Introduction to the Atmosphere

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CHAPTER OUTLINE

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CHAPTER OUTLINE, CONTINUED

ATMOSPHERIC PRESSURE AND DENSITY

- Basic Concepts
- Barometric Pressure and Sea-Level Pressure

DIVIDING UP THE ATMOSPHERE

- The Troposphere
- The Stratosphere
- The Mesosphere and Thermosphere

AN INTRODUCTION TO WEATHER MAPS

- Basic Concepts
- The Station Model

TIME ZONES

WEATHER WATCHES, WARNINGS, AND ADVISORIES

PUTTING IT ALL TOGETHER

- Summary
- Key Terms
- Review Questions
- Observation Activities

AFTER COMPLETING THIS CHAPTER, YOU SHOULD BE ABLE TO:

- Describe the components of the atmosphere
- List the different layers of the atmosphere in order of ascending altitude
- Explain the relationship between atmospheric pressure and altitude
- Read a weather map
- Distinguish between weather watches and warnings

INTRODUCTION

It's a hot, muggy summer night at the baseball stadium. The Atlanta Braves are on their way to another winning baseball season, and they are taking a night "off" to play an exhibition game against a minor league all-star team. The standing-room-only crowd, the largest in years, applauds as future Hall of Fame players take the field.

Midway through the game, however, the **weather** turns violent. High winds suddenly blow chairs off the stadium roof. Then the sky explodes with light and sound as lightning strikes an electric transformer on a pole out beyond center field. A fireball dances along the power lines, and the stadium lights go dark.

Frightened, the baseball players run off the field into the dugouts, and panicked fans shriek as the thunder crashes. One little boy dives under his stadium seat in terror, only to peek out and observe ominous purple and green **clouds** racing overhead. Reports of a funnel cloud—a tornado in the thunderstorm clouds above the stadium—spread among the crowd. Flooding rains descend, and sopping-wet spectators splash through puddles and duck lightning bolts as they flee to their cars.

Conversations on the way home focus on the rain, the wind, the lightning, and the possible tornado, not on the game everyone eagerly anticipated just a couple of hours before. The American pastime of baseball has been upstaged by the universal spectacle of the weather.

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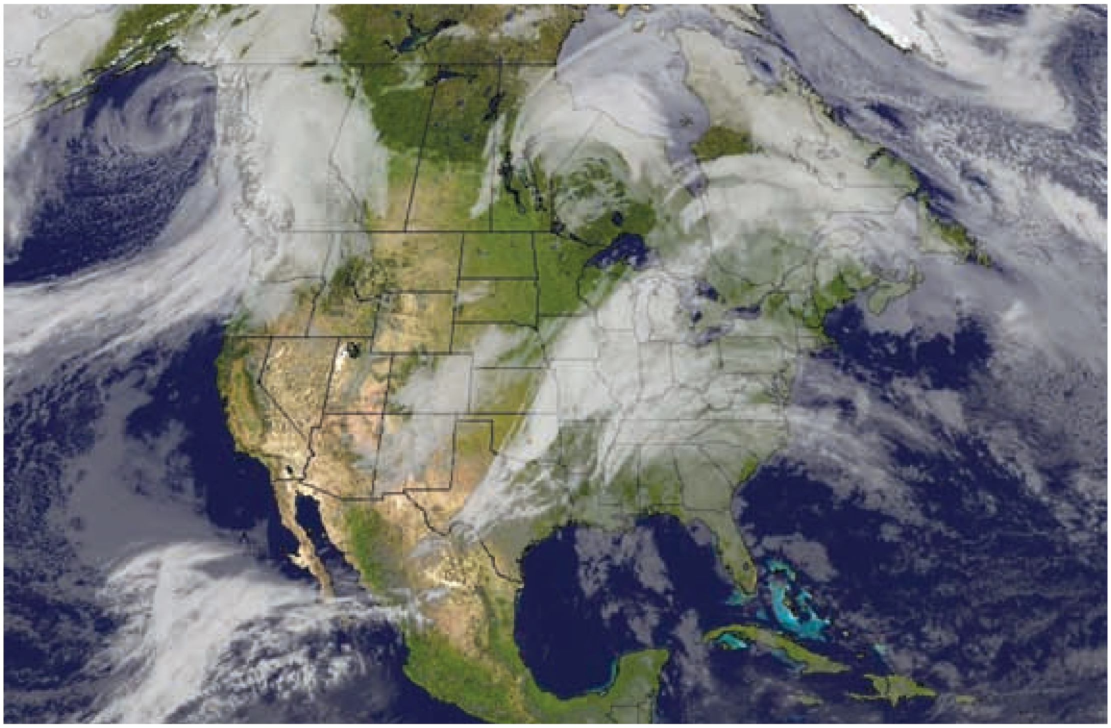

FIGURE 1-1 This weather satellite image, taken on November 29, 2006, presents a view of North America as you would see it if you were above Earth looking down. A storm is developing over the central United States, and a large weather system is moving into the Pacific Northwest.

As this true story illustrates, weather affects every facet of our lives, even when we least expect it. We all experience weather through our senses: the flash of lightning, the crack of thunder, the stickiness of a summer night, and the peculiar smell of rain. In some cases, an event is so memorable that we experience long-ago weather in stories told at family gatherings. In this book, we will pay close attention to how you sense the atmosphere, using sight, sound, touch, and even stories. We hope that years from now you'll remember how observations of the atmosphere help to explain the weather around you.

Meteorology, the study of weather and climate, is a science—a young and exciting science. Meteorologists sense the **atmosphere** like everyone else. As we'll see, young scientists using only their eyes and brains have made some of the greatest discoveries in meteorology. Today, meteorologists also use a variety of specialized techniques and tools, including weather satellites, to supplement their senses (**FIGURE 1-1**). In this book, you will learn about the atmosphere in the context of how it is sensed by meteorologists. Our goal is to help you understand the science behind weather forecasts for tomorrow and predictions of global warming in future years.

We begin our exploration of meteorology in this chapter with the basics: what the atmosphere is made of and how our observations of it are turned into weather maps.

WEATHER AND CLIMATE

Weather is the condition of the atmosphere at a particular location and moment. Each day current weather conditions are given in local weather reports. These reports usually include current temperature, relative humidity, dew point, pressure, wind speed and direction, cloud cover, and precipitation. Such weather information is important to us because it influences our everyday activities and plans. Before going out for the day, we want to know how cold or hot it will be and whether it will rain or snow. Meteorology is the study of these weather variables, the processes that cause weather, and the interaction of the atmosphere with the Earth's surface, ocean, and life.

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The fundamental cause of weather is the effect of the Sun on the Earth. At any time, only half of the Earth is warmed by the Sun, while the Earth's other side is shadowed. This causes uneven heating of the Earth's surface by the Sun every day, with some regions warmer than others. For reasons we explore in later chapters, temperature differences cause weather: winds, clouds, and precipitation. Seasonal weather patterns result from variations in temperature caused by the Earth's tilt toward the Sun in summer and away from the Sun in winter. The distribution of water and land and the topography of the land contribute to the shaping of Earth's weather patterns on smaller scales. In Chapter 2, we explore in more detail the uneven heating of the Earth by the Sun and its effects on weather and climate.

The **climate** of a region, in contrast to the weather, is the condition of the atmosphere over many years. On average, Florida will have a mild climate all year long. Minnesota, however, will have a climate with warm, even hot, summers and very cold winters. The climate of a region is described by long-term averages of atmospheric conditions such as temperature, moisture, winds, pressure, clouds, visibility, and precipitation type and amount. The description of a region's climate must include extremes as well as averages—for example, record high and low temperatures. We learn more about this in Chapter 3.

Climatology is the study of climate. Climatologists examine the long-term averages and extremes of the atmosphere. Increasingly, climatologists also investigate the changes of climate in the past and possible climate changes in the future. The study of climate also includes these kinds of variations and the frequency of the variations.

A close relationship exists between meteorology and climatology. Both fields study the atmosphere. However, climatology has been more concerned than meteorology with how oceans, landforms, and living organisms affect the atmosphere. The atmosphere, the thin ocean of air that we live in, is the main focus of meteorology. In this chapter, we examine the basics of the atmosphere that are essential for both meteorology and climatology.

THE EARTH'S MAJOR SURFACE FEATURES

Our atmosphere receives energy from the Sun. Much of the energy transfer occurs at the bottom of the atmosphere, where the surface of the Earth exchanges energy and water with the atmosphere. The distribution of land and water therefore plays a major role in determining climatic conditions and weather patterns. Approximately 70% of Earth's surface is water. The four major water bodies are, from largest to smallest in surface area, the Pacific, Atlantic, Indian, and Arctic Oceans.

Asia, Africa, North America, South America, Antarctica, Europe, and Australia are the seven continents in order from largest to smallest in surface area. More than two-thirds of these landmasses are located in the Northern Hemisphere (**FIGURE 1-2**). Differences in current climate and weather patterns between the northern and southern hemispheres can often be attributed to differences in the amount of land in each.

Surrounding Earth's surface is the atmosphere—a thin envelope of gases no taller than the distance of an hour's drive on the highway. The atmosphere protects us from the Sun's high-energy radiation and provides the air we breathe and the water we drink.

MAKING AN ATMOSPHERE: GASES AND GRAVITY

In our everyday lives we encounter matter in three forms: solid, liquid, and gas. For example, we are all familiar with water as solid ice, liquid water, or a vapor. The atmosphere is made primarily of a mixture of gases that includes liquid and solid particles suspended in air, such as water droplets, ice crystals, and dust particles.

The **molecules** of gases and liquids are in constant motion. They naturally spread or **diffuse** from areas of high to low concentration. If someone peels an orange, its aroma will soon permeate the room. The aromatic molecules diffuse from an area of high concentration, right around

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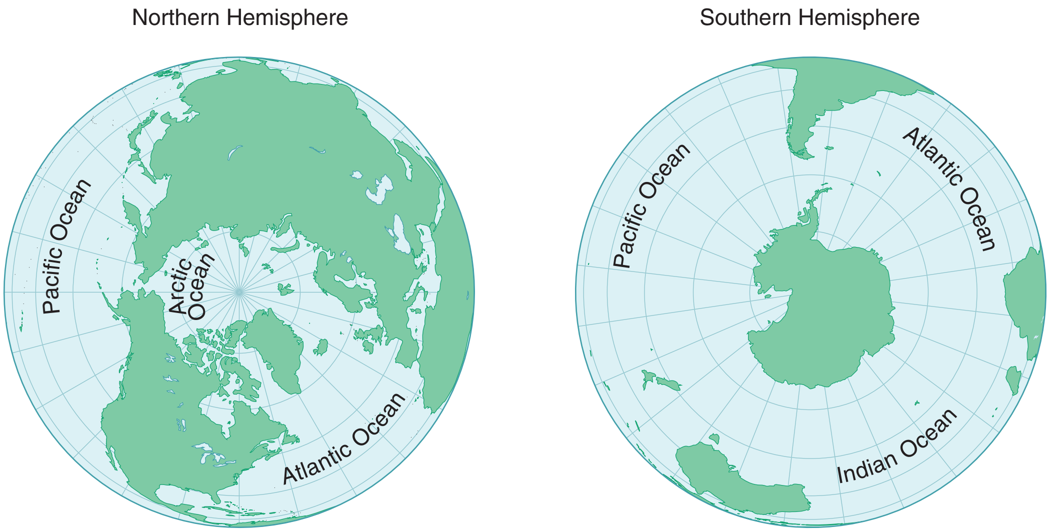

FIGURE 1-2 The global distribution of land and water strongly influences weather and climate patterns.

the orange, to areas where there are few, if any, "orange aroma" molecules. If our atmosphere is an area of concentrated molecules, then why don't they eventually diffuse into empty outer space?

Gravity, the mutual attraction between objects, is the force that holds the atmosphere in place. Gravity keeps the Moon orbiting the Earth, the planets orbiting the Sun, and you from floating into space. The Earth's gravity exerts a pull on gas molecules in the atmosphere and keeps them from diffusing out to space.

Gravitational attraction between objects depends on the masses of the objects. If an object has a large mass, it will have a strong gravitational attraction and can attract objects that do not have much mass. For example, the Sun is large and is composed mostly of light gases such as hydrogen and helium. The Earth is much smaller than the Sun, and its atmosphere contains little hydrogen and helium. The Moon is much smaller than the Earth and does not even have an atmosphere! Gravitational attraction also depends on the distance between the objects and weakens rapidly with distance. An object twice as far from Earth as another feels only one-fourth as much "pull" as a result of gravity.

By itself, gravity would turn the atmosphere into a layer cake with the heaviest molecules near the Earth's surface and the lightest molecules at the top of the atmosphere. However, weather processes "stir" the atmosphere, helping to keep it well-mixed almost to its outer edge. This is how heavier-than-air molecules, such as **chlorofluorocarbons** (**CFC**s), are able to reach the stratosphere.

ATMOSPHERIC EVOLUTION AND COMPOSITION

Gravitational attraction plays an important role in the evolution of the concentration of gases in our atmosphere. Since their formation approximately 4.5 billion years ago, the Earth and its atmosphere have undergone extraordinary changes. In the beginning, the Earth's atmosphere was hot and consisted mostly of hydrogen (H), helium (He), methane (CH_4), and ammonia (NH_3).

The **permanent gases** composing today's atmosphere are mostly **nitrogen** (**N_2**, 78%), **oxygen** (**O_2**, 21%) and **argon** (**Ar**, 1%), with much smaller "trace" amounts of some of the gases found in the early Earth's atmosphere.

Some gases in the atmosphere, however, experience changes in their concentrations in space and time. These **variable gases** include **water vapor** (**H_2O**, 0% to 4%) and the **trace gases**, which include **carbon dioxide** (**CO_2**), **methane** (**CH_4**), **nitrous oxide** (**N_2O**), **ozone** (**O_3**), and CFCs. **TABLE 1-1** lists the major permanent and variable gases composing our current atmosphere. In particular, the amount of water vapor in the atmosphere varies from day to day

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TABLE 1-1 Composition of the Atmosphere

	Symbol	Percentage by Volume (%)
Major Permanent Gas		
Nitrogen	N_2	78.08
Oxygen	O_2	20.95
Argon	Ar	0.93
Variable Gas		
Water vapor	H_2O	0 to 4
Carbon dioxide	CO_2	0.039
Methane	CH_4	0.00018
Nitrous oxide	N_2O	0.00003
Ozone	O_3	0 to 7×10^{-6}
CFCs	CFCs	2×10^{-9} to 5×10^{-8}

and place to place. This variability and the movement of water in all three phases underlie many aspects of weather, including changes in the weight of air (**BOX 1-1**).

The gases in today's atmosphere are largely a result of emissions by volcanoes over billions of years. A volcanic eruption throws ash and rock and large amounts of gases into the atmosphere. The major gases in a volcanic plume are water vapor, carbon dioxide, and nitrogen. What happened to these gases after their release into the atmosphere over billions of years?

After its formation, the Earth began to cool. During the cooling process, the water vapor from volcanic eruptions condensed and formed clouds. Precipitation from the clouds eventually formed the oceans, glaciers, lakes, and rivers. The development of the oceans affected atmospheric concentrations of carbon dioxide. Some carbon dioxide from the atmosphere dissolved and accumulated in the oceans as they formed.

Box 1-1 Moist Air Is Lighter Than Dry Air

For now we define moist air as a volume of air with many water vapor molecules and dry air as a volume of air that contains only a few water vapor molecules. To understand why moist air is lighter than dry air at the same temperature, we have to define a few concepts.

- A molecule of water has the properties of water and is composed of two hydrogen atoms and one oxygen atom.
- The weight of an individual atom is represented by its atomic weight. The (rounded) atomic weight of hydrogen (H) is 1, oxygen (O) is 16, nitrogen (N) is 14, and carbon (C) is 12. The weight of a molecule is determined by summing the atomic weights of its atoms. A water molecule (H_2O) has a molecular weight of 18 (1 + 1 + 16). Free nitrogen (N_2) has a molecular weight of 28 (14 + 14), and an oxygen molecule (O_2) has an atomic weight of 32. Therefore, a water molecule is lighter than either a nitrogen or oxygen molecule.
- A fixed volume of a gas at constant pressure and temperature has the same number of molecules. It does not matter what the gas is—the same number of molecules will exist in that volume. This is known as Avogadro's Law.

To make a given volume of air moister, we need to add water vapor molecules to the volume. To add water molecules to the volume, we must remove other molecules to conserve the total number of molecules in the volume (Avogadro's Law). Dry air consists mostly of nitrogen and oxygen molecules, which weigh more than water molecules. And so this means that when a given volume of air is made moister, heavier molecules are replaced with lighter molecules. Therefore, moist air is lighter than dry air (if both are at the same temperature and pressure). As we shall see later, severe thunderstorms can form when heavier dry air overlies lighter moist air, a condition that can lead to an unstable atmosphere.

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What happened to the nitrogen outgassed by volcanoes? Nitrogen is a chemically stable gas, which means that it does not interact with other gases or the Earth's surface. After nitrogen enters the atmosphere, it tends to stay there. This accounts for the high concentration in today's atmosphere; nitrogen has been accumulating over billions of years.

Volcanoes emit very little oxygen. Then how did oxygen come to comprise such a large amount of today's atmosphere? Approximately 3 billion years ago, tiny one-celled green-blue algae evolved in the ocean. Water protected the one-celled organisms from the Sun's lethal ultraviolet light. The algae produced oxygen as a by-product of photosynthesis, the process plants use to convert solar energy, water, and carbon dioxide into food. Today's oxygen levels are the result of billions of years of accumulation.

As the oxygen from plants slowly accumulated in the atmosphere, ozone began to form. Ozone is both caused by and provides protection from damaging ultraviolet energy emitted by the Sun. The development of an atmospheric "ozone layer" allowed life to move out of the oceans and onto land. We cover ozone in more detail in Chapter 2.

VARIABLE GASES AND AEROSOLS

Despite their small concentrations, variable gases are vitally important to meteorology and climatology. The three major variable gases in the atmosphere are carbon dioxide, water vapor, and ozone. These gases play important roles in the energy cycles of the atmosphere. Methane and CFCs, as well as other variable gases, also matter despite their very small concentrations. These gases are important because they interact with other gases and modify the energy balance of the atmosphere (discussed in the next chapter). In addition to gases, small particles suspended in the atmosphere are also important in determining the quality of the air we breathe and the transfer of energy in the atmosphere. For climatic predictions, it is important to know how and why the concentrations of these gases and particles change over time.

To know how the concentration of a gas changes, we have to know how it enters and departs the atmosphere. A **source** is a mechanism that supplies a gas to the atmosphere, and a **sink** removes a gas from the atmosphere. The routes by which a gas enters and leaves the atmosphere are known collectively as a cycle. In this section, we first consider the carbon dioxide and hydrologic (water) cycles before moving on to discuss methane, CFCs, and aerosols. (The formation and destruction of ozone are discussed in the next chapter.)

Carbon Dioxide Cycle

The atmospheric carbon dioxide cycle (**FIGURE 1-3**) describes how carbon dioxide moves between the atmosphere, the ocean, and the land. Nearly half of the carbon dioxide that enters the atmosphere moves between the ocean and plants. Here we review how carbon dioxide enters and leaves the atmosphere.

As mentioned earlier, volcanoes inject carbon dioxide into the atmosphere and are therefore an atmospheric source of carbon dioxide. Plants, through the process of photosynthesis, use sunlight, water, and carbon dioxide to manufacture food. Plants remove carbon dioxide from the atmosphere during photosynthesis, where it becomes incorporated into their tissues in the form of other chemicals such as sugars. Photosynthesis is a process that allows plants to become a temporary sink of atmospheric carbon dioxide. When the plants die and decay, they release the stored carbon dioxide into the atmosphere. Dead plant tissue and other dead organisms are therefore a source of atmospheric carbon dioxide. Plant decomposition and geological forces over millions of years have generated coal and oil fields underground. The burning of these fuels returns carbon dioxide into the atmosphere. Through respiration, animals inhale atmospheric oxygen and exhale carbon dioxide and are, therefore, another source of atmospheric carbon dioxide.

The atmospheric concentration of carbon dioxide is monitored throughout the world. The concentrations that have been carefully measured at Mauna Loa, Hawaii, since 1958, are shown in **FIGURE 1-4**. The steady increase in carbon dioxide concentration is attributed to the

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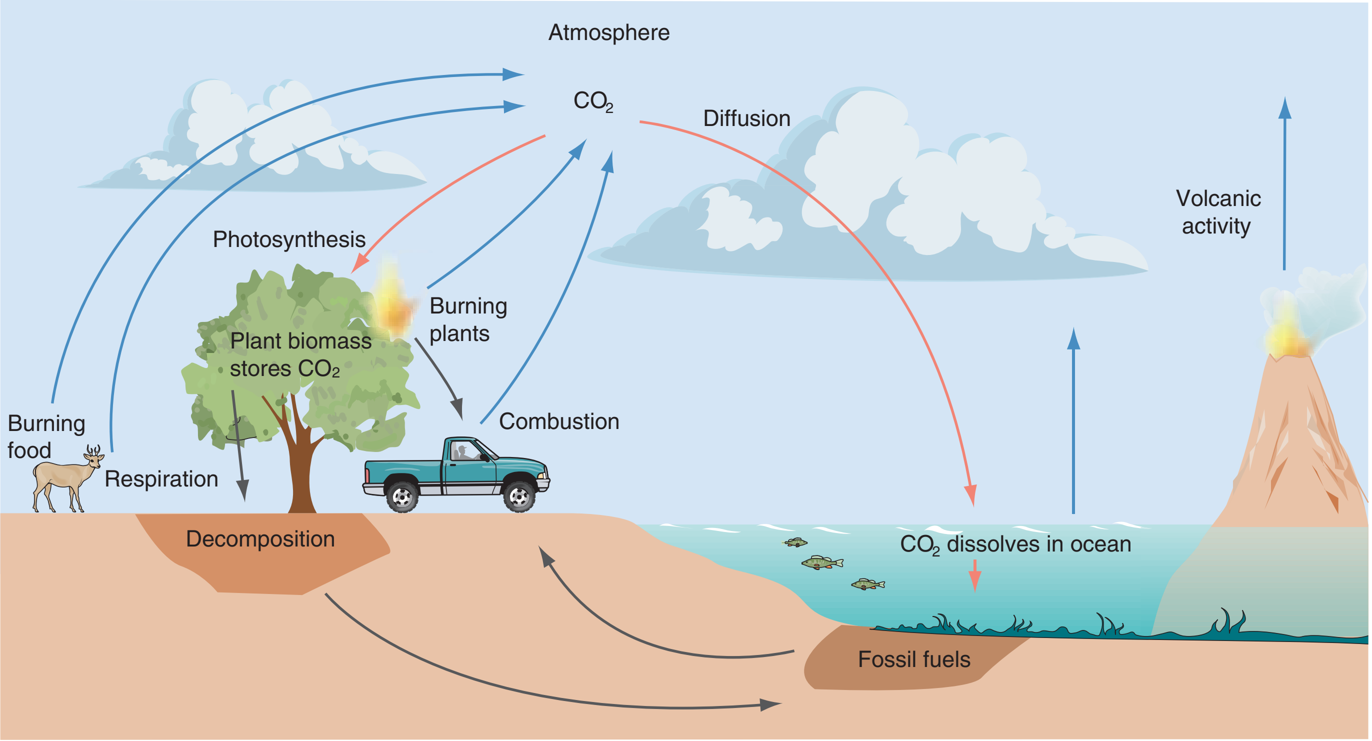

FIGURE 1-3 The carbon dioxide cycle. The blue lines represent processes by which carbon dioxide enters the atmosphere. Red lines represent the primary processes by which carbon dioxide is removed from the atmosphere. Black arrows represent processes that store carbon in the Earth.

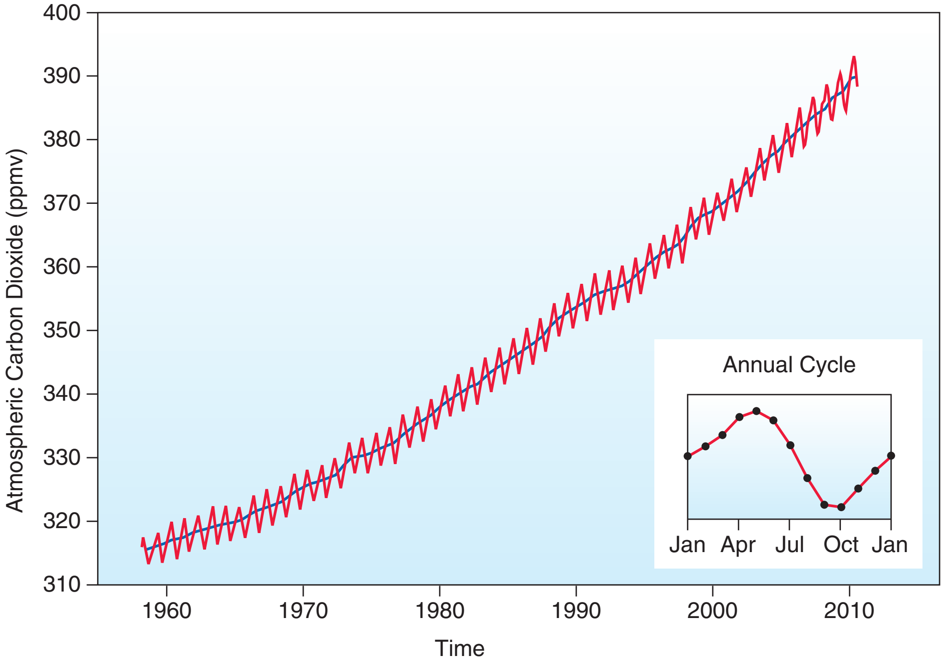

FIGURE 1-4 Carbon dioxide measurements made monthly since 1958 at Mauna Loa, Hawaii. Currently, human activity is causing a significant year-to-year change in the amount of carbon dioxide in the atmosphere. This accounts for the rise of the curve from left to right. The shorter term seasonal oscillations in the curve are caused mostly by the worldwide effect of plants on the carbon dioxide cycle. The blue curve is the annual mean atmospheric concentration of carbon dioxide in parts per million by volume (ppmv).

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burning of fossil fuels and, to a lesser extent, deforestation. Imposed on this increasing trend is a repetitive cycle of peaks and valleys.

Because most of the land surface of the world is in the Northern Hemisphere (Figure 1-2), the life cycle of plants in the Northern Hemisphere drives this seasonal cycle of peaks and valleys of carbon dioxide. During winter, dormant plants stop removing carbon dioxide from the atmosphere. However, at the same time decaying plants continue to release the carbon dioxide stored in their tissues into the atmosphere. Because the source is greater than the sink, atmospheric concentrations of carbon dioxide increase throughout the winter until late spring. In summer, decomposition also occurs, but photosynthesis is at a maximum, and carbon dioxide is removed from the atmosphere in large quantities. The sink is now larger than the source. This causes a decrease in carbon dioxide concentrations throughout the summer, leading to minimum yearly values in early autumn.

The amount of carbon dioxide in the atmosphere is an important factor that influences atmospheric temperature. Warm periods in the Earth's long-term history are associated with high levels of atmospheric carbon dioxide. As we discuss in the next chapter and Chapter 15, the increase of atmospheric carbon dioxide caused by burning of fossil fuels plays a vital role in the planet's warming. When discussing predictions of global climate warming, you should keep in mind that large quantities of carbon dioxide are dissolved or stored in the oceans. The ocean contains 50 times more carbon dioxide than the atmosphere. Marine organisms use some of the carbon dioxide in the oceans to build shells. When they die, their shells accumulate on the bottom of the ocean and form carbonate rocks, removing carbon from the cycle. Scientists do not completely understand how much carbon dioxide the oceans will be able to absorb as the amount of carbon dioxide in the atmosphere changes.

Hydrologic Cycle

In the atmospheric sciences, water is very important because it couples, or connects, the atmosphere with the surface of the Earth. Water is also the only substance that exists naturally in the atmosphere in all three phases: gas, solid, and liquid. Changing from one phase of water to another, such as from liquid to gas, is an important means of transferring energy in the atmosphere.

The **hydrologic cycle** (FIGURE 1-5) describes the circulation of water from the ocean and other watery surfaces to the atmosphere and the land. A major source of atmospheric water vapor (i.e., water in the gas phase) is evaporation from the oceans. **Evaporation** is the change of phase of liquid water to water vapor. Evaporation from lakes and glaciers supplies a relatively small amount of water to the atmosphere. **Transpiration**, the process by which plants release water vapor into the atmosphere, is also a source of atmospheric water vapor. The surface of the Earth is the major source of atmospheric water vapor, so the amount of water vapor in the atmosphere is generally largest near the surface and rapidly decreases with distance from the surface.

Often atmospheric water vapor changes phase to form solid and liquid particles. The change of phase from water vapor to liquid is called **condensation**. You see condensation occurring whenever a cold drink glass becomes wet on a hot humid day. Similarly, clouds form in the atmosphere via condensation. Usually more than 50% of the globe is covered with clouds. The occurrence of clouds is more frequent in some areas of the world and less frequent in others. FIGURE 1-6 depicts the cloud cover on a single day, as measured from several different weather satellites. Global patterns in cloud cover are evident. A lack of clouds is observed at about 30° north and south latitude, particularly over the deserts of Africa. A band of clouds is observed in the vicinity of the equator. The reasons for the global cloud patterns shown in Figure 1-6 are discussed in Chapter 7.

Precipitation, such as rain, snow, sleet, freezing rain, and hail, falls from clouds. Precipitation is a sink of atmospheric water because it removes water from the atmosphere. Precipitation returns water to the Earth's surface after it has evaporated and completes the hydrologic cycle. Precipitation on land may collect in lakes, run in rivers directly back to the sea, or percolate into the soil.

Precipitation may fall on glaciers, which then store the water. The occurrence and extent of glaciers are functions of the temperature of the atmosphere and the amount of precipitation. The presence of glaciers will also affect the atmospheric temperature. They reflect most solar energy

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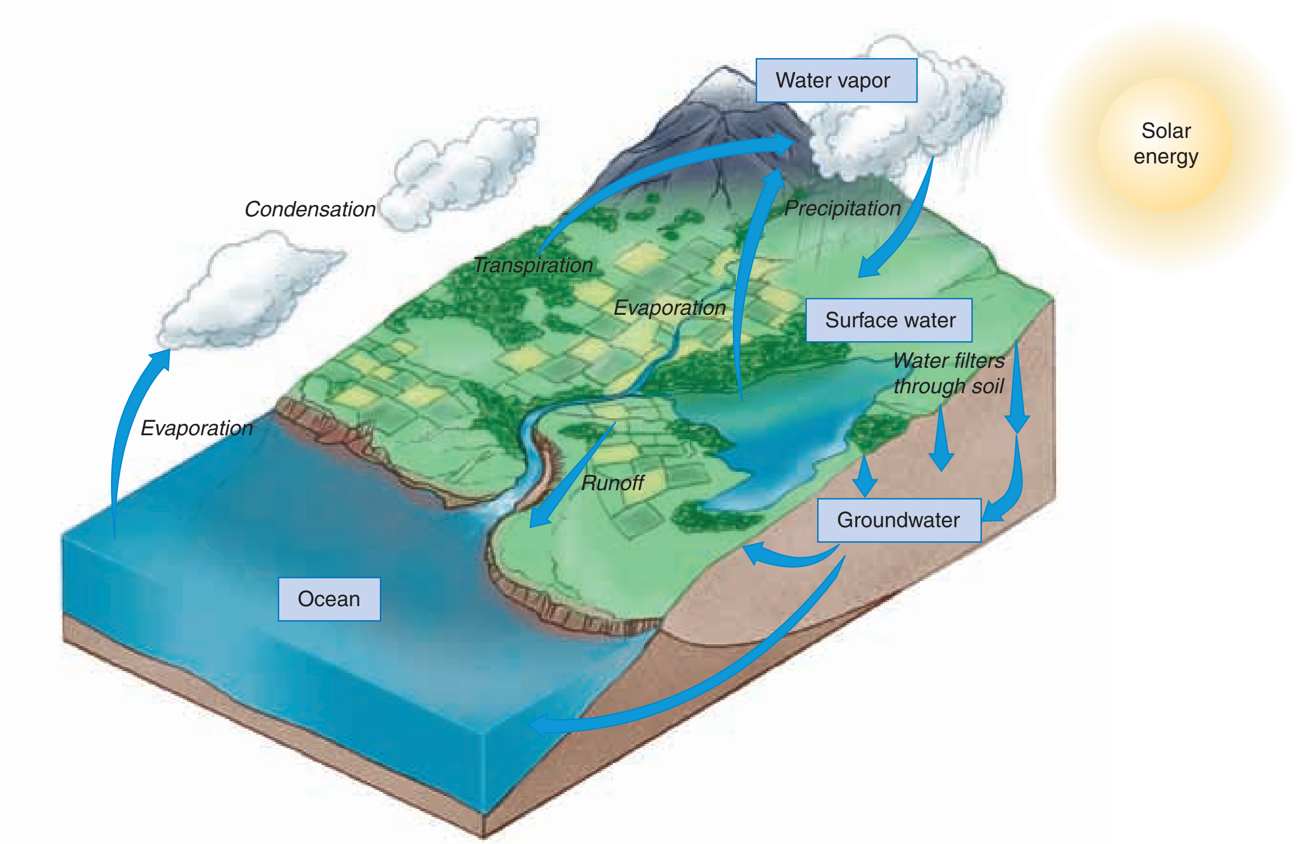

FIGURE 1-5 The hydrologic cycle describes how water enters and leaves the atmosphere.

back to space, reducing the amount that can be absorbed to heat the Earth. Like rivers, glaciers flow, but usually extremely slowly. Evaporation from lakes returns water to the atmosphere. Lake water and precipitation seep below the surface of the Earth and are stored there. Water stored in the soil ultimately flows back to the oceans, as does precipitation and river and glacier flows, completing the cycle.

Because water plays a major role in weather and climate, it is important to understand the hydrologic cycle. A change in one component of the hydrologic cycle can affect weather. For

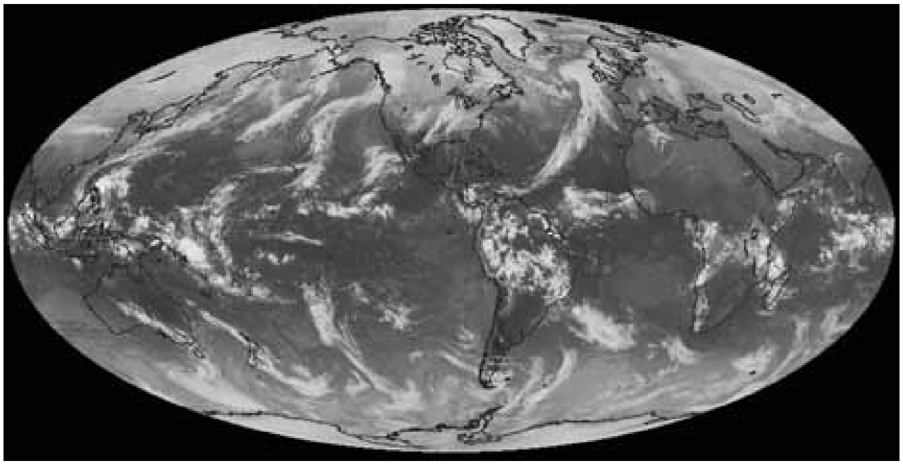

FIGURE 1-6 Satellites are used to determine global distributions of cloud amounts. This is a view of Earth from a combination of weather satellites on the same day as shown in Figure 1-1 (November 29, 2006). Can you find the growing storm over the central United States and the large weather system moving into the Pacific Northwest? Also, notice the very large storm over the north Atlantic. The global cloud patterns provide insight regarding atmospheric wind patterns.

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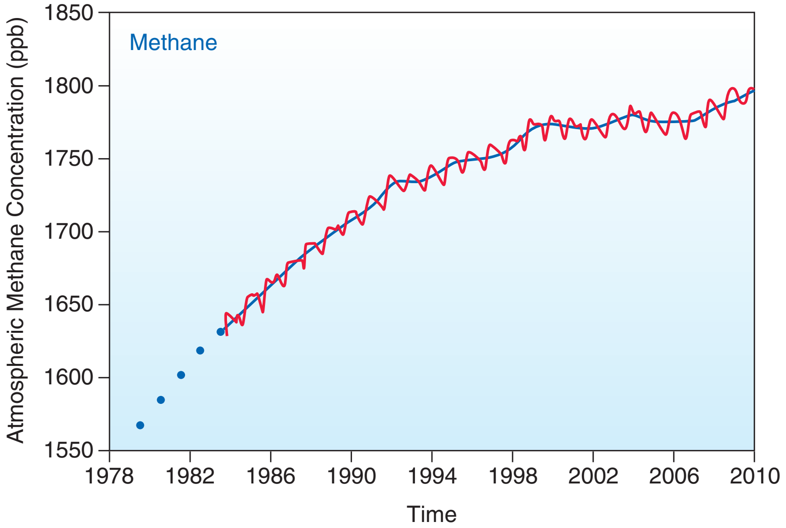

FIGURE 1-7 Atmospheric methane concentrations since 1978. Rapid increases in methane are presumably caused by agricultural, industrial, and animal sources tapered off in the mid-1990s, but the most recent observations suggest another rise in methane. (*Source*: NOAA/ESRL Global Monitoring Division—THE NOAA ANNUAL GREENHOUSE GAS INDEX [AGGI]. [n.d.]. Retrieved from http://www.esrl.noaa.gov/gmd/aggi/.)

example, a decrease in the amount of cloud cover over land during the day will allow more solar energy to reach the surface and warm the ground and the atmosphere above.

Methane

In addition to adding carbon dioxide to the atmosphere, human activities are changing the atmospheric concentration of other trace gases, such as methane. For example, the concentration of methane has doubled since the beginning of the Industrial Revolution. We do not fully understand either those earlier increases in atmospheric methane or the leveling off of methane concentrations since about the year 2000 (**FIGURE 1-7**). Human activities that contribute to the increased methane concentration include the decay of organic substances in landfills and rice paddies (the cultivation of rice has doubled since 1940), natural gas production, the burning of forests, coal mining, and even cattle raising. Methane is a by-product of cows' digestive process and accounts for 28% of human-related methane emissions globally!

Methane and other trace gases play key roles in the global warming debate. Not only do they affect the Earth's energy balance, their concentrations can be affected by warming temperatures. For example, some recent scientific observations have found that warmer land and ocean temperatures are causing bubbles of methane to escape from underground into the ocean (**FIGURE 1-8**) and atmosphere. An understanding of how trace gases increase the global

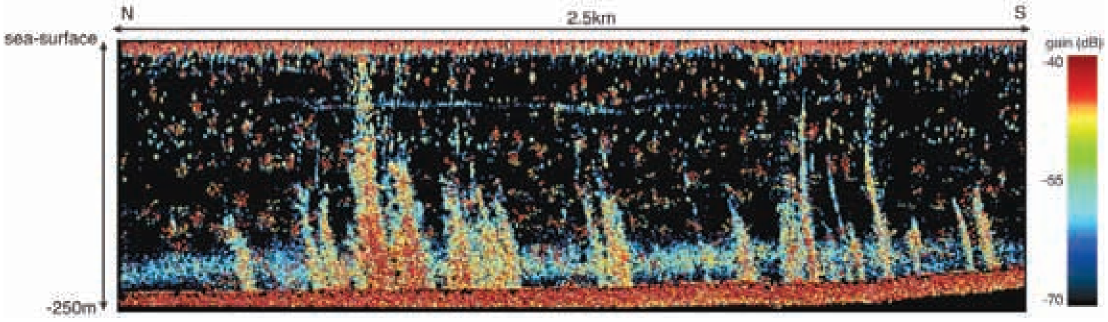

FIGURE 1-8 Methane bubbles observed by sonar rising from the bottom of the Arctic Ocean off Norway, as reported in a 2009 research paper. This region of the Arctic Ocean has warmed 1° C (1.8° F) in the past 30 years, helping to release the bubbles from the sea floor.

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average temperature, and how that warming can in turn affect the concentration of trace gases, requires us to revisit so-called greenhouse warming throughout this book.

Chlorofluorocarbons

Chlorofluorocarbons (CFCs) do not occur naturally. They were invented by chemists in 1928 and were used as propellants in spray cans, in Styrofoam puffing agents, and as coolants for refrigerators and air conditioners. In 1974, these human-made, or **anthropogenic**, gases were first linked to ozone destruction (see Chapter 2). In response to public concerns, the United States banned the use of CFCs in 1978. Later, in response to the discovery of the "ozone hole" (see Chapter 15), representatives from 23 nations met in Montreal, Canada, in 1987 to address concerns of ozone depletion by CFCs. The resulting Montreal Protocol called for a 50% reduction in the usage and production of CFCs by the year 1999. This and subsequent international agreements, combined with the introduction of substitute chemicals, largely eliminated the use of CFCs worldwide. Although the global use of these chemicals has declined for over two decades, their concentrations in the atmosphere have decreased only very slowly in recent years (**FIGURE 1-9**). This is because CFCs are very stable molecules and will stay in the atmosphere for nearly 100 years after their release before they decompose.

Aerosols

Clouds are not the only liquid and solid particles present in the atmosphere. Smoke, salt, ash, smog, and dust are examples of particles suspended in the atmosphere. These particles are collectively known as **aerosols**.

The size of an aerosol particle is measured in **microns** (one millionth of a meter) and varies with the type of aerosol (**FIGURE 1-10**). The amount and type of aerosol can influence the climate of a region by modifying the amount of solar energy that reaches the surface. The largest airborne particles are those thrown into the atmosphere during volcanic eruptions, forest fires, and tornadoes. Most atmospheric aerosols are too small to be visible to the naked eye, but they serve an important purpose (discussed in Chapter 4)—they are needed to form most clouds.

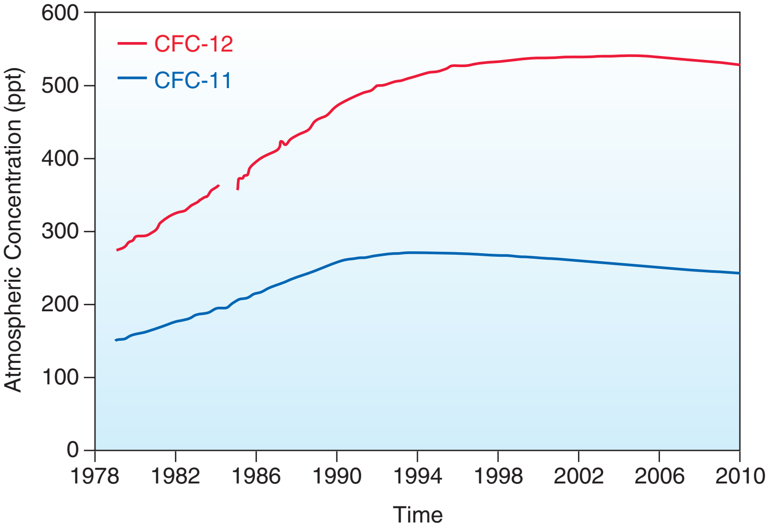

FIGURE 1-9 Concentrations of CFC-11 and CFC-12 in parts per trillion per volume since 1978. Although the usage of CFCs has declined in recent years, the concentration in the atmosphere has not declined as quickly. This is because CFCs are very chemically stable, and thus, after these molecules enter the atmosphere, they remain there for approximately a century. (*Source*: NOAA/ESRL Global Monitoring Division—THE NOAA ANNUAL GREENHOUSE GAS INDEX [AGGI]. [n.d.]. Retrieved from http://www.esrl.noaa.gov/gmd/aggi/.)

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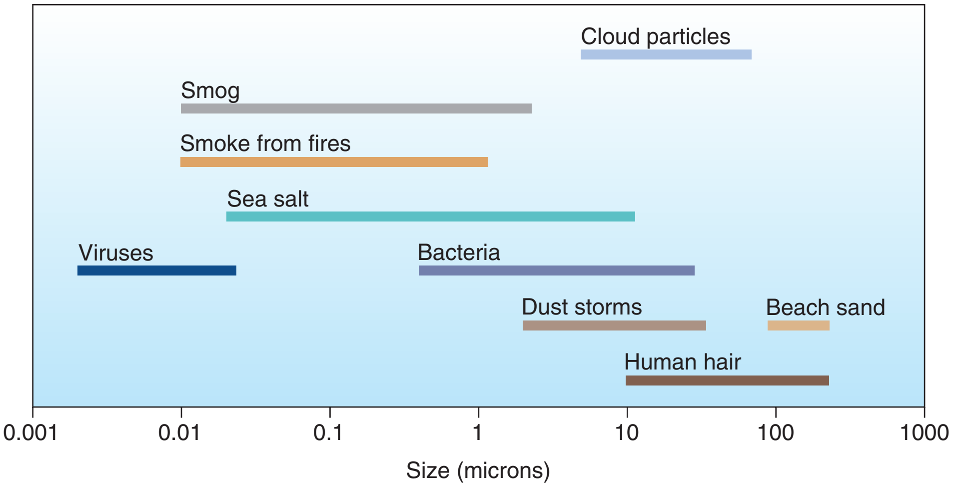

FIGURE 1-10 Aerosols are liquid and solid particles that are suspended in the atmosphere. Typical sizes of different aerosols are shown. For reference, the diameter of a human hair, beach sand, viruses, and bacteria is also shown.

Aerosols are more prevalent in certain regions of the world than others. For example, dust derived from soil is very common over deserts. Atmospheric winds can transport this dust to other regions of the globe where it may be deposited. Dust deposits are found on the ice sheets of Greenland. Dust is not generated in large quantities over Greenland, so these deposits must have originated in another location and then been transported toward the Arctic. An analysis of the Greenland ice sheet indicates an increased amount of dust present in the atmosphere at the end of the last "ice age," suggesting persistent dry, windy conditions. Dust deposits over glaciers are therefore a window into the weather of centuries past.

Sea salt is an aerosol that commonly occurs over the oceans and along shorelines. Sea salt enters the atmosphere from the oceans when spray from waves evaporates, leaving behind tiny salt particles in the atmosphere. Sea salt particles are important in the formation of clouds.

Other primary sources of aerosols are wind erosion, fires, volcanoes, and human activity. Wind erosion is a natural way of getting aerosols into the atmosphere. Winds lift soil particles off the bare ground and transport them into the atmosphere. Fires produce large amounts of aerosols. Air heated by fire can lift particles several thousand feet above the ground, where winds can carry the aerosols far away from their original source (**FIGURE 1-11**).

Click on "Mexican Smoke over the Midwestern States" to view a 10-day cycle of northward smoke movement from Central America.

Volcanic eruptions spew huge amounts of particles into the atmosphere. The eruption of Mount St. Helens in Washington State on May 18, 1980, injected approximately 472 million metric tons (520 million tons) of ash into the atmosphere! Chapter 3 presents a discussion of how aerosols generated in the largest volcanic eruptions can lower Earth's temperature.

Airborne particles generated by human activity are referred to as anthropogenic aerosols. Sources of these aerosols include fuel combustion, construction, crop spraying, and industrial processes. Large anthropogenic aerosols are generated in mechanical processes such as grinding and spraying. The smaller particles are generated in processes where combustion is incomplete, such as in automobiles.

ATMOSPHERIC PRESSURE AND DENSITY

Basic Concepts

Pressure is the force exerted on a given area. The atmosphere is made up of gas molecules that are constantly in motion. These molecules exert a pressure when they strike an object. The pressure exerted by the molecules hitting you is a function of their speed, number, and mass. Because the molecules that compose the air are moving in all directions, the pressure is exerted in all directions.

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FIGURE 1-11 Smoke from fires in southern California and northern Baja California on October 23, 2007. The locations of fires are denoted in red. In this picture, taken by a weather satellite, the smoke plumes extend for hundreds of miles over the Pacific Ocean. Hot, dry "Santa Ana winds" that blow toward the Pacific coast from the deserts of the western United States helped to fan the flames, which forced 1,000,000 people from their homes, the largest evacuation in California's history.

The concentration of molecules is measured in terms of **density**, or mass per unit volume. The atmospheric density at sea level for a standard temperature of 15° C (59° F) is 1.225 kilograms per cubic meter. In comparison, the density of liquid water is much greater, approximately 1025 kilograms per cubic meter. The pressure, temperature, and density of a gas are related to one another through a mathematical formula known as the ideal gas law (**BOX 1-2**). Changing one of these variables will cause a change in one or both of the others.

The ideal gas law states that the ratio of pressure to the product of the density times the temperature is always the same:

$$\frac{\text{Pressure}}{\text{Density} \times \text{Temperature}} = \text{Constant}$$

If one of the three variables changes, then the other two also have to change to keep this ratio constant. For example, air that is warmed at constant pressure has to have a lower density. In other words, warmer air is less dense than colder air. Or, if the air pressure is reduced, then either the density, temperature, or both need to decrease too. As we'll see shortly, this agrees with the vertical distribution of density and temperature in the troposphere.

Air has mass and, because of gravity, has weight. You may find it useful to think of atmospheric pressure as the weight of a column of air above you. **FIGURE 1-12** depicts how pressure and density vary with altitude. As you move upward from the surface, you are decreasing the amount of air above you and therefore its weight or pressure. Because air is compressible, the air near the surface is more compressed by the weight of the air above it than is air at higher altitudes. As a result, *atmospheric pressure and density decrease rapidly as you go up from the Earth's surface.*

Barometric Pressure and Sea-Level Pressure

Television weather reports show atmospheric pressure in terms of inches or millimeters of mercury. In meteorology, it is more common to report atmospheric pressure in millibars or Pascals (named after the 17th-century scientist Blaise Pascal, who in 1648 discovered the variation of pressure with altitude) rather than inches of mercury. One **millibar** (mb) equals 100 Pascals and 0.76 millimeters (0.03 inches) of mercury. The average surface pressure at sea level is 1013.25 mb, or 29.92 inches, of mercury. Pressure is also sometimes expressed in terms of pounds per square inch (psi); air pressure in tires is frequently measured in psi. One millibar is equivalent to 0.0145 psi. A common pressure in automobile tires is 32 psi, which converts to 2206 mb, or 65.3 inches, of mercury—more than twice the atmospheric pressure at sea level!

First we need to explain the science behind the terminology of atmospheric pressure. What does atmospheric pressure in "inches of mercury" really mean? The TV meteorologist is reporting atmospheric pressure in terms of the height of a column of mercury in an atmospheric pressure measuring device known as a **barometer**. To understand how a barometer works, consider **FIGURE 1-13**, in which a tube with no air in it is placed upside down in a liquid. Because gravity pulls objects toward the center of the Earth, the weight of an object exerts a downward pressure on a surface it rests on. Air has mass and because of gravity exerts a downward pressure on objects. The molecules in the air collide with and exert a pressure on

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Box 1-2 The Ideal Gas Law

Mathematics is a convenient and powerful tool for expressing physical ideas. Most atmospheric processes can be explained in descriptive terms; however, mathematical equations provide further insight. The ideal gas law describes the relationship between pressure, temperature, and volume of a gas. It is written as follows:

$$\text{Presssure} \times \text{Volume} = k \times \text{Temperature}$$

In this equation, k is a constant of proportionality that depends on the size of the gas sample. Although this law is an approximation of how a gas behaves, it is an excellent one for atmospheric studies. The ideal gas law can also be written as follows:

$$\text{Presssure} = R \times \text{Density} \times \text{Temperature}$$

where R is a constant that depends on the gases that compose the atmosphere. For dry air, the value of R is 287.05 Joules per kilogram per degree Kelvin.

We will use the ideal gas law to understand the relationship between pressure, volume, and temperature of a gas. Changing one of these properties changes the others. Let us start by considering a fixed volume of a gas. You can envision this as a gas stored in a thick metal container. If we double the temperature of the gas, then to make the left-hand side of the equation to equal the right-hand side, the pressure inside the container must double. If we fix pressure at a constant value, then doubling the temperature of the gas would also double the volume of the gas.

The study of how one variable changes with respect to another variable is a fundamental concept of the mathematics subject known as *calculus*. Because weather variables change with respect to each other and across time and space, students planning to be meteorologists must study calculus.

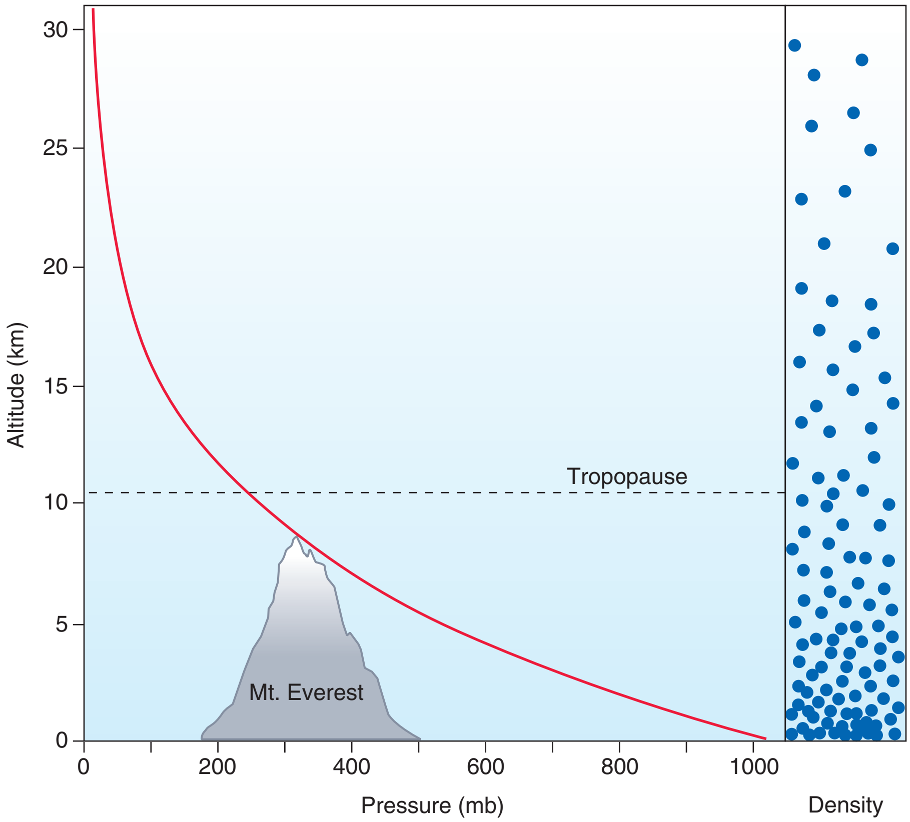

FIGURE 1-12 Atmospheric pressure and the density of air both decrease rapidly with increasing distance from the Earth's surface. (Adapted from Rauber, R. M., Walsh, J. E. and Charlevoix, D. J. *Severe & Hazardous Weather: An Introduction to High Impact Meteorology, Third edition*. Kendall/Hunt, 2008.)

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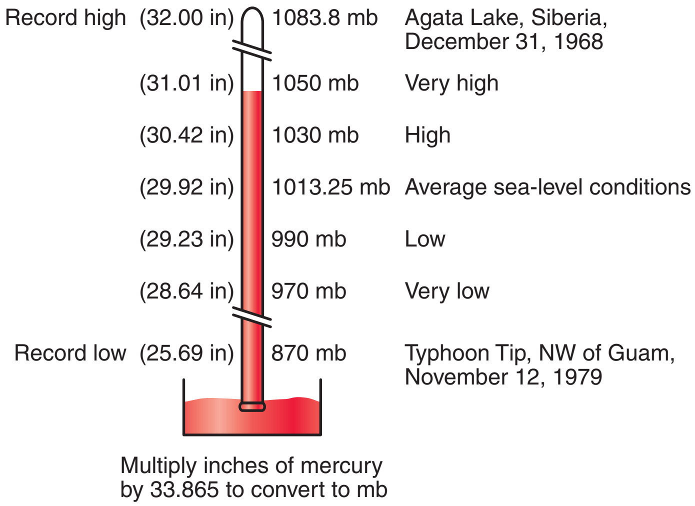

FIGURE 1-13 A summary of observed sea level atmospheric pressure. The average sea level pressure of the planet is 1,013.25 mb (29.92 inches of mercury). The lowest sea level pressure ever measured is 870 mb (25.69 inches), and the highest is 1,083.8 mb (32.00 inches). If these pressure units are unfamiliar, you can use this figure as a reference to determine whether observed pressures are considered to be low or high values.

the surface of the liquid. This pressure pushes the fluid up the tube. The greater the pressure, the higher the column of fluid is. The height of this column is a measure of the **barometric pressure**.

As we go higher in the atmosphere, the number of molecules colliding with the fluid surface decreases, and so the pressure exerted on the fluid is less. Thus, the column of fluid in the barometer is lower. This property of the atmosphere helps explain how the human body reacts to airplane travel and mountain climbing (**BOX 1-3**).

The decrease of atmospheric pressure with altitude creates a problem for interpreting pressure readings at locations with different altitudes. For example, Denver is approximately 1.6 kilometers (1 mile) above sea level, whereas San Francisco is near sea level. Because pressure always decreases with altitude, the barometric pressure measured at Denver will always be lower than that measured at San Francisco regardless of the weather situation. To avoid this apples-and-oranges situation when comparing the pressure of different locations, meteorologists always adjust all surface barometric pressure measurements to a single altitude: sea level. Standardizing to **sea-level pressure** removes the effect of altitude on pressure and allows the meteorologist to focus on the smaller, but important, surface pressure differences resulting from weather systems.

Let's learn how to do sea-level pressure conversions. Assume that on a given day that the barometric pressure in Denver is 850 mb and the barometric pressure at sea level in San Francisco reads 1013 mb, which is the average pressure at sea level. Denver's pressure sounds very low compared with San Francisco's. How can we adjust Denver's pressure to sea level? A city at sea level, such as San Francisco, has 1 more mile of air above it than Denver has. To adjust Denver's barometric pressure for sea level we have to add the pressure caused by the difference resulting from that extra mile of air. The lowest mile of air has a pressure of approximately 170 mb. The pressure in Denver adjusted to sea level is then 850 mb + 170 mb = 1020 mb.

This calculation shows that in our example Denver's weather is being affected by higher-than-average pressure, despite our initial impressions to the contrary. In a similar way, atmospheric pressure readings across the world are standardized by calculating what the pressure would be if the weather station were located at sea level.

Click on "Sea Level Pressure Conversion" to convert observed pressure to estimated sea level pressure.

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Box 1-3 Why Do Your Ears Pop?

Have you ever felt pressure in your ears when you were on an airplane flight or climbing a mountain? Have you noticed that the discomfort is worse if you have a cold and that chewing gum or yawning helps to alleviate it? Have your ever had trouble hearing an airline crew member make an announcement shortly after takeoff or shortly before landing because of loudly crying babies? A combination of meteorology and biology explains all of these observations.

As discussed in this chapter, atmospheric pressure decreases rapidly as you go up. In most of the western and eastern United States, it is possible to drive from sea level to 1 kilometer (3300 feet) elevation or higher in a few hours. This is equivalent to a pressure decrease of roughly 100 mb.

Pressure changes in an airplane are even quicker. Commercial airplanes cruise at an altitude of about 10 kilometers (33,000 feet) where atmospheric pressure is so low the interior of the plane must be pressurized to keep the crew members and the passengers conscious. Although the plane's cabin is pressurized, during flight, it is not kept at the same pressure as at the ground. To do so would place too much stress on the plane's structure when the far less dense air at cruising altitude surrounds it. Instead, cabin pressure during the middle of a long flight is usually about 750–800 mb. Because of this, cabin pressure decreases some during takeoff and increases some during landing.

If you chart the changes in surface atmospheric pressure throughout the day, you will observe that pressure does not usually change more than a few millibars a day. Because pressure varies slowly with time, our bodies have had no need to adapt to rapid changes in pressure. Yet, this is precisely what happens in an airplane or when climbing a mountain. If there is a rapid change in pressure, our bodies are slow to react to it. To understand how a rapid pressure change hurts our ears, we have to review some biology.

The pinna (the part of the ear that is visible) collects sounds and directs the sound waves into the auditory canal to the eardrum (tympanic membrane). Sound waves traveling through air are variations in pressure. When these pressure variations strike the eardrum, they cause the eardrum to vibrate. Tiny bones (the hammer, anvil, and stirrup) sense these vibrations and pass them to the inner ear. To hear sounds clearly requires the tympanic membrane to vibrate freely. Air on either side of the membrane exerts a pressure that maintains the proper tension for the eardrum to vibrate. The ear is connected to the nasal passage and throat by the Eustachian tube. This tube is a passageway for air to enter and leave the middle ear to balance the pressure exerted by air on the auditory canal side of the eardrum.

A rapid change in altitude results in a pressure imbalance on the eardrum. When the air pressure rapidly drops, the eardrum bulges outward, causing discomfort. To balance this pressure difference at the eardrum, air molecules must escape through the Eustachian tube. When the pressure inside your middle ear adjusts to the outside pressure, the eardrum returns to its normal tension. This movement of the eardrum makes a popping sound, and we say that your ear "pops."

Now we can explain the usefulness of yawning and chewing gum on an airplane. When you yawn or swallow, you are allowing the Eustachian tube to open wider and equalize this pressure difference more rapidly. A cold may block the Eustachian tube, making it more difficult to adjust to changes in air pressure. This increases the distortion of the eardrum and causes pain.

Babies on airplanes are too young to understand that they need to yawn or swallow. Furthermore, their Eustachian tubes are tiny and are easily blocked during colds or ear infections, which babies frequently endure. Therefore, during airplane takeoffs and landings, babies feel intense pressure and pain in their ears, and they respond by crying. Remember this with some sympathy the next time you fly on an airplane accompanied by the serenade of screaming infants!

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DIVIDING UP THE ATMOSPHERE

Meteorologists find it useful to divide the atmosphere into layers. We can divide the atmosphere vertically according to pressure. For example, in this book we will often discuss the winds at an altitude where the atmospheric pressure equals 500 mb. Why are we interested in 500 mb? The average atmospheric pressure at the Earth's surface is a little over 1000 mb, so if we were at an altitude of 500 mb, approximately half the atmosphere would lie above us and half below us. We learn in later chapters that the winds at about 500 mb help "steer" atmospheric storms. This makes the 500-mb level especially important for weather forecasting.

We can also divide the atmosphere according to temperature. Unlike pressure, temperature does not always decrease with increasing distance from the surface. If we were to average temperature over many years at many different locations across the globe for many different altitudes, however, a distinct pattern would emerge between temperature and distance from the surface. FIGURE 1-14 presents an example of this pattern. Based on this temperature profile, the atmosphere can be divided into four main layers: the troposphere, stratosphere, mesosphere, and thermosphere.

The Troposphere

From the surface up to approximately 10 to 16 kilometers (6 to 10 miles), temperature generally decreases with altitude. This is because the atmosphere is nearly transparent to the Sun's energy and is instead heated from below by the Earth's surface, like a pot of water on a stove. The region of the atmosphere closest to Earth, where the temperature decreases as you go up, is called the **troposphere**. The word *troposphere* is derived from the Greek word *tropein,* meaning "to change." Almost all of what we normally call "weather" occurs in the troposphere, and approximately 80% of the atmosphere's mass is located in the troposphere. For these reasons, the troposphere is the focus of this book.

The top of the troposphere is referred to as the **tropopause.** It acts as an upper lid on most weather patterns, just as a lid on a pot of water on a stove keeps the water from escaping. The height

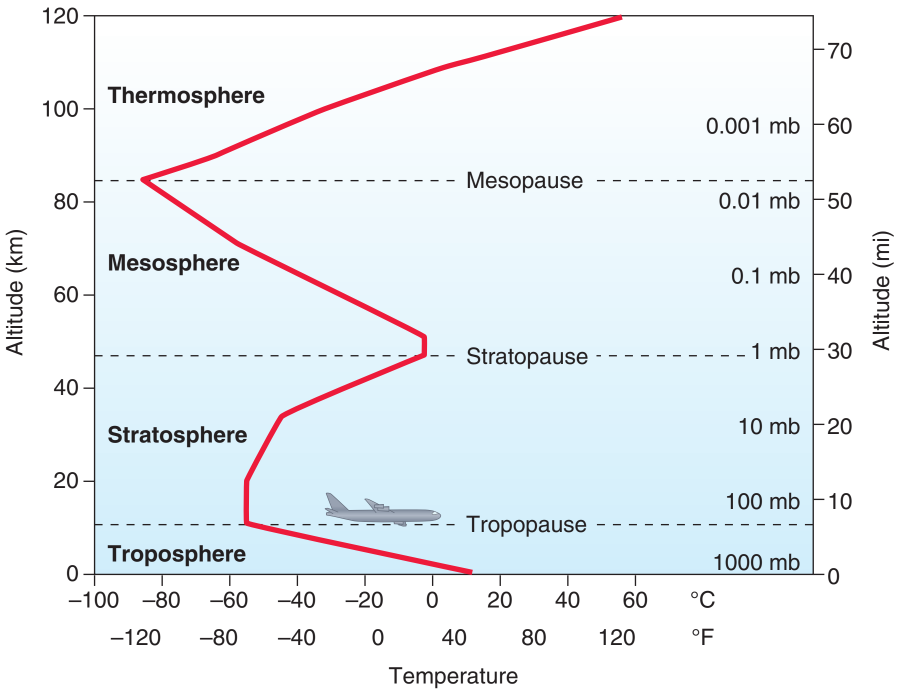

FIGURE 1-14 The atmosphere is subdivided into layers based on how air temperature changes with altitude. (Adapted from Rauber, R. M., Walsh, J. E. and Charlevoix, D. J. *Severe & Hazardous Weather: An Introduction to High Impact Meteorology, Third edition*. Kendall/Hunt, 2008.)

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of the tropopause is a function of latitude. It is higher in the equatorial regions, where the tropospheric air is warmer and expands upward to about 16 km, than in the cold polar regions, where the tropopause height is closer to 10 km. Weather systems can also affect the height of the tropopause, as we'll see in Chapter 10.

The Stratosphere

Above the tropopause lies the **stratosphere**, where temperature increases with altitude. Temperature is increasing because ozone molecules in the stratospheric "ozone layer" (see Chapter 2) are absorbing solar energy within the stratosphere. Air flow in the stratosphere is much less turbulent than in the troposphere. For this reason, jet aircraft like to cruise at stratospheric altitudes, where the flight is less "bumpy." The increasing temperature with altitude of the stratosphere makes it difficult for tropospheric air to mix into the stratospheric air, as explained in later chapters. The lack of mixing and turbulence makes the stratosphere very layered or "stratified"—hence its name. In the vicinity of storms with strong up-and-down wind motions, such as thunderstorms and low-pressure systems, tropospheric air can penetrate into the stratosphere, and stratospheric air can descend into the troposphere.

The **stratopause** marks the top of the stratosphere. On average, the stratopause occurs at an altitude of approximately 50 kilometers (31 miles). Its average temperature is close to 0° C, and during the winter the stratopause can be warmer than the ground far beneath it. But don't consider the stratopause a likely holiday vacation destination. Nearly 20% of the Earth's atmosphere is in the stratosphere, meaning that at the stratopause, the pressure is only 0.1% of that at the Earth's surface. Human beings could not survive at such low pressures; the liquids in their bodies would literally boil away!

The Mesosphere and Thermosphere

Above the stratopause lies the **mesosphere**. Temperature decreases with altitude in the mesosphere, just as it does in the troposphere. The **mesopause** separates the mesosphere from the **thermosphere** at an average altitude of about 85 kilometers (53 miles). In the thermosphere, the temperature again increases with altitude. The density of the atmosphere in the thermosphere is so low that above about 120 kilometers (75 miles) the atmosphere gradually blends into interplanetary space. The entire Earth's atmosphere is extremely thin, less than 2% as thick as the Earth itself.

From the mesosphere on up, the atmosphere becomes more and more affected by high-energy particles from the Sun. These particles break apart atmospheric molecules, which then form ions. For this reason, the region of the mesosphere and thermosphere is sometimes called the *ionosphere.* Some interesting visual phenomena occur in the mesosphere and thermosphere as a result of the interaction of solar particles and the atmosphere, such as the aurora (**FIGURE 1-15**). In addition, the ionosphere reflects radio waves, permitting radio stations to be heard far beyond the horizon.

AN INTRODUCTION TO WEATHER MAPS

Basic Concepts

An important part of studying meteorology is simply paying attention to weather conditions and applying your knowledge to what you observe. However, many different variables including temperature, moisture, cloudiness, precipitation, and others are used to describe weather. All of these must be considered and analyzed numerically. Furthermore, the weather at one location is often caused by larger weather patterns. So it is not enough to consider the weather locally. We must also analyze the weather for many other locations. This means even more numbers.

To identify key weather-making patterns, we need to see all of the numbers describing weather at many locations, all at once. It is also vital to see how the observations relate to each other geographically. A list of numbers doesn't help much; we need a picture. So, we plot weather

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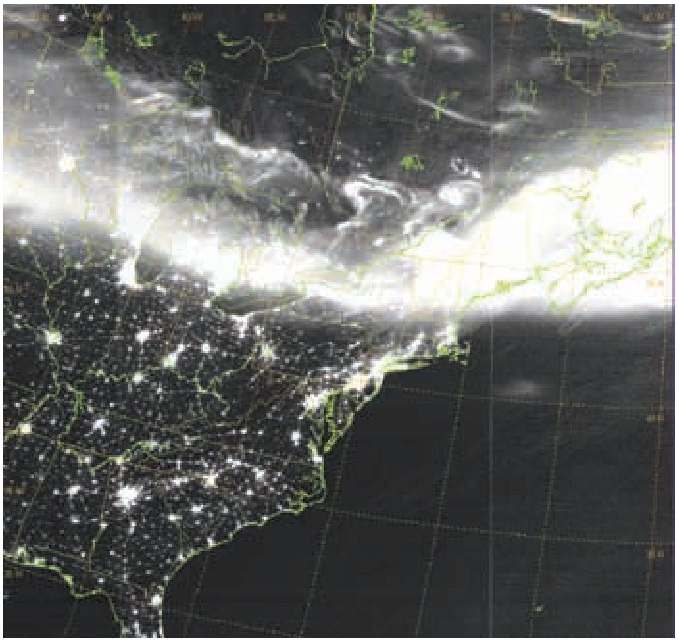

FIGURE 1-15 A visible satellite image of eastern North America at night on November 8, 2004. In addition to the lights of major cities, a bright band is seen extending from Minnesota to Michigan and across the entire state of Maine into Canada. This bright band is an aurora caused by a strong flow of solar particles near the end of the last "solar maximum." The next peak in solar activity, bringing with it more auroral activity, is expected by 2014.

variables on a weather map to understand the relationships among them. To paraphrase the saying "A picture is worth a thousand words," a weather map is worth a thousand numbers—or more. In this section, we learn how to interpret weather maps, in particular the **surface chart** that depicts weather at the Earth's surface.

Perhaps the most obvious features on surface weather maps are fronts. A **front** is a boundary between two regions of air that have different meteorological properties, such as temperature and humidity. A **cold front** denotes a region where cold air is replacing warmer air. A **warm front** indicates that warm air is replacing cooler air. We will discuss fronts in detail in Chapters 9 and 10 of this book.

All surface weather maps today depict frontal locations because they are regions of rapidly changing and sometimes dangerous weather conditions. The frontal lines drawn on a weather map represent the locations where the fronts meet the Earth's surface (**FIGURE 1-16**). On a weather map, a blue line with blue triangles indicates a cold front. The triangles point in the direction the front is moving. A warm front is shown as a red line with red semicircles pointing in the direction of frontal movement. A **stationary front** is a front that is not moving and is represented as shown in the lower-left corner of Figure 1-16. The **occluded front**, represented as a purple line with alternating triangles and semicircles, has characteristics of both cold and warm fronts and is discussed in more detail in Chapters 9 and 10.

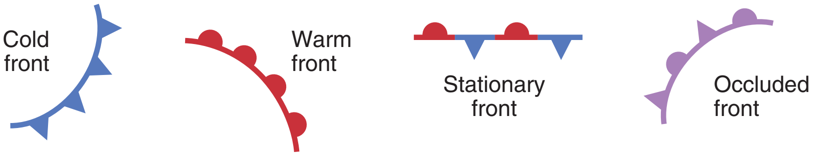

FIGURE 1-16 The colors and symbols for the four types of fronts: cold, warm, stationary, and occluded.

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To locate the position and type of a front on any given day requires the analysis of the weather conditions from locations over a wide geographic area. To help in this analysis, we often draw lines on weather maps connecting locations that have the same temperature. Lines of constant temperature are called **isotherms** (from *iso*, "same," and *therm*, "temperature"). Similarly, **isobars** connect locations with the same sea level atmospheric pressure. Both isotherms and isobars are often shown on television and newspaper weather maps. **Isotachs** connect locations with the same wind speed. **Isopleth** is a more general term describing contours along which any particular variable is constant.

Click on "Learning to Contour Weather Maps" to practice how to contour weather maps.

The Station Model

Television weather reports sometimes represent local weather conditions with smiling suns, rainy clouds, or flashing bolts of lightning. However, one smiling sun can cover several states and gives you no information about temperature, wind, and pressure. Meteorologists need a way to condense all the numbers describing the current weather at a location into a compact diagram that takes up as little space as possible on a weather map. This compressed graphical weather report is called a **station model.**

A simplified example of a station model plot used to represent meteorological conditions near the surface for a specific location is shown in **FIGURE 1-17**. The station model depicts weather

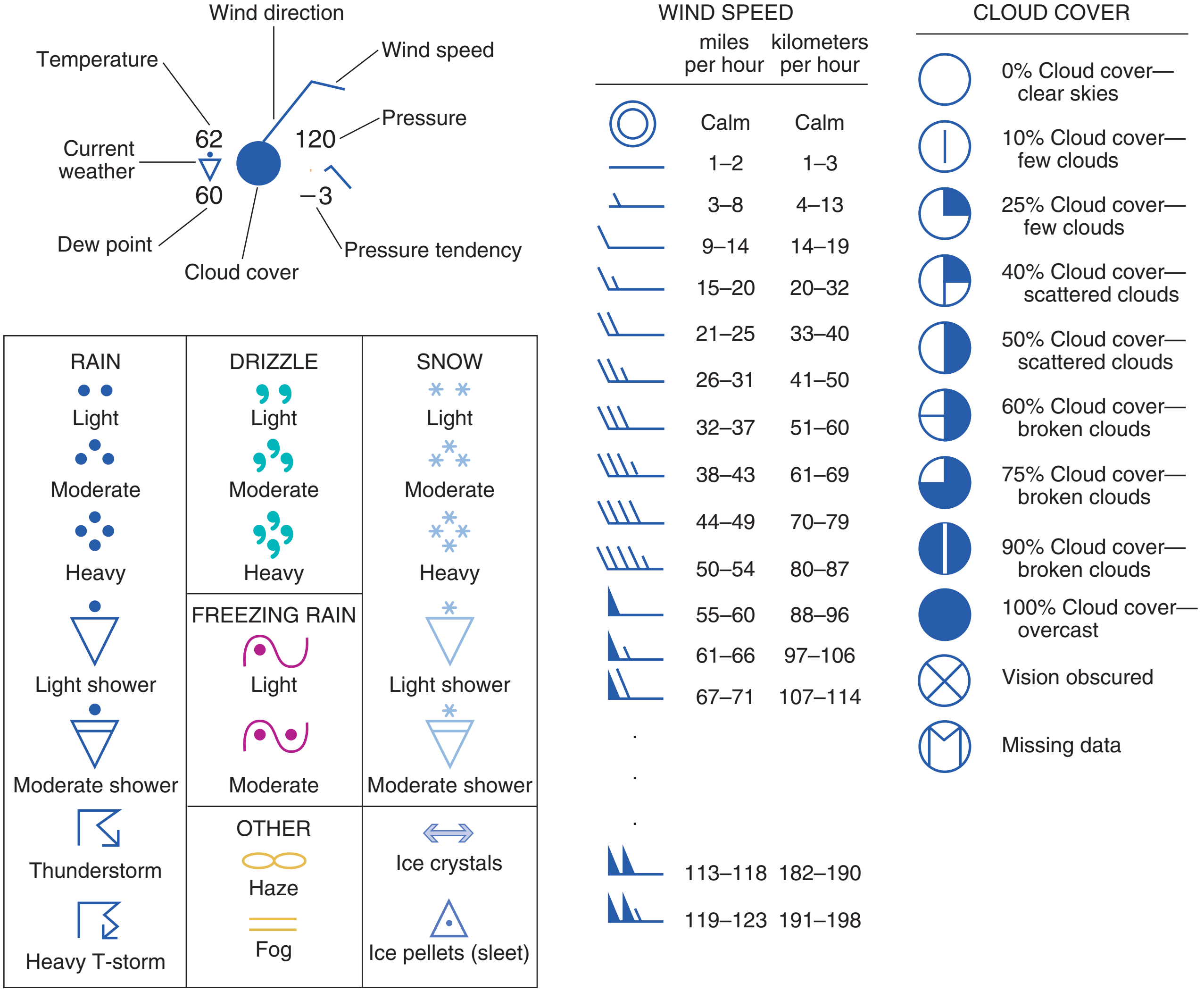

FIGURE 1-17 The station model for a typical weather situation (top left) and selected symbols used in the station model and their meaning. See the text and Web site for an explanation of how to decode a station model.

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conditions at a particular time in a specific location, plus cloud cover, wind speed, wind direction, temperature, dew point temperature, atmospheric pressure adjusted to sea level, and the change in pressure over the last 3 hours. In Figure 1-17, nine weather variables commonly reported on the evening news are plotted—much more information than a smiling sun can convey, in much less space.

Let's decode the station model at the top of Figure 1-17. First, cloud cover is depicted graphically by the type of shading inside the circle, which represents the location of the weather station. The circle is completely shaded, so this means 100% cloud cover or "overcast" conditions.

Next, the temperature reading is located at the 10 o'clock position with respect to the circle (i.e., just above and to the left of it). In the United States, temperature is reported on weather maps in degrees Fahrenheit. Therefore, in our example the temperature is 62° F. The dew point temperature, which is a measure of the amount of moisture in the atmosphere, is located at the eight o'clock position. In our example it is 60° F.

Current weather conditions are symbolically represented in between the temperature and dew point temperature. Some symbols for common weather conditions are shown in the lower part of Figure 1-17. In our example, the station is currently reporting a light rain shower. If there is no precipitation, haze, or fog occurring at the time of observation, the current weather condition location is left blank.

Wind speed and direction are also depicted graphically on a station model by the position of the "flagpole" extending out from the circle at the center. The pole points to the direction from which the wind is coming. So, the wind blows from the "flagged" end toward the "pointed" end. The "flags" are long and short lines that indicate wind speed, as explained in Figure 1-17.

The measured atmospheric pressure is adjusted to sea level and printed in the upper-right corner of the station model. The units used are millibars. Sea level pressures outside of tornadoes and hurricanes are always between 900 and 1099 mb. To save space on the map, the leading 9 or 10 is dropped, as is the decimal point. To decode the value of pressure on the station model, add a 9 if the first number is a 7, 8, or 9; otherwise add a 10. (This rule does not work in situations with very low or high pressure, but in those rare cases, the pattern of isobars helps you to know whether the leading digit(s) should be a 9 or a 10.) In our example, the "120" means that the station's sea level atmospheric pressure is 1012.0 mb. If it had been "831" instead, the sea level pressure would be 983.1 mb.

The change in surface pressure during the last 3 hours is plotted numerically and graphically on the lower right of the station model. The change in pressure is represented by a value (in tenths of a millibar) and a line that describes how the pressure was changing over time from left to right. In our example, the line goes up and then goes down, indicating that the pressure rose and then fell over the past 3 hours, a total change of 0.3 mb. A more complete explanation of how to decode pressure tendency symbols is provided on this text's Web site.

Click on "Decoding the Surface Station Model" for a complete guide to station models and for practice deciphering several examples.

Many other weather variables can be depicted on the station model: visibility (next to current weather conditions), weather conditions during the past hour (lower right), precipitation amounts (near pressure tendency), and peak wind gusts during the past hour (number in knots [1 knot = 1.15 mph] next to the "flags" on the "flagpole"). In this text, we will not look at all station model variables at once; instead, we will focus on different variables in different chapters. This text's Web site contains a complete guide to the station model and examples of current weather maps that use surface station models.

An example of an actual surface weather map is given in **FIGURE 1-18**. This map corresponds to the satellite image shown in Figure 1-1. The surface weather map shows that much of the central United States is cloudy, in agreement with Figure 1-1.

Focusing on the station model for Dallas, Texas, in north-central Texas, we see that the temperature is 77° F and the dew point temperature is 63° F. The sea level pressure at Dallas is 1006.0 mb; the winds are strong and from the south, and Dallas is experiencing broken cloud conditions. Interestingly, just to the north of Dallas in Oklahoma City, the temperature is

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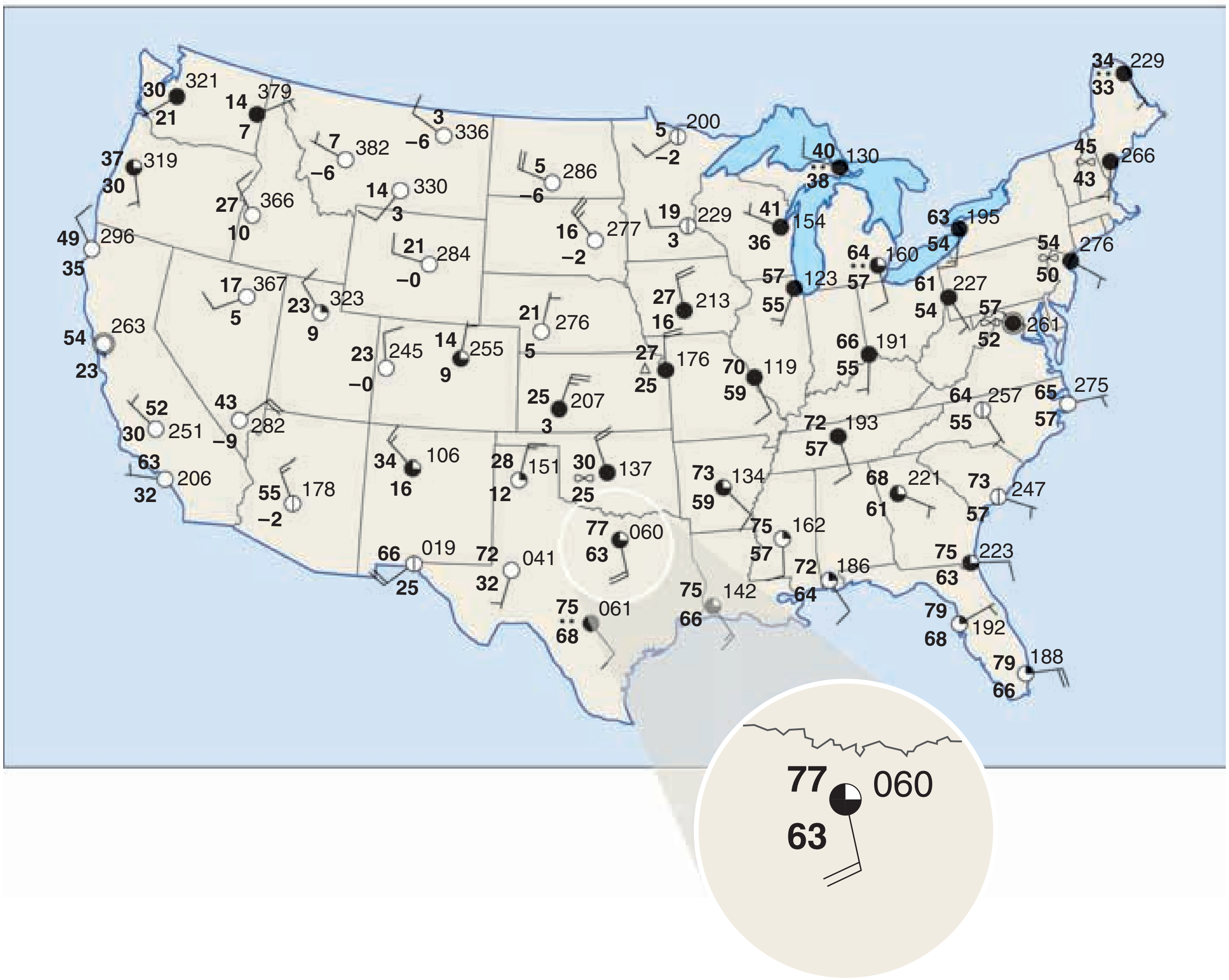

FIGURE 1-18 A surface weather map for 2200 UTC on November 29, 2006, using station models as explained in Figure 1-17. Compare this map and the weather described by it to the satellite image in Figure 1-1. (Adapted from Plymouth University Weather Center [http://vortex.plymouth.edu/make.html.]. Accessed June 10, 2010.)

only 30° F with strong winds from the *north*. This is a sign that a front lies between Dallas and Oklahoma City, as we learn in Chapter 9.

The weather observations in Figure 1-18 were all made at the same time. Unlike television programming, Eastern Time is not the reference for these maps. In the following, we learn how to decode meteorological time.

TIME ZONES

To depict current weather patterns using a weather map and to predict future weather, it is important to coordinate the time of global weather observations. To aid in this coordination, weather organizations throughout the world have adopted the Coordinated Universal Time (**UTC**, for **Universel Temps Coordonné**) as the reference clock. UTC is also denoted by the abbreviations GMT (Greenwich Meridian Time) or, often with the last two zeroes omitted, Z (Zulu).

The reference **time zone** for UTC is centered on Greenwich, England (**FIGURE 1-19**). The International Date Line (180° longitude, halfway around the world from Greenwich) separates

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FIGURE 1-19 A map depicting the conversions between UTC (Universal Coordinated Time) and local times throughout the world. (Courtesy of *The World Factbook*, 2009.)

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one day from the next. Just to the east of the dateline is 24 hours earlier than just to the west of the dateline.

Meteorology also uses the 24-hour military-style clock. For example, 1:30 PM UTC is 1330 (1200 + 130) UTC, and 0130 UTC is 1:30 AM. Observations of the upper atmosphere are coordinated internationally to be made at 0000 UTC (midnight at Greenwich) and 1200 UTC (noon at Greenwich). The Eastern Standard Time zone of the United States is 5 hours earlier than Greenwich time. So, an observation made at 1300 in New York City would be recorded as 1800 UTC time.

Why is Eastern Standard Time 5 hours earlier than Greenwich time? Since the Earth has 360° of longitude and rotates around its axis once every 24 hours, this means that local time should be 1 hour earlier for every $(360°/24) = 15°$ of longitude west of Greenwich. (In practice, the exact lines dividing time zones are sometimes drawn along rivers and state and province boundaries, not along longitude lines.) New York City is at approximately 74° west longitude, or 74°W. This is almost $5 \times 15°$ of longitude west of Greenwich. Using the 15° rule, this explains why Eastern Standard Time is 5 hours earlier than Greenwich or UTC time.

Using the same reasoning, New Orleans (90°W) and the rest of the Central Standard Time zone are 6 hours earlier. Denver (105°W) and the rest of Mountain Standard Time are 7 hours earlier. Los Angeles (118°W) and the rest of Pacific Standard Time are 8 hours earlier. Juneau (134°W) and the rest of Alaskan Standard Time are 9 hours earlier, and Honolulu (158°W), and the rest of Hawaiian Standard Time is 10 hours earlier than Greenwich.

In our example in Figure 1-19, the weather observations were taken at 22Z or 2200 UTC on November 29, 2006. Although the observations were all taken at about the same moment, the clock read 5:00 PM local time in hazy New York City, 4:00 PM in rainy Chicago and warm Dallas, 3:00 PM in frigid Denver, and 2:00 PM in clear Los Angeles. (In most of North America, Europe, and northern Asia, Daylight Saving Time moves local time forward 1 hour. In the U.S., Daylight Saving Time has begun on the second Sunday in March and has ended on the first Sunday in November since 2007.)

WEATHER WATCHES, WARNINGS, AND ADVISORIES

As you follow the weather, you will notice that certain meteorological conditions may pose a threat to life and property. Under these conditions, the National Weather Service issues advisories, weather watches, and weather warnings. A weather **watch** informs us that current atmospheric conditions are favorable for hazardous weather. When the hazardous weather will soon occur in an area, a warning is issued. Weather watches and warnings are issued for a wide variety of hazardous weather, including tornadoes, hurricanes, severe thunderstorms, winter storms, and flooding. **FIGURE 1-20** depicts the weather warnings and watches issued on the day corresponding to Figure 1-18. Notice that many of the watches and warnings are in the vicinity of the clash between warm and cold air over the central United States.

The National Weather Service issues weather watches and warnings under specific weather conditions (**TABLE 1-2**). It is important to understand the difference between a weather watch, a weather warning, and a weather advisory. The term **watch** implies that you should be aware that a weather hazard may develop in your area. A **warning** is issued when the hazard is developing in your area. You should take immediate action in the event of a warning. An advisory is a less urgent statement issued to bring to the public's attention a situation that may cause some inconvenience or difficulty for travelers or people who have to be outdoors.

Pinpointing the location of hazardous weather in advance is extremely difficult. For this reason, watches are usually issued for large regions, sometimes covering several states (Figure 1-20). Warnings are often issued for smaller areas because they are based on actual observations of hazardous weather.

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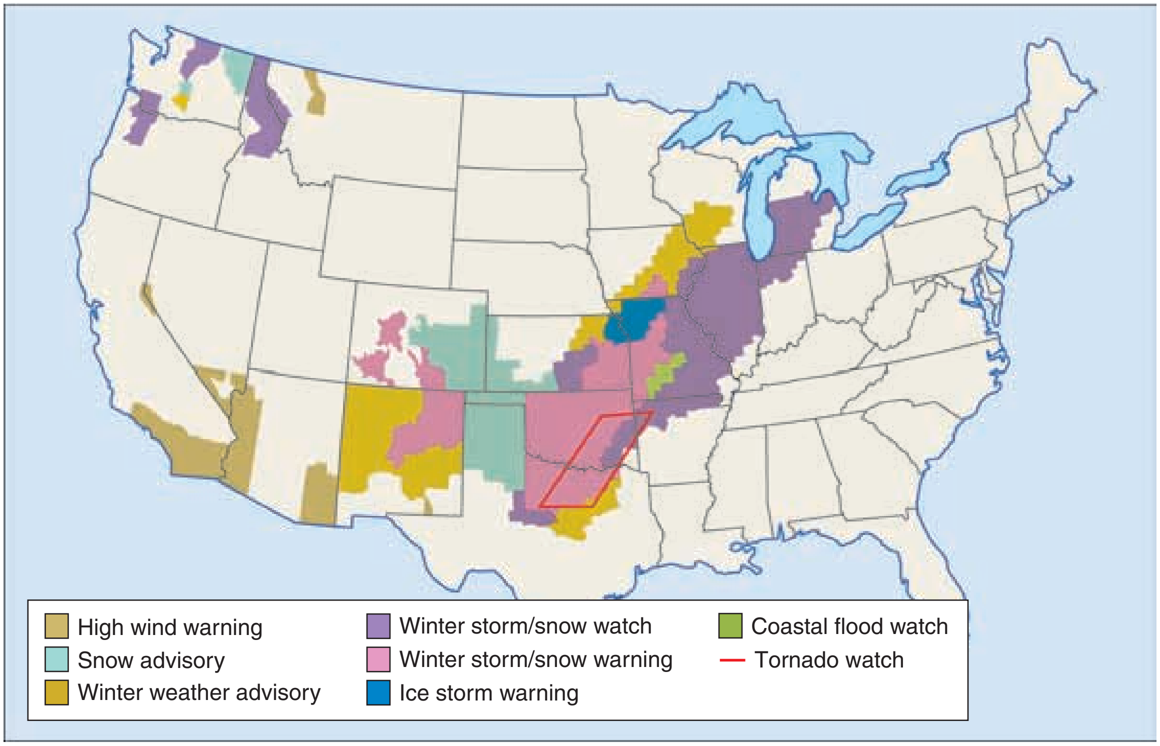

FIGURE 1-20 The National Weather Service's weather watches and warnings for the busy weather day of November 29, 2006 (compare with Figures 1-1, 1-6, and 1-18, which are for the same day and time). Winter storm watches and warnings cover a large part of the central United States from Texas to Michigan, as well as parts of New Mexico and Colorado and the Pacific Northwest. An ice-storm warning has been issued for northwest Missouri, with a flood watch for the Ozark region of southwestern Missouri. A tornado watch box extends through parts of Texas and Oklahoma. A high-wind warning has been posted for parts of Southern California and other scattered regions of the West. (Courtesy of SSEC, University of Wisconsin-Madison.)

You should know in advance what to do if hazardous weather threatens your area. Throughout this text we will discuss many types of weather hazards, the ways in which they kill, and the steps you can take to protect yourself from the awesome, and sometimes awful, pageant of weather.

PUTTING IT ALL TOGETHER

Summary

Weather is the state of the atmosphere at a particular time, and meteorology is the study of weather. The state of the atmosphere on longer time scales, including its interactions with oceans, land, and living things, is called climate. As with daily weather, the climate of a region changes with time, although on much longer time scales than the weather.

Earth's atmosphere has been shaped by billions of years of volcanic emissions and plant life. It is composed primarily of nitrogen and oxygen gases. Atmospheric concentrations of water vapor, carbon dioxide, methane, nitrous oxide, ozone, CFCs, and aerosols are very small but also very important to the study of weather and climate. Understanding the concentrations of water vapor and carbon dioxide, among other gases, requires taking into account the cycles of water and carbon from the air to the land and ocean and back to the air. The concentrations of most of these trace gases are increasing as a result of human activities.

The different molecules of the atmosphere are continually moving, exerting pressure in all directions. Atmospheric pressure is related to the weight of the column of air above you. As your altitude increases, the number of molecules above you decreases. For this reason, atmospheric

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TABLE 1-2 **Typical National Weather Service Criteria for Issuing Selected Weather Watches and Warnings**

Weather Hazard	Watch	Warning
Hurricane	Hurricane conditions are possible in a given region within 48 hours.	The arrival of a hurricane is expected within the warned region within 36 hours.
Severe thunderstorm	Conditions are favorable for the development of severe thunderstorms in and close to the watch area.	A severe thunderstorm has been sighted visually or indicated by radar. This is issued when a thunderstorm produces hail 1 inch or larger in diameter and/or winds exceed 58 mph.
Tornado	Conditions are favorable for the development of tornadoes in and close to the watch area.	A tornado has been sighted visually or indicated by radar.
Flash flood	Conditions are forecast that could result in flash flooding in or close to the watch area.	Flash flooding will occur within 6 hours and will threaten life and/or property. Dam breaks or ice jams can also create flash flooding.
Winter storm	Conditions are favorable for the development of hazardous weather such as heavy snow, sleet, or freezing rain.	Hazardous winter weather is imminent or very likely.
Ice storm	Conditions are favorable for a significant and possibly damaging accumulation of ice on exposed objects, such as trees, power lines, and roadways.	Freezing rain/drizzle is occurring with a significant accumulation of ice (more than 0.25 inch) or accumulation of 0.5 inch of sleet.
High wind	Conditions are favorable for high wind speeds developing that may pose a hazard or is life-threatening during the next 24 to 36 hours.	Sustained wind speeds of 40 mph or greater will last for 1 hour or longer, or winds of 58 mph or greater are occurring for any duration of time.

pressure always decreases with distance from the surface. This simple concept is important in understanding the formation of clouds and the transfer of energy in the atmosphere. To compare measurements of atmospheric pressure at locations that are at different altitudes, the measurements must be adjusted to sea level.

Unlike pressure, temperature does not always decrease with increasing distance from the surface. The vertical changes in temperature neatly divide the atmosphere into four distinct layers: the troposphere, stratosphere, mesosphere, and thermosphere. Most weather occurs in the troposphere, which is the focus of this text.

Weather maps show the weather conditions for many locations at the same time. Many variables describe weather at a specific location, including temperature, pressure, and wind. The station model is a graphic way to compress large amounts of weather data for one location into a very small area on a weather map. Weather observations are taken at the same time at locations all over the world. This requires a system of time zones and a universal standard of time, known as UTC and referenced to Greenwich, England.

The National Weather Service issues watches when hazardous weather may occur in a region and issues warnings for more localized areas when hazardous weather has been observed nearby. Warnings require immediate action on your part to protect life and property.

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Key Terms

You should understand all of the following terms. Use the glossary and this chapter to improve your understanding of these terms.

Aerosols
Anthropogenic
Argon
Atmosphere
Barometer
Barometric pressure
Carbon dioxide
Chlorofluorocarbons (CFCs)
Climate
Climatology
Cloud
Cold front
Condensation
Density
Diffuse
Evaporation
Front
Gravity
Hydrologic cycle
Isobar
Isopleth
Isotach
Isotherm
Mesopause
Mesosphere
Meteorology
Methane
Micron
Millibar
Molecule
Nitrogen
Nitrous oxide
Occluded front
Oxygen
Ozone
Permanent gases
Pressure
Sea-level pressure
Sink
Source
Stationary front
Station model
Stratopause
Stratosphere
Surface chart
Thermosphere
Time zones
Trace gases
Transpiration
Tropopause
Troposphere
Universel Temps Coordonné (UTC)
Variable gases
Warm front
Warning
Watch
Water vapor
Weather

Review Questions

1. What is one difference between weather and climate?
2. Explain why the meteorology of the Northern Hemisphere differs from that of the Southern Hemisphere, with reference to Figure 1-2.
3. Although the production of CFCs has been drastically reduced over the past quarter century, their atmospheric concentrations are only slowly decreasing. Why?
4. If pressure is force per area, then the atmospheric pressure over a large area such as the United States must be tiny compared with the atmospheric pressure over a city. Find the flaw in this reasoning.
5. What aspect of meteorology might make it easier to hit a home run at Coors Field in Denver than at PETCO Park in coastal San Diego, California?
6. Why is there no such field as lunar (Moon) meteorology?
7. The pressure at a weather station 1.6 kilometers above sea level is 900 mb. Based on the example discussed in the chapter, what is the sea level pressure of this station? Is this station experiencing unusually high, low, or normal atmospheric pressure?
8. Why does atmospheric pressure decrease with altitude?
9. If a raft filled with air is thrown into a cold lake, it appears to deflate, even though no air escapes. Explain.
10. Why does air that is rapidly compressed into a small volume get hot?
11. You are halfway between two layers of the atmosphere in which temperature increases with altitude. What is your approximate pressure, and in what layer of the atmosphere are you?
12. Using the station model decoding information in Figure 1-17, completely decode the station model for New York City in Figure 1-18.
13. You are asked to investigate the weather conditions at Boston at 7:00 PM on Monday, February 28, 2012. To get this information, you have to know the right day and time for this situation in coordinated universal time (UTC). What is the correct UTC day, date, and time?
14. Practice contouring weather maps using the Web link to Contouring Weather Maps.
15. Practice decoding the weather station model using the Web link to Decoding the Weather.

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Observation Activities

1. Place a balloon over the open end of an empty glass bottle. Run hot water over the bottle (not the balloon). What happens to the balloon? Explain what you observe. Then fill a balloon with air, and place it in a refrigerator. Remove it from the refrigerator after 20 minutes, and describe its appearance. Explain what you observe.
2. Visit http://www.spaceweather.com/aurora/gallery_01nov04.htm to see beautiful photographs from the ground of the November 2004 aurora shown from space in Figure 1-16.
3. Weather reports include pressure observations as well as how the pressure has been changing (increasing, decreasing, or steady). Observe these pressure changes with respect to changes of precipitation. Do you observe any relationship between precipitation and change in pressure?
4. Throughout the course, visit a NOAA web page to keep track of the different types of warnings and watches issued nationally and for your region (see, for example, the graphic on http://www.weather.gov/). How many different types of potentially hazardous weather were occurring when you visit the site?
5. Find a good internet site that plots the station model for your region (e.g., http://profhorn.meteor.wisc.edu/wxwise/station_model/sago.html for Wisconsin). Observe the weather outside, and see how your observations are plotted on a weather map. How does the weather in your region compare with that in neighboring cities?

This rain cloud icon is your clue to go to the *Meteorology* Web site at http://physicalscience.jbpub.com/ackerman/meteorology/. Through animations, quizzes, web exercises, and more, you can explore in further detail many fascinating topics in meteorology.

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