Weather and the Redistribution of Thermal Energy

When we describe weather, we typically speak in terms of temperature, humidity, wind, and the presence or absence of precipitation. Weather, however, is not a set of random acts of nature, but a response to the unequal heating of Earth's atmosphere. Imbalances in rates of heating and cooling from one place to another within the atmosphere create temperature gradients. In response to these gradients, the atmosphere circulates and thermal energy is redistributed. While there are a number of complicating factors within the redistribution equation, it is important for students to understand this basic premise.

Heat versus Temperature

It is important to note the distinction between *temperature* and *heat*. The most common descriptions of weather generally relate to temperature: "How cold is it outside?" or "Is it going to be hot today?" However, the *redistribution of heat* is the driving force behind weather. What is the difference between temperature and heat? Temperature is defined as the *average* kinetic energy, or energy of motion, per atom or molecule of a particular substance. The greater the kinetic energy of the atoms or molecules, the higher the temperature. Heat, on the other hand, is defined as the *total* kinetic energy of all of the atoms or molecules composing a given amount of a substance.

The distinction between heat and temperature can be appreciated through the following example. Compare a pot of water at 90° C, close to the boiling point of water, with a bathtub filled with water at 40° C. The water in the pot has a higher *temperature* than the water in the tub —i.e. the average kinetic energy of the water molecules in the pot is higher than that in the tub. However, the water in the tub has more *heat* because the tub contains so many more molecules of water. Heat, remember, is the *total amount* of kinetic energy of *all* of the atoms or molecules composing a substance.

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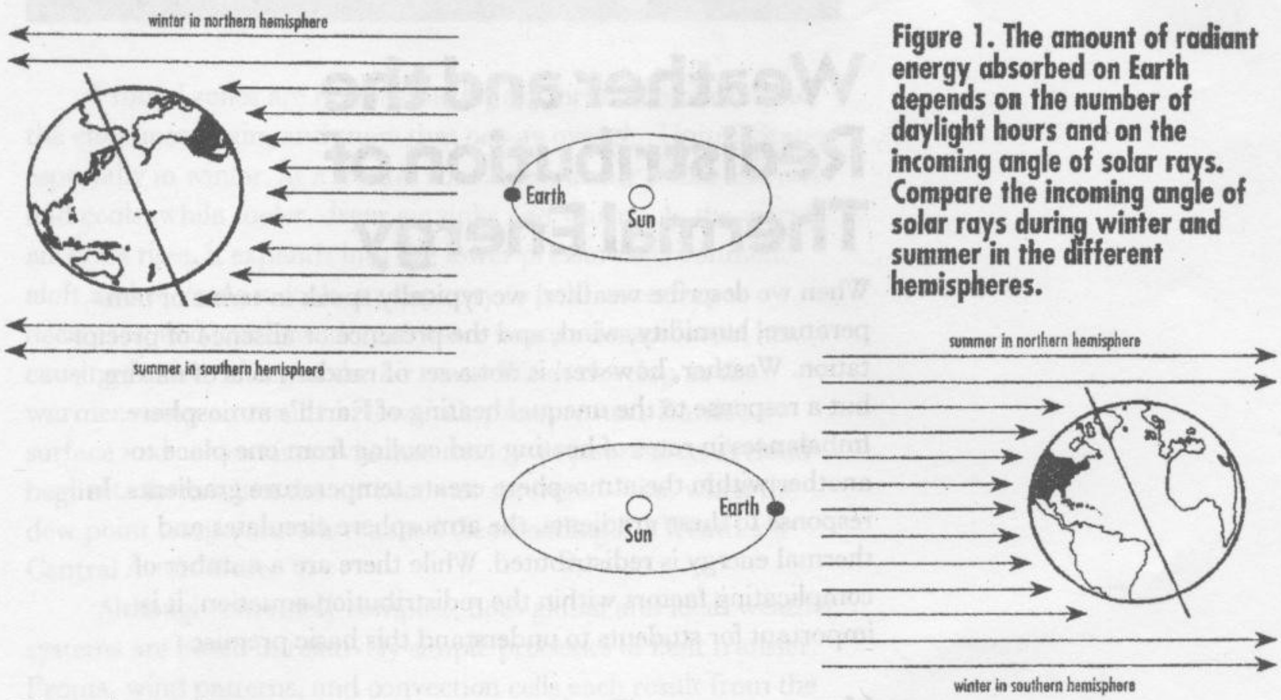


Figure 1. The amount of radiant energy absorbed on Earth depends on the number of daylight hours and on the incoming angle of solar rays. Compare the incoming angle of solar rays during winter and summer in the different hemispheres.

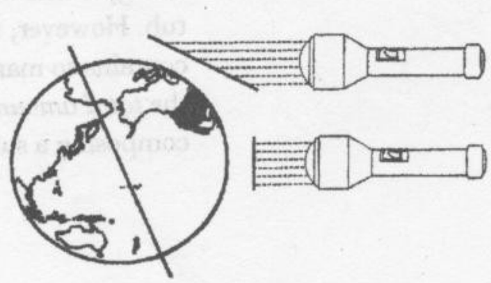
Heating the Earth

Earth's atmosphere is heated by solar radiation and by re-radiation of solar energy reflected from Earth's surface. For all practical purposes we can say that Earth receives nearly a constant rate of radiant energy from the sun. This energy, however, is not uniformly distributed throughout the planet. The 23.5 degree tilt in Earth's axis causes maximum intensities of solar radiation to strike the northern hemisphere during the middle months of the year and the southern hemisphere during the beginning and ending of the year (see Figure 1).

In addition, the curvature of Earth's surface affects the distribution of solar energy. At the equator, the sun's rays fall most nearly perpendicular. This transmits the highest amount of solar radiation because those rays strike a smaller surface area than do rays striking near the poles. This concentrating effect means that the amount of energy per square unit of surface area is greater near the Equator than near the poles. (see Figure 2; this is demonstrated in Activity 6, "Why is it Hotter at the Equator than at the Poles?")

The atmosphere is transparent to most incident solar radiation. However, some radiation is absorbed, scattered, or reflected by the atmosphere, depending on its wavelength. Radiation of some wavelengths is

Figure 2. Earth's shape affects how its surface heats. More heat is transferred where the sun's rays strike Earth directly (near the equator) than where they strike Earth slanted (near the poles). Slanted rays transfer less heat largely because they are dispersed over a much larger area than are direct rays. This principle is demonstrated by measuring the area covered by a flashlight's beam on perpendicular and slanted surfaces.



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absorbed by water vapor, ozone, and dust particles; other wavelengths are scattered by air molecules; still others are reflected by clouds. A large portion of the total solar radiation reaching Earth passes through the atmosphere and reaches the ground, where it either is reflected or absorbed. Some land materials—e.g. rocks, snow, and sand—readily reflect most of the sun's radiations. In contrast, bodies of water absorb, rather than reflect, most of the radiations they receive.

Heat Transfer Within the Atmosphere

Overall, Earth's *atmosphere* transmits, scatters, and reflects more radiant energy from the sun than it absorbs. Earth's *surface*, on the other hand, absorbs more solar energy, on average, than it reflects. On knowing only these facts, one might expect the atmosphere to be cooling while the surface heats. However, this is not the case because that imbalance is counteracted by the transfer of heat energy from the surface back to the atmosphere.

This transfer of heat occurs primarily through two different but interactive mechanisms: sensible heating and latent heating. Sensible heating involves the processes of conduction and convection. It accounts for about 23 percent of the overall heat energy transferred into the atmosphere from Earth's surface. Latent heating involves the transfer of heat as a consequence of changes in phase of water. This kind of heating accounts for about 77 percent of the heat transferred from Earth's surface to the atmosphere.

One mechanism of sensible heating, conduction, involves the transfer of heat energy from a warmer object to a cooler one through direct contact. Conduction is the principle underlying why the handle of a fireplace poker becomes hot when just the tip is left in a fire. Heat energy is transferred from the fire to the tip of the poker, and the metal in the poker transfers (i.e. conducts) the heat energy from one end to the other. Within the atmosphere, conduction is significant only in a very thin layer of air that is in immediate contact with Earth's surface.

Convection, on the other hand, is the process of heat distribution within a fluid (such as air), achieved through movement of the fluid itself. Convection is an important process in atmospheric heating. It results from density differences between

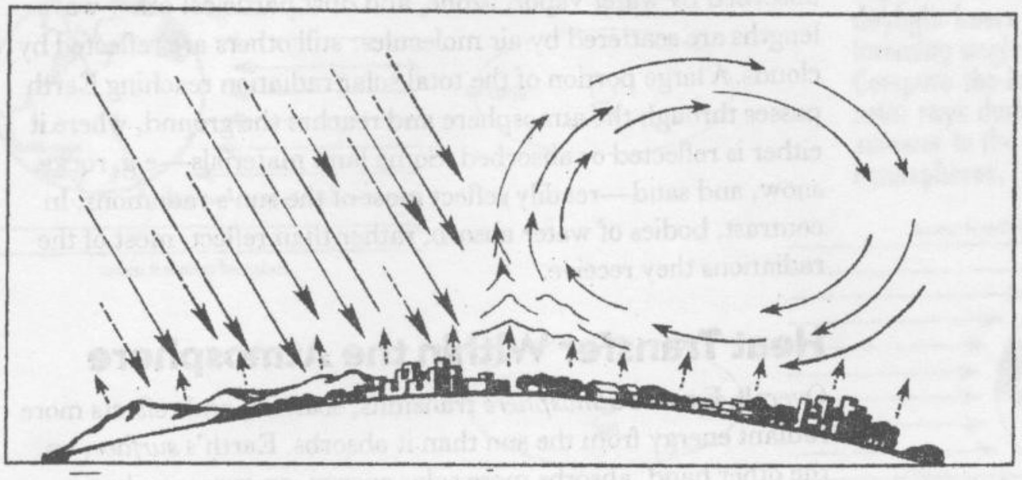

Figure 3. Heat transfer through convection

parcels of air with differing temperatures. The process of atmospheric convection begins when a parcel of air near Earth's surface is warmed. Warner air is less dense than cooler air, thus it rises away from the surface. As it rises, it is replaced by cooler air underneath. That cooler air may, in turn, be warmed by the surface, become less dense and rise, repeating the process. As the warm air rises, it expands and cools, becoming more dense and sinking. Convection currents or cells are established through this process of heating and cooling. This circulation transports heat energy into the atmosphere (see Figure 3). The principle of convection is used in home heating systems, with heaters or hot air vents usually placed at floor level rather than near the ceiling.

The convection process is facilitated by changes in air pressure. As warm air rises, its pressure decreases, causing the air to expand and cool. As cool air sinks, its pressure increases and it is compressed and warmed. The expansional cooling and compressional warming mechanisms are important aspects of the atmospheric convection process.

As previously mentioned, latent heating is a major mechanism for atmospheric heating, much more so than is sensible heating. Latent heat is the heat energy released or absorbed when a substance changes phase: from solid to liquid, liquid to gas, gas to liquid, etc. The latent heat associated with changes in phase of water is described in Figure 4, which illustrates how energy is absorbed and released as one gram of ice at –10° C is transformed into one gram of water vapor at 110° C. As heat energy is applied to the ice, its temperature increases until it

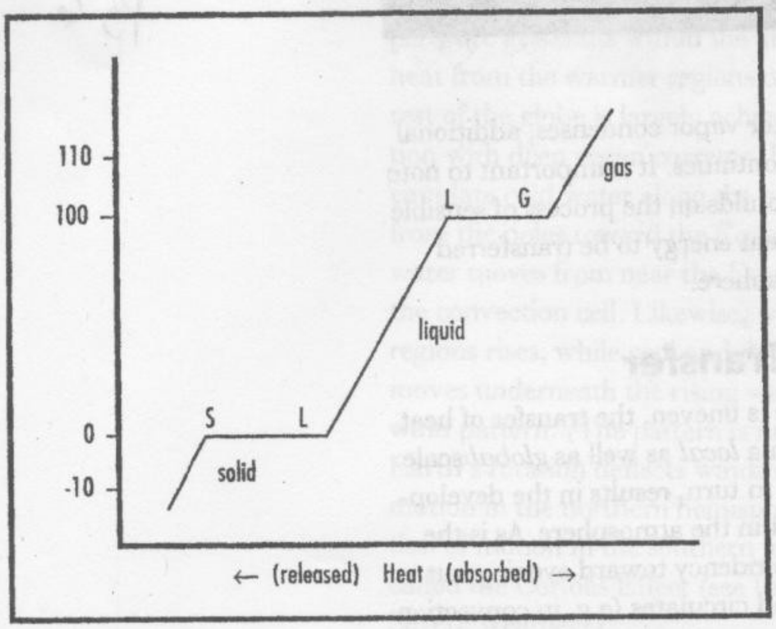

Figure 4. Changes of phase for water

reaches 0° C, the melting point of water. An additional amount of heat energy must be absorbed by the water to change its phase from solid to liquid (between points S and L on the graph in Figure 4). The amount of heat energy required for this transformation is called the *latent heat of fusion*. During the addition of the latent heat of fusion, the temperature of the water remains constant until all of the solid ice is melted into liquid water.

As more heat energy is added to the gram of (now liquid) water, its temperature increases steadily until it reaches 100° C, water's boiling point. Just as with the transition from solid to liquid, an additional amount of heat energy must be absorbed by the water to change its phase from liquid to vapor. This amount of heat energy is called the *latent heat of vaporization*. As during melting, the water's temperature remains constant until all the liquid is evaporated to water vapor, a gas.

As more heat energy is added to the gram of water vapor, the temperature of the gas increases from 100° C to 110° C.

If the process were reversed, the same amount of heat energy that was absorbed when the water was warmed would be released as the water cooled. Heat energy is released when the gas cools, when the gas condenses into liquid water, when the liquid cools, when the liquid freezes into a solid, and when the ice cools further.

Latent heating of Earth's atmosphere occurs as heat energy from the sun causes water on Earth's surface to evaporate into the overlying air. When liquid water from the surface evaporates, the latent heat of vaporization is stored in the water vapor. As air containing the water vapor is warmed by Earth's surface (through conduction and convection), it rises, carrying the water vapor with it. As the air rises, it expands and cools, and when the air becomes saturated some of the water vapor condenses into water droplets. This change of phase releases the stored latent heat of vaporization into the atmosphere, where it warms the surrounding air further and causes it to rise more. As the rising air

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expands and cools, additional water vapor condenses, additional heat is released, and the process continues. It is important to note that the process of latent heating builds on the process of sensible heating and allows considerable heat energy to be transferred from Earth's surface into its atmosphere.

Local Effects of Heat Transfer

Because heating of Earth's surface is uneven, the transfer of heat energy to the atmosphere varies on a *local* as well as *global* scale. Variations in atmospheric heating, in turn, results in the development of temperature gradients within the atmosphere. As is the case in other situations, there is a tendency toward evening out this heat distribution. Air moves and circulates (e.g. in convection cells) as a result. This motion causes winds. From the slightest breeze to a raging hurricane, temperature gradients are responsible for producing wind. It is important to remember, however, that winds can be created on a local as well as a global level.

An example of a local wind system caused by temperature gradients is the sea breeze/land breeze system that develops at a seashore or lake shore (see Figure 5). Bodies of water change temperature more slowly than do land masses. Thus, a sea or lake shore heats faster than does the nearby water. During the day, the air over land tends to be warmer and has a lower density than does the air over the lake or ocean. The warm air above the land rises and the cooler air above the water moves in under the warm air to replace it; a sea breeze is established. At night, the land cools faster than the ocean, with the air above the land becoming cooler and more dense. The relatively warm air over the water rises and a land breeze results as the movement of cool air towards the water occurs.

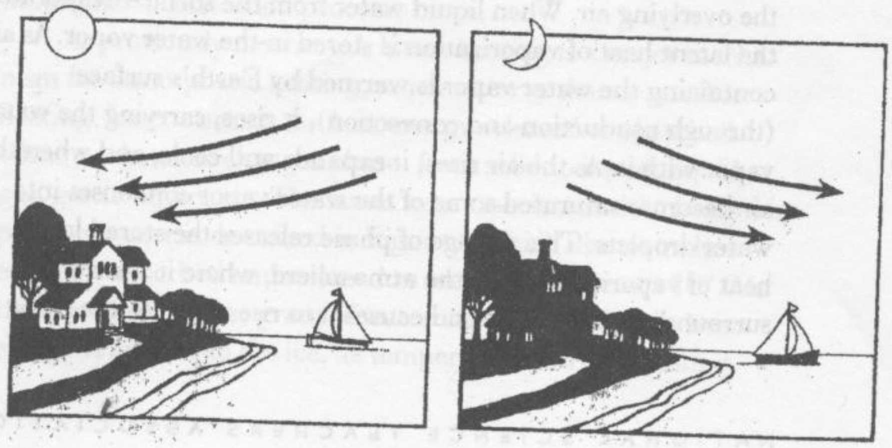

Figure 5. Land and sea breezes result from differential heating and cooling of land and water

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Global patterns of air motion likewise develop from temperature gradients within the atmosphere. The distribution of heat from the warmer regions of Earth's surface throughout the rest of the globe is largely achieved by global winds in combination with deep ocean currents. Deep water ocean currents slowly circulate cold water along the ocean bottom in a general direction from the poles toward the Equator. Toward the surface warm water moves from near the Equator toward the poles to complete the convection cell. Likewise, warm and moist air from equatorial regions rises, while cool and dry air from the poles sinks and moves underneath the rising warm air. This produces a global wind pattern. (The pattern is not strictly a circular cell because Earth's rotation deflects winds to the right of their direction of motion in the northern hemisphere and to the left of their direction of motion in the southern hemisphere. This deflection is called the Coriolis Effect (see Reading 9, "The Inner Workings of Severe Weather").

Air Masses and Fronts

A region or body of air that has consistent temperature and moisture content throughout is called an air mass. When two or more air masses with significantly different properties meet, they do not readily mix. The two masses interact along a boundary called a frontal zone or front. There are several types of fronts, including:

Cold front: A cold air mass advances against a warm air mass, forcing the warm air upward. Clouds, precipitation, and sometimes severe weather result during the passage of a cold front. Cooler, dryer air moves into an area after the passage of a cold front.

Warm front: A warm air mass advances against a cooler air mass, riding up over the cooler air in front of it. Clouds and precipitation in the form of rain, snow, sleet or freezing rain can result during the passage of a warm front. Warmer moist air moves into an area after the passage of a warm front.

Stationary front: A condition where neither the cold air mass nor the warm air mass can advance against the other. The interaction of warm and cool air along the front is responsible for rain, thunderstorms, and snow.

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Frontal zones are responsible for the formation of much of the cloudiness, rain, and snow that occurs over the United States, especially in winter. At a frontal zone, the warmer moist air rises and cools, while cooler, dryer air sinks and warms. As the warm air mass rises, it expands into the lower pressure environment aloft and cools. As it cools, its capacity to hold water vapor decreases, and condensation of water vapor releases latent heat, causing further lifting of the air mass. Winds develop as the warmer rising air results in lower air pressure near Earth's surface and cooler air moves into the low pressure area. A cloud begins to form when the air becomes saturated—i.e. when the dew point temperature is reached (see Reading 8, "Weather's Central Actor: Water").

Although extremely complex, both global and local weather systems are based in relatively simple processes of heat transfer. Fronts, wind patterns, and convection cells each result from the unequal accumulation of thermal energy over Earth's surface and the mechanisms that exist for its redistribution. Understanding these basic processes forms the foundation for understanding the weather around us.