

**Meteorology Today: An Introduction to  
Weather, Climate, and the Environment**

**Ninth Edition**

**C. Donald Ahrens**

Development Editor: Jake Warde

Assistant Editor: Liana Monari

Editorial Assistant: Paige Leeds

Technology Project Manager: Alexandria Brady

Marketing Manager: Joe Rogove

Marketing Assistant: Elizabeth Eong

Marketing Communications Manager:  
Belinda Krohmer

Project Manager, Editorial Production:  
Hal Humphrey

Art Director: Vernon Boes

Print Buyer: Rebecca Cross

Permissions Editor:  
Margaret Chamberlain-Gaston

Production Service: Janet Bollow Associates

Text Designer: Janet Bollow

Art Editor: Janet Bollow

Copy Editor: Stuart Kenter

Illustrator: Charles Preppernau

Cover Designer: William Stanton

Cover Image: Copyright R. Hoelzl/  
Peter Arnold, Inc.

Compositor: Graphic World, Inc.

© 2009, 2007 Brooks/Cole, Cengage Learning

ALL RIGHTS RESERVED. No part of this work covered by the copyright herein may be reproduced, transmitted, stored or used in any form or by any means graphic, electronic, or mechanical, including but not limited to photocopying, recording, scanning, digitizing, taping, Web distribution, information networks, or information storage and retrieval systems, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without the prior written permission of the publisher.

For product information and technology assistance, contact us at  
**Cengage Learning Customer & Sales Support, 1-800-354-9706**

For permission to use material from this text or product,  
submit all requests online at **cengage.com/permissions**

Further permissions questions can be emailed to  
**permissionrequest@cengage.com**

Library of Congress Control Number: 2008928602

ISBN-13: 978-0-495-55573-5

ISBN-10: 0-495-55573-8

**Brooks/Cole**

10 Davis Drive  
Belmont, CA 94002  
USA

Cengage Learning is a leading provider of customized learning solutions with office locations around the globe, including Singapore, the United Kingdom, Australia, Mexico, Brazil, and Japan. Locate your local office at:

**international.cengage.com/region**

Cengage Learning products are represented in Canada by Nelson Education, Ltd.

For your course and learning solutions, visit **academic.cengage.com**

Purchase any of our products at your local college store or at our preferred  
online store **www.ichapters.com**

creases. When air cools to the dew point, the relative humidity becomes 100 percent and the air is saturated. Continued cooling condenses some of the vapor into tiny cloud droplets.

## Condensation Nuclei

Actually, the condensation process that produces clouds is not quite so simple. Just as dew and frost need a surface to form on, there must be airborne particles on which water vapor can condense to produce cloud droplets.

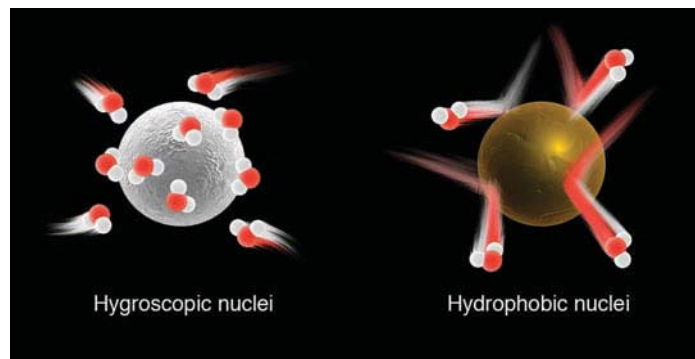
Although the air may look clean, it never really is. On an ordinary day, a volume of air about the size of your index finger contains between 1000 and 150,000 particles. Since many of these serve as surfaces on which water vapor can condense, they are called **condensation nuclei**. Without them, relative humidities of several hundred percent would be required before condensation could begin.

Some condensation nuclei are quite small and have a radius less than  $0.2\ \mu\text{m}$ ; these are referred to as *Aitken nuclei*, after the British physicist who discovered that water vapor condenses on nuclei. Particles ranging in size from  $0.2$  to  $1\ \mu\text{m}$  are called *large nuclei*, while others, called *giant nuclei*, are much larger and have radii exceeding  $1\ \mu\text{m}$  (see ▼ Table 5.1). The condensation nuclei most favorable for producing clouds (called *cloud condensation nuclei*) have radii of  $0.1\ \mu\text{m}$  or more. Usually, between 100 and 1000 nuclei of this size exist in a cubic centimeter of air. These particles enter the atmosphere in a variety of ways: dust, volcanoes, factory smoke, forest fires, salt from ocean spray, and even sulfate particles emitted by phytoplankton in the oceans. In fact, studies show that sulfates provide the major source of cloud condensation nuclei in the marine atmosphere. Because most particles are released into the atmosphere near the ground, the largest concentrations of nuclei are observed in the lower atmosphere near the earth's surface.

Condensation nuclei are extremely light (many have a mass less than one-trillionth of a gram), so they can remain suspended in the air for many days. They are most abundant over industrial cities, where highly polluted air may contain nearly 1 million particles per cubic centimeter. They decrease

▼ **TABLE 5.1** Characteristic Sizes and Concentration of Condensation Nuclei and Cloud Droplets

TYPE OF PARTICLE	APPROXIMATE RADIUS (MICROMETERS)	NO. OF PARTICLES (PER $\text{CM}^3$ )	
		Range	Typical
Small (Aitken) condensation nuclei	$<0.2$	1000 to 10,000	1000
Large condensation nuclei	0.2 to 1.0	1 to 1000	100
Giant condensation nuclei	$>1.0$	$<1$ to 10	1
Fog and cloud droplets	$>10$	10 to 1000	300



● **FIGURE 5.3** Hygroscopic nuclei are “water-seeking,” and water vapor rapidly condenses on their surfaces. Hydrophobic nuclei are “water-repelling” and resist condensation.

in cleaner “country” air and over the oceans, where concentrations may dwindle to only a few nuclei per cubic centimeter.

Some particles are **hygroscopic** (“water-seeking”), and water vapor condenses upon these surfaces when the relative humidity is considerably lower than 100 percent. Ocean salt is hygroscopic, as is common table salt. In humid weather, it is difficult to pour salt from a shaker because water vapor condenses onto the salt crystals, sticking them together. Moreover, on a humid day, salty potato chips left outside in an uncovered bowl turn soggy. Other hygroscopic nuclei include sulfuric and nitric acid particles. Not all particles serve as good condensation nuclei. Some are **hydrophobic\*** (“water-repelling”)—such as oils, gasoline, and paraffin waxes—and resist condensation even when the relative humidity is above 100 percent (see ● Fig. 5.3). As we can see, condensation may begin on some particles when the relative humidity is well below 100 percent and on others only when the relative humidity is much higher than 100 percent. However, at any given time there are usually many nuclei present, so that haze, fog, and clouds will form at relative humidities near or below 100 percent.

## Haze

Suppose you visit an area that has a layer of **haze** (that is, a layer of dust or salt particles) suspended above the region. There, you may notice that distant objects are usually more visible in the afternoon than in the morning, even when the concentration of particles in the air has not changed. Why? During the warm afternoon, the relative humidity of the air is often below the point where water vapor begins to condense, even on active hygroscopic nuclei. Therefore, the floating particles remain small—usually no larger than about one-tenth of a micrometer. These tiny *dry haze* particles selectively scatter some rays of sunlight, while allowing others to penetrate the air. The scattering effect of dry haze produces a bluish

\*A synthetic hydrophobic is PTFE, or Teflon—the material used in rain-repellent fabric.

to only about 200  $\mu\text{m}$ . If the air beneath the cloud is moist, the droplets may reach the ground as *drizzle*, the lightest form of rain. If, however, the stratus cloud base is fairly high above the ground, the drops will evaporate before reaching the surface, even when the relative humidity is 90 percent.

Clouds that have above-freezing temperatures at all levels are called *warm clouds*. In such clouds, precipitation forms by the collision and coalescence process. For example, in tropical regions, where warm cumulus clouds build to great heights, convective updrafts of at least 1 m/sec (and some exceeding many tens of meters per second) occur. Look at the warm cumulus cloud in • Fig. 7.5. Suppose a cloud droplet of 100  $\mu\text{m}$  is caught in an updraft whose velocity is 6.5 m/sec (about 15 mi/hr). As the droplet rises, it collides with and captures smaller drops in its path and grows until it reaches a size of about 1000  $\mu\text{m}$ . At this point, the updraft in the cloud is just able to balance the pull of gravity on the drop. Here, the drop remains suspended until it grows just a little bigger. Once the fall velocity of the drop is greater than the updraft velocity in the cloud, the drop slowly descends. As the drop falls, larger cloud droplets are captured by the falling drop, which then grows larger. By the time this drop reaches the bottom of the cloud, it will be a large raindrop with a diameter of over 5000  $\mu\text{m}$  (5 mm). Because raindrops of this size fall faster and reach the ground first, they typically occur at the beginning of a rain shower originating in these warm, convective cumulus clouds.

Raindrops that reach the earth's surface are seldom larger than about 5 mm. The collisions between raindrops (whether glancing or head-on) tend to break them up into many

smaller drops. Additionally, a large drop colliding with another large drop may result in oscillations within the combined drop. As the resultant drop grows, these oscillations may tear the drop apart into many fragments, all smaller than the original drop.

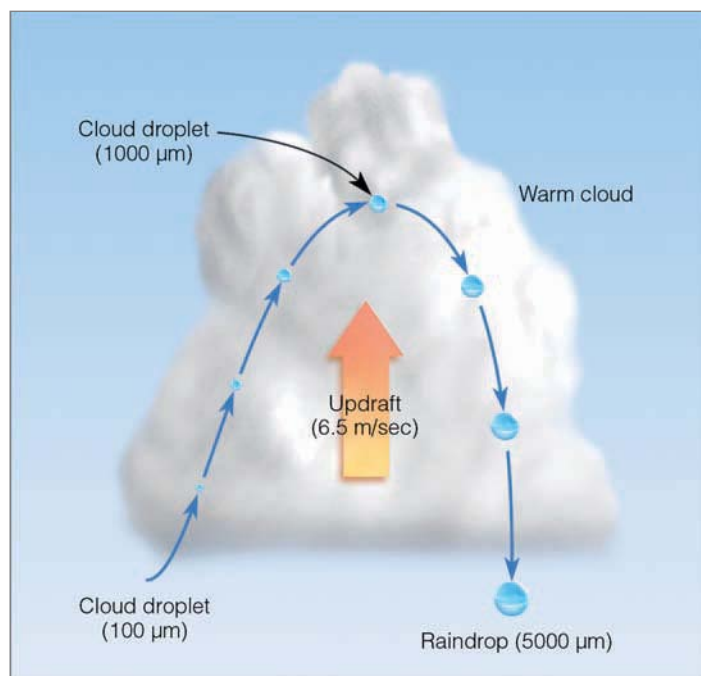
So far, we have examined the way cloud droplets in warm clouds (that is, those clouds with temperatures above freezing) grow large enough by the collision-coalescence process to fall as raindrops. Rain that falls from warm clouds is sometimes called *warm rain*. The most important factor in the production of raindrops is the cloud's *liquid water content*. In a cloud with sufficient water, other significant factors are:

1. the range of droplet sizes
2. the cloud thickness
3. the updrafts of the cloud
4. the electric charge of the droplets and the electric field in the cloud

Relatively thin stratus clouds with slow, upward air currents are, at best, only able to produce drizzle, whereas the towering cumulus clouds associated with rapidly rising air can cause heavy showers. Now, let's turn our attention to see how clouds with temperatures below freezing are able to produce precipitation.

**ICE-CRYSTAL PROCESS** The **ice-crystal** (or **Bergeron**)\* **process** of rain formation is extremely important in middle and high latitudes, where clouds extend upward into regions where the air temperature is well below freezing. Such clouds are called *cold clouds*. • Figure 7.6 illustrates a typical cold cloud that has formed over the Great Plains, where the "cold" part is well above the 0°C isotherm.

Suppose we take an imaginary balloon flight up through the cumulonimbus cloud in Fig. 7.6. Entering the cloud, we observe cloud droplets growing larger by processes described in the previous section. As expected, only water droplets exist here, for the base of the cloud is warmer than 0°C. Surprisingly, in the cold air just above the 0°C isotherm, almost all of the cloud droplets are still composed of liquid water. Water droplets existing at temperatures below freezing are referred to as **supercooled**. Even at higher levels, where the air temperature is  $-10^{\circ}\text{C}$  ( $14^{\circ}\text{F}$ ), there is only one ice crystal for every million liquid droplets. Near 5500 m (18,000 ft), where the temperature becomes  $-20^{\circ}\text{C}$  ( $-4^{\circ}\text{F}$ ), ice crystals become more numerous, but are still outnumbered by water droplets.† The distribution of ice crystals, however, is not uniform, as the downdrafts contain more ice than the updrafts.

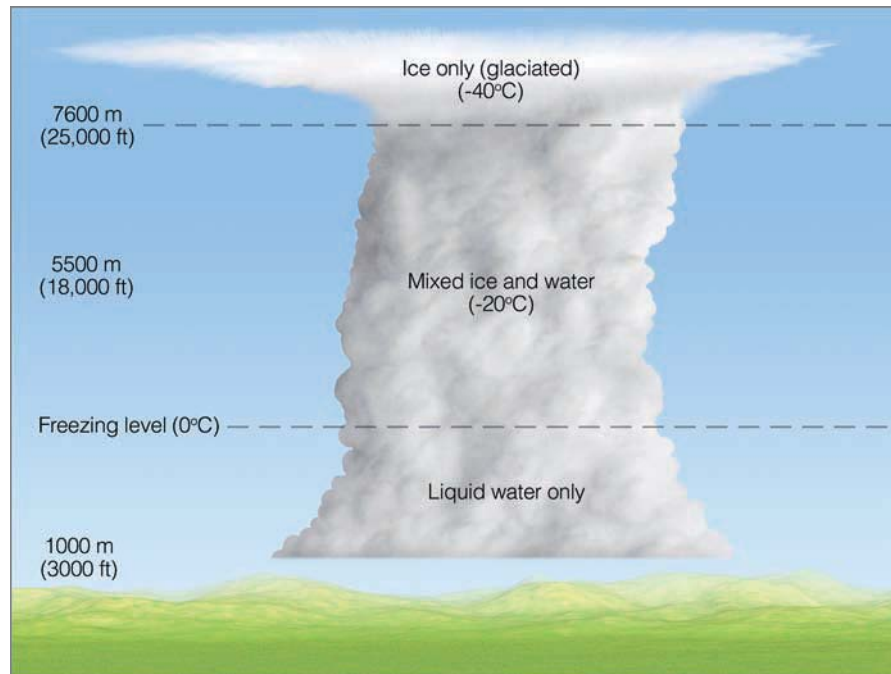


• **FIGURE 7.5** A cloud droplet rising then falling through a warm cumulus cloud can grow by collision and coalescence, and emerge from the cloud as a large raindrop.

\*The ice-crystal process is also known as the *Bergeron process* after the Swedish meteorologist Tor Bergeron, who proposed that essentially all raindrops begin as ice crystals.

†In continental clouds, such as the one in Fig. 7.6, where there are many small cloud droplets less than 20  $\mu\text{m}$  in diameter, the onset of ice-crystal formation begins at temperatures between  $-9^{\circ}\text{C}$  and  $-15^{\circ}\text{C}$ . In clouds where larger but fewer cloud droplets are present, ice crystals begin to form at temperatures between  $-4^{\circ}\text{C}$  and  $-8^{\circ}\text{C}$ . In some of these clouds, glaciation can occur at  $-8^{\circ}\text{C}$ , which may be only 2500 m (8200 ft) above the surface.

● **FIGURE 7.6** The distribution of ice and water in a cumulonimbus cloud.



Not until we reach an elevation of 7600 m (25,000 ft), where temperatures drop below  $-40^{\circ}\text{C}$  (also  $-40^{\circ}\text{F}$ ), do we find *only* ice crystals. The region of a cloud where only ice particles exist is called *glaciated*. Why are there so few ice crystals in the middle of the cloud, even though temperatures there are well below freezing? Laboratory studies reveal that the smaller the amount of pure water, the lower the temperature at which water freezes. Since cloud droplets are extremely small, it takes very low temperatures to turn them into ice. (More on this topic is given in the Focus section on p. 171.)

Just as liquid cloud droplets form on condensation nuclei, ice crystals may form in subfreezing air on particles called **ice nuclei**. The number of ice-forming nuclei available in the atmosphere is small, especially at temperatures above  $-10^{\circ}\text{C}$  ( $14^{\circ}\text{F}$ ). However, as the temperature decreases, more particles become active and promote freezing. Although some uncertainty exists regarding the principal source of ice nuclei, it is known that clay minerals, such as kaolinite, become effective nuclei at temperatures near  $-15^{\circ}\text{C}$  ( $5^{\circ}\text{F}$ ). Some types of bacteria in decaying plant leaf material and ice crystals themselves are also excellent ice nuclei. Moreover, particles serve as excellent ice-forming nuclei if their geometry resembles that of an ice crystal. However, it is difficult to find substances in nature that have a lattice structure similar to ice, since there are so many possible lattice structures. In the atmosphere, it is easy to find hygroscopic (“water seeking”) particles. Consequently, ice-forming nuclei are rare compared to cloud condensation nuclei.

In a cold cloud, there may be several types of ice-forming nuclei present. For example, certain ice nuclei allow water vapor to deposit as ice directly onto their surfaces in cold, saturated air. These are called *deposition nuclei* because, in this situation, water vapor changes directly into ice without

going through the liquid phase. Ice nuclei that promote the freezing of supercooled liquid droplets are called *freezing nuclei*. Some freezing nuclei cause freezing after they are immersed in a liquid drop; some promote condensation, then freezing; yet others cause supercooled droplets to freeze if they collide with them. This last process is called **contact freezing**, and the particles involved are called *contact nuclei*. Studies suggest that contact nuclei can be just about any substance and that contact freezing may be the dominant force in the production of ice crystals in some clouds.

We can now understand why there are so few ice crystals in the cold mixed region of some clouds. Cloud droplets may freeze spontaneously, but only at the very low temperatures usually found at high altitudes. Ice nuclei may initiate the growth of ice crystals, but they do not abound in nature. Because there are many more cloud condensation nuclei than ice nuclei, we are left with a cold cloud that contains many more liquid droplets than ice particles, even at temperatures as low as  $-10^{\circ}\text{C}$  ( $14^{\circ}\text{F}$ ). Neither the tiny liquid nor solid particles are large enough to fall as precipitation. How, then, does the ice-crystal (Bergeron) process produce rain and snow?

In the subfreezing air of a cloud, many supercooled liquid droplets will surround each ice crystal. Suppose that the ice crystal and liquid droplet in ● Fig. 7.7 are part of a cold ( $-15^{\circ}\text{C}$ ) supercooled, saturated cloud. Since the air is saturated, both the liquid droplet and the ice crystal are in equilibrium, meaning that the number of molecules leaving the surface of both the droplet and the ice crystal must equal the number of molecules returning. Observe, however, that there are more vapor molecules above the liquid. The reason for this fact is that molecules escape the surface of water much easier than they escape the surface of ice. Consequently, more molecules escape the water surface at a given temperature,





## FOCUS ON A SPECIAL TOPIC

### The Freezing of Tiny Cloud Droplets

Over large bodies of fresh water, ice ordinarily forms when the air temperature drops slightly below  $0^{\circ}\text{C}$ . Yet, a cloud droplet of pure water about  $25\ \mu\text{m}$  in diameter will not freeze spontaneously until the air temperature drops to about  $-40^{\circ}\text{C}$  ( $-40^{\circ}\text{F}$ ) or below.

The freezing of pure water (without the benefit of some nucleus) is called *spontaneous* or *homogeneous freezing*. For this type of freezing to occur, enough molecules within the water droplet must join together in a rigid pattern to form a tiny ice structure, or *ice embryo*.

When the ice embryo grows to a critical size, it acts as a nucleus. Other molecules in the droplet then attach themselves to the nucleus of ice and the water droplet freezes.

Tiny ice embryos form in water at temperatures just below freezing, but at these temperatures thermal agitations are large enough to weaken their structure. The ice embryos simply form and then break apart. At lower temperatures, thermal motion is reduced, making it eas-



© C. Donald Ahrens

ier for bigger ice embryos to form. Hence, freezing is more likely.

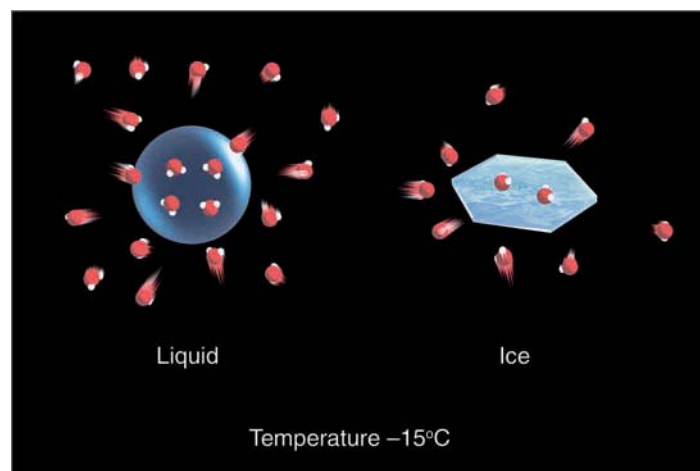
The chances of an ice embryo growing large enough to freeze water before the embryo is broken up by thermal agitation increase with larger volumes of water. Consequently, only larger cloud droplets will freeze by homogeneous freezing at air temperatures higher than  $-40^{\circ}\text{C}$ . In air colder than  $-40^{\circ}\text{C}$ , however, it

is almost certain that an ice embryo will grow to critical size in even the smallest cloud droplet. Thus, any cloud that forms in extremely cold air (below  $-40^{\circ}\text{C}$ ), such as cirrus clouds (see Fig. 1), will almost certainly be composed of ice, since any cloud droplets that form will freeze spontaneously.

#### ● FIGURE 1

This cirrus cloud is probably composed entirely of ice crystals, because any liquid water droplet, no matter how small, must freeze spontaneously at the very low temperature (below  $-40^{\circ}\text{C}$ ) found at this altitude, 9 km (29,500 ft).

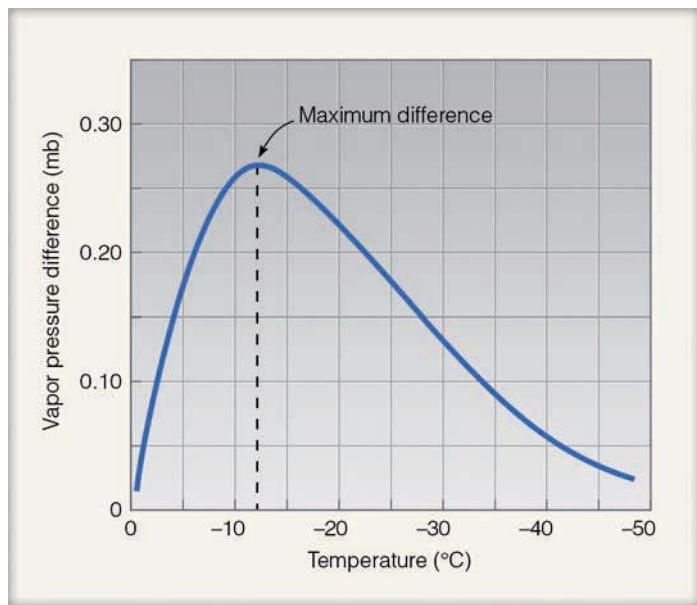
requiring more in the vapor phase to maintain saturation. This situation reflects the important fact discussed briefly in Chapter 4: At the same subfreezing temperature, *the saturation vapor pressure just above a water surface is greater than the saturation vapor pressure above an ice surface*. This difference in saturation vapor pressure between water and ice is illustrated in ● Fig. 7.8.



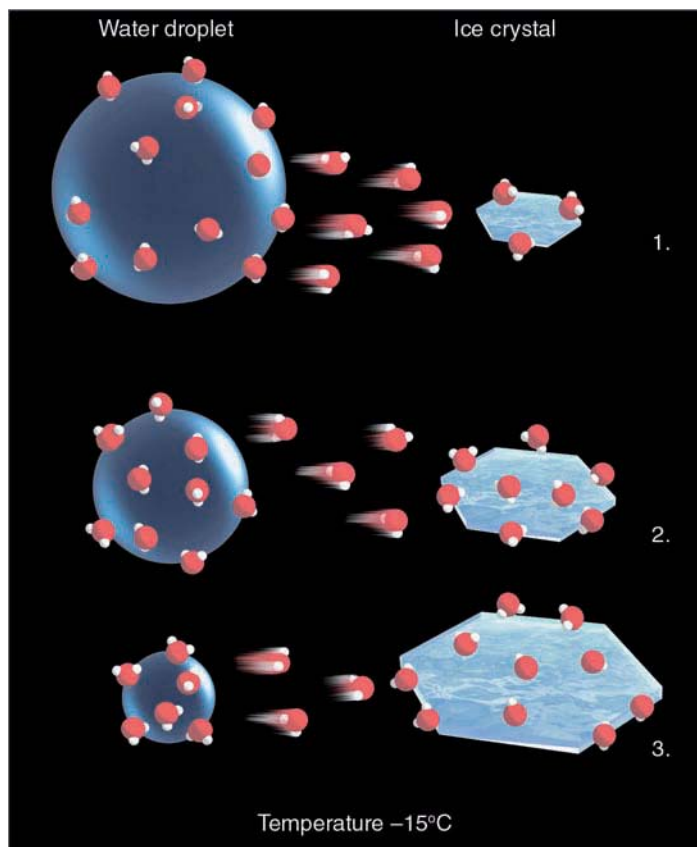
This difference in vapor pressure causes water vapor molecules to move (diffuse) from the water droplet toward the ice crystal. The removal of vapor molecules reduces the vapor pressure above the water droplet. Since the droplet is now out of equilibrium with its surroundings, it evaporates to replenish the diminished supply of water vapor above it. This process provides a continuous source of moisture for the ice crystal, which absorbs the water vapor and grows rapidly (see ● Fig. 7.9). Hence, during the *ice-crystal (Bergeron) process*, *ice crystals grow larger at the expense of the surrounding water droplets*.

The constant supply of moisture to the ice crystal allows it to enlarge rapidly. At some point, the ice crystal becomes heavy enough to overcome updrafts in the cloud and begins to fall. But a single falling ice crystal does not comprise a snowstorm; consequently, other ice crystals must quickly form.

● FIGURE 7.7 In a saturated environment, the water droplet and the ice crystal are in equilibrium, as the number of molecules leaving the surface of each droplet and ice crystal equals the number returning. The greater number of vapor molecules above the liquid indicates, however, that the saturation vapor pressure over water is greater than it is over ice.



● **FIGURE 7.8** The difference in saturation vapor pressure between supercooled water and ice at different temperatures.



**ACTIVE FIGURE 7.9** The ice-crystal (Bergeron) process. (1) The greater number of water vapor molecules around the liquid droplet causes water molecules to diffuse from the liquid droplet toward the ice crystal. (2) The ice crystal absorbs the water vapor and grows larger, while (3) the water droplet grows smaller.

In some clouds, especially those with relatively warm tops, ice crystals might collide with supercooled droplets. Upon contact, the liquid droplets freeze into ice and stick together. This process of ice crystals growing larger as they collide with supercooled cloud droplets is called **accretion**. The icy matter that forms is called **graupel** (or *snow pellets*). As the graupel falls, it may fracture or splinter into tiny ice particles when it collides with cloud droplets. These splinters may grow to become new graupel, which, in turn, may produce more splinters.

In colder clouds, the delicate ice crystals may collide with other crystals and fracture into smaller ice particles, or tiny seeds, which freeze hundreds of supercooled droplets on contact. In both cases a chain reaction may develop, producing many ice crystals. As the ice crystals fall, they may collide and stick to one another. The process of ice crystals colliding then sticking together is called **aggregation**.\* The end product of this clumping together of ice crystals is a **snowflake** (see ● Fig. 7.10). If the snowflake melts before reaching the ground, it continues its fall as a raindrop. Therefore, much of the rain falling in middle and high latitudes—even in summer—begins as snow.

For ice crystals to grow large enough to produce precipitation there must be many, many times more water droplets than ice crystals. Generally, the ratio of ice crystals to water droplets must be on the order of 1:100,000 to 1:1,000,000. When there are too few ice crystals in the cloud, each crystal grows large and falls out of the cloud, leaving the majority of cloud behind (unaffected). Since there are very few ice crystals, there is very little precipitation. If, on the other hand, there are too many ice crystals (such as an equal number of crystals and droplets), then each ice crystal receives the mass of one droplet. This would create a cloud of many tiny ice crystals, each too small to fall to the ground, and no precipitation. Now, if the ratio of crystals to droplets is on the order of 1:100,000, then each ice crystal would receive the mass of 100,000 droplets. Most of the cloud would convert to precipitation, as the majority of ice crystals would grow large enough to fall to the ground as precipitation.

The first person to formally propose the theory of ice-crystal growth due to differences in the vapor pressure between ice and supercooled water was Alfred Wegener (1880–1930), a German climatologist who also proposed the geological theory of continental drift. In the early 1930s, important additions to this theory were made by the Swedish meteorologist Tor Bergeron. Several years later, the German meteorologist Walter Findeisen made additional contributions to Bergeron’s theory; hence, the ice-crystal theory of rain formation has come to be known as the *Wegener-Bergeron-Findeisen process*, or, simply, the *Bergeron process*.

View this concept in action on the Meteorology Resource Center at [academic.cengage.com/login](http://academic.cengage.com/login)

\*Significant aggregation seems possible only when the air is relatively warm, usually warmer than  $-10^{\circ}\text{C}$  ( $14^{\circ}\text{F}$ ).