Unit 4

The Atmosphere and the Oceans

Off the Na Pali coast in Hawaii, clouds stretch toward the horizon. In this unit, you'll learn how the atmosphere and the oceans interact to produce clouds and crashing waves. You'll come away from your studies with a deeper understanding of the common characteristics shared by Earth's oceans and its atmosphere.

Unit Contents

NATIONAL GEOGRAPHIC

Go to the **National Geographic Expedition** on page 880 to learn more about topics that are connected to this unit.

Kauai, Hawaii

Chapter 11

Atmosphere

What You'll Learn

- The composition, structure, and properties that make up Earth's atmosphere.
- How solar energy, which fuels weather and climate, is distributed throughout the atmosphere.
- How water continually moves between Earth's surface and the atmosphere in the water cycle.

Why It's Important

Understanding Earth's atmosphere and its interactions with solar energy is the key to understanding weather and climate, which control so many different aspects of our lives.

Earth Science Online

To find out more about the atmosphere, visit the Earth Science Web Site at earthgeu.com

CONTENTS

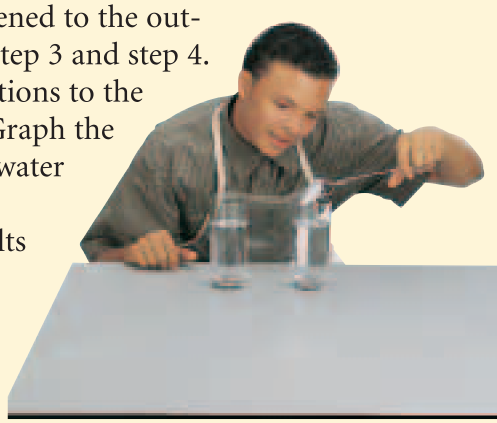
Discovery Lab

Dew Formation

Dew forms when moist air near the ground cools and the water vapor in the air changes into water droplets. In this activity, you will model the formation of dew.

1. Fill a glass about two-thirds full of water. Record the temperature of the room and the water.
2. Add ice cubes until the glass is full. Record the temperature of the water at 10-second intervals.
3. Observe the outside of the glass. Note the time and the temperature at which changes occurred on the outside of the glass.
4. Repeat the experiment outside. Record the temperature of the water and the air outside.

Observe In your science journal, describe what happened to the outside of the glass in step 3 and step 4. Relate your observations to the formation of dew. Graph the temperature of the water during both experiments. Did the results vary with location? Explain.



SECTION 11.1 *Atmospheric Basics*

OBJECTIVES

- **Describe** *the composition of the atmosphere.*
- **Compare** *and* **contrast** *the various layers of the atmosphere.*
- **Identify** *three methods of transferring energy throughout the atmosphere.*

VOCABULARY

ozone
troposphere
stratosphere
mesosphere
thermosphere
exosphere
radiation
conduction
convection

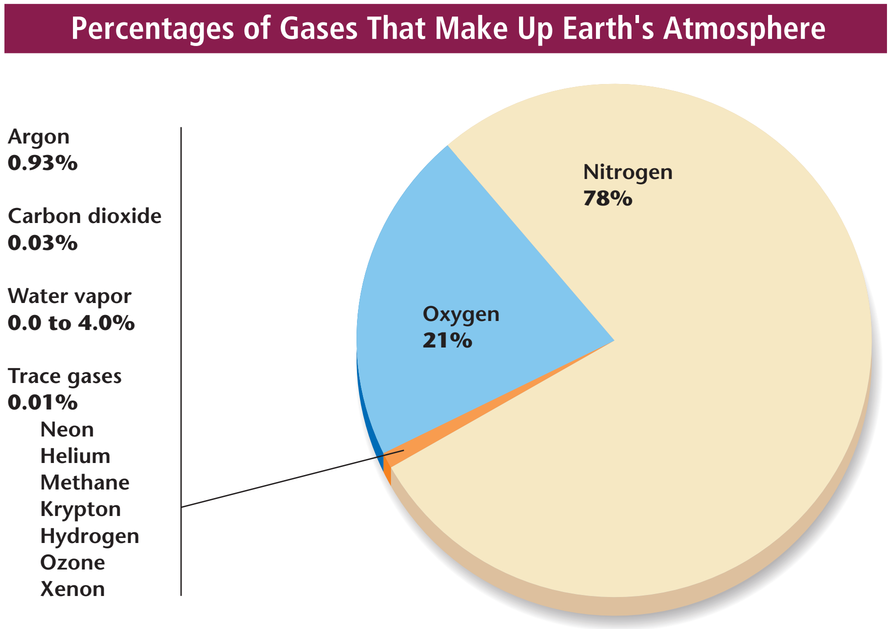
Imagine living in the blazing heat of the Sahara desert, near the equator. Then imagine living in the frozen vastness above the arctic circle. Why are these places so different? The answer lies in how solar energy interacts with the atmosphere, and how the interactions combine to produce weather and climate.

ATMOSPHERIC COMPOSITION

The ancient Greeks thought that air was one of the fundamental elements that could not be broken down into anything else. Today, we know that air is a combination of many gases, each with its own unique characteristics. Together, these gases form Earth's atmosphere, which extends from Earth's surface to outer space.

About 99 percent of the atmosphere is composed of nitrogen and oxygen, with the remaining one percent consisting of small amounts of argon, hydrogen, carbon dioxide, water vapor, and other gases. The percentages of the main components, nitrogen and oxygen, are critical to life on Earth. If either were to change significantly, life as we know it could not exist. Among the lesser-percentage gases, however,

Figure 11-1 Nitrogen makes up 78 percent of the gases in Earth's atmosphere. Oxygen makes up 21 percent. The remaining one percent consists of small amounts of various other gases.



there is some variability, particularly in water vapor and carbon dioxide. *Figure 11-1* shows the composition of the atmosphere.

Key Atmospheric Gases The amount of water vapor in the atmosphere at any given time or place changes constantly. It can be as much as four percent of the atmosphere or as little as almost zero. The percentage varies with the seasons, with the altitude of a particular mass of air, and with the surface features beneath the air. Air over deserts, for instance, is drier than air over oceans. Carbon dioxide, another variable gas, makes up under one percent of the atmosphere. Why is it necessary to even mention these seemingly insignificant gases?

The level of both carbon dioxide and water vapor are critical because they play an important role in regulating the amount of energy the atmosphere absorbs. Water vapor, the gaseous form of water, is the source of clouds, rain, and snow. In addition, water is the only substance in the atmosphere that exists in three states: solid, liquid, and gas. This is important because when water changes from one state to another, heat is either absorbed or released, and this heat greatly affects the atmospheric motions that create weather and climate.

The atmosphere also contains solids in the form of tiny particles of dust and salt. Dust is carried into the atmosphere by wind. Salt is picked up from ocean spray. Dust and salt play a role in cloud formation, as you'll learn later. Ice is the third solid found in the atmosphere, usually in the form of hail and snow.

Ozone Another component of the atmosphere, **ozone** (O_3), is a gas formed by the addition of a third oxygen atom to an oxygen molecule (O_2). Ozone exists in small quantities mainly in a layer well above Earth's surface. It is important because it absorbs ultraviolet radiation from the Sun. If ozone did not control the amount of ultraviolet radiation reaching Earth's surface, our fragile skin could not tolerate exposure to the Sun for long. Evidence indicates that the ozone layer is thinning. You'll learn more about this issue in the *Science in the News* feature at the end of this chapter and in later chapters.

ENVIRONMENTAL CONNECTION

STRUCTURE OF THE ATMOSPHERE

The atmosphere is made up of several different layers, as shown in ***Figure 11-2.*** Each layer differs in composition and temperature.

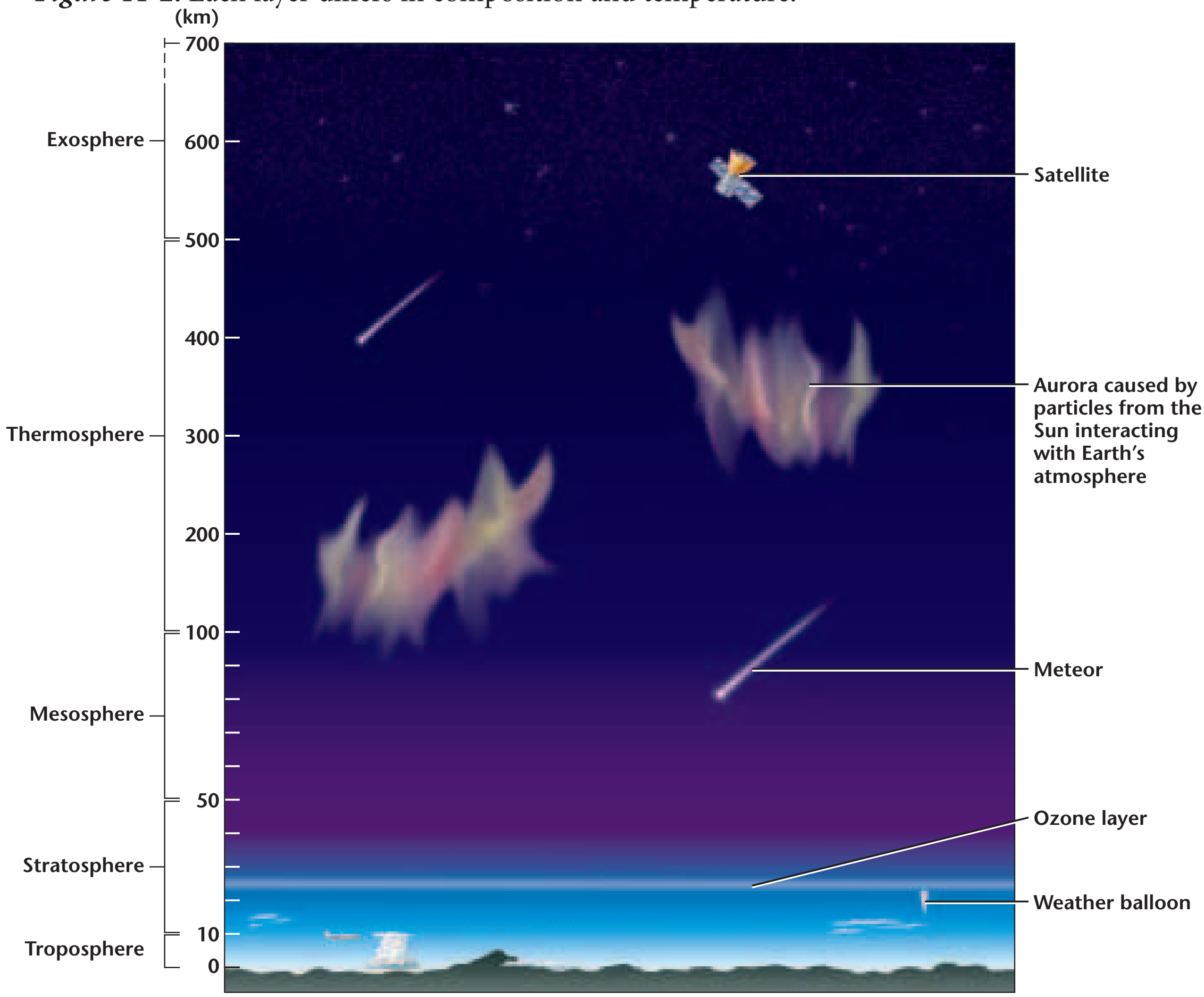


Figure 11-2 The five main layers of the atmosphere vary in temperature and chemical composition.

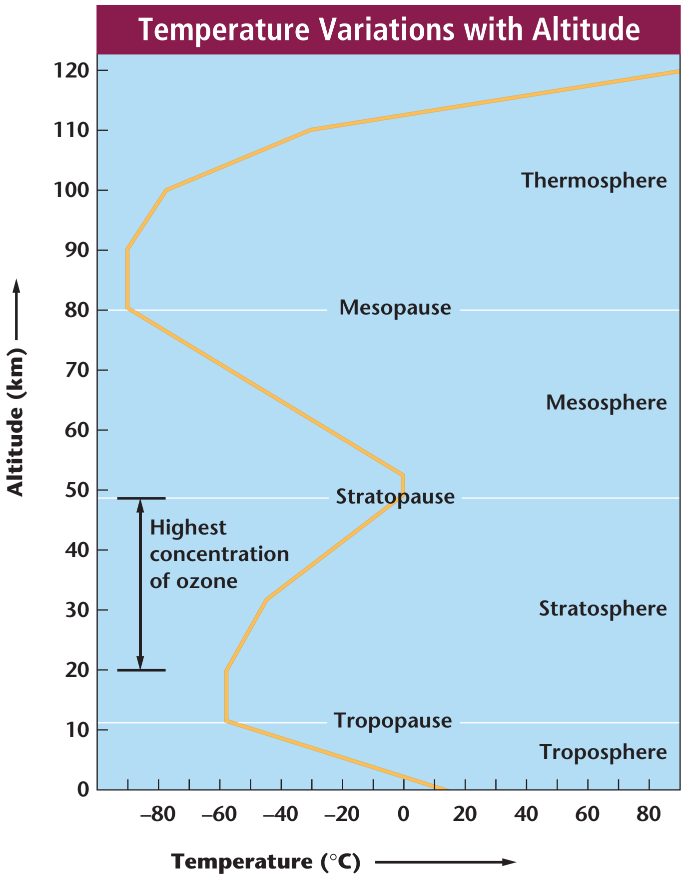


Figure 11-3 Differences in chemical composition cause air temperatures to vary throughout the atmosphere.

Lower Atmospheric Layers The layer closest to Earth's surface, the **troposphere,** contains most of the mass of the atmosphere, including water vapor. This is the layer in which most weather takes place and most air pollution collects. The troposphere is characterized by a general decrease in temperature from bottom to top. The upper limit of the troposphere, called the tropopause, varies in height. It's about 16 km above Earth's surface in the tropics and about 9 km or less at the poles. The tropopause is where the gradual decrease in temperature stops.

Above the tropopause is the **stratosphere,** a layer made up primarily of concentrated ozone. Ozone absorbs more ultraviolet radiation than does air in the troposphere. As a result, the stratosphere is heated, and air gradually increases in temperature to the top of the layer, called the stratopause, located about 50 km above Earth's surface.

Upper Atmospheric Layers Above the stratopause is the **mesosphere.** There is no concentrated ozone in the mesosphere, so the temperature decreases once again, as shown in ***Figure 11-3.*** The top of this layer, the mesopause, is the boundary between the mesosphere and the next layer, the thermosphere. The **thermosphere** contains only a minute portion of the atmosphere's mass. What air does exist in this layer increases in temperature once again, this time to more than 1000°C. In the thermosphere, however, the molecules that make up air are so sparse and widely spaced that, despite the high temperature, this layer would not seem warm to a human passing through it.

The ionosphere is part of the thermosphere. It is made up of electrically charged particles and layers of progressively lighter gases. The **exosphere** is the outermost layer of Earth's atmosphere. Light gases such as helium and hydrogen are found in this layer. Above the exosphere lies outer space. There is no clear boundary between the atmosphere and space. There are simply fewer and fewer molecules with increasing altitude until, for all practical purposes, you have entered outer space.

Solar Fundamentals

The Sun is the source of all energy in the atmosphere. This energy is transferred to Earth and throughout the atmosphere in three ways.

Radiation The Sun is shining on, and therefore warming, some portion of Earth's surface at all times. This method of energy transfer is called radiation. **Radiation** is the transfer of energy through space by visible light, ultraviolet radiation, and other forms of electromagnetic waves. All substances that have temperatures above absolute zero emit radiation. The higher the temperature of a substance, the shorter the wavelength it emits.

While Earth is absorbing solar radiation, it is also continuously sending energy back into space. As you can see from ***Figure 11-4,*** about 35 percent of incoming solar radiation is reflected into space by Earth's surface, the atmosphere, or clouds. Another 15 percent is absorbed by the atmosphere itself. This means that only about 50 percent of incoming solar radiation is absorbed directly or indirectly by Earth's surface. The rate of absorption for any particular area varies depending on the physical characteristics of the area and the amount of solar radiation it receives. Different areas absorb energy and heat up at different rates. For example, water heats up and cools down more slowly than land. And, as a general rule, darker objects absorb energy faster than lighter ones.

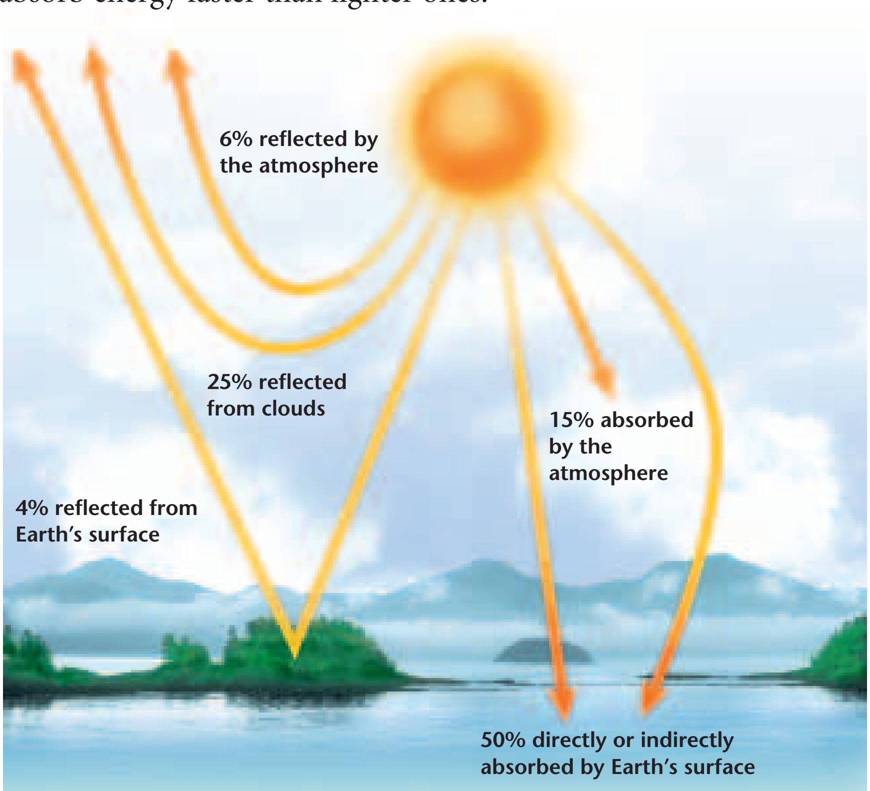


Figure 11-4 Over the course of a year, Earth sends back into space just about as much energy as it receives from the Sun. This is fortunate: if Earth sent back too much, it would gradually cool off, while if it sent back too little, it would warm up to potentially dangerous levels.

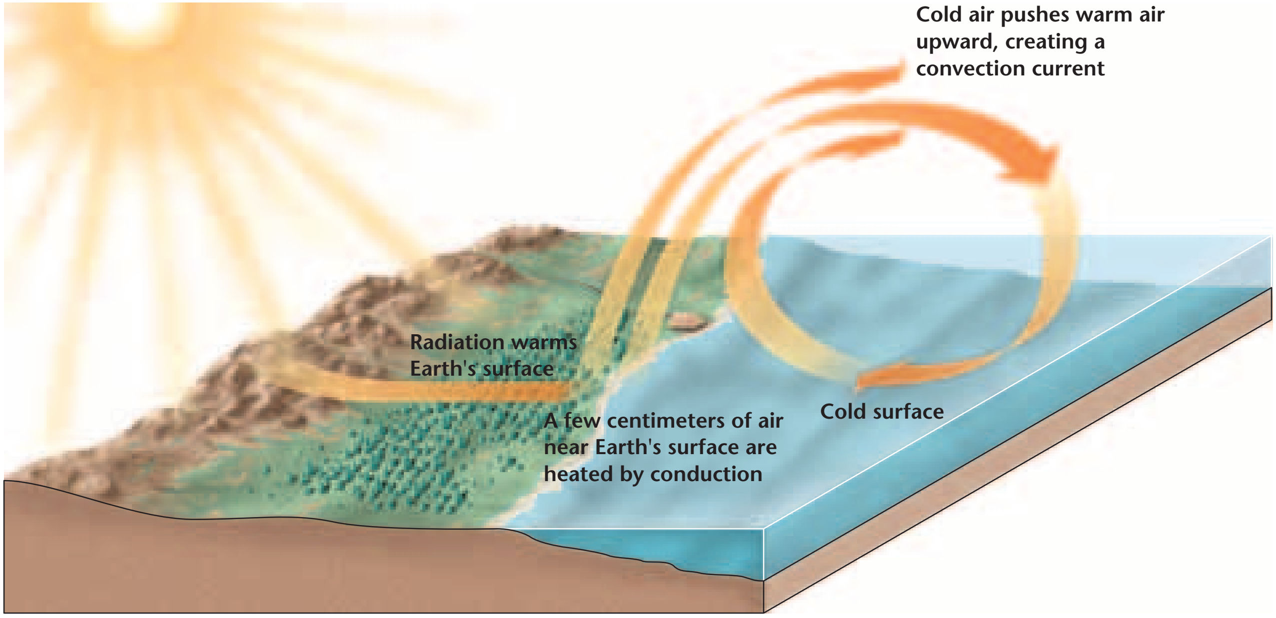


Figure 11-5 Energy is transferred throughout the atmosphere by the processes of conduction, convection, and radiation.

For the most part, solar radiation does not heat air directly. How, then, does air become warm? Most of the solar radiation that travels through the atmosphere does so at short wavelengths. The atmosphere does not easily absorb short wavelengths, so much of the solar radiation passes through the atmosphere and is absorbed by Earth's surface. The surface then radiates energy, but the radiation it gives off has a longer wavelength than the energy coming from the Sun. The energy radiated by Earth's surface does not pass back through the atmosphere. Rather, it is absorbed by the atmosphere and warms air through the processes of conduction and convection, which, along with radiation, make up the three methods of energy transfer illustrated in ***Figure 11-5.***

Conduction To understand how the energy radiated by Earth's surface warms the atmosphere, think about what happens when you turn on a burner on the stove. The hot burner radiates energy much like Earth's surface does.

Now, imagine that you place a pot of water on the burner. Through **conduction,** which is the transfer of energy that occurs when molecules collide, energy is transferred from the bottom of the pot into the lowest part of the water. In the same way, energy is transferred from the particles of air near Earth's surface to the particles of air in the lowest layer of the atmosphere. For conduction to occur, substances must be in contact with one another. That's why conduction affects only a very thin atmospheric layer near Earth's surface.

Figure 11-6 Many different factors, including convection currents, cause the different types of weather shown here.

Convection Once the energy has made its way into the lower part of the atmosphere, can it ever move higher? Recall the pot of water. Energy has been transferred by conduction to the lowest layer of water molecules. This heated water expands, becomes less dense, and forms bubbles that rise. The rising bubbles bring the warm water to the top. The water at the top then cools, causing pockets of cool water to sink and become reheated when they come into contact with the bottom of the pot. This process is known as **convection,** the transfer of energy by the flow of a heated substance—in this case, the water. A similar process takes place in the atmosphere. Pockets of air near Earth's surface are heated, become less dense than the surrounding air, and rise. As the warm air rises, it expands and starts to cool. When it cools below the temperature of the surrounding air, it increases in density and sinks. As it sinks, it warms again and the process starts anew. Convection currents, as these movements of air are called, are among the main mechanisms responsible for the vertical motions of air, which in turn cause the different types of weather shown in ***Figure 11-6.***

SECTION ASSESSMENT

1. Describe the importance of water vapor in the atmosphere.
2. Why does temperature increase with height through the stratosphere?
3. Rank the main atmospheric gases in the troposphere in order from most abundant to least abundant. Do not include trace gases.
4. **Thinking Critically** Based on what you know about radiation and conduction, what conclusion might you make about summer temperatures in a large city compared with those in the surrounding countryside?

SKILL REVIEW

5. **Predicting** Of the three main processes of energy transfer throughout the atmosphere, which do you think plays the greatest role in warming the upper troposphere? Why? For more help, refer to the *Skill Handbook.*

SECTION 11.2 State of the Atmosphere

OBJECTIVES

- **Describe** *the various properties of the atmosphere and how they interact.*
- **Explain** *why atmospheric properties change with changes in altitude.*

VOCABULARY

temperature
heat
dew point
condensation
lifted condensation level
temperature inversion
humidity
relative humidity

When people talk about the weather by saying that it's sunny or cloudy or cold, they're describing the current state of the atmosphere. Scientists describe the atmosphere, too, using words such as *temperature, air pressure, wind speed,* and *the amount of moisture in the air.* These are atmospheric properties that describe weather conditions. We'll examine each in turn, beginning with temperature.

TEMPERATURE VERSUS HEAT

Most of us tend to think of heat and temperature as being essentially the same thing. They are, in fact, two different concepts. **Temperature** is a measurement of how rapidly or slowly molecules move around. More molecules or faster-moving molecules in a given space generate a higher temperature. Fewer molecules or slower-moving molecules generate a lower temperature and cause a substance—air, for instance—to cool. **Heat,** on the other hand, is the transfer of energy that occurs because of a difference in temperature between substances. The direction of heat flow depends on temperature. Heat flows from an object of higher temperature to an object of lower temperature. How does this relate to the atmosphere? Heat is the transfer of energy that fuels atmospheric processes, while temperature is used to measure and interpret that energy.

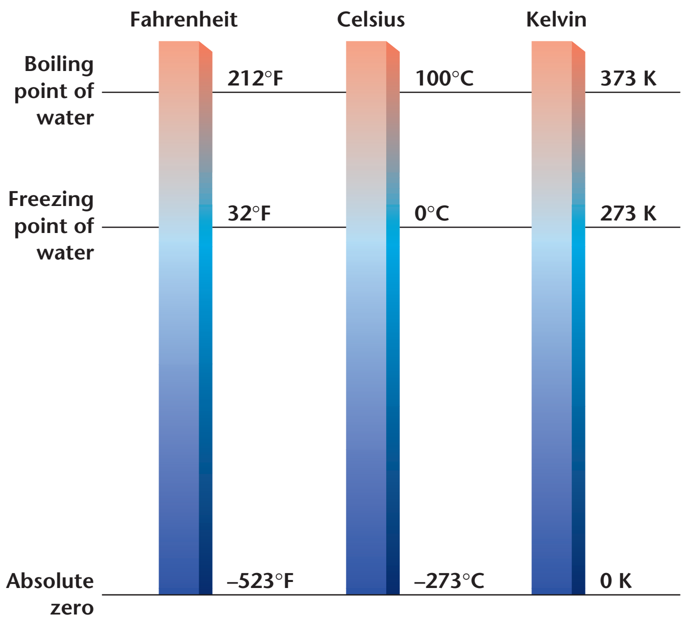


Figure 11-7 The Kelvin scale starts at 0 K, which corresponds to −273°C and −523°F.

Measuring Temperature Temperature can be measured in degrees Fahrenheit (°F), in degrees Celsius (°C), or in kelvins (K). Fahrenheit is the scale most commonly used in the United States. Celsius, the scale used in this book, is convenient because the difference between its freezing and boiling points is exactly 100 degrees. The kelvin is the SI unit of temperature. The Kelvin scale measures the number of kelvins above absolute zero, which corresponds to approximately −273°C and −523°F. This scale is a more direct measure of molecular activity, because at absolute zero, molecular motion theoretically stops. Because nothing can be colder than absolute zero, there are no negative numbers on the Kelvin scale. ***Figure 11-7*** compares the different temperature scales.

Dew Point Another atmospheric measurement is the dew point. The **dew point** is the temperature to which air must be cooled at constant pressure to reach saturation. Saturation is the point at which the air holds as much water vapor as it possibly can. The dew point is important because until air is saturated, condensation cannot occur. **Condensation** occurs when matter changes state from a gas to a liquid. In this case, water vapor changes into liquid water and eventually falls as rain. Given its role in this process, the dew point is often called the condensation temperature.

VERTICAL TEMPERATURE CHANGES

The temperature on a mountaintop is cooler than at lower elevations because the temperature of the lower atmosphere decreases with increasing distance from its heat source—Earth's surface. Individual masses of air moving upward through the atmosphere experience a change in temperature, too. An air mass that does not exchange heat with its surroundings will cool off by about 10°C for every 1000-m increase in altitude. This is called the dry adiabatic lapse rate—the rate at which unsaturated air to which no heat is added or removed will cool. If the air is able to continue rising, eventually it will cool to its condensation temperature. The height at which condensation occurs is called the **lifted condensation level** (LCL). As shown in ***Figure 11-8,*** clouds form when water vapor condenses into water droplets, so the height of the LCL often corresponds to the base of clouds. Above the LCL, air becomes saturated and cools more slowly. The rate at which saturated air cools is called the moist adiabatic lapse rate. This rate ranges from about 4°C/1000 m in very warm air to almost 9°C/1000 m in very cold air.

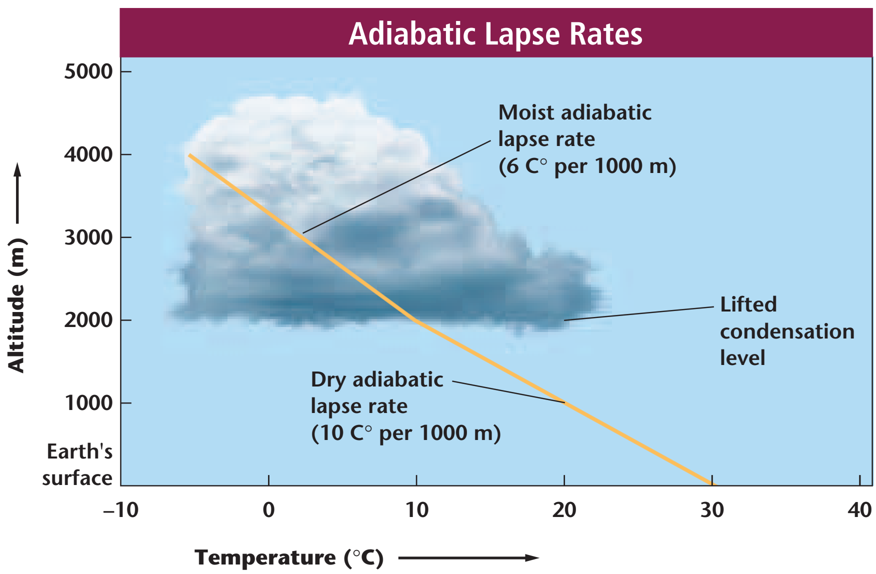


Figure 11-8 Condensation occurs at the lifted condensation level (LCL). Air above the LCL is saturated and thus cools more slowly than air below the LCL.

Table 11-1 Density Changes With Altitude			
Altitude km	Density g/L	Altitude km	Density g/L
0	1.23	30	0.018
2	1.01	40	0.004
4	0.82	50	0.001
6	0.66	60	0.0003
8	0.53	70	0.00009
10	0.41	80	0.00002
15	0.19	90	0.000003
20	0.09	100	0.0000005

Air Pressure and Density

Just like water in the ocean, air has mass and constantly exerts pressure on our bodies. Why? The gravitational attraction between Earth and atmospheric gases causes particles of gas to be pulled toward the center of Earth. You don't notice this pressure because you have spent your whole life under it and are accustomed to it. A fish living deep in the ocean exists under pressure that would crush our bodies, but the fish survives because its body is adapted to such pressure. Just as water pressure increases with depth in the ocean, pressure increases as you near the bottom of the atmosphere because of the greater mass of the atmosphere above you. Conversely, atmospheric pressure decreases with height because there are fewer and fewer gas particles exerting pressure.

The density of air is proportional to the number of particles of air occupying a particular space. As ***Table 11-1*** shows, the density of air increases as you get closer to the bottom of the atmosphere. This is because gases at the top of the atmosphere press down on the air below, thereby compressing the particles and increasing the density of the air. Thus, at the top of a mountain, temperature, pressure, and density are all less than they are at lower elevations.

Table 11-2 Atmospheric Relationships
As T ↑, P ↑
As T ↓, P ↓
As T ↓, D ↑
As T ↑, D ↓

T = Temperature
P = Pressure
D = Density
↑ = Increases
↓ = Decreases

Pressure-Temperature-Density Relationship

The previous discussion raises an important point about the atmosphere: temperature, pressure, and density are related, as shown in ***Table 11-2.*** In the atmosphere, temperature is directly proportional to pressure. So, if an air mass maintains a certain density—that is, the number of gas particles in a fixed volume remains the same—as temperature increases or decreases, pressure does, too. By the same token, as pressure increases or decreases, temperature does, too. You will further explore this relationship in the *GeoLab* at the end of this chapter.

The relationship between temperature and density, on the other hand, is inversely proportional. So, if an air mass maintains a certain pressure, as temperature increases, density decreases, and as temperature decreases, density increases. This is why air rises when its temperature increases—it becomes less dense.

In most atmospheric interactions, however, neither density nor pressure remains unchanged, and this muddles the relationship among temperature, pressure, and density. Earlier, for example, we noted that both temperature and density decrease with increasing altitude in the troposphere. If density decreases with height, how can temperature decrease as well if it is inversely proportional to density? The answer lies in the fact that temperature varies with changes in both pressure and density. In this case, temperature is proportional to the ratio of pressure to density, which decreases with increasing altitude.

Temperature Inversions In the atmosphere, the relationship between temperature and pressure is not always fixed. Although temperature and pressure in the overall troposphere decrease with height, there is an exception to this rule known as a temperature inversion. A **temperature inversion** is an increase in temperature with height in an atmospheric layer. It's called a temperature inversion because the temperature-altitude relationship is inverted, or turned upside down. This can happen in several ways. We'll consider one that involves the rapid cooling of land on a cold, clear, winter night when the wind is calm. Under these circumstances, the lower layers of the atmosphere are not receiving heat from Earth's surface—they're losing heat. As a result, the lower layers of air become cooler than the air above them, so that temperature increases with height and forms a temperature inversion. In some cities, such as the one shown in ***Figure 11-9,*** a temperature inversion can worsen air-pollution problems by acting like a lid to trap pollution under the inversion layer. In all cases, the presence or absence of inversions can have a profound effect on weather conditions, as you'll learn in the next chapter.

Figure 11-9 A temperature inversion in Long Beach, California, traps air pollution above the city.

Figure 11-10 When wind blows over these sand dunes in Namibia, it encounters more friction than when it blows over water.

WIND

You may have entered a large, air-conditioned building on a hot summer day. As you opened the door, a sudden rush of cool air greeted you. This happened because the air conditioner created an imbalance between the warm, less-dense air outside the building and the cool, more-dense air inside. The cool air, being denser, had settled toward the bottom of the building. When the door opened, the cool, dense air rushed out to try to relieve the imbalance. The rush of air that you experienced is commonly known as wind.

In essence, the atmosphere works much like an air-conditioned building. Cool air, being more dense, sinks and forces warm, less-dense air upward. In the lower atmosphere, air generally moves from areas of high density to areas of low density. The air moves in response to density imbalances created by the unequal heating and cooling of Earth's surface. These imbalances, in turn, create areas of high and low pressure. In its simplest form, wind can be thought of as air moving from an area of high pressure to an area of low pressure. Wind is usually measured in miles per hour or kilometers per hour. Ships at sea usually measure wind in knots. One knot is equal to 1.85 km/h.

Like temperature and pressure, wind changes with height in the atmosphere. Why? Near Earth's surface, wind is constantly disrupted by the friction that results from its contact with trees, buildings, and hills—even the surface of water affects air motion. Farther up from Earth's surface, air encounters less friction, and wind speeds increase. Look at ***Figure 11-10.*** Would you expect the wind to blow more strongly over the ocean or across the dunes?

Relative Humidity

Just for fun, reach out and grab a handful of air. You may not know it, but you also grabbed some water vapor. Air in the lower portion of the atmosphere always contains at least some water vapor, even though that amount may be very small. The amount of water vapor in air is referred to as **humidity.**

Imagine now that you take your handful of air—and its water vapor—into a room full of dry air and let it go. Would that roomful of air have the same humidity as your handful? No, because the water vapor in that handful would be very small relative to how much water vapor that roomful of air could actually hold. The ratio of water vapor in a volume of air relative to how much water vapor that volume of air is capable of holding is called **relative humidity.** As the graph in the *Problem-Solving Lab* shows, relative humidity varies with temperature. Warm air is capable of holding more moisture than cool air. Thus, if the temperature of a room increased, the air in

Using Math

Using Numbers At 20°C, a cubic meter of air can hold a total of 17 g of water vapor. What is the air's relative humidity if it holds only 6 g of water vapor?

Problem-Solving Lab

Interpreting Graphs

Determine relative humidity

Relative humidity is the ratio of water vapor in a given volume of air compared with how much water vapor that volume of air can actually hold. Use the graph at the right to answer the following questions.

Analysis

1. How much water vapor can a cubic meter of air hold at 25°C?
2. How much water vapor can the same volume of air hold at 15°C?

Thinking Critically

3. Why do the values in questions 1 and 2 differ?
4. If the relative humidity of the air in question 1 was 50 percent, how much water vapor would it hold?
5. If you wanted to decrease the relative humidity of a room, would you increase or decrease its temperature? Explain your answer.

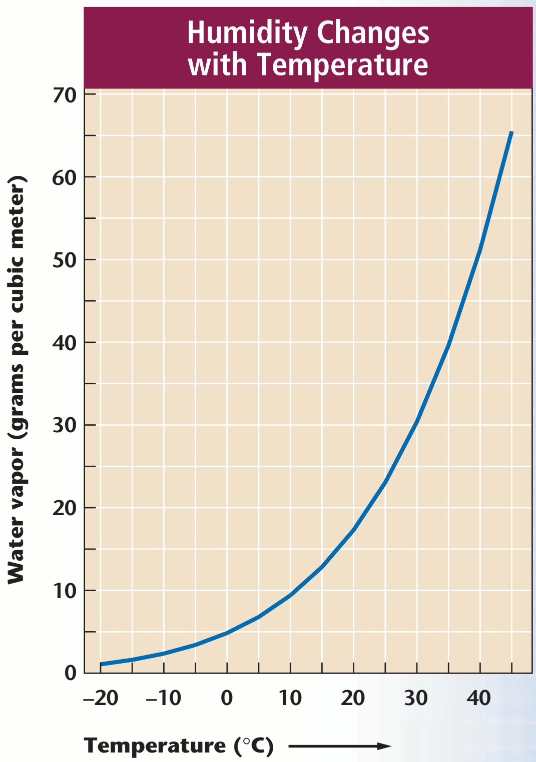


Figure 11-11 Clouds form when a mass of rising air becomes saturated and condenses its water vapor into large groups of water droplets.

the room would be capable of holding more moisture. If no additional water vapor was added to the air, its relative humidity would decrease. Conversely, if more water vapor was added to the air, its relative humidity would increase. Do the *Problem-Solving Lab* on the previous page to learn more about relative humidity.

Relative humidity is expressed as a percentage. If a certain volume of air is holding as much water vapor as it possibly can, then its relative humidity is 100 percent. If that same volume of air is holding half as much water vapor as it can, its relative humidity is 50 percent, and so on. Recall that air is saturated when it holds as much water vapor as it possibly can. As you'll see next, this has important implications for the development of precipitation and clouds such as those shown in ***Figure 11-11.***

SECTION ASSESSMENT

1. How is dew point related to saturation?
2. What is the relationship between temperature and altitude in a temperature inversion?
3. How does atmospheric pressure change with height in the atmosphere? Why does it change?
4. Compare and contrast humidity and relative humidity.
5. **Thinking Critically** Which would melt more ice—a pot of hot water or a tub of warm water? Explain your answer.

SKILL REVIEW

6. **Designing an Experiment** Design an experiment that shows how average wind speeds change over different types of surfaces. For more help, refer to the *Skill Handbook.*

earthgeu.com/self_check_quiz

SECTION 11.3 *Moisture in the Atmosphere*

OBJECTIVES

- **Explain** *how clouds are formed.*
- **Identify** *the basic characteristics of different cloud groups.*
- **Describe** *the water cycle.*

VOCABULARY

condensation nuclei
orographic lifting
stability
latent heat
coalescence
precipitation
water cycle
evaporation

Would you like to be able to predict the weather? To do so, you'll probably need to learn more about clouds. Certain types of clouds are associated with certain types of weather. Before learning about cloud types, however, you need to understand how clouds form.

CLOUD FORMATION

You know that air generally contains some amount of water vapor and that warm, less-dense air rises, while cool, more-dense air sinks. This tendency to rise or sink as a result of differences in density is called buoyancy. As you can see in ***Figure 11-12,*** clouds form when warm, moist air rises, expands, and cools in a convection current. As the air reaches its dew point, the water vapor in the air condenses around condensation nuclei. **Condensation nuclei** are small particles in the atmosphere around which cloud droplets can form. They come from a variety of sources, including sea salt and dust. When millions of these droplets collect, a cloud forms.

Clouds can also form when wind encounters a mountain and the air has no place to go but up. The effect is the same as with any rising air—it expands and cools. This method of cloud formation, shown in ***Figure 11-13A*** on the next page, is called **orographic lifting.** Another method of cloud formation involves the collision of air masses of different temperatures, as shown in ***Figure 11-13B*** on the next page. Recall that cold, more-dense air is heavier than warm, less-dense air, so it tends to collect near Earth's surface. As warmer air moves into the area, some of it will warm up the cold air, but the bulk of it will be forced to rise over the more-dense, cold air. As the warm air cools, the water vapor in it condenses and forms a cloud.

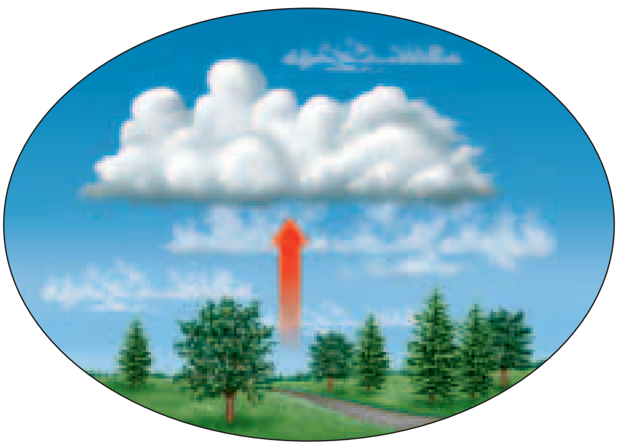


Figure 11-12 Clouds form when warm air is forced up in a convection current.

Stability Regardless of how a cloud forms, all rising air expands and cools. How rapidly any given mass of air cools determines its stability. **Stability** is the ability of an air mass to resist rising. Imagine an air mass that is warmer than the surface beneath it. Heat flows from the warmer air to the colder surface. The lower layer of the air mass thus loses heat and cools. The cooling air resists rising—it is stable. The rate at which an air mass cools depends in part on the temperature of the surface beneath the air. The temperature of surrounding air masses and the temperature of the air mass itself also play a role in determining the cooling rate.

Air can become unstable if it is cooler than the surface beneath it. In this case, heat flows from the warmer surface to the cooler air. The air warms and becomes less dense than the surrounding air. The less-dense air mass rises. If temperature conditions are right and the air mass rises rapidly, it can produce the type of clouds associated with thunderstorms.

Latent Heat As water vapor in the air condenses, heat is released. Where does this heat come from? It takes energy to change liquid water into a gaseous state. The energy that is transferred to the gas doesn't just go away; it is stored in the water vapor and will not be released into the air until condensation occurs. The stored energy is called **latent heat.** Until condensation occurs, latent heat is not available to warm the atmosphere.

When condensation takes place, latent heat is released and warms the air. At any given time, the amount of water vapor present in the atmosphere is a significant source of energy because of the latent heat it contains. When condensation occurs, this latent heat can provide energy to a weather system, thereby increasing its intensity.

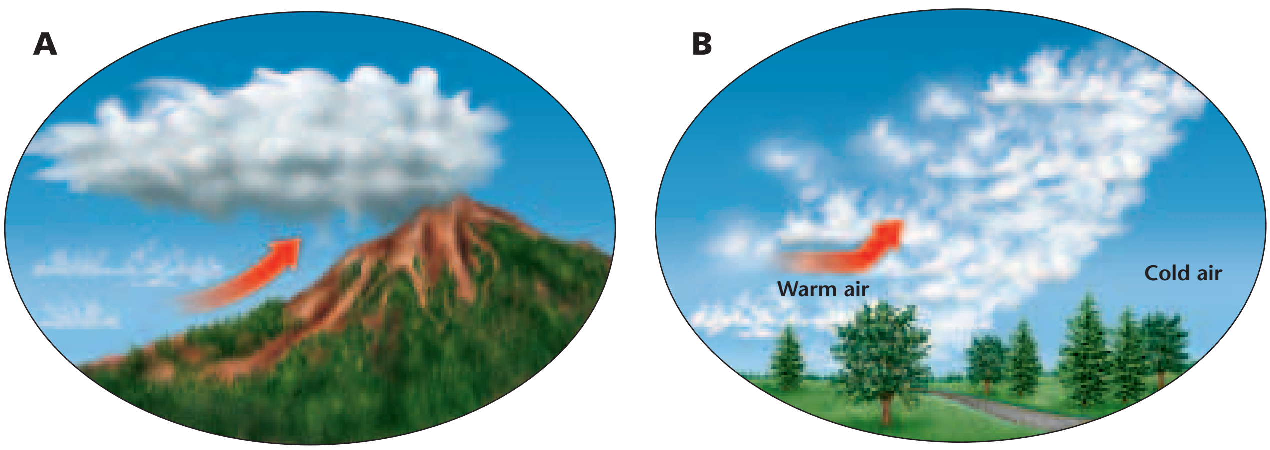


Figure 11-13 Clouds form when warm moist air is forced to rise over a mountain **(A)** and when two air masses of different temperatures meet **(B).**

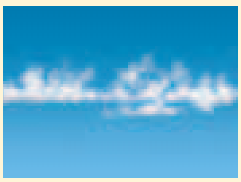
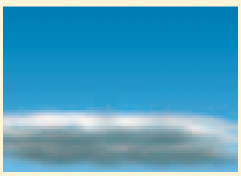
Types of Clouds

When a mass of rising air reaches its lifted condensation level or LCL, water vapor condenses into droplets of liquid water or ice, depending on the temperature. If the density of these droplets is great enough, they become visible in the form of a cloud. While this is the basic principle behind the formation of all clouds, this process can take place at many different altitudes—sometimes even in contact with Earth's surface, in which case it is known as fog. In addition to forming at different heights, clouds form in different shapes, depending on the factors involved in their formation.

Clouds are generally classified according to a system originally developed by English naturalist Luke Howard in 1803. As shown in ***Table 11-3,*** the modern system groups clouds by the altitude at which they form and by their shape. Low clouds typically form below 2000 m. Middle clouds form mainly between 2000 m to 6000 m. High clouds composed of ice crystals form above 6000 m. The final group of clouds includes those that spread throughout all altitudes—at the same time, no less. These are vertical development clouds.

> **Earth Science Online**
>
> **Topic: Clouds**
> To find out more about clouds, visit the Earth Science Web Site at earthgeu.com
>
> **Activity:** Make a poster or media presentation showing the types of clouds you observed during a one-week period.

Table 11-3 Cloud Classification

Height: Prefix			Shape: Prefix		
Cirro	Describes high clouds with bases starting above 6000 m.		**Cirrus**	Latin meaning: "hair." Describes wispy, stringy clouds.	
Alto	Describes middle clouds with bases between 2000 m to 6000 m.		**Cumulus**	Latin meaning: "pile or heap." Describes puffy, lumpy-looking clouds.	
Strato	Refers to low clouds below 2000 m.		**Stratus**	Latin meaning: "layer." Describes featureless sheets of clouds.	
			Nimbus	Latin meaning: "cloud." Describes low, gray rain clouds.	

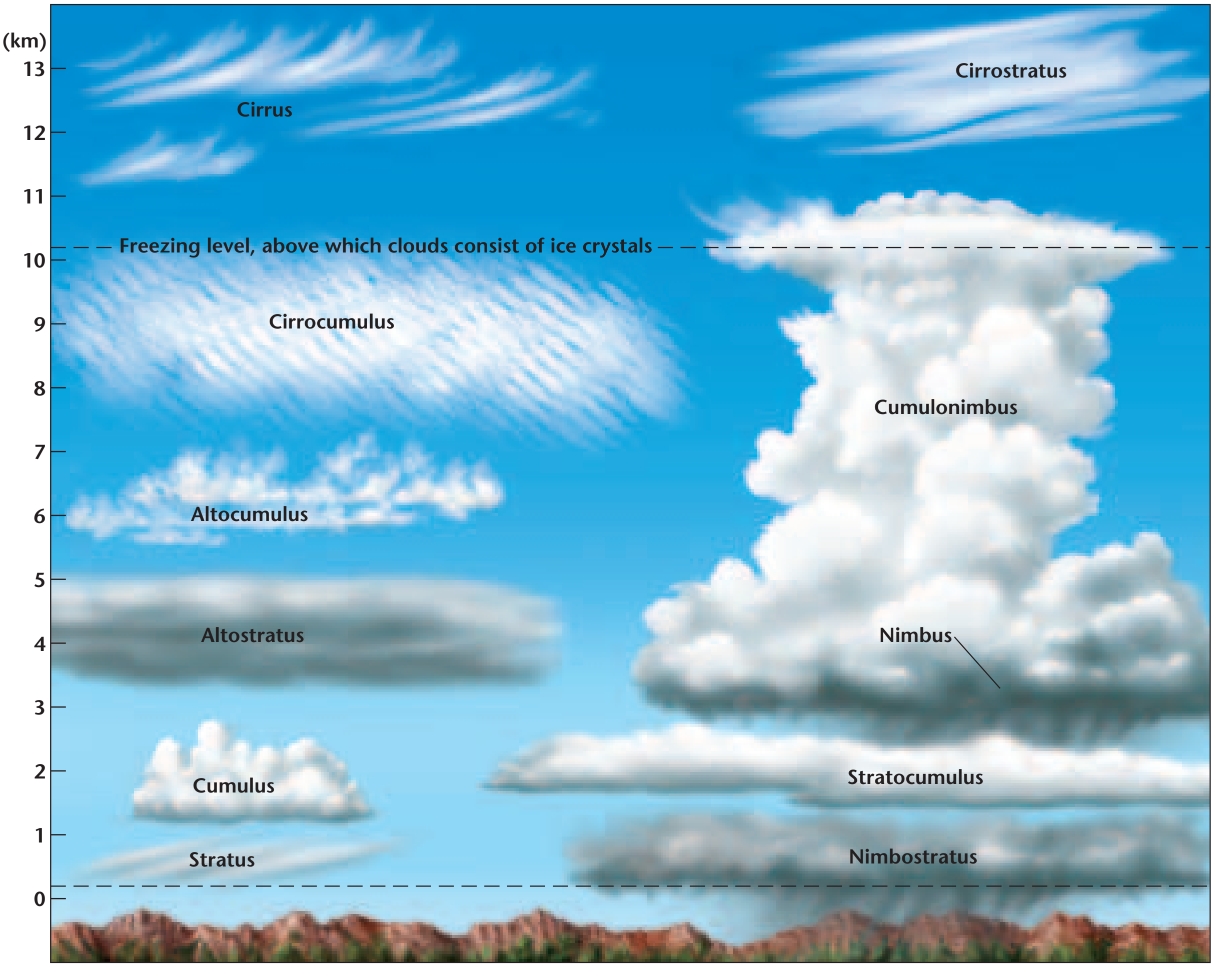


Figure 11-14 Clouds form at different heights and in different shapes. ***Compare and contrast cirrus and stratus clouds.***

Low Clouds Imagine a warm, summer afternoon. The Sun is beating down, heating Earth's surface. In areas where the heating is particularly intense, such as fields with dark soil, conduction causes air above the surface to become warmer than the surrounding air. As the temperature rises, the air expands. Its density becomes lower than that of surrounding air and it begins to rise and cool by further expansion. When it reaches its LCL, it becomes saturated, and the water vapor it contains condenses into water droplets. These droplets eventually become numerous enough to form a visible cloud. If the air stays warmer than the surrounding air, the cloud will continue to grow. If the air does not stay warmer than the surrounding air, the cloud will flatten out and winds will spread it horizontally into stratocumulus or layered cumulus clouds. Another type of low cloud that forms at heights below 2000 m is a stratus, a layered cloud that covers much or all of the sky in a given area. Stratus clouds often form when fog lifts away from Earth's surface. ***Figure 11-14*** shows these and other types of clouds.

Middle Clouds Altocumulus and altostratus clouds, which form at heights between 2000 m and 6000 m, can be either all liquid or a mixture of liquid and ice crystals. This is due to the cooler temperatures generally present at the heights at which these clouds form. Middle clouds are usually layered. Altocumulus clouds often resemble white fish scales. Altostratus clouds are dark but thin veils of clouds that sometimes produce mild precipitation.

High Clouds Because they form above heights of 6000 m, where temperatures are below freezing, high clouds are made up of ice crystals. Thus, some, such as cirrus clouds, often have a wispy, indistinct appearance. Another type of cirriform cloud, called a cirrostratus, forms as a continuous layer that sometimes covers the sky. Cirrostratus clouds can vary in thickness from being almost transparent to being dense enough to block out the Sun or Moon.

Clouds of Vertical Development If the air that makes up a cumulus cloud is unstable enough, the cloud will be warmer than the surface or surrounding air and will continue to grow. As it rises, water vapor condenses, and the air receives additional warmth from the release of latent heat. The cloud can grow through middle altitudes as a towering cumulus; if conditions are right, it can reach nearly 18 000 m. Its top is then composed of ice crystals. Strong winds can spread it into a familiar anvil shape. A puffy, white cumulus cloud can thus develop into a full-fledged cumulonimbus, as shown in ***Figure 11-15.*** What began as a small mass of moist air is now an atmospheric giant, capable of producing the torrential rains and strong winds that are characteristic of thunderstorms.

PRECIPITATION

When cloud droplets collide, they join together to form a larger droplet in a process called **coalescence.** As the process continues, the droplet eventually becomes too heavy to be held aloft. At this point, gravity takes over and the droplet falls to Earth as precipitation. **Precipitation** includes all forms of water, both liquid and solid, that fall from clouds. Rain, snow, sleet, and hail are the four main types of precipitation. Coalescence is the primary process responsible for the formation of precipitation from warm clouds. Precipitation from cold clouds generally involves the interaction of ice and

Figure 11-15 Cumulonimbus clouds, such as this one, in Arizona, are associated with thunderstorms.

MiniLab

What affects the formation of clouds and precipitation?

Model the water cycle.

Procedure

1. Pour about 125 mL of warm water into a clear, plastic bowl.
2. Loosely cover the top of the bowl with plastic wrap. Overlap the edges by about 5 cm.
3. Fill a self-sealing plastic bag with ice cubes, seal it, and place it in the center of the plastic wrap on top of the bowl. Push the bag of ice down so that the plastic wrap sags in the center, but doesn't touch the surface of the water.
4. Use tape to seal the plastic wrap around the bowl.
5. Observe the surface of the plastic wrap directly under the ice cubes every 10 minutes for one-half hour, or until the ice melts.

Analyze and Conclude

1. What formed on the underside of the wrap? Infer why this happened.
2. Relate your observations to processes in the atmosphere.
3. Predict what would happen if you repeated this activity with hotter water.

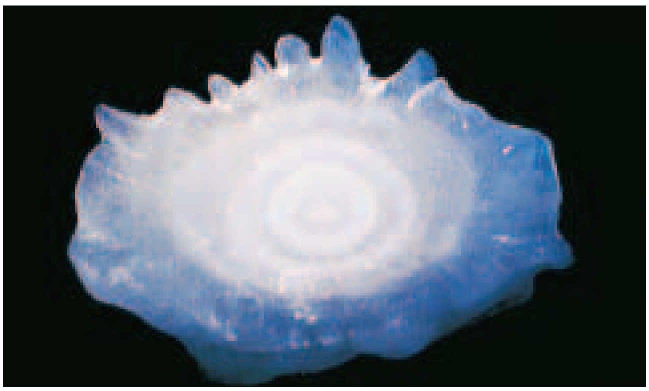


Figure 11-16 Note the distinctive layers in the cross-section of the hailstone. ***Infer how the layers formed.***

water molecules in the clouds. Do the *MiniLab* on this page to model the formation of clouds and precipitation.

Why are there so many variations in precipitation? When precipitation forms at cold temperatures, it takes the form of ice crystals or snow. Sometimes, convective currents carry the droplets up and down through freezing and nonfreezing air, thereby forming ice pellets or sleet. If that up-and-down motion is especially strong and takes place over large stretches of the atmosphere, it can form very large ice pellets known as hail. ***Figure 11-16*** shows a sample of hail.

THE WATER CYCLE

The total amount of water on Earth is constant, and probably has been for millions of years. More than 97 percent of Earth's water is salt water found in oceans. Only three percent is freshwater, and two-thirds of this is frozen in ice caps at the poles. At any one time, only a small percentage of water is present in the atmosphere. Still, this water is vitally important because as it continually moves between the atmosphere and Earth's surface, it nourishes living things. The constant movement of water between the atmosphere and Earth's surface is known as the **water cycle.**

The water cycle, shown in ***Figure 11-17,*** receives its energy from the Sun. Radiation from the Sun causes liquid water to change into a gas. The process of water changing from a liquid to a gas is called **evaporation.** This is the first step in the water cycle. Water evaporates from lakes, streams, and oceans

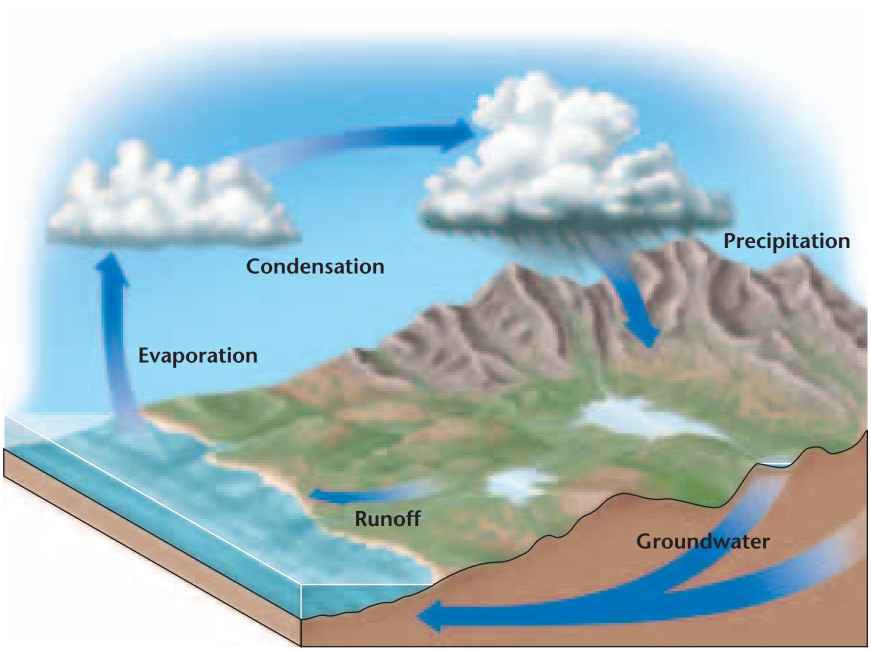


Figure 11-17 Water moves from Earth to the atmosphere and back to Earth in the water cycle.

and rises into Earth's atmosphere. As water vapor rises, it cools and changes back into a liquid. This process, as you have learned, is called condensation, the second step of the water cycle. When water vapor condenses, it forms clouds.

In the third step of the water cycle, water droplets combine to form larger drops that fall to Earth as precipitation. This water soaks into the ground and enters lakes, streams, and oceans, or it falls directly into these bodies of water and eventually evaporates, and the water cycle continues.

SECTION ASSESSMENT

1. Explain why a cumulonimbus cloud is not considered to be a low, middle, or high cloud.
2. Describe the process that causes a water droplet to fall to Earth as precipitation.
3. What determines whether precipitation will fall as rain or snow?
4. **Thinking Critically** Based on what you have learned about latent heat, explain why the lapse rate of moist air is less than that of dry air.

SKILL REVIEW

5. **Concept Mapping** Use the following terms to construct a concept map that describes the processes of the water cycle. For more help, refer to the *Skill Handbook.*

water cycle | evaporation | condensation | precipitation

water changes from liquid to gas | water changes from gas to liquid | water falls as rain, snow, sleet, or hail

CONTENTS

GeoLab

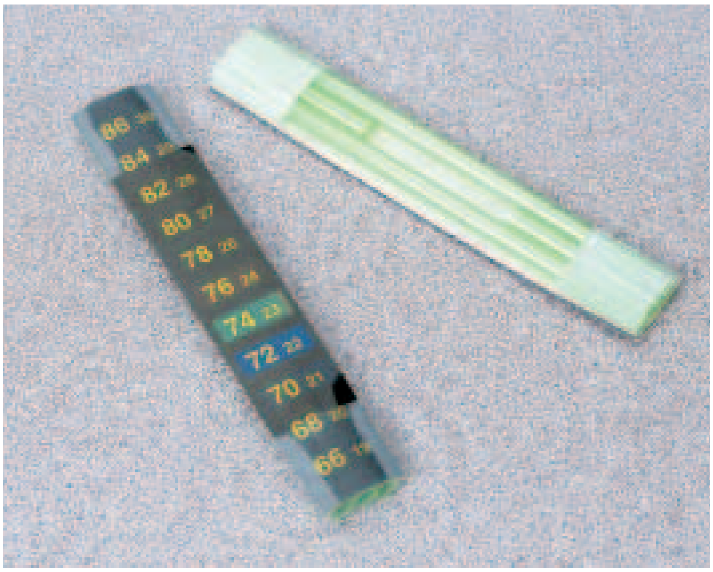
Interpreting Pressure-Temperature Relationships

As you go up a mountain, both temperature and air pressure decrease. These effects are easily explained. Temperature decreases as you get farther away from the atmosphere's heat source, Earth's surface. Pressure decreases as you ascend the mountain because there are fewer and fewer particles of air above you. Pressure and temperature, however, are also related through the expansion and compression of air, regardless of height. In this activity, you will demonstrate that relationship.

Preparation

Problem

Demonstrate the relationship between temperature and pressure.



Objectives

In this GeoLab, you will:

- **Model** the temperature and pressure changes that take place as a result of the expansion and compression of air.
- **Relate** the changes to processes in the atmosphere.

Materials

clean, clear, plastic 2-L bottle with cap
plastic straws
scissors
thin, liquid-crystal temperature strip
tape
watch or timer

Safety Precautions

Always wear safety goggles and an apron in the lab.

CONTENTS

Procedure

1. Cut two pieces of straw, each the length of the temperature strip. Then cut two 2-cm pieces of straw. Lay the two long pieces on a table. Place the two shorter pieces within the space created by the longer pieces so that the four pieces form a supportive structure for the temperature strip, as shown in the photograph on the previous page.
2. Tape the four pieces of straw together. Place the temperature strip lengthwise upon the straws. Tape the strip to the straws.
3. Slide the temperature strip-straw assembly into the clean, dry bottle. Screw the cap on tightly.
4. Place the sealed bottle on the table so that the temperature strip faces you and is easy to read. Do not handle the bottle any more than is necessary so that the temperature inside will not be affected by the warmth of your hands.
5. Record the temperature of the air inside the bottle as indicated by the temperature strip.
6. Next, position the bottle so that about half its length extends beyond the edge of the table. Placing one hand on each end of the bottle, push down on both ends so that the bottle bends in the middle. Hold the bottle this way for two minutes. During this time, your partner should record the temperature every 15 seconds.
7. Release the pressure on the bottle. Observe and record the temperature every 15 seconds for the next two minutes.

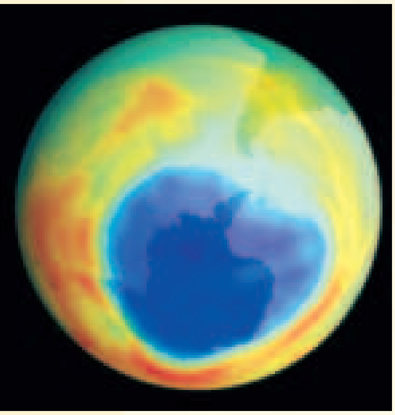
Analyze

1. What was the average temperature of the air inside the bottle as you applied pressure to the bottle? How did this differ from the average temperature of the bottled air when you released the pressure on the bottle?
2. Make a graph of the temperature changes you recorded throughout the experiment.
3. Explain how these temperature changes are related to changes in pressure.

Conclude & Apply

1. Predict how the experiment would change if you took the cap off the bottle.
2. Given your observations and what you know about the behavior of warm air, would you expect the air over an equatorial desert at midday to be characterized by high or low pressure?

Science in the News



The Montreal Protocol and the Ozone Layer

In 2002, scientists reported that the amount of ozone-destroying chemicals in the atmosphere, particularly chlorine, was decreasing. This decrease is largely due to the efforts of the countries that have signed the Montreal Protocol, an international treaty which set restrictions on the global production and use of chlorofluorocarbons (CFCs) and other ozone-destroying chemicals that can reach the atmosphere.

The ozone layer, located in the stratosphere, absorbs up to 99 percent of incoming ultraviolet radiation. Overexposure to ultraviolet radiation can lead to the development of skin cancer and cataracts.

Chemical Reactions

Once they enter the atmosphere, CFCs, chemicals that were used in refrigerators and air conditioners, and halons, used in fire extinguishers, are broken down by ultraviolet light. The products of these breakdowns include highly reactive chlorine and bromine. The chlorine and bromine atoms destroy ozone molecules during chemical reactions. A single chlorine or bromine atom can destroy hundreds of ozone molecules before it reacts with another gas, thus ending the destruction. Because of all this, a small amount of reactive chlorine or bromine can have a large impact on the ozone layer.

International Effort

After the discovery of the “hole” in the ozone layer, an international effort began to stop the destruction of the ozone layer. At its inception in 1987, 24 countries signed the Montreal Protocol. The Montreal Protocol called for a phase-out in the production and use of most ozone-destroying chemicals by developed countries by the year 2005. Developing countries around the world are working to achieve the same goal by 2015. By 2003, 186 countries had signed and were abiding by the restrictions of the Montreal Protocol.

Future Outlooks

Recent studies indicate that actions taken as a result of the Montreal Protocol restrictions have an effect on levels of chlorine in the atmosphere, which are decreasing each year. Scientists warn that even complete compliance with the Montreal Protocol will still leave the ozone layer vulnerable for the next decade. However, based on current trends in data, a return to pre-1980 ozone amounts over Antarctica is expected by the middle of this century.

Activity

Research the latest information about the Montreal Protocol. What amendments were added in 1999? What has occurred since 1999? Write a short report explaining the latest goals of and changes to the Montreal Protocol.

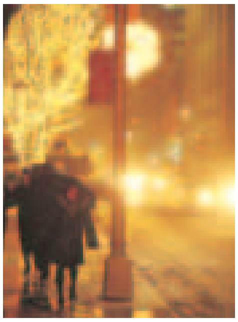
CHAPTER 11

Study Guide

Summary

SECTION 11.1

Atmospheric Basics



Main Ideas

- Earth's atmosphere is made of a combination of several gases, primarily nitrogen and oxygen. It also contains small amounts of water vapor, carbon dioxide, ozone, and dust, which play key roles in the production of weather and climate.
- The atmosphere consists of several layers characterized by differences in temperature. The most important for weather is the lowest layer, the troposphere, where most of the mass of the atmosphere is found.
- The Sun is the source of energy in Earth's atmosphere. Solar energy absorbed by Earth's surface is transferred throughout the atmosphere by the processes of radiation, conduction, and convection.

Vocabulary

conduction (p. 276)
convection (p. 277)
exosphere (p. 274)
mesosphere (p. 274)
ozone (p. 273)
radiation (p. 275)
stratosphere (p. 274)
thermosphere (p. 274)
troposphere (p. 274)

SECTION 11.2

State of the Atmosphere

Main Ideas

- Heat is the transfer of energy that occurs because of a difference in temperature between substances. Temperature is the measure of how rapidly or slowly molecules move around. Atmospheric temperature generally decreases with altitude.
- Air has mass and exerts a force called atmospheric pressure. Because there are fewer molecules of gas in the upper atmosphere, atmospheric pressure decreases with increasing altitude.
- Wind is the movement of air that results from differences in pressure. Wind speed is affected by friction; mountains, forests, and buildings slow wind down.

Vocabulary

condensation (p. 279)
dew point (p. 279)
heat (p. 278)
humidity (p. 283)
lifted condensation level (p. 279)
relative humidity (p. 283)
temperature (p. 278)
temperature inversion (p. 281)

SECTION 11.3

Moisture in the Atmosphere

Main Ideas

- Clouds are formed as warm, moist air is forced upward, expands, and cools. Orographic lifting is a method of cloud formation that involves air moving up the side of a mountain. Clouds may also form when air masses of different temperatures collide.
- Clouds are generally classified according to the altitudes at which they form and their shapes.
- As cloud droplets collide, they coalesce into larger droplets, which may fall to Earth as precipitation. The four main types of precipitation are rain, snow, sleet, and hail.
- In the water cycle, water continually moves between Earth's surface and the atmosphere through the processes of evaporation, condensation, and precipitation.

Vocabulary

coalescence (p. 289)
condensation nuclei (p. 285)
evaporation (p. 290)
latent heat (p. 286)
orographic lifting (p. 285)
precipitation (p. 289)
stability (p. 286)
water cycle (p. 290)

earthgeu.com/vocabulary_puzzlemaker

CHAPTER 11
Assessment

Understanding Main Ideas

1. What process describes the change of state of water from a liquid to a gas?
   a. condensation
   b. evaporation
   c. melting
   d. drying

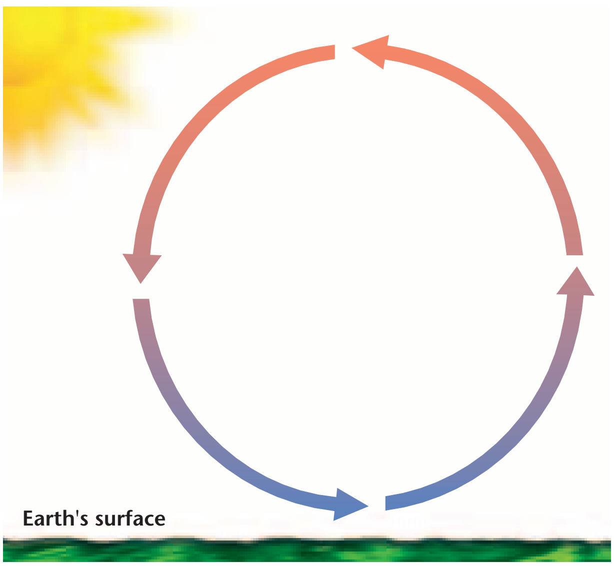
2. Condensation nuclei are involved in the formation of which of the following?
   a. cloud droplets
   b. ozone
   c. dry ice
   d. carbon dioxide

3. Which atmospheric layer contains most of the mass of Earth's atmosphere?
   a. tropopause
   b. troposphere
   c. stratosphere
   d. mesosphere

4. Which object would heat up most rapidly?
   a. water
   b. asphalt
   c. grass
   d. cement

5. What percentage of incoming solar radiation does Earth's atmosphere absorb?
   a. 100 percent
   b. 15 percent
   c. 50 percent
   d. 35 percent

Use this diagram to answer questions 6–8.



6. What type of energy transfer is shown in the diagram on this page?
   a. radiation
   b. convection
   c. conduction
   d. vaporization

7. In the diagram, what type of air is rising?
   a. warm
   b. cool
   c. dry
   d. cold

8. Which statement describes the rising air in the diagram in relation to the surrounding air?
   a. The rising air is more dense.
   b. The rising air is less dense.
   c. The rising air is cooler.
   d. The rising air is thicker.

9. What do we call the temperature at which air becomes saturated?
   a. humidity
   b. the lapse rate
   c. the LCL
   d. the dew point

10. What type of cloud is a stratus cloud?
    a. low
    b. vertical development
    c. high
    d. middle

11. What causes wind?
12. Describe a temperature inversion.
13. What is latent heat?
14. How do clouds form? How are they classified?
15. Explain the three main processes involved in the water cycle.

Test-Taking Tip

QUIET ZONE It's best to study in a similar environment to the one in which you'll be tested. Thus, try to study in a quiet, disturbance-free, well-lit place. Avoid blaring stereos, video games, chatty friends, and television screens.

Applying Main Ideas

16. If clouds absorb only a small amount of solar radiation, how is Earth's atmosphere heated?
17. Which two gases make up most of Earth's atmosphere? List other important atmospheric gases.
18. Use the following terms to construct a concept map that shows the three methods of energy transfer in the atmosphere.

- conduction
- convection
- energy transfer
- radiation
- transfers energy by electromagnetic waves
- occurs when molecules collide
- occurs through the flow of a heated substance

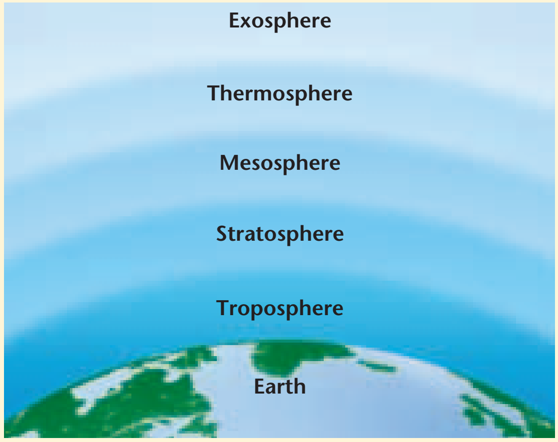
19. What type of cloud might produce the most intense precipitation? Explain your answer.

Thinking Critically

20. A summer rain could begin as a snowstorm in the clouds overhead. How is this possible?
21. Given that air cannot rise through a stable inversion layer, predict the effects of a temperature inversion on a heavily populated, highly industrial city located beneath the inversion.
22. Given the varying depths of the troposphere, why do holes in the ozone layer tend to appear mainly in the polar regions?
23. A spoon that sits in a bowl of hot soup feels hot when touched. How was energy transferred to the spoon?

Standardized Test Practice

INTERPRETING DATA Use the diagram below to answer questions 1 and 2.



(not to scale)

1. In which layer of Earth's atmosphere is air most likely warmed by conduction?
   a. troposphere **c.** thermosphere
   b. stratosphere **d.** exosphere
2. Which of the following is NOT true of ozone?
   a. It absorbs ultraviolet radiation.
   b. Its concentration is decreasing or thinning.
   c. It is concentrated in the atmospheric layer called the mesosphere.
   d. It is a gas formed by the addition of one oxygen atom to an oxygen molecule.
3. Which of the following is most likely to cause orographic lifting?
   a. a sandy beach **c.** a rocky mountain
   b. a flowing river **d.** a sand dune
4. Which clouds are most likely to form when fog lifts away from Earth's surface?
   a. cumulus **c.** stratus
   b. cirrostratus **d.** altocumulus