Box 2: Solar and Earth Radiation and the Greenhouse Effect (adapted from Mackenzie, 2003)

The principal source of energy at the Earth's surface is from the sun in the form of ultraviolet, visible, infrared and other forms of electromagnetic radiation. Only small amounts of energy come from the Earth's interior. Radiation has been described both in terms of particles (photons) and waves. A basic relationship between the two is

$$E = hc/\lambda = h\upsilon$$

where E is the energy of the photon, λ is the radiation wavelength, h is Plank's constant with a value of 6.626×10^{-34} joule-second, υ is the frequency of the radiation, and c is the velocity of light (2.998×10^{8} m/sec). It can be seen from the preceding equation that photons with shorter wavelengths have higher energies that photons with shorter wavelengths. The quantity of radiation emitted by a radiating body can be described by Planck's law

$$\Psi = a\lambda^{-5}\, e^{(-b/\lambda T)}$$

where Ψ is the energy flux at a given wavelength of radiation λ, a and b are constants, and T is the temperature in Kelvin (K). From the preceding relationship, Wein's displacement law can be obtained as

$$\lambda = 2898/T$$

where λ is the wavelength of the radiation in micrometers, and T is the temperature in K. This law holds true for blackbodies, which are objects that emit or absorb electromagnetic radiation with 100% efficiency at all wavelengths. The radiation emitted by a blackbody is called blackbody radiation. For the sun with an effective surface temperature of 5780 K, the maximum in its radiated energy is at 0.5 micrometers or 500 nanometers in the middle of the visible electromagnetic spectrum (see Box 1). For Earth with an effective surface temperature of 288 K, its peak emission in radiation is at 10 micrometers, well into the infrared region of electromagnetic radiation (Box 1 and Figure 6). The term effective radiating temperature is the temperature that a true blackbody would need to have to radiate the same amount of energy as an object radiates.

It also can be shown from Planck's law that the energy flux emitted by a blackbody is related to the fourth power of the body's absolute temperature in K

$$F = \alpha T^4$$

where F is the flux, T is temperature in K, and α is a constant with a numerical value of 5.67×10^{-8} watts per square meter per K^4 ($W/m^2/K^4$). This relationship is known at the Stefan-Boltzmann law. Our sun with a surface temperature of 5780 K has an energy flux per unit are of 6.3×10^{7} W/m^2. If we treat Earth as a blackbody with an effective radiating temperature of T_E, the total energy emitted by Earth is

$$\alpha T_E^{\,4} \times 4\pi R^2 \text{ (the surface area of the Earth)}$$

where T_E is the effective radiating temperature of Earth, $\pi = 3.1416$, and R_E is the radius of Earth. The total energy absorbed by Earth is

$$\pi R_E^{\,2} \times S \times (1\text{-}A)$$

where S is the solar flux of energy, and A is the albedo (percentage of incoming solar radiation reflected back to space) of Earth. The planetary energy balance to a first approximation implies that the energy emitted by Earth is equal to the energy absorbed by Earth or

$$\alpha T_E^{\,4} = S/4(1\text{-}A).$$

By solving for T_E in the preceding equation, we obtain

$$T_E = [S/4\alpha \times (1\text{-}A)]^{1/4}.$$

This is the effective radiating temperature of Earth. Using the known values of S of 1370 W/m^2, A of 30% or 0.30, and an α of 5.67×10^{-8} $W/m^2/K^4$, the Earth's effective radiating temperature is calculated to be very cold, -18^{o} C (255K). The actual surface temperature is 15^{o} C (288K). The difference between the two temperatures is due the greenhouse effect of the atmosphere. The naturally occurring greenhouse gases of water vapor, carbon dioxide, nitrous oxide, methane, and tropospheric ozone absorb part of the infrared Earth radiation radiated upward from Earth's surface and reemit it in all directions. It is anticipated that increasing greenhouse gas concentrations in the atmosphere would eventually lead to warming of the Earth's surface and decreasing concentrations would lead to cooling.