

Chapter 20

Humidity, Clouds, and Atmospheric Energy



LET IT SNOW!

Most students like “snow days.” The opportunity to sleep late, have some free time, and even play in the snow can be a welcome change from one’s usual school routine. The likelihood of winter storms leaving a thick blanket of snow depends on where you live. People who live near the eastern shore of Lake Erie and Lake Ontario receive more snow than any other locations in New York State.

The Tug Hill Plateau, east of Lake Ontario, holds the state record for snowfall. On January 11–12 of 1997, an observer for the National Weather Service measured a snowfall of more than 6 feet in 24 hours. This storm dumped an additional 2 feet of snow over a period of 4 days. Fortunately, the Tug Hill Plateau is one of the least populated areas of New York State and local residents have learned to cope with these monster storms.

The Buffalo area, near the eastern end of Lake Erie, also receives more than its share of the winter snow. A December 25, 2001, snowstorm in Buffalo practically shut down the city when 6 feet of snow fell over a 4-day period. Unlike the Tug

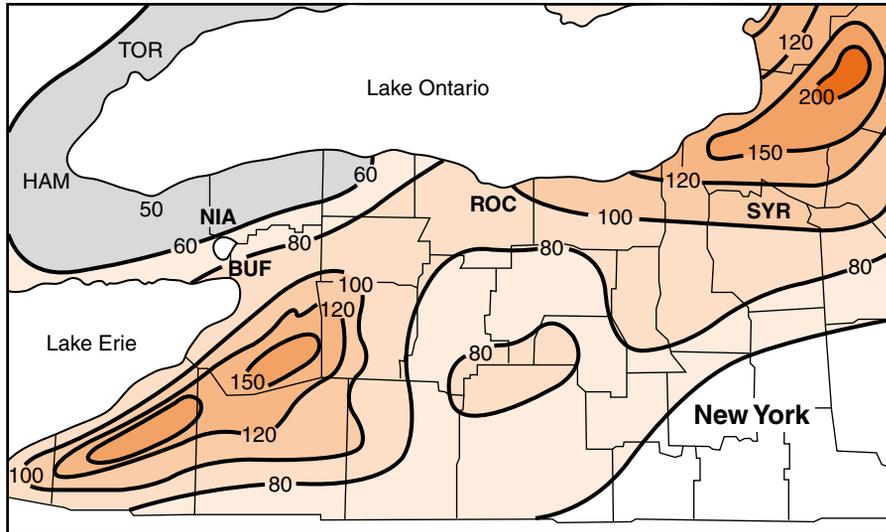


Figure 20-1 Two locations with the greatest average winter snowfall in New York State are located just east of Lakes Erie and Ontario.

Hill Plateau region, the Buffalo metropolitan area has a population of more than 1 million people. There was too much snow to push aside on many streets, so snow had to be transported out of the city in trucks. Fortunately, this storm was localized, and snow removal equipment was rushed in from other towns and cities in Western New York. Figure 20-1 shows the average annual snowfall in inches for parts of western New York State. Notice the two areas of maximum snowfall just east of each of the two Great Lakes.



Lake-Effect Storms

Why do these areas receive so much snow? Both locations are in the path of weather events known as **lake-effect storms**. These are mainly winter-weather events that result from a combination of atmospheric phenomena and geographic factors. The most common wind direction in New York State is from the west. Air traveling more than 320 km (200 miles) over the Great Lakes picks up large amounts of moisture. In the winter, lakes do not cool as quickly as the air, and generally remain free of ice cover. Therefore, in early winter, air blowing over the warm water readily absorbs moisture.

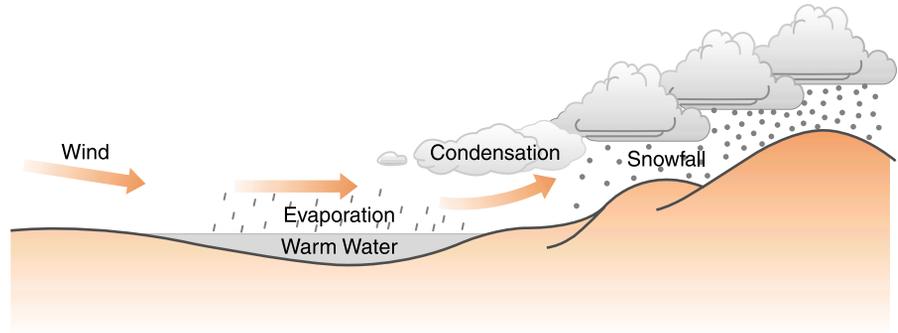


Figure 20-2 Lake-effect storms are most common in the winter when the lakes' water is warmer than the surrounding land areas. Sustained winds blowing over the Great Lakes absorb moisture. When the air is cooled over land, clouds and precipitation form. Additional cooling caused by the moist air rising over the hills increases precipitation.

However, as this moist air moves over land, it cools. When air cools, it loses its ability to hold water, causing clouds and precipitation. Precipitation increases when air rises over the hills at the ends of the lakes. If the westerly winds continue, the process is like a conveyor belt, picking up moisture from the lakes and dumping it on the land over a period of days. Figure 20-2 shows how lake-effect storms form.

ACTIVITY 20-1 RATE OF EVAPORATION

A small sponge cube can be used to investigate the variables that affect evaporation. The cube should be mounted on a string or thread that has been drawn through the cube.

After allowing the cube to absorb water, excess water that might drip should be squeezed out. The mass of the wet cube should be measured with an electronic balance at the beginning and the end of a uniform evaporation time.

Each group will select a location for its cube where the cube will experience evaporation. Make sure cubes are placed throughout the classroom. Consider limitations such as requiring that cubes be placed at least a predetermined distance from electrical devices.

Evaporation is indicated by the percent of original mass lost. Nothing other than air should touch the wet cube, which must be gently handled by its string.

What factors were most important in maximizing evaporation?



HOW DOES THE ATMOSPHERE STORE ENERGY?

In Chapter 19, you learned that most of the atmosphere's energy comes from the sun. You also learned that insolation warms the air and causes increased motion of molecules. We can feel and measure this motion as temperature. However, kinetic heat energy is not the principal reservoir of atmospheric energy. The energy released by a thunderstorm can be greater than the energy of the first nuclear bombs dropped over Japan in 1945. It is clear that large quantities of energy must be stored in the atmosphere and released in weather events. That potential is stored in a special form of heat energy called latent heat.

Has anyone ever suggested that you have hidden talents? Most people have some kind of special ability that enables them to do something better than most other people. For some individuals, school brings out those abilities. For others, unfortunately, they remain hidden. If you have undiscovered abilities, you possess latent talents. Latent means hidden or not apparent. As you will soon learn, heat energy can also be latent, or hidden.



States of Matter

Water, like other forms of matter, exists in three states: solid, liquid, and gas. Solid water is ice. Liquid water is simply called "water." In the form of a gas it is known as water vapor. The temperatures that occur on our planet allow water to exist in all three states in the natural surface environment.

The expression **phases of matter** is sometimes used as a synonym for states of matter.

When water changes among these states, a great deal of energy is involved. Heating that causes a change in temperature shows up as increased kinetic energy of molecules. However, energy that transforms solids to liquids and liquids to gases does not show up as a temperature change. In this sense, it is hidden, or latent energy. **Latent heat** is therefore energy that is absorbed or released when matter changes state.

A variety of units can be used measure energy. It is convenient to use calories. A **calorie** can be defined as the energy absorbed when the temperature of 1 gram of water increases 1 Celsius degree. That could be from 20 to 21°C or 86 to 87°C. One calorie is also released when 1 gram of water cools 1 Celsius degree.

Different substances absorb different amounts of energy as they change temperature. The reason is that they have different specific heats. **Specific heat** is the energy needed to raise the temperature of 1 gram of a substance 1 Celsius degree, without changing its state. The higher the specific heat of a substance, the more energy needed to raise its temperature. For example, it takes more energy to heat 1 gram of water (specific heat = 1 calorie/gram · °C) 1 degree Celsius than it takes to heat 1 gram of lead (specific heat = 0.03 calorie/gram · °C) the same amount. Figure 21-3 on page 523, from the *Earth Science Reference Tables*, lists the specific heats of some common materials.



Changes in State

For now, you will deal only with heating and cooling of water. Consider what happens to 1 gram of water that starts as ice at a temperature of -20°C and absorbs energy. Figure 20-3 on page 488 graphs the process. Because ice has a lower specific heat than liquid water, ice warms more readily. It takes only 10 calories to warm the ice to the melting temperature of 0°C . The ice stays the same temperature as it continues to absorb energy. In fact, it takes 80 calories to melt a single gram of ice with no change in temperature. That is why

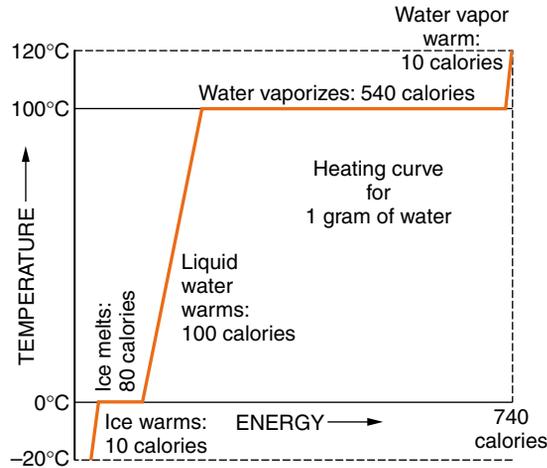


Figure 20-3 This graph is called a heating curve. It shows what happens as water absorbs energy, changing from ice at -20°C to water vapor at 120°C . Notice that most of the energy is used to change liquid water into water vapor with no change in temperature. The level parts of this graph indicate absorption of latent heat.

the name “latent” is applied to energy used for a change in state.

MELTING The change from a solid to a liquid is called **melt-*ing***. Once the ice has melted, its temperature can increase. The energy used to melt a gram ice at a constant temperature of 0°C (80 calories) is nearly as much energy as it takes to heat the gram of water from its melting temperature of 0°C to the boiling temperature of 100°C (100 calories).

VAPORIZATION The change in state from liquid to gas (vapor) at any temperature is **vaporization**. **Boiling**, a form of vaporization, is the change in state from a liquid to a gas at the boiling point of the substance. Of all its changes in state, vaporization of water requires the most energy: 540 calories. Again, during boiling there is no change in temperature. After all the water becomes vapor, the addition of a final 10 calories, heats the gram of water vapor to a temperature of 120°C . Of the total energy involved in these five changes, vaporization alone took 73 percent. The evaporation of water is the principle way that the atmosphere absorbs solar energy as shown in Figure 20-4.

CONDENSATION You have read that vaporization is the most important way that insolation adds energy to the atmosphere. How does the atmosphere release that energy to make wind and weather? The energy absorbed by the atmosphere in

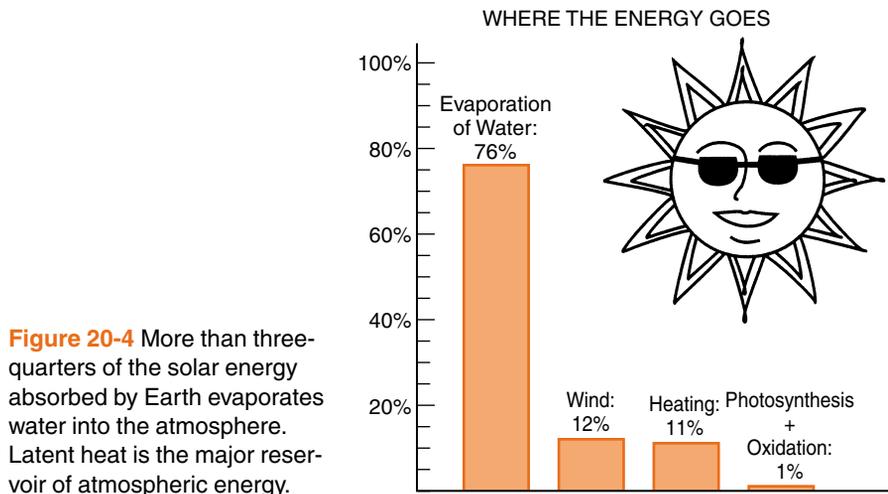


Figure 20-4 More than three-quarters of the solar energy absorbed by Earth evaporates water into the atmosphere. Latent heat is the major reservoir of atmospheric energy.

phase changes is released when water returns to lower energy phases. For example, the 540 calories used to vaporize each gram of water is released when water vapor changes back to a liquid. **Condensation** is the change from a gas, such as water vapor, to a liquid, such as water.

Have you ever noticed that grass is sometimes wet on a cool, moist, but clear summer morning? Water that collects on outdoor surfaces when moist air is cooled is called dew. Where did the moisture come from? **Dew** is moisture that condenses from water vapor in the atmosphere onto cold surfaces. Dew does not fall from the sky, so it is not considered a form of precipitation.

FREEZING Energy absorbed to melt ice is also released when water freezes. **Freezing** is the change in state from a liquid to a solid. Although freezing releases only 80 calories of heat energy per gram (compared with 540 calories per gram for condensation), this is still an important contribution to heating the atmosphere.

Frost is similar in origin to dew. It is composed of ice crystals that form directly from water vapor in contact with surfaces below 0°C. The change of a vapor directly to a solid, skipping the liquid phase, is generally referred to as deposition. This change releases latent heat of vaporization (520 calories per gram) and latent heat of freezing (80 calories per gram). Figure 20-5 on page 490, from the *Earth Science Refer-*

Properties of Water

Energy gained during melting.....	80 calories/gram
Energy released during freezing.....	80 calories/gram
Energy gained during vaporization.....	540 calories/gram
Energy released during condensation.....	540 calories/gram
Density at 3.98°C.....	1.00 gram/milliliter

Figure 20-5 Properties of water.

ence Tables, shows these properties of water. (The density of water is listed at 3.98°C because at this temperature water is most dense. Consequently, it is generally cold water that sinks to the bottom of the ocean.)

Ice is the lowest energy phase of water. When ice is made of delicate crystals, it is known as snow. Ice must absorb energy

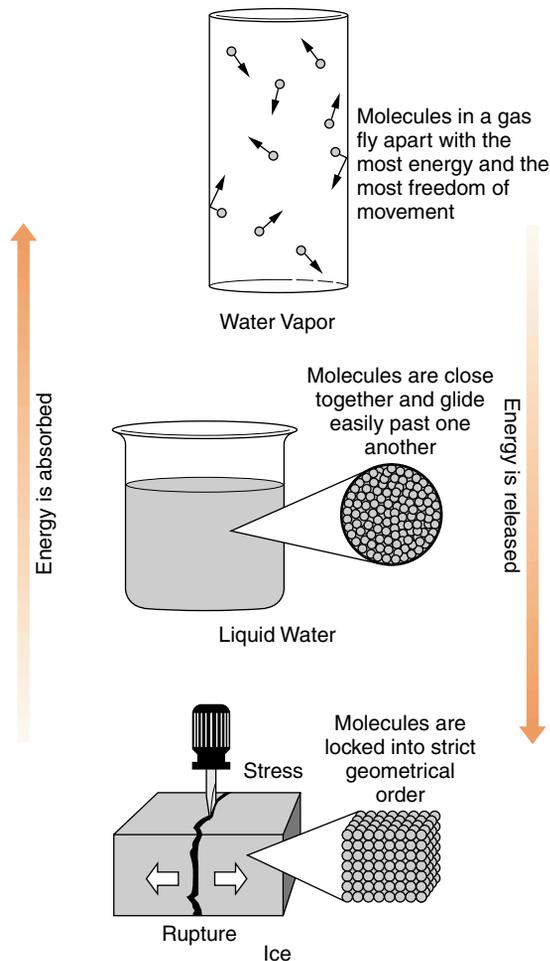


Figure 20-6 When water changes state, latent potential energy is absorbed or given off. During melting and vaporization water absorbs energy. Condensation and freezing release energy.



LAB 20-1: Observing Latent Heat

Materials: safety goggles, 250-mL beaker, hot plate or burner, thermometer about 15 cm long (0–120°C), stirring rod, timer or clock, snow or crushed ice, scale, graph paper, heat protection (such as a fire-retardant glove)

SAFETY PRECAUTIONS:

1. Wear safety goggles whenever you heat anything in the lab or whenever you mix two liquids and at least one is not water.
2. Use care around flames or heat sources. The teacher should carefully supervise all lab group setups and procedures.
3. At the end of the procedure, let hot objects cool before they are cleaned and put away.

Procedure:

1. Place fine ice chips or snow in a 250-mL beaker. Add just enough water so that it is visible under the snow near the bottom of the beaker. A total of 200 mL of ice and water works well.
2. Take the initial ice-water temperature and place the beaker on a hot plate or over a medium burner flame. Stir the water-ice mixture and record the temperature every 30 seconds. Continue until the water has been at a full boil for 5 minutes or until half the water has boiled away. (Whichever comes first.) CAUTION: Use heat protection for your hand while stirring. The air above the beaker and the stirring rod may become very hot.
3. It is important to stir the ice-water mix with the stirring rod until all the ice has melted. DO NOT use the thermometer as a stirring rod. The thermometer can rest in the water. Be careful not to hit the thermometer with the stirring rod. Note on your data sheet when the ice has completely melted and when the water comes to a full boil.
4. Graph your data with time on the horizontal axis. What section(s) of the graph indicate latent heat?

to change to liquid water. Liquid water must absorb energy to change to water vapor. Water vapor is the phase of water with the highest energy because of the latent heat it contains. Water vapor can release energy to become liquid water and then ice. Figure 20-6 shows the three phases of water relative to their latent energy. It also shows when energy is absorbed or released during changes in state.

What happens when energy is released by condensation or freezing? That energy warms the air, or at least prevents it from cooling as much as it would without the addition of latent heat. For example, as air rises, expansion causes it to cool. If a cloud is forming as water vapor condenses into cloud droplets, the cooling is slowed. This can keep air in a cloud warmer than its surroundings and keep the air rising. The release of latent heat causes rising air currents that can lead to violent weather, such as thunderstorms and hurricanes.



HOW DOES THE ATMOSPHERE ABSORB WATER VAPOR?

E evaporation is the most important way that moisture enters the atmosphere. If you have ever observed puddles disappear after a rain storm, or dew vanish in the morning sunlight, you have observed evaporation. **Evaporation** can be defined as the vaporization of water when the temperature is below the boiling point.



Evaporation and Kinetic Energy

How can water change to water vapor below the boiling temperature? You may recall that temperature is defined as a measure of the average kinetic energy of molecules. This indicates that within a substance some molecules have more energy than others. Within liquid water, only those molecules that absorb enough energy to transform into water vapor escape as a gas. The cooler molecules are left behind. This is why your body often feels cooler when you get out of the water at a beach or swimming pool. It is like separating the tallest individuals from a crowd of people. With the tallest people gone, the average height of people in the crowd would be less than it was when the tall people were still there. Evaporation is a similar process. The escape of the most energetic

molecules reduces the average energy of the molecules remaining.



Sources of Water

Evaporation from the oceans is the primary source of water vapor in the atmosphere. Covering almost three-quarters of our planet, the oceans provide a vast area for evaporation. On land, freshwater and groundwater also contribute to atmospheric humidity through evaporation.

Moisture also enters the atmosphere from plants. Plants draw water from the soil through their roots. Plants use water for a variety of functions, such as transporting nutrients from the soil throughout the plant. Plants also need water to carry on photosynthesis. Carbon dioxide is combined with water in the presence of sunlight to produce glucose for energy.

Water evaporates from plants, especially from their leaves, in a process known as **transpiration**. In some places on land, more water enters the atmosphere by transpiration than by evaporation from surface water and from the ground.



Rate of Evaporation

The rate at which water evaporates depends on four factors:

- *Availability of water*—The greater the exposed surface area, the more water that can evaporate. This is why oceans are the primary source of atmospheric water vapor. It is also the reason the atmosphere is relatively dry in desert regions. Here there is little surface water, and the ground is usually dry.
- *Energy to support evaporation*—You have learned that tropical regions receive stronger sunlight than polar areas do. Therefore, evaporation is active in the tropics for two reasons. Solar energy (insolation) is strongest when the sun is high in the sky, as it usually is in the

tropics, and the energy of warm air itself also supports evaporation.

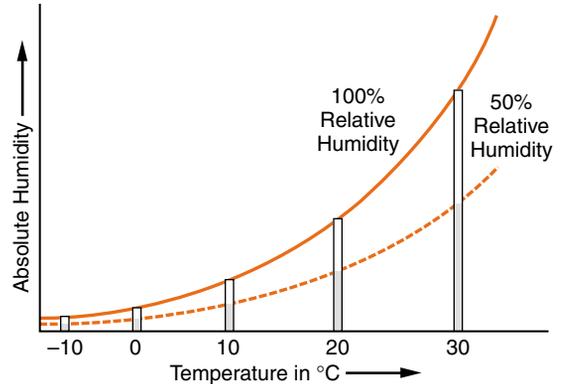
- *Ability of air to hold moisture*—The atmosphere has a limited ability to hold moisture. You have learned that warm air can absorb much more moisture than cool air. The present water vapor content of the air is also important. If the air is holding as much moisture as it can hold at its present temperature, the air is *saturated*. A sponge is a useful model. Sponges are good for picking up liquid spills. If the sponge is full, or saturated with water, it will not pick up any more water. In a similar way, dry air can absorb water, but air that is saturated cannot.
- *Wind*—This factor is related to the ability of water to hold moisture. If the air over a water surface does not move, it becomes saturated, and evaporation stops. The movement of air is needed to bring in a constant supply of dry air. You may have noticed that water evaporates faster on a windy day than it does when the air is calm. As wind speed increases, so does the supply of drier air, and therefore, evaporation also increases.



HOW DO WE MEASURE WATER IN THE ATMOSPHERE?

The *humidity* of air is an indication of its moisture content. Humid air contains more water vapor than dry air. Humidity can be described in terms of absolute humidity and relative humidity. **Absolute humidity** is the mass of water vapor in each cubic unit of air. It is sometimes measured in grams per cubic meter. However, absolute humidity is seldom reported because the ability of air to hold water vapor changes so much with temperature. Figure 20-7 shows that for each 10°C rise in temperature, air can hold roughly twice as much water vapor. Knowing the absolute humidity does not indicate whether the air is close to saturation, unless the air temperature is also indicated.

Figure 20-7 For every 10°C increase in temperature, the atmosphere can hold about twice as much moisture. The dotted line shows how much water vapor air is actually holding at any given temperature when the relative humidity is 50 percent.



Dew Point

The dew-point temperature may be used as an indication of absolute humidity. Figure 20-7 shows that as air is cooled, its ability to hold moisture decreases. If moisture is not taken out of the air, it can be cooled until the air is saturated. The temperature at which this occurs is known as the *dew-point temperature*. Sometimes this temperature is just called the dew point. It is called the dew point because when the outside temperature falls below the dew point, dew (or frost) can form on exposed surfaces.

The dew-point temperature can be demonstrated with a glass of ice water. If the glass cools the adjacent air below its dew-point temperature, a film of water will form on the cold outside surface of the glass. In theory, you can measure the dew point with the glass of water. As the surface of the glass is cooled very slowly, the dew point is the temperature of the water when a film of water starts to condense on the outside of the glass. In practice, it is difficult to observe just when condensation begins. Therefore, the results of this method tend to be inconsistent.

ACTIVITY 20-2 EXTRACTING MOISTURE FROM AIR

Place a mixture of ice and water in a glass. (If available, a shiny metal container works even better.) Determine the mass of the glass and mixture with an electronic scale. Then let the glass sit

until the ice has melted. You may be able to observe moisture that has condensed on the outside of the glass. Measure the mass a second time. Can you see a change in mass?

Where did the moisture on the outside of the glass come from? Does this procedure work better on some days than others? Why?

A better way to find the dew point is to use an instrument called a **psychrometer** (sigh-CRAH-met-er). A psychrometer is a form of **hygrometer**, an instrument used to measure humidity. Figure 20-8 illustrates a sling psychrometer. It is made from two thermometers mounted side by side on a narrow frame. The sling is the cord or chain that is used to suspend the instrument. One thermometer records air temperature. This is the **dry-bulb temperature**. A wet cloth called a wick covers the bulb of the second thermometer. This

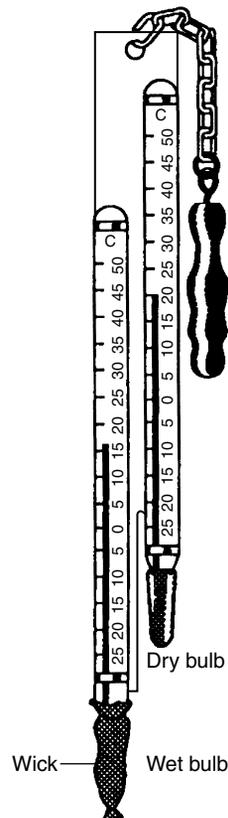


Figure 20-8 A sling psychrometer consists of two thermometers mounted side-by-side, one with its bulb covered by a wet wick. When the instrument is moved through the air, the dry-bulb thermometer records air temperature. The wet-bulb thermometer is used to measure cooling caused by evaporation. The difference between these temperatures is the key to finding the dew point.

thermometer gives us the **wet-bulb temperature**. The wet bulb is usually mounted lower than the dry bulb to keep the water from splashing on the dry bulb.

When the psychrometer is swung through the air, evaporation from the wet wick causes the wet bulb to register a lower temperature. Depending on the design of the psychrometer, it may be necessary to swing the instrument for a minute or so to get accurate temperature readings. The dryer the air, the more evaporation from the wet wick and the greater the cooling effect. It is the amount of evaporation and cooling that allows us to determine the dew-point temperature. Unless they are equal, the wet-bulb temperature is always lower than the dry-bulb temperature.

Dew point can be confusing. Although it is expressed as a temperature in degrees Celsius (or Fahrenheit), it is not the actual temperature of the air. Instead, it tells you to what temperature the air can be cooled before condensation will begin. Dew point is a temperature, but it is used to indicate how much moisture is in the air. A table can be used to translate dew-point temperatures into absolute humidity, measured as the mass of water vapor per cubic meter. That is why dew point is a good indicator of absolute humidity.

Figure 20-9 on page 498 is taken from the *Earth Science Reference Tables*. This table is used with readings from a sling psychrometer to find the dew-point temperature of the air. A common mistake students make in using this table is to read the top scale of numbers as wet-bulb temperatures. The label clearly indicates that this scale is the *difference* between the thermometer readings. Remember that there is no wet-bulb scale on this table.

SAMPLE PROBLEMS

Problem 1 When you swing a sling psychrometer, the air temperature (dry bulb) is 18°C while the wet-bulb thermometer records 12°C . What is the dew point?

Solution The difference between 18°C and 12°C is 6°C . Use the dew-point temperature chart. Follow the vertical column down from 6 until it meets the horizontal row from the dry-bulb (air) temperature of 18°C . They meet at 7, therefore the dew-point temperature is 7°C .

Dew-point Temperatures

Dry-Bulb Temperature (°C)	Difference Between Wet-Bulb and Dry-Bulb Temperatures (C°)														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
-20	-33														
-18	-28														
-16	-24														
-14	-21	-36													
-12	-18	-28													
-10	-14	-22													
-8	-12	-18	-29												
-6	-10	-14	-22												
-4	-7	-12	-17	-29											
-2	-5	-8	-13	-20											
0	-3	-6	-9	-15	-24										
2	-1	-3	-6	-11	-17										
4	1	-1	-4	-7	-11	-19									
6	4	1	-1	-4	-7	-13	-21								
8	6	3	1	-2	-5	-9	-14								
10	8	6	4	1	-2	-5	-9	-14	-28						
12	10	8	6	4	1	-2	-5	-9	-16						
14	12	11	9	6	4	1	-2	-5	-10	-17					
16	14	13	11	9	7	4	1	-1	-6	-10	-17				
18	16	15	13	11	9	7	4	2	-2	-5	-10	-19			
20	19	17	15	14	12	10	7	4	2	-2	-5	-10	-19		
22	21	19	17	16	14	12	10	8	5	3	-1	-5	-10	-19	
24	23	21	20	18	16	14	12	10	8	6	2	-1	-5	-10	-18
26	25	23	22	20	18	17	15	13	11	9	6	3	0	-4	-9
28	27	25	24	22	21	19	17	16	14	11	9	7	4	1	-3
30	29	27	26	24	23	21	19	18	16	14	12	10	8	5	1

Figure 20-9 Use this table with wet-bulb and dry-bulb temperature readings to determine the dew point. Follow the vertical column below the difference between wet- and dry-bulb temperatures until it meets the horizontal row to the right of the dry-bulb (air) temperature. Where they meet, read the dew-point temperature.

Problem 2 A student used a sling psychrometer to obtain readings of 8°C and 11°C. What was the dew point?

Solution This problem introduces two new issues. First, although it is not stated, the dry-bulb temperature must be the higher temperature: 11°C. (Evaporation always makes the wet-bulb temperature the lower of the two temperatures.) Second, 11°C is not listed on the dry-bulb scale. It will be necessary to estimate its position between 10°C and 12°C. The difference between 11°C and 8°C is 3°C. The vertical column below 3°C intercepts the two closest dry-bulb temperatures at 4°C and 6°C. Therefore, you estimate the dew point at an intermediate value of 5°C.

Problem 3 If dry-bulb temperature is 24°C and the wet-bulb temperature is also 24°C, what is the dew point?

Solution This can be solved logically. If there is no difference between the two temperatures, it is because water was not evaporating from the wet bulb. When

no evaporation takes place, the air must be saturated. If the air is saturated (humidity is 100 percent), the temperature is at the dew point. Consequently, the dew point is also 24°C.



Practice Problem 1

If the dry bulb on a psychrometer reads 24°C while the reading on the wet bulb is 12°C, what is the dew point? What does this indicate about the humidity?

ACTIVITY 20-3 A STATIONARY HYGROMETER

Materials: Two thermometers, ring stand or frame, 30 cm of string, 2- to 4-cm section of a hollow, cotton shoelace (the wick), small dish, fan made of cardboard or any other convenient material.

An instrument to measure humidity can be set up on a counter or table. Suspend the two thermometers next to each other from the ring stand or frame. Place one thermometer bulb in the wet, hollow shoelace. The other end of the shoelace should rest in water in the dish.

Before you use the fan, record the two temperatures. Use your readings with the Dew-point Temperature Table to determine a dew point.

Repeat the procedure, but this time fan the thermometers for one minute before taking wet- and dry-bulb readings. Use this data to determine a second dew point.

Which determination of dew point is more accurate? Why?



Relative Humidity

Weather reports often include relative humidity rather than absolute humidity or even dew point. This is because relative humidity is easier for most people to understand. Relative humidity is a measure of how full of moisture the air is. *Relative humidity* can be calculated by dividing the absolute humidity

by the capacity of the air to hold water vapor. This ratio is expressed as a percent of saturation:

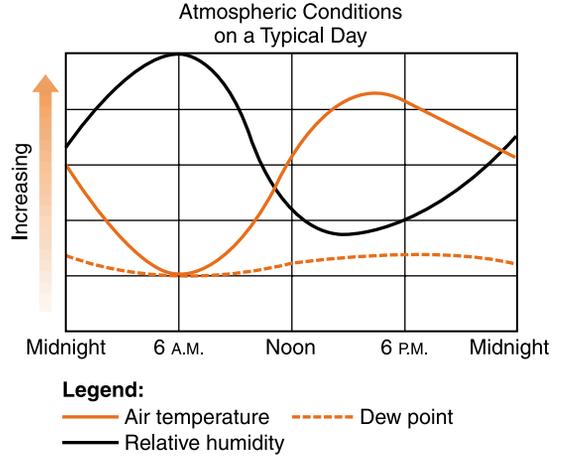
$$\text{Relative humidity} = \frac{\text{amount of water vapor in the air}}{\text{maximum water vapor the air could hold at this temperature}}$$

For example, if the relative humidity is 20 percent, the air is holding 20 percent, or one-fifth, of its moisture capacity. That is quite dry, and evaporation can readily add moisture to the air. However, if the relative humidity is 80 percent, the moisture content of the air is near saturation. Evaporation will be slow and the humidity is likely to be uncomfortable. Sweat may remain on your skin, and clothing does not dry well. These conditions apply at a constant relative humidity regardless of air temperature. That is the advantage of reporting relative humidity.

Relative humidity is not likely to remain the same if the air temperature changes. Consider a parcel of air that is cooling. If there is no evaporation or condensation, the absolute humidity (amount of moisture) in this body of air will remain constant. Remember that relative humidity is a ratio between two values. The ability of air to hold moisture decreases with decreasing temperature. As the air becomes cooler, it is closer to saturation, and the relative humidity increases. This frequently occurs at night when temperatures decrease, leading to the formation of dew or frost.

Figure 20-10 shows typical changes in air temperature, dew point, and relative humidity over a period of one day. The thick black line indicates changes in air temperature. The changes in temperature are the result of overnight cooling and daytime heating by insolation. Over this period there is little change in the dew point, indicating that the absolute humidity is relatively constant, as shown by the dotted line. However, changes in relative humidity depend on air temperature and dew point. At night, the thin line indicates that as the air temperature cools to the dew point, the relative humidity increases to 100 percent. This situation changes when the sun warms the air in the morning. Relative humidity drops as the air is warmed and its ability to hold water vapor increases.

Figure 20-10 The daily cycle of temperature and humidity shows that if the dew point stays nearly constant, changes in air temperature will cause the opposite changes in relative humidity. Although the absolute humidity has changed very little, the relative humidity is affected by air temperature.



Relative humidity can be determined by using a table found on the same page of the *Earth Science Reference Tables* as the dew point table. This table is reproduced in Figure 20-11. The dry- and wet-bulb temperatures from a sling psychrometer also are used with this table.

Relative Humidity (%)

Dry-Bulb Temperature (°C)	Difference Between Wet-Bulb and Dry-Bulb Temperatures (°C)														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
-20	28														
-18	40														
-16	48	0													
-14	55	11													
-12	61	23													
-10	66	33	0												
-8	71	41	13												
-6	73	48	20	0											
-4	77	54	32	11											
-2	79	58	37	20	1										
0	81	63	45	28	11										
2	83	67	51	36	20	6									
4	85	70	56	42	27	14									
6	86	72	59	46	35	22	10	0							
8	87	74	62	51	39	28	17	6							
10	88	76	65	54	43	33	24	13	4						
12	88	78	67	57	48	38	28	19	10	2					
14	89	79	69	60	50	41	33	25	16	8	1				
16	90	80	71	62	54	45	37	29	21	14	7	1			
18	91	81	72	64	56	48	40	33	26	19	12	6	0		
20	91	82	74	66	58	51	44	36	30	23	17	11	5	0	
22	92	83	75	68	60	53	46	40	33	27	21	15	10	4	0
24	92	84	76	69	62	55	49	42	36	30	25	20	14	9	4
26	92	85	77	70	64	57	51	45	39	34	28	23	18	13	9
28	93	86	78	71	65	59	53	47	42	36	31	26	21	17	12
30	93	86	79	72	66	61	55	49	44	39	34	29	25	20	16

Figure 20-11

SAMPLE PROBLEMS

Problem 4 If wet- and dry-bulb temperatures recorded with a sling psychrometer are 14°C and 24°C , respectively, what is the relative humidity?

Solution The difference between these temperatures is 10°C . The column leading down from 10°C meets the row extending to the right of the dry-bulb temperature, 24°C , at the number 30. Therefore, the relative humidity is 30 percent.

Problem 5 If both thermometers on a sling psychrometer record -4°C , what is the relative humidity?

Solution This is similar to Sample Problem 3. The table can be used but it is not needed. If there is no cooling of the wet-bulb thermometer, there was no evaporation, and the air is saturated: 100 percent humidity.

**Practice Problem 2**

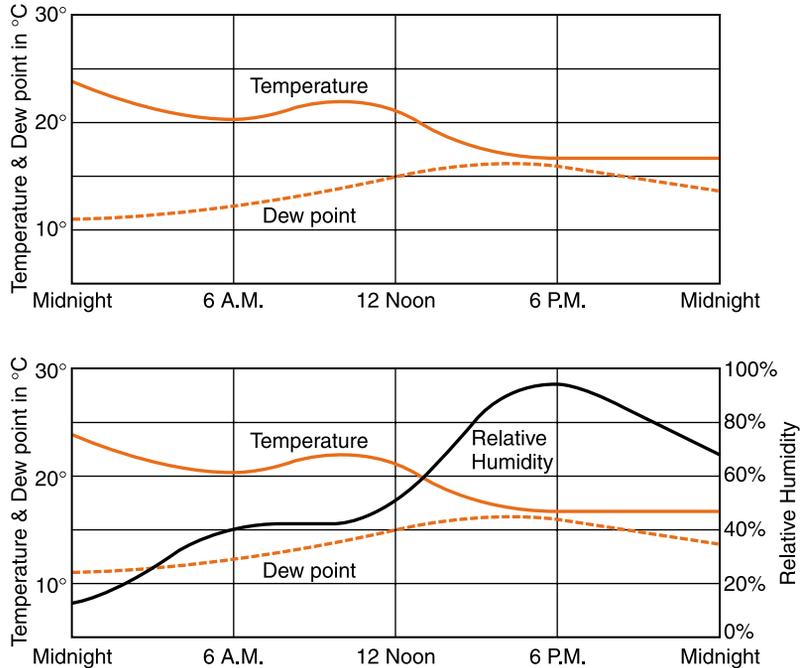
What is the relative humidity when the wet-bulb temperature is 11°C and the dry-bulb temperature is 15°C ?

**Predicting Precipitation**

One of the reasons meteorologists measure air temperature and determine the dew point is to predict precipitation. When the air temperature and dew point are close, the chance of precipitation increases. Figure 20-12 illustrates atmospheric conditions over a period of one day at a specific location. The top graph shows the temperature dropping in the late afternoon until it is close to the dew point. This is when precipitation is most likely. The bottom graph makes the prediction more clear by the addition of a line indicating relative humidity. Rising relative humidity indicates that the air is coming closer to saturation in the late afternoon. Again, this is a strong indicator of precipitation.

Predictions are based on weather observations from the past. Precipitation predictions are often expressed as a per-

Figure 20-12 The top graph shows air temperature drawing close to the dew-point temperature in the late afternoon. This is a sign that the likelihood of precipitation is greatest in late afternoon. The bottom graph has a third line to show relative humidity during the same period. The chance of precipitation is greatest when relative humidity is high.



cent chance of rain (or snow, etc.). For example, an 80 percent chance of precipitation means that during the past, of 10 days with similar conditions, there was precipitation on eight of the 10 days. A 20 percent chance of precipitation means that precipitation is possible, but not likely. A 50 percent chance of rain indicates that the chance of having rain equals the chance of not having precipitation.



HOW DO CLOUDS FORM?

You have learned that most of the energy for weather events comes from sunlight, and that energy enters the atmosphere primarily through evaporation. You also know that condensation (and deposition) release latent energy as water vapor changes into tiny water droplets and ice crystals to form clouds. Too small to fall as precipitation, the cloud droplets remain suspended in the air. A large body of these tiny droplets



Figure 20-13 Clouds are large regions of ice crystals or water droplets too small to fall through the air. Cloud formation releases energy that warms the air, creating updrafts. This often results in more cloud formation.

or ice crystals is known as a **cloud**, such as the cloud pictured in Figure 20-13. For clouds to form, several conditions must be met.



Cooling of Air

For condensation to occur, air must be cooled below its dew point. At ground level, air is cooled by contact with cold surfaces. How can air be cooled higher in the atmosphere? To understand how this occurs, it is useful to observe what happens when air is compressed. Have you ever felt a pump used to force air into automobile tires? The compressor on the pump gets warm. Some of this energy comes from friction. However, most of it is the result of compressing the air. It takes energy to compress air, and that energy turns to heat, which makes the air and the pump warm.

The opposite change occurs when air expands. Allowing air to expand takes energy out of the air. This causes the temperature of the air to lower. If you depress the pin in a tire valve, air rushes out. A thermometer held in the rushing air shows that the expanding air is cooler than the air in the tire. When air rises into the atmosphere, it expands due to reduction of atmospheric pressure with altitude. Expansion of a gas causes it to become cooler. If the air cools below its dew point, condensation can create a cloud.

ACTIVITY 20-4 THE EFFECT OF COMPRESSION AND EXPANSION ON AIR TEMPERATURE

If you place a plastic, liquid-crystal, digital thermometer in a transparent 1-liter soda bottle you can observe small changes in the temperature of air in the bottle. (These thermometers are often sold in aquarium supply stores.) With the thermometer inside, tightly cap the empty soda bottle. (The cap must be airtight.) If you compress the soda bottle by pushing in on its sides, you should be able to see the temperature inside change. How did the temperature change? You can also increase the pressure in the bottle with a special pump cap used to maintain the carbonation in opened soda bottles. These caps are sold in supermarkets.

Whichever way the pressure in the bottle is increased, when the pressure is released, the air temperature inside the bottle will change again. How does the temperature change when the pressure is released? Why do these changes in temperature occur? (Please note that this is not an easy phenomenon to explain. You may need to do some Internet or library research.)

What causes air to rise? Sometimes it is the result of winds blowing over mountains. Sometimes warm, moist air is pushed up by cooler, dryer air that is more dense. However, once the process of cloud formation gets started, it tends to keep going. Remember that condensation and deposition release energy that warms the surrounding air. This causes the air in the cloud to continue rising, and results in more cloud formation. When does it stop? Eventually the cloud runs out of moist air. Without water vapor to feed cloud formation, the atmosphere stabilizes and cloud formation stops.

**Condensation Nuclei**

When dew or frost forms on grass on a cold night, the air must be below its dew-point temperature. Nevertheless, a cloud (fog) is seldom observed. This is because water must condense

on a surface. In the atmosphere, those surfaces are provided by tiny particles of solids suspended in the air. They are called **condensation nuclei**. These particles are added to the atmosphere by dust storms, fires, and the exhaust from automobiles, homes, factories, and power plants. You have probably seen the white trails left by jets flying at high altitude. Actually, the trails are clouds that form on the exhaust particles from the jets' engines. At that altitude, air is usually below the dew point, but the lack of suspended particles prevents cloud formation. After a few minutes, the cloud is scattered, and the trail is no longer visible.

You may have noticed how clear the atmosphere looks after a rainstorm. Precipitation not only takes moisture out of the atmosphere, but it also brings down condensation nuclei. In addition, the falling droplets pick up other suspended particles. In this way, precipitation cleans the atmosphere.

How do clouds disappear? Clouds lose some of their moisture by precipitation. However, precipitation usually stops before the cloud is gone. Furthermore, most clouds do not produce precipitation. Clouds disappear when solar radiation vaporizes the cloud faster than cloud formation takes place. The tiny ice crystals and water droplets change back to water vapor and the cloud disappears.

ACTIVITY 20-5 **HOMEMADE CLOUDS**

Materials: large, wide-mouthed, container (a transparent glass or plastic jar or a large beaker), 1-gallon plastic food storage bag, match, 300 mL of ice, hot and cold tap water

Run a few centimeters of hot tap water into the bottom of the container. Place the crushed ice cubes and about 100 mL of cool water in the plastic bag. (Crushed ice or snow works better than big ice cubes.) Cover the mouth of the container with the bag of ice and water. Do you see a cloud?

Try this again. This time, hold a lit match in the container and blow it out. Allow some smoke from the extinguished match to circulate in the container. Place the bag of ice and water over the

mouth of the container. This time you should clearly see cloud inside the container.

What is the purpose of the hot water, the ice and water, and the smoke?



Altitude of Cloud Formation

Have you ever noticed that bottoms of clouds are often relatively flat while the tops of the clouds are often puffy and irregular? **Cloud-base altitude** is the height at which rising air begins to form clouds. To determine the altitude at which the air could form a cloud use the air (dry-bulb) temperature, the dew-point temperature, and a cloud-base altitude graph (Figure 20-14 on page 508).

Notice that there are two sets of slanted lines on this graph. The slanted lines labeled “dry-bulb temperature” show the rate at which air cools as it rises and expands. This is sometimes called the temperature lapse rate. The dew-point temperature also decreases with altitude, but not as quickly. The rate of change in dew point is shown by the slanted, dotted lines. Where the air temperature line meets the dew-point line, the height at which cloud formation (condensation) begins can be read from either the left or the right side of the graph. The companion diagram in 20-14 may illustrate this more clearly than the graph alone.

SAMPLE PROBLEMS

Problem 6 If the temperature at ground level is 20°C and the dew point is 12°C , how high must the air rise to begin cloud formation?

Solution Follow the slanted solid line above 20°C and the dotted line up from 12°C until they meet. (*Suggestion:* Lay the edge of a ruler or a blank sheet of paper to the right and along the 20° temperature lapse rate line to follow it more clearly.) The altitude of the cloud base in kilometers can be read on either of the vertical scales. In this case, it is 1 km.

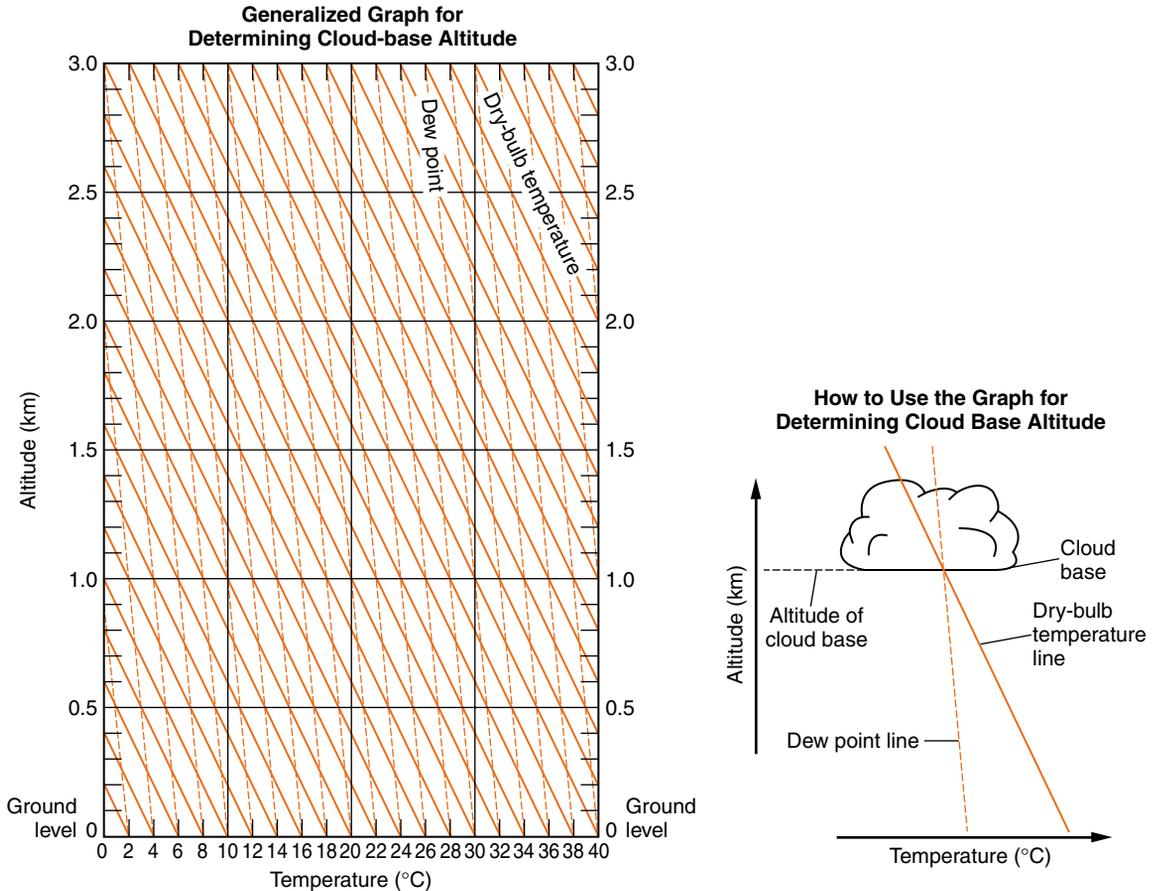


Figure 20-14 If you know the Celsius temperature and the dew point you can determine the elevation at which clouds begin to form in rising air. Follow the slant of the solid line above the dry-bulb temperature. Above the dew point follow the dotted line. They meet at the altitude (in kilometers) of the cloud base.

Problem 7 If you use a psychrometer to find dry-bulb and dew-point temperatures of 23°C and 14°C , respectively, how high must the air rise to form a cloud base?

Solution This air temperature, 23°C , is not printed on the graph. However, it is half way between 22°C and 24°C . Follow the angle of the slanted solid lines in the middle of the space between the lines for 22°C and 24°C . This imaginary line meets the dotted line from 14°C , the dew point, at a height of 1.1 km.

Problem 8 The air temperature is 90°F . The dew point is 50°F . How high must the air rise to form a cloud?

Solution In this problem, you have been given temperatures in degrees Fahrenheit. The temperatures must be converted to Celsius temperatures to use the graph. That conversion can be done using Figure 19-3 or the “Temperature” table in the *Earth Science Reference Tables*. While 90°F is approximately 32°C, 54°F converts to 12°C. On the cloud-base graph, the lines for 32°C air temperature and 12°C dew point converge close to an altitude of 2.5 km. That is the cloud-base altitude.



Practice Problem 3

One day, the air temperature was 77°F and the dew-point temperature was 60°F. What was the cloud-base altitude?

ACTIVITY 20-6 THE HEIGHT OF CLOUDS

Materials: hygrometer or two 30-cm, alcohol-filled glass thermometers mounted on a ring stand with one thermometer’s bulb covered by a wet wick, file folder or similar object to fan the thermometers

Use this apparatus to find the dry-bulb (air) temperature and the wet-bulb temperature. (To get an accurate wet-bulb temperature you will need to fan the wet bulb until the temperature stabilizes. This may take 30 seconds or so.)

Use these temperatures and the “Graph for Determining Cloud-Base Altitude” (Figure 20-14) to find the height at which a cloud could begin to form if the air in the room moved upward into the atmosphere.

Repeat the procedure on days you think the humidity is especially high or low. What would be the most likely sources of error in your determination of cloud base altitude?

TERMS TO KNOW

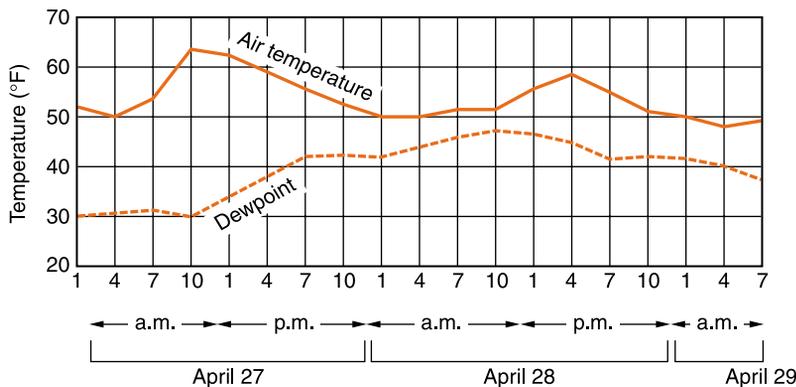
absolute humidity	dew-point temperature	melting
calorie	evaporation	phase of matter
cloud	freezing	psychrometer
cloud-base altitude	frost	specific heat
condensation	hygrometer	transpiration
condensation nuclei	lake-effect storm	vaporization
dew	latent heat	

CHAPTER REVIEW QUESTIONS

- Winds from the west often produce winter snowstorms at the eastern end of lakes Erie and Ontario. These storms are known as lake-effect storms. What causes these winter storms that often occur in the Buffalo and Tug Hill Plateau regions?
 - increased evaporation over the warm lakes followed by warming of the air as it travels over the land
 - increased evaporation over the warm lakes followed by cooling of the air as it travels over the land
 - decreased evaporation over the warm lakes followed by warming of the air as it travels over the land
 - decreased evaporation over the warm lakes followed by cooling of the air as it travels over the land
- Which process occurring within Earth's atmosphere causes the most heating of air?
 - liquid water changing to ice
 - ice changing to liquid water
 - liquid water changing to water vapor
 - water vapor changing to liquid water
- Which process cools the atmosphere by absorbing latent vaporization energy?

(1) evaporation from the oceans	(3) cloud formation
(2) melting glaciers	(4) precipitation

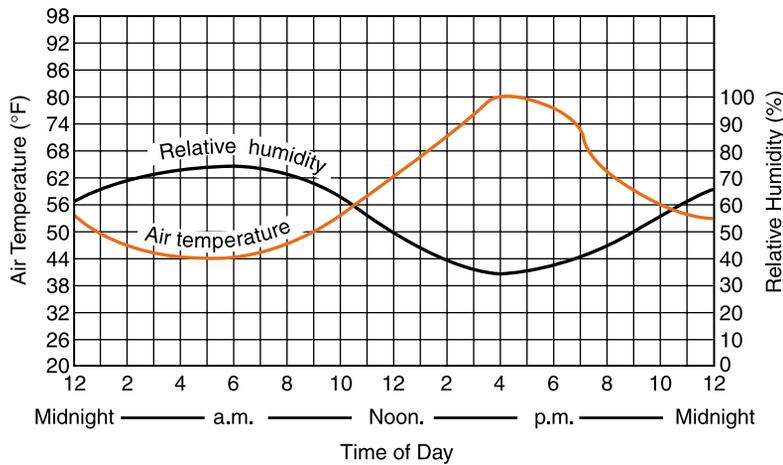
4. During which phase change of water is the most energy released into the environment?
- (1) water freezing
(2) ice melting
(3) water evaporating
(4) water vapor condensing
5. An Earth science class left pan of water outside in the open air to measure the rate of evaporation. For water to be lost by evaporation, the air temperature must be above
- (1) the dew point of the atmosphere.
(2) the freezing point of water.
(3) the boiling temperature of water.
(4) the average annual temperature.
6. When the dry-bulb temperature is 22°C and the wet-bulb temperature is 13°C , the dew point is
- (1) -10°C .
(2) 5°C .
(3) 14°C .
(4) 33°C .
7. The air outside a classroom has a dry-bulb temperature of 10°C and a wet-bulb temperature of 4°C . What is the relative humidity of this air?
- (1) 1%
(2) 14%
(3) 33%
(4) 54%
8. The graph below is a forecast of air temperature and dew point over a period of a little more than two days.



At what time is the rate of evaporation expected to be highest?

- (1) April 27 at 10 A.M.
- (2) April 28 at 10 A.M.
- (3) April 28 at 4 P.M.
- (4) April 29 at 4 P.M.

The graph below shows air temperature and relative humidity at a single location during a 24-hour period. Use this graph to answer the next two questions.

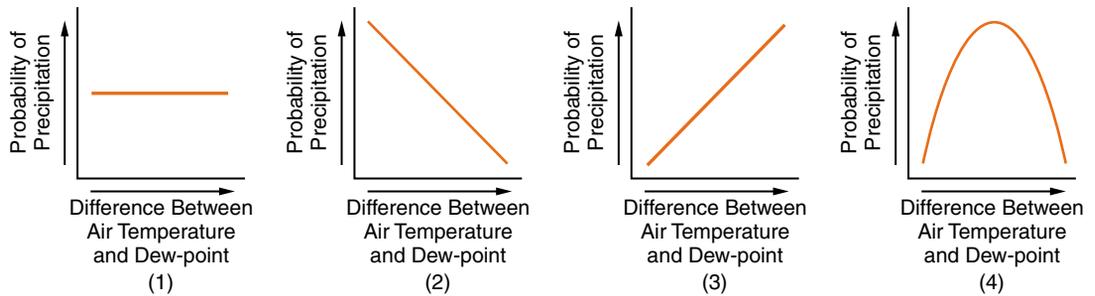


- 9. What is the approximate change in relative humidity from 12 noon to 4 P.M.?
 - (1) 10%
 - (2) 15%
 - (3) 20%
 - (4) 30%

- 10. At which time would the rate of evaporation most likely be greatest?
 - (1) 6 A.M.
 - (2) 10 A.M.
 - (3) 4 P.M.
 - (4) 11 P.M.

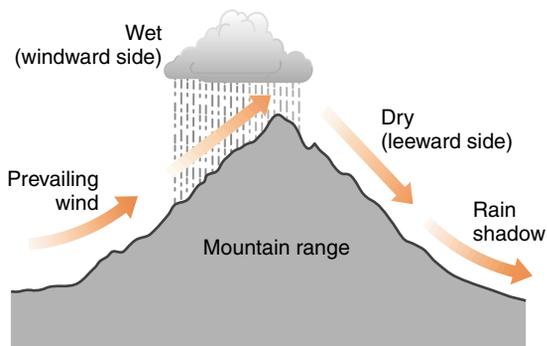
- 11. What was the average rate of temperature change from 9 A.M. to 3 P.M. on this day?
 - (1) 2°C/hour
 - (2) 4°C/hour
 - (3) 6°C/hour
 - (4) 8°C/hour

12. Which graph below best shows the relationship between the probability of precipitation and the difference between air temperature and dew point?



13. Which weather change usually occurs when the difference between the air temperature and the dew-point temperature is *decreasing*?

- (1) The amount of cloud cover decreases.
 - (2) The probability of precipitation decreases.
 - (3) The barometric pressure increases.
 - (4) The relative humidity increases.
14. The cross section below shows how prevailing winds have caused different weather on opposite sides of a mountain range.



Why does the windward side of this mountain have weather that is more moist?

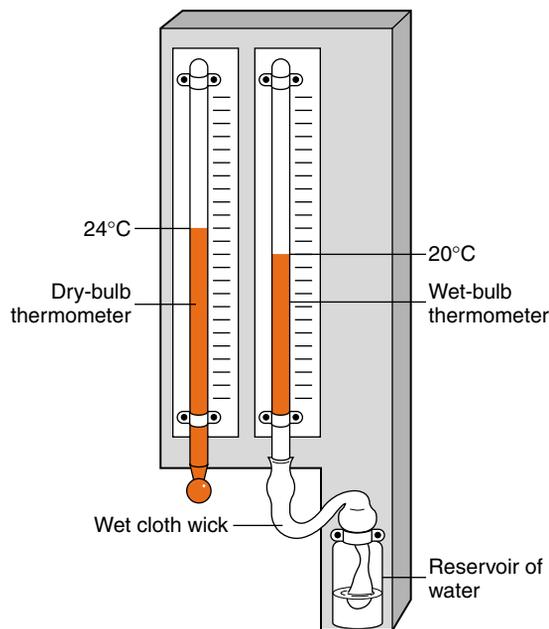
- (1) Rising air compresses and cools, causing the water droplets to evaporate.
- (2) Rising air compresses and warms, causing the water vapor to condense.
- (3) Rising air expands and cools, causing the water vapor to condense.
- (4) Rising air expands and warms, causing the water droplets to evaporate.

15. Clouds can form when

- (1) the air temperature cools below the dew point.
- (2) sinking air is warmed by compression.
- (3) the relative humidity is 0%.
- (4) condensation nuclei have been removed from the air.

Open-Ended Questions

Base your answers to questions 16–18 on the diagram below, which shows a hygrometer located on the wall of a classroom. Temperature readings on the hygrometer are used by students to determine the relative humidity of the air in the classroom.



16. Based on the temperature readings shown in this diagram, determine the relative humidity of the air in the classroom.
17. Besides relative humidity, identify another variable of air in the classroom that may be determined only by using both temperature readings on the hygrometer.
18. Describe how water evaporating from the wick attached to the wet-bulb thermometer lowers the temperature reading of that thermometer.

- 19.** A student using a sling psychrometer obtained a dry-bulb reading of 20°C and a wet-bulb reading of 16°C for a parcel of air outside the classroom.
- (a) State the dew point.
 - (b) State the change in relative humidity as the air temperature and the dew point get closer to the same value.
- 20.** Clouds droplets form around small particles suspended in the atmosphere. Describe how clouds form from water vapor. Include the terms “dew point” and either “condensation” or “condense” in your answer.