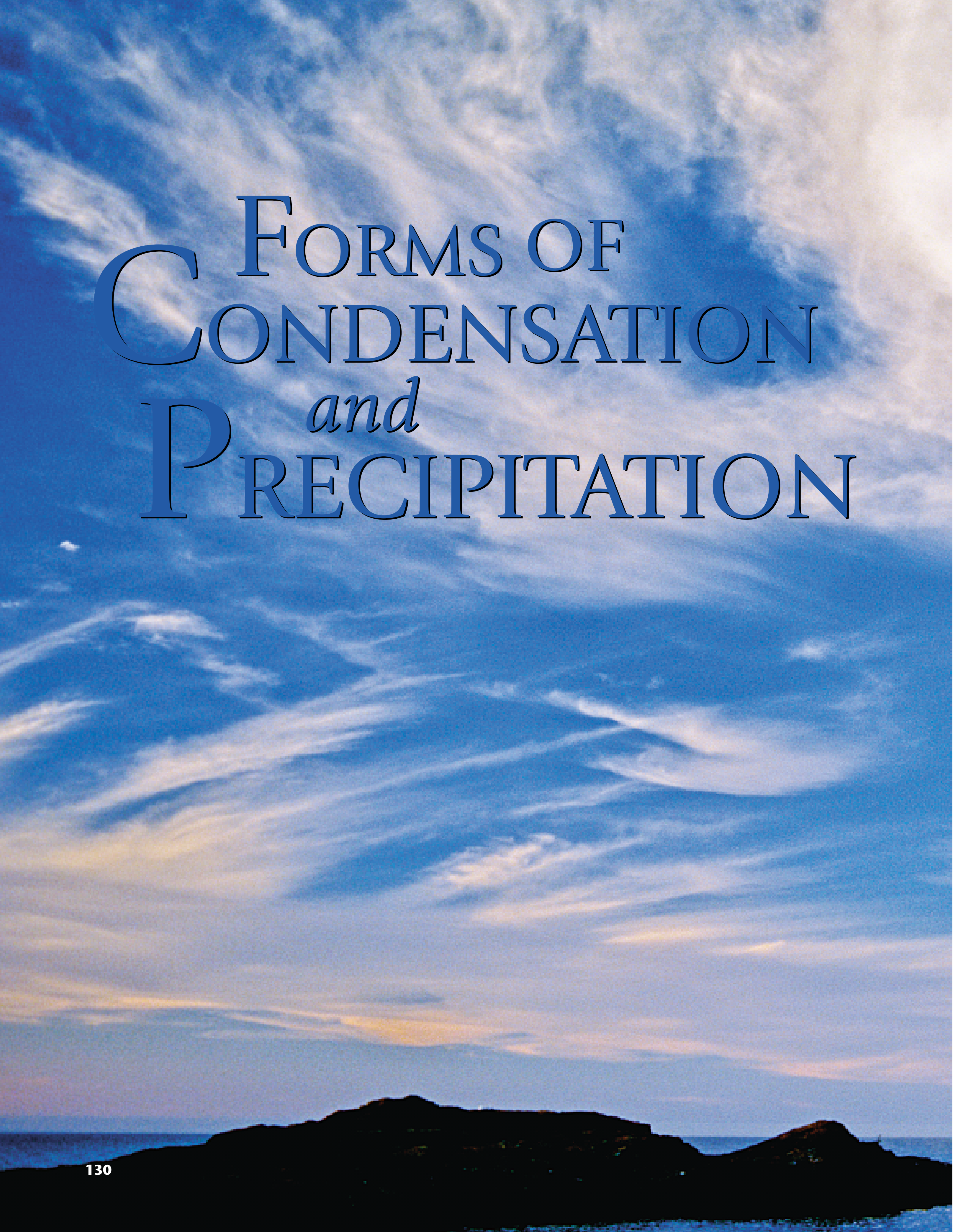
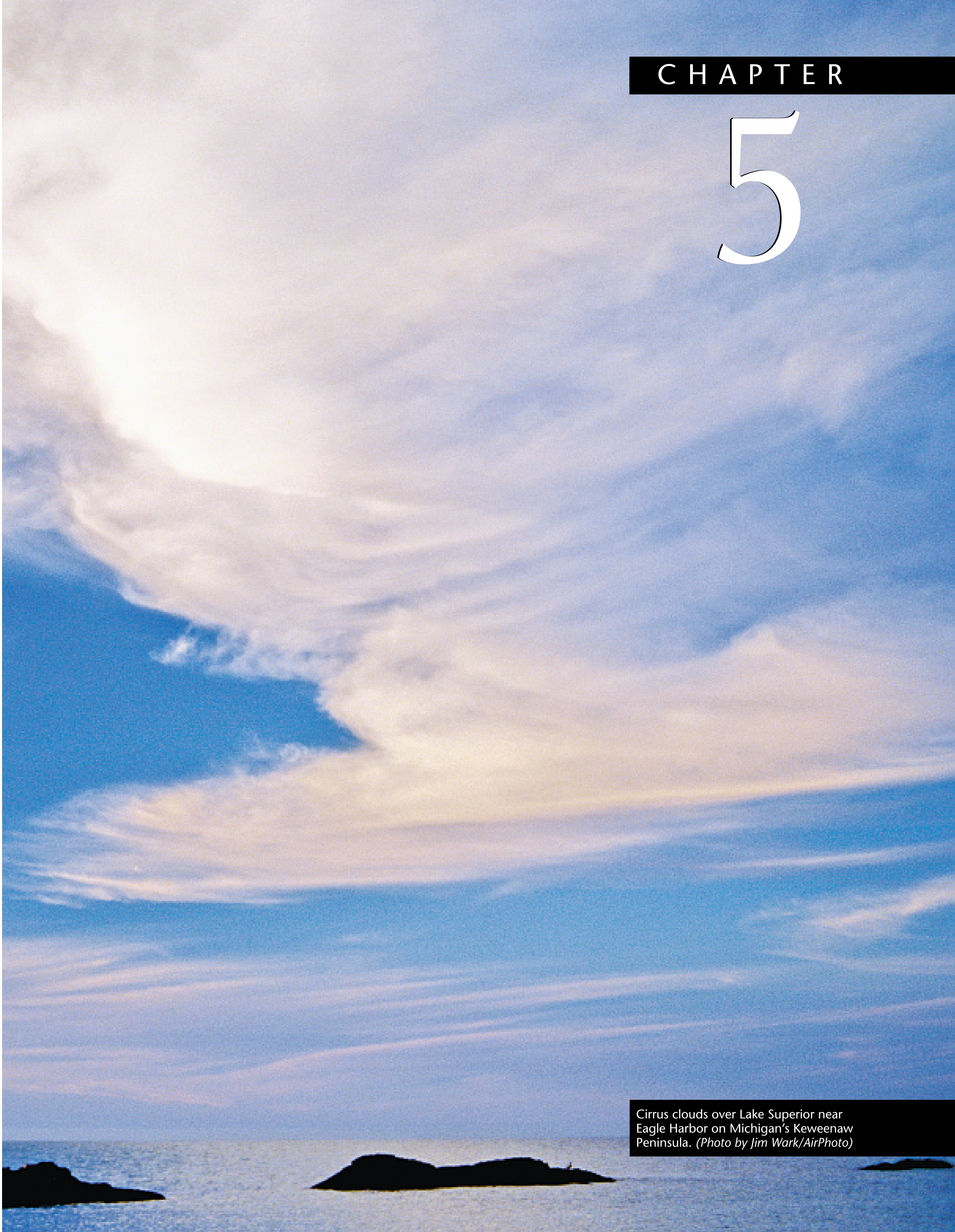
Forms of Condensation and Precipitation



CHAPTER 5



Cirrus clouds over Lake Superior near Eagle Harbor on Michigan's Keweenaw Peninsula. *(Photo by Jim Wark/AirPhoto)*

Clouds, fog, rain, snow, and sleet are among the most observable weather phenomena (Figure 5–1). This chapter will provide a basic understanding of each. In addition to learning the basic scheme for classifying and naming clouds, you will learn that the formation of an average raindrop involves complex processes requiring water from roughly a million cloud droplets. Can scientists make rain by triggering these processes? Can modern weather-modification technology increase the precipitation that falls from a cloud? Can we control weather events such as fog and frost?

Cloud Formation

Clouds can be defined as *visible aggregate of minute droplets of water, or tiny crystals of ice, or a mixture of both.* In addition to being prominent and sometimes spectacular features in the sky, clouds are of continual interest to meteorologists because they provide a visible indication of what is going on in the atmosphere.

Condensation Aloft

Clouds are a form of condensation produced when water vapor condenses in the atmosphere. Clearly the most important cloud-forming process is *adiabatic cooling.* To review, any time a parcel of air ascends, it passes through regions of successively lower pressure. As a result, rising air expands and cools adiabatically. At a height called the *lifting condensation level,* the ascending parcel has cooled to its dew-point temperature, and further ascent (cooling) causes condensation.

As you learned earlier, condensation occurs when water vapor changes to a liquid. The result of this process may be dew, fog, or clouds. Although each type of condensation is somewhat different, they all form when two conditions are met. First, for any form of condensation to occur, the air must be *saturated* (or nearly so). Saturation occurs most often when air is cooled to its dew point. (Condensation may also occur when sufficient water vapor is added to a layer of the atmosphere.) Second, there generally must be a *surface* on which the water vapor can condense. When dew forms, objects at or near the ground, like blades of grass, serve this purpose.

When condensation occurs aloft, tiny particles known as **cloud condensation nuclei** serve as surfaces on which water vapor condenses. Nuclei are important because, if they are absent, a relative humidity well in excess of 100 percent is necessary to produce cloud droplets. (At very low temperatures—low kinetic energies—water molecules will "stick together" in tiny clusters without the presence of condensation nuclei.) Cloud condensation nuclei include microscopic dust, smoke, and salt particles, all of which are profuse in the lower atmosphere. Consequently, in the troposphere the relative humidity seldom exceeds 100 percent.

Growth of Cloud Droplets

Particles that are the most effective sites for condensation are called **hygroscopic** (*water-seeking*) **nuclei.** Some familiar food items, such as crackers and cereals, are hygroscopic, which is why they quickly absorb moisture when exposed to humid air and become stale.

FIGURE 5-1 A pedestrian dashes across the street in downtown Minneapolis. At the time the rainfall rate was about 5 centimeters (2 inches) per hour. *(Photo by Jerry Holt/*Star Tribune*/NewsCom.)*

Over the ocean, salt particles are released into the atmosphere when sea spray evaporates. Because salt is hygroscopic, water droplets begin to form around sea salt particles at relative humidities less than 100 percent. As a result, the cloud droplets that form on salt are generally much larger than those that grow on **hydrophobic** (*water-repelling*) **nuclei.** Although hydrophobic particles are not efficient condensation nuclei, cloud droplets will form on them whenever the relative humidity reaches 100 percent.

Dust storms, volcanic eruptions, and pollen are major sources of cloud condensation nuclei on land. In addition, hygroscopic nuclei are introduced into the atmosphere as a by-product of combustion (burning) from such sources as forest fires, automobiles, and coal-burning furnaces. Because cloud condensation nuclei have a wide range of affinities for water, cloud droplets of various sizes often coexist in the same cloud. This fact has important consequences for the formation of precipitation.

Initially, the growth of cloud droplets is rapid. However, the rate of growth quickly diminishes because the available water vapor is consumed by the large number of competing droplets. The result is the formation of a cloud consisting of billions of tiny water droplets, all so small that they remain suspended in air. Even in very moist air, the growth of cloud droplets by additional condensation is quite slow. Furthermore, the immense size difference between cloud droplets and raindrops (it takes about a million cloud droplets to form a single raindrop) suggests that condensation alone is not responsible for the formation of drops (or ice crystals) large enough to fall to the ground without evaporating. We will investigate this idea later when we examine the processes that generate precipitation.

Students Sometimes Ask…

What is the dryest place on Earth?

The record for the lowest average annual precipitation belongs to Arica, Chile, which receives 0.03 inch of rainfall per year. Over a span of 59 years this region in South America received a total of less than 2 inches of precipitation.

Cloud Classification

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Forms of Condensation and Precipitation

▶ Classifying Clouds

Anyone who observes clouds finds a bewildering variety of these white and gray masses streaming across the sky. Once the basic classification scheme for clouds is known, however, most of the confusion vanishes.

Prior to the beginning of the nineteenth century, there were no generally accepted names for clouds. In 1803 Luke Howard, an English naturalist, published a cloud classification that met with great success and subsequently served as the basis of our present-day system.

Clouds are classified on the basis of two criteria: *form* and *height* (Figure 5–2). Three basic cloud forms are recognized:

- **Cirrus** clouds are high, white, and thin. They are separated or detached and form delicate veil-like patches or extended wispy fibers and often have a feathery appearance. (*Cirrus* is a Latin word meaning “curl” or “filament.”)
- **Cumulus** clouds consist of globular individual cloud masses. Normally they exhibit a flat base and appear as rising domes or towers. Such clouds are frequently described as having a cauliflower-like structure.
- **Stratus** clouds are best described as sheets or layers (strata) that cover much or all of the sky. Although there may be minor breaks, there are no distinct individual cloud units.

All clouds have one of these three basic forms or combinations or modifications of them.

Looking at the second aspect of cloud classification—height—three levels are recognized: high, middle, and low. **High clouds** normally have bases above 6000 meters (20,000 feet); **middle clouds** generally occupy heights from 2000 to 6000 meters; **low clouds** form below 2000 meters (6500 feet). These altitudes are not hard and fast. They vary somewhat by season of the year and by latitude. At high (poleward) latitudes or during cold winter months, high clouds generally occur at lower altitudes. Further, some clouds extend vertically to span more than one height range. These are called **clouds of vertical development.**

Definite weather patterns can be associated with specific clouds or combinations of clouds, so it is important to become familiar with cloud characteristics.

Ten basic cloud types are recognized internationally. We describe them below and summarize them in Table 5–1.

High Clouds

Three cloud types make up the family of high clouds (above 6000 meters/20,000 feet). They are *cirrus, cirrostratus,* and *cirrocumulus.* Because of the low temperatures and small quantities of water vapor present at high altitudes, all high clouds are thin and white and made up primarily of ice crystals.

Cirrus are detached clouds composed of white, delicate icy filaments. Winds aloft often cause these fibrous ice trails to bend or curl. As shown in Figure 5–3a, cirrus clouds with hooked filaments are called “mares’ tails” (see Box 5–1).

Cirrostratus is a transparent, whitish cloud veil of fibrous or sometimes smooth appearance that may cover much or all of the sky. This cloud is easily recognized when it pro-

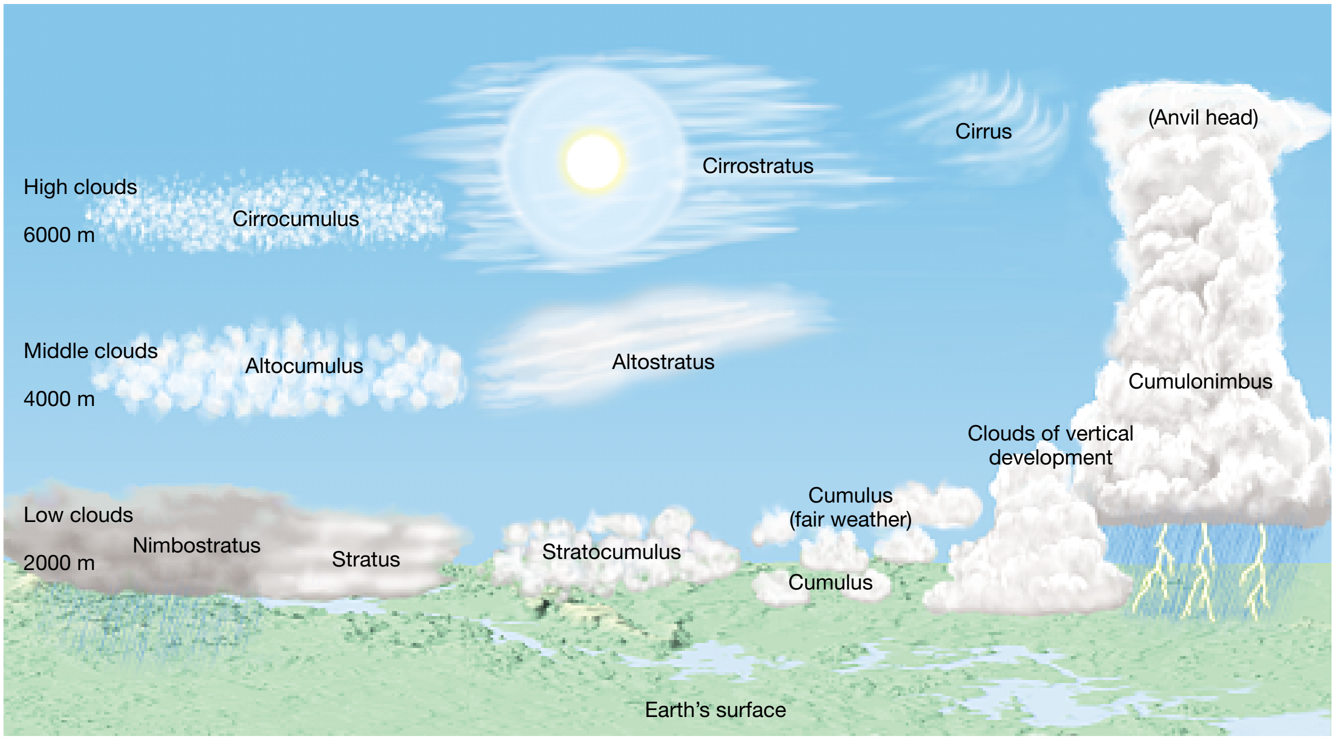


FIGURE 5-2 Classification of clouds according to height and form. *(After Ward's Natural Science Establishment, Inc., Rochester, N.Y.)*

TABLE 5-1 Basic cloud types

Cloud family and height	Cloud type	Characteristics
High clouds—above 6000 m (20,000 ft)	Cirrus (Ci)	Thin, delicate, fibrous ice-crystal clouds. Sometimes appear as hooked filaments called "mares' tails" (cirrus uncinus; Figure 5–3a).
	Cirrostratus (Cs)	Thin sheet of white ice-crystal clouds that may give the sky a milky look. Sometimes produces halos around the Sun and Moon (Figure 5–3b).
	Cirrocumulus (Cc)	Thin, white ice-crystal clouds. In the form of ripples or waves, or globular masses all in a row. May produce a "mackerel sky." Least common of high clouds (Figure 5–3c).
Middle clouds—2000–6000 m (6500 to 20,000 ft)	Altocumulus (Ac)	White to gray clouds often made up of separate globules; "sheepback" clouds (Figure 5–4a).
	Altostratus (As)	Stratified veil of clouds that is generally thin and may produce very light precipitation. When thin, the Sun or Moon may be visible as a "bright spot," but no halos are produced (Figure 5–4b).
Low clouds—below 2000 m (6500 ft)	Stratus (St)	Low uniform layer resembling fog but not resting on the ground. May produce drizzle.
	Stratocumulus (Sc)	Soft, gray clouds in globular patches or rolls. Rolls may join together to make a continuous cloud.
	Nimbostratus (Ns)	Amorphous layer of dark gray clouds. One of the chief precipitation-producing clouds (Figure 5–5).
Clouds of vertical development	Cumulus (Cu)	Dense, billowy clouds often characterized by flat bases. May occur as isolated clouds or closely packed (Figure 5–6).
	Cumulonimbus (Cb)	Towering cloud, sometimes spreading out on top to form an "anvil head." Associated with heavy rainfall, thunder, lightning, hail, and tornadoes (Figure 5–7).

(a)

(b)

(c)

FIGURE 5-3 Three basic cloud types make up the family of high clouds: (a) cirrus, (b) cirrostratus, and (c) cirrocumulus. *(Photos (a) and (c) by E. J. Tarbuck, (b) by A. and J. Verkaik/CORBIS/Stock Market)*

duces a halo around the Sun or Moon (Figure 5–3b). On occasions, cirrostratus may be so thin and transparent that the clouds are barely discernible. With the approach of a warm front, cirrostratus clouds generally thicken and grade into middle-level altostratus clouds.

Cirrocumulus clouds appear as white patches composed of very small cells or ripples (Figure 5–3c). Most often the masses that make up these clouds have an apparent width similar to that of the Sun. Furthermore, these small globules, which may be merged or separate, are often arranged in a regular pattern. This pattern is commonly called "mackerel sky" because of the similarity to the pattern formed by fish scales.

High clouds generally are not precipitation makers. However, when cirrus clouds give way to cirrocumulus clouds that cover even more of the sky, they may warn of impending stormy weather. The following mariner's saying is based on this observation: *Mackerel scales and mares' tails make lofty ships carry low sails.*

Middle Clouds

Clouds that appear in the middle altitude range (2000 to 6000 meters/6500 to 20,000 feet) have the prefix *alto* as part of their name. There are two types: *altocumulus* and *altostratus.*

Altocumulus tend to form in large patches composed of rounded masses or rolls that may or may not merge (Figure 5–4a). Because they are generally composed of water droplets rather than ice crystals, the individual cells usually have a more distinct outline. Altocumulus are most easily confused with two other cloud types: cirrocumulus (which are smaller and less dense) and stratocumulus (which are larger).

(a)

(b)

FIGURE 5-4 Two forms of clouds are generated in the middle-altitude range. (a) Altocumulus tend to form in patches composed of rolls or rounded masses. (b) Altostratus occur as grayish sheets covering a large portion of the sky. When visible, the Sun appears as a bright spot through these clouds. *(Photos by E. J. Tarbuck)*

Altostratus is the name given to a formless layer of grayish clouds covering all or a large portion of the sky. Generally, the Sun is visible through these clouds as a bright spot, but with the edge of its disc not discernible (Figure 5–4b). However, unlike cirrostratus clouds, altostratus do not produce halos. Infrequent precipitation in the form of light snow or drizzle may accompany these clouds. Altostratus clouds are commonly associated with warm fronts. As the front approaches, the clouds thicken into a dark gray layer of nimbostratus that is capable of producing copious rainfall.

Low Clouds

There are three members of the family of low clouds (below 2000 meters/6500 feet): *stratus, stratocumulus,* and *nimbostratus.*

Stratus is a uniform layer that frequently covers much of the sky and, on occasion, may produce light precipitation. When stratus clouds develop a scalloped bottom that appears as long parallel rolls or broken globular patches, they are called *stratocumulus* clouds.

Nimbostratus clouds derive their name from the Latin *nimbus,* "rain cloud," and *stratus,* "to cover with a layer" (Figure 5–5). As the name implies, nimbostratus clouds are one of the chief precipitation producers. Nimbostratus clouds form in association with stable conditions. We might not expect clouds to grow or persist in stable air, yet cloud growth of this type is common when air is forced to rise, as along a front or near the center of a cyclone where converging winds cause air to ascend. Such forced ascent of stable air leads to the formation of a stratified cloud layer that is large horizontally compared to its thickness. Precipitation associated with nimbostratus clouds is generally light to moderate but of long duration and widespread.

Clouds of Vertical Development

Some clouds do not fit into any one of the three height categories. Such clouds have their bases in the low height range and extend upward into the middle or high altitudes; they are referred to as *clouds of vertical development.* Vertically developed clouds are all closely related and are associated with unstable air. There are two types, *cumulus* and *cumulonimbus.*

Cumulus clouds are individual masses that develop into vertical domes or towers, the tops of which often resemble cauliflower. Cumulus clouds most often form on clear days when unequal surface heating causes parcels of air to rise convectively above the lifting condensation level (Figure 5–6). This level is often apparent to an observer because the flat cloud bottoms define it.

On days when cumulus clouds are present, we usually notice an increase in cloudiness into the afternoon as solar heating intensifies. Furthermore, because small cumulus clouds (*cumulus humilis*) rarely produce appreciable precipitation, and because they form on "sunny" days, they are often called "fair-weather clouds."

Although cumulus clouds are associated with fair weather, they may, under the proper circumstances, grow dramatically in height. Once upward movement is triggered, acceleration is powerful, and clouds with great vertical extent are formed. As the cumulus enlarges, its top leaves the low height range, and it is called a *cumulus congestus.* Finally, when the cloud becomes even more towering and rain begins to fall, it becomes a cumulonimbus.

Cumulonimbus are dark, dense, billowy clouds of considerable vertical extent in the form of huge towers (Figure 5–7). In its later stages of development, the upper part of a cumulonimbus turns to ice and appears fibrous. Furthermore, the tops of these clouds frequently spread out in the shape of an anvil. Cumulonimbus towers extend from a few hundred meters above the surface upward to 12 kilometers (7 miles) or, on rare occasions, 20 kilometers (12 miles). These huge towers produce heavy precipitation with accompanying lightning and thunder and occasionally hail. We will consider the development of these important weather producers in Chapter 10, which considers thunderstorms and tornadoes.

FIGURE 5-5 Nimbostratus clouds are one of the chief precipitation producers. These dark gray layers often exhibit a ragged-appearing base. *(Photo by E. J. Tarbuck)*

Cloud Varieties

In addition to the names given to the 10 basic cloud types, adjectives may also be used to describe variations of a particular cloud type. For example, the term *uncinus,* meaning "hook-shaped," is applied to streaks of cirrus clouds that are shaped like a comma resting on its side. Cirrus uncinus are often precursors of bad weather.

When stratus or cumulus clouds appear to be broken into smaller pieces, the adjective *fractus* may be used in their description. In addition, some clouds have rounded protuberances on their bottom surface, not unlike the udders of cows. When these structures are present, the term *mammatus* can be applied. This configuration is sometimes associated with stormy weather and cumulonimbus clouds.

Lens-shaped clouds are referred to as *lenticular.* They are common in areas that have rugged or mountainous topography, where they are called *lenticular altocumulus* (Figure 5–8a). Although lenticular clouds can form whenever the airflow undulates sharply in the vertical, they most frequently form on the lee side of mountains. As air passes over mountainous terrain, a wave pattern develops, as shown in Figure 5–8b. Clouds form where the wavy flow causes air to ascend, whereas areas with descending air are cloud-free.

FIGURE 5-6 Cumulus clouds. These small, white, billowy clouds generally form on sunny days and, therefore, are often called "fair weather clouds." *(Photo by E. J. Tarbuck)*

BOX 5-1 Aircraft Contrails and Cloudiness

You have undoubtedly seen a *contrail* (from *con*densation *trail*), in the wake of an aircraft flying on a clear day (Figure 5–A). Contrails are produced by jet aircraft engines that expel large quantities of hot, moist air. As this air mixes with the frigid air aloft, a streamlined cloud is produced. Because it often takes a few seconds for sufficient cooling to occur, the contrail usually forms a short distance behind the aircraft.

Why do contrails occur on some occasions and not on others? Contrails form under the same conditions as any other cloud—that is, when the air reaches saturation and condensation nuclei exist in sufficient numbers. Most contrails form when the exhaust gases add sufficient water vapor to the air to cause saturation. Further, it has been demonstrated that the exhaust gases of aircraft engines supply abundant sulfate molecules that serve as nuclei to promote the development of contrails.

Contrails typically form above 9 kilometers (6 miles) where air temperatures are a frigid −50°C (−58°F) or colder. Thus, it is not surprising that contrails are composed of minute ice crystals. Most contrails have a very short life span. Once formed, these streamlined clouds mix with surrounding cold, dry air and ultimately evaporate. However, if the air aloft is near saturation, contrails may survive for long periods. Under these conditions, the upper airflow usually spreads the streamlike clouds into broad bands of clouds called *contrail cirrus*.

With the increase in air traffic during the last few decades, an overall increase in cloudiness has been recorded, particularly near major transportation hubs (Figure 5–B). This is most evident in the American Southwest, where aircraft contrails persist in otherwise cloudless or mostly clear skies.

In addition to the added cloud cover associated with increasing levels of jet aircraft traffic, other less noticeable effects are of concern. Research is currently under way to assess the impact of contrail-produced cirrus clouds on the planet's heat budget. Recall from Chapter 3 that high, thin clouds are effective transmitters of solar radiation (most radiation reaches the surface) but are good absorbers of outgoing infrared radiation emitted from Earth's surface. As a consequence, high cirrus clouds tend to have an overall warming effect. However, research indicates that most contrails differ markedly from typical cirrus clouds, which are generated under quite different conditions. Although the results of these studies are inconclusive, it appears that human-induced cirrus clouds may actually lead to surface cooling rather than warming.

FIGURE 5-A Aircraft contrails. Condensation trails produced by jet aircraft often spread out to form broad bands of cirrus clouds. *(Photo by J. F. Towers/CORBIS/ Stock Market)*

Students Sometimes Ask…

How much water is found in a cloud?

That depends a lot on the size of the cloud. Let's consider a modest size cumulonimbus cloud that is roughly 3000 meters (about 2 miles) in width and depth and 10,000 meters high. If our hypothetical cloud contains an average of 0.5 cubic centimeter of liquid per cubic meter, it would contain 45 billion cubic centimeters of water ($3000 \times 3000 \times 10{,}000 \times 0.5$). That equates to 13 million gallons—enough to fill a small pond.

Types of Fog

GEODe ATMOSPHERE **Forms of Condensation and Precipitation**
▸ Types of Fog

Fog is generally considered an atmospheric hazard. When it is light, visibility is reduced to 2 or 3 kilometers (1 or 2 miles). When it is dense, visibility may be cut to a few dozen meters or less, making travel by any mode not only difficult but dangerous. Official weather stations report fog only when the visibility is reduced to 1 kilometer or

FIGURE 5-B This photograph, taken through the window of the International Space Station, shows contrails over the Rhone Valley in eastern France. It is estimated that these "artificial clouds" cover 0.1 percent of the planet's surface, and the percentages are far higher in some places, such as southern California and part of Europe, as illustrated here. *(Photo courtesy of NASA).*

Additional research is still needed to accurately determine the impact of contrails on climate change.

One effect of contrails that is known with some certainty is how these "artificial" clouds impact daily temperature ranges (that is, the difference between daily maximum and minimum temperatures). During the three-day commercial flight hiatus following the September 11 terrorist attacks, contrails all but disappeared. As a result, during these days of "clearer skies," the differences between the high and low temperatures increased by 2°F (1.1°C). This data supports the view that contrails reduce the transfer of both incoming solar radiation and outgoing terrestrial radiation. Consequently, cities located near major air-traffic centers experience lower daily highs and higher daily lows than would be the case if jet aircraft did not produce contrails.

less. Although arbitrary, this figure does permit a more objective criterion for comparing fog frequencies at different locations.

Fog is defined as *a cloud with its base at or very near the ground.* Physically, there is basically no difference between a fog and a cloud; their appearance and structure are the same. The essential difference is the method and place of formation. Clouds result when air rises and cools adiabatically. Fog results from cooling or by the addition of enough water vapor to cause saturation. Let us look at fogs, first those formed by cooling and then those formed by the addition of water vapor.

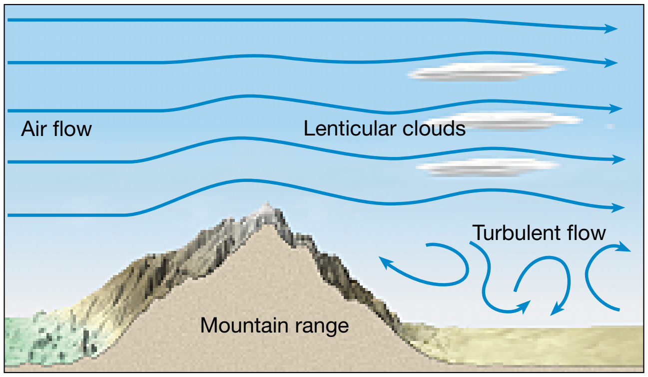
Fogs Formed by Cooling

When the temperature of a layer of air in contact with the ground falls below its dew point, condensation produces fog. Depending upon the prevailing conditions, the ground may become shrouded in radiation fog, advection fog, or upslope fog.

Radiation Fog. As the name implies, **radiation fog** results from radiation cooling of the ground and adjacent air. It is a nighttime phenomenon requiring clear skies and a fairly high relative humidity. Under these circumstances, the ground and the air immediately above it will cool

FIGURE 5-7 Cumulonimbus clouds. These dense, billowy clouds have great vertical extent and can produce heavy precipitation. *(Photo by Doug Millar/Science Source/Photo Researchers, Inc.)*

(a)



(b)

FIGURE 5-8 Lenticular clouds. (a) These lens-shaped clouds are relatively common in mountainous areas. *(Photo by Dennis Tasa)* (b) This diagram depicts the formation of lenticular clouds in the turbulent flow that develops in the lee of a mountain range.

rapidly. Because the relative humidity is high, just a small amount of cooling will lower the temperature to the dew point. If the air is calm, the fog may be patchy and less than a meter deep. For radiation fog to be more extensive vertically, a light breeze of 3 to 5 kilometers (2 to 3 miles) per hour is necessary. Then the light wind creates enough turbulence to carry the fog upward 10 to 30 meters (30 to 100 feet) without dispersing it.

Because the air containing the fog is relatively cold and dense, it drains downslope in hilly terrain. As a result, radiation fog is thickest in valleys, whereas the surrounding hills are clear (Figure 5–9). Normally these fogs dissipate within one to three hours after sunrise. Often the fog is said to "lift." However, it does not rise. Instead, the Sun warms the ground, which in turn heats the lowest layer of air first. Consequently, the fog evaporates from the bottom up, giving the impression of lifting. The last vestiges of radiation fog may appear to be a low stratus cloud layer.

In the eastern United States, radiation fog may also form when the skies clear after a rainfall. In these situations the air near the surface is close to saturation and only a small amount of radiation cooling is needed to promote condensation. Radiation fog of this type often occurs around sunset and can make driving hazardous.

Advection Fog. When warm and moist air is blown over a cold surface, it becomes chilled by contact and, to a certain extent, by mixing with the cold air created by the cold surface below. If cooling is sufficient, the result will be a blanket of fog called **advection fog.** The term *advection* refers to air moving horizontally. Therefore, advection fogs are a consequence of air giving up heat to the surface below during horizontal movement. A classic example is the frequent advection fog around San Francisco's Golden Gate Bridge (Figure 5–10).

A certain amount of turbulence is needed for proper development of advection fog. Thus, winds between 10 and

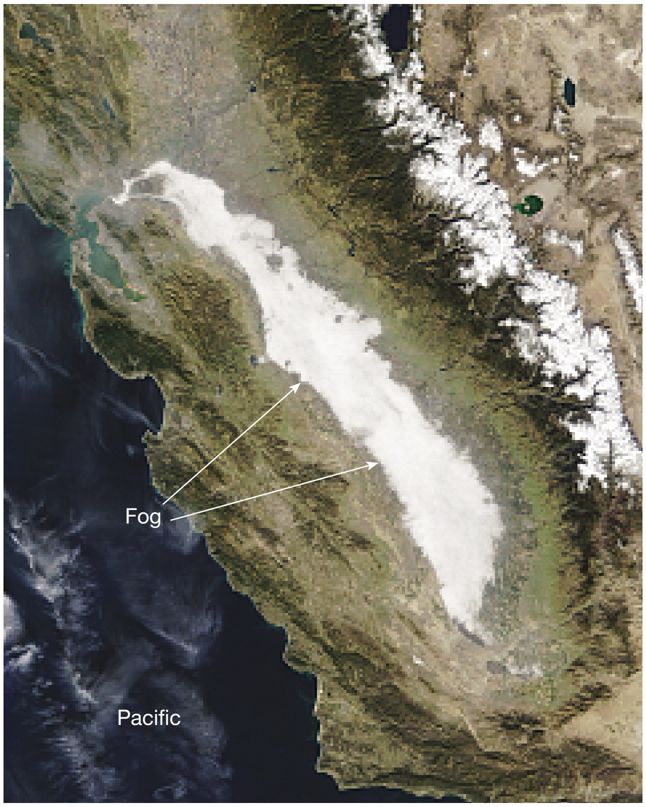


FIGURE 5-9 Satellite image of dense fog in California's San Joaquin Valley on November 20, 2002. This early morning radiation fog was responsible for several car accidents in the region, including a 14-car pileup. The white areas to the east of the fog are the snow-capped Sierra Nevadas. *(NASA image)*

30 kilometers (6 and 18 miles) per hour are usually associated with it. Not only does the turbulence facilitate cooling through a thicker layer of air but it also carries the fog to greater heights. Unlike radiation fogs, advection fogs are often thick (300 to 600 meters deep) and persistent.

Examples of such fogs are common. The foggiest location in the United States is Cape Disappointment, Washington. The name is indeed appropriate because the station averages 2552 hours (106 days) of fog each year. The fog experienced at Cape Disappointment, as well as that at other West Coast locations during the summer and early autumn, is produced when warm, moist air from the Pacific Ocean moves over the cold California Current (Figure 5–10). It is then carried onshore by westerly winds or a local sea breeze.

Advection fog is also a common wintertime phenomenon along the Gulf and Atlantic coasts. Here, comparatively warm, moist air from the Gulf of Mexico and Atlantic moves over cold and occasionally snow-covered surfaces to produce widespread foggy conditions. These fogs are frequently thick and produce hazardous driving conditions.

Upslope Fog. As its name implies, **upslope fog** is created when relatively humid air moves up a gradual sloping plain or, in some cases, up the steep slopes of a mountain. Because of the upward movement, air expands and cools adiabatically (this is the only type of fog that forms adiabatically). If the dew point is reached, an extensive layer of fog may form.

FIGURE 5-10 Advection fog rolling into San Francisco Bay. *(Photo by Ed Pritchard/Getty Images Inc.-Stone Allstock)*

It is easy to visualize how upslope fog might form in mountainous terrain. However, in the United States upslope fog also occurs in the Great Plains. Here, when humid Gulf air moves westward from the Mississippi River toward the Rocky Mountains, it gradually glides upslope. (Recall that Denver, Colorado, is called the "mile-high city," and the Gulf of Mexico is at sea level.) Air flowing "up" the Great Plains expands and cools adiabatically by as much as 12°C (22°F). The result can be an extensive upslope fog in the western plains.

Fogs Formed by Evaporation

When saturation occurs primarily because of the addition of water vapor, the resulting fogs are called *evaporation fogs.* Two types of evaporation fogs are recognized: steam fog and frontal (precipitation) fog.

Steam Fog. When cool air moves over warm water, enough moisture may evaporate from the water surface to saturate the air immediately above. As the rising water vapor meets the cold air, it condenses and rises with the air that is being warmed from below. Because the rising air looks like the "steam" that forms above a hot cup of coffee, the phenomenon is called **steam fog** (Figure 5–11). It is a fairly common occurrence over lakes and rivers on clear, crisp mornings in the fall when the waters are still relatively warm while the air is rather cold. Steam fog is often shallow, for as it rises, the water droplets evaporate as they mix with the unsaturated air above.

Steam fogs can be dense, however. During the winter, cold arctic air pours off the continents and ice shelves onto the comparatively warm open ocean. The temperature contrast between the warm ocean and cold air has been known to exceed 30°C (54°F). The result is an intense steam fog produced as the rising water vapor saturates a large volume of air. Because of its source and appearance, this type of steam fog is given the name *arctic sea smoke.*

Frontal Fog. When frontal wedging occurs, warm air is lifted over colder air. If the resulting clouds yield rain, and the cold air below is near the dew point, enough rain can evaporate to produce fog. A fog formed in this manner is called **frontal** or **precipitation fog.** The result is a more or less continuous zone of condensed water droplets reaching from the ground up through the clouds.

In summary, both steam fog and frontal fog result from the addition of moisture to a layer of air. As you saw, the air is usually cool or cold and already near saturation. Thus, only a relatively modest amount of evaporation is necessary to produce saturated conditions and fog.

The frequency of dense fog varies considerably from place to place (Figure 5–12). As might be expected, fog incidence is highest in coastal areas, especially where cold currents prevail, as along the Pacific and New England coasts. Relatively high frequencies are also found in the Great Lakes region and in the humid Appalachian Mountains of the East. In contrast, fogs are rare in the interior of the continent, especially in the arid and semiarid areas of the West.

Students Sometimes Ask…

Why do I see my breath on cold mornings?

On cold days when you "see your breath," you are actually creating steam fog. The moist air that you exhale saturates a small volume of cold air, causing tiny droplets to form. Like most steam fogs, the droplets quickly evaporate as the "fog" mixes with the unsaturated air around it.

Dew and Frost

Clouds and fog are the most conspicuous and meteorologically important forms of condensation. Dew and white frost must be considered minor by comparison. These common forms of condensation generally result from radiation cooling on clear, cool nights.

FIGURE 5-11 Steam fog rising from upper St. Regis Lake, Adirondack Mountains, New York. *(Photo by Jim Brown/CORBIS/Stock Market)*

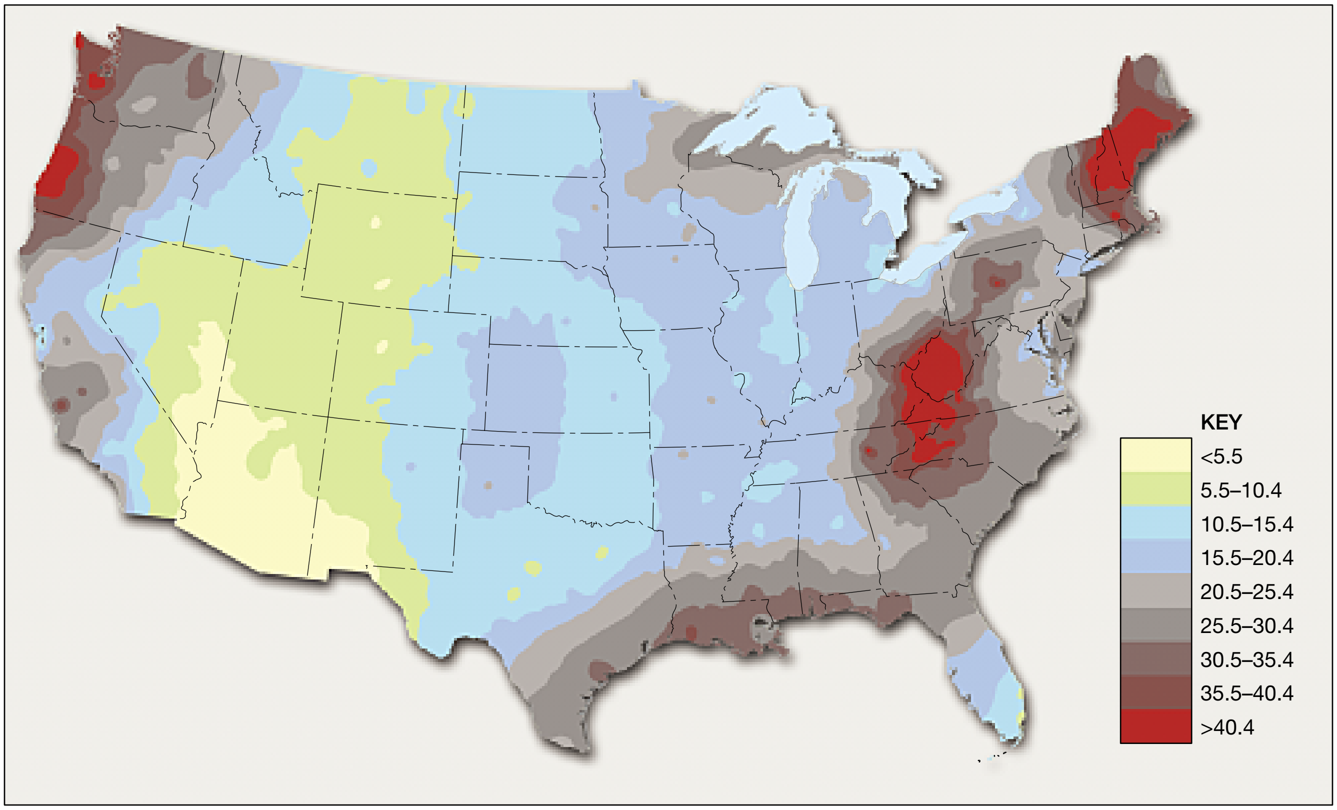


FIGURE 5-12 Map showing average number of days per year with heavy fog. Notice that the frequency of dense fog varies considerably from place to place. Coastal areas, particularly the Pacific Northwest and New England where cold currents prevail, have high occurrences of dense fog.

Dew is the condensation of water vapor on objects that have radiated sufficient heat to lower their temperature below the dew point of the surrounding air. Because different objects radiate heat at different rates, dew may form on some surfaces but not on others. An automobile, for example, may be covered with dew shortly after sunset, whereas the concrete driveway surrounding the car remains free of condensation throughout the night.

Dew is a common sight on lawns in the early morning. In fact, the grass will frequently have a coating of dew when nothing else does. Dew is more frequent on grass because the transpiration of water vapor by the blades raises the relative humidity to higher levels directly above the grass. Therefore, only modest radiation cooling may be necessary to bring about saturation and condensation.

Although dew is an unimportant source of moisture in humid areas, plant life in some arid regions depends on it for survival. In parts of Israel, for example, dew may supply as much as 55 millimeters (2.17 inches) of water annually. Further, this moisture is available mainly during the dry summer months when plants are experiencing the greatest stress.

Contrary to popular belief, white frost is not frozen dew. Rather, **white frost** (*hoar frost*) forms when the dew point of the air is below freezing. Thus, frost forms when water vapor changes directly from a gas into a solid (ice), without entering the liquid state. This process, called *deposition,* produces delicate patterns of ice crystals that frequently decorate windows in northern winters (see Figure 4–5, p. 103).

How Precipitation Forms

GEODe ATMOSPHERE

Forms of Condensation and Precipitation

▶ How Precipitation Forms

Although all clouds contain water, why do some produce precipitation and others drift placidly overhead? This seemingly simple question perplexed meteorologists for many years. Before examining the processes that generate precipitation, we need to examine a couple of facts.

First, cloud droplets are very tiny, 20 micrometers (0.02 millimeter) in diameter (Figure 5–13). (One micrometer equals 0.001 millimeter.) For comparison, a human hair is about 75 micrometers in diameter. The small size of cloud droplets results mainly because condensation nuclei are usually very abundant and the available water is distributed among numerous droplets rather than concentrated into fewer large droplets.

Second, because of their small size, the rate at which cloud droplets fall is incredibly slow (see Box 5–2). An

BOX 5-2 Forces Acting on Cloud Droplets and Raindrops

*Gregory J. Carbone**

Two opposing forces act on cloud droplets—*gravity* and *friction*. Gravitational force pulls a water droplet toward Earth's surface and is equal to the mass of the droplet times gravitational acceleration (gravitational force = droplet mass $\times$ 9.8 m/s^2). Because 1 cubic centimeter (1 cm^3) of volume equals 1 gram of mass, we can substitute volume for mass in the above equation and say that the gravitational force of a droplet increases with its volume. Assuming the droplet is a sphere, its volume is calculated as follows:

$$\text{Volume} = \tfrac{4}{3}\pi r^3$$

As a droplet falls, it encounters air resistance, or frictional force. The magnitude of this force depends on the size of the drop's "bottom"—that is, the surface area resisting the fall (Figure 5–C). Again, assuming the droplet is spherical, frictional force will change with the area of a circle:

$$\text{Area} = \pi r^2$$

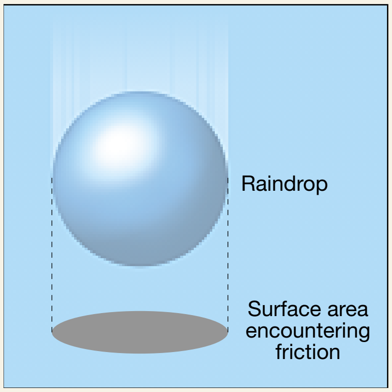


FIGURE 5-C Raindrops and friction.

Frictional drag increases as a droplet accelerates, because a faster droplet encounters more air molecules.

Eventually, frictional and gravitational forces balance, and the droplet no longer accelerates but falls at a constant speed. This speed is referred to as the droplet's *terminal velocity*. Terminal velocity depends on size. Smaller droplets have a lower terminal velocity than do larger droplets, because as droplet radius increases, gravitational force increases to the third power and frictional force increases to the second power. Consequently, larger droplets accelerate to higher speeds before reaching terminal velocity. (Refer to Table 5–3 to find the terminal velocity of different-sized droplets.)

The terminal velocity of individual droplets is important because it

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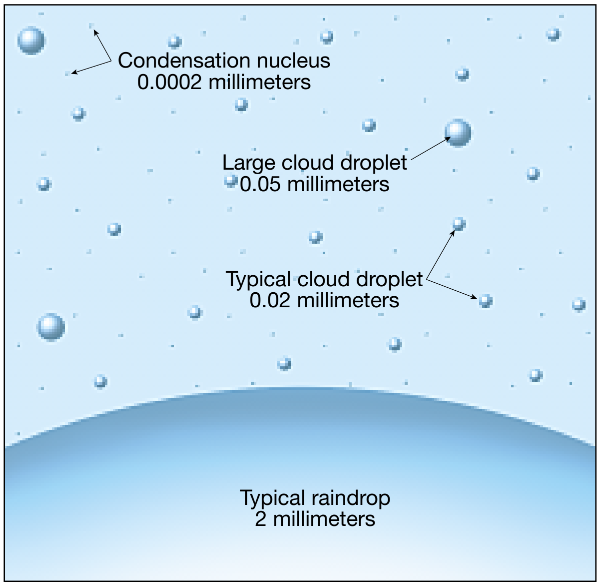
average cloud droplet falling from a cloud base at 1000 meters would require several hours to reach the ground. However, it would never complete its journey. This cloud droplet would evaporate before it fell a few meters from the cloud base into the unsaturated air below.

How large must a droplet grow in order to fall as precipitation? A typical raindrop has a diameter of about 2000 micrometers (2 millimeters), or 100 times that of the average cloud droplet having a diameter of 20 micrometers (0.02 millimeter). However, as shown in Box 5–2, the *volume* of a typical raindrop is a million times that of a cloud droplet. Thus, for precipitation to form, cloud droplets must grow in volume by roughly 1 million times. You might suspect that additional condensation creates drops large enough to survive the descent to the surface. However, clouds consist of many billions of tiny cloud droplets that all compete for the available water. Thus, condensation provides an inefficient means of raindrop formation.

Two processes are responsible for the formation of precipitation: the Bergeron process and the collision–coalescence process.

FIGURE 5-13 Comparative diameters of particles involved in condensation and precipitation processes.



Students Sometimes Ask…

Why does it often seem like the roads are slippery when it rains after a long dry period?

It appears that a buildup of debris on roads during dry weather causes more slippery conditions after a rainfall. One recent traffic study indicates that if it rains today, there will be no increase in risk of fatal crashes if it also rained yesterday. However, if it has been two days since the last rain, then the risk for a deadly accident increases by 3.7 percent. Furthermore, if it has been 21 days since the last rain, the risk increases to 9.2 percent.

determines the probability that a droplet will reach Earth without evaporating or being carried in updrafts. In fact, it is possible to estimate the maximum fall distance before evaporation for droplets of various size. Table 5–A shows such values assuming a barometric pressure of 900 mb, temperature of 5°C, and relative humidity equal to 90 percent. Note that droplets with a radius less than 100 μm (micrometers) are unlikely to reach Earth's surface because cloud bases are typically higher than their maximum fall distance.

TABLE 5-A Maximum fall distance before evaporation

Drop diameter (μm)	Maximum fall distance (m)
2500	280,000
1000	42,000
100	150
10	0.033
0	0.0000033

Because most cloud droplets are too small to reach the surface, precipitation requires processes that cause droplet growth. But condensation is a very slow growth process. Consider a typical cloud droplet of 10-μm radius. To grow to the size of a typical raindrop (1000 μm, or 100 times its original size), the cloud droplet must increase its volume by 1 million times:

$$\text{Volume}_{10\,\mu\text{m}} = \tfrac{4}{3} \times \pi \times (10\,\mu\text{m})^3$$
$$= 4{,}189\,\mu\text{m}^3$$
$$\text{Volume}_{100\,\mu\text{m}} = \tfrac{4}{3} \times \pi \times (1000\,\mu\text{m})^3$$
$$4{,}189{,}000{,}000\,\mu\text{m}^3/4{,}189\,\mu\text{m}^3$$
$$= 1{,}000{,}000$$

Clearly, condensation provides an inefficient means of cloud droplet growth, thus emphasizing the importance of other mechanisms, such as the collision–coalescence and Bergeron process.

*Professor Carbone is a faculty member in the Department of Geography at the University of South Carolina.

Precipitation from Cold Clouds: The Bergeron Process

You have probably watched a TV documentary in which mountain climbers brave intense cold and ferocious snowstorms as they scale an ice-covered peak. Although it is hard to imagine, very similar conditions exist in the upper portions of towering cumulonimbus clouds, even on sweltering summer days. (In fact, in the upper troposphere where commercial aircraft cruise, the temperature typically approaches −50°C (−58°F) or lower.) It turns out that the frigid conditions high in the troposphere provide an ideal environment to initiate precipitation. In fact, in the middle latitudes much of the rain that falls begins with the birth of snowflakes high in the cloud tops, where temperatures are considerably below freezing. Obviously, in the winter, even low clouds are cold enough to trigger precipitation.

The process that generates much of the precipitation in the middle latitudes is named the **Bergeron process** for its discoverer, the highly respected Swedish meteorologist, Tor Bergeron (see Box 5–3). The Bergeron process, which involves ice-crystal growth, depends on the coexistence of water vapor, liquid cloud droplets, and ice crystals. To understand just how this mechanism operates, we must first examine two important properties of water. First, *cloud droplets do not freeze at 0°C as expected.* In fact, pure water suspended in air does not freeze until it reaches a temperature of nearly −40°C (−40°F). Water in the liquid state below 0°C (32°F) is referred to as **supercooled.** Supercooled water will readily freeze if it impacts an object, which explains why airplanes collect ice when they pass through a liquid cloud made up of supercooled droplets. This also explains why the stuff we call *freezing rain* or *glaze* falls as a liquid but then turns to a sheet of ice when it strikes the pavement or a tree branch.

In addition, supercooled droplets will freeze on contact with solid particles that have a crystal form closely resembling that of ice (silver iodide is an example). These materials are called **freezing nuclei.** The need for freezing nuclei to initiate the freezing process is similar to the requirement for condensation nuclei in the process of condensation.

In contrast to condensation nuclei, however, freezing nuclei are sparse in the atmosphere and do not generally become active until the temperature reaches −10°C (14°F) or below. Thus, at temperatures between 0 and −10°C, clouds consist mainly of supercooled water droplets. Between −10 and −20°C, liquid droplets coexist with ice crystals, and below −20°C (−4°F), clouds are generally composed entirely of ice crystals—for example, high-altitude cirrus clouds.

This brings us to a second important property of water. *The saturation vapor pressure above ice crystals is somewhat lower than above supercooled liquid droplets.* This occurs because ice crystals are solid, which means that the individual water molecules are held together more tightly

BOX 5-3 Science and Serendipity*

Serendipity is defined by Nobel Laureate Irving Langmuir as "the art of profiting from unexpected occurrences." In other words, if you are observing something and the entirely unexpected happens, and if you see in this accident a new and meaningful discovery, then you have experienced serendipity. Most nonscientists, some scientists, and, alas, many teachers are not aware that many of the great discoveries in science were serendipitous.

An excellent example of serendipity in science occurred when Tor Bergeron, the great Swedish meteorologist, discovered the importance of ice crystals in the initiation of precipitation in supercooled clouds. Bergeron's discovery occurred when he spent several weeks at a health resort at an altitude of 430 meters (1400 feet) on a hill near Oslo. During his stay, Bergeron noted that this hill was often "fogged in" by a layer of supercooled clouds. As he walked along a narrow road in the fir forest along the hillside, he noticed that the "fog" did not enter the "road tunnel" at temperatures below −5°C, but did enter it when the temperature was warmer than 0°C. (Profiles of the hill, trees, and fog for the two temperature regimes is shown in Figure 5–D.)

Bergeron immediately concluded that at temperatures below about −5°C the branches of the firs acted as freezing nuclei upon which some of the supercooled droplets crystallized. Once the ice crystals developed, they grew rapidly at the expense of the remaining water droplets (Figure 5–D). The result was the growth of ice crystals (rime) on the branches of the firs accompanied by a "clearing-off" between the trees and along the "road-tunnel."

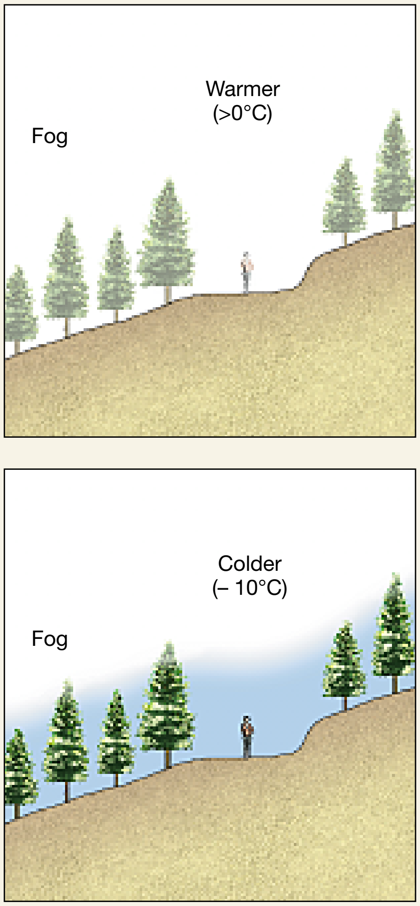


FIGURE 5-D Distribution of fog when the temperature is above freezing and when the temperature falls to −10°C.

From this experience, Bergeron realized that if ice crystals somehow were to appear in the midst of a cloud of supercooled droplets, they would grow rapidly as water molecules diffused toward them from the evaporating cloud droplets. This rapid growth forms snow crystals that, depending on the air temperature beneath the cloud, fall to the ground as snow or rain. Bergeron had thus discovered one way that minuscule cloud droplets can grow large enough to fall as precipitation (see the section entitled "Precipitation from Cold Clouds: The Bergeron Process" on page 145).

Serendipity influences the entire realm of science. Can we conclude that anyone who makes observations will necessarily make a major discovery? Not at all. A perceptive and inquiring mind is required, a mind that has been searching for order in a labyrinth of facts. As Langmuir said, the unexpected occurrence is not enough; you must know how to profit from it. Louis Pasteur observed that "in the field of observation, chance favors only the prepared mind." The discoverer of vitamin C, Nobel Laureate Albert Szent-Gyorgyi, remarked that discoveries are made by those who "see what everybody else has seen, and think what nobody else has thought." Serendipity is at the heart of science itself.

*Based on material prepared by Duncan C. Blanchard.

than those forming a liquid droplet. As a result, it is easier for water molecules to escape from the supercooled liquid droplets. Consequently, when air is saturated (100 percent relative humidity) with respect to liquid droplets, it is supersaturated with respect to ice crystals. Table 5–2, for example, shows that at −10°C (14°F), when the relative humidity is 100 percent with respect to water, the relative humidity with respect to ice is about 110 percent.

With these facts in mind, we can now explain how the Bergeron process produces precipitation. Visualize a cloud at a temperature of −10°C (14°F), where each ice crystal is surrounded by many thousands of liquid droplets (Figure 5–14). Because the air was initially saturated (100 percent) with respect to liquid water, it will be supersaturated (over 100 percent) with respect to the newly formed ice crystals. As a result of this supersaturated condition, the ice crystals collect more water molecules than they lose by sublimation. Thus, continued evaporation from the liquid drops provides a source of water vapor to feed the growth of ice crystals (Figure 5–14).

TABLE 5-2 Relative humidity with respect to ice when relative humidity with respect to water is 100 percent

	Relative humidity with respect to:	
Temperature (°C)	**Water**	**Ice**
0	100%	100%
−5	100%	105%
−10	100%	110%
−15	100%	115%
−20	100%	121%

Because the level of supersaturation with respect to ice can be great, the growth of snow crystals is generally sufficiently rapid to generate crystals large enough to fall. During their descent, these crystals enlarge as they intercept cloud drops that freeze on them. Air movement will sometimes break up these delicate crystals, and the fragments will serve as freezing nuclei for other liquid droplets. A chain reaction develops and produces many snow crystals, which, by accretion, will form into larger masses called snowflakes. Large snowflakes may consist of 10 to 30 individual crystals.

In summary, the Bergeron process can produce precipitation throughout the year in the middle latitudes, provided at least the upper portions of clouds are cold enough to generate ice crystals. The type of precipitation (snow, sleet, rain, or freezing rain) that reaches the ground depends on the temperature profile in the lower few kilometers of the atmosphere. When the surface temperature is above 4°C (39°F), snowflakes usually melt before they reach the ground and continue their descent as rain. Even on a hot summer day a heavy downpour may have begun as a snowstorm high in the clouds overhead.

Precipitation from Warm Clouds: The Collision–Coalescence Process

A few decades ago meteorologists believed that the Bergeron process was responsible for the formation of most precipitation except for light drizzle. Later it was discovered that copious rainfall is often associated with clouds located well below the freezing level (called *warm clouds*), especially in the tropics. Clearly, a second mechanism also must trigger precipitation. Researchers discovered the **collision–coalescence process.**

Research has shown that clouds made entirely of liquid droplets must contain some droplets larger than 20 micrometers (0.02 millimeters) if precipitation is to form. These large droplets form when "giant" condensation nuclei are present, or when hygroscopic particles exist (such as sea salt). Recall that hygroscopic particles begin to remove water vapor from the air at relative humidities under 100 percent.

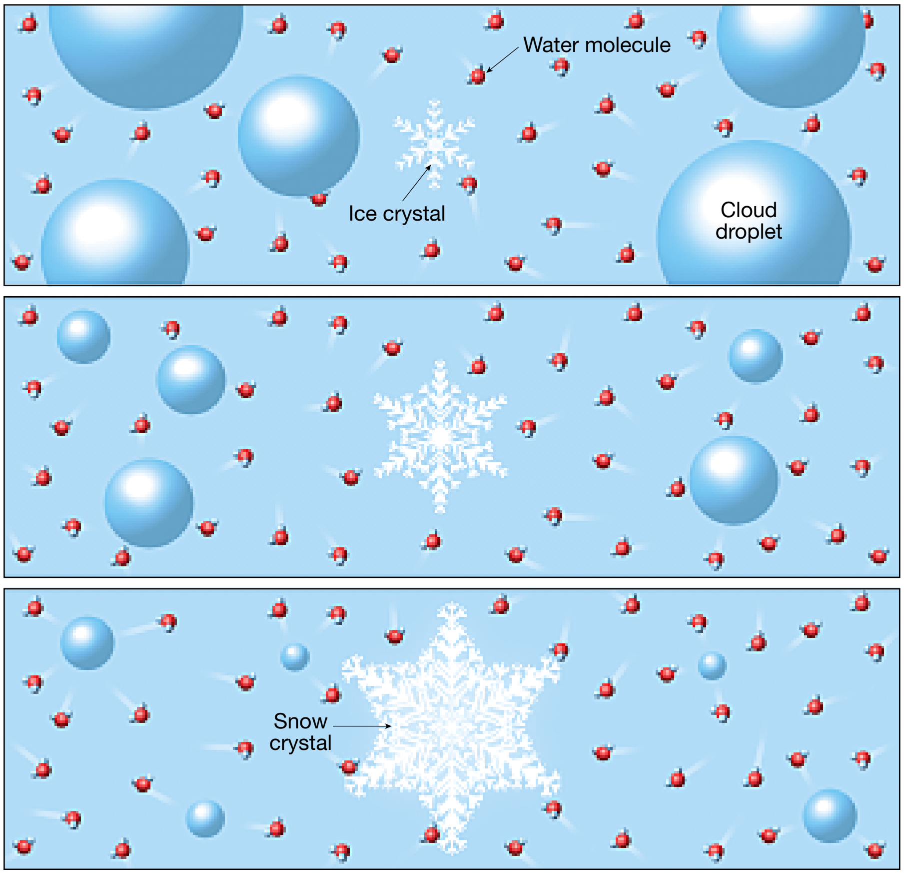


FIGURE 5-14 The Bergeron process. Ice crystals grow at the expense of cloud droplets until they are large enough to fall. The size of these particles has been greatly exaggerated.

Because the rate at which drops fall is size-dependent, these "giant" droplets fall most rapidly. (Table 5–3 summarizes drop size and falling velocities.)

As the larger droplets fall through a cloud, they collide with the smaller, slower droplets and coalesce (see Box 5–2). Becoming larger in the process, they fall even more rapidly (or, in an updraft, they rise more slowly) and increase their chances of collision and rate of growth (Figure 5–15a). After collecting the equivalent of a million or so cloud droplets, they are large enough to fall to the surface without evaporating.

Because of the huge number of collisions required for growth to raindrop size, clouds that have great vertical thickness and contain large cloud droplets have the best chance of producing precipitation. Updrafts also aid this process because they allow the droplets to traverse the cloud repeatedly, colliding with more droplets.

As raindrops grow in size, their fall velocity increases. This in turn increases the frictional resistance of the air, which causes the drop's "bottom" to flatten out (Figure 5–15b). As the drop approaches 4 millimeters in diameter, it develops a depression as shown in Figure 5–15c. Raindrops can grow to a maximum of 5 millimeters when they fall at the rate of 33 kilometers (20 miles) per hour. At this size and speed, the water's surface tension, which holds the drop together, is surpassed by the frictional drag of the air. At this point the depression grows almost explosively, forming a donutlike ring that immediately breaks apart. The resulting breakup of a large raindrop produces numerous smaller drops that begin anew the task of sweeping up cloud droplets (Figure 5–15d).

The collision–coalescence process is not that simple, however. First, as the larger droplets descend, they produce an airstream around them similar to that produced by an automobile when driven rapidly down the highway. The airstream repels objects, especially small ones. If an automobile is driven at night and we use the bugs that fill the air on a summer evening as being like cloud droplets, it is easy to visualize how most cloud droplets, which are tiny, are swept aside. The larger the cloud droplet (or bug), the better chance it will have of colliding with the giant droplet (or car).

Next, collision does not guarantee coalescence. Experimentation has indicated that the presence of atmospheric electricity may be the key to what holds these droplets together once they collide. If a droplet with a negative charge should collide with a positively charged droplet, their electrical attraction may bind them together.

From the preceding discussion, it should be apparent that the collision–coalescence mechanism is most efficient in environments where large cloud droplets are plentiful. It turns out that the air over the tropics, particularly the tropical oceans, is ideal. Here the air is very humid and

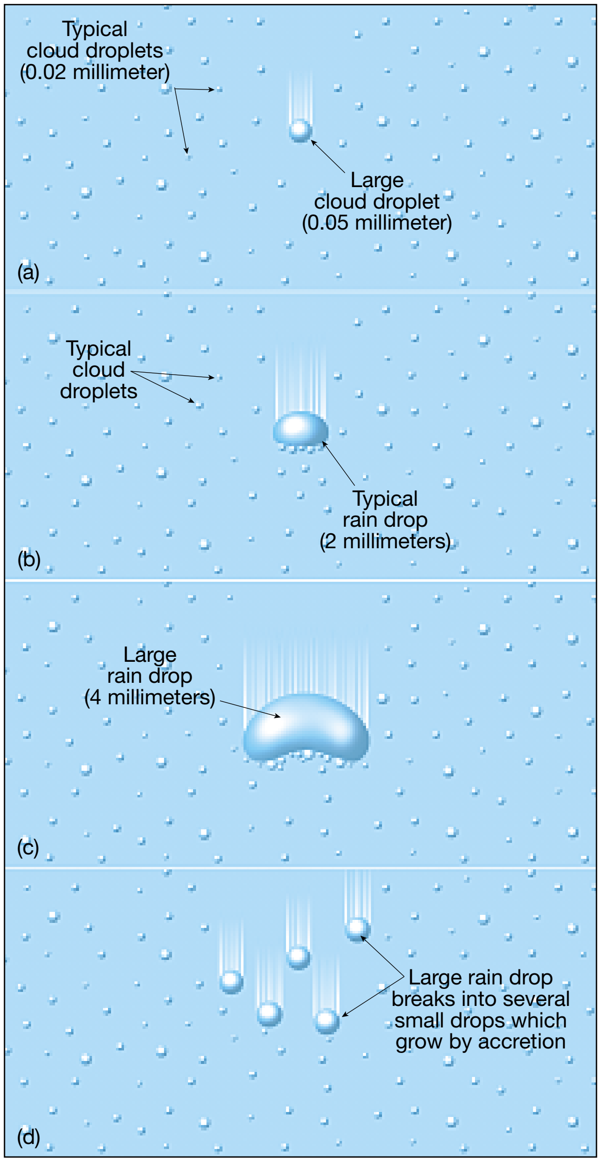


FIGURE 5-15 The collision–coalescence process. (a) Most cloud droplets are so small that the motion of the air keeps them suspended. Because large cloud droplets fall more rapidly than smaller droplets, they are able to sweep up the smaller ones in their path and grow. (b) As these drops increase in size, their fall velocity increases, resulting in increased air resistance, which causes the raindrop to flatten. (c) As the raindrop approaches 4 millimeters in size, it develops a depression in the bottom. (d) Finally, when the diameter exceeds about 5 millimeters, the depression grows upward almost explosively, forming a donutlike ring of water that immediately breaks into smaller drops. (Note that the drops are not drawn to scale—a typical raindrop has a volume equal to roughly 1 million cloud droplets.)

TABLE 5-3 Fall velocity of water drops

Types	Diameter (millimeters)	Fall velocity (km/hr)	Fall velocity (miles/hr)
Small cloud droplets	0.01	0.01	0.006
Typical cloud droplets	0.02	0.04	0.03
Large cloud droplets	0.05	0.3	0.2
Drizzle drops	0.5	7	4
Typical rain drops	2.0	23	14
Large rain drops	5.0	33	20

Data from Smithsonian Meteorological Tables relatively clean, so fewer condensation nuclei exit compared to the air over more populated regions. With fewer condensation nuclei to compete for available water vapor (which is plentiful), condensation is fast-paced and produces comparatively few large cloud droplets. Within developing cumulus clouds, the largest drops quickly gather smaller droplets to generate the warm afternoon showers associated with tropical climates.

In the middle latitudes the collision–coalescence process may contribute to the precipitation from a large cumulonimbus cloud by working in tandem with the Bergeron process—particularly during the hot, humid summer months. High in these towers the Bergeron process generates snow that melts as it passes below the freezing level. Melting generates relatively large drops with fast fall velocities. As these large drops descend, they overtake and coalesce with the slower and smaller cloud droplets that comprise much of the lower regions of the cloud. The result can be a heavy downpour.

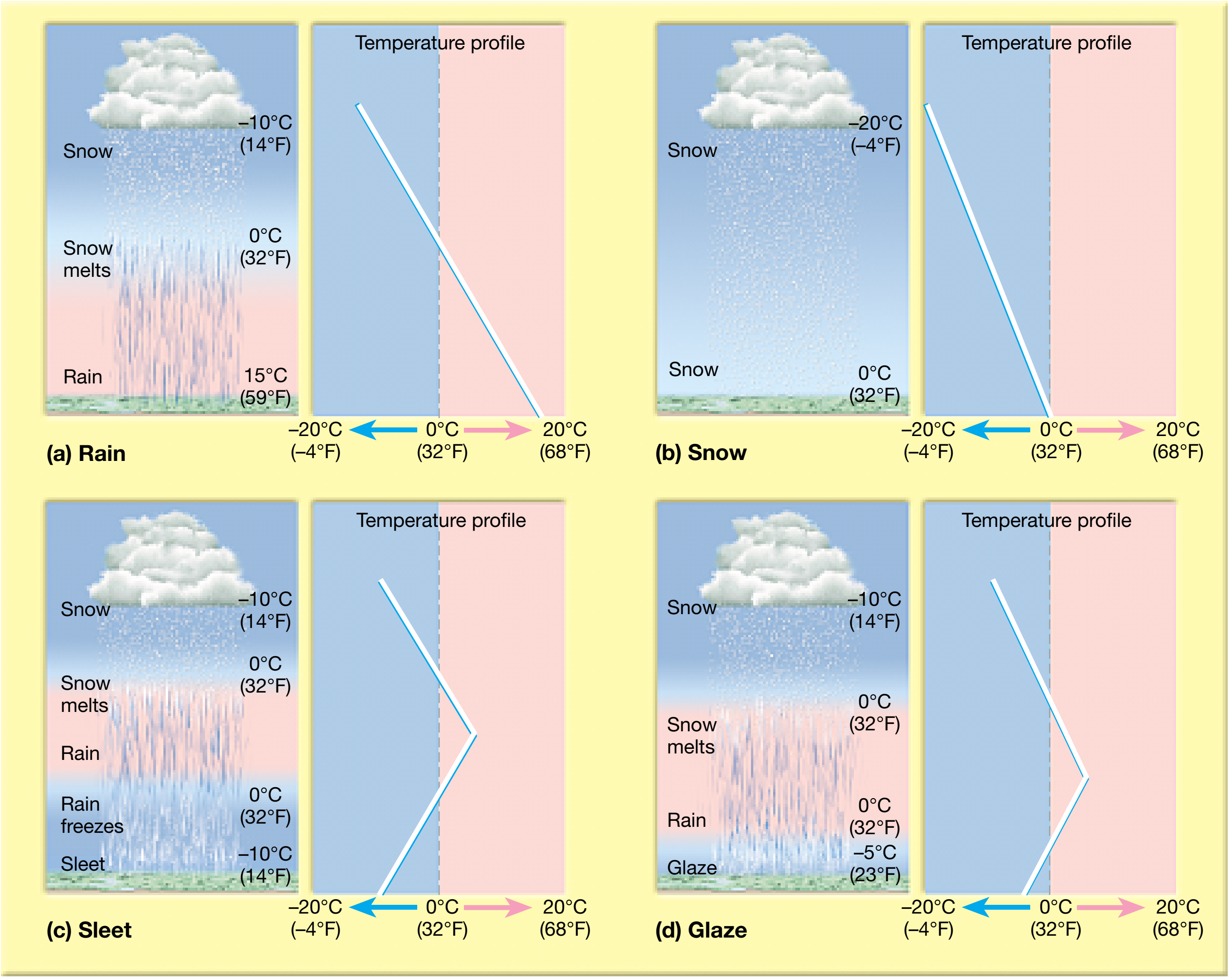
In summary, two mechanisms are known to generate precipitation: the *Bergeron process* and the *collision–coalescence process*. The Bergeron process is dominant in the middle latitudes where cold clouds (or cold cloud tops) are the rule. In the tropics, abundant water vapor and comparatively few condensation nuclei are the norm. This leads to the formation of fewer, larger drops with fast fall velocities that grow by collision and coalescence. No matter which process initiates precipitation, further growth in drop size is through collision–coalescence.

Students Sometimes Ask...

What is the largest annual rainfall ever recorded?

The greatest recorded rainfall for a single 12-month period occurred at Cherrapunji, India, where an astounding 2647 centimeters (1042 inches), over 86 feet, fell. Cherrapunji is located at an elevation of 1293 meters (4309 feet), where orographic lifting of the onshore, monsoon winds greatly contributed to the total.

FIGURE 5-16 Four precipitation types and their temperature profiles.



Forms of Precipitation

Forms of Condensation and Precipitation
▸ Forms of Precipitation

Because atmospheric conditions vary greatly both geographically and seasonally, several different forms of precipitation are possible (Figure 5–16). Rain and snow are the most common and familiar forms, but others listed in Table 5–4 are important as well. The occurrence of sleet, glaze, and hail is often associated with important weather events. Although limited in occurrence and sporadic in both time and space, these forms, especially glaze and hail, may on occasion cause considerable damage.

Rain

In meteorology the term **rain** is restricted to drops of water that fall from a cloud and have a diameter of at least 0.5 millimeter. (This excludes drizzle and mist, which have smaller droplets.) Most rain originates in either nimbostratus clouds or in towering cumulonimbus clouds that are capable of producing unusually heavy rainfalls known as *cloudbursts.* No matter what the rainfall intensity is, the size of raindrops rarely exceeds about 5 millimeters. Larger drops cannot survive, because surface tension, which holds the drops together, is exceeded by the frictional drag of the air. Consequently, large raindrops regularly break apart into smaller ones.

Much of the world's rainfall begins as snow crystals or other solid forms such as hail or graupel, as shown in Figure 5–16a. Entering the warmer air below the cloud, these ice particles often melt and reach the ground as raindrops. In some parts of the world, particularly the subtropics, precipitation often forms in clouds that are warmer than 0°C (32°F). These rains frequently occur over the ocean where cloud condensation nuclei are not plentiful and those that do exist vary in size. Under such conditions, cloud droplets can grow rapidly by the collision–coalescence process to produce copious amounts of rain.

Fine, uniform drops of water having a diameter less than 0.5 millimeter are called *drizzle.* Drizzle and small raindrops generally are produced in stratus or nimbostratus clouds where precipitation may be continuous for several hours, or on rare occasions for days.

Precipitation containing the very smallest droplets able to reach the ground is called *mist*. Mist can be so fine that the tiny droplets appear to float and their impact is almost imperceptible.

As rain enters the unsaturated air below the cloud, it begins to evaporate. Depending on the humidity of the air and size of the drops, the rain may completely evaporate before reaching the ground. This phenomenon produces *virga*, which appear as streaks of precipitation falling from a cloud that extend only part of the way to Earth's surface (Figure 5–17).

TABLE 5-4 Types of precipitation

Type	Approximate size	State of water	Description
Mist	0.005 to 0.05 mm	Liquid	Droplets large enough to be felt on the face when air is moving 1 meter/second. Associated with stratus clouds.
Drizzle	Less than 0.5 mm	Liquid	Small uniform drops that fall from stratus clouds, generally for several hours.
Rain	0.5 to 5 mm	Liquid	Generally produced by nimbostratus or cumulonimbus clouds. When heavy, size can be highly variable from one place to another.
Sleet	0.5 to 5 mm	Solid	Small, spherical to lumpy ice particles that form when raindrops freeze while falling through a layer of subfreezing air. Because the ice particles are small, any damage is generally minor. Sleet can make travel hazardous.
Glaze	Layers 1 mm to 2 cm thick	Solid	Produced when supercooled raindrops freeze on contact with solid objects. Glaze can form a thick coating of ice having sufficient weight to seriously damage trees and power lines.
Rime	Variable accumulations	Solid	Deposits usually consisting of ice feathers that point into the wind. These delicate frostlike accumulations form as supercooled cloud or fog droplets encounter objects and freeze on contact.
Snow	1 mm to 2 cm	Solid	The crystalline nature of snow allows it to assume many shapes, including six-sided crystals, plates, and needles. Produced in supercooled clouds where water vapor is deposited as ice crystals that remain frozen during their descent.
Hail	5 mm to 10 cm or larger	Solid	Precipitation in the form of hard, rounded pellets or irregular lumps of ice. Produced in large convective, cumulonimbus clouds, where frozen ice particles and supercooled water coexist.
Graupel	2 mm to 5 mm	Solid	Sometimes called "soft hail," graupel forms as rime collects on snow crystals to produce irregular masses of "soft" ice. Because these particles are softer than hailstones, they normally flatten out upon impact.

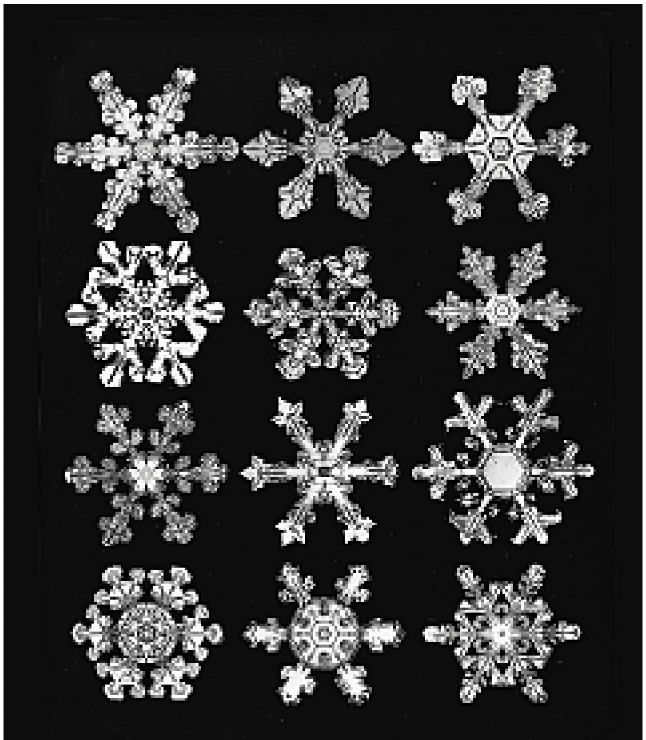
FIGURE 5-17 Virga, latin for "streak." In the arid west, rain frequently evaporates before reaching the ground. *(Photo by Pekka Parviainen/Science Photo Library/Photo Researchers, Inc.)*

Snow

Snow is precipitation in the form of ice crystals (snowflakes) or, more often, aggregates of ice crystals (Figure 5–16b). The size, shape, and concentration of snowflakes depend to a great extent on the temperature at which they form.

Recall that at very low temperatures, the moisture content of air is small. The result is the generation of very light and fluffy snow made up of individual six-sided ice crystals (Figure 5–18). This is the "powder" that downhill skiers talk so much about. By contrast, at temperatures warmer than about −5°C (23°F), the ice crystals join together into larger clumps consisting of tangled aggregates of crystals. Snowfalls consisting of these composite snowflakes are generally heavy and have a high moisture content, which makes them ideal for making snowballs. (For more on winter weather, see Box 5–4.)

FIGURE 5-18 All snow crystals are six-sided, but they come in an infinite variety of forms. *(Courtesy of NOAA, Seattle)*



> ### Students Sometimes Ask…
> *What is the snowiest city in the United States?*
>
> According to National Weather Service Records, Rochester, New York, which averages nearly 239 centimeters (94 inches) of snow annually, is the snowiest city in the United States. However, Buffalo, New York, is a close runner-up.

Sleet and Glaze

Sleet is a wintertime phenomenon and refers to the fall of small particles of ice that are clear to translucent. Figures 5–16c and 5–19 show how sleet is produced: An above-freezing air layer must overlie a subfreezing layer near the ground. When the raindrops, which are often melted snow, leave the warmer air and encounter the colder air below, they freeze and reach the ground as small pellets of ice roughly the size of the raindrops from which they formed.

On some occasions, when the vertical distribution of temperatures is similar to that associated with the formation of sleet, **freezing rain** or **glaze** results instead. In such situations the subfreezing air near the ground is not thick enough to allow the raindrops to freeze (Figure 5–16d). The raindrops, however, do become supercooled as they fall through the cold air and turn to ice. The result can be a thick coating of ice having sufficient weight to break tree limbs, to down power lines, and to make walking and driving extremely hazardous.

In January 1998 an ice storm of historic proportions caused enormous damage in southeastern Canada. Here five days of freezing rain deposited a heavy layer of ice on all exposed surfaces from eastern Ontario to the Atlantic coast. The 8 centimeters (3 inches) of precipitation caused trees, power lines, and high-voltage towers to collapse, leaving over a million households without power—many for nearly a month following the storm (Figure 5–20).

At least 25 deaths were blamed on the storm, which caused damages in excess of $1 billion. Much of the damage was to the electrical grid, which one Canadian climatologist summed up this way: "What it took human beings a half-century to construct, took nature a matter of hours to knock down."

Hail

Hail is precipitation in the form of hard, rounded pellets or irregular lumps of ice. Large hailstones, when cut in half, often reveal nearly concentric shells of differing densities and degrees of opaqueness (Figure 5–21). The layers of ice accumulate as the hailstone travels up and down in a strong convective cloud.

BOX 5-4 Atmospheric Hazard: Worst Winter Weather

Extremes, whether they be the tallest building or the record low temperature for a location, fascinate us. When it comes to weather, some places take pride in claiming to have the worst winters on record. In fact, Fraser, Colorado, and International Falls, Minnesota, have both proclaimed themselves the "ice box of the nation." Although Fraser recorded the low temperature for the 48 contiguous states 23 times in 1989, its neighbor, Gunnison, Colorado, recorded the low temperature 62 times, far more than any other location.

Such facts do not impress the residents of Hibbing, Minnesota, where the temperature dropped to −38°C (−37°F) during the first week of March 1989. But this is mild stuff, say the old-timers in Parshall, North Dakota, where the temperature fell to −51°C (−60°F) on February 15, 1936. Not to be left out, Browning, Montana, holds the record for the most dramatic 24-hour temperature drop. Here the temperature plummeted 56°C (100°F), from a cool 7°C (44°F) to a frosty −49°C (−56°F) during a January evening in 1916.

Although impressive, the temperature extremes cited here represent only one aspect of winter weather. What about snowfall (Figure 5–E)? Cooke City holds the seasonal snowfall record for Montana, with 1062 centimeters (418.1 inches) during the winter of 1977–1978. But what about cities like Sault Ste. Marie, Michigan, or Buffalo, New York? The winter snowfalls associated with the Great Lakes are legendary. Even larger snowfalls occur in many sparsely inhabited mountainous areas.

Try telling residents of the eastern United States that heavy snowfall by itself makes for the worst weather. A blizzard in March 1993 produced heavy snowfall along with hurricane-force winds and record low temperatures that immobilized much of the region from Alabama to the Maritime Provinces of eastern Canada. This event quickly earned the well-deserved title of Storm of the Century.

As we can see, determining which location has the worst winter weather depends on how you measure it. Most snowfall in a season? Longest cold spell? Coldest temperature? Most disruptive storm?

Here are the meanings of some common terms used by the National Weather Service for winter weather events.

Snow flurries Snow falling for short durations at intermittent periods and resulting in generally little or no accumulation.

Blowing snow Snow lifted from the surface by the wind and blown about to a degree that horizontal visibility is reduced.

Drifting snow Significant accumulations of falling or loose snow caused by strong wind.

Blizzard A winter storm characterized by winds of at least 56 kilometers (35 miles) per hour for at least three hours. The storm must also be accompanied by low temperatures and considerable falling and/or blowing snow that reduces visibility to a quarter of a mile or less.

Severe blizzard A storm with winds of at least 72 kilometers (45 miles) per hour, a great amount of falling or drifting snow, and temperatures −12°C (10°F) or lower.

Heavy snow warning A snowfall in which at least 4 inches in 12 hours or 6 inches in 24 hours is expected.

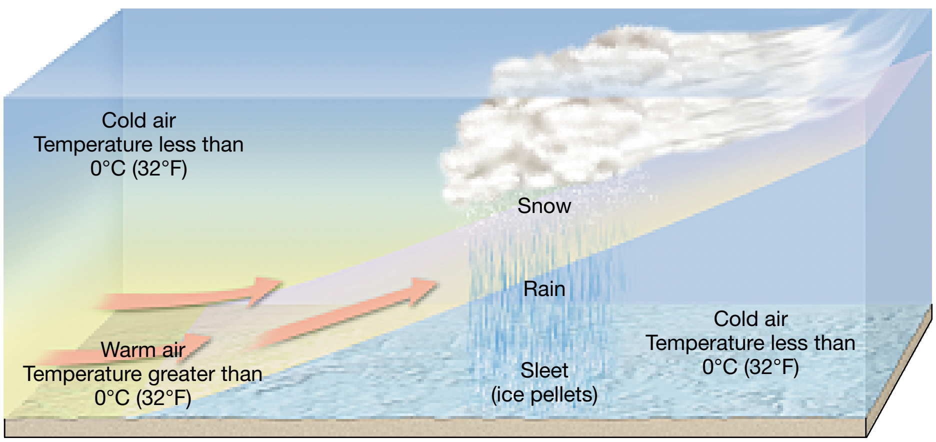


FIGURE 5-19 Sleet forms when rain passes through a cold layer of air and freezes into ice pellets. This occurs most often in the winter when warm air is forced over a layer of cold air.

FIGURE 5-E Rochester, NY, was hit by blizzard conditions that left 24 inches of snow in 24 hours on March 4, 1999. *(Photo by AP/Wide World Photos)*

Freezing rain Rain falling in a liquid form through a shallow subfreezing layer of air near the ground. The rain (or drizzle) freezes on impact with the ground or other objects, resulting in a clear coating of ice known as *glaze*.

Sleet Also called *ice pellets*. Sleet is formed when raindrops or melted snowflakes freeze as they pass through a subfreezing layer of air near Earth's surface. Sleet does not stick to trees and wires, and it usually bounces when it hits the ground. An accumulation of sleet sometimes has the consistency of dry sand.

Travelers' advisory Issued to inform the public of hazardous driving conditions caused by snow, sleet, freezing precipitation, fog, wind, or dust.

Cold wave A rapid fall of temperature in a 24-hour period, usually signifying the beginning of a spell of very cold weather.

Windchill A measure of apparent temperature that uses the effects of wind and temperature on the human body by translating the cooling power of wind to a temperature under calm conditions. It is an approximation only for the human body and has no meaning for cars, buildings, or other objects. (See Box 3–5 for more details.)

FIGURE 5-20 Glaze forms when supercooled raindrops freeze on contact with objects. In January 1998 an ice storm of historic proportions caused enormous damage in New England and southeastern Canada. Nearly five days of freezing rain (glaze) left millions without electricity—some for as long as a month. *(Photo by Syracuse Newspapers/The Image Works)*

FIGURE 5-21 Hail. A cross section of the Coffeyville hailstone. This record-breaking hailstone fell over Coffeyville, Kansas, in 1970 and weighed 0.75 kilogram (1.67 pounds). *(Photo courtesy of University Corporation for Atmospheric Research/National Science Foundation/Visual Communications NCAR)*

Most hailstones have diameters between 1 centimeter (pea size) and 5 centimeters (golf ball size), although some can be as big as an orange or even bigger. Occasionally, hailstones weighing a pound or more have been reported. Many of these were probably composites of several stones frozen together.

The largest hailstone ever recorded in the United States fell during violent thunderstorms that pounded southeastern Nebraska on June 22, 2003. In the town of Aurora, a seven-inch (17.8-centimeter)-wide chunk of ice, almost as large as a volleyball, was recovered. However, this hailstone was not the heaviest hailstone ever measured. Apparently, a chunk of this stone was broken off when it hit the gutter of a house.

The heaviest hailstone in North America fell on Coffeyville, Kansas, in 1970. Having a 5.5 inch (14 centimeter) diameter, this hailstone weighed 1.67 pounds (766 grams). Even heavier hailstones have reportedly been recorded in Bangladesh, where a hailstorm in 1987 killed more than 90 people. It is estimated that large hailstones hit the ground at speeds exceeding 100 miles (160 kilometers) per hour.

The destructive effects of large hailstones are well known, especially to farmers whose crops have been devastated in a few minutes and to people whose windows, roofs, and cars have been damaged (Figure 5–22). In the United States, hail damage each year can run into the hundreds of millions of dollars. One of the costliest hailstorms to occur in North America took place on June 11, 1990, in Denver, Colorado. Total damage was estimated to exceed $625 million.

Hail is produced only in large cumulonimbus clouds where updrafts can sometimes reach speeds approaching 160 kilometers (100 miles) per hour, and where there is an abundant supply of supercooled water. Figure 5–23 shows the process. Hailstones begin as small embryonic ice pellets that grow by collecting supercooled droplets as they fall through the cloud. If they encounter a strong updraft, they may be carried upward again and begin the downward journey anew. Each trip through the supercooled portion of the cloud might be represented by an additional layer of ice. Hailstones can also form from a single descent through an updraft. Either way, the process continues until the hailstone encounters a downdraft or grows too heavy to remain suspended by the thunderstorm's updraft.

Hailstones may contain several layers that alternate between clear and milky ice. High in the clouds, rapid freezing of small, supercooled water droplets traps air bubbles, which cause the milky appearance. By contrast, the clear ice is produced in the lower and warmer regions of the clouds where colliding droplets wet the surface of the hailstones. As these droplets slowly freeze, they produce relatively bubble-free clear ice.

FIGURE 5-22 Hail damage to a used car lot in Fort Worth, Texas, May 6, 1995. This storm, which packed high winds and hail the size of baseballs, killed at least nine people and injured more than 100 as it swept through the northern part of the state. *(Photo by Ron Heflin/AP/Wide World Photos)*

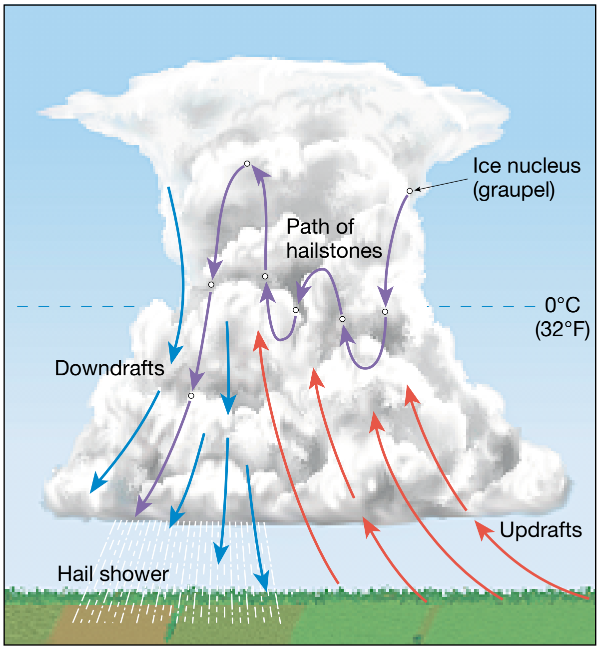


FIGURE 5-23 Growth of hailstones. Hailstones begin as small ice pellets that grow by adding supercooled water droplets as they move through a cloud. Strong updrafts may carry stones upward in several cycles, increasing the size of the hail by adding a new layer with each cycle. Eventually, the hailstones encounter a downdraft or grow too large to be supported by the updraft.

Students Sometimes Ask...

What is the difference between a winter storm warning and a blizzard warning?

A winter storm warning is usually issued when heavy snow exceeding six inches in 12 hours or possible icing conditions are likely. It is interesting to note that in Upper Michigan and mountainous areas where snowfall is abundant, winter storm warnings are issued only if eight or more inches of snow is expected in 12 hours. By contrast, blizzard warnings are issued for periods when considerable falling or blowing snow is accompanied by winds of 35 or more miles per hour. Thus, a blizzard is a type of winter storm in which winds are the determining factor, not the amount of snowfall.

Rime

Rime is a deposit of ice crystals formed by the freezing of supercooled fog or cloud droplets on objects whose surface temperature is below freezing. When rime forms on trees, it adorns them with its characteristic ice feathers, which can be spectacular to behold (Figure 5–24). In these situations, objects such as pine needles act as freezing nuclei, causing the supercooled droplets to freeze on contact. On occasions when the wind is blowing, only the windward surfaces of objects will accumulate the layer of rime.

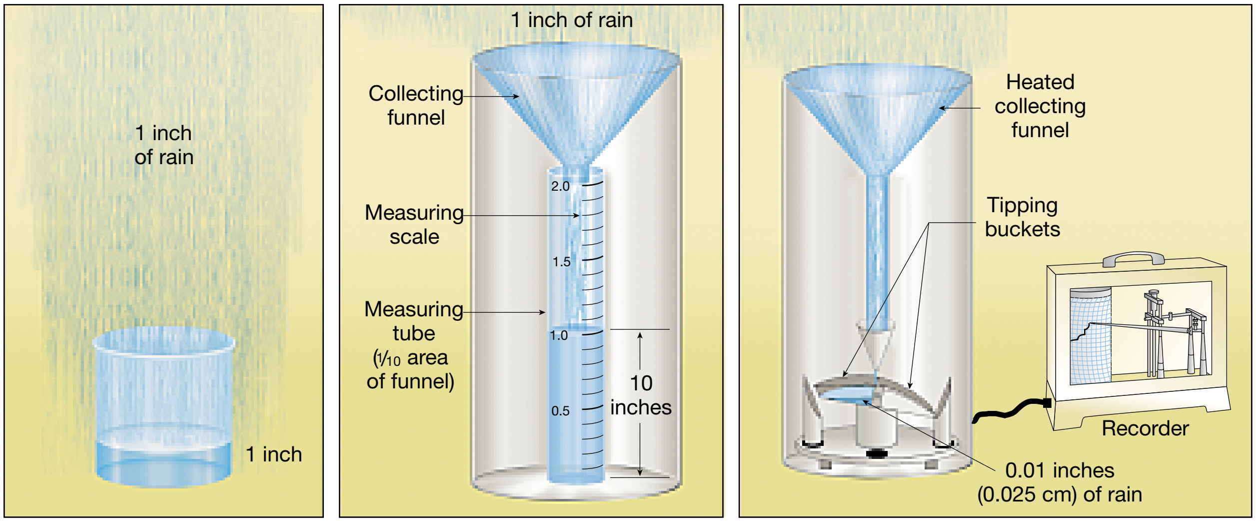
FIGURE 5-24 Rime consists of delicate ice crystals that form when supercooled fog or cloud droplets freeze on contact with objects. *(Photo by John Cancalosi/Stock Boston)*

Precipitation Measurement

The most common form of precipitation, rain, is probably the easiest to measure. Any open container that has a consistent cross section throughout can be a rain gauge (Figure 5–25a). In general practice, however, more sophisticated devices are used to measure small amounts of rainfall more accurately and to reduce loss from evaporation.

Standard Instruments

The **standard rain gauge** (Figure 5–25b) has a diameter of about 20 centimeters (8 inches) at the top. Once the water is caught, a funnel conducts the rain through a narrow opening into a cylindrical measuring tube that has a cross-sectional area only one-tenth as large as the receiver. Consequently, rainfall depth is magnified 10 times, which allows for accurate measurements to the nearest 0.025 centimeter (0.01 inch), and the narrow opening minimizes evaporation. When the amount of rain is less than 0.025



(a) Simple rain gauge (b) Standard rain gauge (c) Tipping–bucket gauge

FIGURE 5-25 Precipitation measurement. (a) The simplest gauge is any container left in the rain. However, these homemade devices are hard to read precisely. (b) The standard rain gauge increases the height of water collected by a factor of 10, allowing for accurate rainfall measurement to the nearest 0.025 centimeter (0.01 inch). Because the cross-sectional area of the measuring tube is only one-tenth as large as the collector, rainfall is magnified 10 times. (c) The tipping-bucket rain gauge contains two "buckets" that hold the equivalent of 0.025 centimeter (0.01 inch) of precipitation. When one bucket fills, it tips and the other bucket takes its place. Each event is recorded as 0.01 inch of rainfall.

centimeter (0.01 inch), it is generally reported as being a **trace of precipitation.**

In addition to the standard rain gauge, several types of recording gauges are routinely used. These instruments not only record the amount of rain, but also its time of occurrence and intensity (amount per unit of time). Two of the most common gauges are the tipping-bucket gauge and the weighing gauge.

As can be seen in Figure 5–25c, the **tipping-bucket gauge** consists of two compartments, each one capable of holding 0.025 centimeter (0.01 inch) of rain, situated at the base of a funnel. When one "bucket" fills, it tips and empties its water. Meanwhile, the other "bucket" takes its place at the mouth of the funnel. Each time a compartment tips, an electrical circuit is closed and 0.025 centimeter (0.01 inch) of precipitation is automatically recorded on a graph.

The **weighing gauge,** as the name would indicate, works on a different principle. Precipitation is caught in a cylinder that rests on a spring balance. As the cylinder fills, the movement is transmitted to a pen that records the data.

Measuring Snowfall

When snow records are kept, two measurements are normally taken—depth and water equivalent. Usually, the depth of snow is measured with a calibrated stick. The actual measurement is not difficult, but choosing a representative spot can be. Even when winds are light or moderate, snow drifts freely. As a rule, it is best to take several measurements in an open place away from trees and obstructions and then average them. To obtain the water equivalent, samples may be melted and then weighed or measured as rain.

Sometimes large cylinders are used to collect snow. A major problem that hinders accurate measurement by snow gauges is the wind. Snow will blow around the top of the cylinder instead of falling into it. Therefore, the amount caught by the gauge is generally less than the actual fall. As is often the practice with rain gauges, shields designed to break up wind eddies are placed around the snow gauge to ensure a more accurate catch.

The quantity of water in a given volume of snow is not constant. A general ratio of 10 units of snow to 1 unit of water is often used when exact information is not available. You may have heard TV weathercasters use this ratio, saying, "Every 10 inches of snow equals 1 inch of rain." But the actual water content of snow may deviate widely from this figure. It may take as much as 30 centimeters of light and fluffy dry snow (30:1) or as little as 4 centimeters of wet snow (4:1) to produce 1 centimeter of water.

Measurement Errors

We tend to be unquestioning when we hear weather reports concerning the past day's events. However, unlike temperature and pressure, which tend to vary only slightly over a few dozen miles, precipitation on one side of the street can be significantly greater than on the other. Further, by its very nature precipitation is difficult to collect, and the techniques used have numerous potential sources for error.

When measuring rain, a certain amount goes unrecorded—some because it splashes out upon impact, and some "wets" the collection funnel and never makes it into the cylinder. Snow in particular is often underestimated by rain gauges. In addition, in certain climates evaporation removes some of the precipitation before it is measured.

No matter which rain gauge is used, proper exposure is critical. Errors arise when gauges are located too close to buildings, trees, or other high objects that block obliquely falling rain. For best results the instrument should be twice as far away from such obstructions as the objects are high. Another cause for error is wind. It has been shown that as wind speed strengthens, turbulence increases, and it becomes more difficult to collect a representative quantity of rain. To offset this effect, a windscreen is often placed around the instrument so that rain falls into the gauge and is not carried across it (Figure 5–26).

Studies have shown that in the United States, annual precipitation errors range between about 7 and 20 percent. Most often the precipitation is underestimated. In some high latitudes, percentage errors are thought to exceed 80 percent.

Precipitation Measurement by Weather Radar

Today's TV weathercasts show helpful maps, like the one in Figure 5–27, to depict precipitation patterns. The instrument that produces these images is the *weather radar.*

The development of radar has given meteorologists an important tool to probe storm systems that may be up to a few hundred kilometers away. All radar units have a transmitter that sends out short pulses of radio waves. The specific wavelengths that are used depend on the objects the user wants to detect. When radar is used to monitor precipitation, wavelengths between 3 and 10 centimeters are employed.

FIGURE 5-26 This standard rain gauge is fitted with metal slats that serve as a windscreen to minimize the undercatch that results because of windy conditions. *(Photo by Bobbé Christopherson)*

These wavelengths can penetrate small cloud droplets but are reflected by larger raindrops, ice crystals, or hailstones. The reflected signal, called an *echo,* is received and displayed on a TV monitor. Because the echo is "brighter" when the precipitation is more intense, modern radar is able to depict not only the regional extent of the precipitation but also the rate of rainfall. Figure 5–27 is a typical radar display in which colors show precipitation intensity. As you will see in Chapters 10 and 12, weather radar can also measure the rate and direction of storm movement.

Students Sometimes Ask…

What places in the United States receive the most snowfall?

Despite the impressive lake-effect snowstorms recorded in cities such as Buffalo and Rochester, New York, the greatest accumulations of snow generally occur in the mountainous regions of the western United States. The record for a single season goes to Mount Baker ski area north of Seattle, Washington, where 2896 centimeters (1140 inches) of snow fell during the winter of 1998–1999.

Intentional Weather Modification

Intentional weather modification is deliberate human intervention to influence atmospheric processes that constitute the weather—that is, to alter the weather for human purposes. This desire to change the weather is nothing new. From earliest recorded times people have used prayer, wizardry, dances, and even black magic in attempts to alter the weather.

During the American Civil War, rainfall seemed to increase following some battles, leading to experiments in which cannons were fired into clouds to trigger more rain. These experiments and many others proved unsuccessful. However, by the nineteenth century, smudge pots, sprinklers, and wind machines were used successfully to fight frost.

Weather-modification strategies fall into three broad categories. The first employs energy to forcefully alter the weather. Examples are the use of intense heat sources or the mechanical mixing of air (such as by helicopters) to disperse fog at some airports.

The second category involves modifying land and water surfaces to change their natural interaction with the lower atmosphere. One often discussed but untried example is the blanketing of a land area with a dark substance. The additional solar energy absorbed by this dark surface would warm the layer of air near the surface and encourage the development of updrafts that might aid cloud formation.

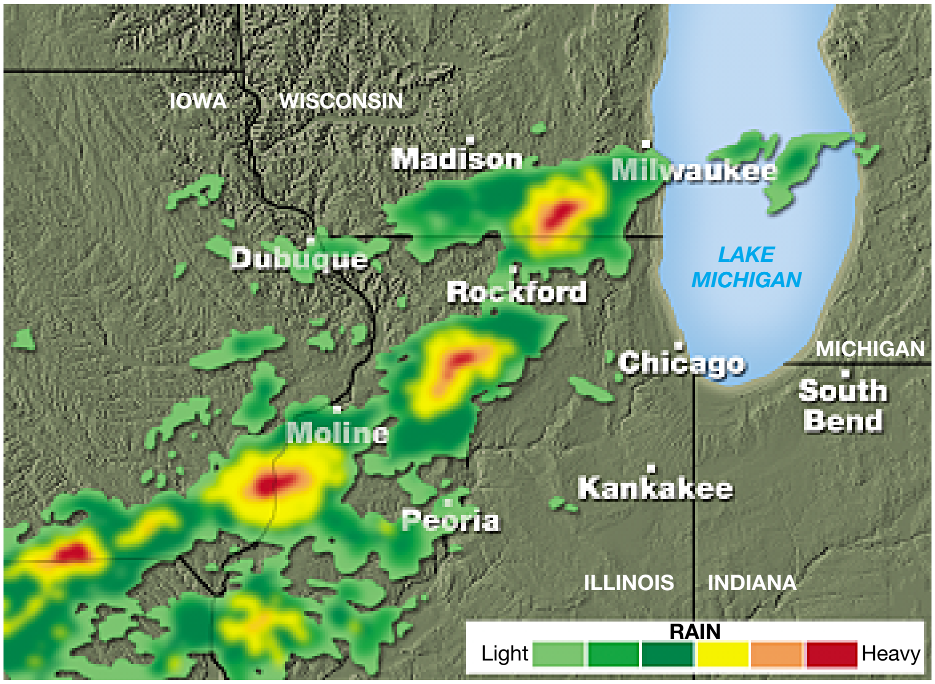


FIGURE 5-27 Doppler radar display commonly seen on The Weather Channel and local TV weathercasts. Colors indicate different intensities of precipitation. Note the band of heavy precipitation extending from northerneastern Iowa to Milwaukee, Wisconsin.

The third category involves triggering, intensifying, or redirecting atmospheric processes. The seeding of clouds with agents such as dry ice (frozen carbon dioxide) and silver iodide to stimulate precipitation is the primary example. Because **cloud seeding** sometimes seems to show promising results and is a relatively inexpensive technique, it has been a primary focus of modern weather-modification technology.

Cloud Seeding

The first breakthrough in weather modification came in 1946 when Vincent J. Schaefer discovered that dry ice, dropped into a supercooled cloud, spurred the growth of ice crystals. Recall that once ice crystals form in a supercooled cloud, they grow larger at the expense of the remaining liquid cloud droplets and, on reaching a sufficient size, fall as precipitation.

Later it was learned that silver iodide could also be used for cloud seeding. The similarity in the structure of silver iodide crystals and ice crystals accounts for silver iodide's ability to initiate ice crystal growth. Thus, unlike dry ice, which simply chills the air, silver iodide crystals act as freezing nuclei. Because silver iodide can be more easily delivered to clouds from burners on the ground or from aircraft, it is a better alternative than dry ice (Figure 5–28).

If cloud seeding is to trigger precipitation, certain atmospheric conditions must exist. Clouds must be present, for seeding cannot create clouds. Also, a portion of the cloud must be supercooled—it must be made of liquid droplets below 0°C (32°F) in temperature.

One type of cloud seeding assumes that cold cumulus clouds are deficient in freezing nuclei and that adding them will stimulate precipitation. The object is to produce just enough ice crystals so they will grow large enough (via the Bergeron process) to fall as precipitation. Overseeding will simply produce billions of ice crystals that are too tiny to fall.

Seeding of winter clouds that form along mountain barriers (orographic clouds) has been tried repeatedly. These clouds are thought to be good candidates for seeding because only a small percentage of the water that condenses in cold orographic clouds actually falls as precipitation. The idea is to increase the winter snowpack, which melts and runs off during warmer months and is collected in reservoirs for irrigation and hydroelectric power generation. Since 1977 Colorado's Vail and Beaver Creek ski areas have used this method to increase winter snows.

In recent years the seeding of warm convective clouds with hygroscopic (water-seeking) particles has received renewed attention. The interest in this technique arose

FIGURE 5-28 Cloud seeding using silver iodide flares is one way that freezing nuclei are supplied to clouds. *(Courtesy of University Corporation for Atmospheric Research/National Science Foundation/National Center for Atmospheric Research)*

when it was discovered that a pollution-belching paper mill near Nelspruit, South Africa, seemed to be triggering precipitation. Flying through clouds near the paper mill, research aircraft collected samples of the particulate matter emitted from the mill. It turned out that the mill was emitting tiny salt crystals (potassium chloride and sodium chloride), which rose with updrafts into the clouds. Because these salts attract moisture, they quickly form large cloud droplets, which grow into raindrops by the collision–coalescence process. Ongoing experiments being conducted over the arid landscape of northern Mexico are attempting to duplicate this process by seeding clouds using flares mounted on airplanes that spread hygroscopic salts. Although the results of these studies are promising, conclusive evidence that such seeding can increase rainfall over economically significant areas is not yet available.

More than two dozen countries around the globe have weather modification programs, mainly rainfall enhancement. China appears to have the greatest number of projects, including efforts in cloud dispersal, which they hope to employ for the 2008 Beijing Olympics. Other projects are aimed at bringing drought relief and hail suppression to a large part of central China.

In the United States, over 50 weather modification projects are currently underway in 10 states. Some of the most promising results come from western Texas, where researchers estimate a 10 percent increase in rainfall from silver iodide–seeded clouds compared to unseeded ones.

In summary, researchers are gaining confidence that precipitation can be enhanced by seeding supercooled clouds. Further, the use of large hygroscopic particles to seed warm convective clouds appears to hold promise, although the processes involved are poorly understood. However, because these studies have been limited in scope, the economic viability of cloud seeding remains uncertain. The major outcome of the last five decades of cloud-seeding experimentation has been the sobering realization that even the simplest weather events are exceedingly complex and not yet fully understood.

Fog and Cloud Dispersal

One of the most successful applications of cloud seeding involves spreading dry ice, particles of solid carbon dioxide at temperatures of −78°C (−108°F), into layers of supercooled fog or stratus clouds to disperse them and thereby improve visibility. Airports, harbors, and foggy stretches of interstate highway are obvious candidates. Such applications trigger a transformation in cloud composition from supercooled water droplets to ice crystals. The ice crystals then settle out, leaving an opening in the cloud or fog (Figure 5–29). Initially the ice crystals are too small to fall to the ground, but as the Bergeron process proceeds and they grow at the expense of the remaining water droplets, and as turbulent air disperses them, they can grow large enough to produce a snow shower. The snowfall is light, and visibility almost always improves. Often a large hole is opened in the stratus clouds or supercooled fog.

FIGURE 5-29 Effects produced by seeding a cloud deck with dry ice. Within one hour a hole developed over the seeded area. *(Photo courtesy of E. J. Tarbuck)*

The U.S. Air Force has practiced this technology for many years at airbases, and commercial airlines have used this method at selected foggy airports in the western United States. The possibility of opening large holes in winter clouds to increase the solar radiation reaching the ground in northerly locations has been discussed, but little experimentation has followed.

FIGURE 5-30 Hail damage to a soybean field north of Sioux Falls, South Dakota. *(AP/Wide World Photos)*

BOX 5-5 The Hail Cannons of Europe

Some of history's more interesting efforts at weather modification have focused on suppressing hail. During the 1500s, village priests often rang church bells and called for prayers to shield nearby farms from hail. Near the turn of the twentieth century, serious attempts at hail suppression in Europe involved the firing of cannons into developing thunderstorms. It was thought that the formation of hailstones could be prevented by injecting smoke particles as condensation nuclei into the developing clouds.

These "hail cannons" were vertical muzzle-loading mortars that resembled huge megaphones. The one shown in Figure 5–F weighed 9000 kilograms (10 tons), was 9 meters (30 feet) tall, and pivoted in all directions. When fired, these cannons produced a loud whistling noise and a large smoke ring that rose to a height of about 300 meters.

During a two-year test of hail cannons in Austria, no hail was observed. At the same time, nearby provinces suffered severe hail damage. Believing from this that hail cannons were effective, these devices spread to other areas in Europe where crops of great value, such as vineyards, frequently experienced hail losses. Soon much of Europe acquired "cannon fever," and by 1899 over 2000 cannons were in use in Italy alone. However, the hail cannons proved to be ineffective, and the practice was abandoned during the next decade.

FIGURE 5-F Around 1900, cannons like this fired smoke particles into thunderstorms to prevent the formation of hail. However, hail shooting proved to be ineffective, and the practice was abandoned after a decade. *(Photo courtesy of J. Loreena Ivens, Illinois State Water Survey)*

It is interesting to note, however, that by the 1960s, Russian scientists were experimenting with a similar approach to hail suppression. Their experiments employed rockets and artillery shells to carry freezing nuclei into the clouds. However, like earlier efforts at hail suppression, the Russian attempts were not much more effective than ringing church bells.

Modern attempts at hail suppression have introduced silver iodide crystals into storm clouds to interrupt the formation and growth of hailstones. It is assumed that each of these crystals, acting as a freezing nucleus, attracts a portion of the cloud's water supply and thereby increases the competition for the available supercooled water droplets. With a diminished supply of supercooled water droplets, hailstones cannot grow large enough to be destructive.

Because of dramatic crop and property losses, hail-suppression technology has been the focus of many field and laboratory studies. The results, however, have been mixed at best. In Russia during the 1960s, scientists used rocket and artillery shells to carry freezing nuclei to the clouds, and they claimed to have extraordinary success.

In the United States during the 1970s, the federal government established the National Hail Research Experiment in northeastern Colorado. This experiment included a randomized seeding test to verify the Russian experience. An analysis of the data collected after three years revealed no statistically significant difference in the occurrence of hail between the seeded and nonseeded clouds, cutting short the planned five-year experiment.

Unfortunately, most fog does not consist of supercooled water droplets. The more common "warm fogs" are more expensive to combat because seeding will not diminish them. Successful attempts at dispersing warm fogs have involved mixing drier, warmer air from above into the fog, or heating the air. When the layer of fog is very shallow, helicopters have been used. By flying just above the fog, the helicopter creates a strong downdraft that forces drier air toward the surface, where it mixes with the saturated foggy air.

At some airports where warm fogs are common, it has become more usual to heat the air and thus evaporate the fog. A sophisticated thermal fog-dissipation system, called Turboclair, was installed in 1970 at Orly Airport in Paris. It uses eight jet engines in underground chambers along the upwind edge of the runway. Although expensive to install, the system is capable of improving visibility for about 900 meters along the approach and landing zones.

Hail Suppression

Hail causes serious crop loss and property damage in many parts of the world (Figure 5–30). Consequently, hail-suppression efforts date from classical Greece to the present. A

(a)

(b)

FIGURE 5-31 Two common frost-prevention methods. (a) Sprinklers distribute water, which releases latent heat as it freezes on citrus. (b) Wind machines mix warmer air aloft with cooler surface air. *(Photos by (a) Bruce Borich/Silver Image Photo Agency, Inc. and (b) Christi Carter/Grant Heilman Photography, Inc.)*

major attempt in Europe near the turn of the twentieth century actually involved firing cannons at thunderstorms (see Box 5–5).

One of the newest attempts to suppress hail-storm damage comes from a Canadian company called HailStop. This company has developed machines that produce 120-decibel sound waves that are fired into storm clouds at 6-second intervals. The intent is to disrupt the hail cycle and decrease the size of the stones or even eliminate them. Although all methods of hail suppression remain unproved, the car manufacturer Nissan is using the HailStop system at one of its plants in Jackson, Mississippi.

Frost Prevention

Frost, the fruit grower's plight, occurs when the air temperature falls to 0°C (32°F) or below. Thus, frost conditions are dependent on temperature and need not be accompanied by deposits of ice crystals (called *white frost*), which only form if the air becomes saturated.

A frost hazard is produced by two conditions: when a cold air mass moves into a region or when sufficient radiation cooling occurs on a clear night. Frost associated with an invasion of cold air is characterized by low daytime temperatures and long periods of freezing conditions that inflict widespread crop damage. By contrast, frost induced by radiation cooling is strictly a nighttime phenomenon that tends to be confined to low-lying areas. Obviously, the latter phenomenon is much easier to combat.

Several methods of frost prevention are being used with varying success. They either conserve heat (reduce the heat lost at night) or add heat to warm the lowermost layer of air.

Heat-conservation methods include covering plants with insulating material, such as paper or cloth, or generating particles that, when suspended in air, reduce the rate of radiation cooling. *Smudge fires*, which produce dense black smoke, have been used to fill the air with carbon particles. Generally, this method has proved unsatisfactory. In addition to polluting the air, the carbon particles impede daytime warming by reducing the solar radiation that can reach the surface.

Warming methods employ water sprinklers, air-mixing techniques, and/or orchard heaters. Sprinklers (Figure 5–31a) add heat in two ways: first, from the warmth of the water and, more important, from the latent heat of fusion released when the water freezes. As long as an ice-water mixture remains on the plants, the latent heat released will keep the temperature from dropping below 0°C (32°F).

Air mixing works best when the air temperature 15 meters (50 feet) above the ground is at least 5°C (9°F) warmer than the surface temperature. By using a wind machine, the warmer air aloft is mixed with the colder surface air (Figure 5–31b).

FIGURE 5-32 Orchard heaters used to prevent frost damage to pear trees, Hood River, Oregon. *(Photo by Bruce Hands/The Image Works)*

Orchard heaters probably produce the most successful results (Figure 5–32). However, because as many as 30 to 40 heaters per acre are required, fuel cost can be significant.

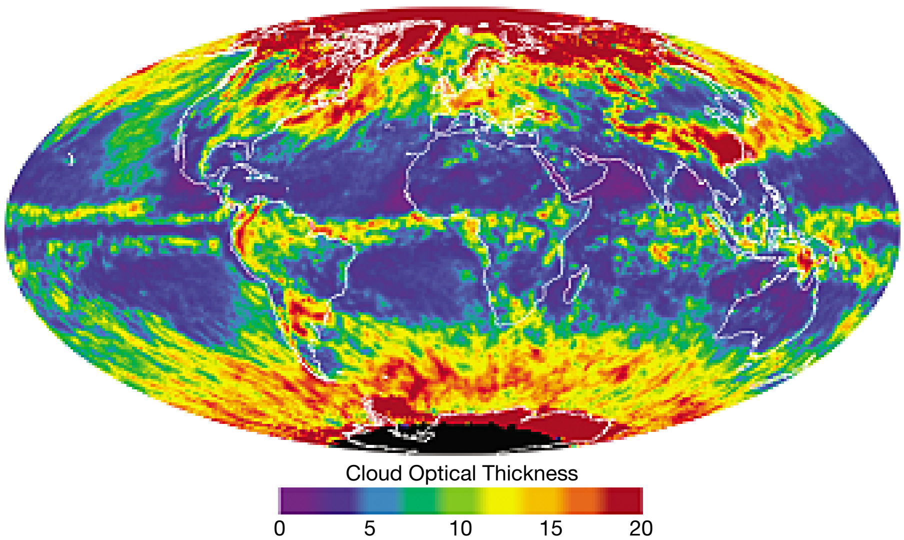
Understanding the Role of Clouds in the Climate System

Views of Earth from space show that clouds are abundant (see Figure 1-11, p. 13). Covering up to 75 percent of our planet at any given time, clouds play a prominent role in determining how much sunlight reaches Earth's surface and how much is reflected back to space. Furthermore, the amount and type of cloud cover strongly influences the amount of heat that escapes the surface in the form of longwave radiation. In short, clouds play a central role in Earth's climate system.

Recently a new tool has become available that will help researchers better understand and predict climate change. The false-color image shown in Figure 5-33 shows a one-month composite of cloud optical thickness measured by Moderate-resolution Imaging Spectroradiometer (MODIS). Optical thickness is a measure of how much solar radiation is able to penetrate the atmosphere. Areas shown in red and yellow indicate very cloudy skies, whereas areas that are green and light blue show moderately cloudy skies. Regions with little or no cloud cover appear dark blue.

MODIS is one of five sensors aboard NASA's *Terra* satellite. In addition to determining cloud thickness, it can determine whether a cloud is composed of ice or liquid water (or both), and it can estimate the size of cloud particles. This instrument is one more tool that will help scientists better understand the complex workings of Earth's climate system.

FIGURE 5-33 This false-color image shows a one-month composite of cloud optical thickness measured for April 2001. Optical thickness is a measure of how much solar radiation penetrates the atmosphere. *(Data from NASA)*



Chapter Summary

- *Condensation* occurs when water vapor changes to a liquid. For condensation to take place, the air must be saturated and there must be a surface on which the vapor can condense. In the air above the ground, tiny particles known as *cloud condensation nuclei* serve as the surfaces on which water vapor condenses.
- *Clouds*, visible aggregates of minute droplets of water or tiny crystals of ice, are one form of condensation. Clouds are classified on the basis of two criteria: form and height. The three basic cloud forms are *cirrus* (high, white, and thin), *cumulus* (globular, individual cloud masses), and *stratus* (sheets or layers). Cloud heights can be either *high*, with bases above 6000 meters (20,000 feet); *middle*, from 2000 to 6000 meters; or *low*, below 2000 meters (6500 feet). Based on the two criteria, 10 basic cloud types, including *cirrostratus, altocumulus,* and *stratocumulus*, are recognized.
- *Fog*, generally considered an atmospheric hazard, is a cloud with its base at or very near the ground. Fogs formed by cooling include *radiation fog* (from radiation cooling of the ground and adjacent air), *advection fog* (when warm and moist air flows over a cold surface), and *upslope fog* (created when air moves up a slope and cools adiabatically). Those formed by the addition of water vapor are *steam fog* (when water vapor evaporates from a warm water body and condenses in cool air above) and *frontal fog* (when warm air that is lifted over colder air generates precipitation that evaporates as it descends and saturates the air near the surface).
- *Dew* is the condensation of water vapor on objects that have radiated sufficient heat to lower their temperature below the dew point of the surrounding air. *White frost (hoar frost)* forms when the dew point of the air is below freezing.
- For precipitation to form, millions of cloud droplets must somehow coalesce into drops large enough to sustain themselves during their descent. The two mechanisms that have been proposed to explain this phenomenon are: the *Bergeron process*, which produces precipitation from cold clouds primarily in the middle latitudes, and the warm-cloud process most associated with the tropics called the *collision–coalescence process.*
- The two most common and familiar forms of precipitation are *rain* (drops of water that fall from a cloud and have a diameter of at least 0.5 millimeter) and *snow* (precipitation in the form of ice crystals or, more often, aggregates of ice crystals). Other forms include *sleet* (falling small particles of ice that are clear to translucent), *glaze* (formed when supercooled raindrops turn to ice on colliding with solid objects), *hail* (hard, rounded pellets or irregular lumps of ice produced in large cumulonimbus clouds), and *rime* (a deposit of ice crystals formed by the freezing of supercooled fog or cloud droplets on objects whose surface temperature is below freezing).
- Rain, the most common form of precipitation, is probably the easiest to measure. The most common instruments used to measure rain are the *standard rain gauge,* which is read directly, and the *tipping bucket gauge* and *weighing gauge,* both of which record the amount and intensity of rain. The two most common measurements of snow are depth and water equivalent. Although the quantity of water in a given volume of snow is not constant, a general ratio of 10 units of snow to 1 unit of water is often used when exact information is not available.
- *Intentional weather modification* is deliberate human intervention to influence atmospheric processes that constitute the weather. Weather modification falls into three categories: (1) the use of energy to forcefully alter the weather, (2) modifying land and water surfaces to change their natural interaction with the lower atmosphere, and (3) triggering, intensifying, or redirecting atmospheric processes. The focus of intentional weather modification using modern weather technology is on *cloud seeding, fog and cloud dispersal, hail suppression,* and *frost prevention.*

Vocabulary Review

advection fog (p. 140)
Bergeron process (p. 145)
cirrus (p. 133)
cloud condensation nuclei (p. 132)
clouds (p. 132)
cloud seeding (p. 158)
clouds of vertical development (p. 133)
collision–coalescence process (p. 147)
cumulus (p. 133)
dew (p. 143)
fog (p. 139)
freezing nuclei (p. 145)
freezing rain (p. 151)
frontal or precipitation fog (p. 142)
frost (p. 161)
glaze (p. 151)
hail (p. 151)
high clouds (p. 133)
hydrophobic nuclei (p. 133)
hygroscopic nuclei (p. 132)
intentional weather modification (p. 157)
low clouds (p. 133)
middle clouds (p. 133)
radiation fog (p. 139)
rain (p. 150)
rime (p. 155)
sleet (p. 151)

Review Questions

1. Clouds are classified on the basis of two criteria. Name them.
2. Why are high clouds always thin in comparison to low and middle clouds?
3. Which cloud types are associated with the following characteristics: thunder, halos, precipitation, hail, mackerel sky, lightning, and mares' tails?
4. What do layered clouds indicate about the stability of the air? What do clouds of vertical development indicate about the stability of air?
5. What is the importance of condensation nuclei?
6. Distinguish between clouds and fog.
7. List five types of fog and discuss how they form.
8. What actually happens when a radiation fog "lifts"?
9. Identify the fogs described in the following situations.
   a. You have stayed the night in a motel and decide to take an early morning swim. As you approach the heated swimming pool, you notice a fog over the water.
   b. You are located in the western Great Plains, and the winds are from the east and fog is extensive.
   c. You are driving through hilly terrain during the early morning hours and experience fog in the valleys but clearing on the hills.
10. Why is there a relatively high frequency of dense fog along the Pacific Coast?
11. Describe the steps in the formation of precipitation according to the Bergeron process. Be sure to include (a) the importance of supercooled cloud droplets, (b) the role of freezing nuclei, and (c) the difference in saturation vapor pressure between liquid water and ice.
12. How does the collision–coalescence process differ from the Bergeron process?
13. If snow is falling from a cloud, which process produced it? Explain.
14. Describe sleet and glaze and the circumstances under which they form. Why does glaze result on some occasions and sleet on others?
15. How does hail form? What factors govern the ultimate size of hailstones?
16. Although an open container can serve as a rain gauge, what advantages does a standard rain gauge provide?
17. How do recording rain gauges work? Do they have advantages over a standard rain gauge?
18. Describe some of the factors that could lead to an inaccurate measurement of rain or snow.
19. Why are silver iodide crystals used to seed supercooled clouds?
20. If cloud seeding is to have a chance of success, certain atmospheric conditions must exist. Name them.
21. How do frost and white frost differ?
22. Describe how smudge fires, sprinkling, and air mixing are used in frost prevention.
23. List three factors that contribute to greater precipitation in and downwind of cities.

Problems

1. Suppose that the air temperature is 20°C (68°F) and the relative humidity is 50 percent at 6:00 P.M., and that during the evening the air temperature drops but its water vapor content does not change. If the air temperature drops 1°C (1.8°F) every two hours, will fog occur by sunrise (6:00 A.M.) the next morning? Explain your answer. (*Hint:* The data you need are found in Table 4–1, p. 105.)

2. By using the same conditions as in Problem 1, will fog occur if the air temperature drops 1 degree every hour? If so, when will it first appear? What name is given to fog of this type that forms because of surface cooling during the night?

3. Assuming the air is still, how long would it take a large raindrop (5 mm) to reach the ground if it fell from a cloud base at 3000 meters? (See Table 5–3, p. 148.) How long would a typical raindrop (2 mm) take if it fell from the same cloud? How about a drizzle drop (0.5 mm)?

4. Assuming the air is still, how long would it take for a typical cloud droplet (0.02 mm) to reach the ground if it fell from a cloud base at 1000 meters? (See Table 5–3) It is very unlikely that a cloud droplet would ever reach the ground, even if the air were perfectly still. Can you explain why?

5. What is the volume of a small raindrop that is 1000 μm diameter (1 mm diameter)? (*Hint:* See Box 5–2.)

6. A large raindrop 5000 μm (5 mm) in diameter is 100 times the diameter of a large cloud droplet (50 μm in diameter). How many times greater is the volume of a large raindrop than a cloud droplet? (*Hint:* See Box 5–2.)

7. What is the area of the "bottom" of a falling drop of 1 mm diameter?

8. How many times greater is the "bottom" area of a falling 5-mm drop?

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