Section 6.7

The Atmosphere

Our atmosphere does more than just provide the oxygen we breathe. This layer of gas helps to maintain the earth's surface temperature and shields us from both interplanetary debris and some of the sun's ultraviolet light. The atmosphere also contributes to the dynamic character of the earth's surface—it forms the weather, moves water about the globe, and creates the winds. In this section, we'll look at the origins and characteristics of these atmospheric phenomena.

Questions To Think About: *What heats the air and why does the air's temperature decrease with increasing altitude? What is the greenhouse effect and why does it matter how much carbon dioxide or ozone the air contains? Why do winds tend to blow from west to east across the United States? Why does the wind at the seashore tend to blow toward shore during the day and toward the water during the night? Why do hurricanes always swirl in the same direction in the northern hemisphere? Why is it calm in the center of a hurricane?*

Experiments To Think About: *Pay attention to the way winds blow and to changes in temperature with passing clouds or time of day. The winds are driven by differences in pressure. In general, regions of hot air are also regions of low pressure near the ground, so that winds flow toward hot regions.*

But there is another interesting experiment to try that will help you visualize how the earth's rotation affects winds. Find a playground merry-go-round or a similar rotating platform and roll a ball across its turning surface. As you stand on the ground nearby, you will see the ball travel in a straight line at a steady pace (constant velocity). Now get on the merry-go-round and roll the ball again. From your new vantage point, the ball will appear to curve to the right or left as it rolls. The direction of the curve depends on the merry-go-round's direction of rotation. This curvature isn't caused by a force—it's the result of viewing straight-line motion from an accelerating frame of reference. The turning earth is actually an accelerating frame of reference, too, and moving objects also appear to curve even though they travel at constant velocity. This type of curvature has enormous effects on the winds and the global air currents, as we'll soon see.

Earth's Temperature and the Greenhouse Effect

Despite variations with time, place, and season, the earth's surface temperature maintains a fairly constant average value of about 15 °C (59 °F). When America is experiencing night, Asia is experiencing day and vice versa. When the northern hemisphere is experiencing winter, the southern hemisphere is experiencing summer and vice versa. It all averages out.

To maintain this constant average temperature, the earth's heat flow must be balanced—the net flow of heat to the earth must be zero. If instead there were a net flow of heat to the earth, its average temperature would increase. And if there were a net flow of heat away from the earth, its average temperature would decrease. The earth maintains its constant average temperature of 15 °C by getting rid of heat just as quickly as that heat arrives. That way the earth's store of thermal energy never changes.

The earth's main source of heat is the sun and this heat reaches the earth mostly as electromagnetic radiation. Because the sun's surface temperature is

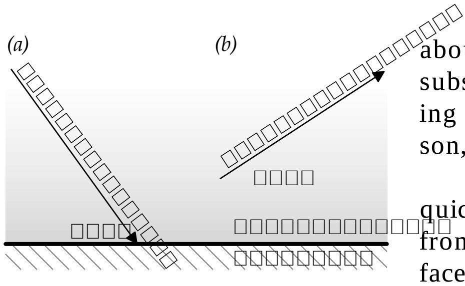

Fig. 6.7.1 - (*a*) Most thermal radiation from the 5500 °C sun is visible light and passes easily through the atmosphere to the ground. (*b*) This energy works its way up through the atmosphere and is radiated away into space as infrared light from an average altitude of about 5 km.

about 5500 °C, solar radiation is primarily visible light, although it also includes a substantial amount of infrared and ultraviolet light. The total solar power reaching the earth is about $1.73 \cdot 10^{17}$ W, or $1.73 \cdot 10^{17}$ J of heat each second. For comparison, the world's total electric generating capacity is roughly $3 \cdot 10^{12}$ W.

To keep its average temperature, the earth gets rid of thermal energy just as quickly. While about 34% of the sunlight is simply reflected or scattered back from the earth's surface and atmosphere, the rest is absorbed by the earth's surface and atmosphere, and must be eliminated by radiating it into the dark, empty space surrounding the earth. Because earth's surface and atmosphere are much colder than the sun, their thermal radiation is mostly infrared light.

If there were no atmosphere, the absorption and emission of thermal radiation would occur at the earth surface and its average surface temperature would be about –18 °C (0 °F). At that equilibrium temperature, the earth would radiate away heat as quickly as it arrived and its thermal energy wouldn't change.

But the atmosphere complicates this balance. The thermal radiation absorbed by the earth is primarily visible light and the thermal radiation emitted by the earth is primarily infrared light. While the atmosphere is nearly transparent to visible light, it absorbs and emits infrared light fairly well. As a result, the earth's surface isn't the principal source of the earth's thermal radiation—the atmosphere is.

Because the atmosphere is so nearly transparent to visible light, the average altitude at which the sun's thermal radiation is *absorbed* is almost ground level (Fig. 6.7.1*a*). However, because the atmosphere absorbs and emits infrared light fairly well, the average altitude at which the earth's thermal radiation is *emitted* is about 5 km above the earth's surface (Fig. 6.7.1*b*). This different between the average altitude at which thermal radiation reaches the earth and the average altitude at which thermal radiation leaves the earth makes the earth's surface warmer by about 33 °C, a phenomenon called the **greenhouse effect**.

To understand why this altitude difference makes the earth's surface warmer, we need to recognize two important facts. First, the air at an altitude of 5 km has a temperature of about –18 °C (0 °F)—the same temperature that the earth's surface would have if there were no atmosphere. In effect, air at this altitude is the source of the earth's thermal radiation and so must have the –18 °C (0 °F) temperature at which heat leaves the earth just as quickly as it arrives. If this air were hotter than –18 °C, the earth would lose heat too quickly and cool off, and if this air were colder than –18 °C, the earth would lose heat too slowly and warm up.

Second, humid air's temperature decreases by about 6.6 °C when it rises upward by 1 km. This effect, which we'll examine more carefully later in this section, reflects the decrease in temperature that occurs when dry air is allowed to expand into a region of lower pressure. Rising air encounters decreasing air pressure and expands, so its temperature drops. The presence of moisture in the air reduces this effect somewhat, but the temperature of the earth's atmosphere still decreases by about 6.6 °C per kilometer. Thus while the air at an altitude of 5 km is about –18 °C (0 °F), the temperature at sea level is about 33 °C higher or about 15 °C (59 °F).

Since life would be difficult at –18 °C, we are fortunate to have the greenhouse effect. However, too large a greenhouse effect could be a problem. If the atmosphere were to become even more effective at absorbing and emitting infrared light, the average altitude from which the earth's thermal radiation is emitted would move upward and the temperature at the earth's surface would increase. We want that altitude to stay about 5 km and not to rise to 6 km or more.

Just how effective the earth's atmosphere is at absorbing and emitting infrared light depends on its chemical makeup. Nitrogen and oxygen molecules, though extremely common in the atmosphere, are remarkably transparent to both infrared and visible lights. It's the less common gas molecules that allow air to absorb and emit infrared light and are thus **greenhouse gases**. While the principal greenhouse gas is water vapor, other gases such as carbon dioxide and methane (natural gas) are also important. The more of these gases there are in the atmosphere, the higher will be the average altitude from which the earth's thermal radiation is emitted and the warmer the earth's surface will become.

It is now fairly certain that the overproduction of greenhouse gases, notably carbon dioxide, is causing a gradual warming of the earth's surface. But the greenhouse effect alone isn't the only factor contributing to the earth's surface temperature and it's very difficult to predict what will ultimately happen if the atmosphere's carbon dioxide content continues to increase. Nonetheless, efforts are underway to slow the rate of increase in the air's content of greenhouse gases, just to be safe. (To see how changes in the greenhouse gases are studied, see ❐.)

❐ Determining the amounts of carbon dioxide and other constituents that were present in the air many years ago is a difficult task. Scientists look for samples of antique air trapped inside objects that were sealed on specific dates long ago. Among the objects studied by atmospheric archeologists are military uniform buttons. This research has shown that the carbon dioxide content of the earth's atmosphere has risen slowly but steadily since the beginnings of the industrial revolution.

CHECK YOUR UNDERSTANDING #1: Making the Most of Sunshine

A greenhouse gets quite warm inside, even during the winter. It's always warmer than the outside air. The greenhouse's glass coating absorbs and emits room temperature thermal radiation fairly well. Why does this glass coating raise the average temperature inside the greenhouse?

Warming the Air and Creating Wind

The air's tendency to absorb infrared radiation does more than simply raise the earth's average surface temperature. It also allows the earth's surface to transfer heat to the atmosphere. Because air is a terrible conductor of heat, little heat flows from the ground to the air by contact between the two. Instead, the main mechanism for warming the air is radiative heating from the earth's surface—infrared radiation from the ground is absorbed by greenhouse gases in the air and the air becomes hotter. Since water vapor is the main greenhouse gas and is concentrated near the ground, the lower atmosphere is heated more effectively than the upper atmosphere.

Because the air is heated from below, the earth's surface temperature has a profound impact on the air above it. Moist air above a hot region of land or water absorbs a great deal of heat while dry air above a cold region absorbs relatively little heat. These variations in heating rates are what cause winds.

To see how wind works, consider the air above a level region of the earth's surface. At first, let's imagine that the surface temperature is uniform across the entire region (Fig. 6.7.2*a*). In this case, the air on the east side of the region is identical to the air on the west side of the region. In each location, the air is hottest near the ground and its temperature decreases slowly with increasing altitude. The air pressure also begins at a certain value near the ground and decreases slowly with increasing altitude.

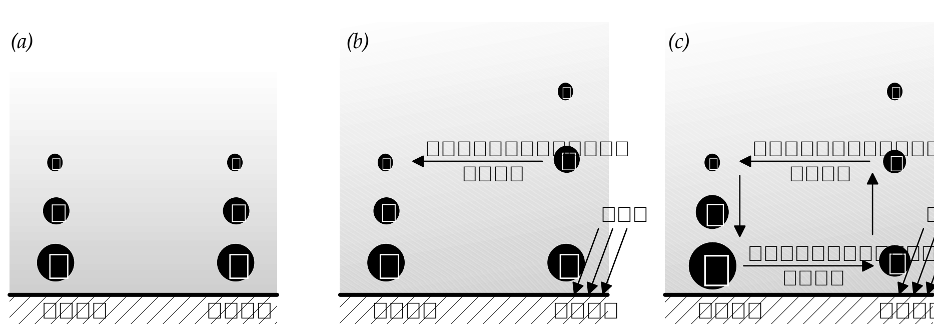

Fig. 6.7.2 - (*a*) When surface temperatures are equal, there are no winds. (*b*) But when the eastern ground becomes hot, the air above it expands upward. A high-altitude wind begins to blow toward the colder western side. (*c*) The addition weight of air on the western side increases the pressure near the ground and a low-altitude wind begins to blow toward the hotter eastern side. A convection cell is established.

So far, there is no wind because there are no horizontal imbalances in pressure. There is a vertical pressure imbalance but it serves to support the air against the downward force of gravity—without a vertical pressure imbalance, the atmosphere would fall. But a horizontal pressure imbalance would cause the air to accelerate horizontally toward the lower pressure. It would create wind.

Now, let's imagine that the rising sun begins to warm the ground only on the east side of the region. This hotter ground quickly warms the air above it. The hotter air expands, just as it does in a hot-air balloon, and the column of air over the east side becomes taller. Because the weight of the air column doesn't change, the air pressure at the ground remains the same. But the upward expansion of the air column slows the rate at which the air pressure decreases as the altitude increases. Since the air and its weight move upward, the pressure gradient associated with increasing altitude also moves upward.

This upward movement of air creates a horizontal pressure imbalance (Fig. 6.7.2*b*). Air far above the hotter eastern side has a higher pressure than corresponding air above the colder western side. High altitude air begins to accelerate toward the colder western side. In effect, the taller air column over the hotter ground acts to reduce its height by flowing toward the shorter air column over the colder ground. A high altitude wind begins to blow from the hotter eastern side to the colder western side.

But this high altitude wind reduces the mass of air above the hotter eastern side and increases the mass of air above the colder western side. As a result, air pressures near the ground begin to change. As the mass of air over the colder western side increases, so does its ground-level air pressure. A higher air pressure is needed to support the increased weight of the air overhead. Similarly, the air pressure at ground level in the hotter eastern side decreases because there is less weight to support.

Now a second wind begins to flow near the earth's surface. This surface wind flows from the colder western side to the hotter eastern side, accelerated in that direction by the ground-level pressure imbalance. Overall, there are two winds: one at high altitude that blows from the hotter side to the colder side and one at low altitude that blows from the colder side to the hotter side. At some intermediate altitude, there is no wind at all.

These two winds create an upward flow of air above the hotter eastern side and a downward flow of air above the colder western side, so the air circulates continuously. An air molecule starting near the ground on the eastern side travels upward, westward, downward, and eastward in an endless cycle. The winds are just the horizontal motions of a huge convection cell.

We have rediscovered convection, but on an atmospheric scale. Air rising above hot ground flows upward and then outward, carrying heat away from the hot ground toward the colder ground somewhere else. The missing air is replaced by a steady flow of colder air from surrounding areas. As usual, heat flows from the hotter region of earth's surface to the colder region and the mechanism of heat transfer is convection.

The winds themselves often contain large amounts of kinetic energy and this energy can be used to do useful tasks, including grinding grain and generating electricity. This wind energy originates as heat in the hotter region and is converted to work by the convection process. The atmosphere acts as a heat engine, moving heat from the hotter region of ground to the colder region of ground while converting a small portion of that heat into work. As usual, the second law of thermodynamics limits the amount of heat that can be converted into work. At best, the earth's winds convert only about 3% of the heat they carry into ordered energy. Nonetheless, there is a huge amount of energy in wind and it has only begun to be exploited for useful purposes.

The pressure differences that cause surface winds can be measured with *barometers*. By determining the air pressure near the ground, a barometer helps predict which way the wind will blow and even what weather it will bring. As we've seen, the expanded column of air above a hot portion of the earth's surface generally has a lower-than-normal air pressure at ground level and is traditionally called a "low." In contrast, the compressed air above a cold portion of the earth's surface usually has a higher-than-normal pressure at ground level and is called a "high." Knowing where highs and lows are located helps to predict wind direction because surface winds accelerate away from highs and toward lows.

❒ Monsoons are caused by a seasonal variation of the sea breeze. Summer heating of the land in Eastern Asia gives rise to giant sea breezes that bring water-laden air far into land from the surrounding oceans. The resulting rains occupy much of the summer months.

As we noted concerning the greenhouse effect, air's temperature changes as it rises or falls through the atmosphere. A portion of air descending to the ground is compressed by the increasing weight of the air above it. Just as in the automobile engine, it takes work to compress air and the result is hotter air. As work is done on the descending portion of air, its temperature increases. In our atmosphere, the temperature of dry air increases by about 10 °C for every kilometer of its descent. Similarly, a portion of dry air that rises away from the ground expands and does work on the air above it. Its temperature decreases by about 10 °C for every kilometer of its ascent. Moist air experiences smaller temperature changes of about 6 or 7 °C per kilometer. These changes in temperature are particularly important for winds that blow down out of mountains and thus experience rises in temperature because of their descent.

Daily or *diurnal* temperature changes give rise to repetitive winds. For example, daily heating and cooling cycles cause the land and sea breezes that occur near the seashore. Land heats up more rapidly than water so that in the morning, a surface sea breeze blows from the cooler water toward the warmer land. At night, the land cools off first and a surface land breeze blows from the cooler land toward the warmer water. Valley and mountain breezes are caused by a similar effect. As the sun rises, the mountainside warms first and a valley wind blows up the side of the mountain. At sunset, the mountainside cools first and a mountain breezes blows down the side of the mountain toward the warmer valley below. A similar seasonal effect produces monsoons (see ❒).

CHECK YOUR UNDERSTANDING #2: On the Edge
Why is a sea breeze usually strongest right at the shore?

Global Wind Patterns and the Coriolis Effect

The global wind patterns would be simple if the earth weren't rotating. Because the sun warms land and water near the earth's equators more than that near the earth's poles, there would be steady thermal winds between the equator and the two poles (Fig. 6.7.3). High altitude winds would blow from the hotter equator toward the colder poles while low altitude winds would return from the colder poles toward the hotter equator. There would always be a low over the equator and highs over both poles.

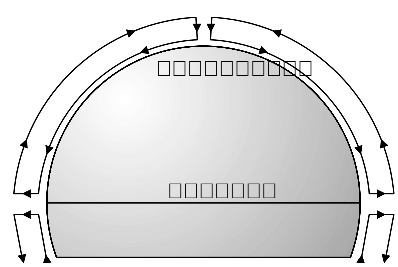

Fig. 6.7.3 - If the earth weren't rotating, thermal winds would extend from the hot equator to each of the colder poles. High altitude winds would blow toward the poles while surface winds would blow toward the equator.

But the earth does rotate and this rotation complicates the global wind patterns. The problem is caused by the **Coriolis effect**—because the earth rotates, an object moving freely across its surface appears to curve. Nothing is actually exerting a horizontal force on the object and it's actually traveling in a straight line. However, the turning earth is an accelerating frame of reference and straight paths may not appear straight from an accelerating reference frame.

To illustrate the Coriolis effect, imagine playing catch with your friend on a carousel (Fig. 6.7.4). Your friend is closer than you to the center of the carousel. If the carousel is stopped, you can easily toss the ball back and forth (Fig. 6.7.4*a*).

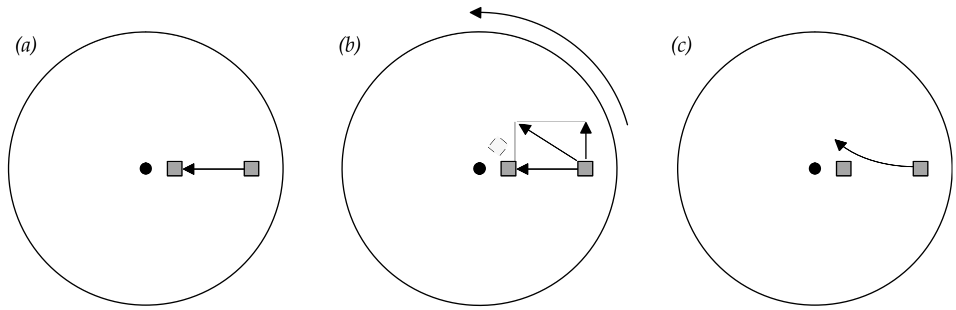

Fig. 6.7.4 - (*a*) If you throw a ball to a friend near the center of a stopped carousel, the ball travels in a straight line and your friend can catch it. (*b*) But if the carousel is turning counter-clockwise, the ball leaves your hand with a sideways component to its velocity and travels to the right of your friend (who has moved with the rotating carousel). (*c*) Viewed from your accelerating reference frame on the carousel, the ball appears to curve toward the right.

You simply aim at your friend and throw. However, if the carousel is turning counter-clockwise, you will have a much harder time throwing the ball so your friend can catch it. If you simply aim at your friend, the ball will miss (Fig. 6.7.4*b*). Because you are moving sideways at the moment you let go of the ball, you inadvertently give the ball a sideways component of velocity. Your friend is also moving sideways, but more slowly than you are because you are farther from the center of the carousel. As a result, the ball heads to the right of your friend. From your perspective on the turning carousel, you see the ball curve toward the right (Fig. 6.7.4*c*).

The ball's curved path is the result of your own accelerating frame of reference. The ball really travels in a straight line and you are the one who is actually curving. Still, it really looks like the ball is curving. This curved motion is sometimes attributed to the Coriolis "force," a fictitious force that appears in rotating frames of reference. To a person watching motion from a rotating frame of reference, the Coriolis "force" appears to cause moving objects to curve away from straight-line paths.

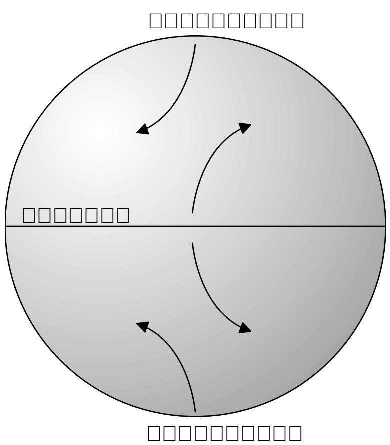

Fig. 6.7.5 - The earth rotates toward the east. As a result, objects in the northern hemisphere appear to curve toward the right and objects in the southern hemisphere appear to curve toward the left.

The Coriolis effect is also present for objects moving about the surface of the earth. Because the earth is rotating toward the east at about 15°/hour, the ground near the equator has an enormous eastward velocity of about 1670 km/hour. As you head north or south from the equator, you move closer to the earth's rotational axis and this eastward velocity decreases. Near the poles, very close to the earth's rotational axis, this eastward velocity is almost zero.

Just as in the carousel example, an object thrown from the equator directly toward the north pole will miss it. The object starts off with a 1670 km/hour eastward component to its velocity and this eastward motion causes it to drift eastward relative to the more slowly moving ground as it heads north toward the pole. According to someone standing on the ground, the object curves toward the right (Fig. 6.7.5).

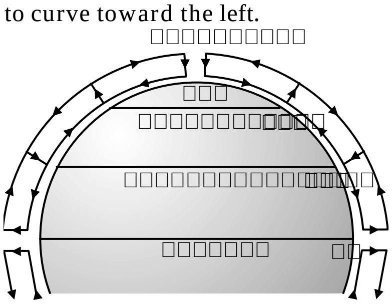

Fig. 6.7.6 - Because of the earth's rotation, the winds in the northern (and southern) hemisphere break up into three sections. Convection currents occur between the equator and the subtropical high at about 30 °north latitude, between the subtropical high and the subpolar low at about 60 °north latitude, and between the subpolar low and the north pole.

Similarly, an object thrown from the north pole toward a point on the equator will also miss it. The object starts off without any sideways velocity, so the moving earth rotates out from under it. The object drifts westward relative to the more rapidly moving ground as it heads south toward the equator. According to someone standing on the ground, the object curves toward the right.

In fact, north of the equator, freely moving objects traveling horizontally always appear to curve to the right. South of the equator, they always appear to curve to the left. Exactly on the equator, there is no Coriolis effect.

We can now look at how the Coriolis effect contributes to the global wind patterns. Over the equator, the air warms and rises upward, causing high-altitude winds to begin blowing toward the poles (Fig. 6.7.6). As the high altitude wind flows north from the equator, it curves toward the right. Instead of traveling directly toward the north pole, this air current curves toward the east. By the time it reaches about 30° north latitude (a third of the way to the north pole), the air is traveling almost due east. This eastward high-altitude flow is called the northern *subtropical jet stream*.

Unable to make further progress toward the pole, the air piles up over this region and creates the northern *subtropical high*. The air in this high-pressure region cools by radiating its heat into space and descends toward the ground. From there, it spreads south toward the equator and north toward the pole. The air returning toward the equator again curves toward the right and begins to head westward. These westward surface winds between 30° north latitude and the equator are called the *trade winds* (Fig. 6.7.7). They were important during the era of sailing ships because they helped to carry ships from Europe to the Americas. At the equator itself, the air is rising and there is little surface wind. This region is called the *doldrums*.

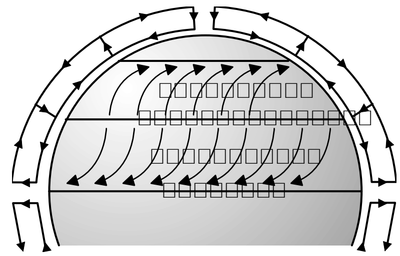

Fig. 6.7.7 - The surface winds over the earth generally flow toward the west between the subtropical high and the equator (the trade winds) and toward the east between the subtropical high and the subpolar low (the westerlies). Regions of relative calm are found at the equator and the subtropical high (the doldrums and horse latitudes).

There is also little surface wind at the subtropical high, a calm region around 30 °north latitude that is sometimes called the *horse latitudes*. But the surface winds again pick up as low-altitude air flows northward toward the pole. It, too, curves to the right and creates surface winds toward the east that are called the *westerlies*. These winds, which in North America extend from Texas up into Canada, cause an overall eastward movement of air. Although the winds may fluctuate locally, on the average they blow toward the east and carry the weather with them.

The northward moving surface air doesn't reach the pole. Instead, it encounters southward moving surface air leaving the pole at about 60° north latitude to form the *subpolar low*. In this region, the air rises and high altitude winds blow both toward the equator and toward the north pole. In all, three convection cycles are present between the equator and the north pole. A similar trio of convection cycles is present between the equator and the south pole.

CHECK YOUR UNDERSTANDING #3: Straight as a Crow Flies?

An airplane flying directly north from the equator will find itself curving toward the east. Why?

Hurricanes, Cyclones, and Anti-Cyclones

On the surface of our rotating earth, the Coriolis effect prevents a surface wind from flowing directly into a region of low pressure. The wind curves as it moves and misses the low. In the northern hemisphere, the wind curves toward the right and ends up circling around the low in a counter-clockwise direction, as viewed from above (Fig. 6.7.8). The pressure imbalance causes the wind to accelerate leftward, toward the low, but the Coriolis effect acts to make the wind curve rightward, away from the low. These two competing effects balance one another and the wind circles around and around the low. This circulation of air around a region of low surface pressure is called a *cyclone*.

When cold air passes over a warm ocean, the air is heated and expands. High altitude winds begin to blow outward and a region of low surface pressure forms. As more cold air rushes in across the water's surface to replace the rising air, the Coriolis effect deflects this inbound air and causes it to circulate around the low pressure region as a cyclone.

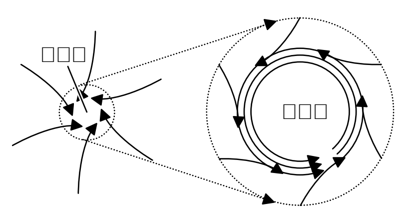

Fig. 6.7.8 - Wind accelerated toward a region of low pressure in the northern hemisphere is deflected toward the right by the Coriolis effect. The wind ends up circling around the low.

In certain special cases, the circulating winds can reach very high speeds, creating a powerful storm we call a hurricane. Hurricanes only form when the conditions are exactly right, requiring several unusual circumstances to occur simultaneously. First, a hurricane will only form above a very warm ocean, one that is warmer than about 26 or 27 °C (80 °F) to a depth of at least 50 m. The hurricane is a giant heat engine and its source of heat is the hot water. For the storm to have a great deal of energy, the water must be prepared to deliver a very large amount of heat. That's why hurricanes only occur in late summer.

Second, the air above the warm ocean must be relatively cool so that air that is heated by the water's surface can rise upward to very great heights. Air that is warm enough to rise upward through colder air above it is called *unstable air*. As it rises, the air expands and cools, so it must be quite warm in order to continue its ascent.

Third, the air rising over the warm ocean must carry a great deal of moisture with it. As is discussed in Section 15.1, moist air releases heat when its moisture condenses to form raindrops and this extra heat helps to propel the air still further upward. Much of the ferocity of hurricanes and thunderstorms comes from energy released by water's changes in phase, from gaseous water vapor to liquid water or solid ice.

Finally, the low and high altitude winds must be favorable or the hurricane will rip itself apart before it starts. At low altitude, the cool winds must converge on the warm ocean water. At high altitude, the winds must help to carry away the air that rises through the center of the storm.

When all of these requirements are met, a region of unusually low surface pressure forms, producing a hurricane. Air accelerates to enormous velocities as it approaches the low, but the Coriolis effect causes it to circulate endlessly around the region of lowest pressure. A calm "eye" forms at the center of the hurricane, protected from the circulating winds by the Coriolis effect. The eye is typically about 60 km in diameter. Just outside the eye, the most violent winds in the storm form a narrow ring only a few kilometers thick. The eye itself has little wind, very low air pressure, and may even be dry and only lightly overcast.

Near the center of the hurricane but outside the eye, air rises upward and carries heat away from the water. This rising air eventually travels outward as high altitude winds. These outward moving high altitude winds also experience the Coriolis effect and they curve weakly in the opposite direction from the surface winds.

In the northern hemisphere, surface winds always spiral counter-clockwise in a hurricane. In the southern hemisphere, the spiral is clockwise because the Coriolis effect is reversed. Because of these opposite spirals, a hurricane spawned in one hemisphere can never cross the equator into the other hemisphere.

CHECK YOUR UNDERSTANDING #4: There She Blows!

When a hurricane traveling toward the west approaches the east coast of the United States, which way will the surface winds begin to blow? It continues inland and the eye passes by the coast. Now which way will the winds blow on the coast?

The Atmosphere's Oxygen Content

The earth's oxygen content is maintained by plants. Plants use a process called *photosynthesis* to convert carbon dioxide and water molecules into carbohydrate and oxygen molecules. Carbohydrates are a broad class of molecules ranging from the cellulose that gives the plant its rigidity to the sugars that provide energy for the plant and for the animals that eat it.

Since the carbohydrate and oxygen molecules contain more chemical potential energy than the carbon dioxide and water molecules from which they're produced, the plant needs an input of energy to carry out the conversion. In the process of photosynthesis, this energy is provided by sunlight.

Plants absorb light in brightly colored photosynthetic pigments, such as the green chemical *chlorophyll,* and these chemicals use the light's energy to perform chemical reactions. In effect, photosynthesis is the opposite of combustion. While it's easy to burn wood in oxygen to form water and carbon dioxide, it's much harder to use light energy to turn carbon dioxide and water into wood and oxygen. Nonetheless, plants have developed very capable mechanisms for performing this reverse-combustion process. Without plants, the earth's atmosphere would quickly become depleted of oxygen. Much of the effort to reduce deforestation throughout the world is motivated by a desire to keep the atmosphere's oxygen level high and its carbon dioxide level low.

Plants are able to use light energy to induce chemical reactions in part because light is emitted and absorbed in discrete packets of energy. Each time it absorbs a packet of light energy, a **photon**, the photosynthetic chemical takes a step toward converting carbon dioxide and water into carbohydrate and oxygen. The energy in a photon is related to the wavelength of the light—long wavelength infrared light is absorbed or emitted as small packets of energy while short wavelength ultraviolet light as is absorbed or emitted as large packets of energy. Visible light falls somewhere in between and has the right range of photon energies to support photosynthesis.

Sunlight also contains photons with so much energy that they can cause chemical damage to plants and animals. Photons of ultraviolet light can contain enough energy to cause permanent *photochemical* damage to the molecules that absorb them. These ultraviolet photons can *denature* proteins—make them nonfunctional—and can cause such injuries as sunburns and cataracts.

Ultraviolet light can even damage DNA and RNA, the molecules of genetic information that cells use to synthesize proteins and to reproduce. When ultraviolet light causes sufficient damage to the genetic information in a cell, it may kill that cell. It can also cause changes to a cell that don't kill the cell, but instead render it defective. One possible defect is cancer.

Tanning is your skin's response to this photochemical threat and it provides a modest amount of protection. Nonetheless, ultraviolet light continues to damage the skin molecules that absorb it. To truly protect your skin from ultraviolet light, you must wear a sunscreen. Sunscreen molecules actually absorb ultraviolet light and convert its energy into thermal energy. Very little of the ultraviolet light penetrates the chemical barrier and reaches your skin.

Fortunately, the atmosphere also acts as a sunscreen. Atmospheric oxygen molecules absorb most of the sun's highest-energy ultraviolet photons so that very little of this extreme ultraviolet light reaches the earth's surface. Once an oxygen molecule absorbs an extreme ultraviolet photon, it can fall apart into two oxygen atoms. One of these oxygen atoms can then combine with another oxygen molecule to form an ozone molecule. Ozone is a moderately toxic gas that's highly reactive chemically, smelling and behaving much like chlorine. Near the earth's surface, ozone is a pollutant and part of photochemical smog. Fortunately, it breaks down quickly into normal oxygen and causes no long-term contamination. Because of its similarity to chlorine and its environmental advantages, ozone is often used instead of chlorine as a disinfectant for swimming pools and a bleaching agent for paper mills.

But in the upper atmosphere, ozone is very important. Oxygen molecules only absorb extreme ultraviolet photons, leaving the earth unprotected from less extreme ultraviolet light. However, ozone molecules absorb this less energetic ultraviolet light. Although the ultraviolet photon may break up the ozone molecule that absorbs it, at least that photon doesn't reach the earth's surface. Without ozone in the upper atmosphere, we would be exposed to far more ultraviolet light and would suffer far more photochemical damage from sunlight.

Ozone molecules are continuously being created and destroyed by ultraviolet light. There are just about the right number of them in the upper atmosphere at any one time to ensure that we don't get too much ultraviolet exposure. However, chlorine-containing molecules released into the atmosphere since the industrial revolution have begun to change that delicate balance. Chlorine atoms act as catalysts, facilitating the conversion of ozone back into normal oxygen. Ozone molecules have extra chemical potential energy and two ozone molecules tend to become three normal oxygen molecules. The only thing preventing this conversion is the activation energy needed to break apart the two ozone molecules so that they can begin to form the three normal oxygen molecules. By reducing the activation energy required, chlorine atoms ease the conversion. The more chlorine atoms we put into the upper atmosphere, the faster ozone reverts to normal oxygen and the less ozone the atmosphere contains.

Recognizing the threat to life posed by a decrease in the atmospheric ozone content, countries have begun to curtail or ban the production of chlorine-containing gases such as chlorofluorocarbons. Still, chlorine atoms have a long lifetime in the upper atmosphere and a single chlorine atom can aid in the destruction of countless ozone molecules. No one knows how long it will take for the ozone balance to be reestablished or how bad the situation will get before it begins to get better.

CHECK YOUR UNDERSTANDING #5: Ultraviolet Light Packs a Wallop
Ultraviolet lights are often used to help disinfect the air in hospitals. Why does ultraviolet light kill germs?

Chaos and Weather Prediction

The atmosphere is a wonderful example of a chaotic system. Because they involve drag and viscosity, surface winds are filled with vortices and eddies, and turbulent flows of this sort are chaotic. Tiny changes in the earth's surface can dramatically affect these turbulent flows and redirect the wind. It's often hypothesized that the turbulence caused by a single butterfly flapping its wings can redirect the flow of the wind and will eventually affect the weather everywhere on earth. The butterfly changes the local winds, which in turn change other winds, and so on until the entire earth has been affected.

Because the atmosphere is essentially a giant chaotic system, the weather is extremely difficult to predict. Subtle changes in the current situation will significantly affect the weather a day or a week from now. To have any hope of accurate predictions, you need accurate data about the current situation. The more long-term your prediction is supposed to be, the more current data you need.

Recent advances in weather prediction come from better data collection and better computer modeling of the physical dynamics of the atmosphere. Still, weather prediction will never be completely reliable nor will it extend very much further into the future than it does today. You simply can't record the movements of every butterfly on earth.

CHECK YOUR UNDERSTANDING #6: Watch Those Typos
How could a single comma change your entire future?