Energy: Warming the Earth and the Atmosphere

Energy, Temperature, and Heat

There are two types of mechanical energy: *kinetic energy,* the energy of motion, and *potential energy*, the energy of position. Kinetic energy resulting from the motion of atoms and molecules is related to *heat energy*. *Radiant energy* is energy in the form of electromagnetic waves created by the Sun. *Internal Energy* is a measure of the total energy of an object due to both *mass* and *temperature.*

Heat is a measure of the energy transfer from one object to another due to a temperature difference between them. The direction of heat flow is always from hot to cold. There are three mechanisms of heat transfer: *Conduction* (transfer of heat between objects in direct contact), *Convection* (transfer of heat by mass movement of fluid), *Radiation* (transfer of heat via electromagnetic waves such as light waves, radio waves, microwaves, etc.).

Temperature may be described as a measure of the average speed (rms) of atoms and molecules within a substance. With a few notable exceptions increasing temperature leads to decreasing density. A very prominent exception is water, which expands and becomes less dense as it begins to freeze. This is the cause of *turnover*, i.e., the fact that ice floats on water. *Absolute zero* is the theoretical lowest point on all temperature scales, and represents the lowest possible temperature. Absolute zero is 0^{o}K, -273^{o}C, or -459^{o}F.

Specific heat is defined as the amount of heat required to raise 1 gram of a substance 1^{o} C. Every substance has a different specific heat. Water, for instance, has a very high specific heat. For this reason, large bodies of water maintain a relatively constant temperature with respect to great swings in ambient temperatures. *Latent heat* is the amount of energy required to change a substance from one *state of matter* to another. There are four distinct states of matter: solid, liquid, gas, plasma.

Condensation is the change of a substance from the gaseous to the liquid state. Energy is liberated in this process due to the *release* of latent heat into the environment. Because of this condensation is referred to as a warming process. *Evaporation* is the change in a substance from a liquid state to a gaseous state. Evaporation is a cooling process because the process of evaporation extracts latent heat from the environment. Condensation and evaporation of water vapor are crucial to all weather related phenomena as these processes release or absorb large amounts of energy in the atmosphere.

Some substances can make noncontiguous phase changes, i.e., "skip" states. It is possible, for example, for dry ice to proceed directly from the solid phase to a gaseous phase without ever becoming a liquid. This process is called *sublimation*. The process by which a substance goes directly from a gaseous phase to a solid phase is called *deposition.*

Heat Transfer in Earth's Atmosphere

Conduction Air is a poor conductor of heat so conduction is not the primary mechanism for heat transfer within the atmosphere except very close to the ground. The shallow layer of air heated due to conduction of heat from the ground is an important element in the dynamics weather.

Convection As the layer at the base of the atmosphere is heated by conduction, the heated air expands (becoming less dense) and rises. A parcel of rising warm air, known as a *thermal*, is capable of transferring heat to the air surrounding it as it rises. Cooler air replaces the departed warm air at the surface beginning a pattern of circulation. This vertical, heat-exchanging circulation is known as convection. *Advection* is the horizontal circulation of heat within the atmosphere.

Rising thermals contain water vapor which condenses from a gaseous state into very small liquid water droplets (cloud droplets) due to the decrease in temperature that accompanies increasing height in the troposphere. This condensation process releases *latent heat* which is an important mechanism by which the atmosphere is heated.

Radiation Electromagnetic waves (e.g., light) do not need air as a medium through which to propagate. The wavelength of an E/M wave (λ) is the distance from the crest of one wave to the next. The wavelengths of visible light range from about 0.4 to 0.7μ. (microns - 10^{-6} meters), 400 to 700 nm (nanometers - 10^{-9} meters), 4000 to 7000 Å (angstroms - 10^{-10} meters). In addition to having wave-like properties, E/M waves also have particle-like properties. Light may be considered as a stream of particles called photons. The energy of an individual photon is given by $E = hc/\lambda$. As λ gets smaller E gets larger. Shorter wavelengths, therefore, represent photons of greater energy than longer wavelengths. Wavelengths from 0.3 to 1.5 microns are important in terms of influencing weather and climate. The Sun's electromagnetic spectrum peaks in intensity at about 0.5 microns.

The earth's atmosphere absorbs almost no heat directly from sunlight because it is largely transparent to sunlight (which is why you can normally see the sun during daylight hours). Instead the sun heats the solid surface of the earth which warms the lower layer of the troposphere due to conduction. Convection, advection and the release of latent heat are then responsible for the distribution of heat energy throughout the atmosphere.

Radiation and Temperature

All objects emit *thermal* radiation. An analysis of thermal radiation shows that it actually consists of a broad spectrum of e/m waves that have a peak intensity related to the temperature of the object. The temperature of a textbook, for example, is about 20^{o} C and its emission spectra peaks in the infrared (long wavelength) region of the spectrum at around 0.7μ. The human eye cannot detect infrared radiation, so the light that one sees coming from a book is reflected light from other sources. Certain objects are both very good absorbers and very good emitters of all radiation in the form of e/m waves. Such objects are called *blackbodies*.

Radiation from the Sun vs. Radiation from the Earth

Most of the Sun's energy is radiated from its surface which is extremely hot (~6000^{o}K ~ $10{,}500^{o}$F). Temperatures within the sun are even higher than this. The sun is an example of a luminous blackbody. *Wein's Displacement Law* relates the temperature of a blackbody to the wavelength of maximum intensity:

$$\lambda_{max}T = 0.2898 \times 10^{-2}\ \mathrm{m \cdot K}$$

where λ_{max} is the wavelength at which maximum emission occurs. For the Sun λ_{max} = 0.2898×10^{-2} m·K/6000^{o}K, which is roughly equal to 0.5μm or 500 nm. This indicates that the sun's radiant energy peaks in the yellow-green portion of the visible spectrum. The earth's surface temperature averages $300^{O}K$ ($81^{O}F$). In this case $\lambda_{max} = 0.2898 \times 10^{-2}$ m·K/$300^{O}K$, which is roughly equal to 10μm, 100 nm, or 10,000 angstroms. This corresponds to emission in the infrared part of the spectrum. As a blackbody, Earth is very efficient at converting sunlight to infrared radiation which is radiated back into space.

The *Stefan-Boltzmann Law* relates the rate at which a black-body emits radiant energy to its temperature times a constant known as the Stefan-Boltzmann constant

($E = \sigma T^4$). If one applies the Stefan-Boltzmann Law to the Sun:

$$E = \sigma(6000^{O}K)^4$$

$$= \sigma\, 1.296 \times 10^{15}\ K^4$$

$$= (5.67 \times 10^{-8} w/m^2K^4)(1.3 \times 10^{15}K^4)$$

$$= 7.3\ w/m^2$$

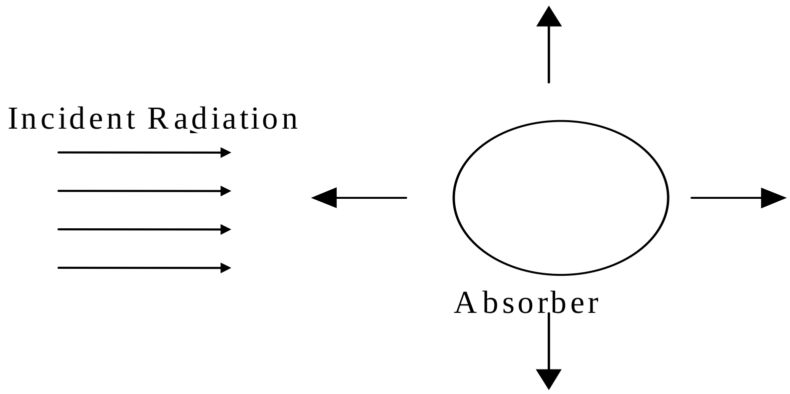
This is a whopping amount of energy when the entire surface area of the sun is taken into account – about 10^{26} watts!

Absorption, Emission, and Equilibrium

The earth absorbs and emits most of the radiation that falls upon it. Recall that objects that have this property are known as blackbodies. The earth is not a perfect blackbody, but it is close enough. The earth is considered to be in *thermal equilibrium* when a balance exists between absorption and emission of thermal radiation.

The earth's *radiative equilibrium temperature* is about 255^{o}K (-18^{o}C, 0^{o}F). This is much lower than the earth's average surface temperature. Why? The earth's atmosphere also absorbs and emits radiation but not in the same manner as a blackbody. The atmosphere is a *selective* absorber of electromagnetic radiation. Selective absorbers are also selective emitters at the same wavelengths. Objects of this type obey *Kirchoff's Law* which states that good absorbers at a particular wavelength are also good emitters at the same wavelength and poor absorbers at a particular wavelength are also poor emitters at that wavelength. Most of the gasses in the earth's atmosphere absorb strongly in the infrared region of the e/m spectrum.

If absorbers of radiation simply absorb and immediately re-emit all of the radiation that falls upon them, what difference do they make in the atmosphere? Consider the following diagram.



As the illustration shows, absorbers of radiation do not emit the radiation they absorb in a preferred direction. Instead they scatter the radiation in all directions including back along the direction of the original wave. Even though the rates of absorption and emission are the same within the absorber, the incident radiation, which was directed before being absorbed, is re-emitted or scattered in all directions. Because the radiation is scattered upon emission, the intensity of the radiation along the original direction is diminished.

As infrared radiation from the earth's surface is radiated back into space it is absorbed and scattered by water vapor, carbon dioxide, methane and other *greenhouse gasses* in the atmosphere. Greenhouse gasses are selective absorbers that allow the sunlight (which is mostly visible) to pass but absorb huge amounts of the infrared radiation that the earth produces. This results in some warming of the atmosphere.

Incoming solar energy

Radiant energy from the sun is the source of energy that drives all atmospheric processes. The *solar constant* is the rate at which radiant energy from the Sun is incident perpendicularly on a surface at the outer edge of the earth's atmosphere. This constant has a value that varies a little with the radiant output of the sun, but is around 1365 – 1372 w/m^2. Once radiant energy from the sun enters the earth's atmosphere it may be *scattered, reflected*, *refracted*, or *absorbed*. The amount of scattering, refraction and absorption depend upon the wavelength of the incoming radiation. *Albedo* is the ratio of incident to reflected radiation at the earth's surface.

The earth's *energy balance* is determined by the amount of incoming vs. outgoing radiation. The earth's energy balance is determined by rates of absorption and reflection in the atmosphere and at the surface of the earth.