FIRE
WEATHER

AGRICULTURE HANOBOOK 360

U.S. Department of Agriculture – Forest Service

FIRE WEATHER ...

A GUIDE FOR APPLICATION OF METEOROLOGICAL INFORMATION TO FOREST FIRE CONTROL OPERATIONS

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PREFACE

Weather is never static. It is always dynamic. Its interpretation is an art. The art of applying complex information about weather to the equally complex task of wildland fire control cannot be acquired easily especially not by the mere reading of a book.

The environment is in control in wildland firefighting. Free-burning fires are literally nourished by weather elements, atmospheric components, and atmospheric motion. Out-guessing Mother Nature in order to win control is an extremely difficult task. We need to soothe her with understanding.

We have attempted to present information in such a way that your daily and seasonal awareness of fire weather can begin with reliable basic knowledge. We have kept the use of technical terms to a minimum, but where it was necessary for clear and accurate presentation, we have introduced and defined the proper terms. Growing awareness of fire weather, when combined with related experience on fires, can develop into increasingly intuitive, rapid, and accurate applications. Toward this end, we have preceded each chapter with a paragraph or two on important points to look for in relating weather factors to fire control planning and action.

The illustrations are designed to help you "see" the weather from many different locations. Sometimes you will need a view of the entire North American Continent-other times you will look at a small area covering only a few square miles or even a few square yards. The illustrations should help you to evaluate fire weather in all of its dimensions, and simultaneously to keep track of its continually changing character.

In the illustrations, **red** represents **heat**, and **blue** represents **moisture**. Watch for changes in these two most important factors and how they cause changes in all other elements influencing fire behavior.

Assistance in the form of original written material, reviews, and suggestions was received from such a large number of people that it is not practical to acknowledge the contribution of each individual.
They are all members of two agencies:
U.S. Department of Commerce,
Environmental Science Services
Administration,
Weather Bureau and U.S. Department of
Agriculture, Forest Service.
Their help is deeply appreciated, for without it this publication would not have been possible.

INTRODUCTION

What is WEATHER? Simply defined, it is the state of the atmosphere surrounding the earth. But the atmosphere is not static-it is constantly changing. So we can say that weather is concerned with the changing nature of the atmosphere. Familiar terms used to describe weather are

Temperature
Pressure
Wind speed
Wind direction
Humidity
Visibility
Clouds
Precipitation

The atmosphere is a gaseous mantle encasing the earth and rotating with it in space. Heat from the sun causes continual changes in each of the above elements. These variations are interdependent; affecting all elements in such a manner that weather is ever changing in both time and space.

Because weather is the state of the atmosphere, it follows that **if there were no atmosphere there would be no weather**. Such is the case on the moon. At high altitudes, where the earth's atmosphere becomes extremely thin, the type of weather familiar to us, with its clouds and precipitation, does not exist.

The varying moods of the ever-changing weather found in the lower, denser atmosphere affect all of us. Sometimes it is violent, causing death and destruction in hurricanes, tornadoes, and blizzards. Sometimes it becomes balmy with sunny days and mild temperatures. And sometimes it is oppressive with high humidities and high temperatures. As the weather changes, we change our activities, sometimes taking advantage of it and at other times protecting ourselves and our property from it.

A farmer needs to understand only that part of the shifting weather pattern affecting the earth's surface-and the crop he grows.

The launcher of a space missile must know, from hour to hour, the interrelated changes in weather in the total height of the atmosphere, as far out as it is known to exist, in order to make his decisions for action.

But the man whose interest is wildland fire is neither limited to the surface nor concerned with the whole of the earth's atmosphere. T he action he takes is guided by understanding and interpreting **weather variations in the air layer up to 5 or 10 miles above the land.** These variations, when described in ways related to their influences on wildland fire, constitute FIRE WEATHER. When fire weather is combined with the two other factors influencing fire behavior**-topography and fuel** - a basis for judgment is formed.

Chapter I

BASIC PRINCIPLES

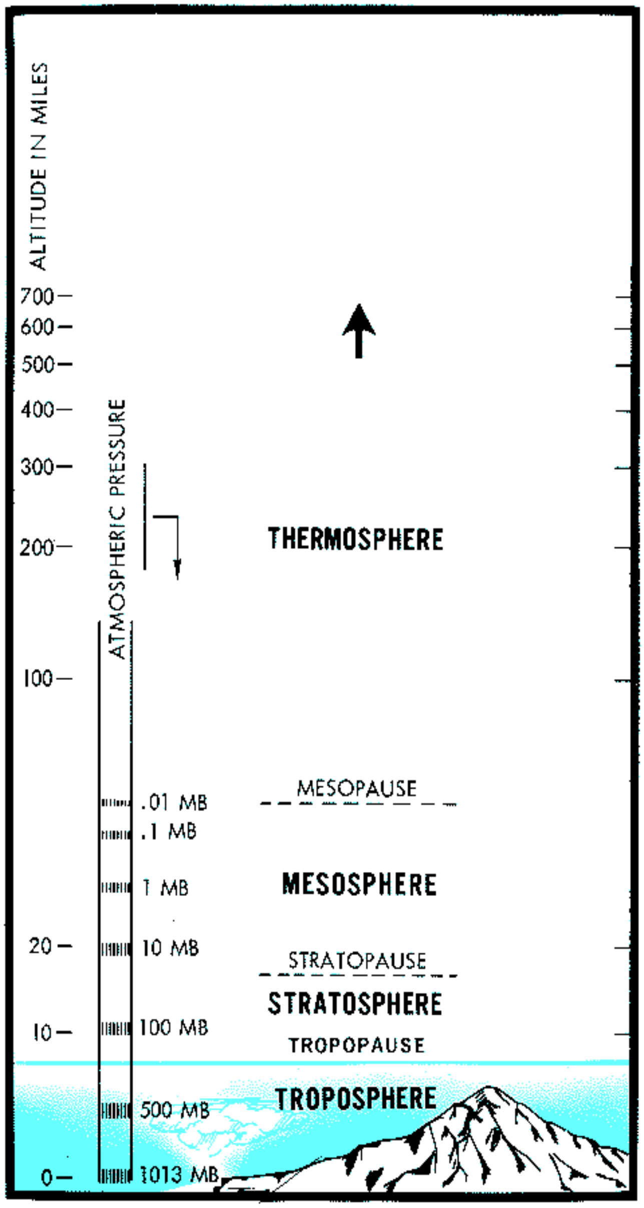
Wildland fires occur in and are affected by the condition of the lower atmosphere at any one moment and by its changes from one moment to the next. At times, fires may be affected only by the changes in a small area at or near the surface; at other times, the region of influence may involve many square miles horizontally and several miles vertically in the atmosphere. All these conditions and changes result from the physical nature of the atmosphere and its reactions to the energy it receives directly or indirectly from the sun.

This chapter presents basic atmospheric properties and energy considerations that are essential to understand why weather and its component elements behave as they do. We can see or feel some of these component elements, whereas others are only subtly perceptible to our senses. But these elements are measurable, and the measured values change according to basic physical processes in the atmosphere. These changes in values of weather elements influence the ignition, spread, and intensity of wildland fires.

BASIC PRINCIPLES

LAYERS OF THE ATMOSPHERE

It is convenient for our purposes to divide the atmosphere into several layers based primarily on their temperature characteristics. The lowest layer is the **troposphere.** Temperature in the troposphere decreases with height, except for occasional shallow layers. This temperature structure allows vertical motion and resultant mixing. Hence, this is a generally mixed, sometimes turbulent layer. Here occur practically all clouds and storms and other changes that affect fire. In this layer, horizontal winds usually increase with height.



Pressure decreases rapidly with height through the troposphere and stratosphere.

The depth of the troposphere varies from about 5 miles over the North and South Poles to about 10 miles over the Equator. In temperate and Polar Regions, the depth increases somewhat in the summer and decreases somewhat in the winter. In the temperate regions, the depth will vary even within seasons as warm or cold air invades these regions.

The troposphere is capped by the **tropopause** - the transition zone between the troposphere and the **stratosphere**. The tropopause is usually marked by a temperature minimum. It indicates the approximate top of convective activity.

Through most of the stratosphere, the temperature either increases with height or decreases slowly. It is a stable region with relatively little turbulence, extending to about 15 miles above the earth's surface.

Above the stratosphere is the **mesosphere**, extending to about 50 miles. It is characterized by an increase in temperature from the top of the stratosphere to about 30 miles above the earth's surface, and then by a decrease in temperature to about 50 miles above the surface.

The **thermosphere** is the outermost layer, extending from the top of the mesosphere to the threshold of space. It is characterized by a steadily increasing temperature with height.

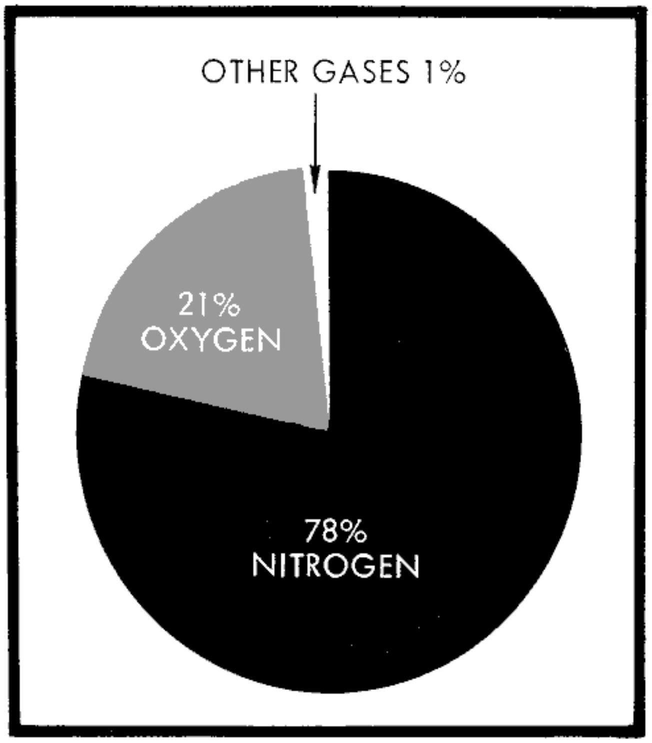
Let us now return to our principal interest - the troposphere - and examine it a little more Closely. The troposphere is a region of change – able weather. It contains about three-quarters of the earth's atmosphere in weight, and nearly all of its water vapor and carbon dioxide.

Composition of the Troposphere

Air in the troposphere is composed mostly of two gases. Dry air consists of about 78 percent nitrogen by volume and about 21 percent oxygen. Of the remainder, argon comprises about 0.93 percent and carbon dioxide about 0.03 percent. Traces of several other gases account for less than 0.01 percent.

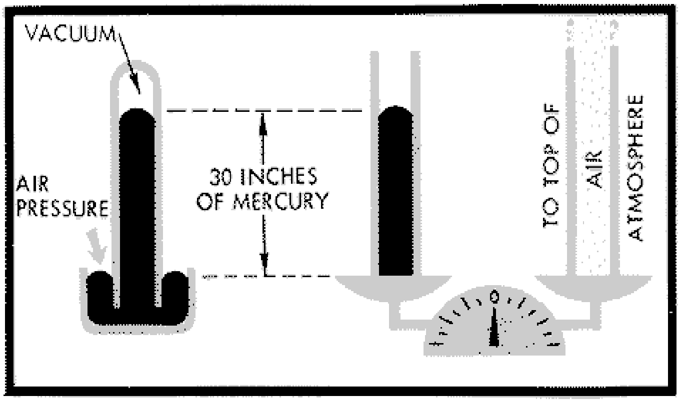
In addition to these gases, the troposphere contains a highly variable amount of water vapor-from near zero to 4 or 5 percent. Water vapor tends to act as an independent gas mixed with the air. It has a profound effect on weather processes, for without it there would be no clouds and no rain. Variations in the amount of water vapor influence the moisture content and flammability of surface fuels.

The troposphere also contains salt and dust particles, smoke, and other industrial pollutants. These impurities affect the visibility through the atmosphere and also may serve as nuclei for the condensation of water vapor in cloud formation.



Air in the troposphere is composed mostly of two gases – nitrogen and oxygen.

Air, although not heavy compared with other familiar substances, does have measurable mass and responds accordingly to the force of gravity. At the outer limits of the atmosphere, the air is extremely rarefied, each cubic foot containing only a few molecules and weighing virtually nothing. At sea level, however, a cubic foot of air, compressed by all the air above it, contains many molecules and weighs 0.08 pounds at 32°F. The total weight of a 1-inchsquare column of air extending from sea level to the top of the atmosphere averages 14.7 pounds. This is the normal pressure exerted by the atmosphere at sea level and is referred to as the **standard atmospheric pressure.**



A column of air from sea level to the top of the atmosphere weighs about the same as a 30-inch column of mercury of the same diameter.

A common method of measuring pressure is that of comparing the weight of the atmosphere with the weight of a column of mercury. The atmospheric pressure then may be expressed in terms of the height of the column of mercury. The normal value at sea level is 29.92 inches. A more common unit of pressure measurement used in meteorology is the millibar (mb.). A pressure, or barometer, reading of 29.92 inches of mercury is equivalent to 1013.25 mb. While this is the standard atmospheric pressure at sea level, the actual pressure can vary from 980 mb. or less in low-pressure systems to 1050 mb. or more in high-pressure systems.

Atmospheric pressure decreases with increasing altitude. Measured at successive heights, the weight of a column of air decreases with increasing altitude. The rate of decrease is about I inch of mercury, or 34 mb., for each 1,000 feet of altitude up to about 7,000 feet. Above about 7,000 feet, the rate of decrease becomes steadily less. In midlatitudes the 500 mb. level is reached at an average altitude of about 18,000 feet. Thus, nearly half the weight of the atmosphere is below this altitude, or within about 3 1/2 miles of the surface.

ENERGY IN THE TROPOSHPERE

Tremendous quantities of energy are fed into the troposphere, setting it in motion and making it work in many ways to create our ever-changing weather. At any time and place, the energy may be in any one form or a combination of several forms. All energy, however, comes either directly or indirectly from the sun.

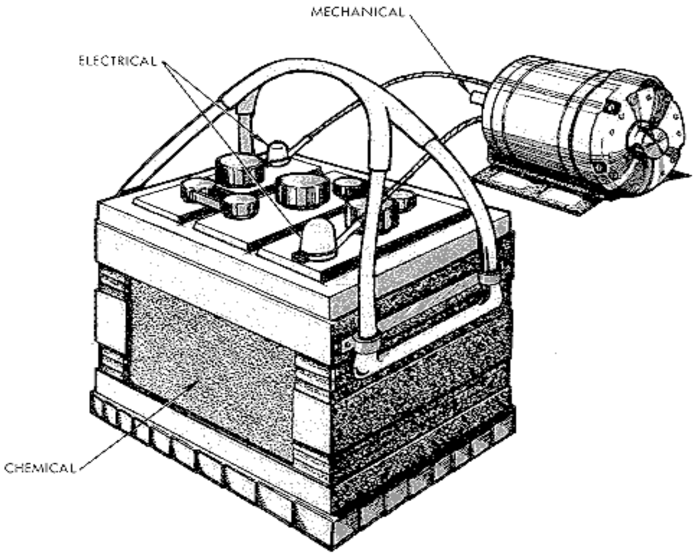
Simply defined, **energy** is the capacity to do work. Its more common forms are heat or **thermal** energy, radiant energy, **mechanical** energy (which may he either **potential** or **kinetic**), **chemical** energy, and **electrical** energy. There are also **atomic, molecular, and nuclear** energy.

Energy can be, and constantly is being, transformed from one form to another, but energy is always conserved in the process. It cannot be created nor destroyed, although a transformation between energy and mass does occur in atomic reactions.

Kinetic energy is energy of motion, whereas potential energy is energy due to position, usually with respect to the earth's gravitational field. The motion of a pendulum is a good example of the interchange of potential and kinetic energy. At the end of its swing, a pendulum has potential energy that is expended in the down stroke and converted to kinetic energy. This kinetic energy lifts the pendulum against the force of gravity on the upstroke, and the transformation back to the potential energy occurs. Losses caused by friction of the system appear in the form of heat energy. The sun is the earth's source of heat and other forms of energy.

The common storage battery in charged condition possesses chemical energy. When the battery terminals are connected to a suitable conductor, chemical reaction produces electrical energy. When a battery is connected to a motor, the electrical energy is converted to mechanical energy in the rotation of the rotor and shaft. When the terminals are connected to a resistor, the electrical energy is converted to thermal energy. When lightning starts forest fires, a similar conversion takes place.

Energy is present in these various forms in the atmosphere. They are never in balance, however, and are constantly undergoing conversion from one form to another, as in the case of the pendulum or the storage battery. Their common source is the radiant energy from the sun. Absorption of this energy warms the surface of the earth, and heat is exchanged between the earth's surface and the lower troposphere.

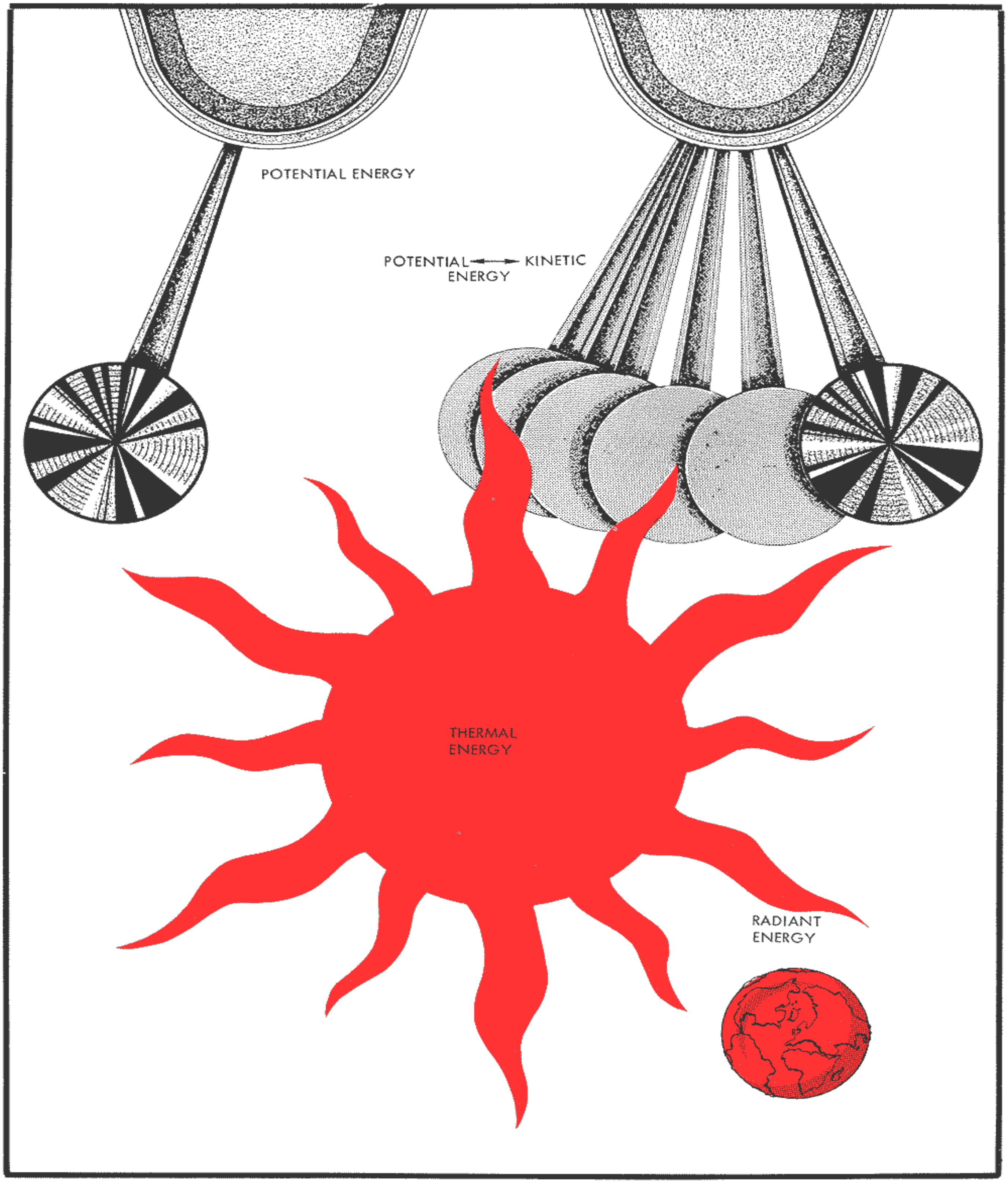


Chemical energy can be transformed into electrical energy, which in turn can be transformed into mechanical energy or thermal energy.

Heat Energy and Temperature

Heat energy represents the total molecular energy of a substance and is therefore dependent upon both the number of molecules and the degree of molecular activity. **Temperature,** although related to heat, is defined as the degree of the hotness or coldness of a substance, determined by the degree of its molecular activity. Temperature reflects the **average** molecular activity and is measured by a thermometer on a designated scale, such as the Fahrenheit scale or the Celsius scale.

If heat is applied to a substance, and there is no change in physical structure (such as lee to water or water to vapor), the molecular activity increases and the temperature rises. If a substance loses heat, again without a change in physical structure, the molecular activity decreases and the temperature drops.



All forms of energy in the atmosphere stem originally from the radiant energy of the sun that warms the surface of the earth. Energy changes from one to another in the atmosphere; so does energy in a swinging pendulum.

Heat and temperature differ in that heat can be converted to other forms of energy and can be transferred from one substance to another, while temperature has neither capability. Temperature, however, determines the direction of net heat transfer from one substance to another. Heat always flows from the substance with the higher temperature to the one with the lower temperature, and stops flowing when the temperatures are equal. In this exchange of heat, the energy gained by the cooler substance equals that given up by the warmer substance, but the temperature changes of the two are not necessarily equal.

Since different substances have different molecular structures, the same amount of heat applied to equal masses of different substances will cause one substance to get hotter than the other. In other words, they have different heat capacities. A unit of heat capacity used in the English system of measures is the **British thermal unit (B.t.u.).** One B.t.u. is the amount of heat required to raise the temperature of 1 pound of water 1°F.

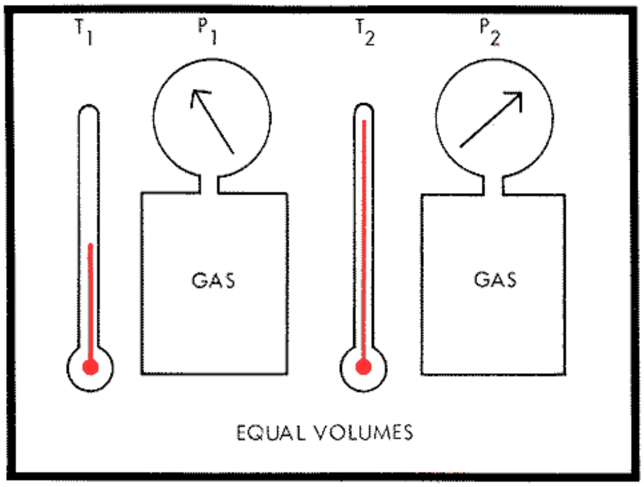
The ratio of the heat capacity of a substance to that of water is defined as the **specific heat** of the substance. Thus, the specific heat of water is 1.0-much higher than the specific heat of other common substances at atmospheric temperatures. For example, most woods have specific heats between 0.45 and 0.65; ice, 0.49; dry air, 0.24; and dry soil and rock, about 0.20. Thus, large bodies of water can store large quantities of heat and therefore are great moderators of temperature.

If heat flows between two substances of different specific heats, the resulting rise in temperature of the cooler substance will be different from the resulting decrease in temperature of the warmer substance. For example, if 1 pound of water at 70°F. is mixed with 1 pound of gasoline, specific heat 0.5, at 60°F., the exchange of heat will cause the temperature of the gasoline to rise twice as much as this exchange causes the water temperature to lower. Thus, when 3 1/3 B.t.u. has been exchanged, the pound of water will have decreased 3 1/3°F. and the pound of gasoline will have increased 6 2/3°F. The temperature of the mixture will then be 66 2/3°F.

With minor exceptions, solids and liquids expand when their molecular activity is increased by heating.

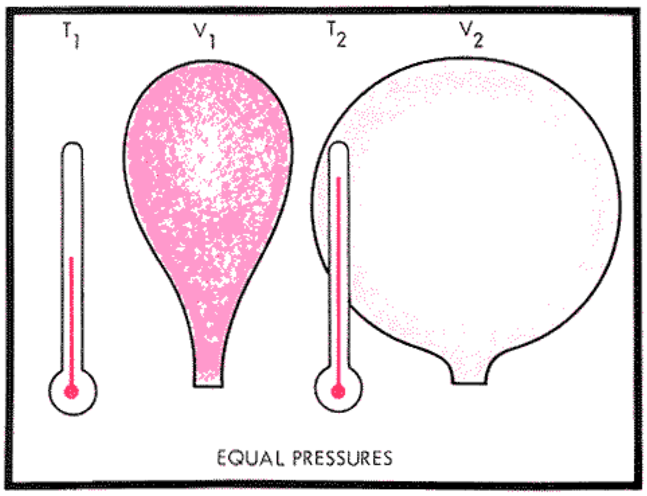
They contract as the temperature falls, and the molecular activity decreases. The amount of expansion or contraction depends on the size, the amount of temperature change, and the kind of substance. The expansion and contraction of liquid, for example, is used in a thermometer to measure temperature change. Thus, volume changes with temperature, but at any given tempera, lure the volume is fixed.

The reaction of gases to temperature changes is somewhat more complex than that of liquids or solids. A change in temperature may change either the volume or pressure of the gas, or both. If the volume is held constant, the pressure increases as the temperature rises and decreases as the temperature falls.



If the volume of a gas is held constant, the pressure increases as the temperature rises, and decreases as the temperature falls.

Since the atmosphere is not confined, atmospheric processes do not occur under constant volume. Either the pressure is constant and the volume changes, or both pressure and volume change. If the pressure remains constant, the volume increases as the temperature rises, and decreases as the temperatures falls. The change in volume for equal temperature changes is much greater in gases under constant pressure than it is in liquids and solids. Consequently, changes in temperature cause significant changes in **density** (mass per unit volume) of the gas. Rising temperature is accompanied by a decrease in density, and falling temperature is accompanied by an increase in density.



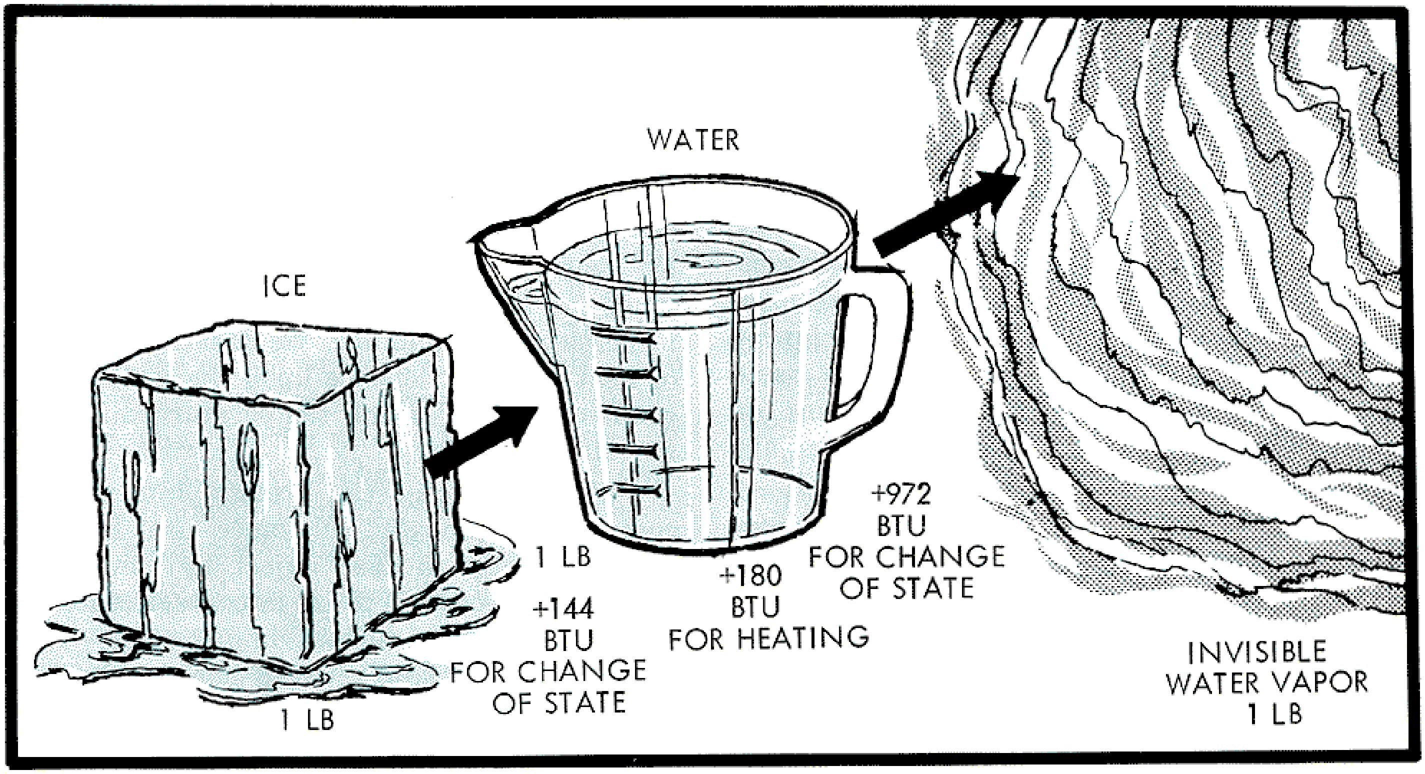
Under constant pressure, the volume increases and the density decreases as temperature rises, and the volume decreases and the density increases as temperature falls.

When gas expands, it must perform work in the process and therefore expend some of its internal (molecular) energy. Decreasing the internal energy lowers the temperature. Therefore, expansion is essentially a cooling process. Conversely, when a gas is compressed, work is done **on** the gas and this results in an increase in the internal energy of the gas. Thus, compression is a heating process. Compression and expansion are continuing processes in the atmosphere and account for both stabilization and change in weather activity.

Changes of State

Much more dramatic, because of the greater energy levels involved, are the transformations in our atmosphere between solid (ice) and liquid (water), and also between liquid (water) and gas (water vapor). These "change of state" transformations account for much of the energy involved in weather phenomena.

If a block of ice is heated continuously, its temperature will rise until it reaches the melting point, 32°F. The ice will then begin to melt, and its temperature will remain at 32°F. until all of the ice is melted. The heat required to convert 1 pound of ice into liquid water at 32°F. is 144 B.t.u. This is known as the **heat of fusion.** Continued heating will cause the temperature of the liquid water to rise until it reaches the boiling point, 212°F. (at sea--level pressure). The water will then begin to



To change ice at 32°F. to water vapor at 212°F. at sea-level pressure requires the addition of: (1) The heat of fusion, (2) he heat required he raise he temperature of the water to the boiling point, and (3) the heat of vaporization.

change to vapor, and its temperature will remain at 212°F. until all of the water is changed to vapor. The heat required to change 1 pound of water into vapor at 212°F. is 972 B.t.u. This is known as the **heat of vaporization.** Through **evaporation,** water will change to vapor below 212°F. However, the mount of heat required at lower temperatures is somewhat higher than at the boiling point. At 86°F., for example, 1,044 B.t.u. would be required to change 1 pound of water into vapor.

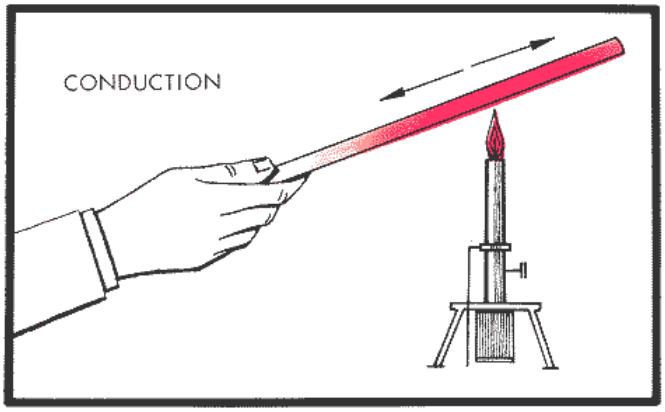
When this process is reversed-and vapor changes to liquid water and water changes to ice-the same amounts of heat energy are released. The **condensation** of water vapor into liquid water, during the formation of clouds and precipitation, furnishes a tremendous amount of energy to the atmosphere. About 1,000 times as much heat is released by condensation as by the cooling of a similar amount of water 1 Fahrenheit degree.

At subfreezing temperatures, water in the solid state-such as ice, snow, or frost--may change directly into vapor. For example, on very cold, dry days, snow will vaporize without first changing to liquid. At subfreezing temperatures, water vapor will also change directly into snow or frost. Either process is known as **sublimation.** The amount of heat involved in sublimation equals the sum of the heat of fusion and the heat of vaporization.

Principles of Heat Transfer

We have already seen that heat can be converted to other forms of energy and then back to heat. Heat can also flow between substances or within a substance by one of three basic processes without involving other forms of energy. These direct transfer processes are **conduction, convection, and radiation.**

Conduction is the transfer of heat by molecular activity. As the first molecules are heated, they are speeded up, and this energy is transferred to adjacent molecules, etc. Heat applied to one portion of a metal rod increases the molecular activity and the temperature in that part of the rod. This increased molecular activity is imparted to adjacent molecules, and the temperature thus increases progressively along the rod.



Heat added to one portion of a metal rod is conducted away, and the temperature rises progressively along the rod.

Some substances, such as copper, are good heat conductors. In copper-clad kitchenware, for example, heat is quickly and evenly distributed over the bottom of the utensils. Other substances like glass, wood, paper, and water are poor conductors. Forest litter is also a poor conductor. Most gases, including air, are poor conductors; for example, dead airspaces are used in the walls of buildings as insulation to prevent rapid heat exchange.

The rate at which heat moves between or within substances is affected by the **temperature difference** between the source of heat and the substance or part of the substance being heated, as well as by the **thermal conductivity** of the material. The rate of heat transfer is directly proportional to this temperature difference. Within a given substance, such as a metal rod, the rate at which the cold end is heated by heat traveling from the hot end depends upon the length of the rod. When these two principles are combined, we see that the rate of heat transfer depends upon the **temperature gradient,** which is the temperature difference per unit distance.

If another object is brought into physical contact with a heated substance, heat is transferred directly to that object by conduction. The surfaces of both areas in contact reach the same temperature almost immediately. Heat will continue to flow between both surfaces at a rate determined by the speed with which additional heat can be fed to the heating surface, and by the speed with which the receiving surface can dissipate its heat into the absorbing material. For solid objects, the rate is determined by the thermal conductivities of the respective materials, the size of the contact area, and the temperature gradients established within the contacting bodies.

In the atmosphere, the principal role of conduction is the heating and cooling of the air as it contacts hot or cold surfaces. A shallow layer adjacent to the ground is heated during the day and cooled at night.

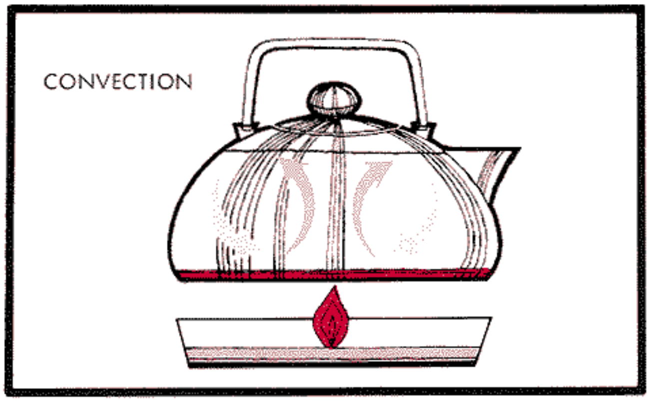
Convection is the transfer of heat within liquids and gases resulting from the motion of the fluid. Convection is much faster than conduction. When heat is applied to the bottom of a pan of water, the water touching the bottom of the pan is heated by conduction. As this portion of the water is heated, it expands and becomes less dense than the surrounding water. Any substance surrounded by a more dense fluid is forced to rise by **buoyant forces** imposed on the less dense substance. The cooler, more dense fluid flows in to replace the warmer, less dense fluid that rises. The rate of flow depends upon the differences in density produced by the differences in temperature.

By placing one or two drops of dye in the water, the patterns of rising and sinking currents will be shown. By this convective circulation, the mass transfer of water carrying its acquired heat with it eventually heats the entire pan of water. As the convection continues, the dye becomes evenly distributed in the water, producing a uniform color. Thus, convection is also a mixing process,

Convection is the initial motion responsible for the development of wind currents in the troposphere, and as a mixing process it is responsible for the transfer of heat from the hotter to the cooler portions of the earth. The rate of heat transfer by convection is highly variable, but, like the rate of heat transfer by conduction, it depends basically on the temperature gradients resulting from unequal heating and cooling over the earth's surface.

Convection is extremely important in weather processes and will be referred to frequently in later chapters, particularly when the general circulation and smaller scale winds are discussed.

Radiation is the transfer of energy by electromagnetic waves moving at the speed of light, 186,000 miles per second. This process, unlike conduction and convection, does not require the presence of intervening matter. Transfer of energy by radiation occurs over a wide spectrum of wavelengths ranging from very long radio waves to extremely short X-rays, gamma rays, and cosmic rays. Visible light appears near the middle of this range.



Heating a kettle of water sort up convection currents which transfer heat throughout the water,

We will be concerned only with that portion of the spectrum in which radiation acts as a heat-transfer mechanism. This radiation occupies the electromagnetic spectrum from the shortest ultraviolet wavelengths, through visible light, to the longest infrared wavelengths. Only radiation in this part of the spectrum is important in weather processes in the troposphere. We refer to this radiation as **thermal radiation.** Thermal radiation is emitted by any substance when its molecules are excited by thermal energy.

Heat transfer by radiation is accomplished by the conversion of thermal energy to radiant energy. The radiant energy travels outward from the emitting substance and retains its identity until it is absorbed and reconverted to thermal energy in an absorbing substance. The emitting substance loses heat and becomes cooler, while the absorbing substance gains heat and becomes warmer in the process. Radiant energy reflected by a substance does not contribute to its heat content.

All substances radiate energy when their temperatures are above absolute zero (-4600P.), the temperature at which all molecular motion ceases. The intensity and wavelength of the radiation depend upon the tomperature and the nature of the radiating substance. At low temperatures, all the radiation is in the invisible long wavelengths or infrared range. As the temperature rises, radiation increases in progressively shorter wavelengths as well as in the longer wavelengths. The increase, however, is faster in short-wave radiation than in long wave radiation. Therefore, as the temperature of the radiating surface increases, the maximum radiation intensities shift toward shorter and shorter wavelengths.

With increasing temperature, the visible spectrum appears in the following order: Dull red, bright red, orange, yellow, and white. All radiation from the earth is in the long wave or infrared range, while most radiation from the sun is in the short wave or visible range.

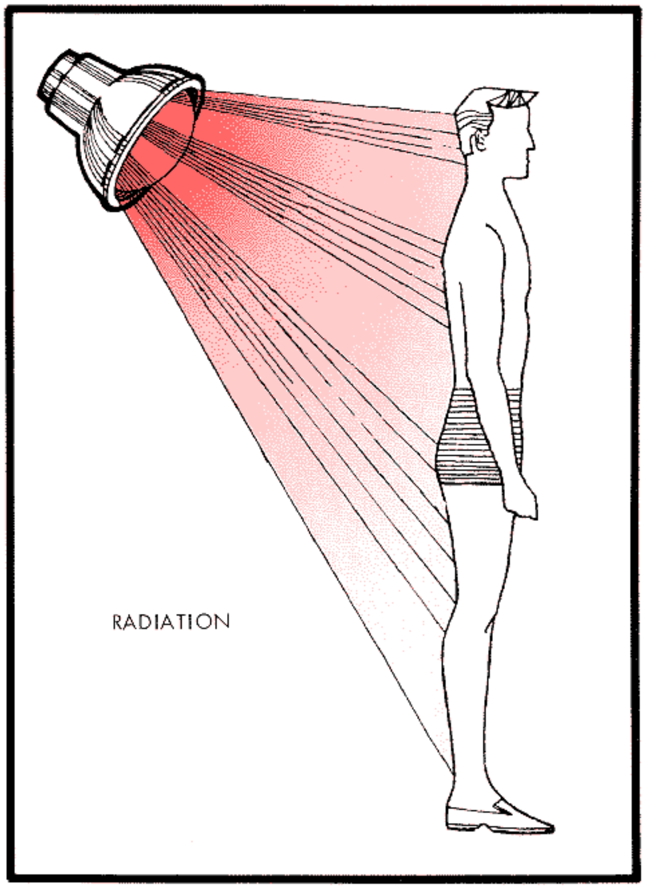
Not all substances are good radiators. Opaque substances are better radiators than transparent substances. Among solid materials, nonmetals are better radiators than metals, particularly at lower temperatures. The ideal radiator would be one capable of emitting the maximum heat at all wavelengths. Since black surfaces approach this emittance most nearly, the perfect radiator is called a **black body.** The **emissivity** of any substance is the ratio of its radiation, at any specified wavelength and temperature, to that of a black body at the same wavelength and temperature. The highest value of emissivity is one, and the lowest value is zero.

The intensity of the thermal radiation emitted by any substance depends upon its temperature. Actually, the intensity is proportional to the fourth power of the temperature.[1] If the Kelvin temperature of the emitting substance doubled, the radiation intensity would increase 2^4 or 16 times.

The intensity of radiant energy received by a substance depends on two factors in addition to the intensity of the radiation at the source. These are the **distance** between the radiator and the substance and the **angle** at which the radiation strikes the substance.

Since radiation travels outward in straight lines, the intensity of thermal radiation received from a point source will vary inversely as the square of the distance of the receiving substance from the source. The amount of energy received 3 feet from the source will be only one-ninth the amount received 1 foot from the source. From a larger radiating surface, the combined effects from all of the points within the surface must be considered. The reduction in intensity with distance is then somewhat less than from a point source. For practical purposes we may consider the sun as being a point source of radiant energy.

The amount of radiant energy received by a unit area will be greater if the receiving surface is perpendicular to the radiation than if it is at an angle other than perpendicular. A beam of the same width striking at such an angle must cover a larger surface area than a beam striking perpendicularly. As we will see later, the angle not only affects the amount of radiation received from the sun at different times during the day, but it is also the cause of our seasons.



The intensity of radiation decreases as the distance from the source increases.

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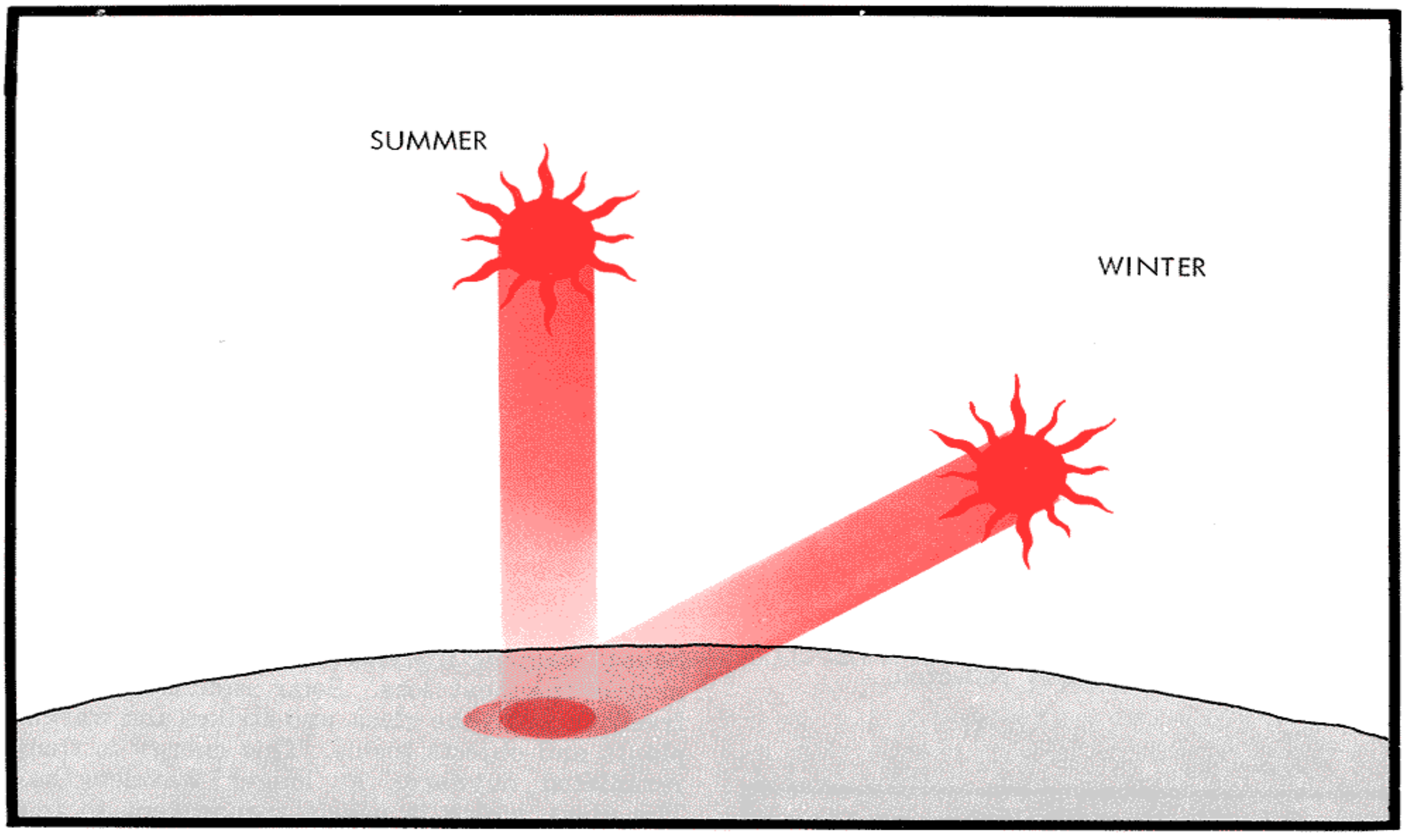
[1] For the relationship the temperature must be expressed by use of absolute (Kelvin) scale where 0°K. is -460°F.



A beam of radiation of the same width striking at an angle must cover a larger surface area than a beam striking perpendicularly.

Substances vary in their ability to absorb, as well as to emit, radiation. Those that are good emitters are also good absorbers at the same wavelength. Black clothing, for example, is a good absorber of the sun's radiation and should not be worn on hot days. White clothing is a good reflector and will help keep the body cool.

SOLAR RADIATION EFFEGFS IN THE TROPOSPHERE

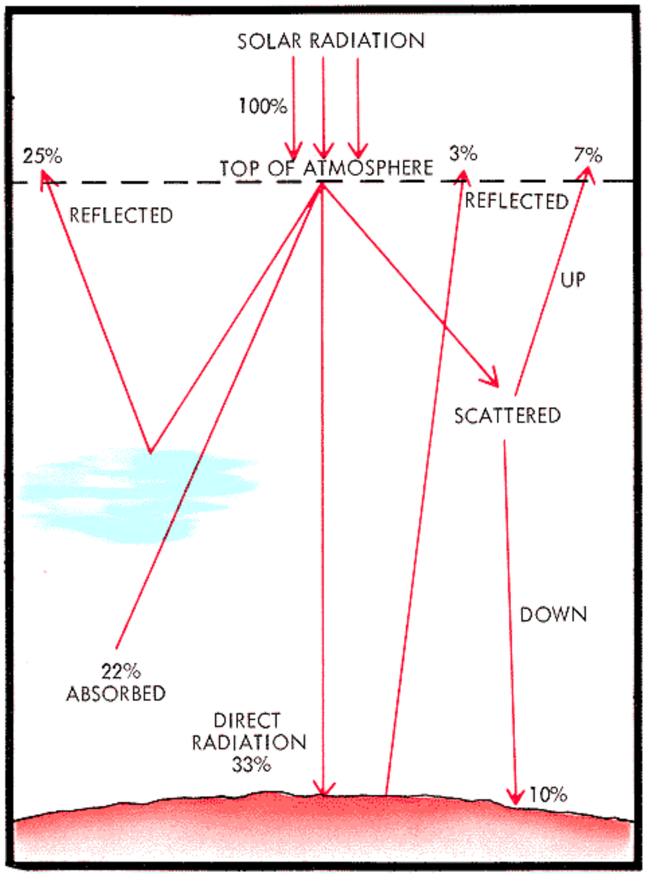
Radiation is the process by which the earth receives heat energy from the sun, about 93 million miles away. This energy is produced in the sun, where the temperature is many million degrees, by nuclear fusion, a process in which hydrogen is converted into helium. In the process, some of the sun's mass is converted to thermal energy. Although this nuclear reaction is occurring at a tremendous rate, the mass of the sun is so great that the loss of mass in millions of years is negligible.

The sun emits radiation as would a black body at a temperature of about 10,000°F. As a result, the maximum solar radiation is in the visible portion of the electromagnetic spectrum, and lesser amounts appear on either side in the ultraviolet and infrared.

Radiation Balance Day and Night

The intensity of solar radiation received at the outer limits of the earth's atmosphere is quite constant. However, the amount that reaches the earth's surface is highly variable, depending greatly on the amount of clouds in the atmosphere. Some solar energy is reflected back from the tops of clouds and is lost to space. In the absence of clouds, most of the solar radiation passes directly through the atmosphere and reaches the surface.

Some solar radiation is scattered in the atmosphere by gas molecules and by minute particles of solid matter. Of this scattered radiation, some is lost to space, some is absorbed by gases in the atmosphere and by solid particles such as smoke, and some reaches the earth's surface. Water vapor, ozone, and carbon dioxide each absorb radiation within certain wavelengths. If clouds are present, water droplets also absorb some radiation. Of the radiation finally reaching the earth's surface, part is absorbed and part is reflected. When cloudiness is average, the earth's surface absorbs about 43 percent, the atmosphere absorbs about 22 percent (20 of the 22 percent within the troposphere), and 35 percent is reflected.



Approximate distribution of incoming solar radiation during average cloudiness.

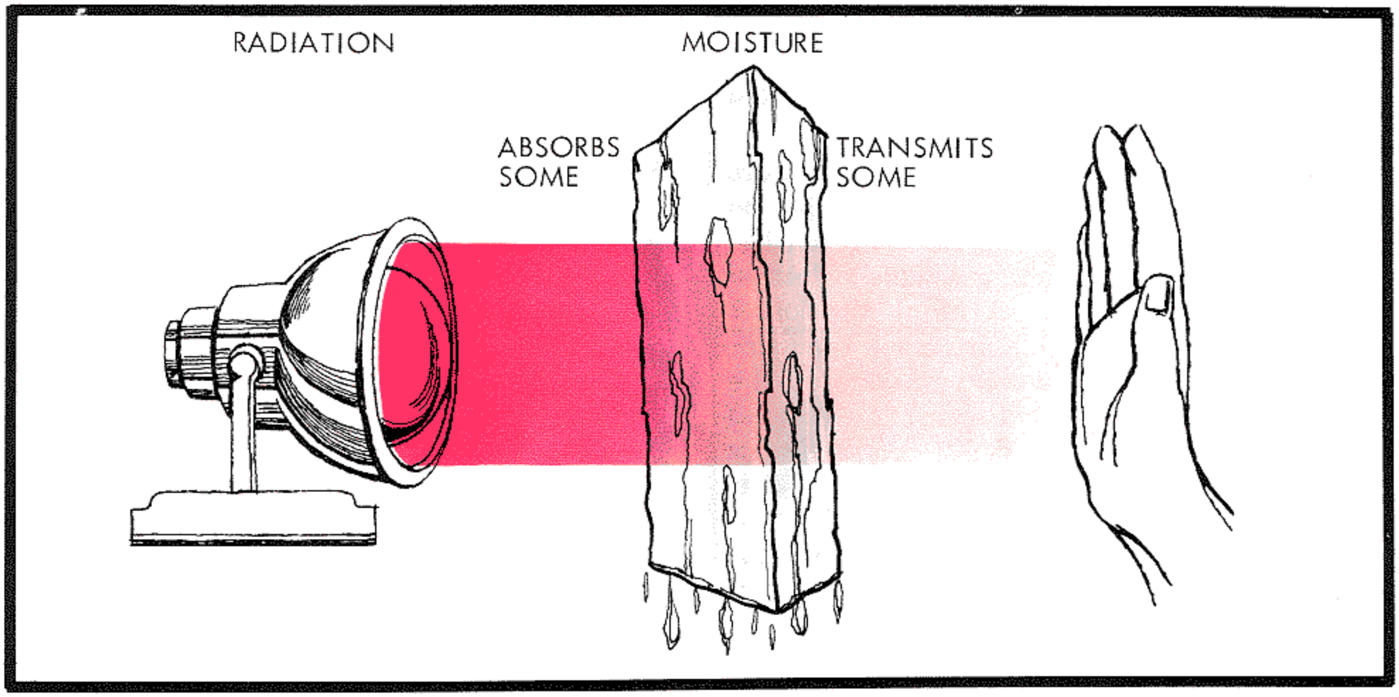
The reflected solar radiation is unchanged in character. However, the solar radiation, which is absorbed, either by the atmosphere or by the earth, is converted back to thermal energy. It warms up the substance that absorbs it, and may then be reradiated as radiant energy at lower temperatures and longer wavelengths.

The solar radiation, which reaches the earth's surface, warms the surface. However, the earth's average temperature does not change, because the earth in turn radiates energy to the atmosphere and to space. The outgoing radiation is at the earth's temperature and has its maximum in the infrared region of the spectrum.

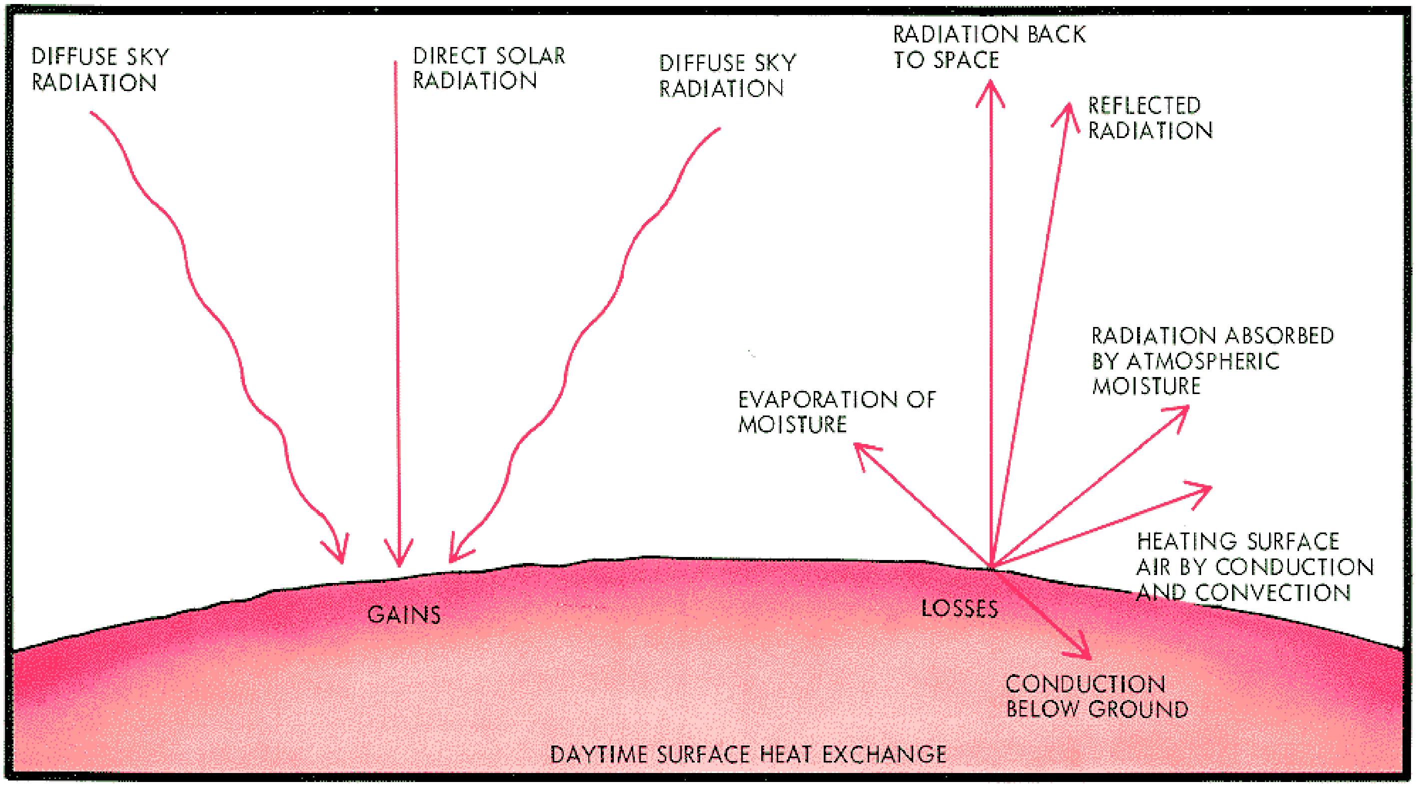
It is important to life on earth and to weather processes that the radiation received and that emitted by the earth are at different wavelengths. Because of this difference, **the atmosphere acts much like the glass in a greenhouse,** trapping the earth's radiation and minimizing the heat loss. Solar radiation passes freely through the glass, and strikes and warms plants and objects inside. This energy is then reradiated outwards at longer wavelengths. The glass, which is nearly transparent to the visible wavelengths, is nearly opaque to most of the infrared wavelengths. Therefore, much of the heat stays inside, and the greenhouse warms up.

In the atmosphere it is water vapor that is primarily responsible for absorbing the infrared radiation, and the greenhouse effect varies with the amount of water vapor present. It is much less in dry air over deserts than in moist air over the Tropics.

The energy that reaches the earth as direct solar radiation and diff use sky radiation during the day is dissipated in several ways. Some of this radiation, as we have seen, is reflected back, and since this is short-wave radiation, most of it is lost to space. A large portion is absorbed and radiated back as long wave radiation, and much of this radiation, as already mentioned, is absorbed again by the water vapor in the atmosphere. Another large portion is used in the evaporation of surface moisture and is transmitted to the atmosphere as latent heat. Some is used to heat surface air by conduction and convection, and some is conducted downward into the soil. The presence



Moisture in any form-solid, liquid, or vapor-absorbs much of the long wave radiation.

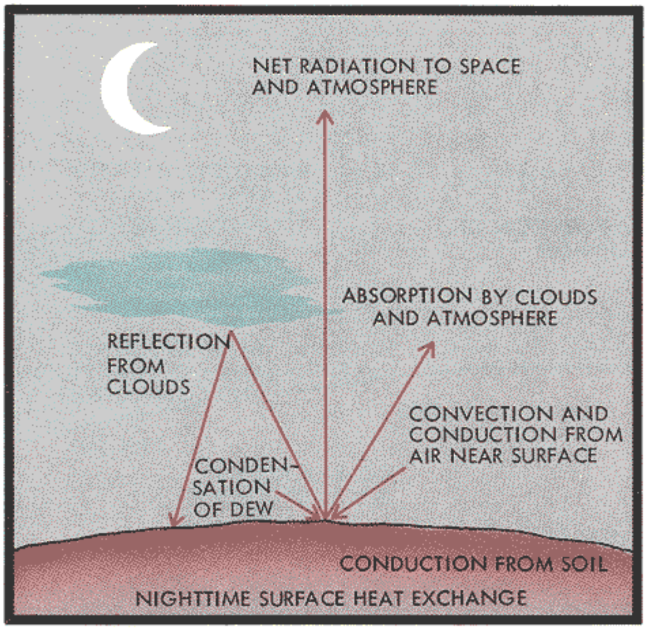


Solar radiation that reaches the earth’s surface during the daytime is dissipated in several ways.

of clouds is important because clouds reflect and absorb both short-wave radiation reflected from the earth and long wave radiation emitted by the earth.

The earth radiates energy, and therefore loses heat, both day and night. At night, no appreciable solar radiation is received (on the dark side), so there is no appreciable reflection of short-wave radiation. At night the losses through long wave radiation are much the same as during the day. However, because of the cooling of the earth's surface until it becomes colder than either the air above or the deeper soil, some heat is transported back to the surface by conduction from the deeper soil below and by conduction and convection from the air above. Again, clouds influence heat losses. They are very effective in reflecting and absorbing and in reradiating energy from the earth's surface. Because of this trapping by clouds, the drop in surface temperatures is far less on cloudy nights than on clear nights.

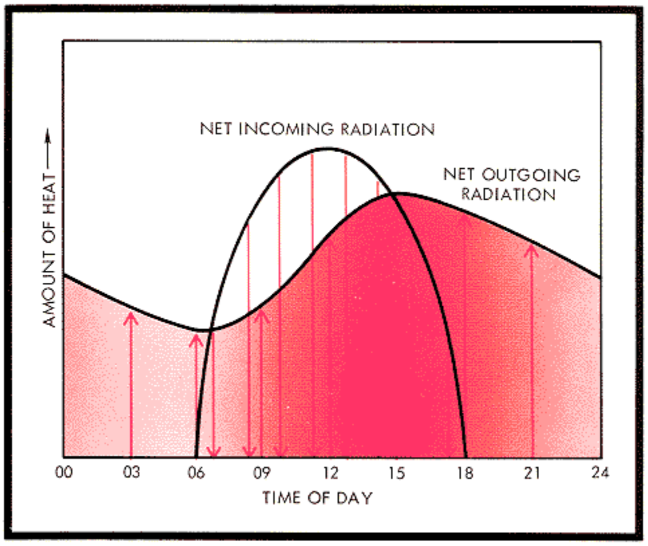
The amount of heat received in any given area varies because of the angle with which the sun's rays strike the earth. Heating begins when the sun's rays first strike the area in the morning, increases to a maximum at noon (when the sun is directly overhead), and decreases again to near zero at sunset. The earth warms up as long as it receives heat faster than it loses heat, and cools off when it loses heat faster than it receives it. It is this balance that results in the maximum temperature occurring about mid-afternoon instead of at the time of maximum heating, and the minimum temperature occurring near sunrise. The rate at which the earth radiates heat varies with the temperature; therefore, it is minimum at the time of the temperature minimum, and maximum at the time of the temperature maximum.



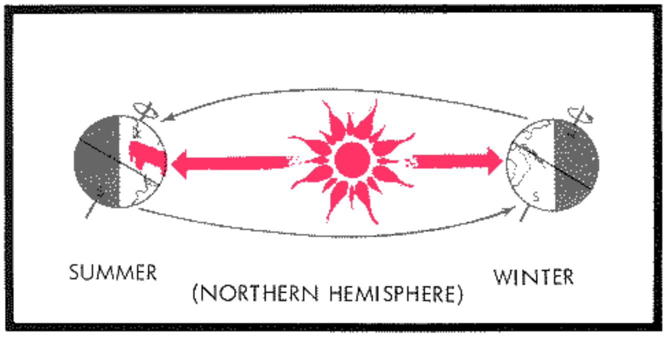
At night there is not cooling of the earth's surface although some heat is returned by various methods.

Seasons

We are all familiar with the four seasons that occur at latitudes greater than about 23° winter, spring, summer, and autumn. These seasons are due to the variation in the amount of solar radiation received by both the Northern and Southern Hemispheres throughout the year. The earth not only rotates on its axis once every 24 hours, but it also revolves around the sun in an elliptical orbit once in about 365 1/4 days. The sun is at a focus of the ellipse, and the earth is actually nearer to the sun during the northern winter than during the northern summer. But this difference in distance is much less important in relation to the earth's heating than is the inclination of the earth's axis relative to the plane of the earth's orbit.



The log in the time of maximum and minimum temperature is due to the difference between incoming and outgoing radiation.

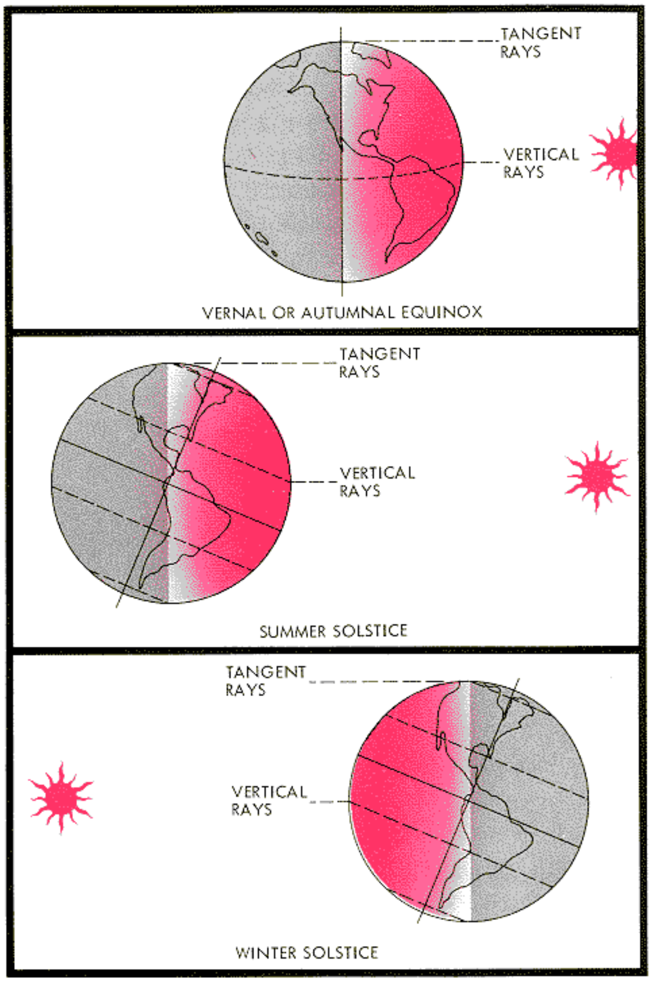


The earth rotates on its tilted axis once every 24 hours and revolves around the sun in an elliptical orbit once in about 365 ¼ days.

This inclination, or tilt, of the axis is 231/2 degrees from the vertical.

At all times the sunshines on half of the earth's surface. But because of the different angles with which the sun's rays strike various parts of the earth, the amount of solar radiation received per unit area varies widely. The greatest amount is received where the sun's rays strike perpendicularly. The amount diminishes toward the edge of the illuminated half where the rays become tangential to the earth's surface. If the earth's axis were not tilted, the amount of radiation any area on the earth would receive would remain nearly constant throughout the year; the revolution of the earth around the sun would have little effect on climate. (Of course climate would still vary greatly from place to place.)

Because of the tilt, however, the sun's rays strike the surface at a higher (more perpendicular) angle during the summer than during the winter; thus, more heat is received during the summer. Also, because of the inclination (tilt) of the earth's axis, the days are longer during the summer; every area away from the Equator is in the illuminated half of the earth more than half of the day. On June 21 the number of daylight hours is 12 at the Equator and increases to 24 at 66 1/2°N. and northward. In the winter the opposite is true. On December 22, the number of daylight hours is 12 at the Equator and decreases to 0 at 66 1/2°N. and northward. When the sun is directly above the Equator throughout the day, at the time of the vernal or autumnal equinox (March 21 and September 23), the (lay and night are 12 hours long everywhere.



At the time of either equinox the days and nights are equal. The tilt of the earth's axis causes the sun's rays to strike the earth's surface at a higher angle during summer than during winter. Therefore, more heat is received during the summer.

The annual march of temperature has a lag similar to the lag of the daily march of temperature described above. That is, the highest normal temperatures do not occur at the time of greatest heating, nor do the lowest normal temperatures occur at the time of least heating. In the Northern Hemisphere, the warmest month is July and the coldest month is January, whereas the greatest heating takes place on June 21 and the least heating on December 21. To see why, one must look at the heat balance.

During the spring the Northern Hemisphere receives more heat each day than it radiates back to space. Consequently, its mean temperature rises. After June 21, the Northern Hemisphere begins receiving less heat each day, but the amount received is still greater than the amount radiated, so the mean temperature still rises. In July, in the Northern Hemisphere, at the time the amount received is equal to the amount radiated, the mean temperature is highest. Thereafter, the amount received each day is less than the amount radiated, so the mean temperature declines. The time of lowest normal temperature may be similarly explained.

Of course, the temperature curve for any given year at any one place may vary consider ably from the normal for that place. This is not due to a variation in the amount of heat reaching the outer atmosphere from the sun, but rather to the predominance of either cold or warm air masses and to the predominance of either cloudy or clear weather, at various periods during the year at that location.

REACTION OF THE TROPOSPHERE TO HEATING

In this chapter we are concerned with basic concepts, which we will use in studying the ways of the weather. So far we have considered the structure of the atmosphere, thermal energy principles, and, in a general way, the heating of the earth. Now we will consider briefly how the atmosphere reacts to heating and cooling by looking at horizontal and vertical motion and atmospheric stability. These items will be treated in more detail in later chapters, but they will be introduced here because of their basic nature. Weather processes are so interrelated that it is not possible to discuss one process thoroughly without having some familiarity with the others.

Weather implies motion in the atmosphere, and this motion is initiated by unequal heating. Over any long period of time, the amount of energy received and lost by the earth and atmosphere must nearly balance, since there is very little long-term change in temperatures. But at a given moment and place, the gains and losses are not in balance. **An attempt to regain balance is largely responsible- for most disturbances in the atmosphere-the weather.**

Horizontal and Vertical Motion

Since horizontal distances around the earth are so much greater than vertical depths in the lower atmosphere, most of the air motion concerned with weather is in the form of horizontal winds. These winds could not blow, however, if it were not for the continuing transport of energy aloft by vertical motion resulting from heating at the surface. Upward motions in the atmosphere range from light updrafts in weak convection cells to very intense up drafts in thunderstorms. Compensating down drafts are occasionally severe, such as in thunderstorms, but more frequently they occur as **subsidence-a** gradual settling of the air over relatively large areas.

Heated air rises over the Equator and flows toward the poles aloft. Cooled air in turn settles over the poles and initiates return flow toward the Equator to complete the circulation. Other factors, primarily the rotation of the earth, as we will see later, complicate this simple picture. But as an end result, this sort of heat energy exchange does take place.

Land and water surfaces warm and cool at different rates because of their different heat transfer properties. This differential heating produces differences in pressure in the atmosphere, which in turn cause air motion. On a daily basis along the coast, temperature and pressure reversals result in local land and sea breezes. But over longer periods of time, cumulative differences in temperature and pressure develop broad areas of high and low pressure. Broad scale differences in the earth's land surfaces, which vary from bare soil to dense cover, have similar effects.

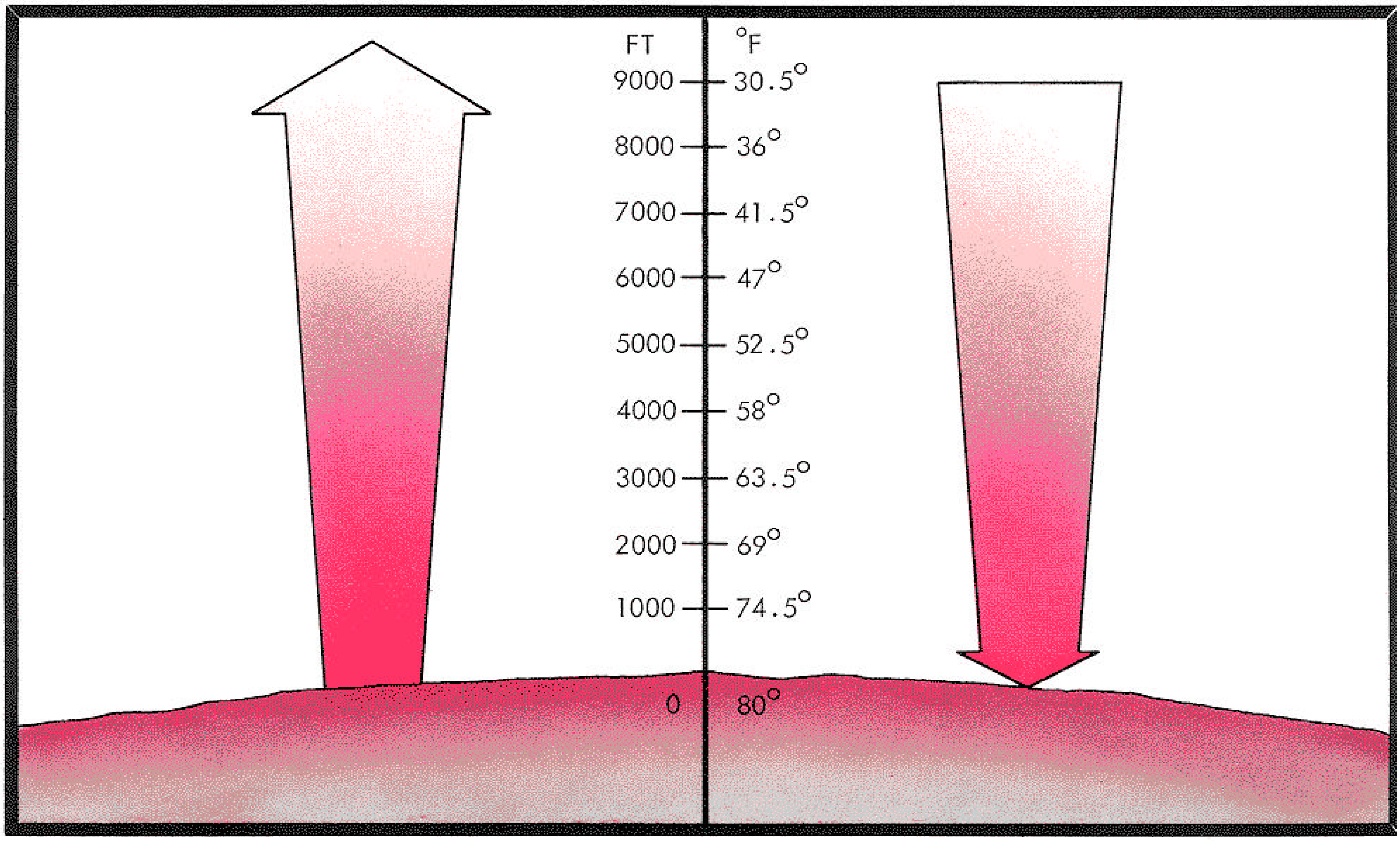
In general, air sinks in high-pressure areas, flows from high- to low-pressure areas at the surface, rises in low-pressure areas, and returns aloft. Again, other forces-the effects of the earth's rotation, centrifugal force, and friction-complicate this pattern, but we will postpone our detailed consideration of these forces until later chapters. Here it is sufficient to point out that motion in the atmosphere takes place on various scales-from the hemispheric motion of the general circulation, through intermediate-scale motion involving broad high- and low-pressure areas, through smaller and smaller circulations, to small eddy motion.

Atmospheric Stability

Vertical motion in the atmosphere encounters resistance because of the temperature or density structure of the atmosphere. In fact, we can define **atmospheric stability** as the resistance of the atmosphere to vertical motion. We have already learned the two basic concepts necessary to understand atmospheric stability -first, that pressure in the atmosphere de, creases with height, and second, that the temperature of a small mass or parcel of air decreases as the air expands, provided no heat is added to the parcel. The converse of these concepts is also true.

Rising air encounters lower pressures in the surrounding air, permitting it to expand. The energy required for expansion comes from the heat energy in the rising air. Consequently, the temperature of the rising air lowers. Descending air, by the reverse process, is compressed and warmed. If no heat is gained or lost by mixing with the surrounding air, this is an adiabatic process. In the **adiabatic** lifting process, unsaturated air-cools at the fixed rate of approximately 5.5°F. per 1,000 feet increase in altitude. This is the **dry-adiabatic** lapse rate. Unsaturated air brought downward adiabatically warms at the same rate.

If a lifted parcel of air, which has cooled at the **dry-adiabatic rate**, becomes immersed in warmer, less dense air, it will fall to its original level or to the level at which it has the same temperature as the surrounding air. Similarly, if the parcel is lowered and is then surrounded by cooler, more dense air, it will rise to its original level. The surrounding atmosphere is then **stable**. If a parcel, moved up or down in the atmosphere, tends to remain at its new level, the atmosphere is **neutral**. If a parcel, moved up or down, tends to continue to rise or fall of its own accord, the atmosphere is **unstable**.



Rising air expands and cools. Sinking air is compressed and warmed. If no heat is gained or lost by mixing with surrounding air, this is an adiabatic process.

Atmospheric stability can be determined from the measured rate of temperature change with change in height in the free air, called the **environmental lapse rate.** A change of 5.5°F. per 1,000 feet indicates a neutrally stable atmosphere. A parcel of dry air moved up or down is then at exactly the same temperature as the surrounding air. If the environmental lapse rate is less than 5.5°F. per 1,000 feet, the atmosphere is stable with respect to unsaturated air. In such an atmosphere, a parcel of air moved up (or down) would be colder (or warmer) than the surrounding air and would tend to return to its original level. A layer of air in which the temperature increases with height is an extremely stable layer. Such a layer is called an **inversion.** If the environmental lapse rate is greater than 5.5°F. per 1,000 feet, an unsaturated atmosphere is unstable. A raised (or lowered) parcel of air would then be warmer (or colder) than its surroundings and would continue its vertical movement.

A similar process applies to an air parcel that has been cooled enough to condense part of its water vapor. In this case, the rate of temperature change of the parcel is less than the dry-adiabatic rate because of the addition of the **latent heat of vaporization**. This rate varies according to the amount of water vapor in the parcel and is usually between 2°F. and 5°F. per 1,000 feet. This is the **moist-adiabatic rate**. The surrounding atmosphere is then judged to be stable, neutral, or unstable by comparing its lapse rate with the moist-adiabatic rate.

Moisture in the atmosphere, clouds, precipitation, and many other weather phenomena are directly related to these adiabatic responses of air to lifting and sinking.

With the background of this chapter, we are now ready to consider more thoroughly some of the static properties of the atmosphere, such as temperature and humidity, and then we will consider the dynamic weather processes.