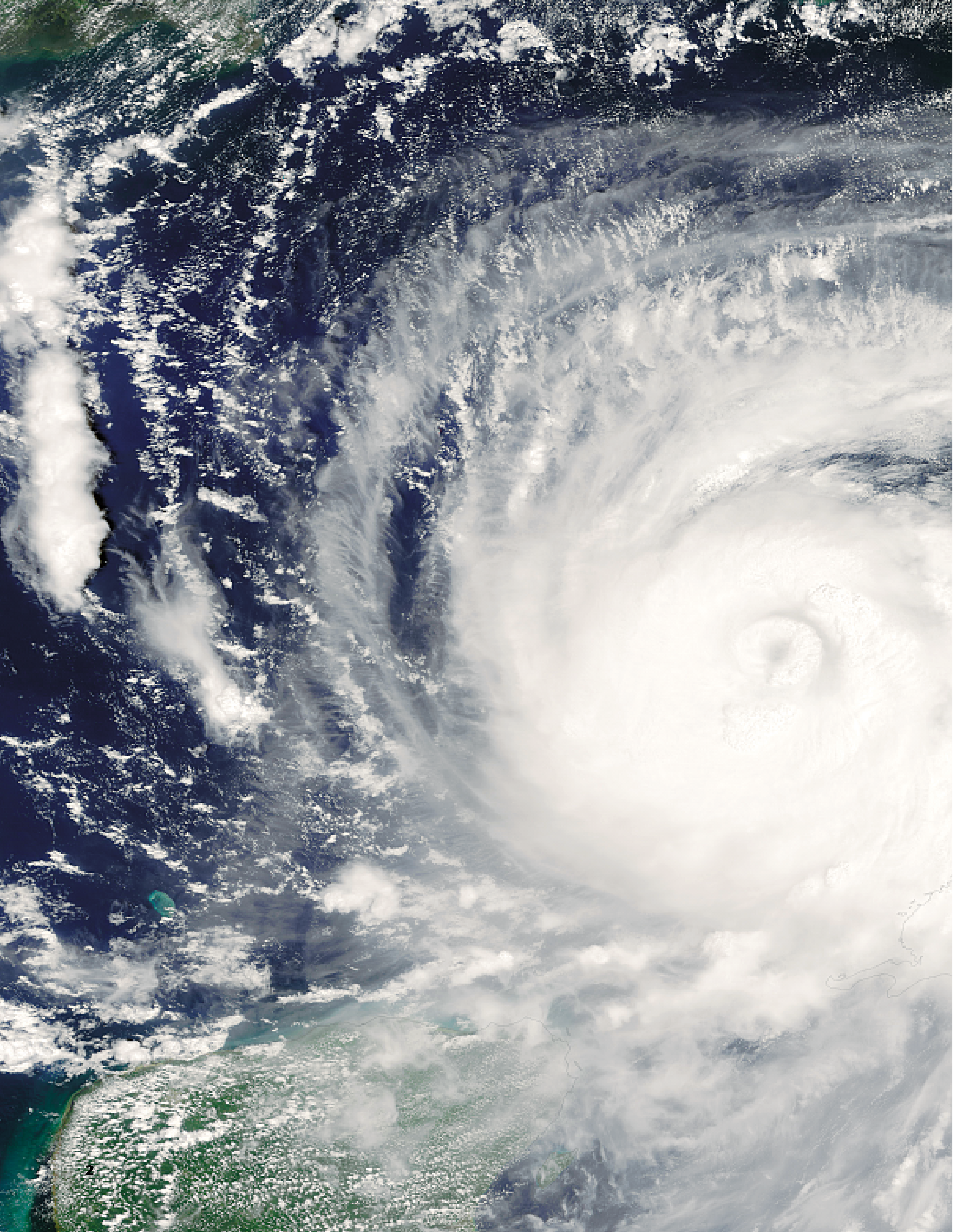
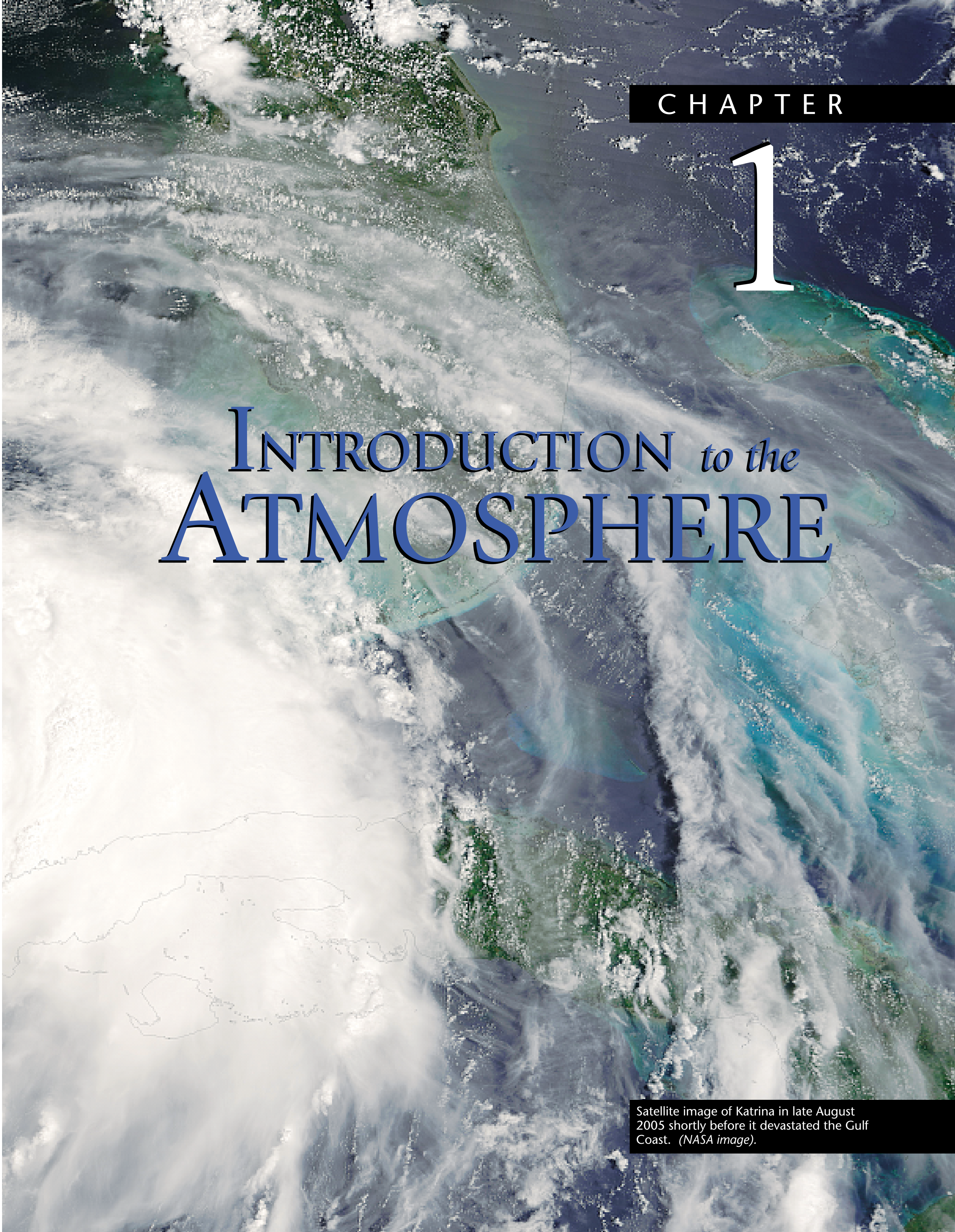


CHAPTER

1

INTRODUCTION *to the* ATMOSPHERE



Satellite image of Katrina in late August 2005 shortly before it devastated the Gulf Coast. *(NASA image).*

Weather influences our everyday activities, our jobs, and our health and comfort. Many of us pay little attention to the weather unless we are inconvenienced by it or when it adds to our enjoyment of outdoor activities. Nevertheless, there are few other aspects of our physical environment that affect our lives more than the phenomena we collectively call the weather.

The United States occupies an area that stretches from the tropics to the Arctic Circle. It has thousands of miles of coastline and extensive regions that are far from the influence of the ocean. Some landscapes are mountainous, and others are dominated by plains. It is a place where Pacific storms strike the West Coast, while the East is sometimes influenced by events in the Atlantic and the Gulf of Mexico. For those in the center of the country, it is common to experience weather events triggered when frigid southward bound Canadian air masses clash with northward-moving tropical ones.

Stories about weather are a routine part of the daily news (Figure 1–1a). Articles and items about the effects of heat, cold, floods, drought, fog, snow, ice, and strong winds are commonplace. Of course, storms of all kinds are frequently front-page news (see chapter opening photo). The hurricane season of 2005 was one for the record books. In late August Hurricane Katrina devastated portions of the Gulf Coast and during the next two months hurricanes Rita and Wilma also made headlines. Earlier in the year, heavy January rains and significant snows pushed rivers in parts of Indiana, Kentucky, and Illinois past flood stage. Later in January a blizzard buried New England, paralyzing travel and disrupting electrical power (Figure 1–1b). Meanwhile, the Pacific Northwest was experiencing much less snow than average. This was important because melting snows feed the region's streams during the summer, so when little snow falls, drought ensues. By contrast, southern California was hit by day after day of winter storms that led to flooding, mudflows, and huge mountain snows (Figure 1–1c).

These memorable weather events serve to illustrate the fact that the United States has the greatest variety of weather of any country in the world. Severe weather events such as tornadoes, flash floods, and intense thunderstorms, as well as hurricanes and blizzards, are collectively more frequent and more damaging in the United States than in any other nation. Beyond its direct impact on the lives of individuals, the weather has a strong effect on the world economy, by influencing agriculture, energy use, water resources, transportation, and industry.

Weather clearly influences our lives a great deal. Yet it is also important to realize that people influence the atmosphere and its behavior as well. There are, and will continue to be, significant political and scientific decisions to make involving these impacts. Answers to questions regarding air pollution and its control and the effects of various emissions on global climate and the atmosphere's ozone layer are important examples. So there is a need for increased awareness and understanding of our atmosphere and its behavior.

FIGURE 1–1 There are few aspects of our physical environment that influence our daily lives more than the weather. (a) Aerial view of Punta Gorda, Florida, after Hurricane Charley struck on August 13, 2004. This Category 4 storm, one of four to strike Florida in 2004, had sustained winds of 233 kilometers (145 miles) per hour. *(Photo by Rhona Wise/EPA/NewsCom)* (b) Residents of Boston dig out after a blizzard dropped up to two feet of snow in the area on January 23, 2005. *(AP Photo/Michael Dwyer)* (c) Exceptional winter rains in 2005 triggered many debris flows in Southern California, including this one at La Conchita that killed 10 people and destroyed 18 homes. *(Photo by G. Delaurentis/AP Wide World Photos).*

(a)

(b)

(c)

Meteorology, Weather, and Climate

GEODe ATMOSPHERE

Introduction to the Atmosphere

▸ Weather and Climate

The subtitle of this book includes the word *meteorology*. **Meteorology** is the scientific study of the atmosphere and the phenomena that we usually refer to as *weather*. Along with geology, oceanography, and astronomy, meteorology is considered one of the *Earth sciences*—the sciences that seek to understand our planet. It is important to point out that there are not strict boundaries among the Earth sciences; there are many situations in which these sciences overlap. Moreover, all of the Earth sciences involve an understanding and application of knowledge and principles from physics, chemistry, and biology. You will see many examples of this fact in your study of meteorology.

Acted on by the combined effects of Earth's motions and energy from the Sun, our planet's formless and invisible envelope of air reacts by producing an infinite variety of weather, which in turn creates the basic pattern of global climates. Although not identical, weather and climate have much in common.

Weather is constantly changing, sometimes from hour to hour and at other times from day to day. It is a term that refers to the state of the atmosphere at a given time and place. Whereas changes in the weather are continuous and sometimes seemingly erratic, it is nevertheless possible to arrive at a generalization of these variations. Such a description of aggregate weather conditions is termed **climate.** It is based on observations that have been accumulated over many decades. Climate is often defined simply as "average weather," but this is an inadequate definition. In order to more accurately portray the character of an area, variations and extremes must also be included, as well as the probabilities that such departures will take place. For example, it is not only necessary for farmers to know the average rainfall during the growing season, but it is also important to know the frequency of extremely wet and extremely dry years. Thus, climate is the sum of all statistical weather information that helps describe a place or region.

Maps similar to the one in Figure 1–2 are familiar to everyone who checks the weather report in the morning newspaper or on a local television station. In addition to showing predicted high temperatures for the day, this map shows other basic weather information about cloud cover, precipitation, and fronts.

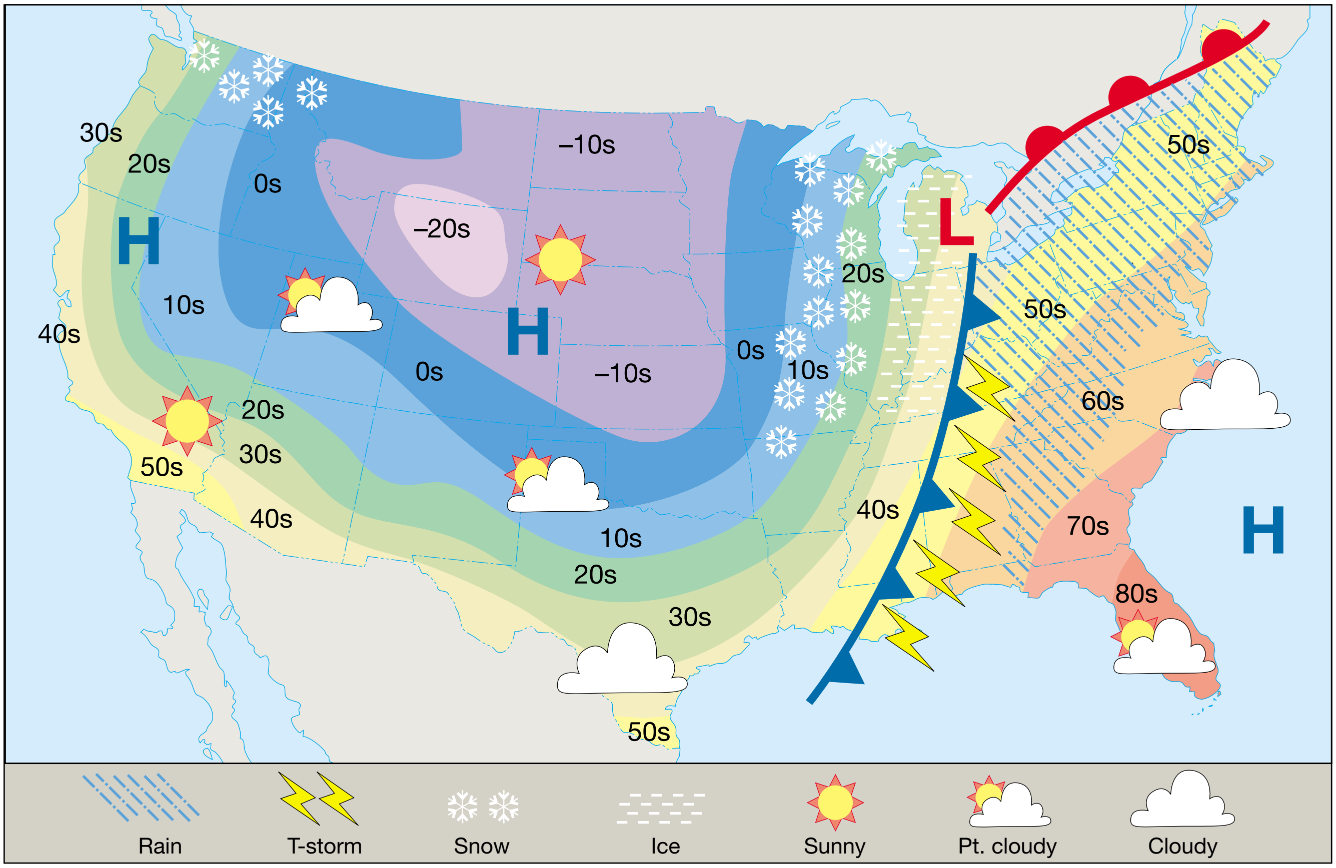


FIGURE 1–2 A typical newspaper weather map for a day in late December. The temperatures shown on the map are the highs forecast for the day.

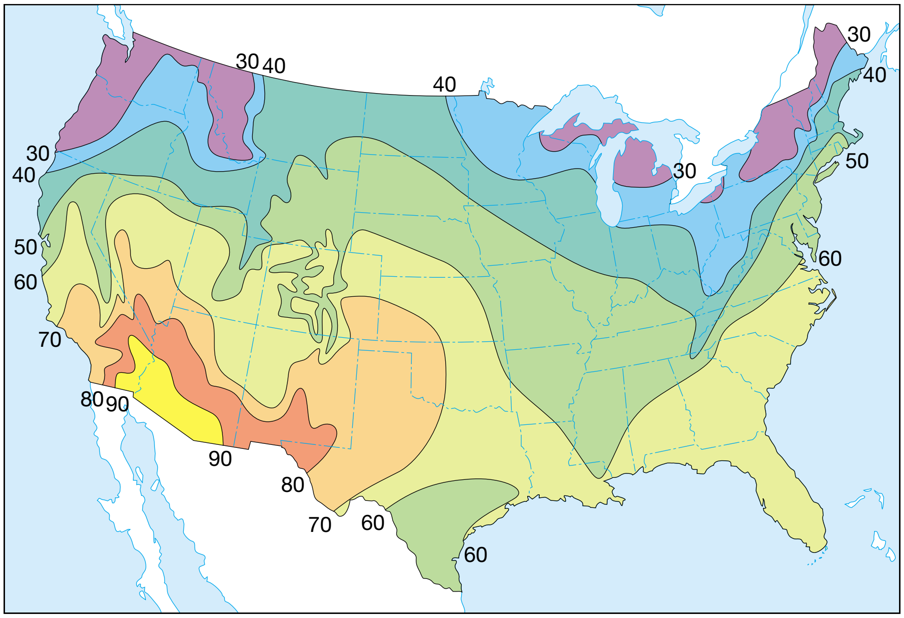


FIGURE 1–3 Mean percentage of possible sunshine for November. Southern Arizona is clearly the sunniest area. By contrast, parts of the Pacific Northwest receive a much smaller percentage of the possible sunshine. Climate maps such as this one are based on many years of data.

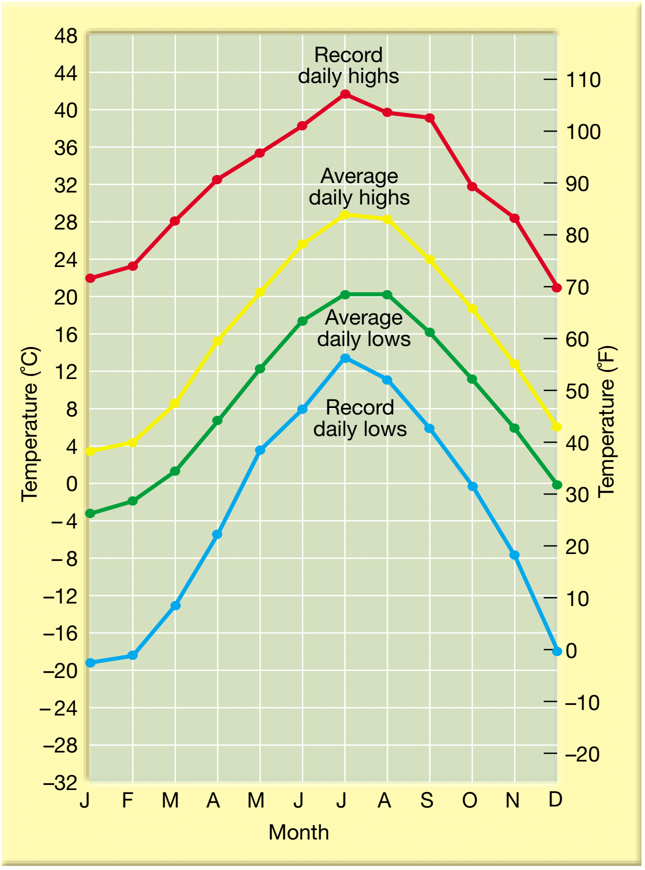


FIGURE 1–4 Graph showing daily temperature data for New York City. In addition to the average daily maximum and minimum temperatures for each month, extremes are also shown. As this graph shows, there can be significant departures from the average.

Suppose you were planning a vacation trip to an unfamiliar place. You would probably want to know what kind of weather to expect. Such information would help as you selected clothes to pack and could influence decisions regarding activities you might engage in during your stay. Unfortunately, weather forecasts that go beyond a few days are not very dependable. Thus, it would not be possible to get a reliable weather report about the conditions you are likely to encounter during your vacation.

Instead, you might ask someone who is familiar with the area about what kind of weather to expect. "Are thunderstorms common?" "Does it get cold at night?" "Are the afternoons sunny?" What you are seeking is information about the climate, the conditions that are typical for that place. Another useful source of such information is the great variety of climate tables, maps, and graphs that are available. For example, the map in Figure 1–3 shows the average percentage of possible sunshine in the United States for the month of November, whereas the graph in Figure 1–4 shows average daily high and low temperatures for each month, as well as extremes for New York City.

Such information could no doubt help as you planned your trip. But it is important to realize that *climate data cannot predict the weather*. Although the place may usually (climatically) be warm, sunny, and dry during the time of your planned vacation, you may actually experience cool, overcast, and rainy weather. There is a well-known saying that summarizes this idea: "Climate is what you expect, but weather is what you get."

The nature of both weather and climate is expressed in terms of the same basic **elements**, those quantities or properties that are measured regularly. The most important are (1) the temperature of the air, (2) the humidity of the air, (3) the type and amount of cloudiness, (4) the type and amount of precipitation, (5) the pressure exerted by the air,

Students Sometimes Ask…

Does meteorology have anything to do with meteors?

Yes, there is a connection. Most people use the word "meteor" when referring to solid particles (meteoroids) that enter Earth's atmosphere from space and "burn up" due to friction ("shooting stars"). The term "meteorology" was coined in 340 BC when the Greek philosopher Aristotle wrote a book entitled *Meteorlogica,* which included explanations of atmospheric and astronomical phenomena. In Aristotle's day *anything* that fell from or was seen in the sky was called a meteor. Today we distinguish between particles of ice or water in the atmosphere (called *hydrometeors*) and extraterrestrial objects called meteoroids or "meteors."

and (6) the speed and direction of the wind. These elements constitute the variables by which weather patterns and climate types are depicted. Although you will study these elements separately at first, keep in mind that they are very much interrelated. A change in one of the elements often produces changes in the others.

Atmospheric Hazards: Assault by the Elements

Natural hazards are a part of living on Earth. Every day they adversely affect literally millions of people worldwide and are responsible for staggering damages. Some, such as earthquakes and volcanic eruptions, are geological. But a greater number are related to the atmosphere.

Occurrences of severe weather have a fascination that ordinary weather phenomena cannot provide. A spectacular lightning display generated by a severe thunderstorm can elicit both awe and fear. Of course, hurricanes and tornadoes attract a great deal of much deserved attention (Figure 1-5). A single tornado outbreak or hurricane can cause billions of dollars in property damage, much human suffering, and many deaths. For example, the four hurricanes that struck the United States in August and September 2004 collectively caused more than $40 billion in damages and 152 deaths. These figures were surpassed in 2005 when Hurricane Katrina struck. Estimates for this single storm are staggering. Although imprecise, the final accounting may approach $300 billion, with more than 1300 deaths.

In a typical year the United States experiences thousands of violent thunderstorms, hundreds of floods and tornadoes, and several hurricanes. According to the National Weather Service, during the 30-year span 1975–2004, tornadoes took an average of 65 lives each year, whereas hurricanes were responsible for about one-quarter as many deaths. Surprisingly (to many), lightning and flash floods were deadlier. During the 1975–2004 period, lightning annually claimed 66 lives, and floods were responsible for an average of 107 fatalities each year.

Of course, there are other atmospheric hazards that adversely affect us. Some are storm-related, such as blizzards, hail, and freezing rain. Others are not the direct result of a storm. Heat waves, cold waves, and drought are important examples. In some years the loss of human life due to excessive heat or bitter cold exceeds that caused by all other weather events combined. Moreover, although severe storms and floods usually generate more attention, droughts can be just as devastating and carry an even bigger price tag.

FIGURE 1–5 The awesome power of a tornado is obvious in this image. Many people have incorrect perceptions of weather dangers and are unaware of the relative differences of weather threats to human life. For example, they are awed by the threat of hurricanes and tornadoes and plan accordingly on how to respond (e.g. "Tornado Awareness Week" each spring), but they fail to realize that lightning or winter storms can be greater threats. *(Photo by Alan R. Moller/Getty Images Inc.-Stone Allstock)*

Between 1980 and 2004 the United States experienced 62 weather-related disasters in which overall damages and costs reached or exceeded $1 billion (Figure 1-6). The combined costs of these events exceeded $390 billion (normalized to 2002 dollars)! Table 1–1 lists the 25 "billion-dollar weather disasters" that occurred during the span 1998 through 2004. As you can see, although hurricanes, tornadoes, and floods stand out, ice storms, drought, heat waves, and hail also figure prominently.

At appropriate places throughout this book you will have an opportunity to learn about atmospheric hazards. Two entire chapters (Chapter 10, Thunderstorms and Tornadoes, and Chapter 11, Hurricanes) focus almost entirely on hazardous weather. In addition, a number of the book's special-interest boxes are devoted to a broad variety of atmospheric hazards, including heat waves, winter storms, floods, dust storms, drought, mudslides, and lightning. To alert you to these discussions, each of the boxes that examines an atmospheric hazard is identified by the same small icon you see at the beginning of this section.

Every day our planet experiences an incredible assault by the atmosphere, so it is important to develop an awareness and understanding of these significant weather events.

Students Sometimes Ask…

According to the graph in Figure 1–6, a single weather event in 1988 caused the greatest total damage for any of the years shown. What was the event?

The costly event was a summer drought and heat wave in the central and eastern U.S., with severe losses to agriculture and related industries. There were also up to 10,000 heat-related deaths. The second-ranking year, 1980, experienced a similar event.

The Nature of Scientific Inquiry

All science is based on the assumption that the natural world behaves in a consistent and predictable manner that is comprehensible through careful, systematic study. The overall goal of science is to discover the underlying patterns in nature and then to use this knowledge to make predictions about what should or should not be expected, given certain facts or circumstances. For example, by understanding the processes and conditions that produce certain cloud types, meteorologists are often able to predict the approximate time and place of their formation.

The development of new scientific knowledge involves some basic logical processes that are universally accepted. To determine what is occurring in the natural world, scientists collect scientific *facts* through observation and measurement. Because some error is inevitable, the accuracy of a particular measurement or observation is always open to question. Nevertheless, these data are essential to science and serve as the springboard for the development of scientific theories.

Hypothesis

Once facts have been gathered and principles have been formulated to describe a natural phenomenon, investigators try to explain how or why things happen in the manner observed. They often do this by constructing a tentative (or untested) explanation, which is called a scientific **hypothesis** or **model.** (The term model, although often used synonymously with hypothesis, is a less precise term because it is sometimes used to describe a scientific theory as well.) It is best if an investigator can formulate more than one hypothesis to explain a given set of observations. If an individual scientist is unable to devise multiple models, others in the scientific community will almost always develop alternative explanations. A spirited debate frequently ensues. As a result, extensive research is conducted by proponents of opposing models, and the results are made available to the wider scientific community in scientific journals.

Before a hypothesis can become an accepted part of scientific knowledge, it must pass objective testing and analysis. (If a hypothesis cannot be tested, it is not scientifically useful, no matter how interesting it might seem.) The verification process requires that *predictions* be made based on the model being considered and the predictions be tested by comparing them against objective observations of nature. Put another way, hypotheses must fit observations other than those used to formulate them in the first place. Those hypotheses that fail rigorous testing are ultimately discarded. The history of science is littered with discarded hypotheses. One of the best known is the Earth-centered model of the universe—a proposal that was supported by the apparent daily motion of the Sun, Moon, and stars around Earth. As the mathematician Jacob Bronowski so ably stated, "Science is a great many things, but in the end they all return to this: Science is the acceptance of what works and the rejection of what does not."

Theory

When a hypothesis has survived extensive scrutiny and when competing models have been eliminated, a hypothesis may be elevated to the status of a scientific **theory.** In everyday language we may say, "That's only a theory." But a scientific theory is a well-tested and widely accepted view that the scientific community agrees best explains certain observable facts.

Scientific theories, like scientific hypotheses, are accepted only provisionally. It is always possible that a theory that has withstood previous testing may eventually be modified or completely disproved. As theories survive more testing, they are regarded with higher levels of confidence. Theories that have withstood extensive testing, such as the

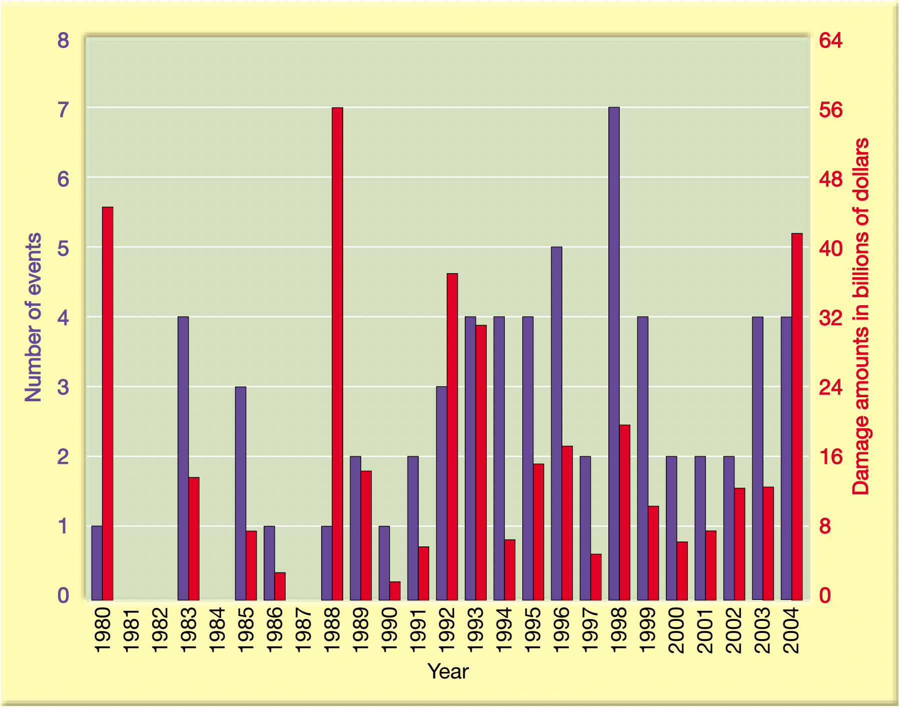


FIGURE 1–6 Between 1980 and 2004 the United States sustained 62 weather-related disasters in which overall damages and costs reached or exceeded $1 billion. This bar graph shows the number of events that occurred each year and the damage amounts in billions of dollars (normalized to 2002 dollars). The total losses for the 62 events exceeded $390 billion! *(After NOAA)*

TABLE 1-1 Billion-dollar weather events 1998–2004*

Event	Date	Damage/Costs†	Fatalities
Hurricane Jeanne	September 2004	$6.5 billion	28
Hurricane Ivan	September 2004	$12 billion	52
Hurricane Frances	September 2004	$9 billion	38
Hurricane Charley	August 2004	$14 billion	34
Southern California Wildfires (drought and winds)	October-November 2003	$2.5 billion	22
Hurricane Isabel	September 2003	$5 billion	55
Severe Storms and Tornadoes in Midwest and South	May 2003	$3.4 billion	51
Severe Storms and Hail in Midwest and South	April 2003	$1.6 billion	3
Drought in 30 states	Spring-Fall 2002	$10 billion	0
Western Fire Season (drought and winds)	Summer 2002	$2 billion	21
Tropical Storm Allison	June 2001	$5.1 billion	43
Midwest and Ohio Valley Hail and Tornadoes	April 2001	$1.9 billion	3
Drought/Heat Wave in South	Spring-Summer 2000	$4.2 billion	140
Western Fire Season (drought and winds)	Summer 2000	$2.1 billion	0
Hurricane Floyd	September 1999	$6.5 billion	77
Eastern Drought and Heat Wave	Summer 1999	$1.1 billion	256
Oklahoma-Kansas Tornadoes	May 1999	$1.7 billion	55
Arkansas-Tennessee Tornadoes	January 1999	$1.4 billion	17
Texas Flooding	October-November 1998	$1.1 billion	31
Hurricane Georges	September 1998	$6.5 billion	16
Hurricane Bonnie	August 1998	$1.1 billion	3
Southern Drought and Heat Wave	Summer 1998	$6.6-9.9 billion	200
Minnesota Severe Storm/Hail	May 1998	$1.7 billion	1
Southeast Severe Weather (tornadoes and floods)	Winter-Spring 1998	$1.1 billion	132
Northeast ice storm	January 1998	$1.5 billion	16

*Source: National Climatic Data Center/NOAA
†To allow for more accurate comparison, dollar amounts are normalized to 2002.

FIGURE 1–7 Gathering data is a basic part of the scientific method. This Automated Surface Observing System (ASOS) installation is one of nearly 900 in use for data gathering as part of the U.S. primary surface observing network. For more on ASOS, see Figure 12–4, p. 350. *(Source: Bobbe Christopherson)*

theory of plate tectonics and the theory of evolution, are held with a very high degree of confidence.

Scientific Methods

The processes just described, in which scientists gather facts through observations and formulate scientific hypotheses and theories, is called the *scientific method.* Contrary to popular belief, the scientific method is not a standard recipe that scientists apply in a routine manner to unravel the secrets of our natural world. Rather, it is an endeavor that involves creativity and insight. Rutherford and Ahlgren put it this way: "Inventing hypotheses or theories to imagine how the world works and then figuring out how they can be put to the test of reality is as creative as writing poetry, composing music, or designing skyscrapers."*

There is no fixed path that scientists always follow that leads unerringly to scientific knowledge. Nevertheless, many scientific investigations involve the following steps: (1) collection of scientific facts (data) through observation and measurement (Figure 1–7); (2) development of one or more working hypotheses or models to explain these facts; (3) development of observations and experiments to test the hypotheses; and (4) the acceptance, modification, or rejection of the hypotheses based on extensive testing.

Other scientific discoveries may result from purely theoretical ideas that stand up to extensive examination. Some researchers use high-speed computers to simulate what is happening in the "real" world. These models are useful when dealing with natural processes that occur on very long time scale, or take place in extreme or inaccessible locations. Still other scientific advancements have been made when a totally unexpected happening occurred during an experiment. These serendipitous discoveries are more than pure luck; for as Louis Pasteur stated, "In the field of observation, chance favors only the prepared mind."

Scientific knowledge is acquired through several avenues, so it might be best to describe the nature of scientific inquiry as the *methods* of science rather than *the* scientific method. In addition, it should always be remembered that even the most compelling scientific theories are still simplified explanations of the natural world.

Students Sometimes Ask…

In class you compared a hypothesis to a theory. How is each one different from a scientific law?

A *scientific law* is a basic principle that describes a particular behavior of nature that is generally narrow in scope and can be stated briefly—often as a simple mathematical equation. Because scientific laws have been shown time and time again to be consistent with observations and measurements, they are rarely discarded. Laws may, however, require modifications to fit new findings. For example, Newton's laws of motion are still useful for everyday applications (NASA uses them to calculate satellite trajectories), but they do not work at velocities approaching the speed of light. For these circumstances, they have been supplanted by Einstein's theory of relativity.

Observing the Atmosphere

Scientific study of the atmosphere began in the seventeenth century as instruments were developed to measure different elements. The instruments provided data that helped observers begin to gain an understanding of atmospheric processes. In 1593 Galileo invented an early version of the thermometer, and in 1643 Torricelli built the first barometer (for measuring air pressure). By 1661 Robert Boyle discovered the basic relationship between pressure and volume in a gas. During the eighteenth century, instruments were improved and standardized, and extensive data collection began. The acquisition of such data was fundamental to the study of physical processes and the development of explanations about atmospheric phenomena.

It became obvious to those studying the atmosphere that gathering data from only ground-level sites significantly limited understanding. In the late 1700s the only data for conditions at high altitudes came from observations made in the mountains. In 1752 Benjamin Franklin, using a kite, made his famous discovery that lightning is an electrical discharge. Not many years later, kites were being used to

*F. James Rutherford and Andrew Ahlgren, *Science for All Americans* (New York: Oxford University Press, 1990), p. 7.

observe temperatures above the surface. In the late eighteenth century, manned balloons were used in an attempt to investigate the composition and properties of the "upper" atmosphere. Although several manned ascents were attempted over the years, they were dangerous undertakings. Unmanned balloons, on the other hand, could rise to higher altitudes, but there was no assurance that the instruments carried aloft would be recovered. Notwithstanding the difficulties and dangers, considerable data were gathered on the nature of the air above.

Today balloons continue to play a significant role in the systematic investigation of the atmosphere. Giant balloons are launched regularly, primarily for research purposes (Figure 1–8a). Such balloons can stay aloft for extended periods and represent an important means of carrying monitoring instruments into the region of the atmosphere known as the stratosphere.

Since the late 1920s balloons have carried aloft **radiosondes.** These lightweight packages of instruments are fitted with radio transmitters that send back data on temperature, pressure, and relative humidity in the lower portions of the atmosphere (Figure 1–8b). Radiosondes are sent aloft twice daily from an extensive network of stations worldwide. The data that they supply are essential for making accurate weather forecasts.

Other important means for exploring the atmosphere include rockets and airplanes. After World War II, rockets revolutionized the study of the upper atmosphere. Prior to this time, knowledge of the atmosphere beyond about 30 kilometers (20 miles) came almost exclusively from indirect ground-based measurements. Airplanes also play a significant role in atmospheric studies. High-flying aircraft are capable of reaching portions of the stratosphere. Others are designed to measure such relatively small-scale yet complex phenomena as cloud systems or to fly directly into hurricanes to monitor their current state of development.

Among the methods of studying the atmosphere that are best known to the general public and most useful to atmospheric scientists are weather radar and satellites. Today, when we watch a television weather report, we expect to see satellite images that show moving cloud patterns and radar displays that depict the intensity and regional extent of precipitation (Figure 1–9). Recent technological advances greatly enhance the value of weather radar for the purpose of storm detection, warning, and research. Meteorological satellites give us a perspective of the atmosphere that is unique

(a) (b)

FIGURE 1–8 Exploring the atmosphere using balloons. (a) Giant balloons such as this one are filled with helium and carry instrument packages high into the atmosphere. *(Source: University Corporation for Atmospheric Research/National Center for Atmospheric Research/National Science Foundation)* (b) A lightweight package of instruments, the radiosonde, is carried aloft by a small weather balloon. *(Photo by Mark Burnett/Photo Researchers, Inc.)*

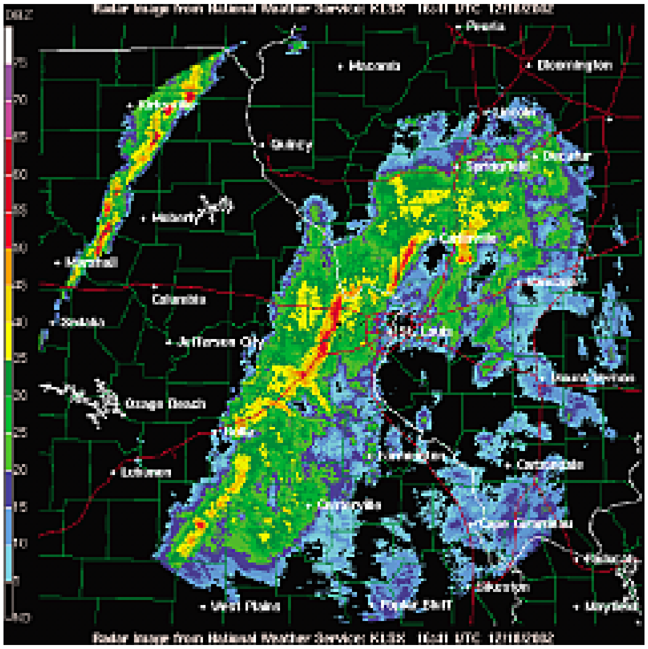


FIGURE 1–9 Radar images show the distribution and intensity of precipitation. This National Weather Service image shows the St. Louis, Missouri, region on the morning of December 18, 2002. The unusual spring-like weather included heavy rain, severe thunderstorms, and a tornado watch. (National Weather Service)

and invaluable. For example, they provide images that allow us to study the distribution of clouds and the circulation patterns that they reveal (Figure 1–10). Moreover, they let us see the structure and determine the speed of weather systems over the oceans and other regions where observations are scanty or nonexistent. One obvious benefit is that storms can be detected early and tracked with great precision.

In addition to enabling us to monitor storms from space, instruments aboard modern satellites permit us to measure and monitor many variables including winds, solar radiation, temperatures, precipitation, and changes in atmostpheric composition. Box 1–1 briefly describes one of these modern research satellites, the Tropical Rainfall Measuring Mission (TRMM). Moreover, data relating to phenomena such as the extent of sea ice and glaciers, ocean circulation, vegetative cover, and many other variables are gathered from space.

Students Sometimes Ask…

Who provides all of the data needed to prepare a weather forecast?

Data from every part of the globe are needed to produce accurate weather forecasts. The World Meteorological Organization (WMO) was established by the United Nations to coordinate scientific activity related to weather and climate. It consists of 187 member states and territories representing all parts of the globe. Its World Weather Watch provides up-to-the-minute standardized observations through member-operated observation systems. This global system involves 10 satellites, 10,000 land-observation and 7000 ship stations, as well as hundreds of automated data buoys and thousands of aircraft.

The Atmosphere: A Part of the Earth System

GEODe ATMOSPHERE **Introduction to the Atmosphere**
▸ A View of Earth

A view such as the one in Figure 1–11a provided the *Apollo 8* astronauts as well as the rest of humanity with a unique perspective of our home. Seen from space, Earth is

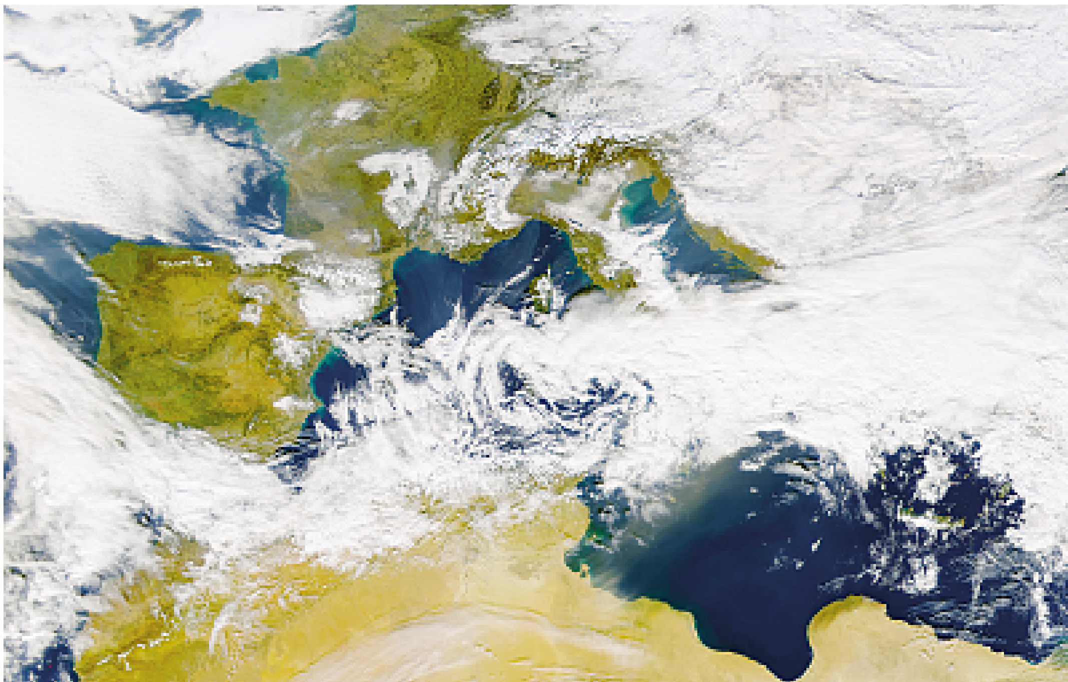


FIGURE 1–10 Satellites are invaluable tools for tracking storms and gathering atmospheric data. This image shows severe winter storms that swept across much of Europe on December 16, 2001, delivering bitter cold temperatures, high winds, heavy snowfall, and flooding in some regions. Transportation via road and rail was brought to a halt in parts of many countries while tens of thousands of people were left without power. *(Image provided by ORBIMAGE. © Orbital Imaging Corporation and processing by NASA Goddard Space Flight Center)*

BOX 1-1 Monitoring Earth From Space

Scientific facts are gathered in many ways, including laboratory experiments and field observations and measurements. Satellites provide another very important source of data. Satellite images give us perspectives that are difficult to gain from more traditional sources. Moreover, the high-tech instruments aboard many satellites enable scientists to gather information from remote regions where data are otherwise scarce.

The image in Figure 1–A is from NASA's *Tropical Rainfall Measuring Mission* (TRMM). TRMM is a research satellite designed to expand our understanding of the hydrologic cycle and its role in our climate system. By covering the region between the latitudes 35°N and 35°S, it provides much needed data on rainfall and the heat release associated with rainfall. Many types of measurements and images are possible.

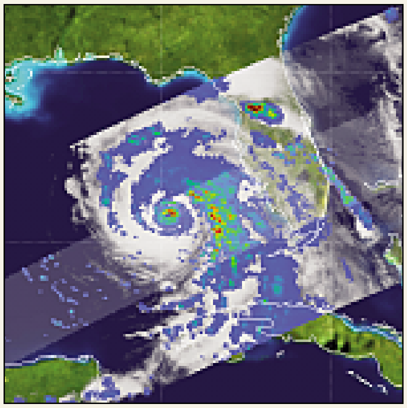


FIGURE 1–A Satellite image of Hurricane Dennis at 5:59 pm EDT on July 9, 2005. This image of Hurricane Dennis shows the pattern of rainfall intensity. Dark red indicates intense rainfall rates of 50 millimeters (2 inches) per hour. *(NASA/TRMM image)*

The map in Figure 1–B was made using data from the TRMM satellite. In addition to data for land areas, this satellite provides extremely precise measurements of rainfall over the oceans where conventional land-based instruments cannot see. This is especially important because much of Earth's rain falls in ocean-covered tropical areas, and a great deal of the globe's weather-producing energy comes from heat exchanges involved in the rainfall process. Until the TRMM, information on the intensity and amount of rainfall over the tropics was scanty. Such data are crucial to understanding and predicting global climate change.

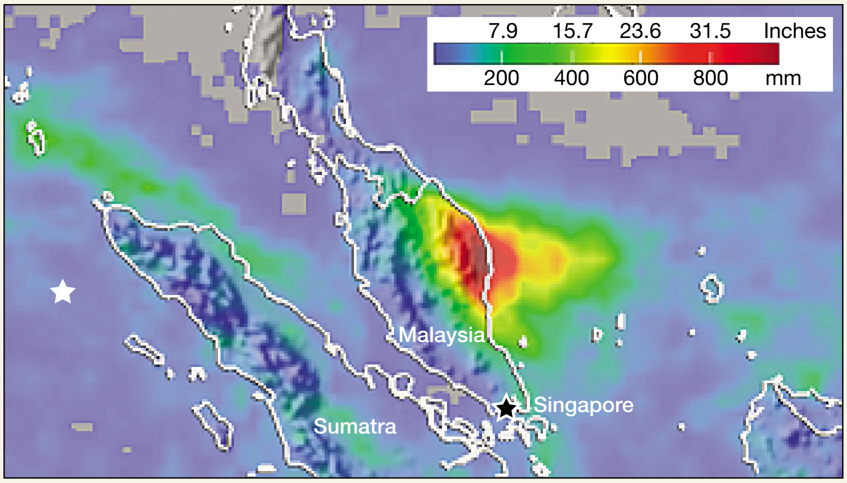


FIGURE 1–B This map of rainfall for December 7–13, 2004, in Malaysia was constructed using TRMM data. Over 800 millimeters (32 inches) of rain fell along the east coast of the peninsula (darkest red area). The extraordinary rains caused extensive flooding and triggered many mudflows. *(NASA/TRMM image)*

breathtaking in its beauty and startling in its solitude. Such an image reminds us that our home is, after all, a planet—small, self-contained, and in some ways even fragile.

As we look closely at our planet from space, it becomes apparent that Earth is much more than rock and soil. In fact, the most conspicuous features in Figure 1–11a are not continents but swirling clouds suspended above the surface of the vast global ocean. These features emphasize the importance of water on our planet.

The closer view of Earth from space shown in Figure 1–11b helps us appreciate why the physical environment is traditionally divided into three major parts: the solid Earth, the water portion of our planet, and Earth's gaseous envelope. In addition, our physical environment supports a vast array of life forms that constitute a fourth major part of our planet.

It should be emphasized that our environment is highly integrated and is not dominated by rock, water, or air alone. It is instead characterized by continuous interactions as air comes in contact with rock, rock with water, and water with air.

Figure 1–12 provides us with one easy-to-visualize example. The shoreline is an obvious meeting place for rock, water, and air. In this scene, ocean waves that were created by the drag of air moving across the water are breaking against the rocky shore. The force of the water can be powerful, and the erosional work that is accomplished can be great.

Earth's Four Spheres

On a human scale Earth is huge. Its surface area occupies 500,000,000 square kilometers (193 million square miles). As indicated, we divide this vast planet into four independent parts. Because each part loosely occupies a shell around Earth, we call them spheres. The four spheres include the *geosphere* (solid Earth), the *atmosphere* (gaseous envelope), the *hydrosphere* (water portion), and the *biosphere* (life). It is important to remember that these spheres are not separated by well-defined boundaries; rather, each sphere is intertwined with all of the others. In addition, each of Earth's four major spheres can be thought of as being composed of numerous interrelated parts.

The Geosphere. Lying beneath the atmosphere and the ocean is the solid Earth or **geosphere.** The geosphere extends from the surface to the center of the planet, a depth of about 6400 kilometers (nearly 4000 miles), making it by far the largest of Earth's four spheres.

Based on compositional differences, the geosphere is divided into three principal regions: the dense inner sphere, called the *core;* the less dense *mantle;* and the *crust,* which is the light and very thin outer skin of Earth. Soil, the thin veneer of material at Earth's surface that supports the growth of plants, may be thought of as part of all four spheres. The solid portion is a mixture of weathered rock debris (geosphere) and organic matter from decayed plant and animal life (biosphere). The decomposed and disintegrated rock debris is the product of weathering processes that require air (atmosphere) and water (hydrosphere). Air and water also occupy the open spaces between the solid particles.

The Atmosphere. Earth is surrounded by a life-giving gaseous envelope called the **atmosphere.** When we view the atmosphere from the ground, it seems to be very deep (Figure 1–13). However, when compared to the thickness (radius) of the solid Earth (about 6400 kilometers or 4000 miles), the atmosphere is a very shallow layer. More than 99 percent of the atmosphere is within 30 kilometers (20 miles) of Earth's surface. This thin blanket of air is nevertheless an integral part of the planet. It not only provides the air that we breathe but also acts to protect us from the dangerous radiation emitted by the Sun. The energy exchanges that continually occur between the atmosphere and Earth's surface and between the atmosphere and space produce the effects we call *weather*. If, like the Moon, Earth had no atmosphere, our planet would not only be lifeless, but many of the processes and interactions that make the surface such a dynamic place could not operate.

The Hydrosphere. Earth is sometimes called the *blue planet*. Water more than anything else makes Earth unique. The **hydrosphere** is a dynamic mass that is continually on the move, evaporating from the oceans to the atmosphere, precipitating to the land, and running back to the ocean again. The global ocean is certainly the most prominent feature of the hydrosphere, blanketing nearly 71 percent of Earth's surface to an average depth of about 3800 meters (12,500 feet). It accounts for about 97 percent of Earth's water (Figure 1–14). However, the hydrosphere also includes the fresh water found in clouds, streams, lakes, and glaciers, as well as that found underground.

Although these latter sources constitute just a tiny fraction of the total, they are much more important than their meager percentage indicates. Clouds, of course, play a vital role in many weather and climate processes. In addition to providing the fresh water that is so vital to life on the land, streams, glaciers, and groundwater are responsible for sculpturing and creating many of our planet's varied landforms.

The Biosphere. The **biosphere** includes all life on Earth. Ocean life is concentrated in the sunlit surface waters of the sea. Most life on land is also concentrated near the surface, with tree roots and burrowing animals reaching a few meters underground and flying insects and birds reaching a kilometer or so above the surface. A surprising variety of life forms are also adapted to extreme environments. For example, on the ocean floor, where pressures are extreme and no light penetrates, there are places where vents spew hot, mineral-rich fluids that support communities of exotic life forms. On land, some bacteria thrive in rocks as deep as 4 kilometers (2.5 miles) and in boiling hot springs. Moreover, air currents can carry microorganisms many kilometers into the atmosphere. But even when we consider these extremes, life still must be thought of as being confined to a narrow band very near Earth's surface.

(a)

(b)

FIGURE 1–11 (a) View that greeted the *Apollo 8* astronauts as their spacecraft emerged from behind the Moon. (NASA Headquarters) (b) Africa and Arabia are prominent in this image of Earth taken from *Apollo 17.* The tan cloud-free zones over the land coincide with major desert regions. The band of clouds across central Africa is associated with a much wetter climate that in places sustains tropical rain forests. The dark blue of the oceans and the swirling cloud patterns remind us of the importance of the oceans and the atmosphere. Antarctica, a continent covered by glacial ice, is visible at the South Pole. *(Courtesy of NASA/Science Source/Photo Researchers, Inc.)*

FIGURE 1–12 The shoreline is one obvious example of an *interface*—a common boundary where different parts of a system interact. In this scene, ocean waves (*hydrosphere*) that were created by the force of moving air (*atmosphere*) break against California's rocky Big Sur shore (*geosphere*). *(Photo by Carr Clifton).*

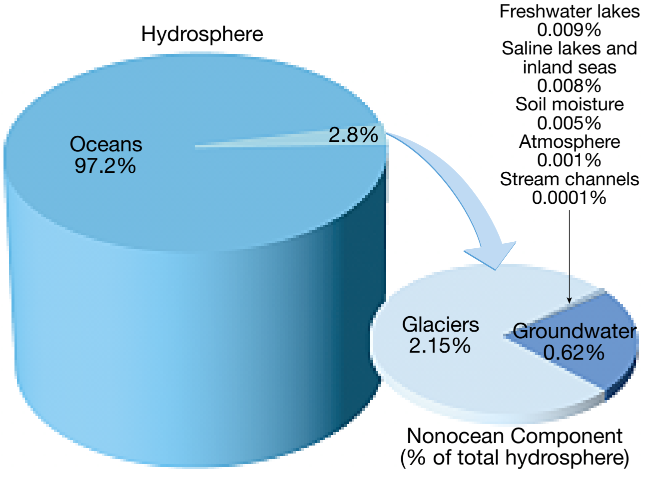
FIGURE 1–13 This jet is flying high in the atmosphere at an altitude of more than 9000 meters (30,000 feet). More than two-thirds of the atmosphere is below this height. To someone on the ground, the atmosphere seems very deep. However, when compared to the thickness (radius) of the solid Earth, the atmosphere is a very shallow layer. *(Photo by Warren Faidley/Weatherstock.)*

Plants and animals depend on the physical environment for the basics of life. However, organisms do more than just respond to their physical environment. Through countless interactions, life forms help maintain and alter their physical environment. Without life, the makeup and nature of the geosphere, hydrosphere, and atmosphere would be very different.

Earth System Science

Anyone who studies Earth soon learns that our planet is a dynamic body with many separate but highly interactive parts or *spheres*. The atmosphere, hydrosphere, biosphere, and geosphere and all of their components can be studied separately. However, the parts are not isolated. Each is related in some way to the others to produce a complex and continuously interacting whole that we call the *Earth system.*

FIGURE 1–14 Distribution of Earth's water. Obviously most of Earth's water is in the oceans. Glacial ice represents about 85 percent of all the water *outside* the oceans. When only *liquid freshwater* is considered, more than 90 percent is groundwater.



A simple example of the interactions among different parts of the Earth system occurs every winter as moisture evaporates from the Pacific Ocean and subsequently falls as rain in the hills of southern California, triggering destructive landslides such as the one pictured in Figure 1–1c. The processes that move water from the hydrosphere to the atmosphere and then to the solid Earth have a profound impact on the plants and animals (including humans) that inhabit the affected regions.

Scientists have recognized that in order to more fully understand our planet, they must learn how its individual components (land, water, air, and life forms) are interconnected. This endeavor, called *Earth system science*, aims to study Earth as a *system* composed of numerous interacting parts, or *subsystems*. Using an interdisciplinary approach, those who practice Earth system science attempt to achieve the level of understanding necessary to comprehend and solve many of our global environmental problems.

What Is a System? Most of us hear and use the term *system* frequently. We may service our car's cooling *system*, make use of the city's transportation *system*, and be a participant in the political *system*. A news report might inform us of an approaching weather *system*. Further, we know that Earth is just a small part of a larger system known as the *solar system*, which in turn is a subsystem of an even larger system called the Milky Way Galaxy.

Loosely defined, a **system** can be any size group of interacting parts that form a complex whole. Most natural systems are driven by sources of energy that move matter and/or energy from one place to another. A simple analogy is a car's cooling system, which contains a liquid (usually water and antifreeze) that is driven from the engine to the radiator and back again. The role of this system is to transfer heat generated by combustion in the engine to the radiator, where moving air removes it from the system. Hence, the term cooling system.

Systems like a car's cooling system are self-contained with regard to matter and are called **closed systems.** Although energy moves freely in and out of a closed system, no matter (liquid in the case of our auto's cooling system) enters or leaves the system. (This assumes you don't get a leak in your radiator). By contrast, most natural systems are **open systems** and are far more complicated than the foregoing example. In an open system both energy and matter flow into and out of the system. In a weather system such as a hurricane, factors such as the quantity of water vapor available for cloud formation, the amount of heat released by condensing water vapor, and the flow of air into and out of the storm can fluctuate a great deal. At times the storm may strengthen; at other times it may remain stable or weaken.

Feedback Mechanisms. Most natural systems have mechanisms that tend to enhance change, as well as other mechanisms that tend to resist change and thus stabilize the system. For example, when we get too hot, we perspire to cool down. This cooling phenomenon works to stabilize our body temperature and is referred to as a **negative**

feedback mechanism. Negative feedback mechanisms work to maintain the system as it is or, in other words, to maintain the status quo. By contrast, mechanisms that enhance or drive change are called **positive feedback mechanisms.**

Most of Earth's systems, particularly the climate system, contain a wide variety of negative and positive feedback mechanisms. For example, substantial scientific evidence indicates that Earth has entered a period of global warming. One consequence of global warming is that some of the world's glaciers and ice caps have begun to melt. Highly reflective snow- and ice-covered surfaces are gradually being replaced by brown soils, green trees, or blue oceans, all of which are darker, so they absorb more sunlight. The result is a positive feedback that contributes to the warming.

On the other hand, an increase in global temperature also causes greater evaporation of water from Earth's land-sea surface. One result of having more water vapor in the air is an increase in cloud cover. Because cloud tops are white and highly reflective, more sunlight is reflected back to space, which diminishes the amount of sunshine reaching Earth's surface and thus reduces global temperatures. Further, warmer temperatures tend to promote the growth of vegetation. Plants in turn remove carbon dioxide CO_2 from the air. Since carbon dioxide is one of the atmosphere's *greenhouse gases,* its removal has a negative impact on global warming.*

In addition to natural processes, we must also consider the human element. Extensive cutting and clearing of the tropical rain forests and the burning of fossil fuels (oil, natural gas, and coal) result in an increase in atmospheric CO_2. Such activity appears to have contributed to the increase in global temperature that our planet is experiencing. One of the daunting tasks of Earth system scientists is to predict what the climate will be like in the future by taking into account many variables, including technological changes, population trends, and the overall impact of the numerous competing positive and negative feedback mechanisms.

Earth As a System

The Earth system has a nearly endless array of subsystems in which matter is recycled over and over again. One familiar subsystem briefly considered earlier is the *hydrologic cycle* (Figure 1–15). It represents the unending circulation of Earth's water among the hydrosphere, atmosphere, biosphere, and geosphere. Water enters the atmosphere by evaporation from Earth's surface and by transpiration from plants. Water vapor condenses in the atmosphere to form clouds, which in turn produce precipitation that falls back to Earth's surface. Some of the rain that falls onto the land sinks in to be taken up by plants or becomes groundwater, and some flows across the surface toward the ocean.

Energy for the Earth System. The Earth system is powered by energy from two sources. The Sun drives external processes that occur in the atmosphere, hydrosphere, and at Earth's surface. Weather and climate, ocean circulation, and erosional processes are driven by energy from the Sun. Earth's interior is the second source of energy. Heat remaining from when our planet formed, and heat that is continuously generated by decay of radioactive elements powers the internal processes that produce volcanoes, earthquakes, and mountains.

The Parts are Linked. The parts of the Earth system are linked so that a change in one part can produce changes in any or all of the other parts. For example, when a volcano erupts, lava from Earth's interior may flow out at the surface and block a nearby valley. This new obstruction influences the region's drainage system by creating a lake or causing streams to change course. The large quantities of volcanic ash and gases that can be emitted during an eruption might be blown high into the atmosphere and influence the amount of solar energy that can reach Earth's surface. The result could be a drop in air temperatures over the entire hemisphere.

Where the surface is covered by lava flows or a thick layer of volcanic ash, existing soils are buried. This causes the soil-forming processes to begin anew to transform the new surface material into soil (Figure 1–16). The soil that eventually forms will reflect the interactions among many parts of the Earth system—the volcanic parent material, the climate, and the impact of biological activity. Of course, there would also be significant changes in the biosphere. Some organisms and their habitats would be eliminated by the lava and ash, whereas new settings for life, such as the lake, would be created. The potential climate change could also impact sensitive life forms.

The Earth system is characterized by processes that vary on spatial scales from fractions of millimeters to thousands of kilometers. Time scales for Earth's processes range from milliseconds to billions of years. As we learn about Earth, it becomes increasingly clear that despite significant separations in distance or time, many processes are connected, and a change in one component can influence the entire system.

Humans are *part of* the Earth system, a system in which the living and nonliving components are entwined and interconnected. Therefore, our actions produce changes in all of the other parts. When we burn gasoline and coal, dispose of our wastes, and clear the land, we cause other parts of the system to respond, often in unforeseen ways. Throughout this book you will learn about some of Earth's subsystems, including the hydrologic system and the climate system. Remember that these components *and we humans* are all part of the complex interacting whole we call the Earth system.

*Greenhouse gases absorb heat energy emitted by Earth and thus help keep the atmosphere warm.

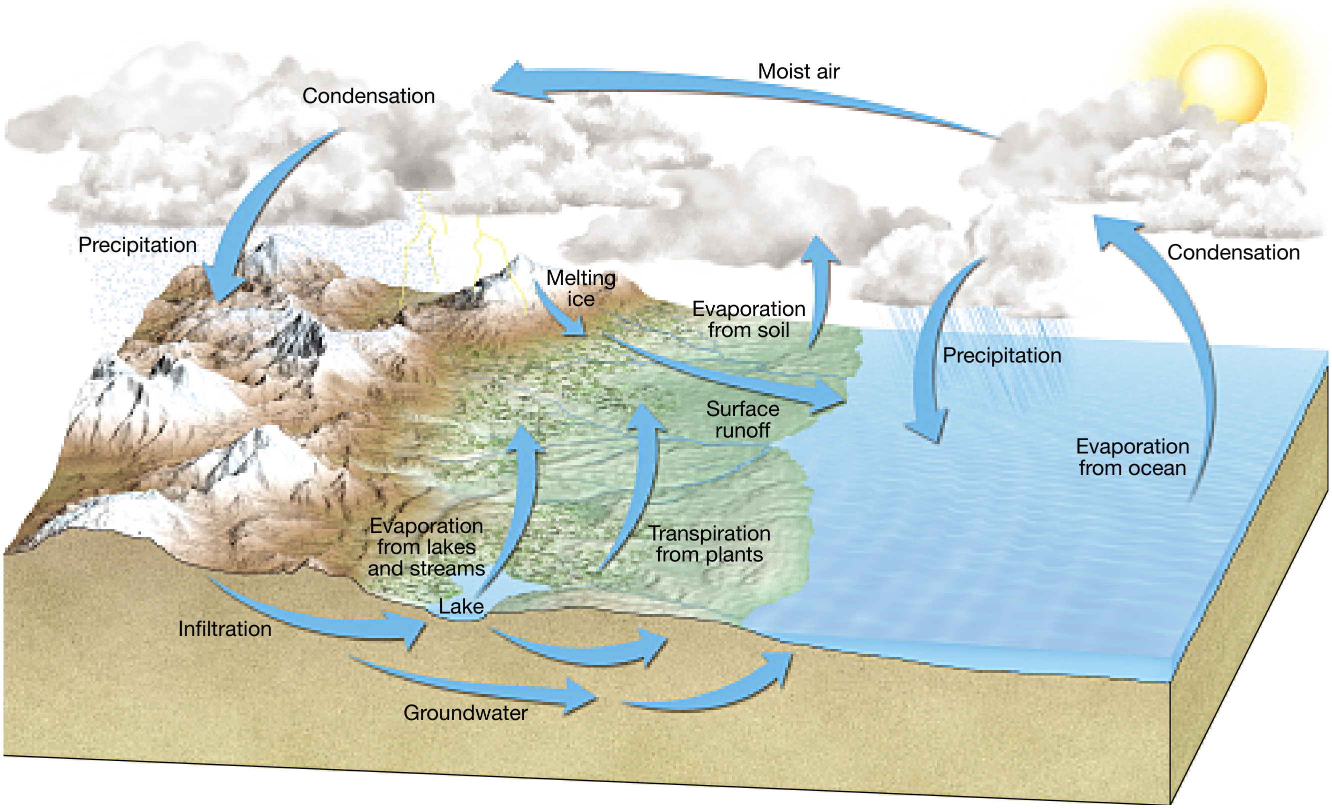


FIGURE 1–15 The hydrologic cycle is just one of Earth's many subsystems. Our planet's water is constantly cycled among all four of Earth's major spheres.

FIGURE 1–16 When Mount St. Helens erupted in May 1980, the area shown here was buried by a volcanic mudflow. Now, plants are reestablished and new soil is forming. *(Photo by Jack Dykinga)*

Composition of the Atmosphere

GEODe ATMOSPHERE **Introduction to the Atmosphere**
▸ A View of Earth

In the days of Aristotle, air was believed to be one of four fundamental substances that could not be further subdivided into constituent components. The other three substances were fire, earth (soil), and water. Even today the term **air** is sometimes used as if it were a specific gas, which of course it is not. The envelope of air that surrounds our planet is a *mixture* of many discrete gases, each with its own physical properties, in which varying quantities of tiny solid and liquid particles are suspended.

Major Components

The composition of air is not constant; it varies from time to time and from place to place (see Box 1–2). If the water vapor, dust, and other variable components were removed from the atmosphere, we would find that its makeup is very stable up to an altitude of about 80 kilometers (50 miles).

As you can see in Figure 1–17 and Table 1–2, two gases—nitrogen and oxygen—make up 99 percent of the volume of clean, dry air. Although these gases are the most

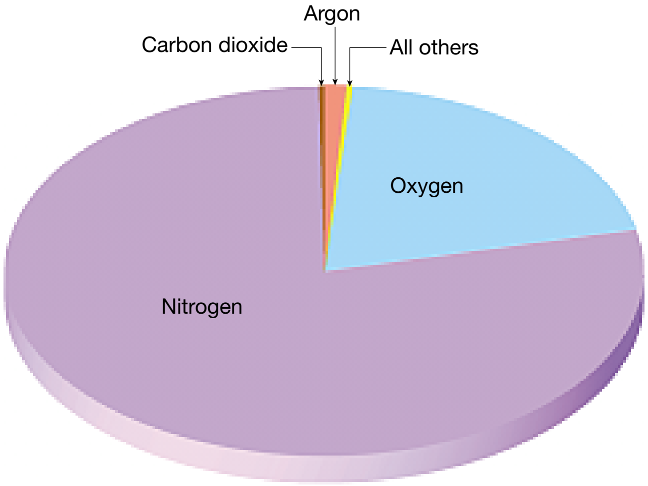


FIGURE 1–17 Proportional volume of gases composing dry air. Nitrogen and oxygen obviously dominate.

plentiful components of the atmosphere and are of great significance to life on Earth, they are of little or no importance in affecting weather phenomena. The remaining 1 percent of dry air is mostly the inert gas argon (0.93 percent) plus tiny quantities of a number of other gases.

Carbon Dioxide

Carbon dioxide, although present in only minute amounts (0.038 percent), is nevertheless a meteorologically important constituent of air. Carbon dioxide is of great interest to meteorologists because it is an efficient absorber of energy emitted by Earth and thus influences the heating of the atmosphere. Although the proportion of carbon dioxide in the atmosphere is relatively uniform, its percentage has been rising steadily for more than a century (Figure 1–18). This rise is attributed to the burning of ever increasing quantities of fossil fuels, such as coal and oil. Some of this additional carbon dioxide is absorbed by the waters of the ocean or is used by plants, but nearly half remains in the air. Estimates project that by sometime in the second half of the twenty-first century, carbon dioxide levels will be twice as high as they were early in the twentieth century.

The precise impact of the increased carbon dioxide is difficult to predict, but most atmospheric scientists agree that it will bring about a warming of the lower atmosphere and thus trigger global climate change. The role of carbon dioxide in the atmosphere and its possible effect on climate are examined in more detail in Chapters 2 and 14.

TABLE 1-2 Principal gases of dry air

Constituent	Percent by volume	Concentration in parts per million (PPM)
Nitrogen (N_2)	78.084	780,840.0
Oxygen (O_2)	20.946	209,460.0
Argon (Ar)	0.934	9,340.0
Carbon dioxide (CO_2)	0.038	380.0
Neon (Ne)	0.00182	18.2
Helium (He)	0.000524	5.24
Methane (CH_4)	0.00015	1.5
Krypton (Kr)	0.000114	1.14
Hydrogen (H_2)	0.00005	0.5

Students Sometimes Ask…

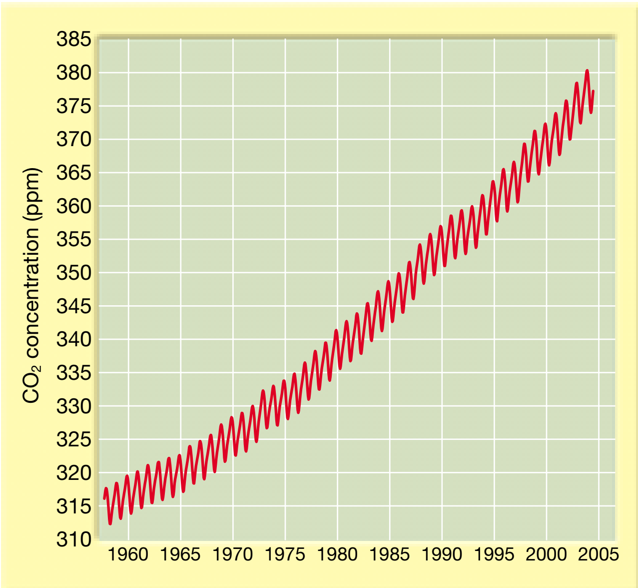
Could you explain a little more about why the graph in Figure 1–18 has so many "ups and downs"?

Sure. Carbon dioxide is removed from the air by photosynthesis, the process by which green plants convert sunlight into chemical energy. In spring and summer, vigorous plant growth removes carbon dioxide from the atmosphere, so the graph takes a dip. As winter approaches, many plants die or shed leaves. The decay of organic matter returns carbon dioxide to the air, causing the graph to spike upward.

Variable Components

Air includes many gases and particles that vary significantly from time to time and place to place. Important examples include water vapor, dust particles, and ozone. Although usually present in small percentages, they can have significant effects on weather and climate.

FIGURE 1–18 Changes in the atmosphere's carbon dioxide (CO_2) as measured at Hawaii's Mauna Loa Observatory. The oscillations reflect the seasonal variations in plant growth and decay in the Northern Hemisphere.



BOX 1-2 Earth's Atmosphere Evolves

Earth's atmosphere is unlike that of any other body in the solar system. No other planet exhibits the same life-sustaining mixture of gases as Earth. Today the air you breathe is a stable mixture of 78 percent nitrogen, almost 21 percent oxygen, about 1 percent argon (an inert gas), and trace gases like carbon dioxide and water vapor. But our planet's original atmosphere, several billion years ago, was far different.

Earth's very earliest atmosphere probably was swept into space by the *solar wind*, a vast stream of particles emitted by the Sun. As Earth slowly cooled, a more enduring atmosphere formed. The molten surface solidified into a crust, and gases that had been dissolved in the molten rock were gradually released, a process called *outgassing*. Outgassing continues today from hundreds of active volcanoes worldwide. Thus, geologists hypothesize that Earth's original atmosphere was made up of gases similar to those released in volcanic emissions today: water vapor, carbon dioxide, nitrogen, and several trace gases.

As the planet continued to cool, the water vapor condensed to form clouds, and great rains commenced. At first the water evaporated in the hot air before reaching the ground, or quickly boiled away upon contacting the surface, just like water sprayed on a hot grill. This accelerated the cooling of Earth's crust. When the surface had cooled below water's boiling point (100°C, or 212°C), torrential rains slowly filled low areas, forming the oceans. This reduced not only the water vapor in the air but also the amount of carbon dioxide, for it became dissolved in the water. What remained was a nitrogen-rich atmosphere.

If Earth's primitive atmosphere resulted from volcanic outgassing, we have a quandary, because volcanoes do not emit free oxygen. Where did the very significant percentage of oxygen in our present atmosphere (nearly 21 percent) come from?

The major source of oxygen is green plants (Figure 1–C). Put another way, *life itself* has strongly influenced the composition of our present atmosphere. Plants did not just adapt to their environment; they actually influenced it, dramatically altering the composition of the entire planet's atmosphere by using carbon dioxide and releasing oxygen. This is a good example of how Earth operates as a giant system in which living things interact with their environment.

How did plants come to alter the atmosphere? The key is the way in which plants create their own food. They employ *photosynthesis*, in which they use light energy to synthesize food sugars from carbon dioxide and water. The process releases a waste gas—oxygen. Those of us in the animal kingdom rely on oxygen to metabolize our food, and we in turn exhale carbon dioxide as a waste gas. The plants use this carbon dioxide for more photosynthesis, and so on, in a continuing system.

The first life forms on Earth, probably bacteria, did not need oxygen. Their life processes were geared to the earlier, oxygenless atmosphere. Even today many *anaerobic* bacteria thrive in environments that lack free

Water Vapor. The amount of water vapor in the air varies considerably, from practically none at all up to about 4 percent by volume. Why is such a small fraction of the atmosphere so significant? Certainly the fact that water vapor is the source of all clouds and precipitation would be enough to explain its importance. However, water vapor has other roles. Like carbon dioxide, it has the ability to absorb heat given off by Earth, as well as some solar energy. It is therefore important when we examine the heating of the atmosphere.

When water changes from one state to another (see Figure 4–3, p. 102), it absorbs or releases heat. This energy is termed *latent heat,* which means "hidden" heat. As we shall see in later chapters, water vapor in the atmosphere transports this latent heat from one region to another, and it is the energy source that helps drive many storms.

Aerosols. The movements of the atmosphere are sufficient to keep a large quantity of solid and liquid particles suspended within it. Although visible dust sometimes clouds the sky, these relatively large particles are too heavy to stay in the air for very long. Still, many particles are microscopic and remain suspended for considerable periods of time. They may originate from many sources, both natural and human made, and include sea salts from breaking waves, fine soil blown into the air, smoke and soot from fires, pollen and microorganisms lifted by the wind, ash and dust from volcanic eruptions, and more (Figure 1–19a). Collectively, these tiny solid and liquid particles are called **aerosols.**

Aerosols are most numerous in the lower atmosphere near their primary source, Earth's surface. Nevertheless, the upper atmosphere is not free of them, because some dust is carried to great heights by rising currents of air, and other particles are contributed by meteoroids that disintegrate as they pass through the atmosphere.

From a meteorological standpoint, these tiny, often invisible particles can be significant. First, many act as surfaces on which water vapor may condense, an important function in the formation of clouds and fog. Second, aerosols can absorb or reflect incoming solar radiation. Thus, when an air-pollution episode is occurring or when ash fills the sky

FIGURE 1–C Life has strongly influenced the composition of our atmosphere. The primary source of the abundant oxygen in Earth's atmosphere is photosynthesis by green plants. *(Photo by Art Wolfe/Photo Researchers, Inc.)*

oxygen. Later, primitive plants evolved that used photosynthesis and released oxygen. Slowly the oxygen content of Earth's atmosphere increased. The geologic record of this ancient time suggests that much of the first free oxygen did not remain free, because it combined with (oxidized) other substances dissolved in water, especially iron. Iron has tremendous affinity for oxygen, and the two elements combine to form iron oxides (rust) at any opportunity.

Then, once the available iron satisfied its need for oxygen, substantial quantities of oxygen accumulated in the atmosphere. By the beginning of the Paleozoic era, about 4 billion years into Earth's existence (after seven-eighths of Earth's history had elapsed) the fossil record reveals abundant ocean-dwelling organisms that require oxygen to live. Hence, the composition of Earth's atmosphere has evolved together with its life forms, from an oxygenless envelope to today's oxygen-rich environment.

following a volcanic eruption, the amount of sunlight reaching Earth's surface can be measurably reduced. Finally, aerosols contribute to an optical phenomenon we have all observed—the varied hues of red and orange at sunrise and sunset (Figure 1–19b).

Ozone. Another important component of the atmosphere is **ozone.** It is a form of oxygen that combines three oxygen atoms into each molecule (O_3). Ozone is not the same as the oxygen we breathe, which has two atoms per molecule (O_2). There is very little ozone in the atmosphere. Overall, it represents just three out of every 10 million molecules. Moreover, its distribution is not uniform. In the lowest portion of the atmosphere, ozone represents less than one part in 100 million. It is concentrated well above the surface in a layer called the *stratosphere,* between 10 and 50 kilometers (6 and 31 miles).

In this altitude range, oxygen molecules (O_2) are split into single atoms of oxygen (O) when they absorb ultraviolet radiation emitted by the Sun. Ozone is then created when a single atom of oxygen (O) and a molecule of oxygen (O_2) collide. This must happen in the presence of a third, neutral molecule that acts as *a catalyst* by allowing the reaction to take place without itself being consumed in the process. Ozone is concentrated in the 10- to 50-kilometer height range because a crucial balance exists there: The ultraviolet radiation from the Sun is sufficient to produce single atoms of oxygen, and there are enough gas molecules to bring about the required collisions (see Box 1–3).

The presence of the ozone layer in our atmosphere is crucial to those of us who dwell on Earth. The reason is that ozone absorbs the potentially harmful ultraviolet (UV) radiation from the Sun. If ozone did not filter a great deal of the ultraviolet radiation, and if the Sun's UV rays reached the surface of Earth undiminished, our planet would be uninhabitable for most life as we know it. Thus, anything that reduces the amount of ozone in the atmosphere could affect the well-being of life on Earth. Just such a problem exists and is described in the next section.

FIGURE 1–19 This satellite image (left) from November 11, 2002, shows two examples of aerosols. First, a large dust storm is blowing across northeastern China toward the Korean Peninsula. Second, a dense haze toward the south (bottom center) is human-generated air pollution. *(Image courtesy NASA)* Dust in the air (right) can cause sunsets to be especially colorful. *(Photo by Steve Elmore/CORBIS/The Stock Market)*

Students Sometimes Ask…

Isn't ozone some sort of pollutant?

Yes, you're right. Although the naturally occurring ozone in the stratosphere is critical to life on Earth, it is regarded as a pollutant when produced at ground level because it can damage vegetation and be harmful to human health. Ozone is a major component in a noxious mixture of gases and particles called photochemical smog. It forms as a result of reactions triggered by sunlight that occur among pollutants emitted by motor vehicles and industries.

Ozone Depletion—A Global Issue

The loss of ozone high in the atmosphere as a consequence of human activities is a serious global-scale environmental problem. For nearly a billion years Earth's ozone layer has protected life on the planet. However, over the past half century, people have unintentionally placed the ozone layer in jeopardy by polluting the atmosphere. The offending chemicals are known as chlorofluorocarbons (CFCs). They are versatile compounds that are chemically stable, odorless, nontoxic, noncorrosive, and inexpensive to produce. Over the decades many uses were developed for CFCs, including as coolants for air-conditioning and refrigeration equipment, cleaning solvents for electronic components, propellants for aerosol sprays, and the production of certain plastic foams.

No one worried about how CFCs might affect the atmosphere until three scientists, Paul Crutzen, F. Sherwood Rowland, and Mario Molina, studied the relationship. In 1974 they alerted the world when they reported that CFCs were probably reducing the average concentration of ozone in the stratosphere. In 1995 these scientists were awarded the Nobel Prize in chemistry for their pioneering work.

They discovered that because CFCs are practically inert (that is, not chemically active) in the lower atmosphere, a portion of these gases gradually makes its way to the ozone layer, where sunlight separates the chemicals into their constituent atoms. The chlorine atoms released this way, through a complicated series of reactions, have the net effect of removing some of the ozone (see Box 1–3).

The Ozone Hole

Although ozone depletion by CFCs occurs worldwide, measurements have shown that ozone concentrations take an especially sharp drop over Antarctica during the Southern

BOX 1-3 Important Reactions Involving Ozone in the Stratosphere

Ozone (O_3) is found naturally in the atmosphere, where it is concentrated in the stratosphere, a layer between about 10 and 50 kilometers above Earth's surface. Here natural processes are continually creating and destroying ozone. These reactions account for the higher temperatures that occur in the stratosphere.

Natural Formation and Destruction of Ozone

Ozone is created in two steps. First, high-energy ultraviolet (UV) rays from the Sun strike ordinary oxygen molecules (O_2) and split them into two single oxygen atoms. Second, a freed oxygen atom (O) combines with an oxygen molecule (O_2) to form a molecule of ozone (O_3). Figure 1–D illustrates these steps.

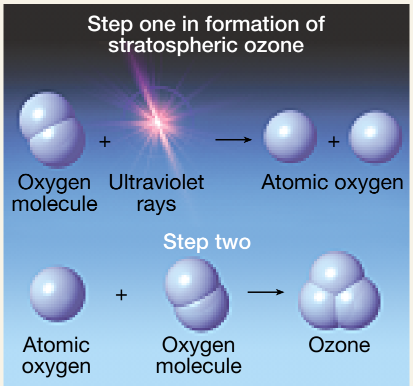


FIGURE 1–D Ozone in the stratosphere is created in two steps.

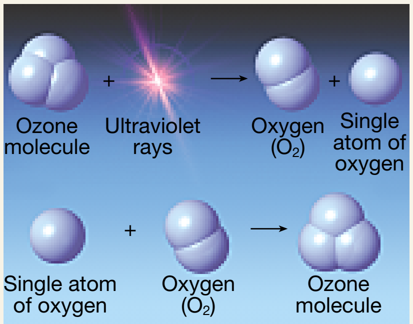


FIGURE 1–E The absorption of solar ultraviolet radiation by ozone during the two-step *ozone-oxygen cycle* causes temperatures in the stratosphere to rise.

When an ozone molecule (O_3) absorbs UV rays, it splits into an oxygen molecule (O_2) and a single atom of oxygen (O). Usually the single oxygen atom quickly collides with and rejoins an oxygen molecule to form another ozone molecule. These reactions, in which ozone is continually being broken down and re-created, are sometimes called the *ozone-oxygen cycle* and are depicted in Figure 1–E.

Ozone Destruction by CFCs

Scientists have learned that the use of certain chlorine-containing chemicals such as chlorofluorocarbons (CFCs) leads to a loss of ozone in the stratosphere. CFCs drift upward into the stratosphere, where they are bombarded by solar ultraviolet rays. In response, CFC molecules break up by releasing chlorine (Cl) atoms. As shown in the top portion of Figure 1–F, these chlorine atoms react with ozone molecules by taking one oxygen atom to form chlorine monoxide (ClO) and leaving behind an oxygen molecule (O_2). Then whenever a molecule of chlorine monoxide encounters a single atom of oxygen (Figure 1–F, bottom), the oxygen "breaks up" the chlorine monoxide, stealing its oxygen atom and releasing chlorine back to the stratosphere to destroy more ozone. The reactions shown in Figure 1–F occur over and over again. In this manner, every chlorine atom that makes its way to the stratosphere is able to destroy *many* molecules of ozone

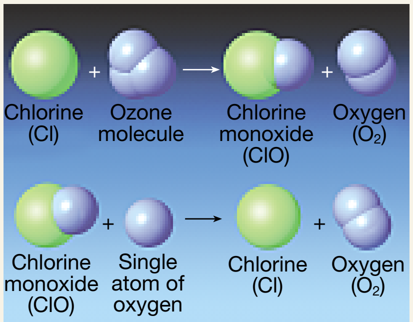


FIGURE 1–F Free chlorine atoms destroy ozone (top). Below, chlorine atoms are released back to the stratosphere where they destroy more ozone. These two reactions occur over and over again.

Hemisphere spring (September and October). Later, during November and December, the ozone concentration recovers to more normal levels (Figure 1–20). Between the early 1980s, when it was discovered, and the early 2000s, this well-publicized *ozone hole* intensified and grew larger until it covered an area roughly the size of North America (Figure 1–21).

The hole is caused in part by the relatively abundant ice particles in the south polar stratosphere. The ice boosts the effectiveness of CFCs in destroying ozone, thus causing a greater decline than would otherwise occur. The zone of maximum depletion is confined to the Antarctic region by a swirling upper-level wind pattern. When this vortex weakens during the late spring, the ozone-depleted air is no longer restricted, and mixes freely with air from other latitudes where ozone levels are higher.

A few years after the Antarctic ozone hole was discovered, scientists detected a similar but smaller ozone thinning

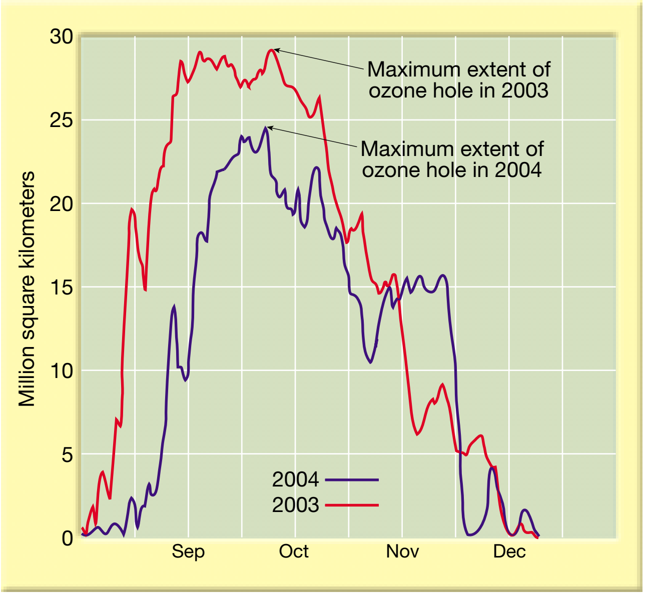


FIGURE 1–20 Changes in the size of the Antarctic ozone hole during 2003 and 2004. The ozone hole in both years began to form in late August and was well developed in September and October. As is typical, each year the ozone hole persisted through November and disappeared in December. At its maximum, the area of the ozone hole was about 29 million square kilometers in 2003, an area slightly larger than all of North America. A relatively warm Antarctic winter in 2004 reduced the thinning of the ozone layer and kept the extent of the hole slightly smaller than in 2003.

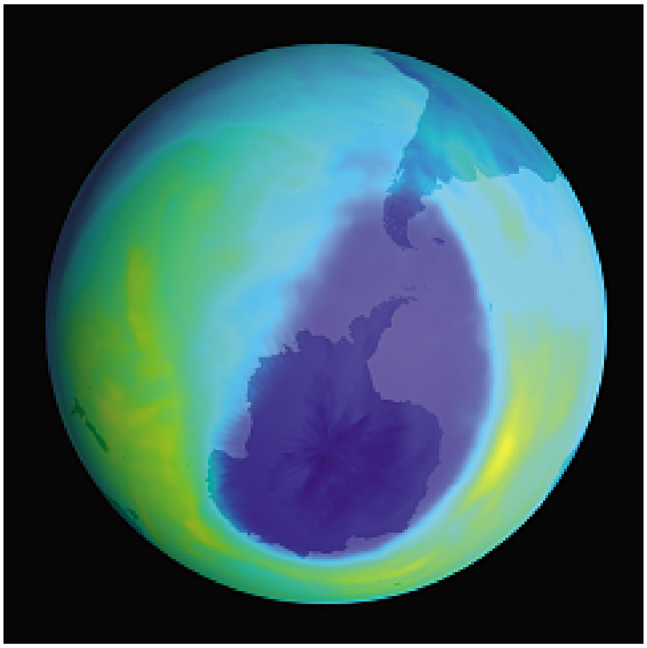


FIGURE 1–21 The Antarctic ozone hole on September 22, 2004. Dark blue colors correspond to the region with the sparsest ozone. Light blue, green, and yellow indicate progressively more ozone. *(Data from NOAA)*

in the vicinity of the North Pole during spring and early summer. When this pool breaks up, parcels of ozone-depleted air move southward over North America, Europe, and Asia.

Effects of Ozone Depletion

Because ozone filters out most of the UV radiation in sunlight, a decrease in its concentration permits more of these harmful wavelengths to reach Earth's surface. Scientists in New Zealand discovered that during the decade of the 1990s, damaging UV radiation gradually increased as concentrations of stratospheric ozone decreased. By 2000, peak sunburning UV levels in New Zealand were about 12 percent higher than 10 years earlier. What are the effects of the increased ultraviolet radiation? Each 1 percent decrease in the concentration of stratospheric ozone increases the amount of ultraviolet radiation that reaches Earth's surface by about 2 percent. Therefore, because ultraviolet radiation is known to induce skin cancer, ozone depletion seriously affects human health, especially among fair-skinned people and those who spend considerable time in the sun.

The fact that up to a half-million cases of these cancers occur in the United States annually means that ozone depletion could ultimately lead to many thousands of additional cases each year.* In addition to upping the risk of skin cancer, an increase in damaging UV radiation can negatively impact the human immune system, as well as promote cataracts, a clouding of the eye lens that reduces vision and may cause blindness if not treated.

The effects of additional UV radiation on animal and plant life are also important. There is serious concern that crop yields and quality will be adversely affected. Some scientists also fear that increased UV radiation in the Antarctic will penetrate the waters surrounding the continent and impair or destroy the microscopic plants, called phytoplankton, that represent the base of the food chain. A decrease in phytoplankton, in turn, could reduce the population of copepods and krill that sustain fish, whales, penguins, and other marine life in the high latitudes of the Southern Hemisphere.

Montreal Protocol

What has been done to protect the atmosphere's ozone layer? Realizing that the risks of not curbing CFC emissions were difficult to ignore, an international agreement known as the *Montreal Protocol on Substances that Deplete the Ozone Layer* was concluded under the auspices of the United Nations in late 1987. The protocol established legally binding controls on the production and consumption of gases known to cause ozone depletion. As the scientific understanding of ozone depletion improved after 1987 and substitutes and alternatives became available for the offending chemicals, the Montreal Protocol was strengthened several times. More than 180 nations eventually ratified the treaty.

*For more on this, see Box 2–3 "The Ultraviolet Index." p. 46

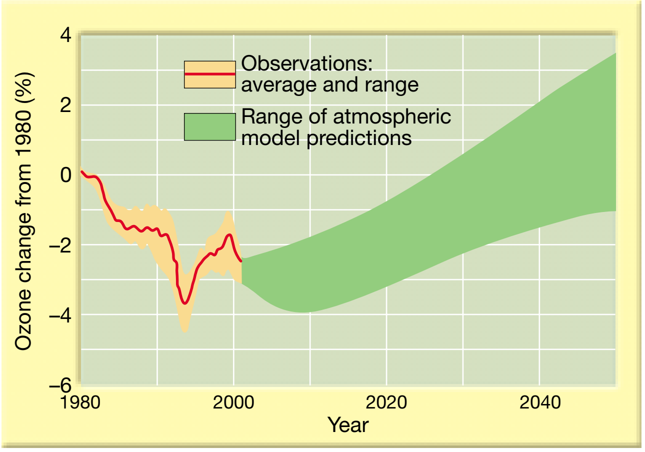


FIGURE 1–22 Global ozone recovery predictions. Observed values of global total ozone decreased beginning about 1980. As emissions of ozone-depleting gases decrease in the early twenty-first century, computer models indicate that ozone values will increase. Model results show that recovery is expected to be significant by 2050, or perhaps sooner.

The Montreal Protocol represents a positive international response to a global environment problem. As a result of the action, the total abundance of ozone-depleting gases in the atmosphere has started to decrease in recent years. If the nations of the world continue to follow the provisions of the protocol, the decreases are expected to continue throughout the twenty-first century. Some offending chemicals are still increasing but will begin to decrease in coming decades. By mid-century, the abundance of ozone-depleting gases should fall to values that existed before the Antarctic ozone hole began to form in the 1980s. Figure 1–22 shows global ozone recovery predictions to the year 2050.

Extent of the Atmosphere

GEODe ATMOSPHERE **Introduction to the Atmosphere**
▸ Extent of the Atmosphere

To say that the atmosphere begins at Earth's surface and extends upward is obvious. However, where does the atmosphere end and outer space begin? There is no sharp boundary; the atmosphere rapidly thins as you travel away from Earth, until there are too few gas molecules to detect.

To understand the vertical extent of the atmosphere, let us examine the changes in atmospheric pressure with height. Atmospheric pressure is simply the weight of the air above. At sea level the average pressure is slightly more than 1000 millibars. This corresponds to a weight of slightly more than 1 kilogram per square centimeter (14.7 pounds per square inch). Obviously, the pressure at higher altitudes is less (Figure 1–23).

One half of the atmosphere lies below an altitude of 5.6 kilometers (3.5 miles). At about 16 kilometers (10 miles) 90 percent of the atmosphere has been traversed, and above

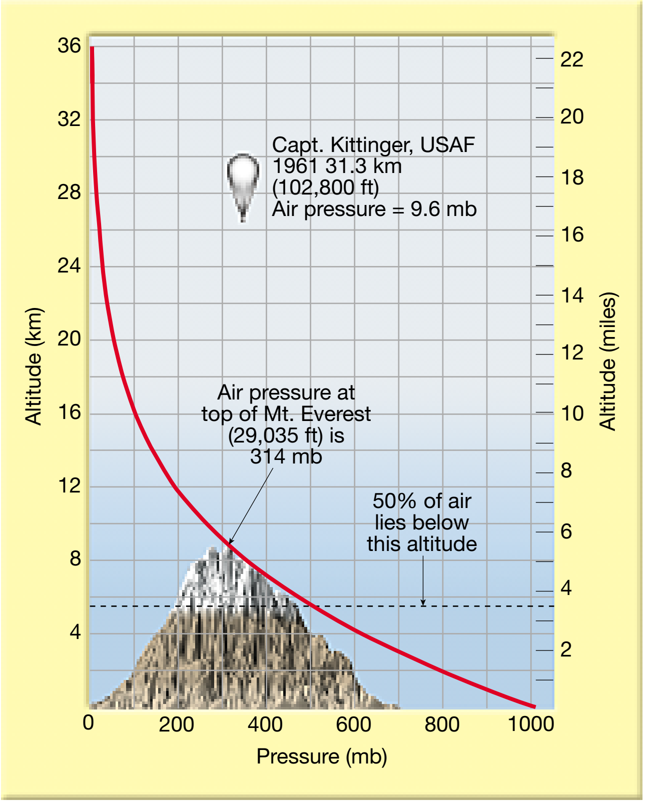


FIGURE 1–23 Atmospheric pressure changes with altitude. The rate of pressure decrease with an increase in altitude is not constant. Rather, pressure decreases rapidly near Earth's surface and more gradually at greater heights.

100 kilometers (62 miles) only 0.00003 percent of all the gases composing the atmosphere remain.

At an altitude of 100 kilometers the atmosphere is so thin that the density of air is less than could be found in the most perfect artificial vacuum at the surface. Nevertheless, the atmosphere continues to even greater heights. The truly rarefied nature of the outer atmosphere is described very well by Richard Craig:

> The earth's outermost atmosphere, the part above a few hundred kilometers, is a region of extremely low density. Near sea level, the number of atoms and molecules in a cubic centimeter of air is about 2×10^{19}; near 600 km, it is only about 2×10^{7}, which is the sea-level value divided by a million million. At sea level, an atom or molecule can be expected, on the average, to move about 7×10^{-6} cm before colliding with another particle; at the 600-km level, this distance, called the "mean free path," is about 10 km. Near sea level, an atom or molecule, on the average, undergoes about 7×10^{9} such collisions each second; near 600 km, this number is reduced to about 1 each minute.*

The graphic portrayal of pressure data (Figure 1–23) shows that the rate of pressure decrease is not constant. Rather, pressure decreases at a decreasing rate with an

*Richard Craig. *The Edge of Space: Exploring the Upper Atmosphere* (New York: Doubleday & Company, Inc. 1968), p. 130.

increase in altitude until, beyond an altitude of about 35 kilometers, the decrease is slight.

Put another way, data illustrate that air is highly compressible—that is, it expands with decreasing pressure and becomes compressed with increasing pressure. Consequently, traces of our atmosphere extend for thousands of kilometers beyond Earth's surface. Thus, to say where the atmosphere ends and outer space begins is arbitrary and, to a large extent, depends on what phenomenon one is studying. It is apparent that there is no sharp boundary.

In summary, data on vertical pressure changes reveal that the vast bulk of the gases making up the atmosphere is very near Earth's surface and that the gases gradually merge with the emptiness of space. When compared with the size of the solid Earth, the envelope of air surrounding our planet is indeed very shallow.

Thermal Structure of the Atmosphere

GEODe ATMOSPHERE **Introduction to the Atmosphere**
▸ Thermal Structure of the Atmosphere

By the early twentieth century much had been learned about the lower atmosphere. The upper atmosphere was partly known from indirect methods. Data from balloons and kites had revealed that the air temperature dropped with increasing height above Earth's surface. This phenomenon is felt by anyone who has climbed a high mountain, and is obvious in pictures of snow-capped mountaintops rising above snow-free lowlands (Figure 1–24).

FIGURE 1–24 Temperatures drop with an increase in altitude in the troposphere. Therefore, it is possible to have snow on a mountaintop and warmer, snow-free lowlands below. San Juan Mountains, Colorado. *(Photo by Carr Clifton/Minden Pictures)*

Although measurements had not been taken above a height of about 10 kilometers (6 miles), scientists believed that the temperature continued to decline with height to a value of absolute zero (−273°C) at the outer edge of the atmosphere. In 1902, however, the French scientist Leon Philippe Teisserenc de Bort refuted the notion that temperature decreases continuously with an increase in altitude. In studying the results of more than 200 balloon launchings, Teisserenc de Bort found that the temperature stopped decreasing and leveled off at an altitude between 8 and 12 kilometers (5 and 7.5 miles). This surprising discovery was at first doubted, but subsequent data-gathering confirmed his findings. Later, through the use of radiosondes and rocket-sounding techniques, the temperature structure of the atmosphere up to great heights became clear. Today the atmosphere is divided vertically into four layers on the basis of temperature (Figure 1–25).

Troposphere

The bottom layer in which we live, where temperature decreases with an increase in altitude, is the **troposphere.** The term was coined in 1908 by Teisserrenc de Bort and literally means the region where air "turns over," a reference to the appreciable vertical mixing of air in this lowermost zone.

The temperature decrease in the troposphere is called the **environmental lapse rate.** Its average value is 6.5°C per kilometer (3.6°F per 1000 feet), a figure known as the *normal lapse rate*.* It needs to be emphasized, however, that the environmental lapse rate is not a constant but rather can be highly variable and must be regularly measured using radiosondes. It can vary during the course of a day with fluctuations of the weather, as well as seasonally and from place to place. Sometimes shallow layers where temperatures actually increase with height are observed in the troposphere. When such a reversal occurs, a *temperature inversion* is said to exist.**

The temperature decrease continues to an average height of about 12 kilometers (7.5 miles). Yet the thickness of the troposphere is not the same everywhere. It reaches heights in excess of 16 kilometers (10 miles) in the tropics, but in polar regions it is more subdued, extending to 9 kilometers (5.5 miles) or less (Figure 1–26). Warm surface temperatures and highly developed thermal mixing are responsible for the greater vertical extent of the troposphere near the equator. As a result, the environmental lapse rate extends to great heights; and despite relatively high surface temperatures below, the lowest tropospheric temperatures are found aloft in the tropics and not at the poles.

*For a more complete explanation of the term "normal," see Box 12-5, p. 368.
**Temperature inversions are described in greater detail in Chapter 13.

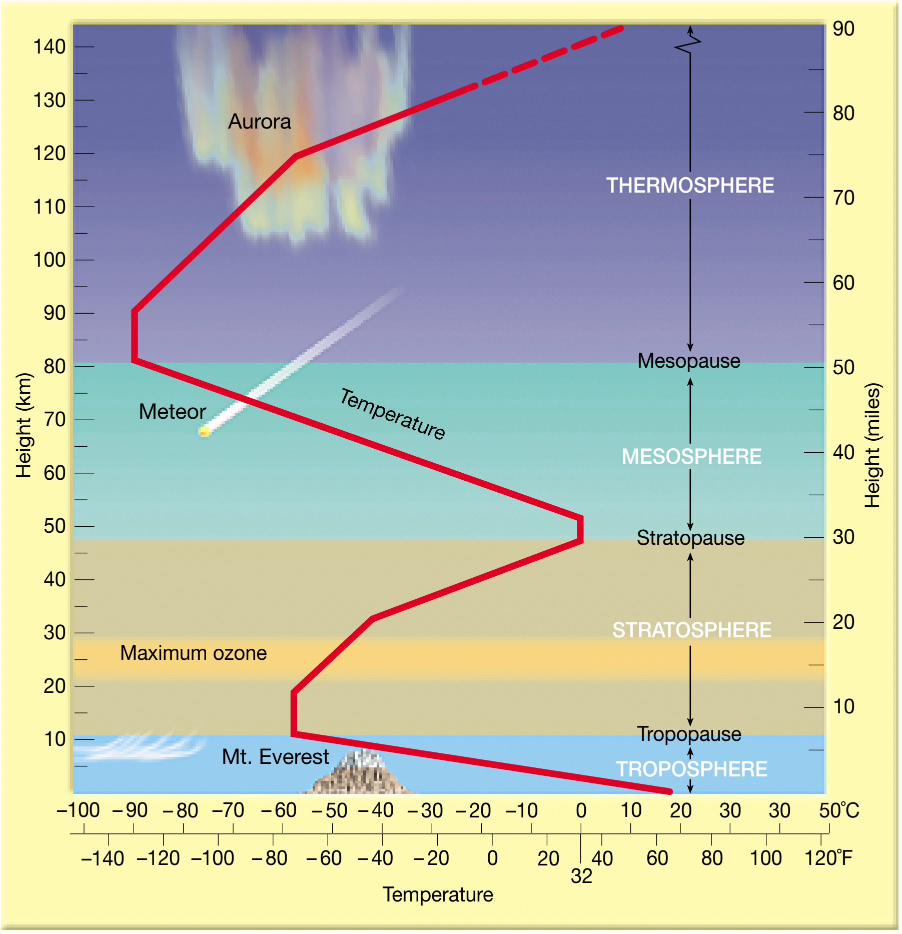


FIGURE 1–25 Thermal structure of the atmosphere.

The troposphere is the chief focus of meteorologists because it is in this layer that essentially all important weather phenomena occur. Almost all clouds and certainly all precipitation, as well as all our violent storms, are born in this lowermost layer of the atmosphere. There should be little wonder why the troposphere is often called the "weather sphere."

Stratosphere

Beyond the troposphere lies the **stratosphere;** the boundary between the troposphere and the stratosphere is known as the **tropopause.** Below the tropopause, atmospheric properties are readily transferred by large-scale turbulence and mixing, but above it, in the stratosphere, they are not. In the stratosphere, the temperature at first remains nearly constant to a height of about 20 kilometers (12 miles) before it begins a rather sharp increase that continues until the **stratopause** is encountered at a height of about 50 kilometers (30 miles) above Earth's surface. Higher temperatures occur in the stratosphere because it is in this layer that the atmosphere's ozone is concentrated. Recall that ozone absorbs ultraviolet radiation from the Sun. Consequently, the stratosphere is heated. Although the maximum ozone concentration exists between 15 and 30 kilometers (9 and 19 miles), the smaller amounts of ozone above this height range absorb enough UV energy to cause the higher observed temperatures.

Mesosphere

In the third layer, the **mesosphere,** temperatures again decrease with height until at the **mesopause**, some 80 kilometers (50 miles) above the surface, the average temperature approaches −90°C (−130°F). The coldest temperatures anywhere in the atmosphere occur at the mesopause. Because accessibility is difficult, the mesosphere is one of the least explored regions of the atmosphere. The reason is that it cannot be reached by the highest research balloons nor is it accessible to the lowest orbiting satellites. Recent technical developments are just beginning to fill this knowledge gap.

Thermosphere

The fourth layer extends outward from the mesopause and has no well-defined upper limit. It is the **thermosphere,** a layer that contains only a minute fraction of the atmosphere's mass. In the extremely rarefied air of this outermost layer, temperatures again increase, owing to the absorption of very shortwave, high-energy solar radiation by atoms of oxygen and nitrogen.

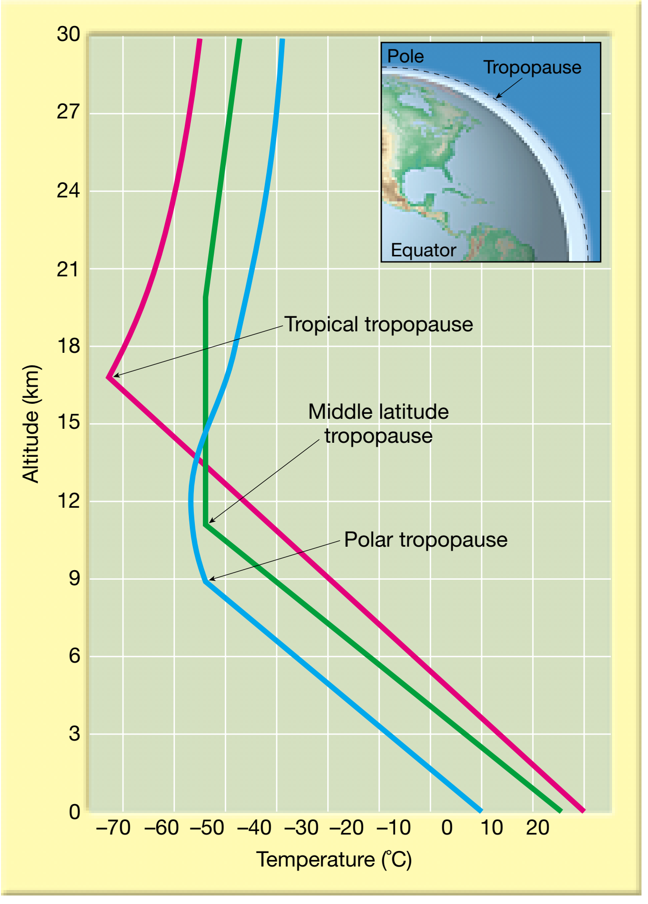


FIGURE 1–26 Differences in the height of the tropopause. The variation in the height of the tropopause, as shown on the small inset diagram, is greatly exaggerated.

Temperatures rise to extremely high values of more than 1000°C (1800°F) in the thermosphere. But such temperatures are not comparable to those experienced near Earth's surface. Temperature is defined in terms of the average speed at which molecules move. Because the gases of the thermosphere are moving at very high speeds, the temperature is very high. But the gases are so sparse that collectively they possess only an insignificant quantity of heat. For this reason, the temperature of a satellite orbiting Earth in the thermosphere is determined chiefly by the amount of solar radiation it absorbs and not by the high temperature of the almost nonexistent surrounding air. If an astronaut inside were to expose his or her hand, the air in this layer would not feel hot.

Vertical Variations in Composition

In addition to the layers defined by vertical variations in temperature, other layers, or zones, are also recognized in the atmosphere. Based on composition, the atmosphere is often divided into two layers: the homosphere and the heterosphere. From Earth's surface to an altitude of about 80 kilometers (50 miles), the makeup of the air is uniform in terms of the proportions of its component gases. That is, the composition is the same as that shown earlier in Table 1–2. This lower uniform layer is termed the *homosphere,* the zone of homogeneous composition.

In contrast, the rather tenuous atmosphere above 80 kilometers is not uniform. Because it has a heterogeneous composition, the term *heterosphere* is used. Here the gases

FIGURE 1–27 (a) Aurora borealis (northern lights) as seen from Alaska. The same phenomenon occurs toward the South Pole, where it is called the aurora australis (southern lights). (*Photo by Michio Hoshino/Minden Pictures*); (b) Aurora australis (southern lights) photographed from the Space Shuttle in May 1991. (*NASA*)

are arranged into four roughly spherical shells, each with a distinctive composition. The lowermost layer is dominated by molecular nitrogen (N_2); next, a layer of atomic oxygen (O) is encountered, followed by a layer dominated by helium (He) atoms; and finally a region consisting of hydrogen (H) atoms. The stratified nature of the gases making up the heterosphere varies according to their weights. Molecular nitrogen is the heaviest, and so it is lowest. The lightest gas, hydrogen, is outermost.

Ionosphere

Located in the altitude range between 80 to 400 kilometers (50 to 250 miles), and thus coinciding with the lower portions of the thermosphere and heterosphere, is an electrically charged layer known as the **ionosphere.** Here molecules of nitrogen and atoms of oxygen are readily ionized as they absorb high-energy shortwave solar energy. In this process, each affected molecule or atom loses one or more electrons and becomes a positively charged ion, and the electrons are set free to travel as electric currents.

Although ionization occurs at heights as great as 1000 kilometers (620 miles) and extends as low as perhaps 50 kilometers (30 miles), positively charged ions and negative electrons are most dense in the range of 80 to 400 kilometers (50 to 250 miles). The concentration of ions is not great below this zone because much of the short-wavelength radiation needed for ionization has already been depleted. In addition, the atmospheric density at this level results in a large percentage of free electrons being swiftly captured by positively charged ions. Beyond the 400-kilometer (250-mile) upward limit of the ionosphere, the concentration of ions is low because of the extremely low density of the air. Because so few molecules and atoms are present, relatively few ions and free electrons can be produced.

The electrical structure of the ionosphere is not uniform. It consists of three layers of varying ion density. From bottom to top, these layers are called the D, E, and F layers, respectively. Because the production of ions requires direct solar radiation, the concentration of charged particles changes from day to night, particularly in the D and E zones. That is, these layers weaken and disappear at night and reappear during the day. The uppermost, or F layer, on the other hand, is present both day and night. The density of the atmosphere in this layer is very low, and positive ions and electrons do not meet and recombine as rapidly as they do at lesser heights, where density is higher. Consequently, the concentration of ions and electrons in the F layer does not change rapidly, and the layer, although weak, remains through the night.

The Auroras

As best we can tell, the ionosphere has little impact on our daily weather. But this layer of the atmosphere is the site of one of nature's most interesting spectacles, the auroras (Figure 1–27). The **aurora borealis** (northern lights) and its Southern Hemisphere couterpart, the **aurora australis** (southern lights), appear in a wide variety of forms. Sometimes the displays consist of vertical streamers in which there can be considerable movement. At other times the auroras appear as a series of luminous expanding arcs or as a quiet glow that has an almost foglike quality.

The occurrence of auroral displays is closely correlated in time with solar-flare activity and, in geographic location, with Earth's magnetic poles. Solar flares are massive magnetic storms on the Sun that emit enormous amounts of energy and great quantities of fast-moving atomic particles. As the clouds of protons and electrons from the solar storm approach Earth, they are captured by its magnetic field, which in turn guides them toward the magnetic poles. Then, as the ions impinge on the ionosphere, they energize the atoms of oxygen and molecules of nitrogen and cause them to emit light—the glow of the auroras. Because the occurrence of solar flares is closely correlated with sunspot activity, auroral displays increase conspicuously at times when sunspots are most numerous.

Chapter Summary

- *Meteorology* is the scientific study of the atmosphere. *Weather* refers to the state of the atmosphere at a given time and place. It is constantly changing, sometimes from hour to hour and other times from day to day. *Climate* is an aggregate of weather conditions, the sum of all statistical weather information that helps describe a place or region. The nature of both weather and climate is expressed in terms of the same basic *elements,* those quantities or properties measured regularly. The most important elements are (1) air temperature, (2) humidity, (3) type and amount of cloudiness, (4) type and amount of precipitation, (5) air pressure, and (6) the speed and direction of the wind.
- All science is based on the assumption that the natural world behaves in a consistent and predictable manner. The process by which scientists gather facts through observation and careful measurement and formulate scientific *hypotheses* and *theories* is called the *scientific method.* To determine what is occurring in the natural world, scientists often (1) collect facts, (2) develop a scientific hypothesis, (3) construct experiments to validate the hypothesis, and (4) accept, modify, or reject the

hypothesis on the basis of extensive testing. Other discoveries represent purely theoretical ideas that have stood up to extensive examination. Still other scientific advancements have been made when a totally unexpected event occurred during an experiment.

- *Balloons* play a significant role in the systematic investigation of the atmostphere by carrying *radiosondes* (lightweight packages of instruments that send back data on temperature, pressure, and relative humidity) into the lower atmosphere. Rockets, airplanes, satellites, and weather radar also play important roles in the study of the atmosphere.
- Earth's four spheres include the *atmosphere* (gaseous envelope), the *geosphere* (solid Earth), the *hydrosphere* (water portion), and the *biosphere* (life). Each sphere is composed of many interrelated parts and is intertwined with all other spheres.
- Although each of Earth's four spheres can be studied separately, they are all related in a complex and continuously interacting whole that we call the *Earth system. Earth system science* uses an interdisciplinary approach to integrate the knowledge of several academic fields in the study of our planet and its global environmental problems.
- A *system* is a group of interacting parts that form a complex whole. *Closed systems* are those in which energy moves freely in and out, but matter does not enter or leave the system. In an open system, both energy and matter flow into and out of the system.
- Most natural systems have mechanisms that tend to enhance change, called *positive feedback mechanisms,* and other mechanisms, called *negative feedback mechanisms,* that tend to resist change and thus stabilize the system.
- The two sources of energy that power the Earth system are (1) the Sun, which drives the external processes that occur in the atmosphere, hydrosphere, and at Earth's surface, and (2) heat from Earth's interior that powers the internal processes that produce volcanoes, earthquakes, and mountains.
- Air is a mixture of many discrete gases, and its composition varies from time to time and place to place. After water vapor, dust, and other variable components are removed, two gases, *nitrogen* and *oxygen,* make up 99 percent of the volume of the remaining clean, dry air. *Carbon dioxide,* although present in only minute amounts (0.038 percent), is an efficient absorber of energy emitted by Earth and thus influences the heating of the atmosphere. Due to the rising level of carbon dioxide in the atmosphere during the past century attributed to the burning of ever increasing quantities of fossil fuels, it is likely that a warming of the lower atmosphere is triggering global climate change.
- The variable components of air include *water vapor, dust particles,* and *ozone*. Like carbon dioxide, water vapor can absorb heat given off by Earth as well as some solar energy. When water vapor changes from one state to another, it absorbs or releases heat. In the atmosphere, water vapor transports this *latent* ("hidden") *heat* from one place to another, and it is the energy source that helps drive many storms. *Aerosols* (tiny solid and liquid particles) are meteorologically important because these often invisible particles act as surfaces on which water can condense and are also absorbers and reflectors of incoming solar radiation. *Ozone,* a form of oxygen that combines three oxygen atoms into each molecule (O_3), is a gas concentrated in the 10- to 50-kilometer height range in the atmosphere that absorbs the potentially harmful ultraviolet (UV) radiation from the Sun.
- Over the past half century, people have placed Earth's ozone layer in jeopardy by polluting the atmosphere with chlorofluorocarbons (CFCs), which remove some of the gas. Ozone concentrations take an especially sharp drop over Antarctica during the Southern Hemisphere spring (September and October). Furthermore, scientists have also discovered a similar but smaller ozone thinning near the North Pole during spring and early summer. Because ultraviolet radiation is known to produce skin cancer, ozone depletion seriously affects human health, especially among fair-skinned people and those who spend considerable time in the Sun. The *Montreal Protocol,* concluded under the auspices of the United Nations, represents a positive international response to the ozone problem.
- No sharp boundary to the upper atmosphere exists. The atmosphere simply thins as you travel away from Earth until there are too few gas molecules to detect. The change that occurs in atmospheric pressure (the weight of the air above) depicts the vertical extent of the atmosphere. One-half of the atmosphere lies below an altitude of 5.6 kilometers (3.5 miles), and 90 percent lies below 16 kilometers (10 miles). Traces of atmosphere extend for thousands of kilometers beyond Earth's surface.
- Using temperature as the basis, the atmosphere is divided into four layers. The temperature decrease in the *troposphere,* the bottom layer in which we live, is called the *environmental lapse rate*. Its average value is 6.5°C per kilometer, a figure known as the *normal lapse rate*. The environmental lapse rate is not a constant and must be regularly measured using radiosondes. A *temperature inversion,* in which temperatures increase with height, is sometimes observed in shallow layers in the troposphere. The thickness of the troposphere is generally greater in the tropics than in polar regions. Essentially all important weather phenomena occur in the troposphere. Beyond the troposphere lies the *stratosphere;* the boundary between the troposphere and stratosphere is known as the *tropopause*. In the stratosphere, the temperature at first remains constant to a height of about 20 kilometers (12 miles) before it begins

a sharp increase due to the absorption of ultraviolet radiation from the Sun by ozone. The temperatures continue to increase until the *stratopause* is encountered at a height of about 50 kilometers (30 miles). In the *mesosphere,* the third layer, temperatures again decrease with height until the *mesopause,* some 80 kilometers (50 miles) above the surface. The fourth layer, the *thermosphere,* with no well-defined upper limit, consists of extremely rarefied air. Temperatures here increase with an increase in altitude.

- Besides layers defined by vertical variations in temperature, the atmosphere is often divided into two layers based on composition. The *homosphere* (zone of homogeneous composition), from Earth's surface to an altitude of about 80 kilometers (50 miles), consists of air that is uniform in terms of the proportions of its component gases. Above 80 kilometers, the *heterosphere* (zone of heterogenous composition) consists of gases arranged into four roughly spherical shells, each with a distinctive composition. The stratified nature of the gases in the heterosphere varies according to their weights.
- Occurring in the altitude range between 80 and 400 kilometers (50 and 250 miles) is an electrically charged layer known as the *ionosphere*. Here molecules of nitrogen and atoms of oxygen are readily ionized as they absorb high-energy, shortwave solar energy. Three layers of varying ion density make up the ionosphere. Auroras (the *aurora borealis,* northern lights, and its Southern Hemisphere counterpart the *aurora australis,* southern lights) occur within the ionosphere. Auroras form as clouds of protons and electrons ejected from the Sun during solar-flare activity enter the atmosphere near Earth's magnetic poles and energize the atoms of oxygen and molecules of nitrogen, causing them to emit light—the glow of the auroras.

Vocabulary Review

Review your understanding of important terms in this chapter by defining and explaining the importance of each term listed here. Terms are listed in alphabetical order. Page references indicate where the term is introduced and defined.

aerosols (p.18)
air (p. 16)
atmosphere (p. 12)
aurora australis (p. 27)
aurora borealis (p. 27)
biosphere (p. 12)
climate (p. 3)
closed system (p. 14)
elements of weather and climate (p. 4)
environmental lapse rate (p. 24)
geosphere (p. 12)
hydrosphere (p. 12)
hypothesis (p. 6)
ionosphere (p. 27)
mesopause (p. 25)
mesosphere (p. 25)
meteorology (p. 3)
model (p. 6)
negative feedback mechanism (p. 14)
open system (p. 14)
ozone (p. 19)
positive feedback mechanism (p. 15)
radiosonde (p. 9)
stratopause (p. 25)
stratosphere (p. 25)
system (p. 14)
theory (p. 6)
thermosphere (p. 25)
tropopause (p. 25)
troposphere (p. 24)
weather (p. 3)

Review Questions

1. Distinguish between the terms "weather" and "climate."
2. The following statements refer to either weather or climate. On the basis of your answer to Question 1, determine which statements refer to weather and which refer to climate. (*Note:* One statement includes aspects of both weather and climate.)
   - **a.** The baseball game was rained out today.
   - **b.** January is Peoria's coldest month.
   - **c.** North Africa is a desert.
   - **d.** The high this afternoon was 25°C.
   - **e.** Last evening a tornado ripped through Canton.
   - **f.** I am moving to southern Arizona because it is warm and sunny.
   - **g.** The highest temperature ever recorded at this station is 43°C.
   - **h.** Thursday's low of −20°C is the coldest temperature ever recorded for that city.
   - **i.** It is partly cloudy.
3. What are the basic elements of weather and climate?
4. How is a scientific hypothesis different from a scientific theory?
5. What is a radiosonde?
6. List and briefly describe the four "spheres" that constitute our environment.
7. How is an open system different from a closed system?

8. Contrast positive feedback mechanisms and negative feedback mechanisms.
9. What are the two sources of energy for the Earth system?
10. What are the major components of clean, dry air?
11. Outline the stages in the formation of Earth's atmosphere. (See Box 1–2)
12. What is responsible for the increasing carbon dioxide content of the air? What is one possible effect of increased carbon dioxide in the atmosphere?
13. Why are water vapor and dust important constituents of our atmosphere?
14. **a.** Why is ozone important to life on Earth?
    b. What are CFCs, and what is their connection to the ozone problem?
    c. What are the effects on human health of a decrease in the stratosphere's ozone?
15. The atmosphere is divided vertically into four layers on the basis of temperature. List the names of these layers and their boundaries in order (from lowest to highest), and list as many characteristics of each as you can.
16. Why does the temperature increase in the stratosphere?
17. Why are temperatures in the thermosphere not strictly comparable to those experienced near Earth's surface?
18. Distinguish between the homosphere and the heterosphere.
19. What is the primary cause of auroral displays?

Problems

1. Refer to the newspaper-type weather map in Figure 1–2 to answer the following:
   a. Estimate the predicted high temperatures in central New York State and the northwest corner of Arizona.
   b. Where is the coldest area on the weather map? Where is the warmest?
   c. On this weather map, H stands for the center of a region of high pressure. Does it appear as though high pressure is associated with precipitation or fair weather?
   d. Which is warmer—central Texas or central Maine? Would you normally expect this to be the case?
2. Refer to the graph in Figure 1–4 to answer the following questions about temperatures in New York City:
   a. What is the approximate average daily high temperature in January? In July?
   b. Approximately what are the highest and lowest temperatures ever recorded?
3. Refer to the graph in Figure 1–6. Which year had the greatest number of billion-dollar weather disasters? How many events occurred that year? In which year was the damage amount greatest?
4. Refer to the graph in Figure 1–23 to answer the following:
   a. Approximately how much does the air pressure drop (in millibars) between the surface and 4 kilometers? (Use a surface pressure of 1000 mb.)
   b. How much does the pressure drop between 4 and 8 kilometers?
   c. Based on your answers to parts a and b, with an increase in altitude, air pressure decreases at a(n) (constant, increasing, decreasing) rate. Underline the correct answer.
5. If the temperature at sea level were 23°C, what would the air temperature be at a height of 2 kilometers under average conditions?
6. Use the graph of the atmosphere's thermal structure (Figure 1–25) to answer the following:
   a. What is the approximate height and temperature of the stratopause?
   b. At what altitude is the temperature lowest? What is the temperature at that height?
7. Answer the following questions by examining the graph in Figure 1–26.
   a. In which one of the three regions (tropics, middle latitudes, poles) is the *surface* temperature lowest?
   b. In which region is the tropopause encountered at the lowest altitude? The highest? What are the altitudes and temperatures of the tropopause in those regions?
8. **a.** On a spring day a middle-latitude city (about 40° north latitude) has a surface (sea-level) temperature of 10°C. If vertical soundings reveal a nearly constant environmental lapse rate of 6.5°C per kilometer and a temperature at the tropopause of −55°C, what is the height of the tropopause?
   b. On the same spring day a station near the equator has a surface temperature of 25°C, 15°C higher than the middle-latitude city mentioned in part a. Vertical soundings reveal an environmental lapse rate of 6.5°C per kilometer and indicate that the tropopause is encountered at 16 kilometers. What is the air temperature at the tropopause?

Atmospheric Science Online

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