GLOBAL EDITION

Geosystems

An Introduction to Physical Geography

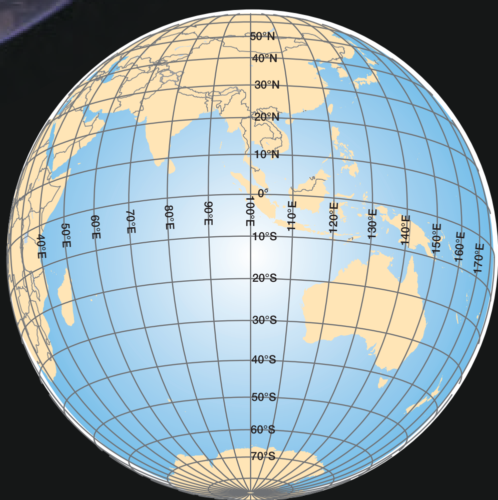
NINTH EDITION

Robert W. Christopherson • Ginger H. Birkeland

ALWAYS LEARNING

PEARSON

Eastern Hemisphere



stability. Such temperature measurements are made daily with *radiosonde* instrument packages carried aloft by helium-filled balloons at thousands of weather stations (see Figure HD 3e on page 107 for an example from Antarctica.)

The *normal lapse rate*, introduced in Chapter 3, is the average decrease in temperature with increasing altitude, a value of 6.4 C°/1000 m (3.5 F°/1000 ft). This rate of temperature change is for still, calm air, and it can vary greatly under different weather conditions. In contrast, the *environmental lapse rate (ELR)* is the actual lapse rate at a particular place and time. It can vary by several degrees per thousand meters.

Two generalizations predict the warming or cooling of an ascending or descending parcel of air. *An ascending parcel of air tends to cool by expansion*, responding to the reduced pressure at higher altitudes. In contrast, *descending air tends to heat by compression*. These mechanisms of cooling and heating are adiabatic. *Diabatic* means occurring with an exchange of heat; **adiabatic** means occurring without a loss or gain of heat—that is, without any heat exchange between the surrounding environment and the vertically moving parcel of air. Adiabatic temperature changes are measured with one of two specific rates, depending on moisture conditions in the parcel: dry adiabatic rate (DAR) and moist adiabatic rate (MAR). These processes are illustrated in Figure GIA 7.

Dry Adiabatic Rate The **dry adiabatic rate (DAR)** is the rate at which "dry" air cools by expansion as it rises or heats by compression as it falls. "Dry" refers to air that is less than saturated (relative humidity is less than 100%). The average DAR is 10 C°/1000 m (5.5 F°/1000 ft).

To see how a specific example of dry air behaves, consider an unsaturated parcel of air at the surface with a temperature of 27°C (81°F), shown in Figure GIA 7.1b. It rises, expands, and cools adiabatically at the DAR, reaching an altitude of 2500 m (approximately 8000 ft). What happens to the temperature of the parcel? Calculate the temperature change in the parcel, using the dry adiabatic rate:

$$(10\ \text{C}^\circ/1000\ \text{m}) \times 2500\ \text{m} = 25\ \text{C}^\circ \text{ of total cooling}$$
$$(5.5\ \text{F}^\circ/1000\ \text{ft}) \times 8000\ \text{ft} = 44\ \text{F}^\circ \text{ of total cooling}$$

Subtracting the 25 C° (44 F°) of adiabatic cooling from the starting temperature of 27°C (81°F) gives the temperature in the air parcel at 2500 m as 2°C (36°F).

In Figure GIA 7.2b, assume that an unsaturated air parcel with a temperature of –20°C at 3000 m (24°F at 9800 ft) descends to the surface, heating adiabatically. Using the dry adiabatic lapse rate, we determine the temperature of the air parcel when it arrives at the surface:

$$(10\ \text{C}^\circ/1000\ \text{m}) \times 3000\ \text{m} = 30\ \text{C}^\circ \text{ of total warming}$$
$$(5.5\ \text{F}^\circ/1000\ \text{ft}) \times 9800\ \text{ft} = 54\ \text{F}^\circ \text{ of total warming}$$

Adding the 30 C° of adiabatic warming to the starting temperature of –20°C gives the temperature in the air parcel at the surface as 10°C (50°F).

Moist Adiabatic Rate The **moist adiabatic rate (MAR)** is the rate at which an ascending air parcel that is moist, or saturated, cools by expansion. The average MAR is 6 C°/1000 m (3.3 F°/1000 ft). This is roughly 4 C° (2 F°) less than the dry adiabatic rate. From this average, the MAR varies with moisture content and temperature and can range from 4 C° to 10 C° per 1000 m (2 F° to 5.5 F° per 1000 ft). (Note that a descending parcel of saturated air warms at the MAR as well, because the evaporation of liquid droplets, absorbing sensible heat, offsets the rate of compressional warming.)

The cause of this variability, and the reason that the MAR is lower than the DAR, is the latent heat of condensation. As water vapor condenses in the saturated air, latent heat is liberated, becoming sensible heat, thus decreasing the adiabatic rate. The release of latent heat may vary with temperature and water-vapor content. The MAR is much lower than the DAR in warm air, whereas the two rates are more similar in cold air.

Stable and Unstable Atmospheric Conditions

The relationship of the DAR and MAR to the environmental lapse rate, or ELR, at a given time and place determines the stability of the atmosphere over an area. In turn, atmospheric stability affects cloud formation and precipitation patterns, some of the essential elements of weather.

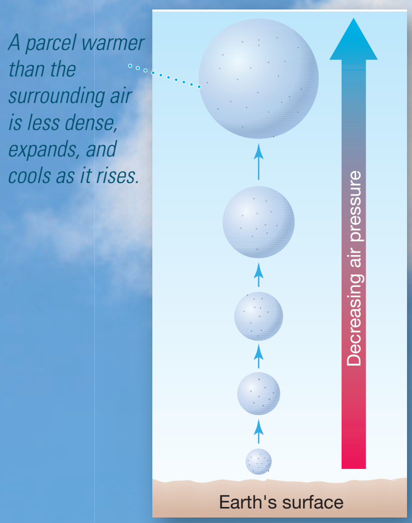
Temperature relationships in the atmosphere produce three conditions in the lower atmosphere: unstable, conditionally unstable, and stable. For the sake of illustration, the three examples in Figure 7.14 begin with an air parcel at the surface at 25°C (77°F). In each example, compare the temperatures of the air parcel and the surrounding environment. Assume that a lifting mechanism, such as surface heating, a mountain range, or weather fronts, is present to get the parcel started (we examine lifting mechanisms in Chapter 8).

Given unstable conditions in Figure 7.14a, the air parcel continues to rise through the atmosphere because it is warmer (less dense and more buoyant) than the surrounding environment. Note that the environmental lapse rate in this example is 12 C°/1000 m (6.6 F°/1000 ft). That is, the air surrounding the air parcel is cooler by 12 C° for every 1000-m increase in altitude. By 1000 m (about 3300 ft), the rising air parcel has cooled adiabatically by expansion at the DAR from 25° to 15°C, while the surrounding air cooled from 25°C at the surface to 13°C. By comparing the temperature in the air parcel and the surrounding environment, you see that the temperature in the parcel is 2 C° (3.6 F°) warmer than the surrounding air at 1000 m. *Unstable* describes this condition because the less-dense air parcel will continue to lift.

Eventually, as the air parcel continues rising and cooling, it may achieve the dew-point temperature, saturation, and active condensation. This point where saturation begins is the *lifting condensation level* that you see in the sky as the flat bottoms of clouds.

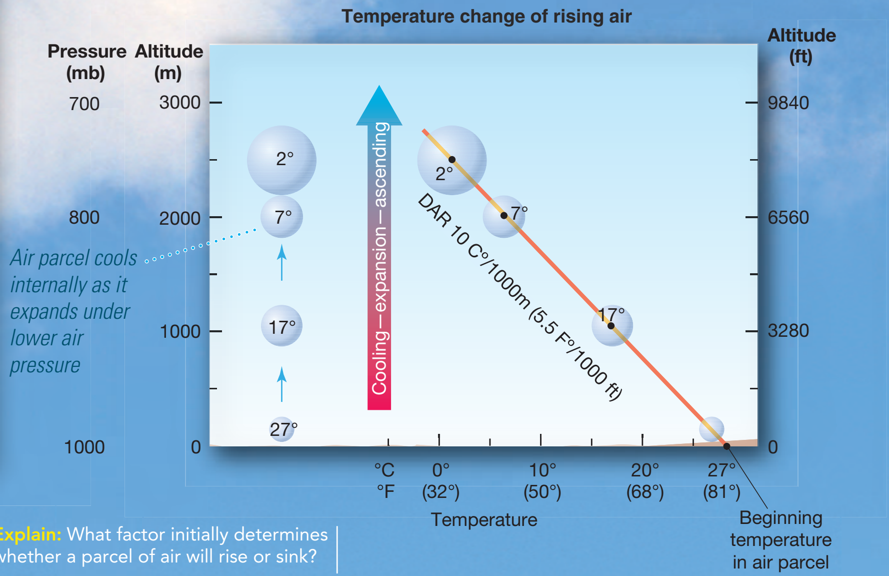
Two forces act on a parcel of air: an upward buoyant force and a downward gravitational force. A parcel's temperature and density determine its buoyancy and whether it will rise, sink, or remain in place. Because air pressure decreases with altitude, air expands as it rises (GIA 7.1a) and is compressed as it sinks (GIA 7.2a). At the same time, its temperature changes due to adiabatic cooling or heating. In an adiabatic process, there is no loss or gain of heat. The temperature change occurs when air rises, expands, and cools (GIA 7.1b) or when air sinks, is compressed, and warms (GIA 7.2b).

7.1a COOLING BY EXPANSION



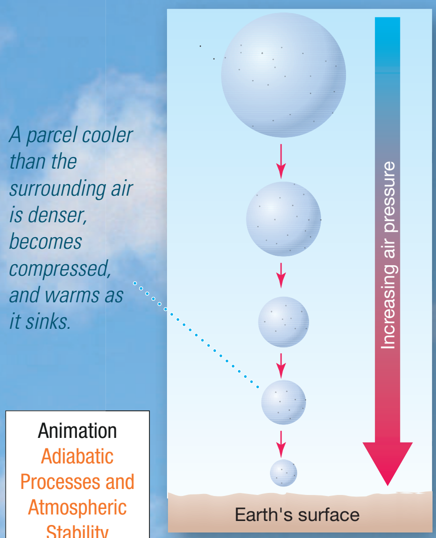
7.1b ADIABATIC COOLING

Temperature cools as pressure falls and altitude increases. The temperature change depends on the relative humidity of the parcel. Rising air that is "dry" (relative humidity less than 100 percent) cools at the *dry adiabatic rate* (DAR) of about 10 C° per 1000 m (5.5 F° per 1000 ft).



Explain: What factor initially determines whether a parcel of air will rise or sink?

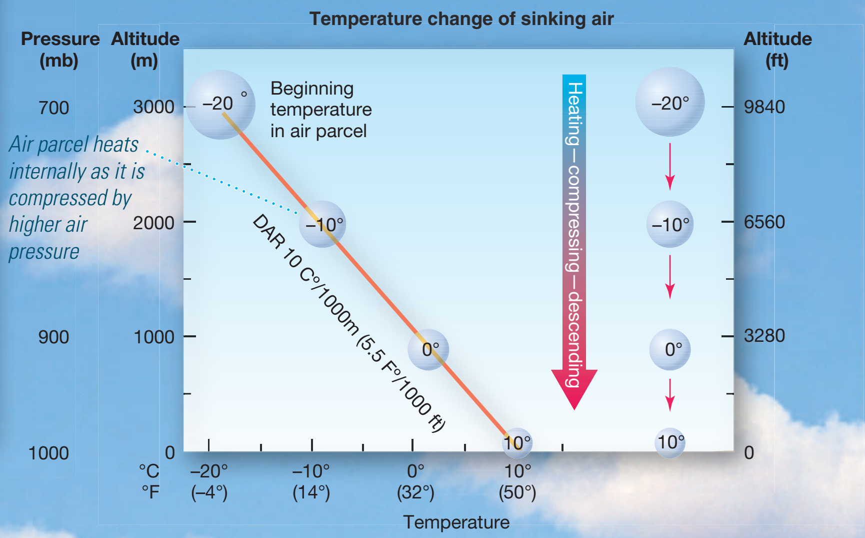
7.2a HEATING BY COMPRESSION



Animation
Adiabatic Processes and Atmospheric Stability

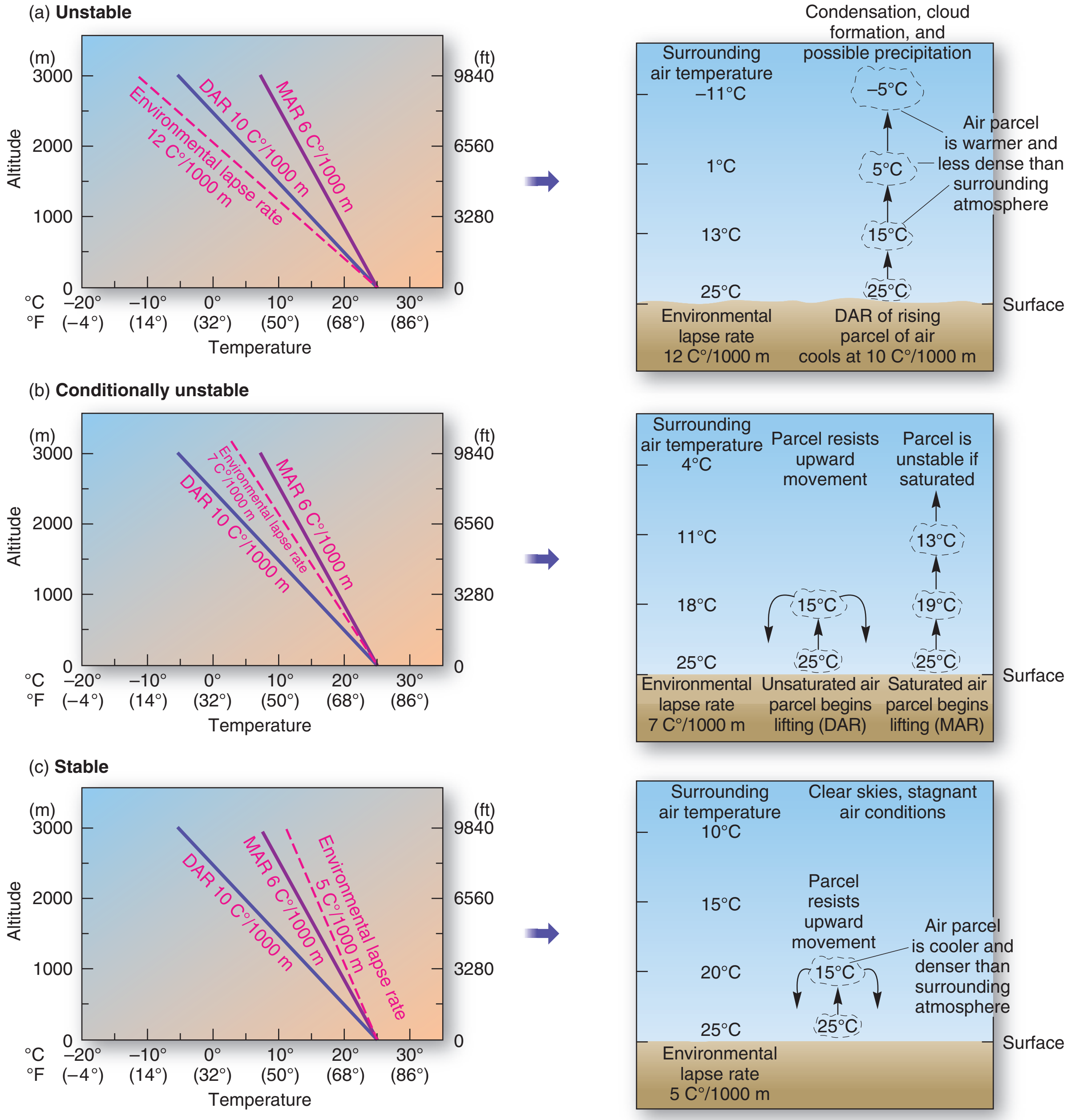
7.2b ADIABATIC HEATING

Temperature warms as pressure increases and altitude decreases. Sinking air that is "dry" warms at the dry adiabatic rate.



GEOquiz

1. **Explain:** Why does the temperature of a parcel of air change as it rises or sinks?
2. **Calculate:** A parcel of air at the surface has a temperature of 25° C (77° F). If the parcel rises and cools at the dry adiabatic rate, what is its temperature at 730 m (2400 ft)?



MG™ Animation Atmospheric Stability

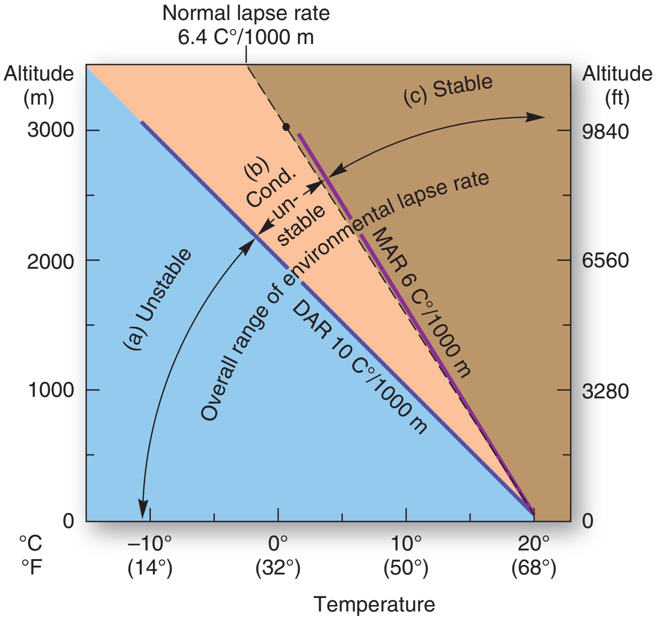
▲**Figure 7.14 Stability—three examples.** Specific examples of (a) unstable, (b) conditionally unstable, and (c) stable conditions in the lower atmosphere. Note the response to these three conditions in the air parcel on the right side of each diagram.

The example in Figure 7.14c shows stable conditions resulting when the ELR is only 5 C°/1000 m (3 F°/1000 ft). An ELR of 5 C°/1000 m is less than both the DAR and the MAR, a condition in which the air parcel has a lower temperature (is more dense and less buoyant) than the surrounding environment. The relatively cooler air parcel tends to settle back to its original position—it is *stable*. The denser air parcel resists lifting, unless forced by updrafts or a barrier, and the sky remains generally cloud-free. If clouds form, they tend to be stratiform (flat clouds) or cirroform (wispy), lacking vertical development. In regions experiencing air pollution, stable conditions in the atmosphere worsen the pollution by slowing exchanges in the surface air.

If the ELR is somewhere between the DAR and the MAR, conditions are neither unstable nor stable. In Figure 7.14b, the ELR is measured at 7 C°/1000 m. Under these conditions, the air parcel resists upward movement, unless forced, if it is less than saturated. But if the air parcel becomes saturated and cools at the MAR, it acts unstable and continues to rise.

One example of such conditionally unstable air occurs when stable air is forced to lift as it passes over a mountain range. As the air parcel lifts and cools to the dew point, the air becomes saturated and condensation begins. Now the MAR is in effect, and the air parcel behaves in an unstable manner. The sky may be clear and without a cloud, yet huge clouds may develop over a nearby mountain range.

The overall relationships between the dry and moist adiabatic rates and environmental lapse rates that produce conditions of stability, instability, and conditional instability are summarized in Figure 7.15. We will work



▲**Figure 7.15 Temperature relationships and atmospheric stability.** The relationship between dry and moist adiabatic rates and environmental lapse rates produces three atmospheric conditions: (a) unstable (ELR exceeds the DAR), (b) conditionally unstable (ELR is between the DAR and MAR), and (c) stable (ELR is less than the DAR and MAR).

more with lapse rates and adiabatic cooling and heating in Chapter 8, where we discuss atmospheric lifting and precipitation.

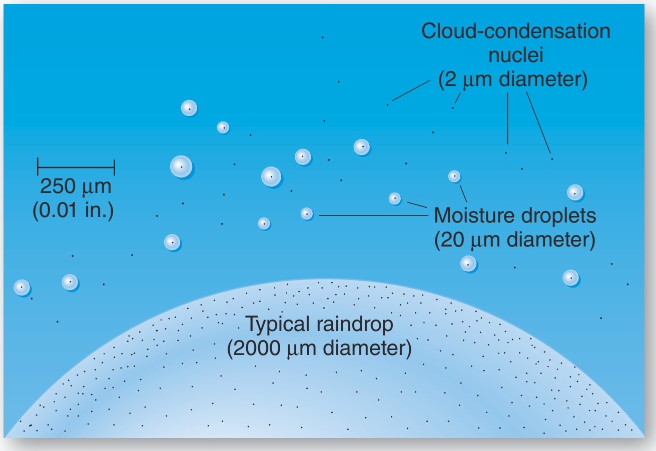
Clouds and Fog

Clouds are more than whimsical, beautiful decorations in the sky; they are fundamental indicators of overall conditions, including stability, moisture content, and weather. They form as air becomes saturated with water. Clouds are the subject of much scientific inquiry, especially regarding their effect on net radiation patterns, as discussed in Chapters 4 and 5. With a little knowledge and practice, you can learn to "read" the atmosphere from its signature clouds.

Cloud Formation Processes

A **cloud** is an aggregation of tiny moisture droplets and ice crystals that are suspended in air and are great enough in volume and concentration to be visible. Fog, discussed later in the chapter, is simply a cloud in contact with the ground. Clouds may contain raindrops, but not initially. At the outset, clouds are a great mass of moisture droplets, each invisible without magnification. A **moisture droplet** is approximately 20 μm (micrometers) in diameter (0.002 cm, or 0.0008 in.). It takes a million or more such droplets to form an average raindrop with a diameter of 2000 μm (0.2 cm, or 0.078 in.), as shown in Figure 7.16.

As an air parcel rises, it may cool to the dew-point temperature and 100% relative humidity. (Under certain conditions, condensation may occur at slightly less or more than 100% relative humidity.) More lifting of the air parcel cools it further, producing condensation of water vapor into water. Condensation requires **cloud-condensation nuclei**, microscopic particles that always are present in the atmosphere.



▲**Figure 7.16 Moisture droplets and raindrops.** Cloud-condensation nuclei, moisture droplets, and a raindrop enlarged many times—compared at roughly the same scale.

Continental air masses, discussed in Chapter 8, average 10 billion cloud-condensation nuclei per cubic meter. These nuclei typically come from dust, soot, and ash from volcanoes and forest fires, and particles from burned fuel, such as sulfate aerosols. The air over cities contains great concentrations of such nuclei. In maritime air masses, nuclei average 1 billion per cubic meter and include sea salts derived from ocean sprays. The lower atmosphere never lacks cloud-condensation nuclei.

Given the presence of saturated air, cloud-condensation nuclei, and cooling (lifting) mechanisms in the atmosphere, condensation will occur. Two principal processes account for the majority of the world's raindrops and snowflakes: the *collision–coalescence process*, involving warmer clouds and falling coalescing droplets, and the *Bergeron ice-crystal process*, in which supercooled water droplets evaporate and are absorbed by ice crystals that grow in mass and fall.

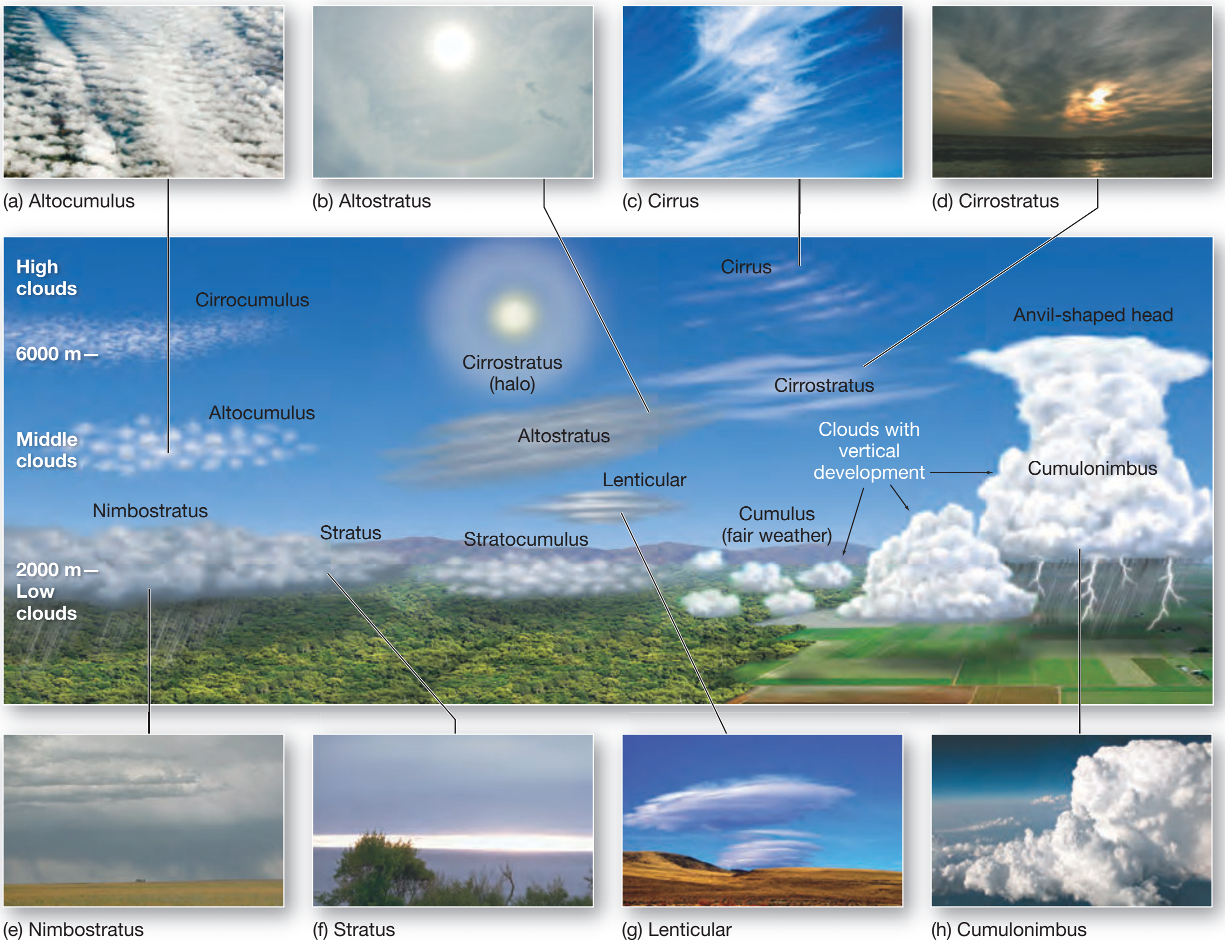
Cloud Types and Identification

In 1803, English biologist and amateur meteorologist Luke Howard established a classification system for clouds and coined Latin names for them that we still use. A sampling of cloud types according to this system is presented in Table 7.1 and Figure 7.17.

Altitude and *shape* are key to cloud classification. Clouds occur in three basic forms—flat, puffy, and wispy—and in four primary altitude classes. Flat and layered clouds with horizontal development are classed as *stratiform*. Puffy and globular clouds with vertical development are *cumuliform*. Wispy clouds, usually quite high in altitude and made of ice crystals, are

TABLE 7.1 Cloud Classes and Types

Cloud Class, Altitude, and Midlatitude Composition	Cloud Type	Description
Low clouds (C_L) • Up to 2000 m (6500 ft) • Water	Stratus (St)	Uniform, featureless, gray clouds that look like high fog.
	Stratocumulus (Sc)	Soft, gray, globular cloud masses in lines, groups, or waves.
	Nimbostratus (Ns)	Gray, dark, low clouds with drizzling rain.
Middle clouds (C_M) • 2000–6000 m (6500–20,000 ft) • Ice and water	Altostratus (As)	Thin to thick clouds, with no halos. Sun's outline just visible through clouds on a gray day.
	Altocumulus (Ac)	Clouds like patches of cotton balls, dappled, and arranged in lines or groups.
High clouds (C_H) • 6000–13,000 m (20,000–43,000 ft) • Ice	Cirrus (Ci)	"Mares' tails" clouds—wispy, feathery, with delicate fibers, streaks, or plumes.
	Cirrostratus (Cs)	Clouds like veils, formed from fused sheets of ice crystals, having a milky look, with Sun and Moon halos.
	Cirrocumulus (Cc)	Dappled clouds in small white flakes or tufts. Occur in lines or groups, sometimes in ripples, forming a "mackerel sky."
Vertically developed clouds • Near surface to 13,000 m (43,000 ft) • Water below, ice above	Cumulus (Cu)	Sharply outlined, puffy, billowy, flat-based clouds with swelling tops. Associated with fair weather.
	Cumulonimbus (Cb)	Dense, heavy, massive clouds associated with dark thunderstorms, hard showers, and great vertical development, with towering, cirrus-topped plume blown into anvil-shaped head.



▲**Figure 7.17 Principal cloud types and special cloud forms.** Cloud types according to form and altitude (low, middle, high, and vertically developed). [(a), (b), (c), and (h) by Bobbé Christopherson; (d), (e), and (f) by author; (g) by Judy A. Mosby.]