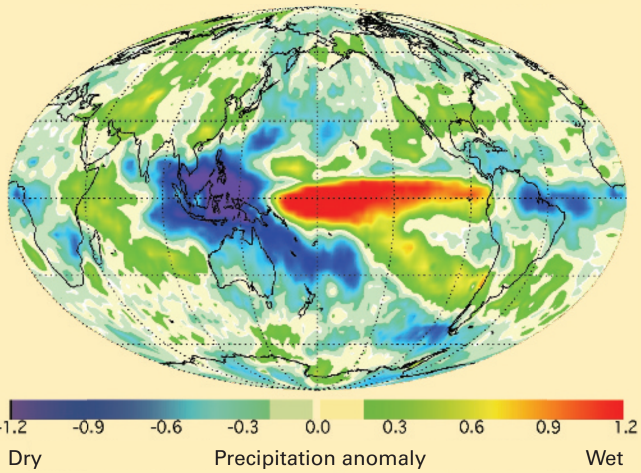
Consider a field of wheat in the plains of Kansas (FIGURE 1.5). Why does wheat grow well here? It is because of the climate. Wheat requires ample moisture in the spring but needs less as it matures and sets its seed—the grain that we harvest for food. Wheat also needs relatively warm conditions, but not too hot, and plenty of sunshine for photosynthesis and growth. It turns out that the Great Plains of the United States have just this type of climate, with cold, dry winters, but adequate rainfall and sunshine arriving in the summer.

Similarly, when engineers build an airport, they need to consider the average speed and direction of the wind so they can align the runways to enable airplanes to land and take off into the wind most frequently. When architects design a new building, they need to know the *heating degree days* and the *cooling degree days* for the region, because these indicate how often the heating and air conditioning in the building will need to be run. In the United States, both of these are determined by the average temperatures and how frequently they fall below or rise above 65°F.

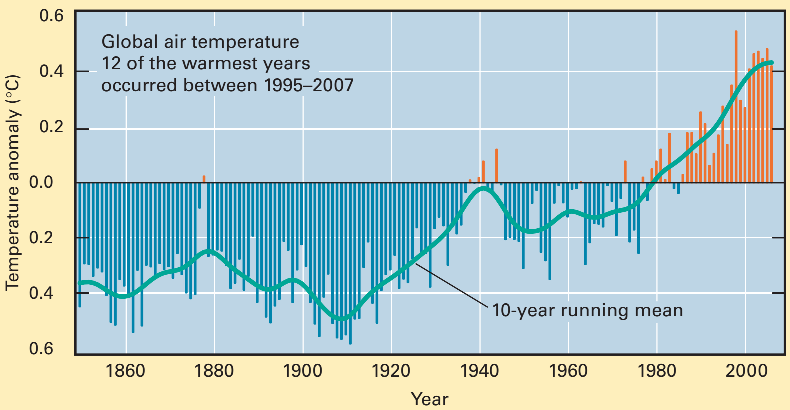
Thus, while the weather can dictate how you dress on a particular day or whether you take an umbrella with you when you go out, the climate can dictate the types of clothes you have in your closet and whether your apartment has an air conditioner, a heater, or both.

Just as weather can vary over time, so can the climate of a given location. However, we do not refer to day-to-day climate changes. Instead, we refer to climate changes over the course of months, years, decades, and

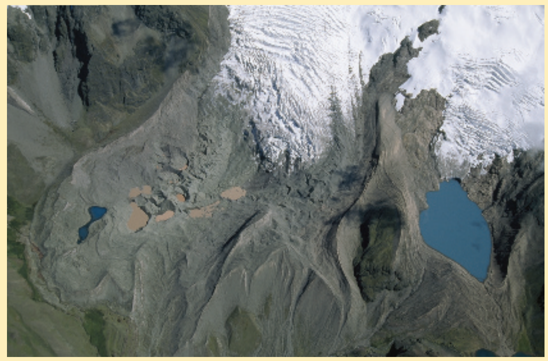
**El Niños**
This satellite image shows the changes in precipitation associated with an El Niño—a change in sea-surface temperatures over the equatorial Pacific. Note that the changes in precipitation stretch eastward from the Pacific into South America and the Atlantic and westward into the Indian Ocean. They also extend northward and southward, producing changes in rainfall around the world.




**Seasons**
The annual bloom of cherry blossoms in Washington, D.C., heralds the arrival of spring, a period of warming temperatures and longer days that is part of the annual cycle.




**Global Warming**
This graph shows that global average temperatures have been increasing since the early 1900s. This rise is coincident with increased emissions of heat-trapping gases like carbon dioxide and methane following the industrial revolution.



**Ice Ages**
A massive glacier (the white area) retreats to the upper-right portion of this photo. Its initial location is marked by the edge of the rounded, gray landforms, which are silt and debris deposited by the glacier as it retreated. During the last glacial period, continental ice sheets covered much of the high- and midlatitude regions of the globe, then melted away quickly starting about 15,000 years ago.

**Climate-change processes** FIGURE 1.6

Climate can change because of many different processes. Here are some we will cover in this book.

even thousands of years. A few examples of the different climate-change processes that you will encounter in this text (FIGURE 1.6) include:

- *Seasons.* Cyclical change in the temperature and moisture characteristics of a given region associated with the orientation of the Earth during its annual passage around the Sun
- *El Niños.* Global-scale changes in winds, temperatures, and rainfall induced by the interaction of the atmosphere with the ocean across the tropical Pacific
- *Global warming.* Commonly used to refer to recent warming of the global-average temperature over the last 100 years, which coincides with significant increases in atmospheric concentrations of heat-trapping gases arising from humans' activities here on the Earth. Looking back farther, the global-average temperatures have both warmed and cooled on time-scales of decades to centuries.
- *Ice ages.* Very slow (over tens of thousands of years) changes in the global average temperature accompanied by the spread and retreat of massive glaciers of ice across the high- and midlatitude regions of the globe

## WEATHER AND CLIMATE

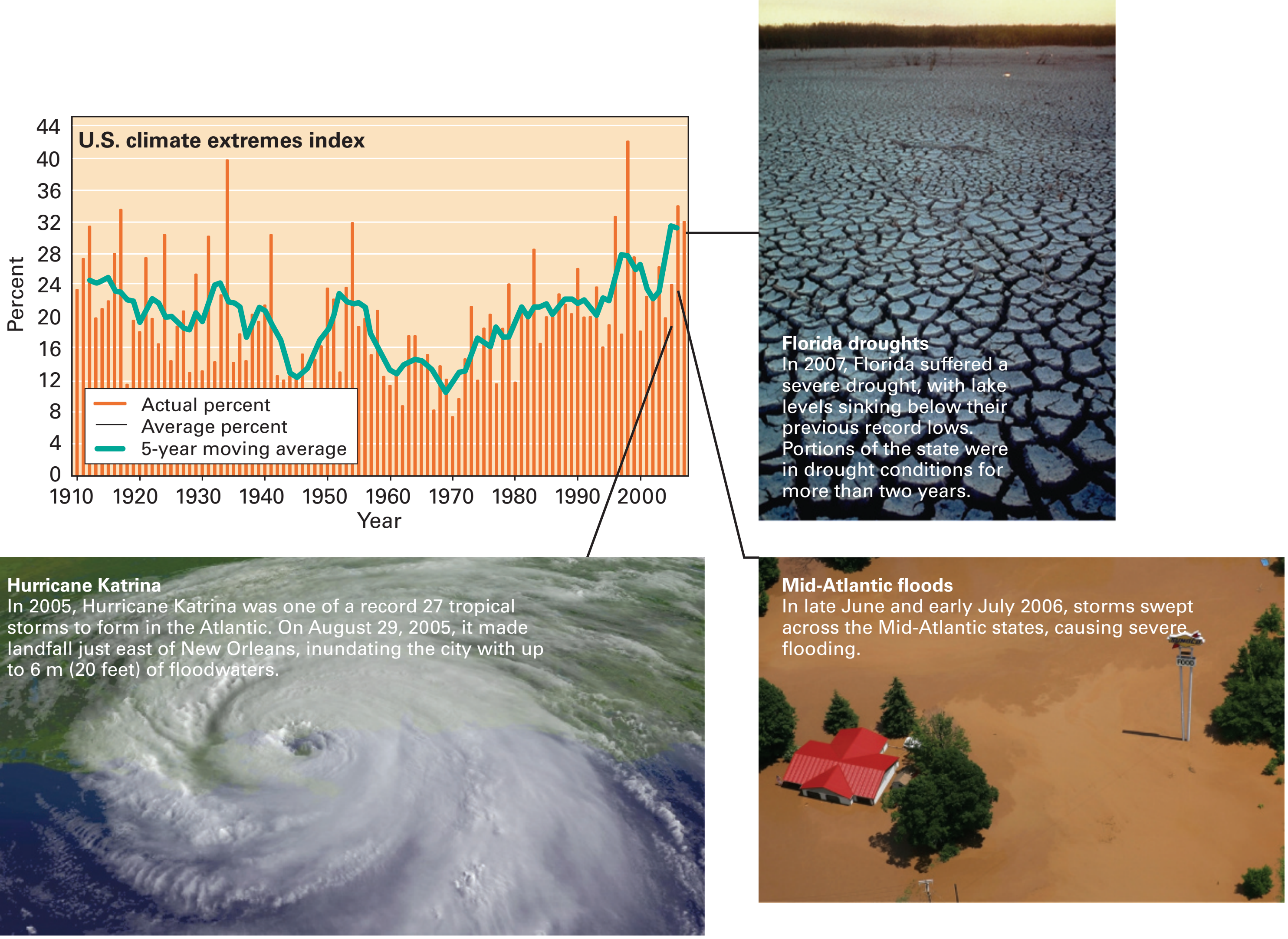
So far we have seen that weather represents the day-to-day changes in the state of the atmosphere in a given region, and climate represents the *average* state of the atmosphere in a given region over a given time period. Are there any other connections between weather and climate? In fact there are quite a few. Climate really represents the average weather found in a given region, whether it is for a particular day of the year, a particular month, or even a particular century. Thus when we talk about a change in climate for a particular region, we are really referring to a change in the weather that affects that region.

As an example, let us consider a climate change you may be familiar with—namely, the change of seasons. Specifically, let us look at the change in weather that accompanies the change in seasons in Central Park in New York City (FIGURE 1.7). The first change in weather comes with the change in temperature—it is much colder in New York City in winter than in summer. While the change in temperatures is predominantly related to a decrease in the amount of *insolation*—incoming solar radiation—New York City receives during winter compared with summer, there are also weather-related reasons for it. During winter, New York City receives wave after wave of cold, dry air coming down from the high latitudes of Canada during *cold-air outbreaks.* These cold-air outbreaks, which can last from a few days to a week, are weather events whose occurrence dramatically drops the average temperature of New York City. Similarly, during summer, New York City receives warm, moist air coming up from the Atlantic Ocean near Florida. While this air brings hot, muggy weather to New York City for just a few days at a time, the constant influence of this air raises New York City's summer temperatures.

What are some other influences of weather on the climate in this region? For starters, the same change in prevailing *air masses*—cold, dry air in winter and warm, moist air in summer—changes the type of precipitation New York City receives. In winter, the drier air coming from Canada cannot support much precipitation, but when precipitation does occur, it occurs as snowfall. In summer, with lots of moisture in the air arriving from the south, precipitation can be much more intense and usually falls as rain. As a result, winters in New York City tend to be drier than summers.

**Winter and summer in New York City** FIGURE 1.7

The types of weather that a region such as New York City experiences change with the seasons. The result is a very different climate in winter than in summer.




**Climate extremes in the United States** FIGURE 1.8

Extreme weather can change from year to year, as well as over longer time periods. This index shows changes in the number of extreme weather events—related to high and low temperatures, rainfall amounts, drought severity, and hurricane strength—affecting the United States during a given year.

Not only do changes in weather affect climate, changes in climate can also bring about changes in the weather. For instance, in winter, New York City experiences the passage of midlatitude cyclones. These weather systems tend to be much stronger in winter than in summer. In addition, they tend to be found further south, over the latitude of New York City, during winter. These large-scale storm systems, along with their accompanying fronts, can produce heavy precipitation over broad regions, coating whole states in snow. In summer, however, the predominant weather systems that influence New York City are fronts and thunderstorms. They tend to produce more localized precipitation, which can be very heavy at times but also last for shorter periods of time. Hence, the type and intensity of weather events that affect New York City change with the seasons.

Similarly, the severity of weather events in the United States has changed over the last 35 years (FIGURE 1.8). During this time, the number and severity of hurricanes that have affected the United States have generally increased. The severity of *droughts*—prolonged periods with little to no rainfall—have also increased. At the same time, when precipitation does occur, it tends to be more intense under today's climate conditions than it was 30 years ago. Finally, the number of extremely warm days—those with temperatures higher than 90% of all recorded values—has also increased.

While the number of extreme weather events affecting the United States during any one year can be very different from the number in the next year, the slow but relatively steady change in the characteristics of weather events affecting the country over the last 35 years may indicate a change in the basic climate of the region. It is also apparent that these severe weather events—ranging from increased droughts that struck the farming regions of the Midwest in 2006 and 2007 to more frequent hurricanes like the one that struck New Orleans in 2005 to the historic floods that swept the Mid-Atlantic states from North Carolina to New York in 2006—significantly affect the livelihood, and lives, of the residents.

Given these changes, we then need to understand the causes. This is particularly important if we humans have a role in producing climate change through our industrial, agricultural, and leisure activities. Many of these activities—which involve the burning of coal, gas, and other fossil fuels—release heat-trapping gases to the atmosphere that subsequently lead to a warming of the global temperatures. In addition, increases in these gases may lead to a change in the characteristics and severity of weather that we experience, both today and well into the future.

**CONCEPT CHECK** STOP

**What** is weather? List some weather systems that can affect weather.

**What** is climate? List some climate-change processes that can affect climate.

**How** are weather and climate related?

# Visualizing Weather and Climate

**LEARNING OBJECTIVES**

**Describe** how graphs are made.

**Define** map projection.

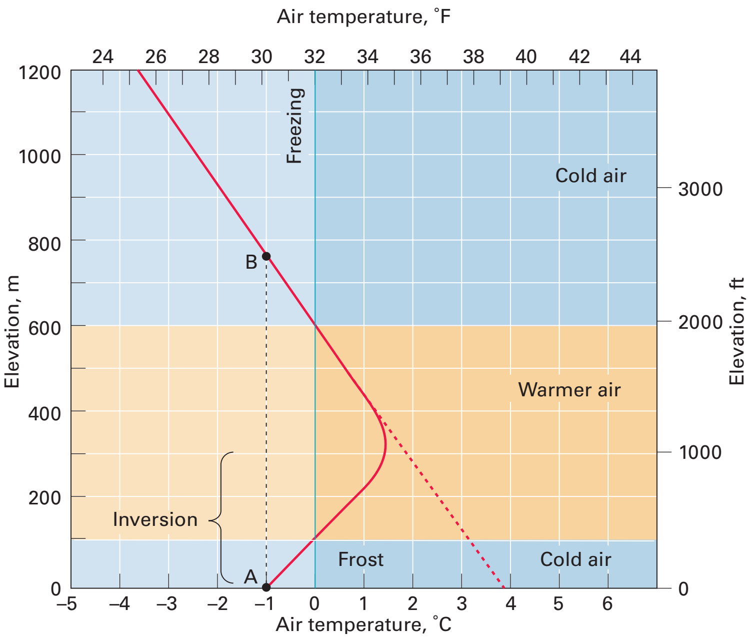
**Explain** different ways that data can be presented on maps.

Scientists use a number of visualization tools to help describe and explain the phenomena they observe. For example, a satellite photo of a midlatitude cyclone makes it easy to see the structure of the cyclone and image its rotating motion. Drawings simplify and focus a picture for easier understanding. Diagrams can display relationships or help describe processes. A very important scientific visualization tool is the *graph* (also called a *plot*), which is used to display scientific data in a way that shows relationships. In addition, *maps* are used to show how phenomena are organized in space.

## GRAPHS

You are probably already familiar with the use of graphs in everyday life. For example, your TV news program may show a daily graph of the Dow-Jones index, which measures the prices of certain industrial stocks. In this case, time is one set of data—or one *variable*—and the value of the Dow-Jones index is another set of data.

We can also plot the state of atmospheric variables with time. *What a Scientist Sees: Actual Temperatures and Temperature Departures* on page 10, shows a graph like this. In that case, there are actually two sets of data plotted with respect to time of year in June—the actual temperature and the average temperature.




## Temperature inversion FIGURE 1.9

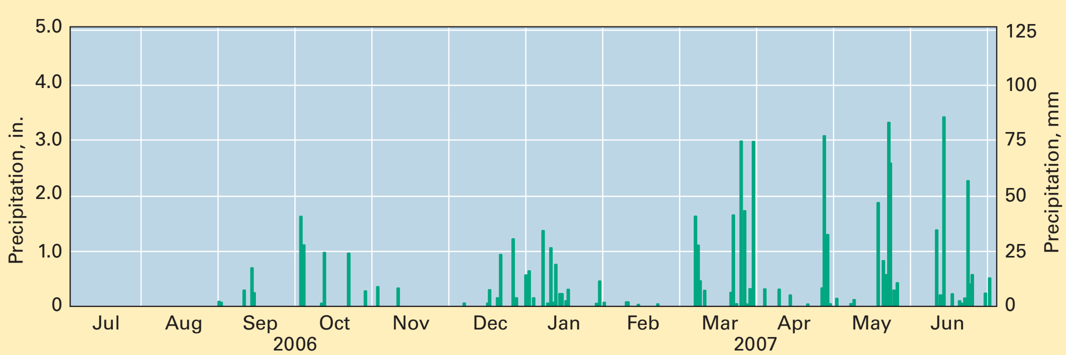
While air temperature normally decreases with altitude (dashed line), in an inversion, temperature increases with altitude. In this example, the surface temperature is at –1°C (30°F), and temperature increases with altitude (solid line) for several hundred meters (1000 ft or so) above the ground. Temperature then decreases with altitude.

However, we do not simply have to plot data with time. We can plot any two sets of data. FIGURE 1.9 shows a graph of a *temperature inversion* in which temperature increases with height above the surface. In this case, we plot temperature as it is related to height above the surface at a particular location. Temperature is given by the horizontal axis—the *x-axis*—while height above the ground is given by the vertical axis—the *y-axis*. Here we chose to plot height on the *y*-axis because we are used to thinking of height as a vertical direction. However, the information would be just the same if we switched around the axes. Plots can also come in different styles.

The plot shown here is called a *line graph,* because it presents the data as a continuous line. By presenting data in this way, we assume that the data vary smoothly as we move up through the atmosphere. Typically, atmospheric data are *discrete*—only available at select points in space or time. When we present these data as a line graph, we presume that there is a smooth transition of the data from one measurement to the next, again either in the intervening times or in the intervening locations.

If we cannot make this assumption, we typically plot the data as a bar graph. An example of a bar graph or bar plot is shown in FIGURE 1.10. This graph shows daily precipitation in Waco, Texas, during June 2007. Rainfall is typically intermittent with successive days of no rain followed by the passage of a storm, which brings rain for a few days. In this case, it is inappropriate to assume that the rainfall changes smoothly from one day to the next. Instead, we can only plot the data that we measure. Bar graphs maintain the discrete nature of these measurements.

Many times, however, whether one uses a bar graph or a line graph is more a matter of choice than it is based on any rigorous rules. Both types of plots will be used extensively throughout this text. In addition, other types of plots—pie charts and scatter plots are two examples—will also be used to present data.




## Precipitation in Waco, Texas FIGURE 1.10

This bar graph shows precipitation amounts for all days from July 2006 through June 2007. The data record the amount falling on a given day, which is often quite different from the amount falling the day before or the day after.

## MAPS

Another way to present data is through the use of maps. The problem of just how to display the Earth, and data at various locations on the Earth, has puzzled *cartographers*, or mapmakers, throughout history (**Figure 1.11**). The oldest maps were limited by a lack of knowledge of the world rather than by difficulties caused by the Earth's curvature. They tended to represent political or religious views rather than geographic reality—ancient Greek maps from the 6th century B.C. show the world as an island, with Greece at its center, while medieval maps from the 14th century placed Jerusalem at the focus.

However, by the 15th century, ocean-faring explorers such as Columbus and Magellan were extending the reaches of the known world. These voyagers took mapmakers with them to record the new lands that they discovered, and navigation charts were highly valued. Mapmakers, who now had a great deal of information about the world to set down, were forced to tackle the difficulty of representing the curved surface of the Earth on a flat page.

**map projection**
A system of parallels and meridians representing the curvature of the Earth drawn on a flat surface.

For any map to be useful, we must know how position on the map relates to position on the Earth's three-dimensional surface. To establish this relation, we divide the globe into what is known as the *geographic grid*. This grid is made up of a system of imaginary circles, called parallels and meridians. Parallels are east-west lines running parallel to the Equator and are used to designate the *latitude* of a location. We define the Equator—the longest parallel—to be at 0° latitude with the North Pole at 90° north latitude (designated 90° N) and the South Pole at 90° south latitude (designated 90° S).

Meridians are north-south lines that join the North and South Poles and are used to designate the *longitude* of a location. Longitude is measured by angular distance from the prime meridian, which passes through Greenwich, England, and marks 0° longitude. Locations to the east of Greenwich have longitudes ranging from 0°–180° east longitude (designated 0°–180° E) and locations to the west of Greenwich have longitudes ranging from 0°–180° west longitude (designated 0°–180° W). Technically, 180° E is at the same longitude as 180° W, and is halfway around the world from Greenwich, England.

However, even with this geographic grid, we still cannot project a curved surface onto a flat sheet without some distortion. One of the earliest attempts to tackle the curvature problem for global-scale maps was made by the Belgian cartographer, Gerardus Mercator, in the 16th century, and it is still used today. A number of other systems, or **map projections**, have been developed to translate the curved surface of the Earth to a flat one. We will concentrate on the two most useful types, including Mercator's. Both have their own advantages and drawbacks.

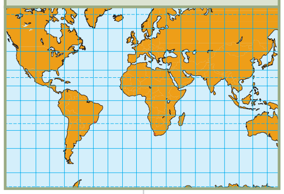
**Ptolemy's map of the world**
**Figure 1.11**

This atlas page shows a reproduction of a map of the world as it was known in ancient Greece.

## Mercator projection

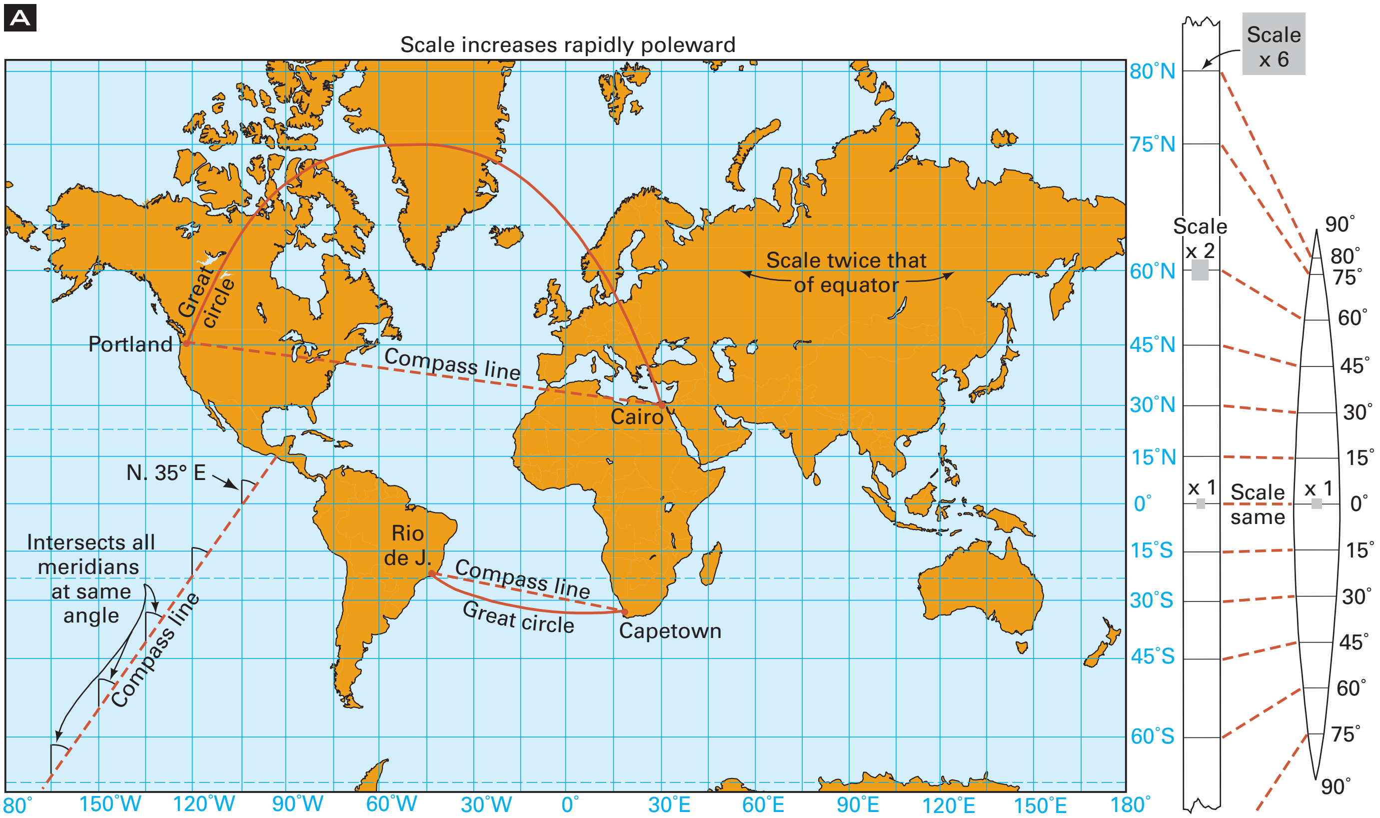
In the **Mercator projection**, the meridians form a rectangular grid of straight vertical lines, while the parallels form straight horizontal lines (FIGURE 1.12A). The meridians are evenly spaced, but the spacing between parallels increases at higher latitude so that the spacing at 60° is double that at the Equator. As the map reaches closer to the poles, the spacing increases so much that the map must be cut off at some arbitrary parallel, such as 80° N. This change of scale artificially enlarges features near the poles relative to features at low latitudes.

**Mercator projection** Map projection of horizontal parallels and vertical meridians, with the space between parallels increasing poleward.



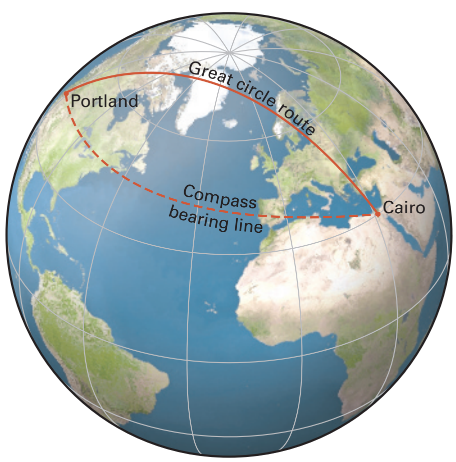
The Mercator projection has several special properties. Mercator's goal was to create a map that sailors could use to determine their course. A straight line drawn anywhere on his map gives you a line of constant compass direction. A navigator can simply draw a line between any two points on the map and measure the bearing, or direction angle of the line, with respect to a nearby meridian on the map. Because the meridian is a true north–south line, the angle will give the compass bearing to be followed. Once aimed in that compass direction, a ship or an airplane can be held to the same compass bearing to reach the final point or destination.

A




The compass line connecting two locations, such as Portland and Cairo, shows the compass bearing of a course directly connecting them. However, the shortest distance between them lies on a great circle, which is the longer, curving line on this map projection.

B

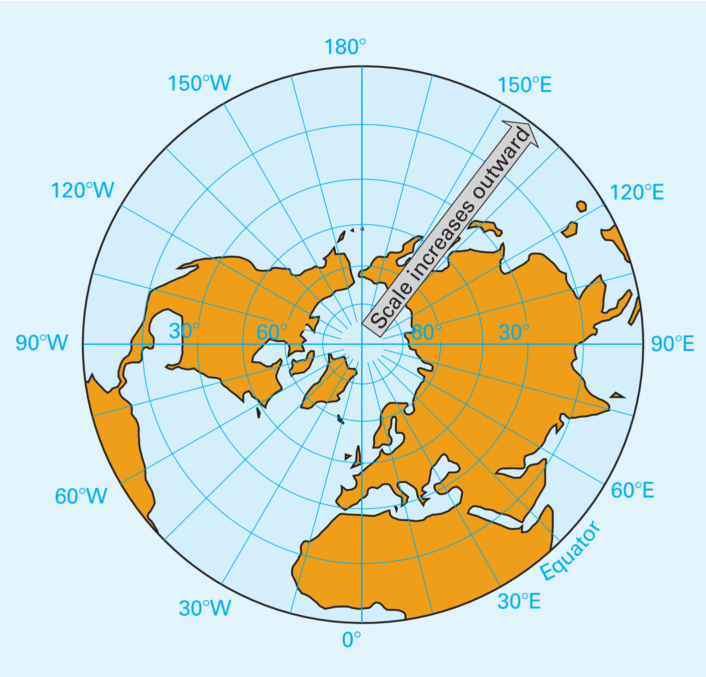



The true shortest distance between two points, drawn over the globe as the crow flies, will appear as a curved line on the Mercator projection.

**The Mercator projection**

FIGURE 1.12

Gerardus Mercator invented his navigator's map in 1569. It is a classic that has never gone out of style.




**A polar projection** FIGURE 1.13

This map centers on the North Pole. All longitude lines are straight lines radiating from the center point, and all latitude lines are concentric circles. The scale fraction increases in an outward direction, making shapes toward the edges of the map appear larger. Because the intersections of the parallels with the meridians always form true right angles, this projection shows the true shapes of all small areas.

However, this line does not necessarily follow the shortest actual distance between two points, which we can easily plot out on a globe (FIGURE 1.12B). We have to be careful—Mercator's map can make the shortest distance between two points appear much longer than the compass line joining them.

Because the Mercator projection shows the true compass direction of any straight line on the map, it is used to show many types of straight-line features. These include wind and ocean current flow lines and lines of equal values, such as lines of equal air temperature or equal air pressure. Thus, the Mercator projection is often chosen for maps of temperatures, winds, and pressures.

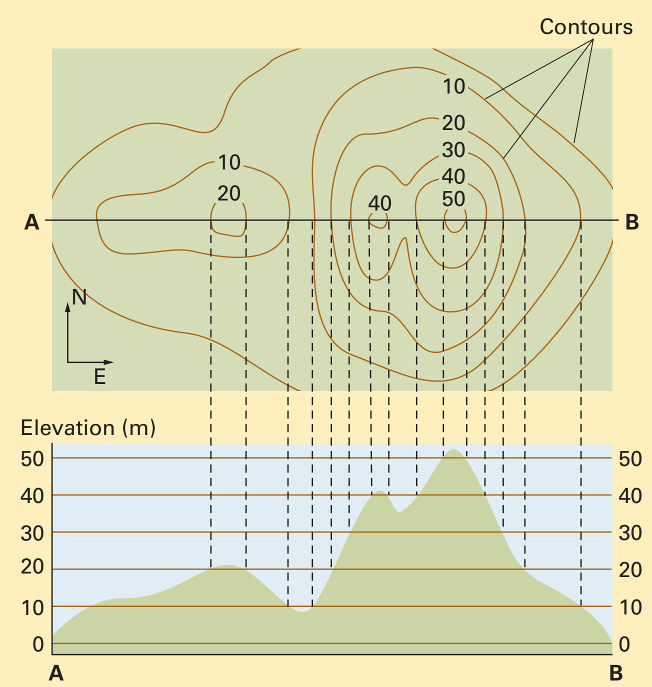
**polar projection** Map projection centered on the Earth's North or South Pole.

## Polar projection

Another map projection used throughout this text is the **polar projection**. The polar projection (FIGURE 1.13) normally centers on either the North or the South Pole, and it is essential for visualizing weather maps of the polar regions. The map is usually cut off at lower latitudes to show only one hemisphere with the Equator forming the outer edge of the map.

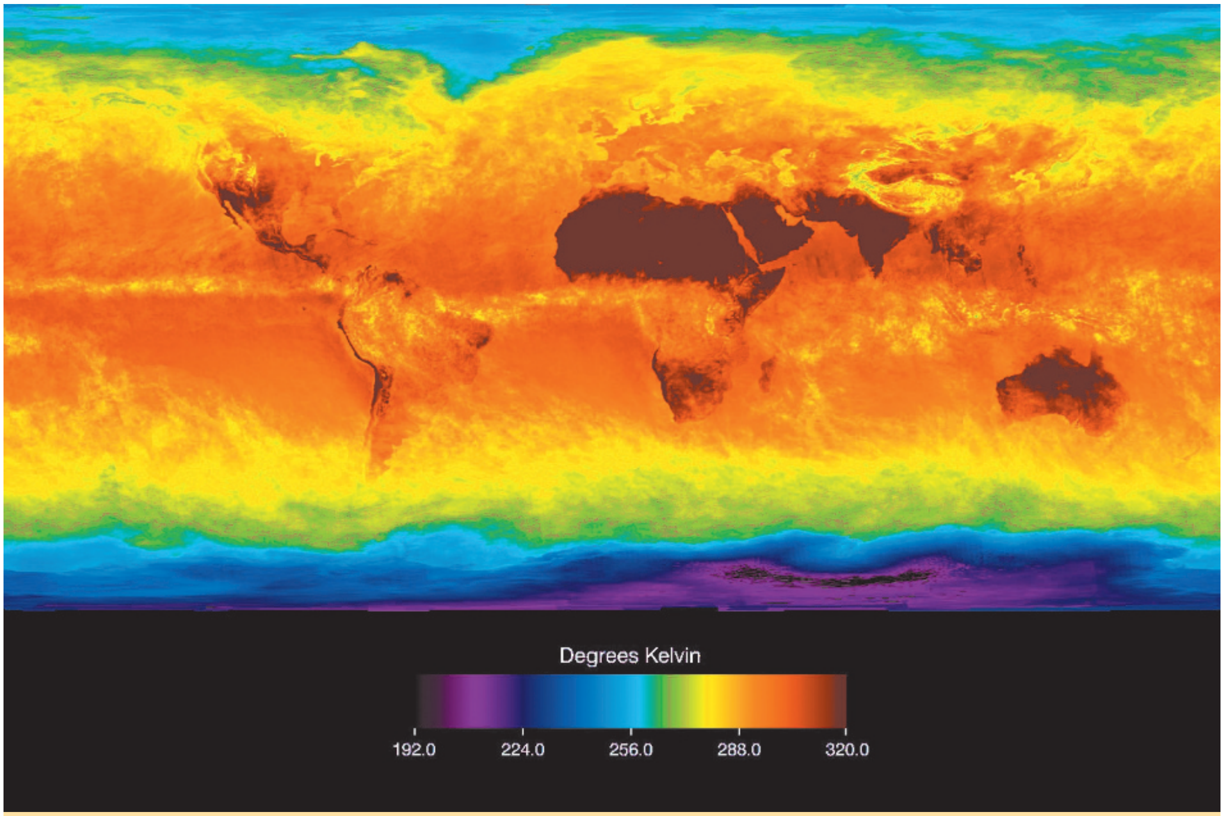
In addition to deciding upon a map projection, it is necessary to decide how to present data given this projection. Many displays of data presented in map format are based on the concept of presenting data with equal values. A simple example is a topographic map, shown in FIGURE 1.14. Maps of this sort show a set of data plotted based on the values at various geographic locations. Here, the data are the elevations of the location above sea level. Running through regions with equal elevations are **isolines**—lines that connect data points

**isolines** Lines on a map that connect locations with equal values of a given variable.




**Contour map of topography** FIGURE 1.14

This map shows lines, or contours, representing regions with constant elevation above sea level. The peak on the right-hand side is 55 m (181.5 ft) above sea level. As you move away from the peak, the number labeling each successive line decreases, indicating a decrease in elevation.




**Global surface and atmospheric temperatures** FIGURE 1.15

Because of their global view, satellites can provide data at locations all across the globe. Shown here is a satellite-based estimate of temperatures. Reds and oranges indicate warmer temperatures, while blues and purples indicate cooler temperatures, as shown by the color bar at the bottom.

with equal values. Isolines are also called *contours*, so we sometimes refer to these types of maps as *contour maps*. Isolines could also be drawn for other types of data, including atmospheric data such as temperatures, rainfall, even wind speed.

Contour maps only show values on isolines. We can also plot data values at all locations. In that case, we typically use different colors to represent the value at a given location. We can use as few as two colors, or we can use millions, in which case one color blends smoothly into another. FIGURE 1.15 shows such a map. Here, the values are based on satellite data that provide estimates of temperatures around the world. We can identify regions that have extremely high temperatures—for example, in the desert regions of Africa, the Middle East, and Australia. These are color-coded red and orange. As we move to higher latitudes, colors blend toward yellows and oranges, indicating cooler temperatures. In the very highest latitudes of the northern and southern hemispheres, temperatures are extremely cold, indicated by the blue and purple colors.

**CONCEPT CHECK** STOP

**What** different ways can data be presented using graphs?

**How** can data be presented on maps?

**How** does the Mercator map projection distort direction and distance compared with the three-dimensional globe?

# Standard Measurements in Weather and Climate

**Learning Objectives**

**Define** the units used in weather and climate.

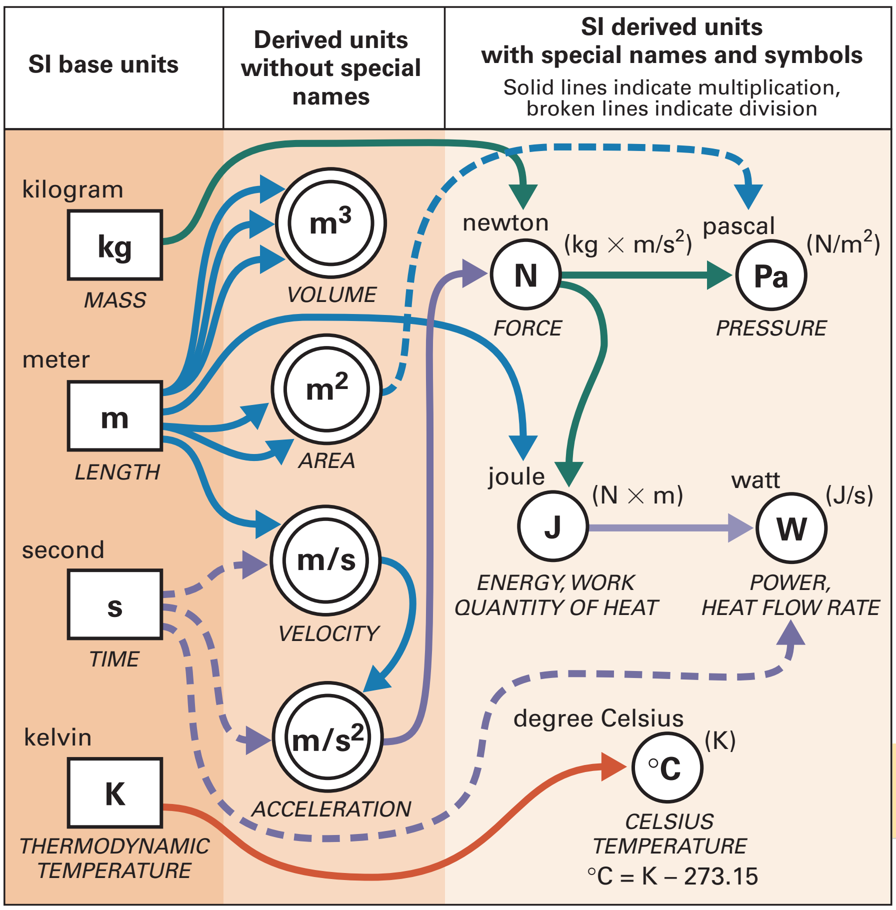
**Describe** the typical atmospheric variables that are measured.

To describe the atmosphere in which we live, we need to use a consistent set of measurement units. In studies of weather and climate, we use the metric units of the SI (Système International), which is the common scientific standard. This system uses meters, kilograms, and seconds as the three basic variables of distance, mass, and time (Figure 1.16).

For temperature, the SI system uses the basic unit of the kelvin (K) and recognizes degrees Celsius (°C) as a derived unit. Kelvin units are very similar to Celsius units in that a one-degree change in kelvins is the same as a one-degree change in Celsius degrees (which is a 9/5th degree change in Fahrenheit). However, the zero value is different for the two. Whereas in Celsius, zero degrees represents the temperature at which water freezes, zero kelvins, or *absolute zero*, represents the temperature at which all molecular motion ceases—it is the hypothetical (and unobtainable) coldest temperature any body can have. Presently, the lowest temperature ever measured is one half-billionth of a degree above zero K.

Why does the SI system use kelvin instead of degrees Celsius? It is principally because the Celsius scale allows for negative temperatures—in fact, any object with a temperature below the freezing point of water will have a negative value. Objects with these temperatures still have energy associated with molecular motions inside of them. Because technically **temperature** measures the amount of energy found in these molecular motions, having negative temperatures does not make physical sense. Instead, we measure the temperature associated with this molecular energy using kelvins. The other reason for converting from °C to K is that many of the mathematical formulas in the text require that the temperature be in K; putting in values with units °C will produce the wrong answer.

**temperature** A measure of the molecular energy within a given substance.




**Metric units and their physical significance** Figure 1.16

Process Diagram

## Using the three temperature scales FIGURE 1.17

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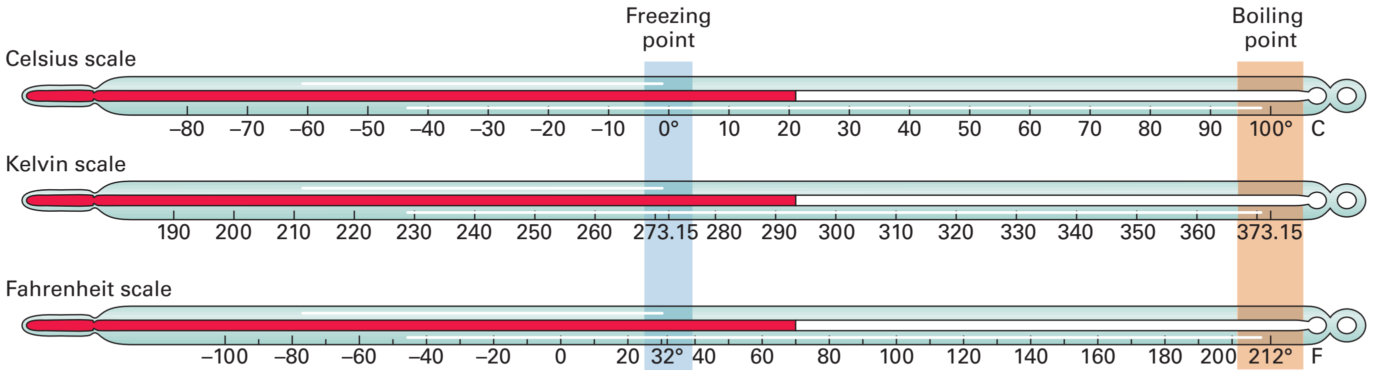



**Celsius scale** The basic unit of temperature used in this text is degrees Celsius, which is the metric unit for temperature and is abbreviated °C. The units are scaled so that 0°C is the temperature at which water freezes and 100°C is the temperature at which water boils, when at sea level. Sometimes this scale is also referred to as the centigrade scale.

**Kelvin scale** A second temperature scale is based on kelvin units, abbreviated K (there is no degree symbol "°" used with kelvin units; the name itself is in lower case while the abbreviation is in upper case). Kelvin units differ from Celsius units only by a constant factor of 273.15. Hence, the freezing point of water is 0°C = 273.15 K and the boiling point of water is 100°C = 373.15 K. A one-degree change in °C is the same as a one-degree change in K. To convert from °C to K, use the following equation: K = °C + 273.15.

**Fahrenheit scale** A third temperature scale is based upon the English units of Fahrenheit, which is abbreviated °F. Water freezes at 32°F and boils at 212°F. Notice that the difference between the freezing point and boiling point of water is greater in °F (212 – 32 = 180°F) compared with °C (100 – 0 = 100°C). Thus a change of 1°C is the same as a change of 180/100°F or 9/5°F = 1.8°F. To convert from temperatures in °C to °F, use the following equation: °F = (9/5 × °C) + 32. To convert from °F to °C, use the following equation: °C = 5/9 × (°F – 32).

The relationship between kelvin, Celsius, and Fahrenheit scales is discussed in FIGURE 1.17.

Now that we have the basic units, we can begin to define other physical quantities. The first is *velocity*, which represents the change in position over some period of time.

$$\text{velocity} = \text{change in position} / \text{time}$$

Velocity has units of meters/second. It also has the property of direction. Velocity without reference to direction is *speed*. In the atmospheric sciences, we use velocity to describe how fast and in what direction the winds are moving. We also use it to describe how fast ocean currents are moving.

Next, we can calculate the change in velocity with time and arrive at the acceleration of an object.

$$\text{acceleration} = \text{change in velocity} / \text{time}$$

Because we are dividing velocity by time, acceleration has units of meters/second$^2$.

Once we have acceleration, if we multiply by the mass that is accelerating, we arrive at the force needed to produce the acceleration:

$$\text{force} = \text{mass} \times \text{acceleration}$$

Because mass has units of kg, force has units of kg × (meters/seconds$^2$). In metric units, force has another name, *newtons* (N), in honor of the famous scientist Sir Isaac Newton.

While forces make objects, such as air molecules, accelerate and hence can change the speed and direction of the winds, in weather and climate studies we are usually more interested in the force applied over a given area, which is called *pressure*.

$$\text{pressure} = \text{force} / \text{area}$$

The units of pressure are kg / (meters × seconds$^2$). As with forces, in metric units they have another name—*pascals* (Pa). However, when pressure in the atmosphere is measured, values are usually given in *millibars*. One millibar is the same as 100 pascals, so 1 millibar is the same as 1 *hectopascal* (hPa). It is becoming more common to use hectopascals for pressure measurements because they are more closely linked with the SI system on which all other atmospheric variables, such as temperature and wind speed, are based.

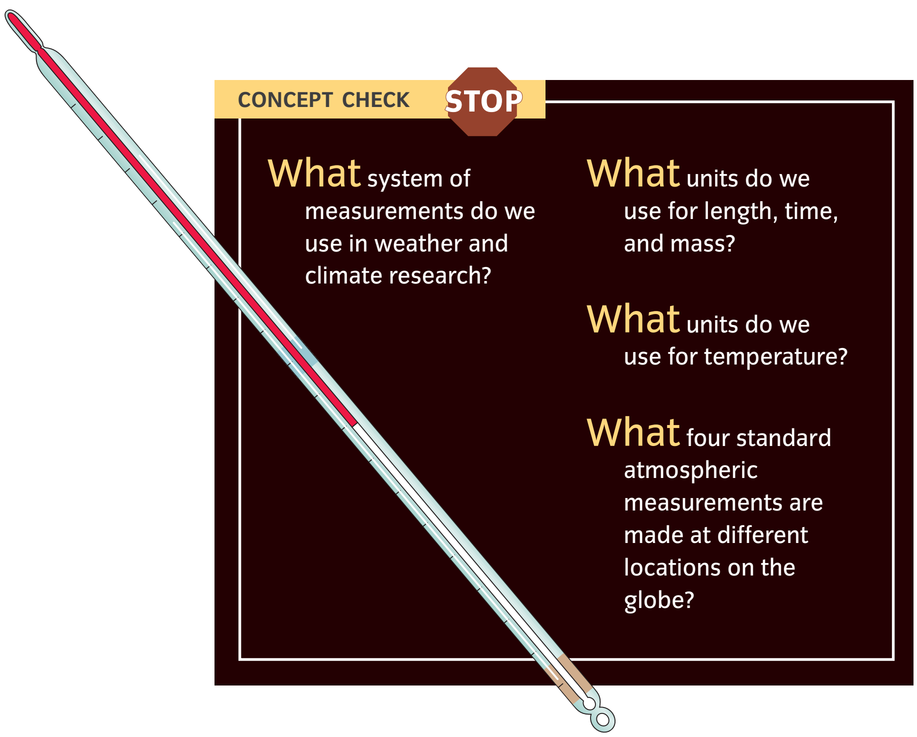
Throughout this text, we will discuss different measurements used to describe the atmosphere. Some typical ones we have discussed so far are *temperature*, *wind speed and direction*, and *pressure*. Another one that we will encounter is *specific humidity*—a measure of how much moisture is contained within a given mass of air. These make up the standard atmospheric measurements taken all over the world. We will also introduce measurements related to the amount of *energy* an object has, which is found by multiplying the force by a change in position.

$$\text{energy} = \text{force} \times \text{change in position}$$

Energy has units of N × meters, which is referred to as *joules* (J). If we then calculate how much energy is entering or leaving an object or a region over a given period of time, we find the energy flow, which is called *power*.

$$\text{power} = \text{change in energy} / \text{time}$$

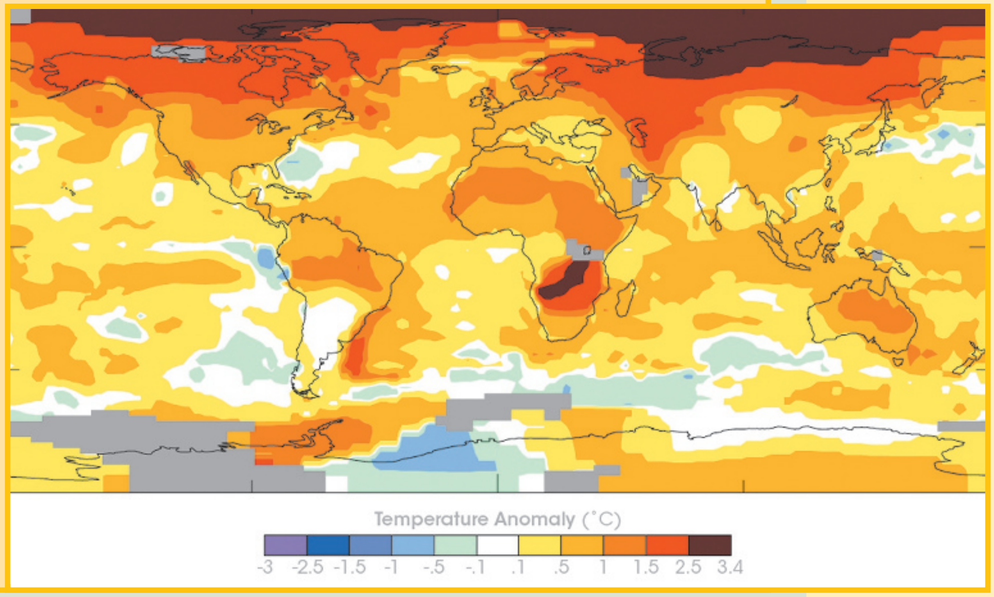
Power has units of J/s and is also given the name *watts* (W).



## What is happening in this picture ?

**Globally, 2005 was considered one of the warmest years on record in the last 150. During that year, a record 27 tropical storms formed in the Atlantic, including Hurricane Katrina, which devastated New Orleans. In addition, severe droughts occurred in Australia, the central United States, and Brazil—which had its worst drought in 60 years.**

**This map shows temperature anomalies during 2005 compared with the 1951–1980 mean temperatures.**




- **Which regions had the largest temperature anomalies?**
- **Which regions had negative temperature anomalies?**
- **Can you tell what type of map is presented here?**

# SUMMARY

## 1 Introducing Weather and Climate

1. **Weather** represents changes in the state of the **atmosphere** over the course of minutes to days. Weather systems are recurring patterns of atmospheric circulation that produce recurring changes in the weather, including changes in temperature, moisture, rainfall, or winds.
2. **Climate** describes the average state of the atmosphere in a given region. The average state can be based on measurements taken over a month, a year, even thousands of years. It represents the average of all the weather events that occurred during that time. Like weather, climate can change, again on time periods ranging from months to years to thousands of years.
3. Weather and climate are intimately related. Changes in the types of weather a given region experiences will produce changes in the climate of the region. At the same time, climate-change processes can produce changes in the type and severity of weather events that affect a given region.

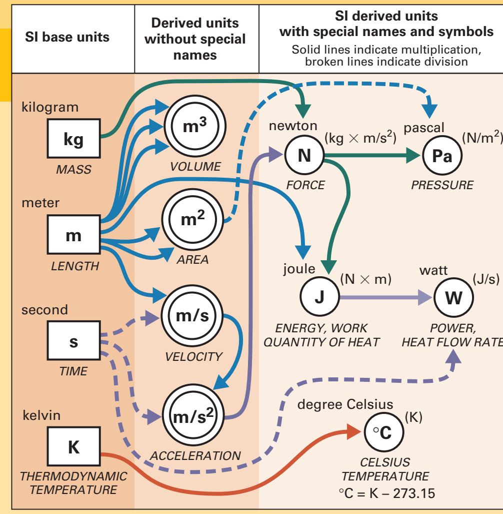
## 2 Visualizing Weather and Climate

1. Scientific visualization tools include photos, drawings, maps, and graphs.
2. Graphs show the relation between one set of data and another. Often they present how one set of data changes with time, although any two sets of data can be plotted with respect to one another. Graphs typically are presented as continuous lines, which implies that the data vary smoothly from one point to another. At other times, data are presented as discrete values, such as with bar graphs.
3. Maps are used to present data at various locations on the Earth. Difficulties arise because representations of the curved Earth surface on a flat map, called **map projections**, can distort the size or shape of mapped objects or regions. Data can be presented by showing lines connecting regions with equal values, called **isolines**. Alternatively, each location can be color-coded based on the data value at that location.

## 3 Standard Measurements in Weather and Climate

1. In studies of weather and climate, the SI system of metric units is used. The basic units are meters (length), kilograms (mass), seconds (time), and Celsius or Kelvin (temperature).

2. From these basic units, we can derive other physical quantities we will encounter throughout the text, including velocity, acceleration, force, pressure, energy, and power.




# KEY TERMS

- **atmosphere** p. 5
- **lithosphere** p. 5
- **hydrosphere** p. 6
- **biosphere** p. 6
- **weather** p. 7
- **climate** p. 7
- **map projection** p. 17
- **Mercator projection** p. 18
- **polar projection** p. 19
- **isolines** p. 19
- **temperature** p. 21

# CRITICAL AND CREATIVE THINKING QUESTIONS

1. If you were to take a photo of the Earth from space, which of the weather systems might you be able to identify? Which ones could you probably not see? 1) Midlatitude Cyclones; 2) Fronts; 3) Tropical Cyclones; 4) Thunderstorms; 5) Tornadoes

2. Discuss the concept of time cycles, and give three examples that vary from short periods to very long periods of time.

3. If you measured the temperature outside, would you expect it to be the same as the average temperature for this time of year? If you took the same measurements over many consecutive days and found the average value, would you expect it to be closer to or farther away from the average temperature for this time of year?

4. What climate-change processes might you expect to witness during your lifetime? Which ones do you think take too long for you to experience?

5. If you wanted to plot the change in temperature over the course of a day, would you use a line graph or a bar graph? What type of graph would you use if you wanted to plot the instantaneous temperature at 20 different cities?

6. If an object moves 20 m in 4 s, what is its velocity? If its velocity then increases by 20 m/s over the next 5 s, what is its acceleration? If the object has a mass of 5 kg, what force is needed to produce this acceleration?

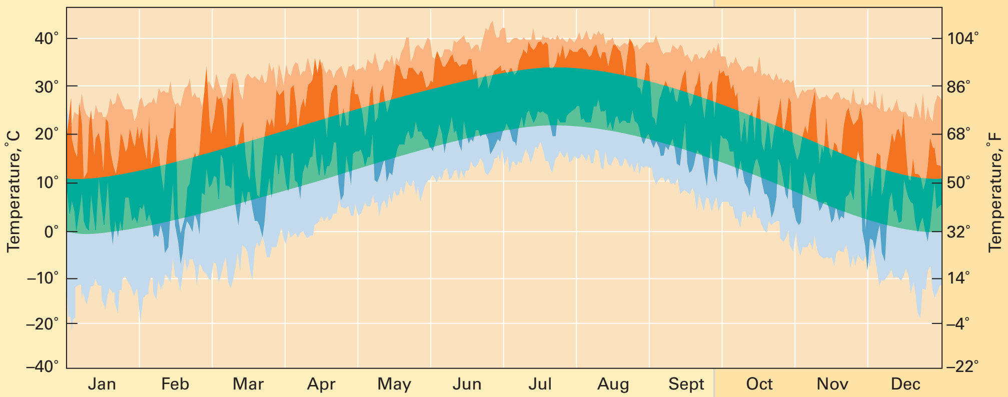
# SELF-TEST

**1.** The Earth's atmosphere is _____________.
   a. constantly changing
   b. stable and immutable
   c. changing extremely slowly
   d. changed only through human activity

**2.** The ___________ encompasses all living organisms of the Earth.
   a. biosphere  c. hydrosphere
   b. lithosphere  d. atmosphere

**3.** The annual revolution of the Earth around the Sun generates a natural rhythm or _______________ of incoming solar energy flow.
   a. time sequence  c. time cycle
   b. phase  d. repetition

**4.** On the diagram below, label the following: (1) the days of the year that had the coldest and warmest actual temperatures; (2) the days of the year that had the coldest and warmest record temperatures.



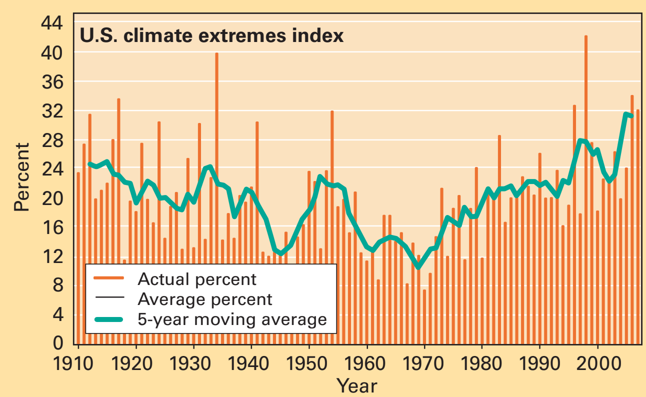

**5.** A _______________ system generates similar changes in the atmospheric state of a given region.
   a. climate-change  c. polar
   b. topographic  d. weather

**6.** Climate refers to the state of the atmosphere measured over the course of _______________.
   a. seconds  c. days
   b. hours  d. a month and longer

**7.** Which of these decisions would be based on what the weather in your location is like today?
   a. Whether to install an air conditioner
   b. Whether to plant wheat or a banana tree
   c. Whether to put on a raincoat or shorts
   d. Whether to buy flood insurance for your house

**8.** Which of these is *not* a climate-change process?
   a. Change of the seasons
   b. Onset of an ice age
   c. Formation of a tropical cyclone
   d. Formation of an El Niño

**9.** On the diagram below, label the following: (1) the 5-year period with the smallest number of extreme weather events affecting the United States; (2) the 5-year period with the largest number of extreme weather events affecting the United States; (3) the year with the smallest number of extreme weather events affecting the United States; (4) the year with the largest number of extreme weather events affecting the United States.



**10.** Which of the following would you use a bar graph to represent?

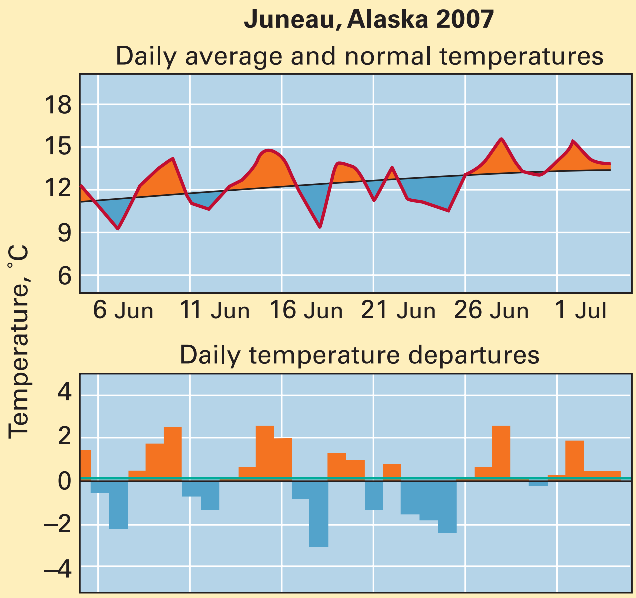
a. Change in temperature over the course of one day

b. Change in wind speed from one airport to the next

c. Change in energy received from the Sun over the course of a year

d. Change in the price of oil over a decade

**11.** On the diagram below, label the following: (1) the days of the month that had the coldest and warmest actual temperatures; (2) the days of the month that had the largest positive and negative departure from normal temperatures.




**12.** The single problem all maps have in common is ____________.

a. that they are flat

b. distortion

c. shape projection

d. that they cannot show the Atlantic and Pacific Oceans on the same map

**13.** A system for changing the geographic grid to a flat grid is a ____________.

a. map

b. curve distortion

c. map projection

d. shape/area distortion

**14.** The ____________ projection centers on the North or South Pole and displays the meridians as ____________ lines.

a. Mercator, curved

b. Goode, straight

c. conic, curved

d. polar, straight

**15.** The ____________ is the metric unit for ____________.

a. meter, temperature

b. second, distance

c. kilogram, mass

d. watt, velocity