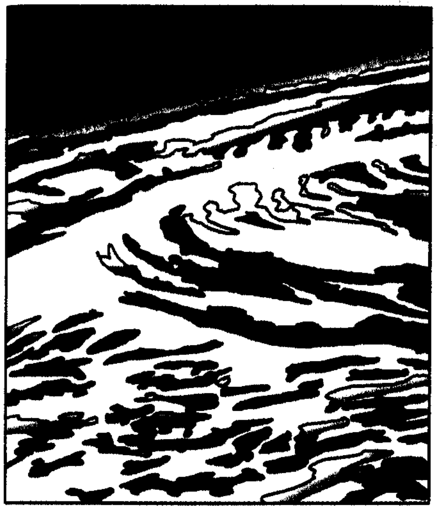
CHAPTER 4



The Atmospheric Circulation System

Key Questions

- Why does air move?
- Are the movements of the winds random across the surface of the Earth, or do they follow regular patterns?
- What implications do these circulatory systems have for global climate?
- What other factors govern the geographic and seasonal distributions of temperature and rainfall?

Chapter Overview

Earth's climate is a central theme of ours. We focus on the role climate plays in the Earth system and explain how Earth's climate works, how climate has changed through time, and how it may change in the future. An important element of Earth's climate is the atmospheric circulation. In Chapter 3 we described the global energy budget and showed that if we average the radiation fluxes around the globe and over a few years there is a balance. Earth emits as much energy as it receives, aside from the issue of anthropogenic increases in the greenhouse effect. If we look at regions smaller than the globe and over time periods of less than a year, however, the situation is very different. There is a significant imbalance in the distribution of energy at various latitudes: The tropics receive a surplus of radiative energy, whereas the poles run a deficit. This imbalance causes an equator-to-pole temperature gradient that results in density and pressure differences in the atmosphere. The density and pressure differences cause air to move in a global-scale pattern of wind belts, which are modified by Earth's rotation and by the distribution of land and water. The net effect is to restore the latitudinal energy balance by moving surplus energy away from the tropics to cancel out the deficit at the poles. In the process, energy is used to evaporate water from the land and ocean surfaces, water vapor is carried by wind, and energy is released when the vapor condenses to form clouds. Thus, there are close interactions between the transport of energy and of water by means of circulating air. In other words, Earth's atmospheric circulation has a direct impact on the global distributions of temperature and precipitation.

The Global Circulatory SubSystems

Anyone who has felt wind blow, watched clouds move, and seen rain fall is aware that large parts of the Earth system are in constant motion. Even the continents and oceans, despite their apparent permanence, are continuously moving. The island of Iceland in the North Atlantic, for example, is spreading, and its two sides are moving away from each other fast enough to be measured by today's instruments. Although these movements may sometimes appear random, they form part of a well-ordered circulation of energy and matter throughout the Earth system.

Like the circulatory system of humans (part of the cardiovascular system), Earth's circulatory subsystems work to maintain the planet in a thermal and chemical balance. The human circulatory system transports dissolved gases, nutrients, and hormones throughout the body; carries away waste products; helps regulate the acidity of body fluids; and is a vital part of the body's thermoregulatory system, carrying warm blood from one area to another. Although the human circulatory system is not an exact analogy to Earth's circulatory subsystems, these systems do have much in common. Essential gases and nutrients are transported throughout the Earth system, and waste products are removed from their area of production. All of Earth's circulatory subsystems act in some way to help regulate the global temperature: The winds and ocean currents redistribute the energy received from the Sun, and the motions of the solid Earth redistribute carbon and help regulate the CO_2 level of the atmosphere. The circulations within the solid Earth are discussed in Chapter 7; here and in Chapter 5 we examine those circulations that occur within the fluid part of the Earth system: the atmosphere and oceans.

The purpose of this chapter is to describe the major characteristics of the atmospheric circulation, to explain why they occur, and to illustrate the way in which they affect the transport of energy and materials around the globe. In Chapter 3 we described the energy input and output from the Earth system as a whole; now we take that system apart and examine some of its internal workings—specifically those related to climate. In doing so, we have two primary objectives. The first is to explain why weather and climate vary across the globe. The second is to emphasize that because of the internal workings of Earth's climate system, the response to global-scale processes and changes may not be uniform around the globe. Organized movements of the atmosphere occur over many different time and space scales. These movements range from centimeter-scale swirls, or *eddies,* to global-scale motions of the wind belts. All of these are important in one way or another, but we limit our discussion to processes that are global in extent and that have the greatest influence on the transport of energy and mass through the Earth system. One of Earth's most important constituents is water. Cycling continuously among the atmosphere, the oceans, and the land surface, water carries with it energy, dissolved nutrients, and other matter—all vital for maintaining an environment suitable for life.

In the same way that the functioning of the cardiovascular system in the human body ultimately depends on the ability of the heart to keep pumping, the functioning of Earth's circulatory subsystems rely on several different pumps. Each of these pumps drives a different circulatory mechanism, and each works at a different speed. Over shorter time scales (years to decades), the most important pump is found in the tropical oceans. This pump is responsible for the movements of the air and the surface ocean over most of the globe. The energy source that drives this pump is radiation from the Sun. Over longer time scales (about 1,000 years), a second pump drives the deep-ocean circulation (Chapter 5). The ultimate energy source is again the Sun. The pump operating over the longest time scales (millions of years) is radioactive decay and the production of heat in Earth's interior. This pump causes the movements of the continents, which we discuss in Chapter 7.

All these circulation subsystems play a vital role in the operation of the Earth system. We know that in humans the cardiovascular system can maintain stability only if the blood keeps moving. Similarly, the Earth system can maintain stability only as long as its circulatory subsystems continue to function. The long-term pump (that is, the processes of internal heat production and plate tectonics) ceased to function on Mars. As we will see in a later chapter, the planet's inability to support an environment suitable for life may be at least partly a result of the failure of this circulation mechanism.

The Atmospheric Circulation

Recall from Chapter 3 that the troposphere is the lowermost layer of the atmosphere. Most of the processes we are interested in take place in the troposphere, so we limit our discussion here to that layer. Although the circulation of the stratosphere plays a role in the depletion of stratospheric ozone, we will save that discussion for Chapter 17.

The Movement of Air

Air moves over Earth's surface because there are horizontal differences in pressure. Air also moves vertically either because it is forced to rise mechanically (e.g., when it encounters a mountain range) or because there are changes in *buoyancy.* **Buoyancy** is the tendency of an object to float in a fluid. Buoyancy is controlled by differences in *density* between the object and the fluid, where density is given by the mass of a substance within a unit volume. (The greater the mass within a given volume, the greater the density.) Ultimately, all of these horizontal and vertical movements (except those due to mechanical forces) can be attributed to differences in temperatures across the globe. To explain how these movements occur, we need to understand how pressure and density are related to temperature.

Vertical Movement. It is easiest to picture these relationships by thinking of vertical and horizontal movenents separately. Imagine the situation with a hot-air bal-oon. Remember from Chapter 3 that heating causes mol-cules to move faster. In this case, the faster the air nolecules move, the more they collide with each other nd with the interior of the balloon. These collisions exert force (i.e., air pressure) on the interior surface. If the alloon was a fixed container (one that could not expand), here would be an increase in the air pressure within the ontainer. Thus we see a connection between the tem-erature and pressure of a gas: As the temperature in-reases, the pressure increases. But the balloon *is* xpandable. As the pressure starts to increase, the air ushes outward on the interior of the balloon, causing it o expand. So in a balloon, it is the volume rather than he pressure that increases (see the Box "A Closer Look: he Relationships between Temperature, Pressure, and olume—The Ideal Gas Law").

If we begin with the balloon partially inflated, it will ontain a certain number of air molecules. As these are eated, the number of molecules does not change, but ey move faster, increasing the pressure on the interior f the balloon; this causes the balloon to expand. We now ave the same number of air molecules as before (the ass [m] hasn't changed), but they occupy a greater volume [V]. This means that the density of the air [ρ] must decrease ($\rho = m / V$). Because the air in the balloon is less dense than the air surrounding it, the balloon becomes *positively buoyant,* and it rises. The balloon will continue to rise until the density of the air outside the balloon matches that inside (*neutral buoyancy*). If the air in the balloon is more dense than the surrounding air, the balloon would have *negative buoyancy,* and it would sink. Exactly the same processes occur in the atmosphere when we heat the surface below a parcel (column) of air. The surface heats the parcel of air at the bottom of the column; the air parcel expands, its density decreases, and the parcel rises through the air column. Cooling a parcel of air higher in the column causes it to become more dense than the surrounding air, and the parcel sinks.

Horizontal Movement. How do horizontal movements occur? We saw that warmer air has a lower density than cooler air. If we consider two adjacent columns of air, one warmer than the other, the cooler column would have a greater density than the warmer column. This difference in density would cause the air to move horizontally from the region of higher-density cool air to the region of lower-density warmer air—the air moves down the den-

A CLOSER LOOK

and Volumes—The Ideal Gas Law

[illegible]

sity gradient. The atmospheric pressure is a force [**F**] determined by the mass [*m*] of the air column and the acceleration [**a**] due to gravity (remember Newton's Second Law of Motion: $\mathbf{F} = m\mathbf{a}$). Averaged globally and through time, the atmosphere exerts a pressure of 1013 mb on Earth's surface. Thus 1013 mb is considered to be one atmosphere of pressure (1 atm). The pressure decreases as you rise up in the atmosphere (because there is less air above you) until, at the top of the atmosphere, the pressure reduces to zero. The actual pressure recorded at any point on the surface or in the atmosphere, however, can be highly variable under different conditions of elevation and temperature. So, for adjacent columns of air with similar volumes, the colder high-density air has a higher atmospheric pressure. Hence, as you see on weather charts, air flows from high pressure regions to regions of low pressure.

From this discussion we can establish two important points that will help explain why air moves:

1. Air tends to move from an area of higher pressure to an area of lower pressure until the two pressures are equalized. In other words, air (wind) will move horizontally in the lower troposphere from higher to lower pressure. Pressure differences among air masses are typically related to the distribution of surface temperatures.
2. If an air mass is heated until its density is lower than that of its surroundings, the lower-density air will rise. This phenomenon is a form of convection. (We discussed this phenomenon in a more general sense in Chapter 3 when we demonstrated the convection of a fluid that is heated from below.) Conversely, if an air mass is cooled until its density is higher than that of the underlying air, it will sink. This phenomenon is referred to as **subsidence**.

The Driving Force: The Global Energy Distribution

We learned in Chapter 3 that the average global temperature is determined by the balance between the solar energy absorbed by Earth and the infrared radiation emitted to space. However, neither the radiation received from the Sun (our primary energy source) nor the infrared emission from Earth is distributed uniformly across Earth's surface. The incoming solar energy varies with latitude and with season, whereas the outgoing terrestrial radiation depends on the temperature of the surface and atmosphere at each location.

The distribution of the incoming solar radiation changes with latitude as a result of the change in surface area presented to the Sun's rays as Earth's surface curves (Figure 4-1). The energy from the Sun radiates outward in all directions; however, by the time the Sun's rays reach Earth, they are essentially parallel to each other. This means that the flux of solar energy passing perpendicularly through the plane *A-B* in Figure 4-1 will be the same at any point. For example, the three "beams" in the diagram are equal in solar flux when they pass through the plane. Because of the curvature of Earth, however, when these beams reach the top of Earth's atmosphere, the same amount of light is spread over a much larger area at the poles than at the equator. Consequently, each square meter of surface receives proportionate-

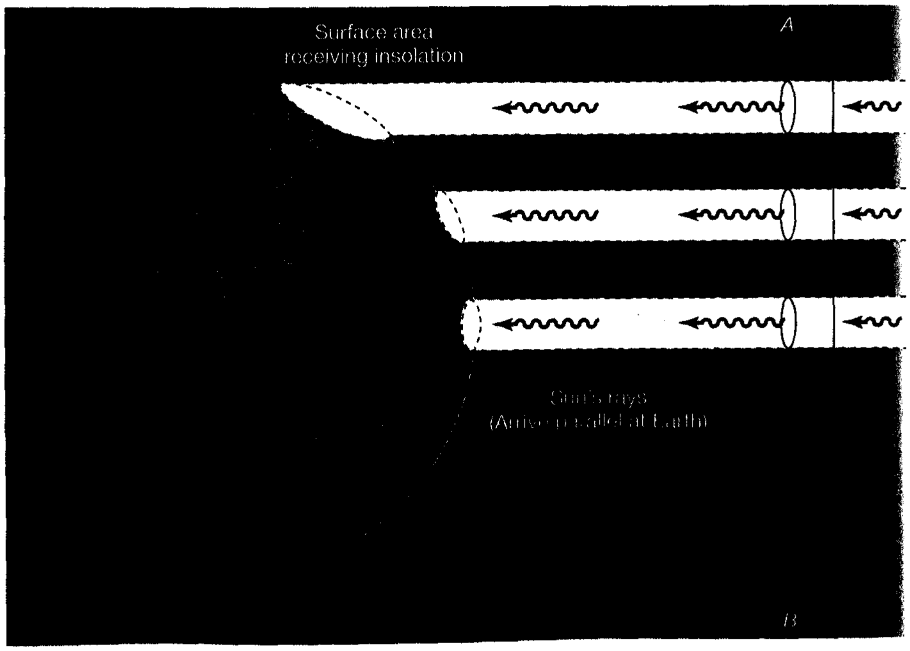


FIGURE 4-1

Variation of incoming solar energy with latitude. The radiation reaching Earth is spread over larger and larger areas as we move from the equator to the poles. Each square meter of the surface receives proportionately less energy as we move to higher latitudes. (From R.W. Christopherson. *Geosystems: An Introduction to Physical Geography,* 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

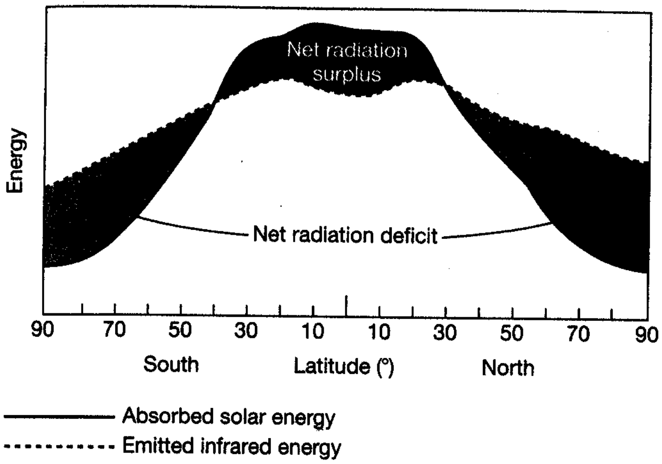


FIGURE 4-2

The distribution of absorbed solar and emitted infrared radiation with latitude. There is a surplus of energy in the tropics, where incoming radiation is greater than outgoing, and a deficit at high latitudes, where more radiation is emitted than is received.

ly less energy at the higher latitudes, and the incoming solar flux thus decreases from the equator toward the poles. (Recall the lightbulb and sheet of paper experiment in Chapter 3.)

The solar radiation absorbed at the surface follows the same general pattern, although the actual amount absorbed varies with cloud cover and atmospheric absorption. This equator-to-pole gradient in the energy absorbed at the surface exerts a primary control on Earth's climate. Figure 4-2 shows this gradient (solid curve) as a function of latitude (i.e., the amount averaged around each latitude band). As we might expect from the previous discussion, the maximum absorbed solar energy is found in the tropics, and the available solar energy decreases rapidly as we move toward the poles. This gradient in absorbed solar energy is the single most important control on temperature. More energy is generally available at the equator than at the poles, so we can assume that temperatures should be highest in the tropics and lowest at high latitudes. Figure 4-2 also shows the latitudinal distribution of infrared radiation emitted from Earth to space (dashed curve). The higher emissions in the tropics are a result of the high surface temperatures there and the correspondingly high temperature in the middle troposphere, from whence the outgoing radiation is emitted. Again, you can refer back to the discussion of the IR flux–temperature feedback described in Chapter 3.

The difference between the incoming solar radiation and the outgoing terrestrial radiation is referred to as *net radiation.* Referring again to Figure 4-2, note that the energy absorbed exceeds the energy emitted in the tropics (net radiation is positive); near the poles, the reverse is true (net radiation is negative). This distribution of available energy is a permanent feature of Earth's climate system. The gradient seems to imply that the tropics should get warmer while the poles get progressively colder. Clearly this does not happen; other processes must be operating to ensure an energy balance at each latitude. In reality, the latitudinal energy gradient produces atmospheric temperature and density differences that force the atmosphere to circulate, carrying warmer air toward the poles and colder air toward the equator. These circulations move energy from regions where there is a surplus to regions where there is a deficit. Most of what we experience as weather and climate is this response of the atmosphere to the unequal latitudinal distributions of energy.

The General Circulation of the Atmosphere

From our description of the energy distribution and our discussion of how air movements occur, we can build a picture of what we would expect the global-scale circulation of the atmosphere to look like. This circulation involves several characteristic features that we will discuss in turn. Taken together, these circulation features represent a negative feedback loop as the atmosphere responds to the temperature gradient by transferring energy latitudinally to reduce the gradient and restore an energy balance. The continuous addition of energy from the sun of course means that the energy distribution is never balanced.

Convergence. We begin with the heating in the tropics. The large solar input to the tropics heats the surface (primarily ocean), which in turn heats the overlying air. As we saw earlier, when heated from below, air will rise by convection. The tropical air near the surface rises, creating a low-pressure region there. But we saw that air tends to move horizontally from an area of higher pressure to an area of lower pressure. Thus, the rising air is replaced by surface air moving equatorward into the region of low pressure from regions of higher pressure (Figure 4-3). The merging of air masses that are moving inward toward a low-pressure region is called **convergence**. The converging air masses that meet at the tropics and rise make up the **intertropical convergence zone (ITCZ)**.

The surface heating produces evaporation in addition to convection. As the convecting air rises, it cools, and the evaporated water (water vapor) in the convecting column condenses to form clouds. As a consequence, the

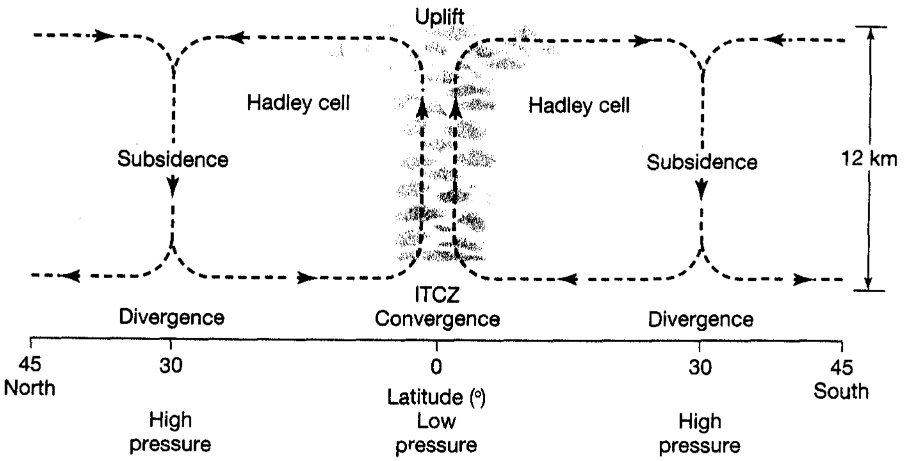


FIGURE 4-3
Convergence, divergence, and the Hadley circulation in the tropics. There is a Hadley cell on either side of the intertropical convergence zone (ITCZ), located over the equator. Rising air in the ITCZ is replaced by inflowing air (convergence) at the surface. Outflowing air (divergence) in the upper troposphere sinks at about 30° N and 30° S, completing the circulations in the two cells.

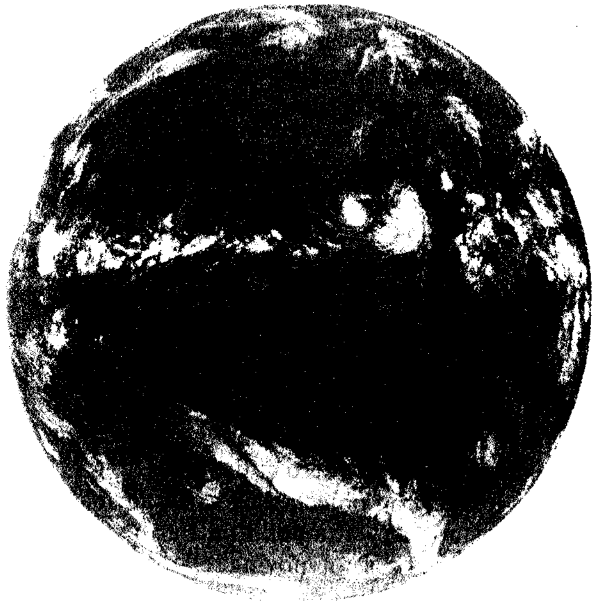
ITCZ is characterized by extensive areas of cloud cover and heavy precipitation. We talk more about evaporation, condensation, and rainfall later in the chapter.

Divergence. The top of the troposphere, located at about 12–15 km in the tropics, forms a barrier to further uplift. Remember that temperatures generally increase in the stratosphere and that the higher temperatures produce a stable structure that limits convection from below. The air that rises in the ITCZ, upon reaching this barrier, is forced to diverge poleward. **Divergence**, in this case, refers to the movement of air outward from a region in the atmosphere. This poleward-moving air subsides at about 30° N and 30° S latitude, replacing the air that is moving equatorward at the surface (Figure 4-3). The air warms as it sinks, which prevents condensation from occurring and clouds from forming. As a result, these regions are characterized by clear skies and low rainfall amounts. If you check an atlas, you will find that such areas coincide with some of the world's largest deserts (e.g., the Sahara and Arabian deserts and the Great Australian Desert). The subsiding air also leads to an area of high pressure and divergence at the surface.

Hadley Circulation. This pattern of air movement, with convergence occurring in the tropics and divergence and subsidence some 30° away in one large convection cell, is called **Hadley circulation**. This circulation pattern was named for George Hadley, the British meteorologist who first explained the phenomenon. The convection cells on either side of the equator, referred to as *Hadley cells*, represent the dominant north–south mode of circulation between 30° N and 30° S latitude. Note, however, that the Hadley cells—and the ITCZ—are not continuous around the globe. The circulation takes place in individual cells of rising and subsiding air, and the pattern is further broken up by land–ocean contrasts. The ITCZ is most obvious in the Atlantic and Pacific Oceans and is readily observed in satellite images such as that shown in Figure 4-4. The large-scale circulation in Southeast Asia and the Indian Ocean is dominated by the monsoon, which is described later in this chapter.

The convection cells in the ITCZ result directly from surface heating in the tropical oceans. In fact, although solar heating provides the fuel for tropospheric circulation, the actual pump that drives the circulation is the release of latent heat during convection. (We discussed latent-heat release in Chapter 3.) The energy of solar radiation, used to evaporate water from the ocean surface, is converted to latent heat, and the latent heat is released to the atmosphere in huge towers of convective cloud clusters within the ITCZ (Figure 4-5). It is this release of latent heat that pumps the air around each Hadley cell.

Midlatitude and High-Latitude Circulation. Thus far we have discussed the atmospheric circulation only between the equator and 30° N or S. What about atmospheric circulation from there to the poles? The very low temperatures at the poles, particularly in winter, result in increased air density near the surface and, thus, in higher pressures than occur in the tropics. The higher density and pressure lead to divergence and a general movement of cold air outward at the surface, that is, toward the equator. The divergence is accompanied by subsidence from above. The equatorward-moving cold air meets the warm air moving poleward from the subtropics, producing a zone of steep temperature gradients called the **polar front zone** at approximately 60° N and S latitude. The two air masses do not mix easily: The warm air is less dense than the cold air, which therefore sinks below the warm air when the two air masses meet (Figure 4-6). The polar front zone, therefore, slopes poleward with increasing altitude in the atmosphere. Note that, because of dynamic processes that come into play when air moves over a curved surface, this frontal zone forms a wavelike structure around the hemisphere. The actual latitude at which the front is located, therefore, varies from place to place.



GURE 4-4
ıtellite image of the eastern Pacific and Central America. These im-
es are obtained from geostationary satellites, which orbit over the
uator at an altitude of about 35,000 km and at an orbital speed that
eps pace with Earth's rotation; thus the satellite appears to remain
ationary over the same spot on the equator. This image was obtained
the National Oceanographic and Atmospheric Administration
OAA) during Northern Hemisphere summer. A line of convective
ouds marks the ITCZ just north of the equator. The clear areas to the
rth and south of the ITCZ mark the descending arms of the Hadley
lls. (GOES infrared image for 9 August, 1996, 21:00 UCT from the
S. National Oceanic and Atmospheric Administration website at
tp://wf.ncdc.noaa.gov/servlets/GoesBrowser/ Courtesy of NDAA/
tional Climatic Data Center.)

When we put Figures 4-3 and 4-6 together, we see an
ternating pattern of northward- and southward-moving
r at the surface (Figure 4-7). Such north–south move-
ent is called *meridional* circulation. If we look at Figure
-7 from above, we might expect to see a general pattern
f surface winds such as those depicted in Figure 4-8. We would expect surface winds to blow out of the high-pressure zones at the poles and at about 30° N and S, and to blow toward the low-pressure zones at the equator and at about 60° N and S. The actual pattern, however, is more complicated because winds tend to blow in east–west directions as well. Indeed, the east–west motions are considerably greater than the north–south motions. We know that differences in solar heating cause the equator-to-pole movement we have been discussing. What causes the east–west movements?

GURE 4-5
nvective towers in the ITCZ. Solar heating evaporates large
ounts of water from the tropical oceans. The air cools and con-
nses as it rises, releasing the energy used for evaporation as latent
at. The release of latent heat in these convective towers is the pump
t drives the Hadley circulation. (From NASA Science Source,
oto Researchers, Inc.)

The Coriolis Effect

East–west movements of surface winds are the result of the Coriolis effect. The **Coriolis effect** (named for Gaspard Gustav de Coriolis, the French mathematician who in 1835 proposed that the concept applies to surface winds) is the apparent tendency for a fluid (air or water) moving across Earth's surface to be deflected from its straight-line path. (Some texts refer to a *Coriolis force* in relation to this effect. This force, however, is only an apparent force due to the observer's frame of reference, not a real force due to an identifiable source, such as the gravitational pull of a planet.) Viewed from Earth, a north–south moving object appears to be deflected to the east or west. Viewed from space, the same object is in fact seen to move in a straight line. The apparent curve that we see is the result of our frame of reference—we normally view the object's movement from *within* the system.

The Coriolis effect applies to any object moving on a rotating body. To visualize this, let us first consider Earth rotating on its axis. The two vertical lines in Figure 4-9a represent the distance moved in a given time interval, and the arrows represent the rotation speed of Earth's sur-