Lightning indicates the presence of electrostatic energy in the atmosphere.

CHAPTER 11
Energy in the Atmosphere

You will know something about changes in the atmosphere if you can:

1. Explain how energy and moisture are added to the atmosphere.
2. Describe the factors that affect the density of the air.
3. Describe the circulation of the atmosphere.
4. Explain how moisture leaves the atmosphere.

In Chapter 10 we considered some of the kinds of weather, or conditions of the atmosphere, that we can observe and measure. Among these were air temperature and pressure, relative humidity or dew point, wind direction and speed, and the presence of clouds or precipitation. We saw, too, that we could observe the movement and interaction of large air masses, each with its own distinct characteristics. Even without knowing any of the "whys" or "wherefores" of weather, we could make weather predictions on the basis of the probability of changes in the weather when we observed certain conditions in the atmosphere. But if we can understand the processes of change in the atmosphere, we will have a better chance to make more accurate predictions. This chapter deals with some of the processes that cause changes in the atmosphere.

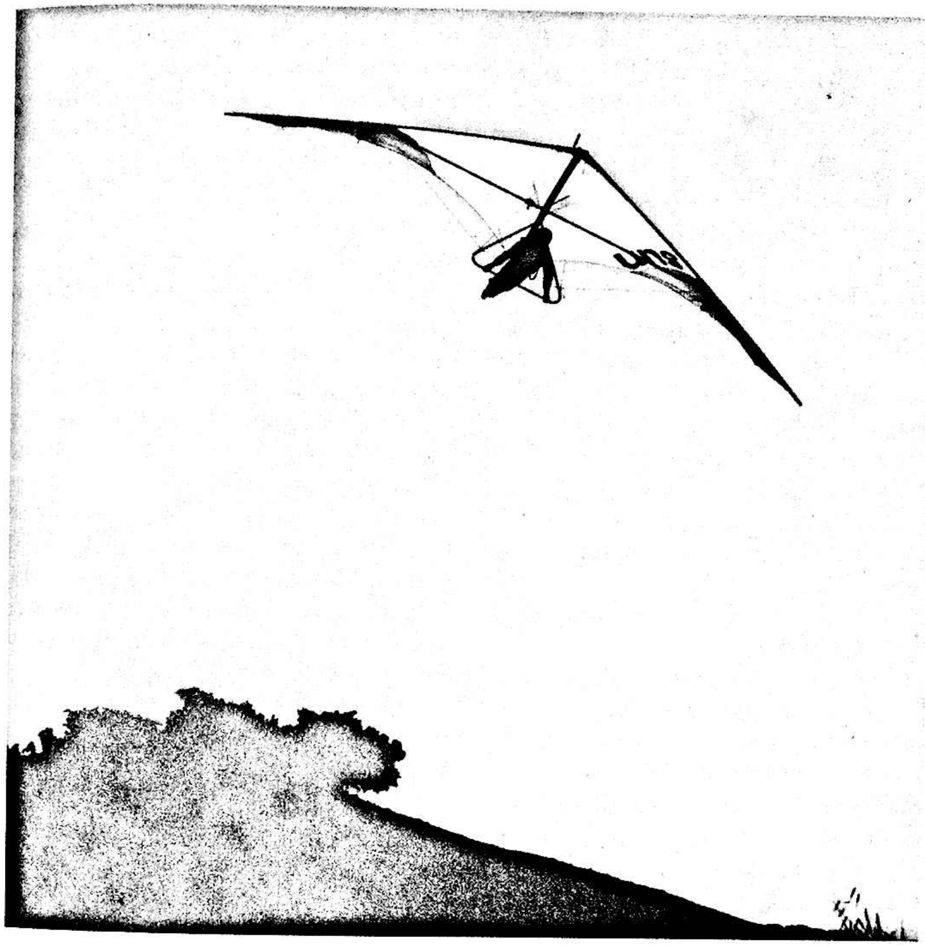


Figure 11-1. Hang gliders use warm updrafts of the air to stay in flight.

HEATING THE ATMOSPHERE

Solar Radiation. Radiation from the sun is the chief source of energy for the atmosphere. But recall from Chapter 9 (page 147) that *most* of the radiant energy from the sun that enters the atmosphere is either reflected back out to space or passes through to the earth's surface. It has very little *direct* warming effect on the atmosphere.

When radiant energy from the sun reaches the earth's surface, then a large part of the energy *is* absorbed. This absorbed energy heats the earth's surface. The earth's surface then reradiates the energy into the atmosphere. The temperature of the earth's surface is much lower than that of the sun. Therefore, much of the earth's radiation is at long wavelengths in the infrared range. These are the wavelengths that the carbon dioxide and water vapor in the atmosphere can absorb. It is energy *reradiated* by the earth's surface that does most of the warming of the atmosphere.

As you study the picture, you see land and water, and on the land you see darker and lighter areas. From Chapter 9 (page 148) you will remember that these different surfaces heat up at different rates by day and cool off at different rates by night. During the day, the land becomes warmer than the water, and the dark areas of the land become warmer than the light areas. Over the warmer areas, more energy is radiated to the atmosphere than over the cooler ones. Some energy is also transferred from the surface to the atmosphere by conduction at the interface between the surface and the air.

Combustion. Radiation and conduction from the earth's surface are the *main* sources of energy for the atmosphere, together with some direct absorption of insolation. But there are a number of minor sources, and you can see some examples of these in the picture. The charcoal fire in the grill is transferring heat to the atmosphere by radiation and conduction. So is the combustion of fuel in the factory and in the engine of the motorcycle. Each of these is a rather intense source of heat in its immediate neighborhood. But for the atmosphere as a whole, all the combustion around the world provides only a tiny fraction of the total energy supply. The oxidation of food by living things also adds a bit of heat to the atmosphere. You can think of yourself as one of the sources of atmospheric energy.

Other Sources. Winds are another small source of energy for the atmosphere. Although you cannot see a wind in the picture, you can see evidence of its action. A wind is air in motion. Where winds blow along the earth's surface, the kinetic energy of the moving air is changed to heat by friction at the interface between the air and the surface. This heat raises the temperature of both the surface and the atmosphere to a very slight extent. There are no volcanoes in the picture, but volcanic eruptions are another very small source of energy for the atmosphere.

The various sources of energy in the picture have different amounts of heating effect at different times of the day or year. There are similar variations in heating of the atmosphere on a global scale. At latitudes around the equator, where intensity of insolation is greatest, surface temperatures are highest and the atmosphere receives the most energy. At the poles, heating of the atmosphere is least. These variations from place to place on the earth, and from time to time during the year, are the chief cause of changes in the weather.

SUMMARY

1. The atmosphere is heated mainly by absorption of infrared radiation from the earth's surface.
2. Other sources of heat for the atmosphere include direct absorption of solar radiation, conduction from the earth's surface, combustion, wind friction, and volcanic eruptions.

Figure 11-2. How water enters the atmosphere. The lake, the trees, the freshly plowed soil, and the people all give off moisture to the atmosphere.

ATMOSPHERIC MOISTURE

In Figure 11-1 we saw examples of various ways in which heat energy is transferred to the atmosphere. Figure 11-2 is a drawing in which some of the ways that *water* enters the atmosphere are pictured. How many can you spot? What processes are involved in each case?

Evaporation. You know that if you leave a pan of water out in the air, the water eventually disappears. You can keep watch over the pan to make sure that your pets or other animals don't drink it, or that the water is not carried off in some other obvious way. If you wash your hands, but don't dry them on a towel, they dry anyway in a few minutes. If you rub your hands together or blow on them, the water disappears more quickly. What happens to the water? We say that it dries up. In more elegant scientific language, we say that it *evaporates*. By this we mean that the liquid water changes to water vapor—a gas. The water has "disappeared" only in the sense that it is no longer visible. But it still exists as a gas mixed with other gases in the air. There are various factors that affect the rate at which this process of evaporation occurs, and we will discuss them later in this chapter.

Where is evaporation likely to be taking place in the scenes in Figure 11-2? Obviously, the lake is a good choice. Evaporation is continuously occurring from large bodies of water, such as lakes and oceans, all over the world. Very likely, the farmer and the camper are perspiring. This water, too, is being evaporated. The freshly plowed soil is probably giving up moisture by evaporation, also. After several minutes, the dark, moist, freshly turned soil may change to a

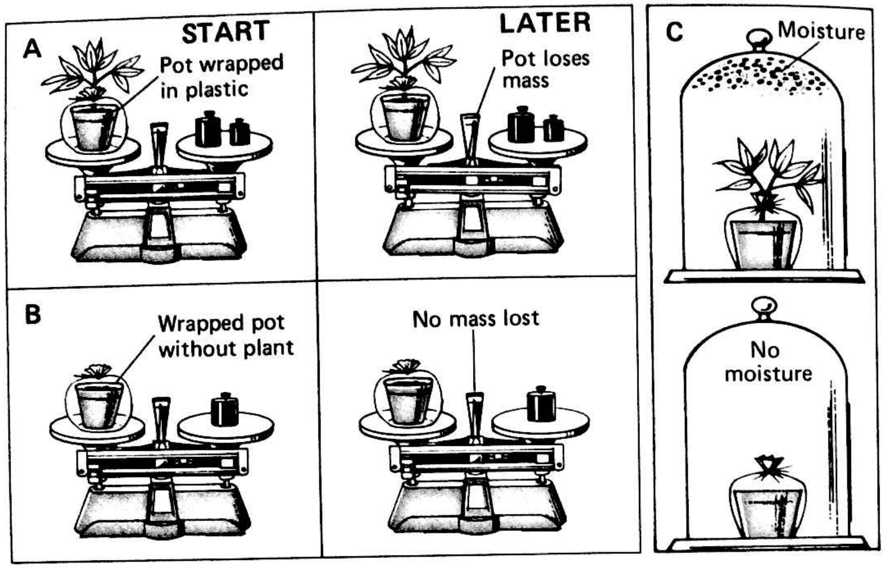


Figure 11-3. Potted-plant experiment. This experiment gives evidence that a plant can remove moisture from the soil and give it off to the atmosphere.

lighter color as it dries out. However, evaporation is not the complete story of how water vapor gets into the atmosphere. There is another important process, not quite as obvious as evaporation, that adds large amounts of water vapor to the air.

Transpiration. Figure 11-3, part *A*, shows a simple experiment that can be carried out with a potted plant. The soil in the pot was watered. Then the pot and the soil were wrapped in a plastic sheet. The plastic was sealed to the plant stem so that no water could be lost to the air by evaporation. The pot and its plant have been placed on a laboratory balance. After a short time, the balance will indicate that the pot and plant are losing mass.

In part *B* of the illustration, a pot of watered soil *without* a plant was wrapped in plastic and placed on a balance. In this case, no change in mass is observed as time passes. In part *C*, a pot-and-plant setup like that in part *A* has been placed under a large glass jar. After a time, a mist of water droplets will appear on the inside surface of the jar, indicating that the air inside the jar has become saturated with water vapor. This does not happen when a wrapped pot *without* a plant (as in part *B*) is placed under the jar. If the soil in the pots is examined after a few days, it will be found to have dried out in the setups *A* and *C*, but not in *B*.

These observations indicate that there is a process by which water can leave the soil and enter the atmosphere by passing through a plant. The process by which living plants transfer moisture to the atmosphere is called *transpiration*. In this process, liquid water enters the plant through its roots and is carried upward through its stems to its leaves. The water then passes through the walls of

the plant cells into spaces within the leaves, where it becomes water vapor and escapes into the air through openings in the leaf surfaces (see Figure 11-4).

Transpiration is a much more rapid process than simple evaporation would be. It is an essential life process of plants. Many substances that plants need are dissolved in soil water in only very small amounts. Transpiration enables a plant to absorb large quantities of water from the soil, take the minerals they need from the water, and then dispose of the surplus water. Large plants, such as trees, give off great quantities of water by transpiration. It is the process that explains the high humidity that is always present in "steaming" tropical jungles.

In some of the scenes in Figure 11-2, the surface is covered with plants. We can assume that large amounts of water vapor are entering the air by transpiration from these plants, as well as by evaporation from the bodies of water. The two processes of evaporation and transpiration are often referred to, in combination, as *evapotranspiration*.

Energy and Evaporation. After taking a swim on a hot summer day, you feel cool for quite a while, even if you're lying in the sun. This happens because the evaporation of water from your skin is a cooling process. In evaporation, the water molecules that break free of the liquid water to form water vapor are those with the greatest kinetic energy. So the average kinetic energy of the molecules left behind in the liquid water is lowered, which means that the temperature of the water is lowered.

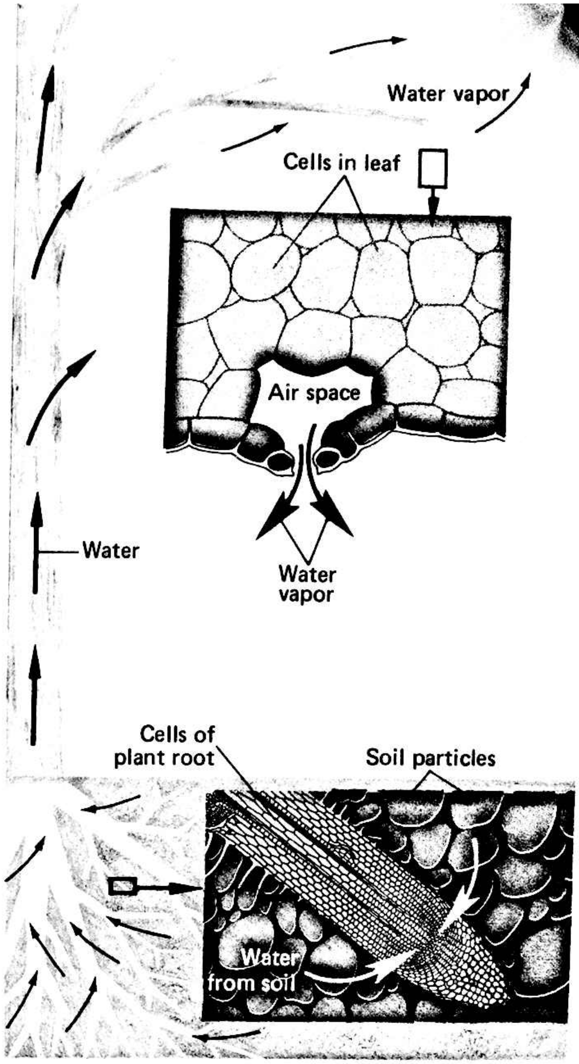


Figure 11-4. Transpiration. In transpiration water enters the plant through the roots and passes upward through the stem into the leaves. The water evaporates into spaces inside the leaves, and then eventually passes out into the air through special openings in the surface of the leaf.

Recall from Chapter 8 (page 132) that the change from liquid water to water vapor requires large amounts of energy. At the boiling point, it takes 540 calories to convert one gram of liquid water to water vapor (steam). In evaporation at temperatures below the boiling point, the heat of vaporization is somewhat less, but still quite large. The heat energy required for evaporation is taken from the water, so the water does drop in temperature. However, the water vapor and the surrounding air are *not* warmed by evaporation. The heat energy is stored in the water vapor as the form of potential energy called latent heat. When the water vapor later condenses back to liquid water, the latent heat then appears as heat energy, and it is at that time that the atmosphere is warmed by it.

Transpiration is basically a process of converting liquid water to water vapor, and the amount of energy used is the same. So transpiration is also an energy-absorbing process. The atmosphere gains energy in the form of latent heat through transpiration as well as through evaporation.

SUMMARY

1. Moisture enters the atmosphere by means of evaporation and transpiration.
2. The oceans and other large bodies of water are the primary sources of moisture for the atmosphere.
3. Energy is required to cause evaporation and transpiration.
4. The atmosphere gains energy through evaporation and transpiration. This energy is in the form of latent heat.

VAPOR PRESSURE

Figure 11-5 shows two mercury barometers. At normal atmospheric pressure, the air pressure can support a column of mercury that is 760 mm in height. This is equivalent to a pressure of 1013 millibars (mb). This is illustrated by the drawing labeled *A*. Remember that the space above the mercury column is empty. We call it a *vacuum*. Therefore, the pressure at the base of the mercury column is due entirely to the weight of the mercury.

In drawing B, a few drops of water have been added to the column. (This can be done by forcing water out of a medicine dropper held under the base of the tube.) When this is done, the mercury column is observed to drop. At 25°C, the height of the column drops about 24 mm, equivalent to about 31 mb.

You might expect the extra weight of the water to cause the mercury level to drop slightly. But the weight of the water alone cannot explain why the whole column drops 24 mm. In fact, since water is much less dense than mercury, the top of the column ought to be slightly *higher* in order to produce the same pressure at the bottom. There must be something in the space above the column that is exerting pressure and adding its effect to the weight of the liquid.

We know that water evaporates, forming water vapor. What has happened in the column is that water vapor has entered the space above the mercury and water. This vapor exerts pressure in the closed space. Look again at the diagram of the normal barometer. We said that the space above the mercury is a vacuum. Actually, it contains some mercury vapor. However, the amount of mercury that evaporates into this space is so small that its pressure can ordinarily be ignored. (In high-precision experiments with mercury columns, the pressure of the mercury vapor does have to be considered.) When water vapor is allowed to form in the space above the column of liquid, the situation is quite different. The pressure of the water vapor is much greater than that of the mercury vapor, and it cannot be ignored.

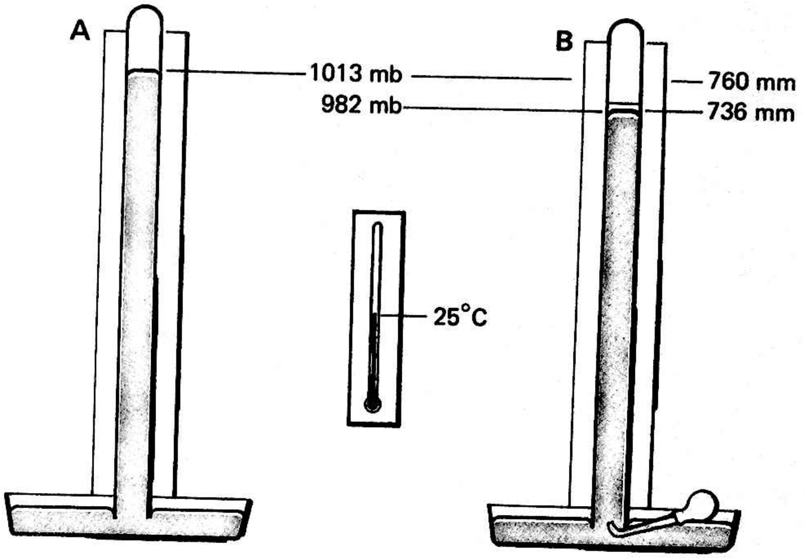


Figure 11-5. The effect of water vapor on the height of a mercury column. A few drops of water inside a mercury barometer causes the column to drop. At 25°C, the drop is about 24 mm.

The pressure of water vapor is called *vapor pressure*. In normal atmospheric pressure, part of the total pressure is due to vapor pressure, part is due to pressure exerted by oxygen, part by nitrogen and so on for all the gases that make up air. The atmospheric pressure is the total of the separate pressures exerted by each of these gases. These separate pressures are called *partial pressures*.

Saturation Vapor Pressure. You will notice that some water in barometer *B* remains on top of the mercury column. It does not completely evaporate into the space above. Why is this so? As the water evaporates at first, the space at the top of the column begins to be filled with water vapor. But this is not a one-way process. Besides the water molecules leaving the liquid, there are also water molecules entering the liquid from the air. In other words, there is condensation as well as evaporation.

Figure 11-6 illustrates this process. At first, there are more molecules leaving the liquid than are returning to it. The rate of evaporation is greater than the rate of condensation, and the vapor pressure keeps increasing. Eventually, the two rates become equal. The number of molecules leaving the liquid equals the number returning to the liquid. A *dynamic equilibrium* has then been reached. This doesn't mean that evaporation

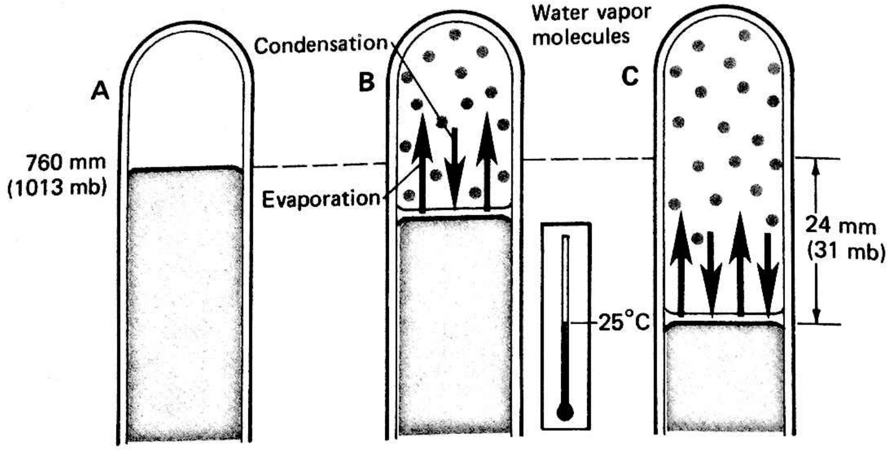


Figure 11-6. The meaning of saturation vapor pressure. In *A*, the normal height of the mercury column in the barometer is shown. In *B*, a small amount of water has been added, and evaporation has just begun. Water molecules are leaving the liquid (evaporation) at a faster rate than vapor molecules are returning (condensation), and vapor pressure is building up above the column. At *C*, equilibrium has been reached. Evaporation and condensation are occurring at the same rate, and the amount of water vapor remains constant. The depression of the mercury column equals the pressure exerted by the water vapor. This is the saturation vapor pressure for the existing temperature. At 25°C, for example, the vapor pressure is 31.4 mb.

and condensation stop occurring. Both processes continue, but at equal rates, so there is no *net* change in either direction. The vapor pressure at this point is called the *saturation vapor pressure.*

The saturation vapor pressure of water is the same in air as it is in the space at the top of a barometer. The presence of the other gases in the air does not affect the equilibrium between water and its vapor. When air is saturated with water vapor, the partial pressure due to the water vapor is the same as the saturation vapor pressure.

Saturation Vapor Pressure and Temperature. From what we have just said you can see that the amount the column drops in barometer *B* is equal to the saturation vapor pressure. The saturation vapor pressure varies with temperature. Barometer *B* in Figure 11-5 shows what happens at 25°C. The saturation vapor pressure at this temperature is 24 mm of mercury, or 31 mb. If we cool the upper portion of the barometer by holding ice cubes against it, the column of mercury will rise. This shows that the vapor pressure has decreased. If we warm the barometer, the column drops, showing that the vapor pressure has increased.

Barometer *B* is thus an instrument that can be used to measure the saturation vapor pressure of water at any temperature between the freezing point and the boiling point. Figure 11-7 is a graph that shows the relationship between saturation vapor pressure and temperature. Note that at 100°C the vapor pressure becomes equal to normal atmospheric pressure (760 mm or 1013 mb). At this temperature, water will boil if the air pressure is normal. This means that the vapor pressure is great enough to form bubbles of vapor inside the liquid (which is what we mean by "boiling").

Water boils whenever the water temperature is raised to the point where saturation vapor pressure is equal to atmospheric pressure. Therefore, where the atmospheric pressure is lower than normal, water will boil below 100°C. Where the atmospheric pressure is higher than normal, the boiling point of water is raised.

Rate of Evaporation. There are three basic factors that affect the rate of evaporation of a liquid. The first is the amount of energy available. The more energy there is available (the higher the temperature), the greater the rate of evaporation. The second is the surface area of the water. The greater the surface area (the greater the interface between water and air), the greater the rate of evaporation. The third is the moisture content, or vapor pressure, of the air over the water. The lower the vapor pressure, the faster the rate of evaporation. The closer the air is to being saturated, the slower the evaporation rate. This is true because as the air nears saturation, the rate of condensation in the air approaches the rate of evaporation from the surface of the liquid.

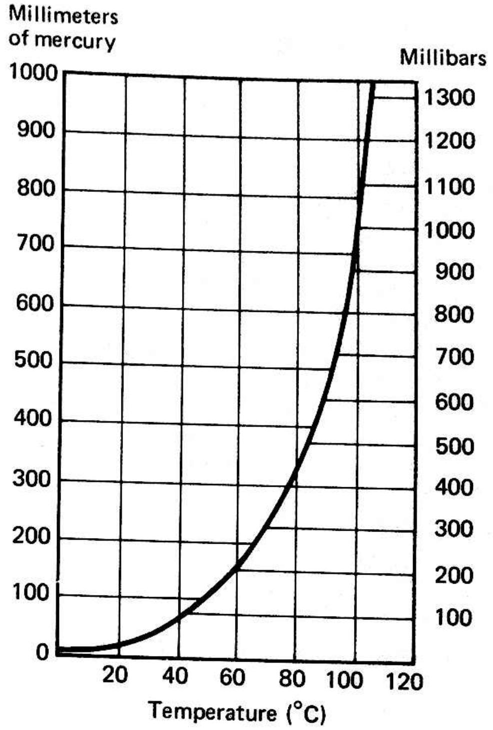


Figure 11-7. Relationship of temperature and saturation vapor pressure.

The air closest to the air-water interface will have a higher water vapor content than air at greater heights, and it will also become saturated sooner. If the air above the liquid is not in motion, it will become saturated. If something then moves the air (a fan or wind), then unsaturated air will be circulated over the liquid, and further evaporation will occur.

SUMMARY

1. The pressure exerted by water vapor is called vapor pressure.
2. The vapor pressure of saturated air is called the saturation vapor pressure.
3. Saturation vapor pressure varies directly with temperature.
4. The rate of evaporation depends on the energy available, the surface area, and moisture content of the air.

THE DENSITY OF THE AIR

Up to this point in the chapter we have been examining the ways in which heat and moisture enters the atmosphere. It is time to consider some of the *effects* of these transfers to the atmosphere. One of the most important effects is a change in the density of the air. Changes in density are important because they are the direct cause of movement of masses of air, both locally on a small scale and worldwide on a large scale. How do changes in temperature and moisture content affect air density?

Temperature and Volume Changes in Air. In this chapter, and in other sections of this book, we will frequently refer to the effects of heating or cooling a portion of the atmosphere. It is often stated that "warm air expands" and "cool air contracts." This idea was discussed briefly in Chapter 2 (page 18). It will be helpful to examine the situation a little more carefully.

Figure 11-8 shows a flask sealed by a stopper. The flask contains air. If the air in the flask is heated by lighting the burner under the flask, will the air in the flask expand? No. Since the flask is airtight, the air inside has no place to go. It can't expand. What does happen is that the *pressure* of the air inside the flask increases as its temperature rises. The pressure increases because the heat being added is causing the kinetic energy of the gas molecules to increase. As a result, the impacts of the molecules on the sides of the flask occur with greater force and with greater frequency, thus creating a greater pressure. If the pressure of the confined gas becomes great enough, it will blow the stopper out of the flask or break the glass, whichever gives way first.

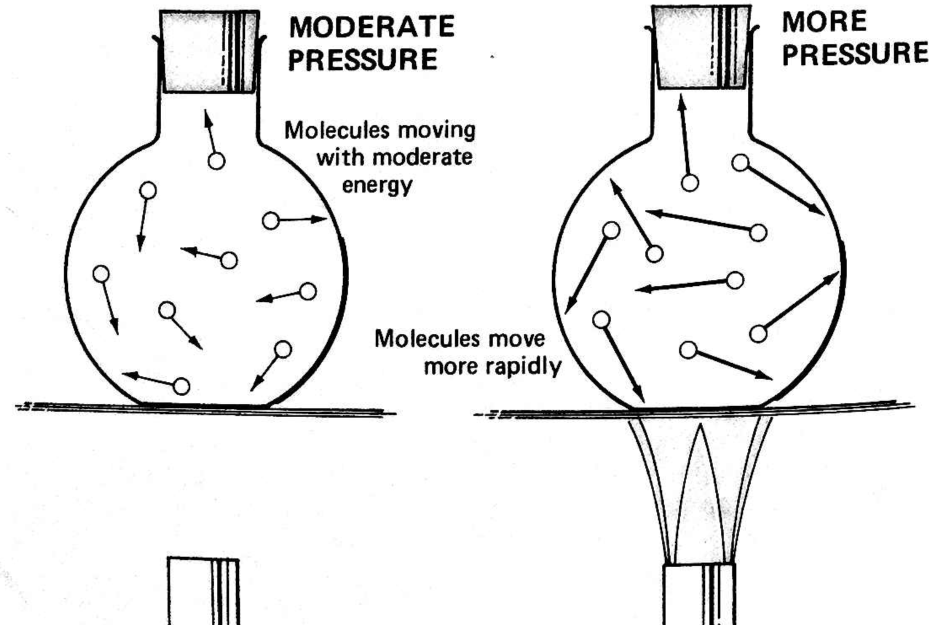


Figure 11-8. Increasing pressure of a confined gas that is being heated. As the temperature of the gas increases, the average kinetic energy of its molecules increases, resulting in an increase in the pressure of the gas.

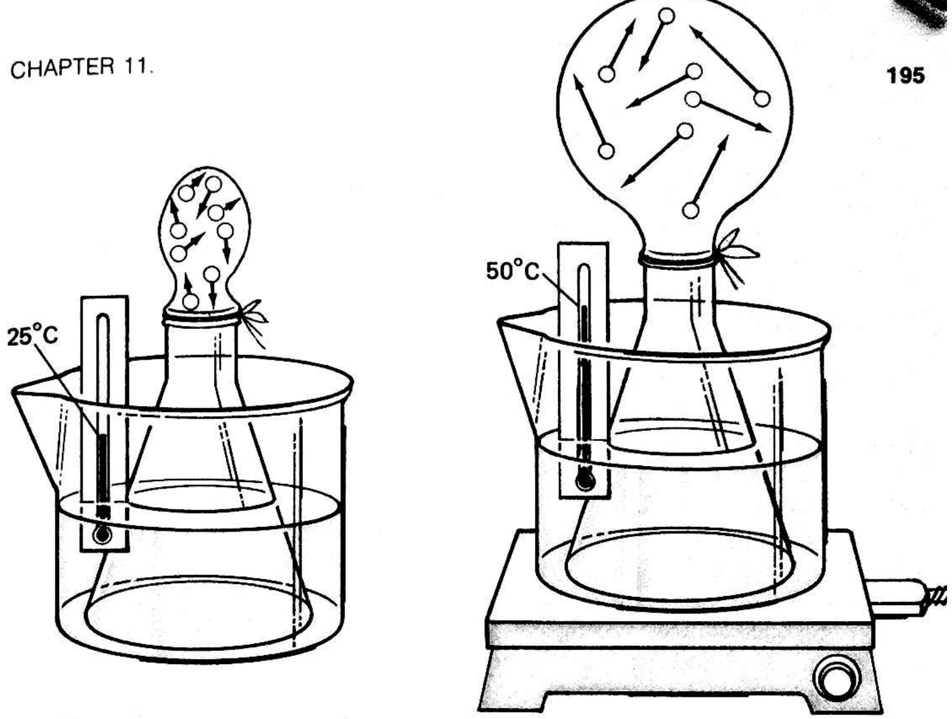


Figure 11-9. Expansion of heated air. If you warm a balloon over a radiator or hotplate, the air molecules inside the balloon acquire more kinetic energy. They are therefore able to expand the balloon to a larger volume. If the balloon is cooled, the air molecules lose kinetic energy and the balloon contracts.

But what happens if the flask is open, and we heat it as before? The first effect of the added heat is to increase the air pressure slightly inside the flask. But this immediately drives some of the gas out through the neck of the flask. Thus the pressure inside the flask doesn't rise, but the number of molecules inside decreases. That is, the mass of the gas in the fixed volume of the flask decreases, resulting in decreased density. This effect was discussed in Chapter 2, page 18.

To help visualize the effect of heating a portion of the atmosphere, let us replace the sealed flask by a tied rubber balloon filled with air (see Figure 11-9). What happens when we heat the balloon? Again, the air inside cannot escape. But this time it stretches the rubber balloon to a larger volume. Again, the density of the air inside the balloon becomes less. But now the density decreases because we have the *same mass* of gas occupying a *larger volume*. The case of the balloon is close to what happens when a region of the atmosphere is heated. The heated "bubble" of the air expands and becomes less dense.

The opposite effects are produced when an air mass loses heat and becomes cooler. Its molecules lose kinetic energy, and the pressure of the surrounding air squeezes the cooler air into a smaller volume, thereby increasing its density. This effect can be demonstrated by cooling a balloon of air. The volume of the balloon will decrease.

You can now see that when we say "warm air expands," we are talking about air that is not confined in a rigid container. That is, we are talking about the situation in the atmosphere, where changes in energy can lead to changes in volume, and hence to changes in density.

Temperature and Density of Air. From the preceding discussion, we can come to an important conclusion. When a portion of the atmosphere is heated, so that its temperature increases, the heated portion of the air will expand and its density will decrease. When air is cooled, it will contract and its density will increase.

Moisture and Air Density. You might expect that when the amount of water vapor in the air increases, the air would become heavier, or more dense, like a sponge absorbing water. Not so! When a sponge absorbs water, there is just as much sponge as before, so the weight of the water is added to the weight of the sponge. But when water vapor enters the air, some of the oxygen, nitrogen, and other gases are "pushed out of the way," or displaced. The water vapor *takes the place* of these gases, so that in the same volume there is more water vapor and less of the other gases than there was before. However, water vapor is less dense than the other gases in air. Oxygen, for example, has a density about 1¾ times as much as that of water vapor. Nitrogen has a density more than 1½ times that of water vapor. Therefore, when water vapor enters a volume of air, denser gases are displaced, and the average density of the air decreases.

We have just seen that a very important change takes place in air when either its temperature or its moisture content increases. The density of the air decreases in both cases. Each of these effects is an inverse relationship—when one quantity goes up, the other goes down. It will be helpful to keep these inverse relationships clearly in mind as we study their effects on the behavior of the atmosphere.

SUMMARY

1. As the temperature of the air increases, its density decreases.
2. As the moisture content of the air increases, its density decreases.

CIRCULATION OF THE ATMOSPHERE

Convection Cells. We have just seen that wherever the air is being warmed, the air is becoming less dense. Wherever moisture is being added to the air, it is also becoming less dense. We also know that different portions of the atmosphere are receiving heat and moisture at different rates. So it is very common to find a region—which may be quite small or very large—in which a mass of air of one density is surrounded by air of a different density.

In Chapter 8 (page 124) we considered what happens in a fluid (liquid or gas) when one portion has a different density from another. The more dense portions tend to sink, while the less dense portions rise. This is the process called *convection.* In Chapter 8 we considered convection as a way in which heat energy is transferred in a fluid. In this chapter we will be more concerned with convection as a cause for movement of air and circulation of the atmosphere.

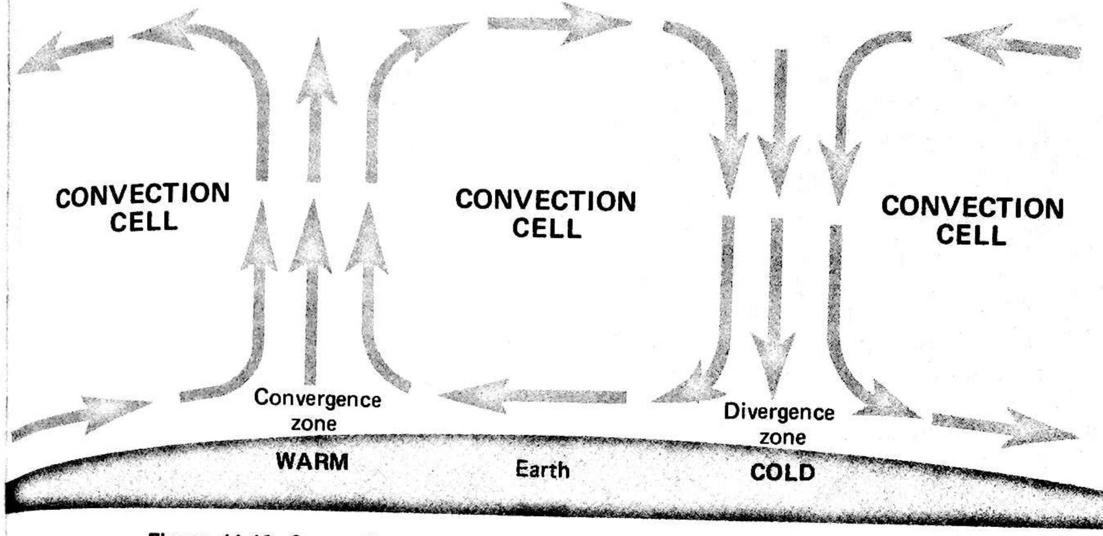


Figure 11-10. Convection cells. In a convection cell, warm air rises at a convergence zone and cool air descends at a divergence zone. Air flows along the surface from the divergence zones toward the convergence zones.

Think of a mass of air over the warm ocean near the equator. This air gains moisture (by evaporation from the ocean surface), and it is warmed by radiation and conduction from the ocean surface. Because the air is both warm and moist, its density is low. It tends to rise. As the warm, moist air rises, its place is taken by cooler, drier air, which moves in underneath it. As this cool, dry air gains moisture and is warmed, it too is forced upward. So, in areas where the air tends to gain moisture and/or heat, there is a steady upward movement of air, with cooler air flowing in from surrounding areas (see Figure 11-10).

We have just described what happens over an area of the earth's surface where the air gains moisture and/or heat. At other locations, conditions are such that the air becomes cooler and drier, and therefore more dense, than the surrounding air. At such locations there is a downward movement of air. This air sinks under the influence of gravity and spreads out horizontally at the surface, forcing less dense air upward. In both situations, we have a circulating system of air currents, which we call a *convection cell.* A region where air is rising in a convection cell is called a *convergence zone (converge* means "to come together"). Air from surrounding areas flows in toward the center of the convergence zone. In the center of the convergence zone the air moves vertically upward.

On the other hand, there are situations in which air loses heat and becomes cooler. This happens to air over cold land masses, such as the northern regions of Canada or Russia.

Such air will become denser and will tend to sink and then spread out horizontally near the earth's surface. A region where this is happening is called a *divergence zone (diverge* means "to move apart"). In the center of a divergence zone, air is moving vertically downward. Near the ground, the air is moving outward, or diverging from the center.

Convection cells can start in two different types of regions. Upward currents of air form in regions where there is relatively high humidity and/or temperature. Downward currents of air form in regions where there is relatively low humidity and/or temperature. So convection cells may form in regions with relatively high humidity and temperature or relatively low humidity and temperature.

Wind. We have defined wind as a horizontal movement of air over the surface of the earth. We experience wind as a local event—as a breeze rustling the leaves of a tree, or as strong gusts causing the entire tree to sway. A wind may, in fact, be the result of local weather factors, such as thunderstorms. But we will see that local winds are also affected by large wind systems that sweep across the earth on a global scale.

When we talk about wind, we must remember that it is a vector quantity—that is, wind must be described in terms of both velocity and direction. As already stated on page 27, winds are named according to the direction they come from. A southeast wind is a wind blowing *from* the southeast toward the northwest.

Air moving in toward a convergence zone or out from a divergence zone is a wind. Here, the wind seems to be the result of convection. Actually, air never moves horizontally unless it is driven by a force, and the force that causes a wind to blow is always the result of a difference in air pressure.

The pressure of the air over a region is directly related to its density. Air pressure is a result of the weight of the air pressing down on a given area. When the air is more dense, the air over a given area weighs more than when it is less dense. Therefore, the denser the air, the greater its pressure.

We have seen (page 196) that cold air is usually denser than warm air. Dry air is usually denser than moist air. We would therefore expect to find that cold, dry air masses are generally centers of high pressure, while warm, moist air masses are centers of low pressure. Observations of air masses show that this is generally the case. Cold, dry air masses are usually present in divergence zones; warm, moist air masses are present in convergence zones. The difference in pressure between the base of a cold, dry air mass and a warm, moist air mass will cause winds to blow outward from the former and in toward the latter.

Although the direction of a wind is basically determined by the location of the centers of high and low pressure, the actual direction of a wind is always affected by the Coriolis force. As explained in Chapter 7 (page 103), this is a force on anything moving along the earth's surface, caused by the earth's rotation. In the Northern Hemisphere, the Coriolis force deflects winds to the right. In the Southern Hemisphere, winds are deflected to the left.

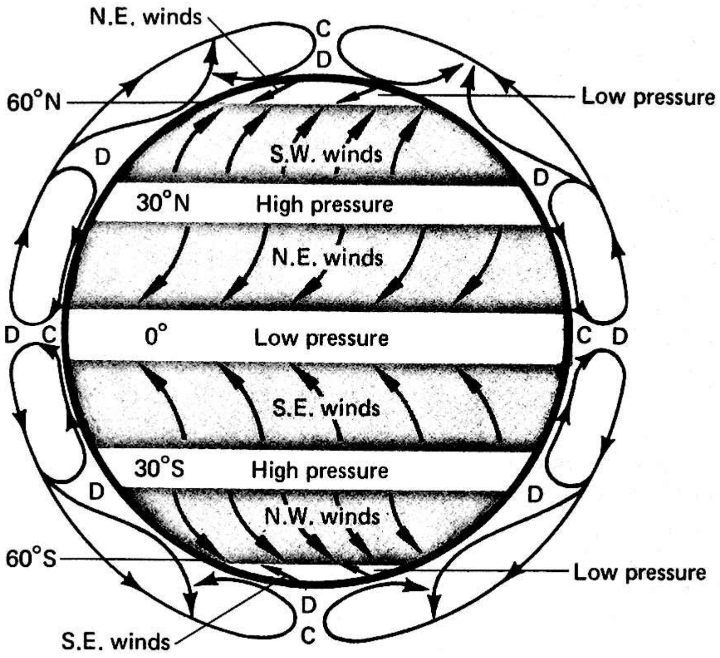


Figure 11-11. Planetary wind and pressure belts in the troposphere. The drawing shows the locations of the belts near the time of an equinox. The locations shift somewhat with the changing latitude of the sun's vertical ray. In the Northern Hemisphere the belts shift northward in summer and southward in winter.

Planetary Winds. We know that the earth's surface is heated unevenly—that the total annual insolation received by areas around the equator is much greater than that received by areas around the poles. Winds transfer heat from regions of high temperature to regions of low temperature and in this way make it possible for life to exist on much of the land areas of the earth.

At the earth's surface, winds blow horizontally from regions of divergence toward regions of convergence. Because of the Coriolis effect, the winds curve to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Figure 11-11 shows the pattern of winds that flow over the surface of the earth. It also shows regions of high pressure and regions of low pressure. The positions of the zones of convergence and divergence and of high pressure and low pressure depend on several factors.

You might expect to find a zone of convergence around the equator, the warmest part of the earth. If you look at Figure 11-11, this is exactly what you find. Here the air is warmed by the strong insolation and it also gains moisture because of the high rate of evaporation from the warm oceans. So there are winds blowing in toward the equator from both sides.

At latitudes of 30°N and 30°S there are divergence zones where cool air from the upper atmosphere sinks to the earth's surface. At latitudes of

60°N and 60°S there are zones of convergence, while at both the North and South poles there are divergence zones. During the course of a year, as the sun's direct rays shift northward and southward, the pattern of planetary winds and pressure also shifts.

As you can see from Figure 11-11, the earth's surface is divided into a series of *planetary wind belts*, and within each belt the winds generally blow in a specific direction. Most of the continental United States is within a region in which the wind direction is generally southwesterly.

SUMMARY

1. Wind direction is modified by the earth's rotation—the Coriolis effect.
2. Convection cells in the atmosphere are caused by differences in density of the air and the effect of gravity.
3. Atmospheric convection is affected by variations in insolation.
4. Air moves from regions of divergence to regions of convergence.
5. There is a series of planetary wind belts within which the winds generally blow in a specific direction.

VERTICAL MOVEMENTS IN THE ATMOSPHERE

Atmospheric Pressure and Altitude. The pressure of the atmosphere at any particular place depends on the weight of the air pressing down at that place. When the air above an area is denser, it exerts greater pressure. Our discussion of air density and pressure has been concerned with these conditions at the earth's surface. What happens to air density and pressure as you climb to higher elevations? The pressure of the air at any particular height depends on the weight of the air in a vertical column *above* that height. At the very top of the atmosphere, the pressure is near zero. As you descend toward the ground, the pressure gradually increases, since there are increasing amounts of air above you. Thus we see that the air pressure depends on altitude, it being less at higher altitudes than at lower. The variation in pressure with altitude is illustrated in Figure 11-12.

Remember, too, that air pressure and density are related. Where the pressure is low, the density will be low. Where the pressure is high, there will be more air compressed into the same volume and the density will be high. Thus, as you rise higher into the atmosphere, not only does the pressure go down, but the density does, also. As a result, most of the mass of the atmosphere is concentrated in its lowest regions. Although traces of air can still be found 1,000 km above the earth's surface, more than half the mass of the atmosphere lies within 6 km of the surface.

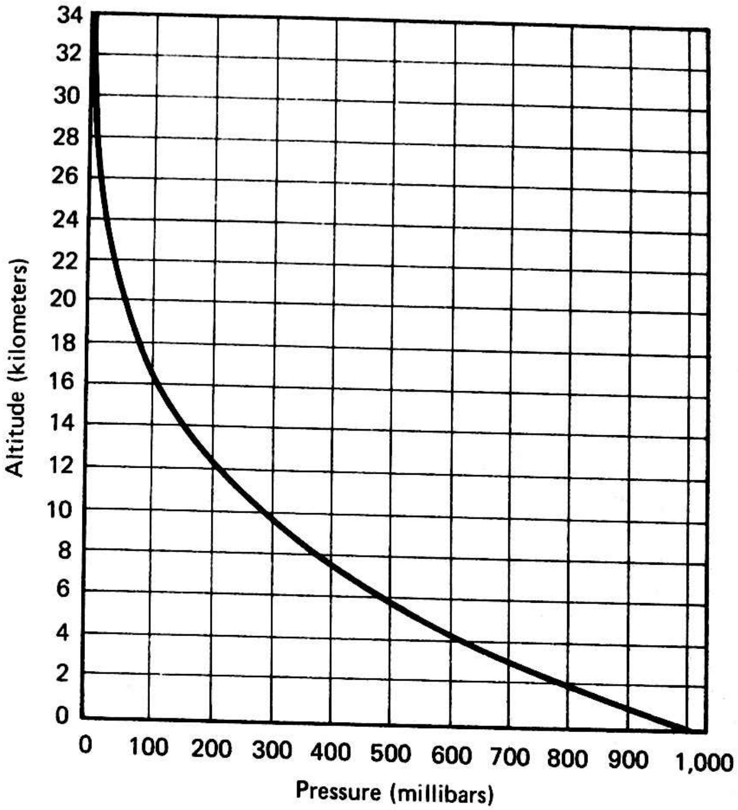


Figure 11-12. Change in pressure with change in altitude. You can see from the smooth curve that pressure decreases steadily with increasing altitude.

Adiabatic Temperature Changes. We know that when heat is added to the air, its temperature rises. This usually results in expansion of the mass of air. When heat is removed from a mass of air, its temperature drops, and the air contracts to a smaller volume. These changes in volume are the results of changes in temperature brought about by adding or removing heat.

What do you think would happen to the volume of a mass of air if the pressure around it was reduced? You are right if you say that the air would expand to a larger volume. Likewise, if the pressure around a mass of air increases, the air will be compressed into a smaller volume. In other words, the volume of air will change when its pressure changes, even though no heat has been added or removed. Any change that occurs without the addition or removal of heat energy is called an *adiabatic* change. The changes in volume that we have been talking about in this paragraph are examples of adiabatic changes.

Now here is a big question that is worth some careful thought. Will the *temperature* of the air change when it expands or contracts during an adiabatic change? Logic seems to say that the answer should be no. Since

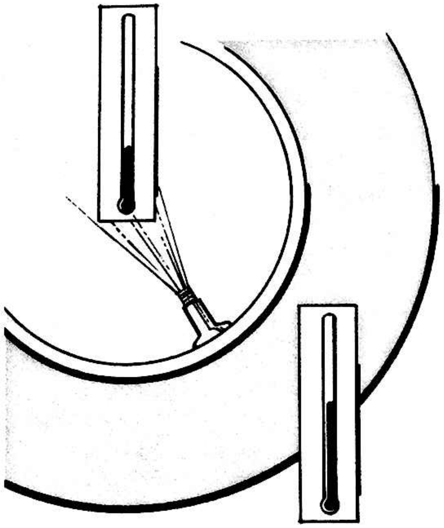


Figure 11-13. Adiabatic cooling. The air leaving the tire is cold because it has gone through an adiabatic expansion.

no heat is added or removed, the temperature should not change. But this is one case where logic lets us down! Experiments show that when a gas expands by an adiabatic process, its temperature drops. Likewise, when a gas is compressed, its temperature rises.

An example of a gas undergoing an adiabatic change is air escaping through the valve of an inflated tire (Figure 11-13). Such a stream of escaping air feels distinctly cold. This is not just the cooling sensation that a breeze may produce. A thermometer will show that the temperature of the escaping air is definitely lower than that of the surrounding air. The escaping air is cold because it expands as it leaves the tire, and the expansion is an adiabatic change.

Changes in the temperature of a gas that occur simply as a result of expansion or compression are called *adiabatic temperature changes*. In an adiabatic expansion, the temperature of the expanding gas decreases. The reason for this is that an expanding gas is doing work, that is, energy is coming out of it. Since no energy goes into the gas during the adiabatic expansion, the energy coming out must come from energy the gas already contained. In the case of simple expansion, the source of this energy is the kinetic energy of the gas molecules. As the expansion proceeds, the kinetic energy of the gas molecules decreases.

In Chapter 8 we saw that a decrease in the kinetic energy of the molecules of a substance means that the temperature of the substance has decreased. So, as the molecules of an expanding gas lose kinetic energy, the temperature of the gas drops.

All of this is reversed when a gas undergoes an adiabatic compression. Work has to be done on a gas to compress it. That is, energy has to be put into the gas. The energy going in becomes increased kinetic energy of the gas molecules, and the temperature of the gas rises.

Adiabatic Temperature Changes in the Atmosphere. Whenever a mass of air either rises or falls, it undergoes an adiabatic temperature change. For example, consider a mass of air that is rising (Figure 11-14). This upward movement may be caused in various ways. It may be the result of convection. It may be caused by a cold air mass moving in under a warm air mass. Or it may be the result of a wind striking the side of a mountain and being deflected upward. Recall that the atmospheric pressure decreases with increasing altitude. Therefore, as a parcel of air rises, the surrounding pressure on it decreases. As a result, the air expands. This expansion is adiabatic, and the temperature of the rising, expanding air decreases. Air rising in the atmosphere is always cooled by the process of adiabatic expansion.

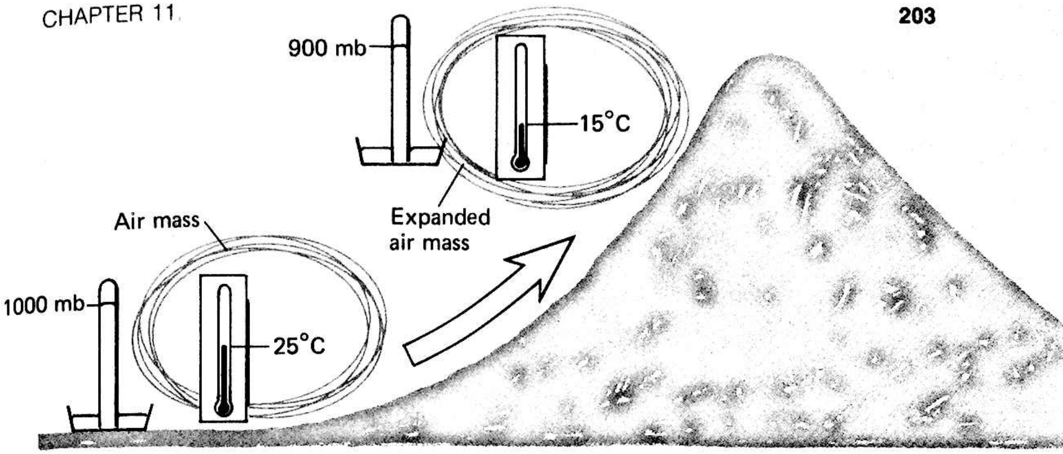
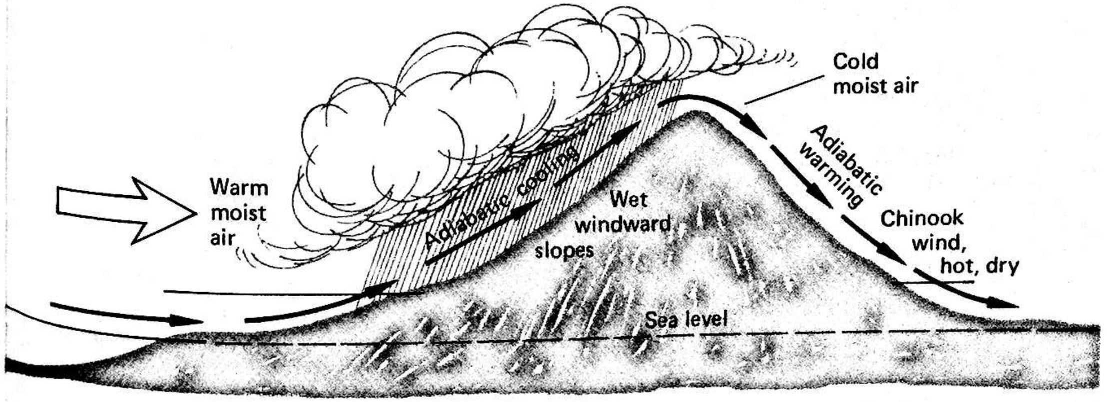


Figure 11-14. Adiabatic expansion in rising air. Whenever a mass of air rises, it undergoes expansion because the pressure is dropping. This expansion is adiabatic, resulting in a drop in temperature.

The opposite occurs in descending air. In this case, the descending air meets increasing pressure, and is compressed into a smaller volume. This compression is adiabatic, and the air temperature increases. Air descending in the atmosphere is always warmed by the process of adiabatic compression.

We can see a dramatic example of adiabatic warming in the *chinook*—a wind that blows down from the Rocky Mountains across the Great Plains. Figure 11-15 shows the conditions that can lead to a wind of this type. Cold air moving over the tops of the mountains moves down the slope on the other side. As it descends, it undergoes adiabatic warming, so by the time it reaches the valley, it is a warm, dry wind.

Figure 11-15. Chinooks. Chinooks, which are warm, dry winds, occur when air rising over a mountain sinks to the valley on the other side.



SUMMARY

1. As altitude increases, the atmospheric pressure decreases.
2. As a mass of air rises, its temperature decreases as a result of adiabatic expansion.
3. As a mass of air descends, its temperature increases as a result of adiabatic compression.

HOW MOISTURE LEAVES THE ATMOSPHERE

Earlier in this chapter we considered some of the sources of moisture for the water vapor in the atmosphere. We also looked at the process of evaporation by which liquid water enters the atmosphere as water vapor. There are also ways for water to come out of the air and return to the ground. *Condensation* and *sublimation* are the two processes by which this happens. Condensation refers to the change of state from gas to liquid. Sublimation is the direct change of state from gas to solid, without passing through a liquid state. Let us see the conditions under which each of these processes is likely to occur.

Condensation. At any given time and place, the air contains a certain amount of water vapor. We know that there is a limit to the amount the air can hold, and this limit depends on the temperature. At higher temperatures, the air can hold more water vapor than at lower temperatures. If the air temperature begins to fall, the amount of water it contains does not change at first. But this amount begins to get closer to the maximum. As the air temperature continues to go down, it eventually reaches a point at which the air is saturated. The water vapor that is present is now equal to the maximum that can be present at that temperature. If the air temperature were to drop any further, the air would be more than saturated. There would be more water vapor present than the air could hold, and some of the vapor would have to come out, either as liquid water or as the solid, ice.

The temperature at which cooling air becomes saturated is called the dew point. If this temperature is above the freezing point of water (0°C), condensation will begin when the dew point is reached. Droplets of water (dew) will appear on the surfaces of objects in contact with the air.

Figure 11-16 shows a simple experiment that you could do to find the dew-point temperature of the air. Your results won't be precise, but they will give you a rough idea of the dew point. The clear plastic cups shown in Figure 11-16 each contain some water. The temperatures vary as shown. Notice that one cup has moisture on its outer surface. The temperature of the water in that cup is about 10°C. The second cup, which is at room temperature (about 20°C), and the third cup, which is warmer than room temperature, do not show any signs of water on the outside.

If you add ice to the water in the second cup and stir the mixture, the temperature gradually drops. If you watch closely, you may be able to find the temperature at which moisture begins to appear on the outside of the cup. The temperature at which it appears is the dew-point temperature.

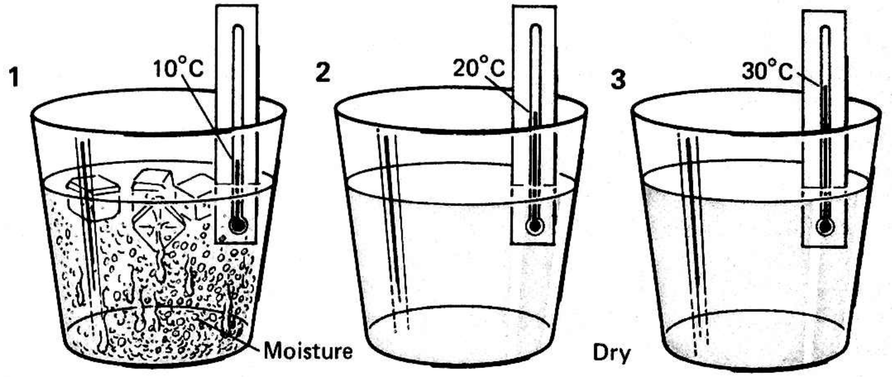


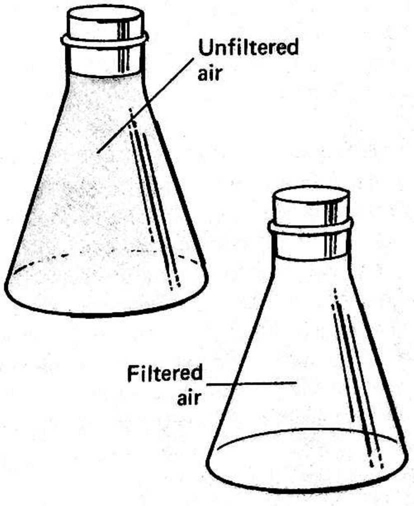
Figure 11-16. Finding the dew-point temperature. You can get a rough idea of the dew-point temperature by adding ice to a cup of water at room temperature and observing the temperature at which condensation begins to form on the outside of the cup.

Condensation Surfaces. There is one important factor in condensation that we have not mentioned up to now. That is, for condensation to occur, there must be a surface for it to occur on. Look at Figure 11-17. On the left is a container filled with moist air. This air has not been filtered—it contains dust, pollen, and many other types of tiny particles called *aerosols*. On the right is a container filled with moist air, but the air has been filtered to remove all dirt, dust, pollen, and other aerosols. Both containers have been cooled to the same temperature. In the container of unfiltered air, we see that a cloud has formed. The air temperature must be at the dew-point temperature or even below it. But the container of filtered air is still clear. No condensation has occurred.

The explanation for this difference between the two containers is that in the unfiltered air the particles act as surfaces on which condensation can occur. In the pure air there are no such surfaces, and condensation cannot begin without them.

When strong winds blow over the ocean, fine sprays of salt water are blown into the air. The water evaporates, leaving tiny crystals of salt, which are carried throughout the atmosphere. Did you ever notice how

Figure 11-17. Condensation nuclei. Condensation will not occur at the dew point in air that has been filtered to remove all aerosols.



sticky the table salt gets when the air is damp? This happens because salt acts as a condensation surface. This happens in the atmosphere too. The salt crystals act as centers on which water droplets can condense. The salt crystals act as *condensation nuclei.*

So, for condensation to occur, two conditions must be met: (1) moist air must be cooled to the dew-point temperature, and (2) a surface must be present on which condensation can form.

Sublimation. The examples of condensation that we have looked at occurred at temperature above 0°C. What happens when the dew-point temperature is 0°C or below? Does water vapor still condense to liquid water? No. At temperatures below 0°C, water vapor condenses directly into the solid state. Instead of water droplets, it forms ice crystals. This process is called *sublimation.* The frost you find on the inside of your window when it is extremely cold outside is the result of sublimation. Air in the room comes in contact with the window, which is below 0°C because of the cold air outside. The water vapor in the inside air *sublimes* on the window, forming frost. The frost you sometimes see on grass or on cars is also the result of sublimation.

When sublimation occurs in the atmosphere, the water vapor forms ice crystals around condensation nuclei, and the result is a snowflake.

Clouds. We have talked about the formation of droplets of water on surfaces in contact with air at the dew point. What happens when air above the ground is cooled to the dew-point temperature? If condensation nuclei are present (and they almost always are), condensation or sublimation will take place on their surfaces. Very small droplets of water or crystals of ice will appear, and these will form a *cloud.* A cloud is a collection of water droplets or ice crystals so small that they can be kept suspended in the air by upward air currents.

Clouds often form in air that is rising. As we have seen, the temperature of rising air decreases because of adiabatic expansion. As the air cools, its temperature approaches the dew point. When the rising air reaches an altitude at which its temperature has dropped to the dew point, clouds will form. For this reason, the bases of a group of clouds are often at about the same altitude. If the rising air started our fairly dry, it has to rise higher before clouds will form. If the air was nearly saturated to begin with, clouds will form at low altitudes. Clouds can even form at ground level. They are then called *fog.*

Condensation Level. What determines the altitude at which condensation occurs and clouds form? Is there any way of predicting the exact altitude at which the temperature of rising air will reach the dew point?

As a parcel of air rises, it undergoes adiabatic expansion and cooling. It has been found that this cooling occurs at a definite rate, called the *adiabatic lapse rate.* Suppose we start out with unsaturated air at ground level. For each 100 meters of altitude it gains, the temperature of this air will drop 1°C until it reaches the dew-point temperature. This lapse rate is called the *dry* adiabatic lapse rate, and it applies to rising unsaturated air.

When the air cools to the dew-point temperature, condensation begins. We know from Chapter 8 (page 132) that condensation releases latent heat. Therefore, once condensation begins, the temperature of rising air drops at a lesser rate because heat is being added to the air by condensation. For saturated air the adiabatic lapse rate is called the *wet* adiabatic lapse rate, and it is 0.6°C per 100 meters of altitude.

So, unsaturated rising air cools at the dry adiabatic lapse rate of 1°C/100 m, while saturated rising air cools at the wet adiabatic lapse rate of 0.6°C/100 m. You might think that if you know the air temperature and dew-point temperature at the surface, you can now figure out the altitude at which condensation occurs. But there is another factor that must be considered. This is that the dew-point temperature of rising air also drops with increasing altitude. The dew-point temperature decreases because as the rising air expands, the amount of water vapor per cubic meter decreases, and so its vapor pressure is lowered. A lower vapor pressure means a lower dew point. As the air rises, its dew-point temperature decreases at a rate of 0.2°C/100 m.

Putting these two factors together, we find that the temperature of rising unsaturated air approaches the dew-point temperature at a rate of 0.8°C/100 m. So, if you know the air temperature at the surface and the dew-point temperature of the air at the surface, you can calculate the altitude at which condensation occurs. An example of this can be seen in Figure 11-18.

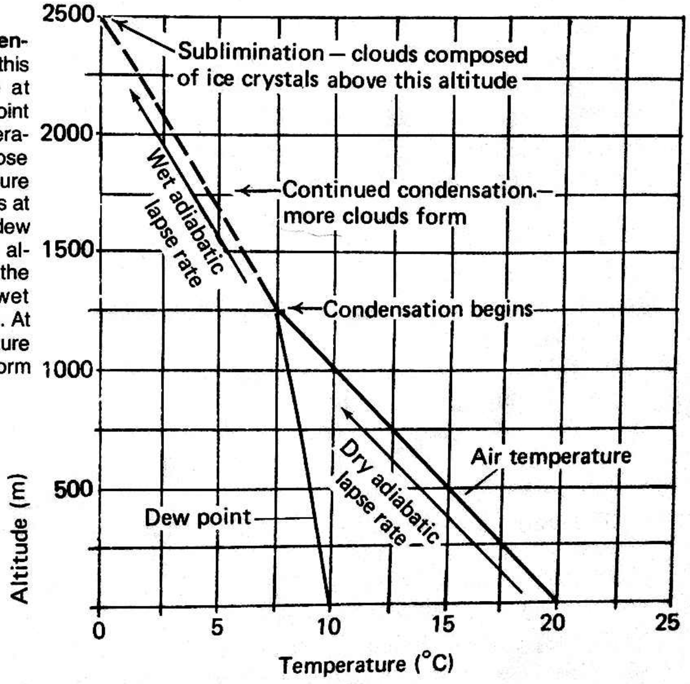


Figure 11-18. Finding the condensation altitude of rising air. In this example, the air temperature at ground level is 20°C and the dew point is 10°C. As the air rises, its temperature drops at the dry adiabatic lapse rate (1°C/100 m) until its temperature drops to the dew point. This occurs at an altitude of 1250 m (where the dew point is only 7.5°C). Above this altitude, condensation occurs and the air temperature drops at the wet adiabatic lapse rate (0.6°C/100 m). At an altitude of 2500 m, the temperature has dropped to 0°C. Ice crystals form by sublimation above this level.

Precipitation. Droplets of water or crystals of ice, no matter how small they are, are still much denser than air and will fall in air. However, because of air friction, small particles fall more slowly than large ones. If the drops or crystals in a cloud are falling through *rising* air, they tend to be kept at the same altitude. That is what keeps a cloud up.

In a dense cloud, tiny droplets of water are constantly colliding. They are therefore constantly joining to form larger and larger drops. As these larger drops form, they begin to fall faster. If the drops become large enough, they fall too fast to be kept up by the rising air currents, and they fall as rain. Any form of water that falls from the atmosphere and reaches the ground is called *precipitation*. Rain is one form of precipitation.

Precipitation and Atmospheric Transparency. Earlier in this chapter we explained how tiny particles—aerosols—in the air act as surfaces on which condensation occurs. These aerosols, including dust, soot, and many other substances, are added to the air both by natural processes, such as volcanic eruptions, and by human activities. The more aerosols there are in the air, the less transparent the air is to insolation. When condensation occurs, some of the aerosols are incorporated into the precipitation, and others are washed down by the falling rain or ice. So precipitation and cloud formation remove some of the aerosols and thus clean the air.

Air-Surface Interaction. As winds blow, there is a direct release of energy by the atmosphere. The moving air sets materials into motion. Dust and small pieces of rock are moved about, resulting in erosion by wind. (This will be considered in Chapters 15 and 16.) Wind also moves water. Waves on lakes and oceans are the result of wind. Wind is one of the factors affecting surface currents in large bodies of water. The Gulf Stream in the Atlantic Ocean is affected by the prevailing wind direction. The wind thus acts as an agent in the transfer of energy from the atmosphere to the surface of the earth.

SUMMARY

1. Condensation can occur when the air is saturated and when a condensation surface is available.
2. Sublimation is the process by which water vapor changes directly to ice at temperatures below 0°C.
3. During condensation and sublimation a significant amount of heat energy is released.
4. Clouds consist of liquid water droplets and/or ice crystals.
5. Precipitation is any form of water that falls from the atmosphere and reaches the ground.
6. Precipitation results when the condensation droplets or ice crystals in a cloud grow large enough to fall.
7. The transfer of energy from the atmosphere can be seen in wind-blown particles of matter and surface ocean currents.

FINDING RELATIVE HUMIDITY

Air at a rather moderate 25°C (77°F) can feel uncomfortably hot and "muggy" if it is humid. On the other hand, the temperature can be well up in the 30's (Celsius)—over 90°F—and still feel fairly comfortable if the air is dry. It's the relative humidity that makes the difference. Physical comfort depends on both the temperature and the relative humidity. That is one reason we would like to be able to measure relative humidity. A comparison of the dew-point temperature and the actual air temperature gives us a general idea of the relative humidity. The greater the difference between them, the lower the relative humidity. But can this information be used to calculate the actual relative humidity in percent? The answer is that it can, but not directly. To see how dew point is related to relative humidity, we need to say something more about vapor pressure.

Relative Humidity and Vapor Pressure. In Figure 11-6 on page 192 you saw how a barometer with a little water in it could be used to find the saturation vapor pressure for any particular air temperature. In the example of Figure 11-6, the air temperature is 25°C and the saturation vapor pressure is 31 mb. The space above the column of liquid inside the barometer is saturated with water vapor. Its relative humidity is 100%.

Suppose that the air had only 25% as much water vapor in it as it has when saturated. The relative humidity would then be 25%. But since there would be only 25% as many molecules of water vapor in the air, the vapor pressure would also be 25% of the saturation pressure. Let us suppose now that more water evaporated into the air, and its vapor content doubled to 50% of saturation. The vapor pressure would also rise to 50% of the saturation pressure. If the air became 75% saturated, the vapor pressure would be 75% of the saturation pressure.

What this tells us is that if we know the actual vapor pressure of the air, and if we know the saturation vapor pressure for the existing air temperature, we can easily calculate the relative humidity. All we have to do is find the ratio of the actual vapor pressure to the saturation vapor pressure and convert it to a percent.

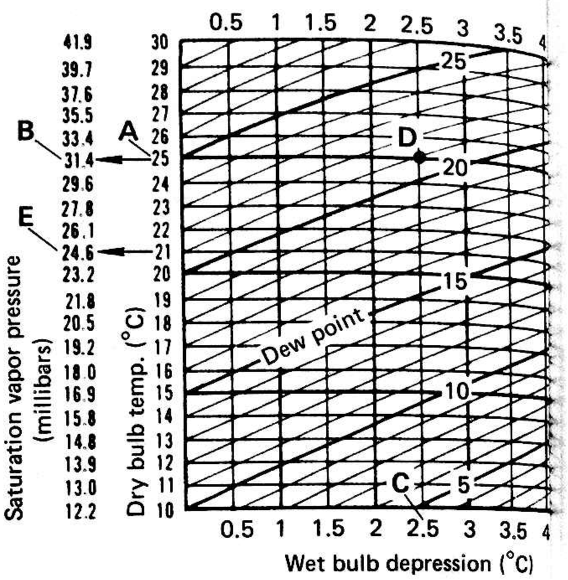
How can we find these two pressures? We have already seen how the saturation vapor pressure can be determined (Figure 11-6). From a series of experiments like this, we can make a table showing saturation vapor pressure for any temperature value. If we measure the temperature of the air, we can then look up its saturation vapor pressure in the table.

Is there any way we can find the actual vapor pressure of the air? We can do this by finding the dew point, as we will see in the next section.

Finding the Dew Point. In Figure 11-16 you saw a method for finding the dew point of the air. This is a difficult and time-consuming process. The dew point can be found in a much simpler way by means of a sling psychrometer (see page 26) and a chart like the one on page 538 in the Appendix. A portion of this chart is shown here (Figure 11-19) in order to explain the method.

Figure 11-19. Using the Dew Point Chart. Assume the dry-bulb reading is 25°C and the wet-bulb is 22.5°C. Then the wet-bulb depression is 2.5°C. Find the dry-bulb temperature along the left edge of the chart (A). The saturation vapor pressure for this temperature is 31.4 mb (B). Find the wet-bulb depression (2.5°) along the bottom (C). Read across from (A) and up from (C) to find the dew point (D). It is 21°. The saturation vapor pressure for 21° is 24.6 mb (E). This must be the actual vapor pressure of the air at its present temperature. Relative humidity is the ratio between actual vapor pressure and saturation vapor pressure, expressed as a percent:

$$\text{Rel. hum.} = \frac{24.6}{31.4} \times 100 = 78\%$$



Using the sling psychrometer, we find the air temperature by reading the dry-bulb thermometer. We find the wet-bulb depression by reading the wet-bulb thermometer and subtracting its reading from the dry-bulb temperature.

Along the lefthand edge of the chart we find the saturation vapor pressure for the existing air temperature. The curved lines running across the chart are dew-point temperature lines. By reading across from the dry-bulb reading and up from the wet-bulb depression, we find the dew point. Following the dew-point line down to the left-hand edge of the chart, we find the saturation vapor pressure corresponding to the dew-point temperature. This is the actual vapor pressure of the air. Since we now know the actual pressure and the saturation vapor pressure, we can calculate the relative humidity by dividing actual vapor pressure by saturation vapor pressure and converting to a percent.

Notice all the information we get from a single observation with the psychrometer: air temperature, dew point, actual vapor pressure, saturation vapor pressure, and relative humidity.

SUMMARY

1. The vapor pressure of a sample of air is directly proportional to its water vapor content.
2. The relative humidity of the air is equal to the ratio of its actual vapor pressure to its saturation vapor pressure, expressed as a percent.
3. The vapor pressure of the air can be determined if its dew point is known.

REVIEW QUESTIONS

Group A

1. What is the main source of heat for the atmosphere?
2. Name some of the minor sources of heat for the atmosphere.
3. How does moisture enter the atmosphere?
4. What are the primary sources of moisture for the atmosphere?
5. Do evaporation and transpiration require energy?
6. Does the atmosphere gain energy through evaporation and transpiration? If so, in what form is this energy?
7. What is *vapor pressure?*
8. What is *saturation vapor pressure?*
9. Is the relationship between saturation vapor pressure and temperature direct or inverse?
10. Name three factors that affect the rate of evaporation.
11. Describe the relationship between the temperature of the air and its density.
12. Describe the relationship between the moisture content of the air and its density.
13. What factor modifies wind direction?
14. What causes convection cells in the atmosphere?
15. In which direction does air move between regions of convergence and regions of divergence?
16. What are the regions called where the winds generally blow in a specific direction?
17. Describe the relationship between altitude and atmospheric pressure.
18. What happens to the temperature of a mass of rising air? What causes this change?
19. What happens to the temperature of a mass of descending air? What causes this change?
20. Under what conditions can condensation occur?
21. What is *sublimation?*
22. What energy change occurs during condensation and sublimation?
23. What are *clouds?*
24. What is *precipitation?*
25. Under what conditions does precipitation occur?
26. How can the transfer of energy from the atmosphere to the earth's surface be observed?
27. How is the vapor pressure of a sample of air related to its water vapor content?
28. How is relative humidity related to the vapor pressure of air?
29. What measurement can be used to find the vapor pressure of the air?

Group B

1. a. Refer to Fig. 11-1 and name several sources of energy that heat the atmosphere.
   b. Describe how the atmosphere is heated through the process of radiation. (Review Chapter 9.)
   c. Describe how the atmosphere is heated through conduction. (Review Chapter 9.)
2. a. What is the process of evaporation?
   b. What is the process of transpiration?
   c. Describe how energy is involved in each process.
3. a. How is vapor pressure related to the amount of moisture in the air?

   b. What is meant by the statement: "At saturation vapor pressure a condition of dynamic equilibrium exists"?
   c. What can be done to increase the saturation vapor pressure of air?
4. Describe two changes in the atmosphere which may cause its density to increase.
5. a. What will happen to a mass of air that is located over the warm ocean near the equator?
   b. What do the terms divergence and convergence mean with respect to the circulation of air?
   c. What is an adiabatic temperature change?
6. a. What is the dew point?
   b. Why are the bases of clouds often flat and at about the same altitude?
7. a. What does relative humidity mean? How is it expressed?
   b. Describe two different ways relative humidity can be measured.

REVIEW EXERCISES

1. Assume that at noon on a particular day, the following conditions exist:

   The air temperature is 83°F.
   The relative humidity is 48%.
   The wind speed is 7 miles per hour and its direction is from the north.
   The barometric pressure is 1026.6.

   Draw a station model showing these weather conditions. See the example of a station model in Figure 10-1, page 157. To find the dew point from the given data, reverse the procedure in Figure 11-19, page 210, using the complete chart on page 538. First find the saturation vapor pressure corresponding to the given air temperature (in °C). Use the given relative humidity percentage to find the actual vapor pressure. Then find the air temperature for which this is the saturation pressure. That temperature is the dew point.
2. Set up a table that will allow you to record the daily weather data for your area for a period of one week. The data should include temperature, barometric pressure, wind speed and direction, relative humidity, precipitation, and cloud cover. This information can be obtained from newspapers, radio, television, or recorded announcements by the National Weather Service. The shorter the intervals between readings, the more meaningful the data will be.

   When you have finished collecting the data, analyze it and try to determine (a) whether there are any patterns in the readings (direct or inverse relationships), and (b) how your readings compare with the average readings for your area for the same time of year.

3. Describe the current weather in your area. What type of air mass is present and what is the probable source region for that air mass? Are your current weather conditions caused by the passage of a front? If so, what type of front is involved? Is your weather modified by any local conditions, such as lakes, hills, etc.?
4. From maps in newspapers or from television reports, follow the path of a severe low-pressure system across the country. Plot the path of the system over the course of a few days on a map of North America. Does this storm track follow the normal pathway?
5. Observe and describe the weather conditions during the passage of a front through your area.
   a. What type of front was it? What type of air mass followed the front?
   b. Did precipitation occur? If so, how long did it last? Was it rain, snow, hail, sleet? Was it gentle or violent?
6. Many old weather sayings have some basis in fact, while others do not. Collect some of these sayings and check their accuracy.
7. Figure 11-16 (page 205) shows a simple way to find the dew-point temperature. Suppose that by using that method, we found that the dew-point temperature was 12°C. Also suppose that the air temperature was 23°C at the time of the experiment. What was the relative humidity? What would happen to the relative humidity if the air temperature increased? Decreased?
8. Assume that the same conditions described in the last problem exist outdoors—air temperature 23°C, dew-point temperature 12°C.
   a. Using the information in Figure 11-18 (page 207), find the altitude at which clouds would begin to form.
   b. Suppose the air temperature at the surface is 25°C and the dew-point temperature remains at 12°C. At what altitude will condensation begin? What will the cloud that forms be composed of?
9. To answer the following questions, construct a graph like the one in Figure 11-18, page 207.
   a. If the surface air temperature is 30°C and the altitude of the cloud base is known to be 4.0 km, what is the composition of the cloud likely to be?
   b. What is the dew-point temperature at the surface?
   c. What is the relative humidity at the surface?