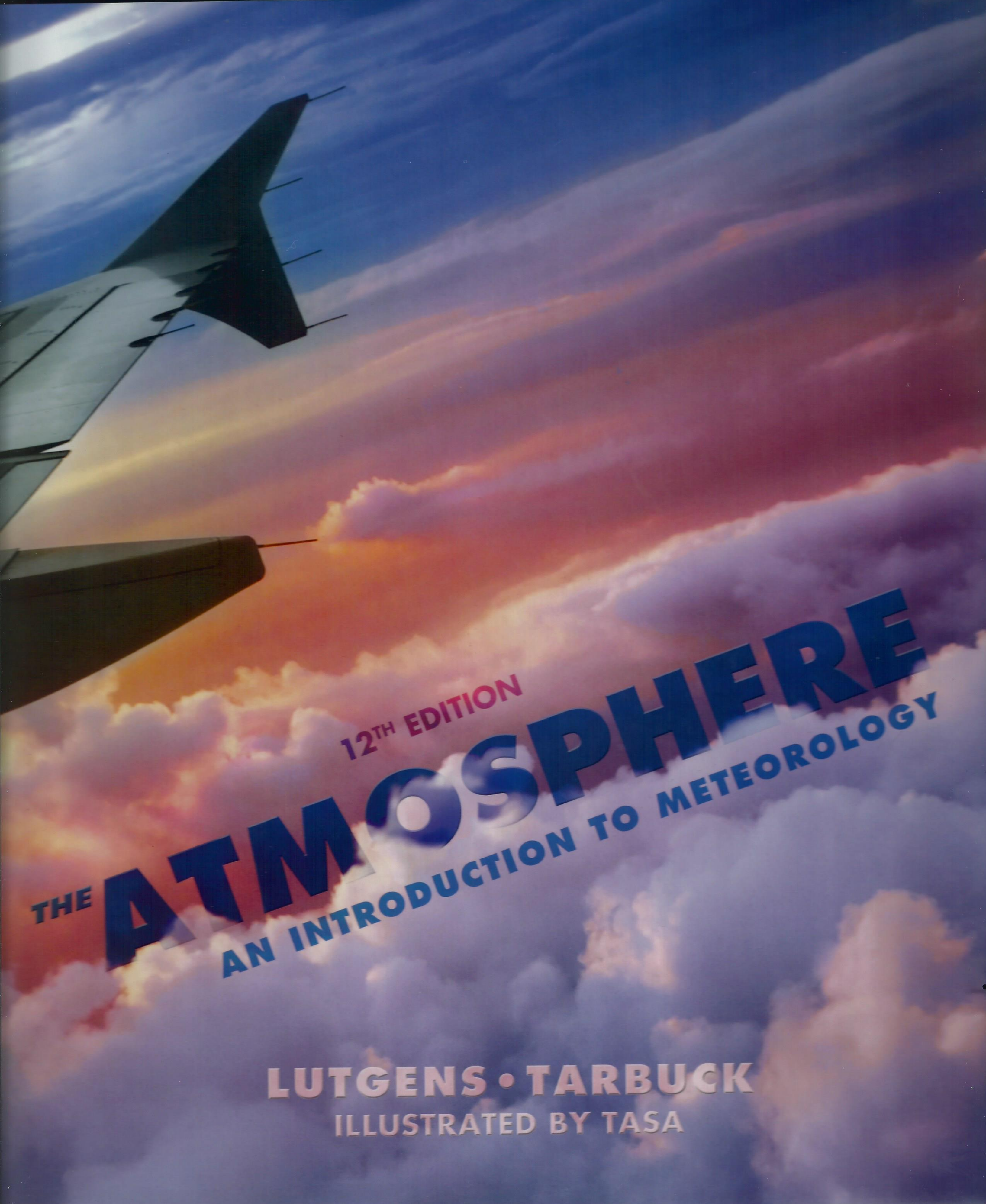


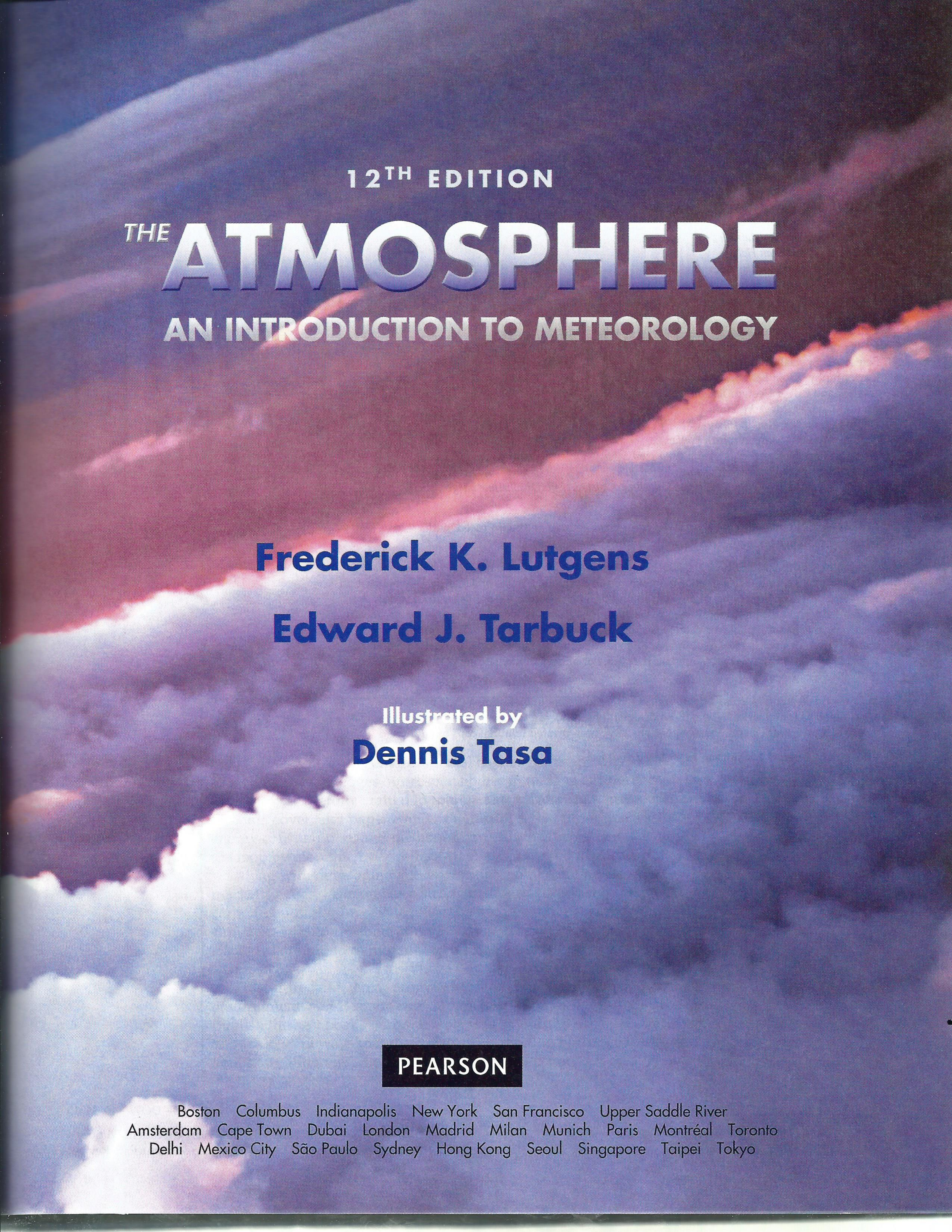
12TH EDITION

THE ATMOSPHERE

AN INTRODUCTION TO METEOROLOGY

LUTGENS • TARBUCK

ILLUSTRATED BY TASA



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Library of Congress Cataloging-in-Publication Data

Lutgens, Frederick K.
The atmosphere : an introduction to meteorology / Frederick K. Lutgens, Edward J. Tarbuck ; illustrated by Dennis Tasa. — 12th ed.
p. cm.
Includes index.
ISBN-13: 978-0-321-75631-2
ISBN-10: 0-321-75631-2
1. Atmosphere. 2. Meteorology. 3. Weather. I. Tarbuck, Edward J. II. Title.
QC861.2.L87 2013
551.5—dc23

2011037045

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1 2 3 4 5 6 7 8 9 10—DOW—15 14 13 12 11
ISBN-10: 0-321-75631-2; ISBN-13: 978-0-321-75631-2 (Student Edition)
ISBN-10: 0-321-78035-3; ISBN-13: 978-0-321-78035-5 (Instructor's Review Copy)

1

Introduction to the Atmosphere

Earth's atmosphere is unique. No other planet in our solar system has an atmosphere with the exact mixture of gases or the heat and moisture conditions necessary to sustain life as we know it. The gases that make up Earth's atmosphere and the controls to which they are subject are vital to our existence. In this chapter we begin our examination of the ocean of air in which we all must live.

Hundreds of cars stranded on Chicago's Lake Shore Drive on February 2, 2011, following a winter blizzard of historic proportions. (AP Photo/ Kiichiro Sato)

Focus On Concepts

After completing this chapter, you should be able to:

- Distinguish between weather and climate and name the basic elements of weather and climate.
- List several important atmospheric hazards and identify those that are storm related.
- Construct a hypothesis and distinguish between a scientific hypothesis and a scientific theory.
- List and describe Earth's four major spheres.
- Define *system* and explain why Earth can be thought of as a system.
- List the major gases composing Earth's atmosphere and identify those components that are most important meteorologically.
- Explain why ozone depletion is a significant global issue.
- Interpret a graph that shows changes in air pressure from Earth's surface to the top of the atmosphere.
- Sketch and label a graph showing the thermal structure of the atmosphere.
- Distinguish between homosphere and heterosphere.

Focus on the Atmosphere

GEODe ATMOSPHERE
Introduction to the Atmosphere
▸ Weather and Climate

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.

Weather in the United States

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 from the Gulf of Mexico.

Stories about weather are a routine part of the daily news. Articles and items about the effects of heat, cold, floods, drought, fog, snow, ice, and strong winds are commonplace (Figure 1–1). Memorable weather events occur everywhere on our planet. The United States likely 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.

Figure 1–1 Few aspects of our physical environment influence our daily lives more than the weather. Tornadoes are intense and destructive local storms of short duration that cause an average of about 55 deaths each year. (Photo by Wave RF/Photolibrary)

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 (Figure 1–2). 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 are important examples. So there is a need for increased awareness and understanding of our atmosphere and its behavior.

Meteorology, 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; in many situations, 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 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 necessary for farmers to know the average rainfall during the growing season, and 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.

(a)

(b)

Figure 1–2 These examples remind us that people influence the atmosphere and its behavior. (a) Motor vehicles are a significant contributor to air pollution. This traffic jam was in Kuala Lumpur, Malaysia. (Photo by Ron Yue/Alamy) (b) Smoke bellows from a coal-fired electricity-generating plant in New Delhi, India, in June 2008. (AP Photo/Gurindes Osan)

Maps similar to the one in Figure 1–3 are familiar to everyone who checks the weather report in the morning newspaper or on a 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.

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

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 titled *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*.

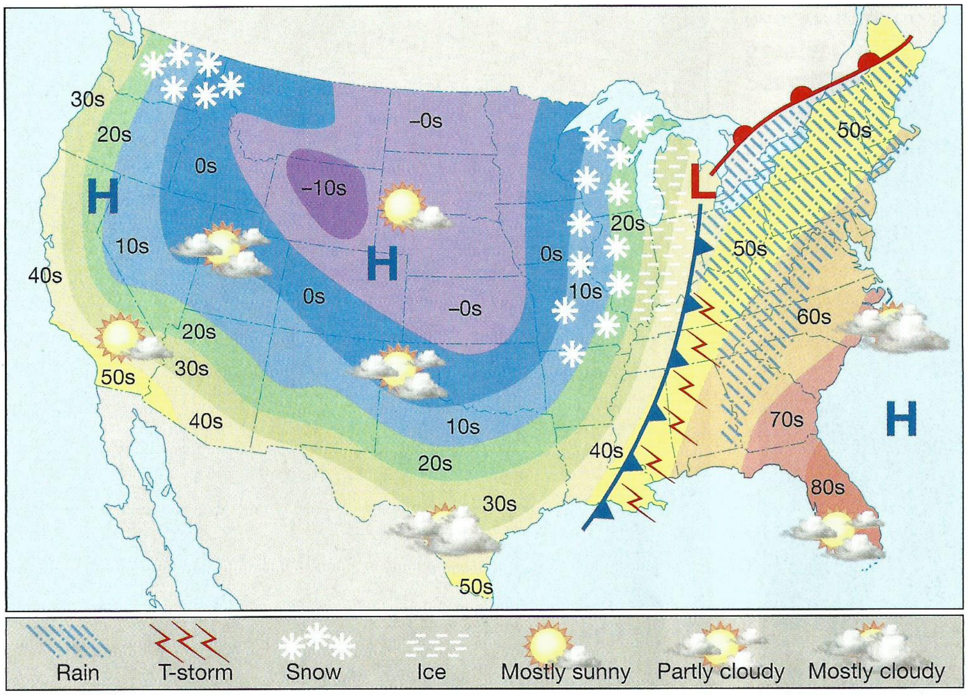


Figure 1–3 A typical newspaper weather map for a day in late December. The color bands show the high temperatures forecast for the day.

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 1–4 shows the average percentage of possible sunshine in the United States for the month of November, and the graph in Figure 1–5 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, 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.

Concept Check 1.1

1 Distinguish among meteorology, weather, and climate.
2 List the basic elements of weather and climate.

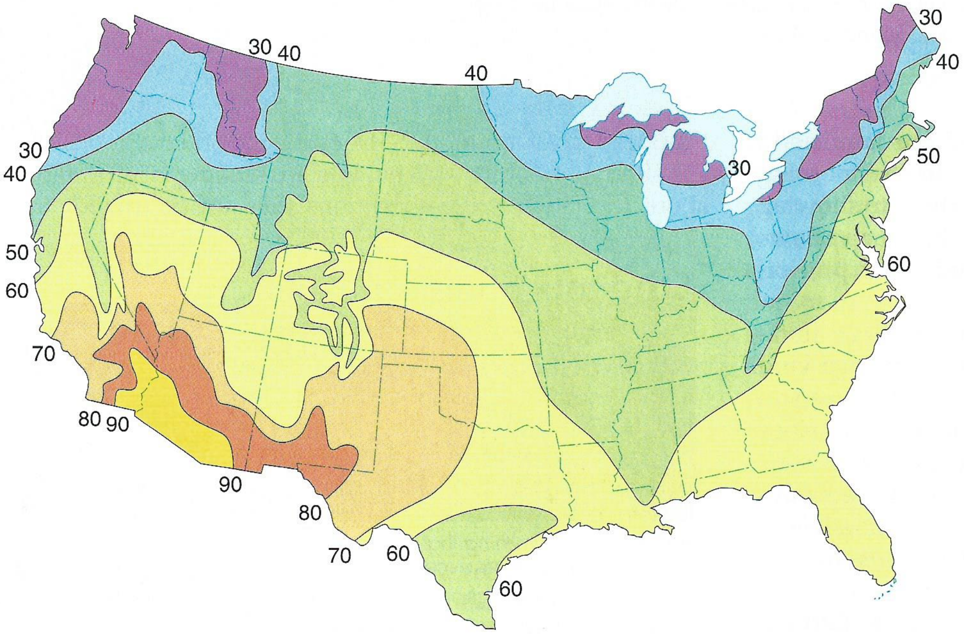


Figure 1–4 Mean percentage of possible sunshine for November. Southern Arizona is clearly the sunniest area. By contrast, parts of the Pacific Northwest receive a much smaller percentage of the possible sunshine. Climate maps such as this one are based on many years of data.

Students Sometimes Ask...

Who provides all 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 more than 15 satellites, 10,000 land-observation and 7300 ship stations, hundreds of automated data buoys, and thousands of aircraft.

Earth's Spheres

The images in Figure 1–9 are considered to be classics because they let humanity see Earth differently than ever before. Figure 1–9a, known as "Earthrise," was taken when the *Apollo 8* astronauts orbited the Moon for the first time in December 1968. As the spacecraft rounded the Moon, Earth appeared to rise above the lunar surface. Figure 1–9b, referred to as "The Blue Marble," is perhaps the most widely reproduced image of Earth; it was taken in December 1972 by the crew of *Apollo 17* during the last manned lunar mission. These early views profoundly altered our conceptualizations of Earth and remain powerful images decades after they were first viewed. Seen from space, Earth is breathtaking in its beauty and startling in its solitude. The photos remind us that our home is, after all, a planet—small, self-contained, and in some ways even fragile. Bill Anders, the *Apollo 8* astronaut who took the "Earthrise" photo, expressed it this way: "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth."

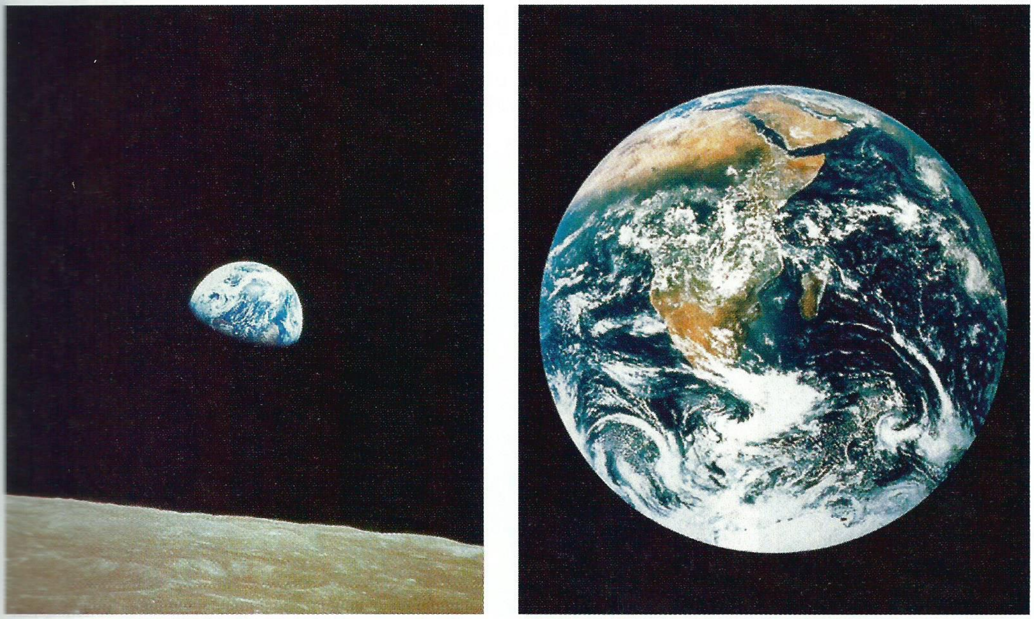
As we look closely at our planet from space, it becomes apparent that Earth is much more than rock and soil. In fact, the most conspicuous features in Figure 1–9a are not continents but swirling clouds suspended above the surface of the vast global ocean. These features emphasize the importance of water on our planet.

The closer view of Earth from space shown in Figure 1–9b 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.

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. Moreover, the biosphere, the totality of life forms on our planet, extends into each of the three physical realms and is an equally integral part of the planet.

The interactions among Earth's four spheres are incalculable. Figure 1–10 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.

On a human scale Earth is huge. Its surface area occupies 500,000,000 square kilometers (193 million square miles). 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).



(a) (b)

Figure 1–9 (a) View, called "Earthrise," that greeted the *Apollo 8* astronauts as their spacecraft emerged from behind the Moon. (NASA) (b) Africa and Arabia are prominent in this classic image called "The Blue Marble" 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. (NASA)

Figure 1–10 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 a rocky shore (*geosphere*). (Photo by Radius Images/photolibrary.com)

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

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** (Figure 1–11). When we watch a high-flying jet plane cross the sky, it seems that the atmosphere extends upward for a great distance. However, when compared to the thickness (radius) of the solid Earth (about 6400 kilometers [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*. More than anything else, water makes Earth unique. The **hydrosphere** is a dynamic mass that is continually on the move, evaporating from the oceans to the atmosphere, precipitating to

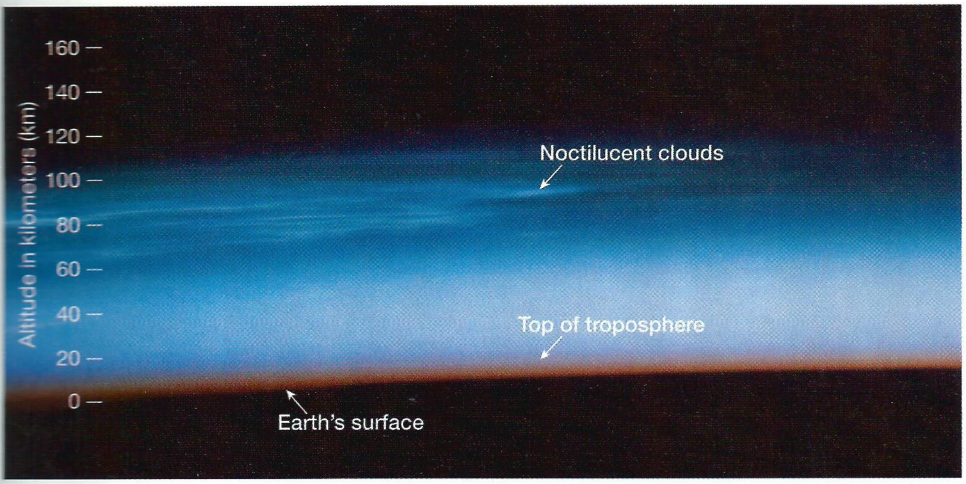


Figure 1–11 This unique image of Earth's atmosphere merging with the emptiness of space resembles an abstract painting. It was taken in June 2007 by a Space Shuttle crew member. The silvery streaks (called *noctilucent clouds*) high in the blue area are at a height of about 80 kilometers (50 miles). Air pressure at this height is less than one-thousandth of that at sea level. The reddish zone in the lower portion of the image is the densest part of the atmosphere. It is here, in a layer called the *troposphere,* that practically all weather phenomena occur. Ninety percent of Earth's atmosphere occurs within just 16 kilometers (10 miles) of the surface. (NASA)

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 1–12). 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 land, streams, glaciers, and groundwater are responsible for sculpting and creating many of our planet's varied landforms.

The Biosphere

The **biosphere** includes all life on Earth (Figure 1–13). 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.

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

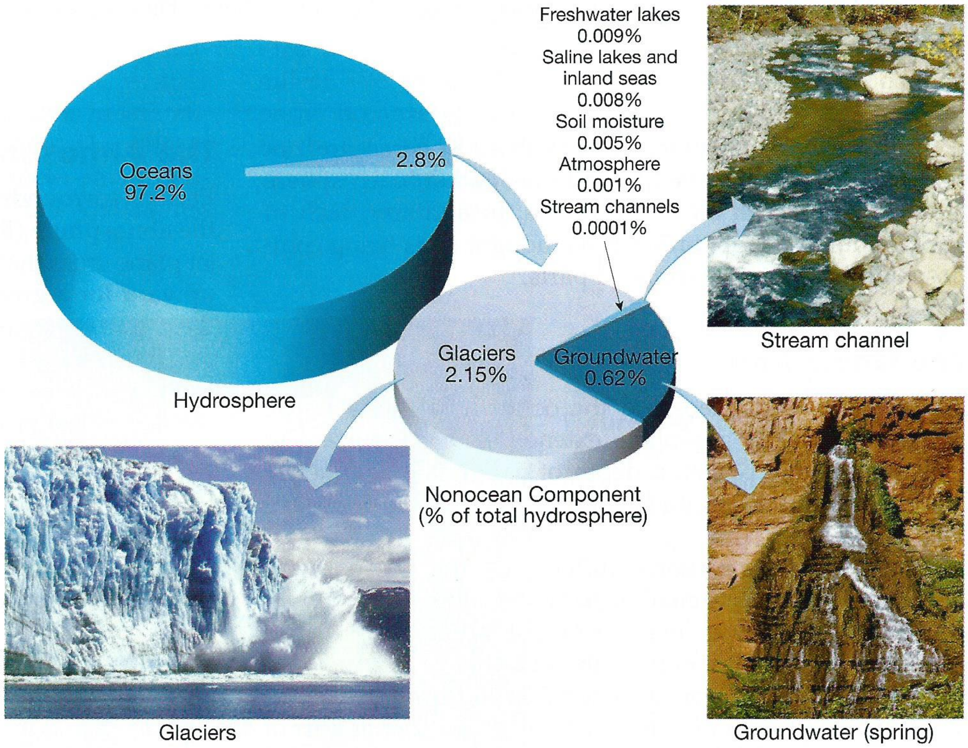
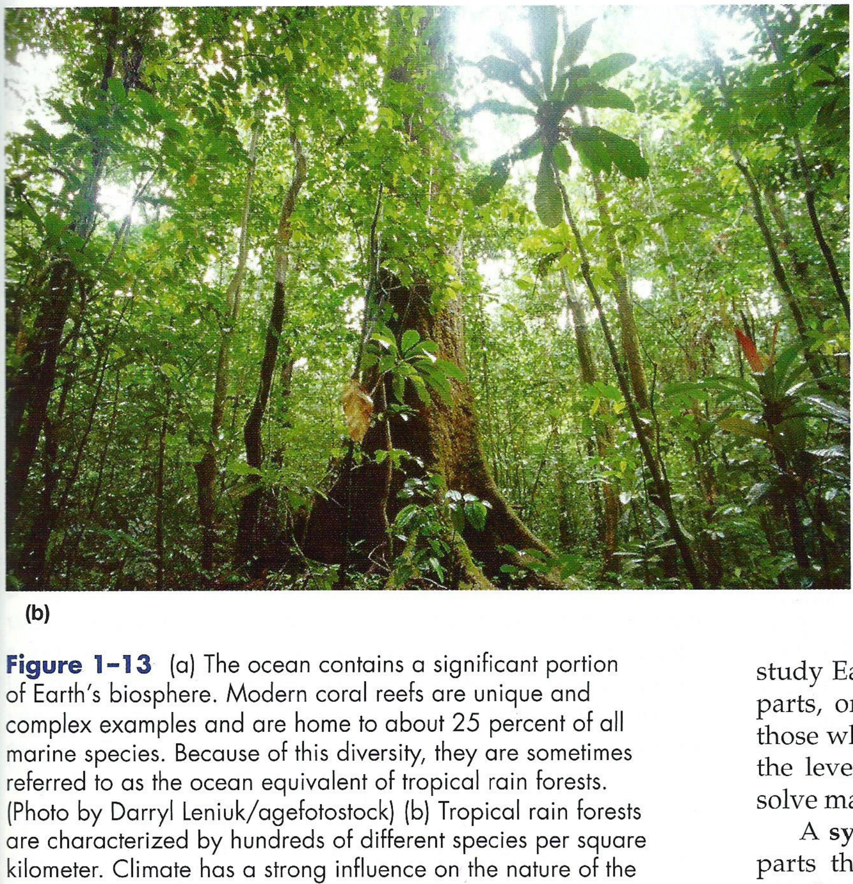


Figure 1–12 Distribution of Earth's water. Obviously, most of Earth's water is in the oceans. Glacial ice represents about 85 percent of all the water *outside* the oceans. When only *liquid freshwater* is considered, more than 90 percent is groundwater. (Glacier photo by Bernhard Edmaier/Photo Researchers, Inc.; stream photo by E.J. Tarbuck; and groundwater photo by Michael Collier)

(a)



(b)

Figure 1–13 (a) The ocean contains a significant portion of Earth's biosphere. Modern coral reefs are unique and complex examples and are home to about 25 percent of all marine species. Because of this diversity, they are sometimes referred to as the ocean equivalent of tropical rain forests. (Photo by Darryl Leniuk/agefotostock) (b) Tropical rain forests are characterized by hundreds of different species per square kilometer. Climate has a strong influence on the nature of the biosphere. Life, in turn, influences the atmosphere. (Photo by agefotostock/SuperStock)

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.

Concept Check 1.4

1 Compare the height of the atmosphere to the thickness of the geosphere.

2 How much of Earth's surface do oceans cover?

3 How much of the planet's total water supply do the oceans represent?

4 List and briefly define the four spheres that constitute our environment.

Earth as a System

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 many ways to the others, producing a complex and continuously interacting whole that we call the *Earth system.*

Earth System Science

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 debris flows (Figure 1–14). The processes that move water from the hydrosphere to the atmosphere and then to the geosphere have a profound impact on the physical environment and 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.

A **system** is a group of interacting, or interdependent, parts that form a complex whole. 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,*

Figure 1–14 This image provides an example of interactions among different parts of the Earth system. On January 10, 2005, extraordinary rains triggered this debris flow (popularly called a mudslide) in the coastal community of La Conchita, California. (AP Wideworld Photo)

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.

The Earth System

The Earth system has a nearly endless array of subsystems in which matter is recycled over and over again. One example that is described in Box 1–2 traces the movements of carbon among Earth's four spheres. It shows us, for example, that the carbon dioxide in the air and the carbon in living things and in certain rocks is all part of a subsystem described by the *carbon cycle*.

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 1–15). 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.

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 radioactive decay power the internal processes that produce volcanoes, earthquakes, and mountains.

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 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.

Concept Check 1.5

1. What is a system? List three examples.
2. What are the two sources of energy for the Earth system?

Figure 1–15 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 Terry Donnelly/ Alamy)

Composition of the Atmosphere

GEODe ATMOSPHERE Introduction to the Atmosphere
▸ Composition of the Atmosphere

In the days of Aristotle, air was thought to be one of four fundamental substances that could not be further divided 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 1–3). 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 1–16, two gases—nitrogen and oxygen—make up 99 percent of the volume of clean, dry air. Although these gases are the most 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 (0.0391 percent, or 391 parts per million), 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

Box 1–2 The Carbon Cycle: One of Earth's Subsystems

To illustrate the movement of material and energy in the Earth system, let us take a brief look at the *carbon cycle* (Figure 1–C). Pure carbon is relatively rare in nature. It is found predominantly in two minerals: diamond and graphite. Most carbon is bonded chemically to other elements to form compounds such as carbon dioxide, calcium carbonate, and the hydrocarbons found in coal and petroleum. Carbon is also the basic building block of life as it readily combines with hydrogen and oxygen to form the fundamental organic compounds that compose living things.

In the atmosphere, carbon is found mainly as carbon dioxide (CO_2). Atmospheric carbon dioxide is significant because it is a greenhouse gas, which means it is an efficient absorber of energy emitted by Earth and thus influences the heating of the atmosphere. Because many of the processes that operate on Earth involve carbon dioxide, this gas is constantly moving into and out of the atmosphere. For example, through the process of photosynthesis, plants absorb carbon dioxide from the atmosphere to produce the essential organic compounds needed for growth. Animals that consume these plants (or consume other animals that eat plants) use these organic compounds as a source of energy and, through the process of respiration, return carbon dioxide to the atmosphere. (Plants also return some CO_2 to the atmosphere via respiration.) Further, when plants die and decay or are burned, this biomass is oxidized, and carbon dioxide is returned to the atmosphere.

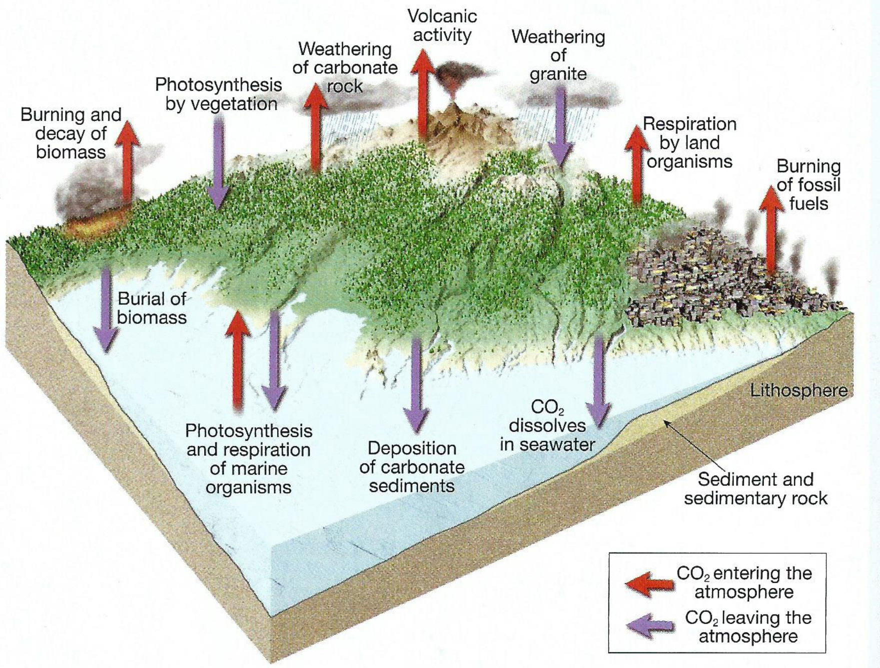


FIGURE 1–C Simplified diagram of the carbon cycle, with emphasis on the flow of carbon between the atmosphere and the hydrosphere, geosphere, and biosphere. The colored arrows show whether the flow of carbon is into or out of the atmosphere.

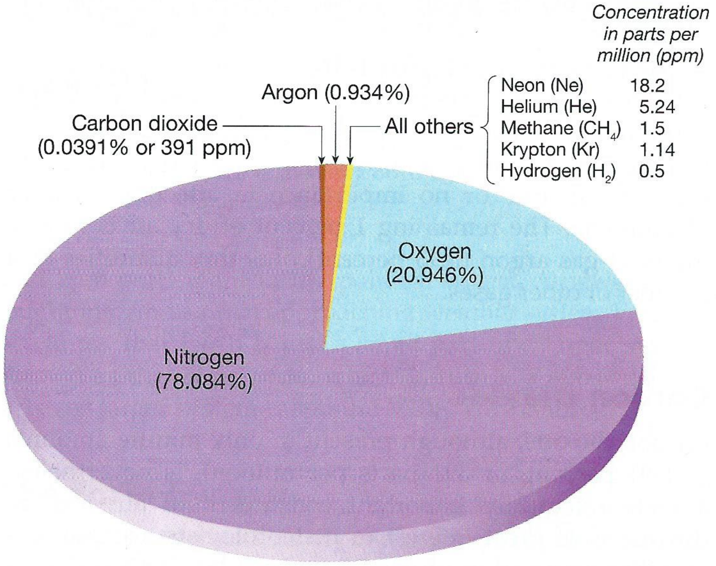


Figure 1–16 Proportional volume of gases composing dry air. Nitrogen and oxygen obviously dominate.

uniform, its percentage has been rising steadily for more than a century. Figure 1–17 is a graph showing the growth in atmospheric CO_2 since 1958. Much of 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 more than 40 percent 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 pre-industrial levels.

Most atmospheric scientists agree that increased carbon dioxide concentrations have contributed to a warming of Earth's atmosphere over the past several decades and will continue to do so in the decades to come. The magnitude of such temperature changes is uncertain and depends partly on the quantities of CO_2 contributed by human activities in the years ahead. The role of carbon dioxide in the atmosphere and its possible effects on climate are examined in more detail in Chapters 2 and 14.

Not all dead plant material decays immediately back to carbon dioxide. A small percentage is deposited as sediment. Over long spans of geologic time, considerable biomass is buried with sediment. Under the right conditions, some of these carbon-rich deposits are converted to fossil fuels—coal, petroleum, or natural gas. Eventually some of the fuels are recovered (mined or pumped from a well) and burned to run factories and fuel our transportation system. One result of fossil-fuel combustion is the release of huge quantities of CO_2 into the atmosphere. Certainly one of the most active parts of the carbon cycle is the movement of CO_2 from the atmosphere to the biosphere and back again.

Carbon also moves from the geosphere and hydrosphere to the atmosphere and back again. For example, volcanic activity early in Earth's history is thought to be the source of much of the carbon dioxide found in the atmosphere. One way that carbon dioxide makes its way back to the hydrosphere and then to the solid Earth is by first combining with water to form carbonic acid (H_2CO_3), which then attacks the rocks that compose the geosphere. One product of this chemical weathering of solid rock is the soluble bicarbonate ion ($2HCO_3^-$), which is carried by groundwater and streams to the ocean. Here water-dwelling organisms extract this dissolved material to produce hard parts (shells) of calcium carbonate ($CaCO_3$). When the organisms die, these skeletal remains settle to the ocean floor as biochemical sediment and become sedimentary rock. In fact, the geosphere is by far Earth's largest depository of carbon, where it is a constituent of a variety of rocks, the most abundant being limestone (**Figure 1–D**). Eventually the limestone may be exposed at Earth's surface, where chemical weathering will cause the carbon stored in the rock to be released to the atmosphere as CO_2.

In summary, carbon moves among all four of Earth's major spheres. It is essential to every living thing in the biosphere. In the atmosphere carbon dioxide is an important greenhouse gas. In the hydrosphere, carbon dioxide is dissolved in lakes, rivers, and the ocean. In the geosphere, carbon is contained in carbonate-rich sediments and sedimentary rocks and is stored as organic matter dispersed through sedimentary rocks and as deposits of coal and petroleum.

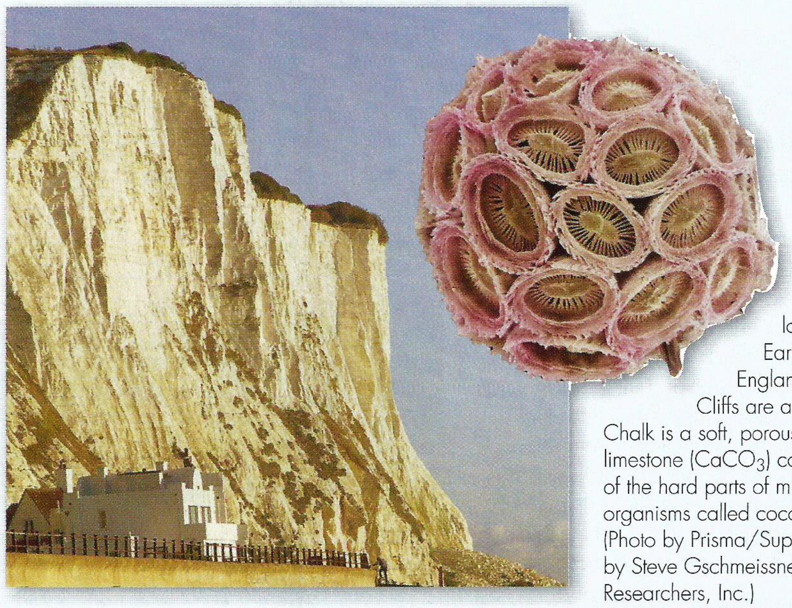


FIGURE 1–D A great deal of carbon is locked up in Earth's geosphere. England's White Chalk Cliffs are an example. Chalk is a soft, porous type of limestone ($CaCO_3$) consisting mainly of the hard parts of microscopic organisms called coccoliths (inset). (Photo by Prisma/SuperStock; inset by Steve Gschmeissner/Photo Researchers, Inc.)

Variable Components

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

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

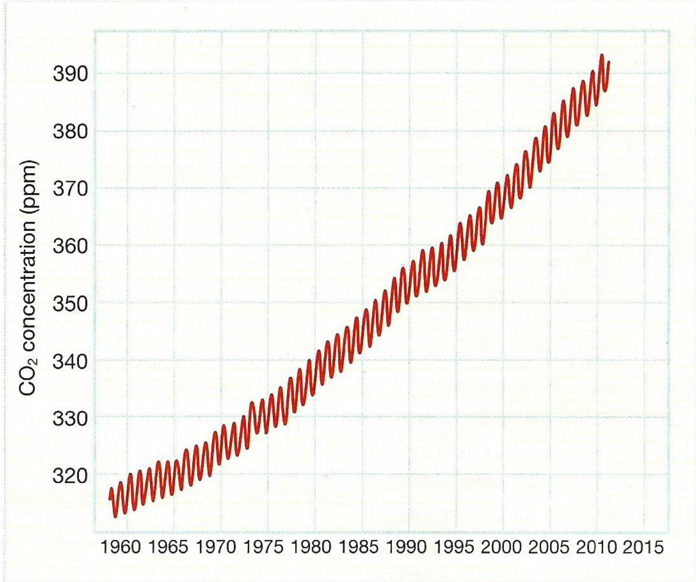


Figure 1–17 Changes in the atmosphere's carbon dioxide (CO_2) as measured at Hawaii's Mauna Loa Observatory. The oscillations reflect the seasonal variations in plant growth and decay in the Northern Hemisphere. During the first 10 years of this record (1958–1967), the average yearly CO_2 increase was 0.81 ppm. During the last 10 years (2001–2010) the average yearly increase was 2.04 ppm. (Data from NOAA)

Box 1–3 Origin and Evolution of Earth's Atmosphere

The air we breathe is a stable mixture of 78 percent nitrogen, 21 percent oxygen, nearly 1 percent argon, and small amounts of gases such as carbon dioxide and water vapor. However, our planet's original atmosphere 4.6 billion years ago was substantially different.

Earth's Primitive Atmosphere

Early in Earth's formation, its atmosphere likely consisted of gases most common in the early solar system: hydrogen, helium, methane, ammonia, carbon dioxide, and water vapor. The lightest of these gases, hydrogen and helium, escaped into space because Earth's gravity was too weak to hold them. Most of the remaining gases were probably scattered into space by strong *solar winds* (vast streams of particles) from a young active Sun. (All stars, including the Sun, apparently experience a highly active stage early in their evolution, during which solar winds are very intense.)

Earth's first enduring atmosphere was generated by a process called *outgassing*, through which gases trapped in the planet's interior are released. Outgassing from hundreds of active volcanoes still remains an important planetary function worldwide (Figure 1–E). However, early in Earth's history, when massive heating and fluid-like motion occurred in the planet's interior, the gas output must have been immense. Based on our understanding of modern volcanic eruptions, Earth's primitive atmosphere probably consisted of mostly water vapor, carbon dioxide, and sulfur dioxide, with minor amounts of other gases and minimal nitrogen. Most importantly, free oxygen was not present.

FIGURE 1–E Earth's first enduring atmosphere was formed by a process called *outgassing*, which continues today, from hundreds of active volcanoes worldwide. (Photo by Greg Vaughn/Alamy)

atmosphere so significant? 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, such as from a gas to a liquid or a liquid to a solid (see Figure 4–3, p. 99), it absorbs or releases heat. This energy is termed *latent heat,* which means hidden heat. As you will 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 drives 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 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 1–18a). 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

Students Sometimes Ask…

Could you explain a little more about why the graph in Figure 1–17 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 in the extensive land areas of the Northern Hemisphere 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.

Oxygen in the Atmosphere

As Earth cooled, water vapor condensed to form clouds, and torrential rains began to fill low-lying areas, which became the oceans. In those oceans, nearly 3.5 billion years ago, photosynthesizing bacteria began to release oxygen into the water. During photosynthesis, organisms use the Sun's energy to produce organic material (energetic molecules of sugar containing hydrogen and carbon) from carbon dioxide (CO_2) and water (H_2O). The first bacteria probably used hydrogen sulfide (H_2S) as the source of hydrogen rather than water. One of the earliest bacteria, *cyanobacteria* (once called blue-green algae), began to produce oxygen as a by-product of photosynthesis.

Initially, the newly released oxygen was readily consumed by chemical reactions with other atoms and molecules (particularly iron) in the ocean (Figure 1–F). Once the available iron satisfied its need for oxygen and as the number of oxygen-generating organisms increased, oxygen began to build in the atmosphere. Chemical analyses of rocks suggest that a significant amount of oxygen appeared in the atmosphere as early as 2.2 billion years ago and increased steadily until it reached stable levels about 1.5 billion years ago. Obviously, the availability of free oxygen had a major impact on the development of life and vice versa. Earth's atmosphere evolved together with its life-forms from an oxygen-free envelope to an oxygen-rich environment.

FIGURE 1–F These ancient layered, iron-rich rocks, called banded iron formations, were deposited during a geologic span known as the Precambrian. Much of the oxygen generated as a by-product of photosynthesis was readily consumed by chemical reactions with iron to produce these rocks. (Photo by John Cancalosi/Photolibrary)

Another significant benefit of the "oxygen explosion" is that oxygen molecules (O_2) readily absorb ultraviolet radiation and rearrange themselves to form *ozone* (O_3). Today, ozone is concentrated above the surface in a layer called the *stratosphere*, where it absorbs much of the ultraviolet radiation that strikes the upper atmosphere. For the first time, Earth's surface was protected from this type of solar radiation, which is particularly harmful to DNA. Marine organisms had always been shielded from ultraviolet radiation by the oceans, but the development of the atmosphere's protective ozone layer made the continents more hospitable.

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 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 1–18b).

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 3 out of every 10 million molecules. Moreover, its distribution is not uniform. In the lowest portion of the atmosphere, ozone represents less than 1 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.

The presence of the ozone layer in our atmosphere is crucial to those of us who are land dwellers. 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

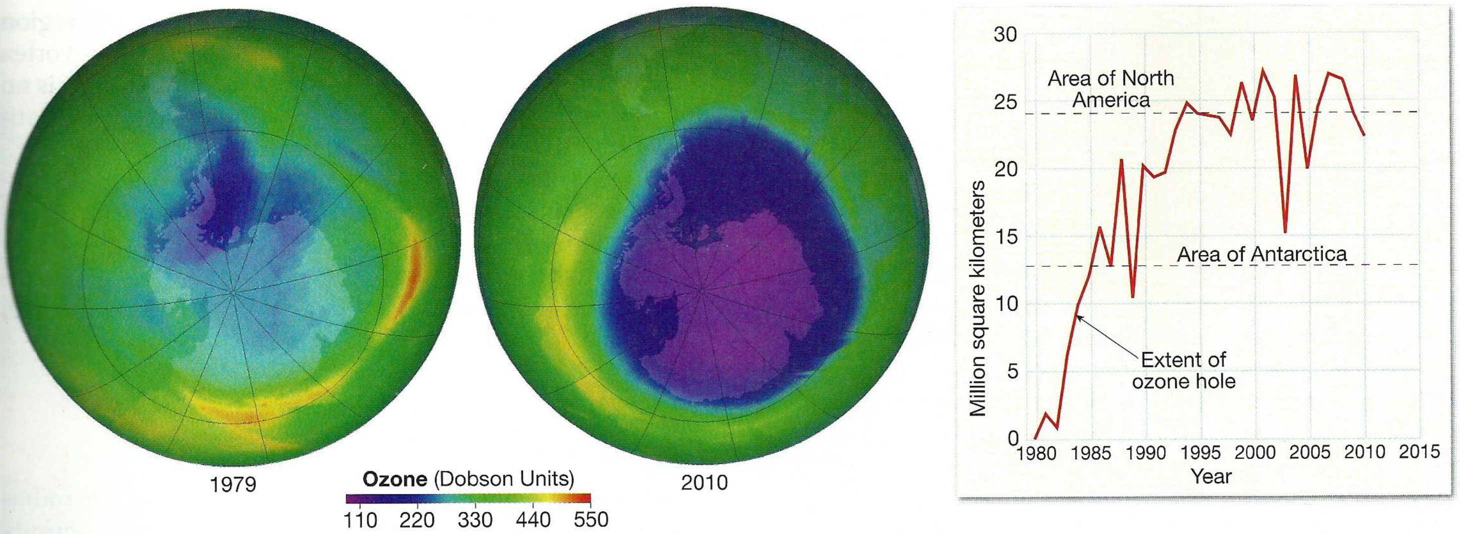


Figure 1–20 The two satellite images show ozone distribution in the Southern Hemisphere on the days in September 1979 and 2010 when the ozone hole was largest. The dark blue shades over Antarctica correspond to the region with the sparsest ozone. The ozone hole is not technically a "hole" where no ozone is present but is actually a region of exceptionally depteted ozone in the stratosphere over the Antarctic that occurs in the spring. The small graph traces changes in the maximum size of the ozone hole, 1980–2010. (NOAA)

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 190 nations eventually ratified the treaty.

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. According to the U.S. Environmental Protection Agency (U.S. EPA), the ozone layer has not grown thinner since 1998 over most of the world.* 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. Between 2060 and 2075, the abundance of ozone-depleting gases is projected to fall to values that existed before the Antarctic ozone hole began to form in the 1980s.

Concept Check 1.7

1. What are CFCs, and what is their connection to the ozone problem?
2. During what time of year is the Antarctic ozone hole well developed?
3. Describe three effects of ozone depletion.
4. What is the Montreal Protocol?

Vertical Structure of the Atmosphere

GEODe ATMOSPHERE
Introduction to the Atmosphere
▶ Extent of the Atmosphere/Thermal Structure 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 where does 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.

Pressure Changes

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 1–21).

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 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

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* U.S. EPA, *Achievements in Stratospheric Ozone Protection, Progress Report.* EPA-430-R-07-001, April 2007, p. 5.

PROFESSIONAL PROFILE

Kathy Orr, Broadcast Meteorologist

KATHY ORR is an award-winning broadcast meteorologist in Philadelphia. (Photo courtesy of Kathy Orr)

Kathy Orr is a trusted and familiar face on the airwaves of Philadelphia. As chief meteorologist for CBS3, Orr has kept the City of Brotherly Love abreast of the weather for 18 years and earned 10 regional Emmy awards in the process.

Orr calls being a television weathercaster a dream come true.

Orr calls being a television weathercaster a dream come true. Growing up in Syracuse, New York, Orr operated her own miniature weather station and marveled at the snow squalls that howled across Lake Ontario. "It could be a sunny afternoon, then the wind would blow over the lake. All of a sudden there was a blinding blizzard," she says.

When not watching the skies, Orr stayed glued to her family's TV set. At the time, she couldn't see how to combine her two major interests. "There weren't any women doing the weather on television back then. There were also not a lot of meteorologists on TV; it was less about the science and more for comic relief," she says.

She majored in broadcasting at Syracuse University and went on to earn a second degree in meteorology at the State University of New York at Oswego. There she learned the basis for the snow squalls that transfixed her as a girl. "These kinds of phenomena are associated with being on the downwind side of a Great Lake. When wind comes along, the lake acts like a snowmaking machine." While still in school, Orr landed a job as the weathercaster on a Syracuse station's brand-new morning show. She's remained a television meteorologist ever since.

Today, Orr says, being a trained meteorologist "is definitely a competitive advantage. It's not the 'rip and read' of years gone by. We take data from the supercomputers in Washington or models by the Navy and make our own forecasts. There are some services that provide forecasts locally and nationally, but they're not located where we are. I can look out the window and tell whether those forecasts are going to be accurate or not."

As a weathercaster, Orr has worked to promote education in science and math. For three years, she led a community program called *Kidcasters*. By offering children a chance to present the weather on TV, Orr hoped to interest elementary school children in science and math. For the past nine summers, she has conducted a similar program called *Orr at the Shore*. Each program highlights environmental issues along the New Jersey coast.

My job is to explain complicated ideas to people in an uncomplicated way.

Orr continues to promote science literacy by volunteering for the American Meteorological Society's DataStreme Atmosphere Project. As a DataStreme mentor, she has visited dozens of schools to train teachers in the science of meteorology. The teachers then promote the use of weather lessons in their districts to pique student interest in science, mathematics, and technology. Orr considers her forecasts educational as well. "My job is to explain complicated ideas to people in an uncomplicated way."

Being a weathercaster, Orr says, is demanding but also exhilarating. "In TV, the hours are crazy. If you work mornings, you're up at 2 AM; if nights, you're up until midnight. So you really have to love it. But if you do, you'll find a way. And I feel blessed to have done this for so long."

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 1–21) shows that the rate of pressure decrease is not constant. Rather, pressure decreases at a decreasing rate with an increase in altitude until, beyond an altitude of about 35 kilometers (22 miles), the decrease is negligible.

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

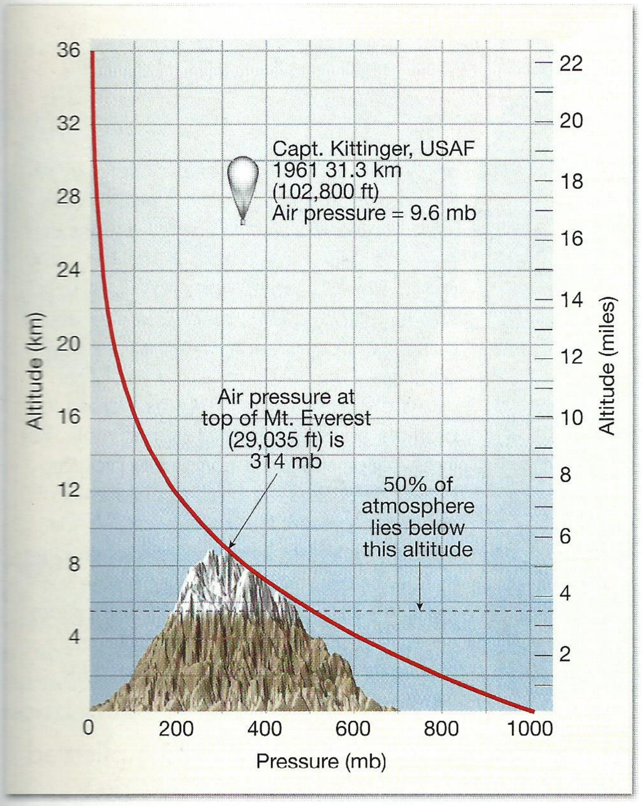


Figure 1–21 Atmospheric pressure changes with altitude. The rate of pressure decrease with an increase in altitude is not constant. Rather, pressure decreases rapidly near Earth's surface and more gradually at greater heights.

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 show 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.

Temperature Changes

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 1–22).

EYE ON THE ATMOSPHERE

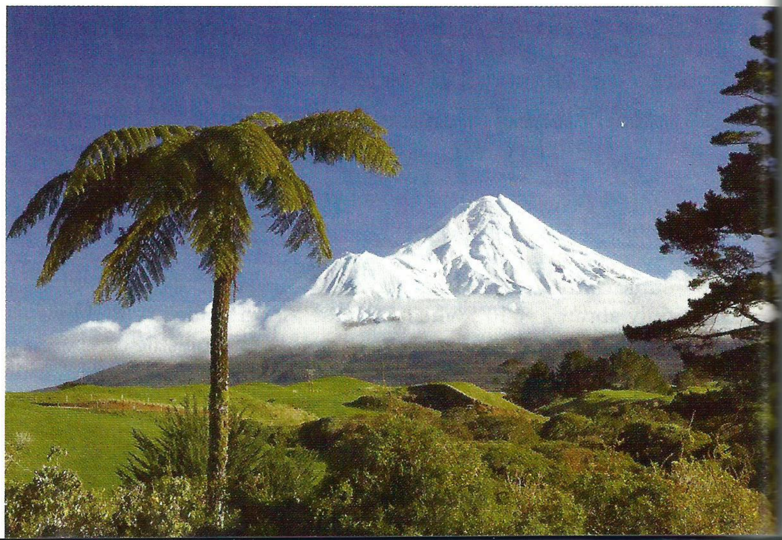
This jet is cruising at an altitude of 10 kilometers (6.2 miles). (Photo by interlight/Shutterstock)

Question 1 Refer to the graph in Figure 1–21. What is the approximate air pressure where the jet is flying?

Question 2 About what percentage of the atmosphere is below the jet (assuming that the pressure at the surface is 1000 millibars)?

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

Figure 1–22 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. (Photo by David Wall/Alamy)



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 balloons 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 1–23).

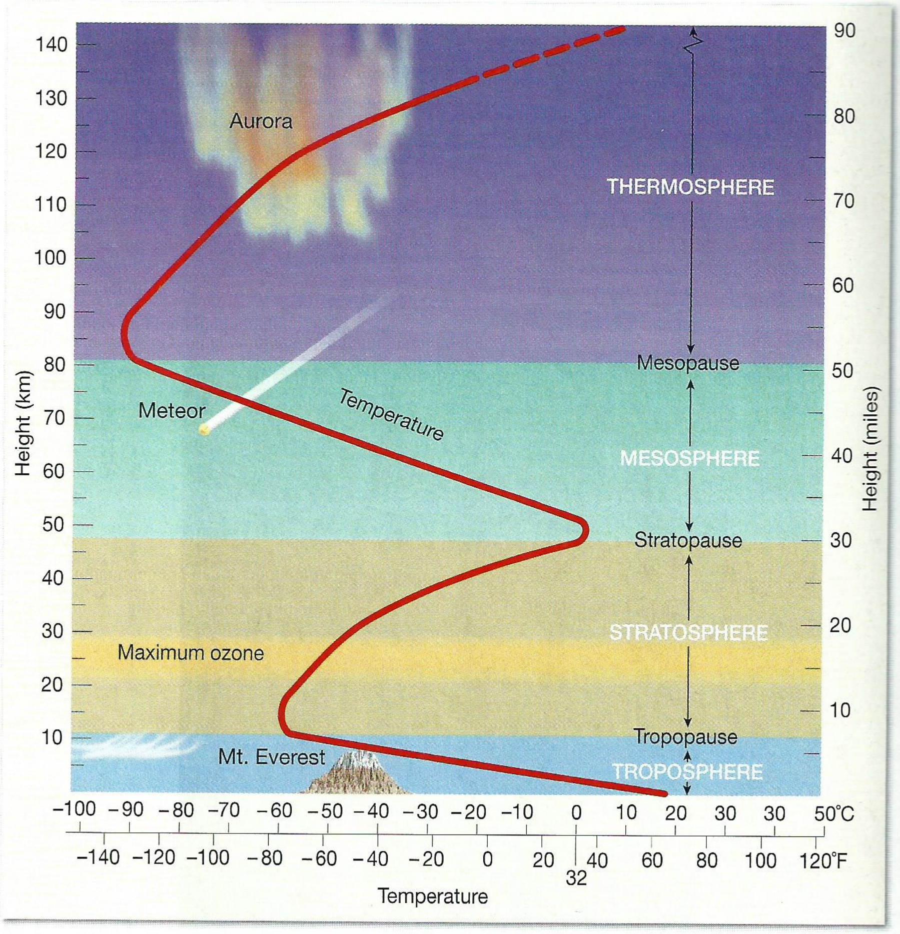


Figure 1–23 Thermal structure of the atmosphere.

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 (3.5°F per 1000 feet), a figure known as the *normal lapse rate*. It should be emphasized, however, that the environmental lapse rate is not a constant but rather can be highly variable and must be regularly measured. To determine the actual environmental lapse rate as well as gather information about vertical changes in air pressure, wind, and humidity, radiosondes are used. A **radiosonde** is an instrument package that is attached to a balloon and transmits data by radio as it ascends through the atmosphere (Figure 1–24). The environmental lapse rate 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 1–25). 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.

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. This is 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 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 by the Sun. 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.

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*Temperature inversions are described in greater detail in Chapter 13.

Figure 1–24 A lightweight instrument package, the *radiosonde,* is suspended below a 2-meter-wide weather balloon. As the radiosonde is carried aloft, sensors measure pressure, temperature, and relative humidity. A radio transmitter sends the measurements to a ground receiver. By tracking the radiosonde in flight, information on wind speed and direction aloft is also obtained. Observations where winds aloft are obtained are called "rawinsonde" observations. Worldwide, there are about 900 upper-air observation stations. Through international agreements, data are exchanged among countries. (Photo by Mark Burnett/ Photo Researchers, Inc.)

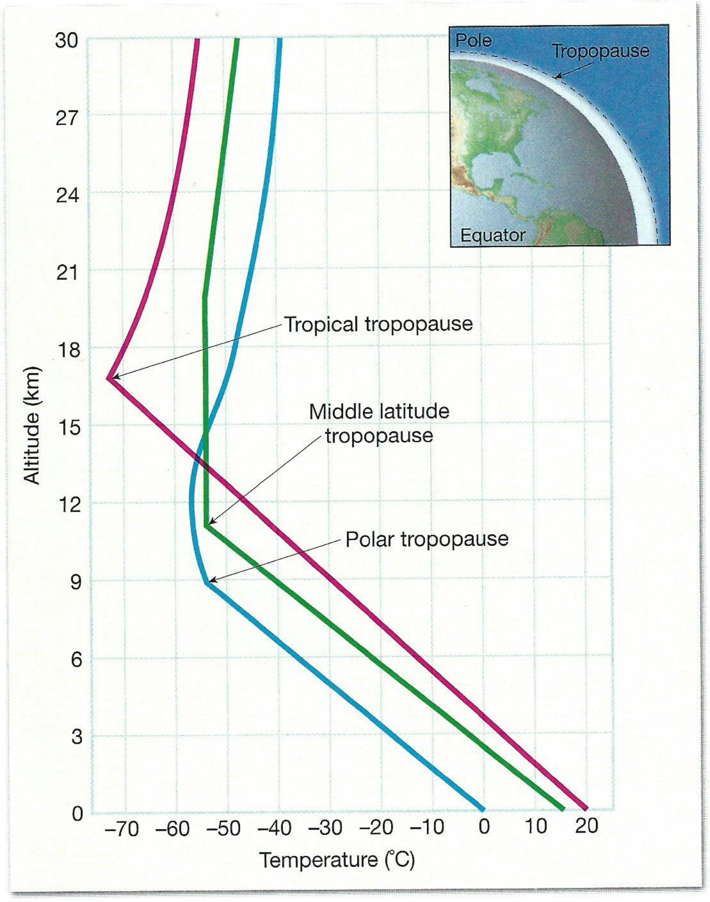


Figure 1–25 Differences in the height of the tropopause. The variation in the height of the tropopause, as shown on the small inset diagram, is greatly exaggerated.

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. The pressure at the base of the mesosphere is only about one-thousandth that at sea level. At the mesopause, the atmospheric pressure drops to just one-millionth that at sea level. 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-flying airplanes and research balloons, nor is it accessible to the lowest-orbiting satellites. Recent technical developments are just beginning to fill this knowledge gap.

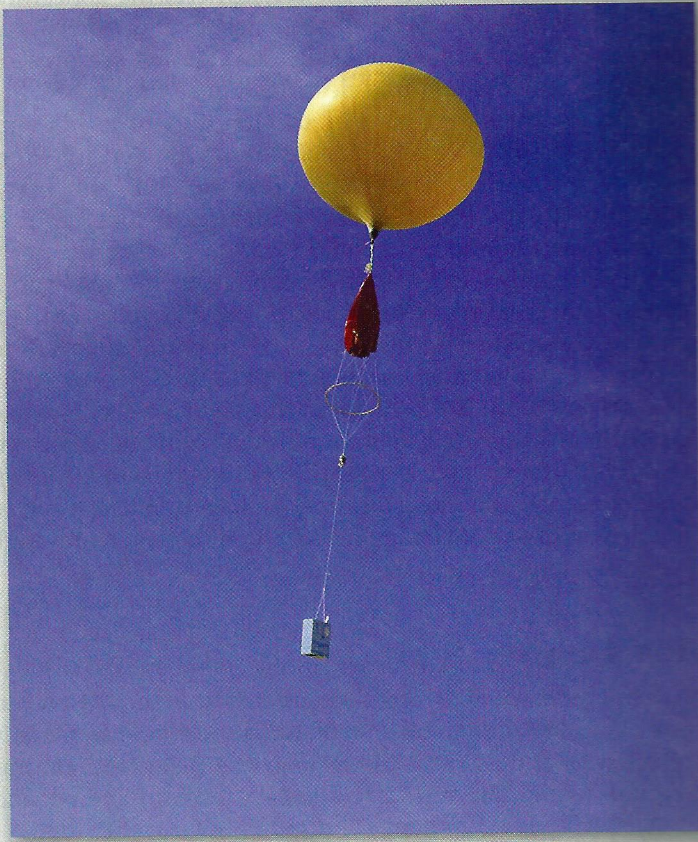
Thermosphere The fourth layer extends outward from the mesopause and has no well-defined upper limit. It is the **thermosphere,** a layer that contains only a tiny fraction of the atmosphere's mass. In the extremely rarified air of this outermost layer, temperatures again increase, due to the absorption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

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.

Concept Check 1.8

1. Does air pressure increase or decrease with an increase in altitude? Is the rate of change constant or variable? Explain.
2. Is the outer edge of the atmosphere clearly defined? Explain.
3. The atmosphere is divided vertically into four layers on the basis of temperature. List these layers in order from lowest to highest. In which layer does practically all of our weather occur?
4. Why does temperature increase in the stratosphere?
5. Why are temperatures in the thermosphere not strictly comparable to those experienced near Earth's surface?

EYE ON THE ATMOSPHERE



When this weather balloon was launched, the surface temperature was 17°C. It is now at an altitude of 1 kilometer. (Photo by David R. Frazier/ Photo Researchers, Inc.)

Question 1 What term is applied to the instrument package being carried aloft by the balloon?

Question 2 In what layer of the atmosphere is the balloon?

Question 3 If average conditions prevail, what air temperature is the instrument package recording? How did you figure this out?

Question 4 How will the size of the balloon change, if at all, as it rises through the atmosphere? Explain.

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 Figure 1–16. This lower uniform layer is termed the *homosphere,* the zone of homogeneous composition.

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